FUTURE NEUTRON THERAPY FACILITIES

BL1B(p)

MESON HALL

M13(π/μ)

M11(π)

M9(π/μ)

M20(μ)

BL2C(p)

M8(π)

BATHO BIOMEDICAL LABORATORY

T1

T2

CHEMISTRY ANNEX

INTERIM RADIOISOTOPE LABORATORY

42 MeV ISOTOPE PRODUCTION CYCLOTRON

NEUTRON ACTIVATION ANALYSIS

THERMAL NEUTRON FACILITY
FOREWORD

After five long years of negotiations TRIUMF was finally born in 1981 as a legal entity, managed by the four funding universities, formally preserving its status quo as a national facility.

Desperately needed experiments' assembly space and offices were provided by the completion of the proton hall extension and an enlargement to the main office building incorporating a new library and a 150-seat auditorium. Funds for this and a Phase II expansion are being provided by the Government of British Columbia through the Educational Institution Capital Finance Act via the three B.C. Universities. This grant reflects the provincial government's recognition of the outstanding growth in NRC's funding of TRIUMF, the excellence of TRIUMF's research programme and the acute need to provide additional working space.

Third-generation experiments are now under way that will make ever increasing demands on the capabilities of the facilities and technical staff. The most recent addition to the list is a test of charge symmetry in neutron-proton scattering that will require TRIUMF to build the largest frozen spin target in North America in addition to the construction of a dedicated beam line to the apparatus. Such experiments require a cross-Canada team of researchers undertake.

Leaving the project, mid-year, after five successful years as Director was Dr. J.T. Sample. He goes on to become Executive Director of the B.C. Science Research Council and will remain in close contact with his friends and associates at TRIUMF. During his five-year term Dr. Sample saw TRIUMF's NRC funding double and the pure research programme successfully complete first- and second-generation experiments. The TRIUMF Board of Management and staff join in congratulating him on his many triumphs as Director and wish him well in his new endeavours.

Returning to TRIUMF as Director was Dr. E.W Vogt from the University of British Columbia. Erich's association with TRIUMF is well known and, in earlier years, he served terms as Associate Director and later as Chairman of the Board. He now has the opportunity to lead TRIUMF during its mature years of research toward the intriguing possibility of the construction of a kaon factory on the main site.

H.E. Petch
Chairman of the Board of Management
TRIUMF was established in 1968 as a laboratory operated and to be used jointly by the University of Alberta, Simon Fraser University, the University of Victoria and the University of British Columbia. The facility is also open to other Canadian as well as foreign users.

The experimental programme is based on a cyclotron capable of producing three simultaneous beams of protons, two of which are individually variable in energy, from 180-520 MeV, and the third fixed at 70 MeV. The potential for high beam currents - 100 µA at 500 MeV to 300 µA at 400 MeV - qualified this machine as a 'meson factory'.

Fields of research include basic science, such as medium-energy nuclear physics and chemistry, as well as applied research, such as isotope research and production and nuclear fuel research. There is also a biomedical research facility which uses mesons in cancer research and treatment.


The laboratory employs approximately 315 staff at the main site in Vancouver and 13 based at the four universities. The number of university scientists, graduate students and support staff associated with the present scientific programme is about 265.
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INTRODUCTION

For TRIUMF the year 1981 has involved scientific progress in the wide areas of science covered by this report and also considerable preparation for the 1980's and beyond.

The history of TRIUMF is quantized into five-year epochs. The change of administration in the project in the middle of 1981 constituted the beginning of TRIUMF's fourth such epoch.

TRIUMF's first epoch under the directorship of Professor J.B. Warren (1968-71) - this epoch was foreshortened to three years, perhaps because of relativistic time dilation if one considers the speed at which the initial work of the project was accomplished - was concerned with the design of TRIUMF's negative ion cyclotron and the initial facilities. TRIUMF's buildings sprang up out of the coastal forest and the cyclotron components were contracted for. Professor Warren remains very active in TRIUMF's experimental programme - not only spinning off many ideas for applied projects but also in the search for muonium-antimuonium transitions from muonium formed in silicon dioxide powders.

The second epoch (1971-76) was under the directorship of Professor J.R. Richardson of UCLA who originally conceived TRIUMF's negative-ion, sector-focused cyclotron as a meson factory (in 1962). It was under his personal guidance as well as his strong project leadership that the cyclotron and the facility were assembled, the first beam extracted and the experimental programme initiated. Professor Richardson is continuing his very active interest in TRIUMF, particularly with regard to the accelerators which might be added to TRIUMF. Achieving the clearly attainable goal of high reliability also implies much more attention to maintenance than was possible in the early years of funding neglect.

The third epoch (1976-81) under the directorship of Professor J.T. Sample achieved full beam intensity and more adequate base funding whose absence had, heretofore, starved TRIUMF of the experimental facilities and cyclotron maintenance programmes which it needed to be a strong competitor with the other two meson factories (LAMPF at Los Alamos and SIN in Zürich). Professor Sample continues a part-time association with TRIUMF while he serves in his new position as Executive Director of the Research Secretariat of British Columbia.

With TRIUMF's recent growth in personnel the new administration found it necessary to organize TRIUMF into five divisions. It is their activities in 1981 which constitute this annual report.

During the year the central interest turned to TRIUMF's cyclotron. It is a cyclotron which has proven its versatility and its promise, which has shown that it is capable of running sweetly over extended periods. However, the year 1981 did not see any records in microampere hours of beam delivered and achievement of reliable cyclotron operation has become the highest project priority. This is especially important as one begins an epoch of high intensity operation.

The approaches toward cyclotron reliability are described in the report of the TRIUMF Cyclotron Division. It was known during the construction of the cyclotron, when compromises had to be made in design to achieve scheduled construction completion, that after a decade some major redesign of the RF systems - and perhaps portions of the injection system, among others - would be essential. It is. Achieving the clearly attainable goal of high reliability also implies much more attention to maintenance than was possible in the early years of funding neglect.

While firmly focused on future reliability the Cyclotron Division has, in addition, made important strides toward improved polarized ion sources and toward higher intensity (209 μA in a pulsed mode).

The science programme of TRIUMF includes important experiments which involve only a few people and a few hours of running time to others which involve large teams working over many years. Some major programmes are completed; others are under way or just beginning. The interest in basic science spans a wide range from chemical reaction
rates to the structure of elementary particles. The many progress reports included in this report extend over the range of size, state of completion and subject matter.

Most of the experiments discussed in TRIUMF's original proposal (1966) have in fact gone at least as far as then envisioned. The survey of nucleon-nucleon cross sections (BASQUE) is essentially complete over TRIUMF's entire energy range and including all the significant polarization parameters. The interest here has shifted to pion production data and to difficult experiments probing fundamental symmetries.

TRIUMF's superb low energy pion facilities were able to measure elastic scattering with pions of both charges from targets as small as a few milligrams of $^{35}\text{S}$. These experiments are obtaining a major boost from the pion spectrometer provided by the Jülich-Heidelberg group.

The μSR industry continues to provide a large number of interesting results for paramagnetic materials, for silicon powders and many other topics.

An example of success in a small scale experiment is the first determination of the Lamb shift in muonium described later.

On the other hand, the large team (from across Canada and including a number of collaborators from abroad) preparing to take measurements on neutrino-less muon-electron conversion using the time projection chamber (TPC) made significant strides toward data-taking. The RF separator has been run at full power and will be installed in early 1982. All systems appear to be ready. The TPC team has a significant time lead over its international competitors and appears to be ready for its first major data runs early in 1982.

The TPC is part of a general shift in the interests of TRIUMF toward particle physics which, in turn, arise from the major breakthrough achieved over the past seven years in understanding the nature of elementary particles in terms of quarks and leptons and the important questions raised by the theories for this purpose. The impact of those questions - about neutrino masses, the generations of quarks and leptons, the weak and strong interactions, etc. - covers the entire subatomic world but also extends to some of the most fundamental astronomical matters.

It raises the possibility of entirely new viewpoints about atomic nuclei and it provides whole new particle spectroscopies. Is the nucleon a quark bag? Is the nucleus a system of quark bags? TRIUMF's theory group has explored questions across the entire field of intermediate energy science but continues also to provide many of the important new ideas about quark bags.

The increasing interest in particle physics has also led to important participation of TRIUMF scientists in such experiments elsewhere, for example the Asterix experiment on antiprotons at CERN. The flow of people and ideas abroad from TRIUMF is essential for the project and is more than compensated for by the continuing flow into TRIUMF of scientists from many countries.

In the proton hall TRIUMF is finally on the threshold of having a facility unique in the world: a high resolution (70 keV) spectrometer, variable energy beams (180-520 MeV) both polarized and unpolarized. Perhaps for a decade TRIUMF will have unique opportunities which should greatly augment the accomplishments of 1981 and other recent years.

The science programme is based on TRIUMF's major experimental facilities which have received such important improvements in 1981 and the few years preceding. The M11 channel was completed, tuned and used in 1981. Beam line 2C (70-100 MeV high current) was installed and ready for radioisotope research and production. The RF separator for M9 was prepared for installation.

In applied programmes 1981 saw PETT VI (positron emission tomograph) near its scheduled completion. Also the long-awaited CP42 isotope-production cyclotron was delivered at the end of the year.

The Accelerator Research Division of TRIUMF provides much support to the whole facility. Perhaps its major interest in 1981 was progress toward the concepts of an accelerator for a kaon factory. Such a factory would use TRIUMF's present accelerator as an injector and could, in ten years time, boost the energy twenty times or more. The particle physics which could be explored with such a facility was discussed at a TRIUMF workshop in August. Some clear choices for initial experiments emerged, and it was evident that an accelerator between 10 and 15 GeV would be best considering all such experiments. Both synchrotrons and cyclotrons for this energy
regime continue to be explored. Such a new facility would use many of TRIUMF's present spectrometers and beam lines and would augment opportunities in most of TRIUMF's present fields. A proposal in a year's time is envisaged.

TRIUMF is a national facility funded by an NRC contribution and managed as a joint venture by four universities. At the end of 1981 the legal documents establishing the joint venture were finally completed (the time span of this project was much greater than that of any TRIUMF experiment).

In addition to the administration changes noted above the accession of the former Associate Director, Karl Erdman, to TRIUMF's Board of Management should be noted. Karl continues to be associated strongly not only with the pion-nucleus experimental programme but also with almost every aspect of facility development. After years of distinguished service Harry Gunning retired from the Board of Management and was replaced by Dr. G. Kaplan, Vice-President (Research) of the University of Alberta.
SCIENCE DIVISION

INTRODUCTION

Forty-four contributions describing either new results or preparation of experiments which will be mounted during the coming year have been submitted to this report. Eleven of these experiments used muon spin rotation techniques and ten utilized the variable energy proton beam.

Very close co-operation has developed between the experimental and theoretical programs, particularly in the area of pion production and the application of the cloudy bag model to pion-nucleon and nucleon-nucleon scattering. Other areas of the experimental program benefiting from this close co-operation are \( \pi \)-nucleus scattering, electromagnetic interactions (\( np + d\gamma \)) and NN bremsstrahlung, as well as kaon and hypernuclear studies relevant to possible future developments.

All the originally envisioned beam lines are now available for experiments. The areas of research using the secondary meson channels include \( \pi \) absorption (Expts. 9, 140, 145), \( \pi \) decay (Expt. 52), \( \mu \) decay (Expts. 104, 134, 137, 185), muonium formation (Expt. 165), \( \mu \) fission (Expts. 89, 151), \( \pi \) scattering (Expt. 178) and pionic atoms (Expt. 127). M8 has been used exclusively for medical research except for a calibration experiment (Expt. 102) which measured the absolute cross section of \( ^{12}\text{C}(\pi^\pm, \pi^0\text{N})^{11}\text{C} \) reactions and energies from 30 to 100 MeV for \( \pi^+ \) and to 90 MeV for \( \pi^- \).

M9 has operated with the DC separator for low energy \( \pi \) and \( \mu \) experiments. The \( \pi + e\nu \) experiment (Expt. 52), measuring values of the pion branching ratio

\[
R = \frac{\Gamma(\pi^+e\nu + \pi^0e\gamma)}{\Gamma(\pi^+\mu\nu + \pi^0\mu\gamma)},
\]

is precisely in agreement with the value predicted using the Weinberg-Salam-Glashow unified gauge theory of weak and electromagnetic interactions. The RF separator is being installed to provide increased flux for the \( \mu + e\gamma \) experiment (Expt. 104) using the TPC. This experiment will provide further tests of weak interactions.

M11 is available to provide pions above 50 MeV and M13 for pions and muons below 50 MeV. Considerable progress has been achieved in commissioning these two channels. Interesting results have been obtained with M13. In the muonium formation experiment (Expt. 168) photons from de-excitation of muonium in the 2S metastable state were seen for the first time. The low energy \( \pi^- \) scattering results (Expt. 178) on \( ^{32}\text{S} \) and \( ^{36}\text{S} \) are consistent with a 100 fm difference between the neutron radii of the two nuclei. Analysis of the \( \mu^+ \) lifetime measurement (Expt. 137) is in progress and expectations are that an accuracy of 0.07 ns in 2200 will be achieved.

Installation of the RF separator on M9 and the full low energy \( \pi \) program scheduled on M13 will restrict the \( \mu\text{SR} \) program in the future. This active program includes the study of muons in solids (Expts. 71, 78, 79, 138, 149, 154, 191), a study of ferromagnetic metals (Expt. 122), muonium formation in gases (Expt. 147) and a study of muonium in condensed media (Expts. 150 and 157).

Proton interactions with nuclei and nucleons are studied using beam lines IB, 4A, 4B and 4C. Areas of research include pion production (Expts. 10, 132, 158, 174, 184), tests of charge symmetry in np elastic scattering (Expt. 121), proton elastic scattering (Expts. 113, 152, 153), proton-induced reactions (Expts. 114, 124, 131, 144, 162, 170), studies of nuclear fragments (Expts. 3, 117, 142, 143), and radiochemistry (Expt. 189).

Pion production is being studied vigorously, both experimentally and theoretically. NN production is being studied in the pp + \( \pi^+d \) channel (Expt. 132) and the spin dependence of the reaction pp + p\( n\pi^+ \) (Expt. 174) is being studied using a polarized beam and a polarized proton target. In the case of pion production from nuclei (Expt. 10) none of the theoretical models developed to date has consistently fitted both the analysing power and differential cross-section data simultaneously. Improved facilities for studying these processes are being considered.
The analysis of the data taken at $T^\pi = 27.4$ and 39.3 MeV has been completed. The results on the reaction $\pi^- p \rightarrow \gamma n$ were presented in last year's annual report as well as at the Versailles conference and the workshop at Liblice, Czechoslovakia. They are compatible with many calculations based on the Born terms but our results have pointed out that the multipole analysis of Smith and Zagury predicts cross sections which are too low in our energy region. This seems to be caused by their selection of data for low energies, and so it is hoped that our results will be a useful addition to their data bank.

At the same time we obtain data on the reaction $\pi^- p \rightarrow \pi^0 n$ and this has also been analysed. In Fig. 1 we illustrate a typical $\gamma$-spectrum obtained in our NaI crystal TINA. The radiative capture is clearly separated from the charge exchange reaction. At a single angular setting of the $\gamma$-ray detector, the energy spectrum of the $\gamma$-rays from the $\pi^0$-decay provides information on the $\pi^0$ angular distribution. In Fig. 2 this point is illustrated for $\theta_{\gamma}(\text{lab}) = 60^\circ$ and $T^\pi = 27.4$ MeV. Note that the $\gamma$-rays from $\pi p \rightarrow \gamma n$ in flight have already been subtracted off. The spectrum is complicated by the appearance of $\gamma$-rays from stopped pions. (This effect is much smaller at $T^\pi = 39.3$ MeV.) The contamination of the spectrum is caused by less than 1% of the passing pions which scatter and stop in the target. The problem is that each stopped pion produces $\gamma$-rays whereas less than 1% of the in-flight pions produce a $\gamma$-ray. In the figure one can see the contribution to the energy spectrum of the $\gamma$-rays from the different Legendre polynomials of the $\pi^0$ angular distribution.

From these results we can obtain a global fit to the data at every angle for one specific pion energy, and thereby produce a result which can be compared with phase-shift analyses.

Perhaps the most interesting point to emerge is that our data refute the recent phase-shift analysis of Zidell, Arndt and Roper [Phys. Rev. D 21, 1289 (1980)]. Scattering lengths from various sources are compared in Table I and it can be seen that our results are compatible with some previous indirect derivations, but this recent phase-shift analysis is in lonely isolation. There is also evidence from dispersion relations that the low-energy dependence of their phase shifts is not correct [Koch, Rome Workshop on Low and Intermediate Energy Kaon-Nucleon Physics, 1980].

In the summer, some considerable effort was devoted to improving the energy resolution...
Table I. Preliminary experimental results of the s-wave scattering length $S_{11}-S_{31}$, for the charge exchange reaction $\pi^- p \rightarrow ^3H n$ (given in natural units, $h/\mu c$).

<table>
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<th>Energy</th>
<th>Value</th>
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<tr>
<td>27.4 MeV</td>
<td>0.265 ± 0.020</td>
</tr>
<tr>
<td>39.3 MeV</td>
<td>0.269 ± 0.020</td>
</tr>
<tr>
<td>Duclos et al.</td>
<td>0.270 ± 0.014</td>
</tr>
<tr>
<td>Zidell et al.</td>
<td>0.302 ± 0.006</td>
</tr>
<tr>
<td>Rowe et al.</td>
<td>0.283 ± 0.008</td>
</tr>
<tr>
<td>Koch and Pietarinen</td>
<td>0.274 ± 0.005</td>
</tr>
<tr>
<td>Bugg et al.</td>
<td>0.262 ± 0.004</td>
</tr>
<tr>
<td>Spuller et al.</td>
<td>0.263 ± 0.005</td>
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</table>

The existence of multiple, seemingly redundant, generations of fundamental particles is one of the major puzzles facing particle physicists. There are at least three lepton generations or flavours, which have in common a set of remarkable features including identical weak interactions, absence of strong interactions, symmetry in the generation structure with the quark sector, absence of flavour-changing interactions, and existence of a conserved additive lepton number for each generation. These aspects of the lepton families are incorporated in the Weinberg-Salam-Glashow (WSG) unified gauge theory of weak and electromagnetic interactions [Weinberg, Phys. Rev. Lett. 19, 1264 (1967), ibid. 27, 1688 (1971); Salam, in Elementary Particle Theory: Relativistic Groups and Analyticity (Wiley, New York, 1969)].

The equality of the weak coupling strengths for the e- and $\mu$-type particles is known as the principle of electron-muon universality or lepton universality. This is built into the WSG theory. Lepton universality leads directly to the requirements for the V-A doublet structure of the lepton sector as well as to the requirement for massless neutrinos [Gatto and Sartori, Phys. Lett. 67B, 467 (1977); Kim and Kim, Phys. Lett. 79B, 278 (1978)]. The absence of lepton flavour-changing interactions in the basic WSG model is also directly related to the assumption of massless neutrinos.

In spite of its extraordinary success in describing observed weak and electromagnetic phenomena, there are still important unanswered questions associated with the standard model; many of these are related to the lepton generation puzzle. The open problems include the neutrino mass spectrum which has important cosmological implications, lepton mixing and neutrino oscillations, CP violation, and the fundamental relationships between quarks and leptons within each generation and between the generations themselves.

Many diverse extensions and additions to the standard model have been proposed to deal with these important issues. One common aspect of the models (such as L-R symmetric models, grand unified theories (GUT) based on SU(5) and O(10), multigenerational GUT, and horizontal gauge models) is that, in general, conservations of baryon number and lepton number are not expected since there is apparently no appropriate global symmetry principle associated with them. In addition, lepton universality, although widely accepted, also has no compelling theoretical foundation. It may or may not be a feature of nature depending on such things as the masses of the neutral leptons, the number and couplings of Higgs scalars, and the existence of exotic gauge bosons.
In this annual report two experiments dealing with the lepton generation problem are described:

1) measurement of the decay $\pi^+ + e^-$
2) the search for muon-electron conversion (Expt. 104, p. 10)

The $\pi^+ + e^-$ branching ratio provides the best available test of lepton universality in the context of the Weinberg-Salam-Glashow model, since the radiative corrections are well determined to the level of $\pm 0.3\%$, in spite of the complications of the strong interactions [Marciano and Sirlin, Phys. Rev. Lett. 36, 1425 (1976)]. The theoretical prediction for the $\pi^+ + e^-$ branching ratio is

$$R = \frac{\Gamma(\pi^+ + e^- + \nu_e)}{\Gamma(\pi^+ + \nu + \nu + \nu)} = 1.233 \times 10^{-4} \left(\frac{f_{\pi e}}{f_{\pi \mu}}\right)^2,$$

(1)

where $f_{\pi e}$ and $f_{\pi \mu}$ are the pion decay constants.

The principle of electron-muon universality in pion decay holds under the assumption that the basic interaction current is of the V-A type if $f_{\pi e} = f_{\pi \mu}$. If a pseudoscalar current were dominant in $\pi^+ + \ell\nu$ decay rather than the axial vector current, then the value of the branching ratio (1) would be radically different:

$$R_{PS} = \left(\frac{m_\pi^2 - m_e^2}{m_\mu^2 - m_e^2}\right)^2 = 5.49.$$

(2)

A new measurement of the $\pi^+ + e^-$ branching ratio has recently been carried out at TRIUMF using the NaI crystal technique. The set-up for the TRIUMF experiment is shown in Fig. 3. Pions at a rate of $\sim 2 \times 10^5/s$ stopped in a five-layer plastic scintillator target (B1-B7), the outer surfaces of which were used to absorb muons from $\pi^+ + \mu^- + \nu_e$ decay. Positrons from $\pi^+ + e^- + \nu_e$ and $\mu^+ + e^- + \nu_e$ decays were detected by a scintillation telescope (T1-T3) with solid angle acceptance $\Delta\omega/4\pi \sim 1\%$ preceding the 46 cm $\phi \times 51$ cm NaI(Tl) crystal TINA. In beam studies, TINA's energy resolution was observed to be $\Delta E/E = 3.5\%$ (FWHM) for 70 MeV positrons. Since NaI detectors are sensitive to both charged particles and gamma rays, this measurement included the IB photons which were emitted generally in the direction of the positrons in $\pi^+ + e^+ + \nu_e$ and $\mu^+ + e^- + \nu_e$ decays. The measured ratio was then

$$R = \frac{\Gamma(\pi^+ + e^+ + \nu_e)}{\Gamma(\pi^+ + \mu^+ + \nu_e)}.$$

(3)

The numbers of positrons from decays at rest were determined by summing the counts in the NaI energy spectra in the 70 MeV region for $\pi^+ + e^-$ and the region <53 MeV for $\pi^+ + e^-$ and $\mu^+ + e^-$. The observed timing spectra for events in the $\pi^- + \mu^-$ and $\pi^+ + e^-$ regions, respectively.

The branching ratio was determined using the method of Di Capua et al. Positrons were detected using two identical time intervals of 25 ns, one beginning at $t_0 \approx 6$ ns after the arrival of the pion and the second beginning $t_\pi = 174$ ns or 6.7 pion lifetimes later. Since the pion lifetime $t_\pi = 26$ ns is short compared to the muon lifetime $t_\mu = 2200$ ns, the second interval essentially contains only positrons from the $\pi^+ - \mu^- + e^-$ chain (N$^2_{\pi\mu e}$) whereas the first interval contains events from both $\pi^- - \mu^- + e^-$ (N$^2_{\pi\mu e}$) and $\pi^- + e^-$ (N$^2_{\pi e}$) origins. The branching ratio can then be expressed as

$$R = \frac{\lambda_\mu}{\lambda_\pi + \lambda_\mu} \left(1 - \frac{-(\lambda_\pi - \lambda_\mu)t_\pi}{N_\pi e} e^{-\frac{(\lambda_\pi - \lambda_\mu)t_\pi}{N_\pi e}}\right),$$

(4)
where $\lambda_\pi$ and $\lambda_\mu$ are the pion and muon decay rates, respectively. In principle, $R$ is independent of several important sources of possible systematic uncertainties including the displacement of the first interval from the arrival time of the pion $t_0$, the positron detector solid angle, the absolute width of the two time gates (as long as they are identical) and the fraction of muons in the beam initially.

Figure 5 shows the positron spectrum for the early time interval in which the resolution of the $\pi + e^+ v_e$ peak is $\Delta E/E \sim 5.5\%$ FWHM. Figure 6 gives the pure $\mu^+ + e^+ v_e \nu_\mu$ spectrum for the late time bin, and Fig. 7 shows the pure $\pi + e^+ v_e$ spectrum derived by subtracting a normalized $\mu$ decay spectrum from the early time spectrum of Fig. 5. There are approximately $2 \times 10^4$ counts in the $\pi + e^+ v_e$ peak. In order to determine the branching ratio it is necessary to calculate the effects due to loss of $\pi + e^+ v_e$ limits in the NaI tail region, multiple scattering, energy straggling, Bhabha scattering, positron annihilation, and radiative processes. The preliminary branching ratio obtained is

$$R = 1.230 \pm 0.014 \times 10^{-4}.\quad (5)$$

This result can be interpreted as a confirmation of electron-muon universality within the context of the WSG model. By comparing Eq. (5) with Eq. (1) it is found that

$$\frac{f_{\pi^0}}{f_{\pi^0}} = 0.998 \pm 0.006.\quad (6)$$

Agreement between the experiment and the WSG theory at the level of $-0.6\%$ places severe constraints on models which incorporate violation of lepton universality. Alternatively, a limit on the contribution of a pseudoscalar current can be deduced:

$$f_p < (0.002 \pm 0.006)f_{\pi^0}m_{\nu_e}$$

(90% confidence level) \quad (7)

where $f_p$ is the pseudoscalar coupling constant.

Search for heavy neutrinos participating in the decay $\pi + e^+$

The positron spectrum (Fig. 7) obtained in the $\pi + e^+$ branching ratio measurement can also be used to obtain limits on the existence of medium mass neutrinos coupled to electrons. The decay $\pi^+ + e^+ v_e$ is helicity suppressed in the V-A theory by a factor $\sim 10^4$ for the case of massless neutrinos. For this reason, even a small contribution from an unsuppressed massive neutrino decay $\pi^+ + e^+ \nu_H$ with say $m_{\nu_H} \sim 80$ MeV could be observable in the positron energy spectrum. We have carefully examined the positron spectrum from $\pi$ decay for evidence of additional peaks in the region below the value expected for zero mass neutrinos.

Due to the short range of the decaying muons in the normal $\pi + \mu\nu$ mode, a large contamination of positrons from the decay $\mu^+ + e^+ \nu_\mu \nu_e$ is unavoidable even if the time of inspection is restricted to the first few tens of nanoseconds after a pion has stopped in the target. This contamination can be subtracted because of the availability of large pure samples of muon decay events at times much larger than the pion lifetime. Below 50 MeV/c the statistical accuracy of the $\nu_e$ distribution is limited by the statistics on the muon decay spectrum.

Evidence for a massive neutrino component in the $\pi + e^+$ decay would be an extra peak in the positron spectrum with a line shape similar to the one observed for the most prominent $\nu_e$ for which $m_{\nu_e} \geq 0$. 

8
**Fig. 5.** Decay positron energy spectrum during the early time bin (6-31 ns).

**Fig. 6.** Decay positron spectrum during the late time bin (173-198 ns).

**Fig. 7.** The $\pi \rightarrow e^+ \nu$ spectrum with the $\pi \rightarrow e^+ \nu$ background subtracted.

**Fig. 8.** Limits on $R_{e1}$, the coupling strength of a mass eigenstate $i$ to the electron neutrino weak eigenstates. (a) limits obtained from the search for monoenergetic peaks in $\pi^+ \rightarrow e^+ \nu$, (b) limit obtained from the $\pi^+ \rightarrow e^+ \nu$ branching ratio, and (c) limit from $K^+ \rightarrow e^+ \nu$ decay.

<table>
<thead>
<tr>
<th>$M_{\nu}$ range (MeV)</th>
<th>Branching ratio relative to $\pi \rightarrow e^+ \nu$ (%)</th>
<th>$10^{-1}$</th>
<th>$R_{e1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>45-60</td>
<td>0.4</td>
<td>$6.5 \times 10^3$</td>
<td>$6.4 \times 10^{-7}$</td>
</tr>
<tr>
<td>60-74</td>
<td>0.4</td>
<td>$1.1 \times 10^4$</td>
<td>$3.7 \times 10^{-7}$</td>
</tr>
<tr>
<td>74-80</td>
<td>6</td>
<td>$1.1 \times 10^4$</td>
<td>$5.6 \times 10^{-6}$</td>
</tr>
<tr>
<td>80-92</td>
<td>6</td>
<td>$1.1 \times 10^4$</td>
<td>$5.6 \times 10^{-6}$</td>
</tr>
<tr>
<td>92-103</td>
<td>5</td>
<td>$8.6 \times 10^3$</td>
<td>$5.8 \times 10^{-5}$</td>
</tr>
<tr>
<td>103-112</td>
<td>4</td>
<td>$7.4 \times 10^3$</td>
<td>$5.4 \times 10^{-6}$</td>
</tr>
<tr>
<td>112-122</td>
<td>4</td>
<td>$4.7 \times 10^3$</td>
<td>$8.6 \times 10^{-6}$</td>
</tr>
<tr>
<td>122-131</td>
<td>4</td>
<td>$2.1 \times 10^3$</td>
<td>$1.9 \times 10^{-5}$</td>
</tr>
<tr>
<td>131-139</td>
<td>3</td>
<td>$4.2 \times 10^2$</td>
<td>$7.2 \times 10^{-5}$</td>
</tr>
</tbody>
</table>
A peak searching program was adapted to our purposes to search for extra bumps on the tail of the \( \mu e \) line shape in the subtracted spectrum. The data were smoothed using a truncated Fourier analysis. Then, the program was asked to locate peaks with areas larger than half the statistical error. The confidence level for retrieving peaks of given areas was established by randomly introducing spurious peaks. For each neutrino mass region Table II gives the branching ratio limits relative to \( \pi + e^\nu \) \((m_{\nu e} = 0)\) for which no peaks are observed at the 90% confidence level, the kinematical and helicity suppression factor \( \rho^{-1} \) and the relative coupling strength \( \rho_{ei} = |U_{ei}|^2 \) as described by Shrock. \( U_{ei} \) is defined by the equation

\[ v_{ei} = \sum_{j=1}^{n} U_{ej} v_j. \]

No evidence for heavy neutrino states has been found. The results are presented in Fig. 8 (curve a), where for each \( v_i \) mass state we have plotted the 90% confidence level limit on the relative coupling strength \( \rho_{ei} = |U_{ei}|^2 \) to the electron weak eigenstates. The analysis of the \( K_{e2} \) decay data produced upper bounds on \( \rho_{ei} \) in the region \( 80 < m_{\nu} < 160 \) MeV represented by curve c on Fig. 8. Following Shrock [Phys. Lett. 96B, 159 (1980); see also Lee and Shrock, Phys. Rev. D 16, 1444 (1977) and Bailin and Dombey, Phys. Lett. 64B, 304 (1976)], an upper limit on the coupling strength can also be deduced by comparing the measured \( \mu e \) \( \nu \mu \nu \) branching ratio Eq. (5) with the theoretically predicted value as a function of massive neutrino coupling. The result is shown as curve b in Fig. 8.

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Experiment 104
Search for muon electron conversion

A time projection chamber (TPC) has been developed for use in an experimental search for muon-electron conversion \( \mu^- + \nu \mu + \text{nucleus} \rightarrow e^- + \nu e + \text{nucleus} \) in which a muon bound in an atomic orbit produces an electron at momentum \( P \approx (105-B) \) MeV/c, where \( B \) is the muon binding energy. Important backgrounds which could produce electrons at the searched-for momentum come from bound muon decay \( \mu^- \rightarrow e^- + \nu e + \nu \mu + \text{nucleus} \), radiative muon capture and subsequent asymmetric photon conversion to \( e^- e^\prime \), cosmic rays and pion contaminations in the muon beam.

The TRIUMF TPC is a large volume drift chamber placed in a magnetic field parallel to the drift direction. The ionization track of a particle which has passed through the chamber drifts towards an end-cap, where there are (p.w.) detectors (see Fig. 9). These serve to measure the \( x \) and \( y \) coordinates of track segments orthogonal to the drift direction, as well as the \( z \) coordinate.

In addition to bending the particles so that momentum can be measured, the magnetic field serves to reduce diffusion of the ionization electrons in the plane transverse to the drift direction; the electrons spiral tightly along the magnetic field lines. Longitudinal \((z)\) diffusion is effectively unchanged. The transverse width of a distribution of drifting ionization electrons varies as \( \sigma = \sqrt{2DL/w} \), where \( L \) is the drift length, \( W \) is the drift velocity, and \( D \) is the diffusion coefficient. In the presence of parallel \( \parallel \mathbf{E} \) and \( \mathbf{B} \), \( D \) depends on the cyclotron frequency \( \omega = \frac{m_e B}{2e} \).
eB/m_0 \text{ and the mean time between collisions } \tau \text{ in the following way:}

\[ D(B) = \frac{D(0)}{1 + \omega^2 \tau^2} \quad . \tag{1} \]

Thus, there can be significant reductions in diffusion when \( \omega \tau \) is large. With our chamber at normal operating conditions mentioned above, we have found that \( \omega \tau \sim 2 \) and \( w = 7 \text{ cm/ps} \).

Local non-uniformities in \( \vec{E} \) and \( \vec{B} \) will cause ionization electrons to drift in the direction \( \vec{E} \times \vec{B} \neq 0 \). The magnet for the TRIUMF TPC was shimmed so that magnetic field was uniform to within \( \pm 0.5\% \) of the central field value. Calculations of electrons drifting in this field showed that the position deviations due to magnetic field non-uniformity would be \( <100 \mu \text{m} \) from those expected for \( \vec{E} \times \vec{B} = 0 \) for the maximum 35 cm drift length. This is within the errors expected due to other sources (e.g., diffusion) described below.

The effects of \( \vec{E} \times \vec{B} \neq 0 \) in the neighborhood of the end-cap p.w. detectors are potentially much greater than 100 \( \mu \text{m} \). To qualitatively examine the effects of non-zero \( \vec{E} \times \vec{B} \) assume \( V_{\text{drift}} = \text{constant} \) and \( \omega \tau = \text{constant} \); consider a trajectory which crosses the p.w. at angle \( \theta \) in the x-y plane as shown in Fig. 10. When \( B = 0 \) the charge arriving on the wire is distributed over a distance \( t = d |\tan \theta| \). However, when \( B \neq 0 \) the ionization trail is projected by an angle \( \alpha = \tan^{-1}(\omega \tau) \) so that the width of the charge distribution on the wire is changed to

\[ t = d |\tan \theta + \omega \tau| \quad . \tag{2} \]

For \( \theta > -\tan^{-1} \omega \tau/2 \) the distribution is widened relative to the \( B = 0 \) case. This results in degradation of the position resolution due to the statistical population of the \( n \approx 80 \) ionization electrons deposited along the track segment by a minimum ionizing particle traversing the gas. For \( \theta < -\tan^{-1} \omega \tau/2 \) the projection is narrowed, thereby improving the intrinsic spatial resolution. For other TPC systems, such as that developed at Berkeley which operates at higher pressure, the statistical degradation of resolution will be reduced.

Data were taken with high energy cosmic ray particles which traversed the chamber and fired two opposite outer scintillation trigger counters. The time of arrival and the z coordinates of each track segment at a p.w. were determined using a leading edge discriminator and a TDC. After amplitude compensation the resolution was \( \sigma_z \sim 1 \text{ mm} \). Each cathode pad was connected to an amplifier and charge-sensitive ADC so that the distribution of induced charge could be determined. An average of \( \sim 8 \) pads was involved in the determination of each x coordinate for a track crossing at \( \sim 30^\circ \) to the anode wire.

Since most of the data were collected in the presence of a magnetic field, the set of x and y positions for a given event were fit to a second-order polynomial which approximated the trajectories for energetic cosmic-ray particles with large radii of curvature. The fitting was done by minimizing the perpendicular distance from the measured point to the fitted track in the x-y plane. The average position resolution in the x-y plane is characterized by \( \sigma \), the variance of the measured position relative to the fit in the direction perpendicular to the track. A linear fit was done for the z coordinates.

The suppression of diffusion in the presence of parallel electric and magnetic fields is demonstrated for cosmic-ray tracks in Fig. 11, which shows the z dependence of the fitted width of the cathode charge distribution \( w \) averaged over the chamber for \( B = 0 \) and \( B = 8.5 \text{ kG} \). The data are fitted in the form

\[(\text{FWHM})^2 = a_1^2 + a_2^2 \text{ z ,} \tag{3}\]
where the constant $a_1$ represents the minimum intrinsic width of the measuring system and $a_2 = \sigma$, the diffusion coefficient.

In Fig. 12 the effects of $E \times B \neq 0$ in the neighborhood of the p.w. can be seen by examining the variation of $w$ with the angle of wire crossing $\theta$ in the x-y plane for a fixed drift distance. The distribution of $w$ is symmetric around $\theta = 0^\circ$ when $B = 0$. However, a marked asymmetry can be seen for $B \neq 0$. The solid line represents a fit to the data for the case $B = 8.5$ kG using the function

$$w(c_1, c_2, \theta) = (c_1^2 + c_2^2(\tan \theta + \omega \tau)^2)^{1/2}, \quad (4)$$

where $c_1$ is the natural width for tracks crossing at $0^\circ$ with $B = 0$, and $c_2$ is the effective entrance slot width. The minimum in $w$ is at $\theta = 30^\circ$. The large variations in the widths of charge distributions due to $E \times B$ effects could result in increased minimum separation required for multi-particle detection in TPC-type detectors.

**Experiment 121**

*Test of charge-symmetry in n-p scattering*

During the past year a great deal of progress has been made in the manufacture of the instrumentation needed for the charge-symmetry experiment. Construction has been completed of the four split-plate secondary emission monitors which are required to determine the incident proton beam position and direction on the LD$_2$ target. Tests showed that with a feedback system to a steering magnet the proton beam can be locked in position within ±0.2 mm. The incident proton beam polarimeter and proton beam energy monitor have been assembled in a new lid for an existing scattering chamber located upstream of the LD$_2$ target. A new spin precession solenoid will be put in the beam line shortly. The refurbished LD$_2$ target has been installed during the last shutdown. Testing of its control system is in progress. New steel inserts for the 9° neutron beam port are being machined. These new inserts will provide a tighter collimation.
Fig. 13. Charge symmetry experiment arrangement on the proton hall floor.
of the neutron beam, more in accord with the dimensions of the frozen spin polarized hydrogen target. The second neutron spin precession dipole magnet is under construction. Installation will be possible in May 1982. Good progress has also been made with the construction of the various components of the frozen spin polarized hydrogen target (to be built by TRIUMF): the cryostat, the dilution refrigerator, the \(^3\)He pumping system, the NMR system, and the rf system. The polarizing superconducting solenoid is being ordered from a commercial firm. Work has still to start on the holding field magnet and the \(^4\)He pumping system. The neutron beam polarimeter is being assembled; a neutron beam profile monitor has been designed. The second neutron detector array is also being assembled; refurbishing of an existing neutron detector array will start early in 1982. Construction of eight 60 cm \(\times\) 60 cm delay line chambers is under way with four chambers scheduled for delivery at the end of the current calendar year, and the remaining four chambers by July 1, 1982. The proton range counters and booms to mount the time-of-flight start counters, delay chambers and the proton range counters have arrived on site ready for installation. A review of the systematic errors has been published as a TRIUMF design note (DN-TRI-81-7). Extensive Monte Carlo simulations of the experiment are in progress. Work is continuing on a software package which allows data acquisition with an Eclipse computer and off-line analysis with either an Eclipse or a VAX computer.

Layout of the apparatus is shown in Fig. 13.

Experiment 132
Measurement of \(pp + d\pi^+ d\pi^+ d\pi^+\)

In this past year Expt. 132 has emerged from a proposal on paper to an apparatus now capable of taking a considerable amount of data on the \(pp + d\pi^+\) differential cross section. An existing rectangular vacuum box for the 4BT1 target position has been used as the Expt. 132 scattering chamber. To this a forward scattering horn was built and attached. This allows for the detection of the forward \(\pi^+ d\pi^+\) reaction.

In order to monitor the actual beam hitting our target a plate was built holding two detector arms consisting of two scintillator counters each. Both arms are at 42° lab scattering angle and monitors the pp elastic cross section from our CH\(_2\) target by placing both arms in coincidence. The angle of 42° was chosen as the monitor counting rate will not change with beam polarization. This is an important consideration for the polarized beam experiment, Expt. 192, which now has EEC approval.

A complete angular distribution has been measured for 500 MeV at 16 settings between \(\cos^2\theta = 0.9\) and \(\cos^2\theta = 0\) in the c.m. system in both the forward and backward hemispheres. At least 40,000 good \(pp + d\pi^+\) (all detectors present) events were taken at each point. Analysis is presently under way.

Experiment 137
Lifetime of the \(\mu^+\)

During the months of May to August the William and Mary group ran a total of 7 weeks on the M11 and M13 channels at TRIUMF, on a precise measurement of the \(\mu^+\) lifetime.

The technique for the measurement of the lifetime consists of recording the time distribution of energetic \(e^+\) decay events following \(\pi^+\) or \(\mu^+\) stops in a large water Čerenkov counter. The presence of an \(e^+\) decay event was signalled by a pulse from the water Čerenkov counter. Figure 14 is a schematic diagram of the counter array used.

Detailed analysis of the data is just underway. Preliminary online analysis performed during the experiment was very encouraging. Based on \(> 10^9\) decay events, the group expects to exceed the precision of 0.12 ns in parts in \(10^5\) as reported in a recent experiment at Saclay and in fact equal to that of the world average of 0.07 ns.

Fig. 14. Pions and muons enter the water Čerenkov counter from the left. The time distribution of decay positrons is observed by the photomultiplier.
Muonium production from foils bombarded by positive muons is expected to be similar to neutral hydrogen production from foils bombarded by protons, if the proton and muon have the same velocity. The proton data show that the fraction of neutral hydrogen produced is reasonably independent of the foil used and its surface history. Significant neutral fractions are formed in the velocity region from 0.006 to 0.02 times the speed of light.

The experiment was performed on the M13 beam line. A schematic diagram of the apparatus used is shown in Fig. 15.

Fig. 15. Schematic diagram of the apparatus.

The muons (about $5 \times 10^4$ per second) pass through the beam line window, through a thin (0.26 mm) scintillator and into a foil sandwich. The foil sandwich has one outer surface of aluminium and the other of gold with mylar in between. The momentum of the beam was adjusted so as to maximize the muon stopping rate in the foil sandwich. The charge distribution of the emergent beam is determined by the last few atomic layers. In this 'skin' of the foil only a small fraction (~1%) of the beam is in the velocity range for which we expect a significant fraction to emerge from the foil as neutrals. The particles that emerge from the foil then pass through the Stark plate region, through a collimator, and into the quench-plate region. The function of the Stark and quench-plate electric fields is to introduce a 2P component to the 2S state, thus permitting the 2S state to decay to the 1S state with a half-life on the order of 3 ns. Light produced in the quench region is viewed by a photomultiplier through a 0.635 cm Perspex window with 1 mg cm$^{-2}$ of sodium salicylate (which fluoresces at about 410 nm under Lyman-alpha radiation) deposited on its lower surface.

A clock is started by every muon detected by the incident-muon scintillator and stopped by the next pulse in the Lyman-alpha photomultiplier detector. With no voltage applied to the Stark plates the time spectrum thus collected has three main components:

1. An exponential decay with the muon lifetime, due mainly to the emission of Čerenkov light by muon-decay positrons incident on the Perspex window.
2. A flat component due to uncorrelated starts and stops of the clock.
3. A foreground peak, about 150 ns wide, due to muonium in the 2S state decaying in the quench plates, having taken about 100–200 ns to traverse the distance from the foil to the quench plates.

Applying a high voltage to the Stark plates should remove the foreground peak without affecting the exponential and flat components. A simple model has been used to calculate the shape of the foreground peak.

Time spectra were collected with a quench field of 684 V cm$^{-1}$ and with the Stark plates either at zero field or at 1140 V cm$^{-1}$. Subtraction of the second spectrum from the first should give the pure foreground spectrum arising from muonium atoms in the 2S state decaying in the quench region. The number of counts in the fitted foreground peak of each spectrum is given in Table III.

### Table III. 2S muonium formation probability.

<table>
<thead>
<tr>
<th>Vacuum (Torr)</th>
<th>Quench plates (V cm$^{-1}$)</th>
<th>Foil</th>
<th>Number of 2P to 1S decays detected</th>
<th>% quenched</th>
<th>Calculated 2S flux from foil per $10^3$ muons incident</th>
</tr>
</thead>
<tbody>
<tr>
<td>$&lt;10^{-5}$</td>
<td>684 Au</td>
<td>562 ± 404</td>
<td>100</td>
<td>2.2 ± 1.5</td>
<td></td>
</tr>
<tr>
<td>$10^{-3}$</td>
<td>684 Au</td>
<td>2031 ± 1424</td>
<td>100</td>
<td>3.6 ± 2.5</td>
<td></td>
</tr>
<tr>
<td>$10^{-4}$</td>
<td>114 Au</td>
<td>431 ± 468</td>
<td>70</td>
<td>1.7 ± 2.1</td>
<td></td>
</tr>
<tr>
<td>$&lt;10^{-4}$</td>
<td>57 Au</td>
<td>-119 ± 566</td>
<td>20</td>
<td>-2.1 ± 9.9</td>
<td></td>
</tr>
<tr>
<td>$&lt;10^{-4}$</td>
<td>684 Al</td>
<td>495 ± 341</td>
<td>100</td>
<td>2.9 ± 2.0</td>
<td></td>
</tr>
</tbody>
</table>

along with the 2S muonium flux calculated using the known solid angles of the collimator and photomultiplier tube, as well as the efficiency of the photomultiplier. It was assumed that the muon momentum was completely randomized by multiple scattering during the slowing down process, giving a simple cosine dependence to the angular distribution of the muonium direction.

The data taken with the gold foil at three values of the electric field were also analysed to obtain a value of the Lamb shift.
Fig. 16. The $\chi^2$ surface of the fit to the gold foil data. 121 data points are fitted with six free parameters. The contours join points of equal $\chi^2$ and are labelled according to their difference from the value of $\chi^2$ at the point of best fit in the centre which was 96.5.

The data were fitted and $\chi^2$ calculated for a grid of values of the Lamb shift and 2S production rate. The $\chi^2$ surface thus obtained was plotted (see Fig. 16) and the Lamb shift determined to be 930 (+570/-640) MHz, which is consistent with the calculated value of 1047.03 MHz [Owen, Phys. Lett. 44B, 199 (1973)].

Techniques are presently being studied to produce larger fluxes of muonium by varying the foil geometry and beam momentum. Improvements to the detection system are also being considered.

Experiment 174
Spin correlation parameters in $pp \rightarrow pnp^+$

The BASQUE group is measuring the spin correlation parameters $A_{LL}$, $A_{SL}$ and $A_{NN}$ for the inelastic reaction $pp \rightarrow pnp^+$ using the variable energy polarized proton beam and the polarized proton target available at TRIUMF.

The apparatus is shown schematically in Fig. 17. The multiwire proportional chamber array used to detect both the proton and pion in the forward direction is the polarimeter used in the previous elastic spin correlation measurements. The neutron detector is moved through the kinematically allowed range of neutron angles. The angular position of all particles in the final state as well as the neutron time of flight are recorded.

A run in March was devoted to commissioning the apparatus and trigger logic. Amplifiers were found necessary for reliable chamber operation with a two charged particle trigger having a relativistic pion. $A_{LL}$ at 515 MeV was measured in August and at 470 and 425 MeV in September. $A_{SL}$ was measured at 515 and 470 MeV in November. $A_{NN}$ will be measured in the spring of 1982.

The momenta of the three final state particles are determined from the measured angular co-ordinates of the three particles using the three conservation of momentum equations. Corrections for the magnetic field of the polarized target are then applied to the angular position using this first approximation to the momenta and the procedure iterated to a stable solution. The differences between the reconstructed neutron momentum and the momentum calculated from time-of-flight measurements are shown in Fig. 18. Conservation of energy allows particle identification of the two charged particles. The difference between the sum of reconstructed kinetic energy of the three final state particles using the best assignment of mass and the incident kinetic energy is shown in Fig. 19.

Data analysis and determination of the system acceptance is in progress.
Experiment 185
Precise measurement of the polarization parameter $\xi$: A search for the effects of a right-handed gauge boson in $\mu^+$

This experiment is due to use its first beam time on M13 in the spring 1982. During 1981 the equipment for this experiment has been manufactured and tested. Installation of the magnets in the M13 cave is due to start at the beginning of January.

The objective of the experiment is to measure $\xi_{\mu}$ to 0.1% and thus to place a constraint on the existence of right-handed gauge bosons. The possible existence of one or more right-handed gauge bosons would be of great consequence to selection of a gauge group for grand unification. Moreover, considerable aesthetic appeal is held out by the possible restoration of "manifest left-right symmetry" to the electroweak interaction above some mass scale. The constraints placed on the existence of right-handed gauge bosons by this and other experiments are shown in Fig. 20 in terms of the physical variables $\delta \equiv (M(W_L)/M(W_R))^2$, where $M(W_L)$/$M(W_R)$ is the mass of the left- [right-] handed gauge boson, and $\zeta$, the angle by which $W_L$ and $W_R$ mix.

Fig. 18. Difference between the calculated and the measured neutron time of flight.

Fig. 19. Difference between incident kinetic energy and sum of final state kinetic energies.

Fig. 20. Limits on the parameters $M(W_R)$ [right-handed weak boson mass] and $\zeta$ [mixing angle between left- and right-handed bosons] describing possible right-handed charged currents, expected from Expt. 185 (UBC/TRIUMF-Berkeley-Northwestern, dotted contour) and from related measurements in progress elsewhere.
NUCLEAR PHYSICS AND CHEMISTRY

Experiment 3
Fragments from proton-nuclear interactions

Although data collection was completed some time ago for the series of measurements undertaken in this experimental program, analysis of the data continues. An article (TRI-PP-81-50) comparing measured Ag(p,^4He) analysing powers with simple direct knockout model approximations has been submitted for publication. It appears unlikely that direct knockout of preformed clusters is a significant component in helium isotope inclusive spectra.

Experiment 10
Pion production by proton bombardment of light nuclei

The study of the (p,π) reaction has reached a stage of development where an international workshop dedicated to review this reaction at intermediate energies has just been completed at the University of Indiana. Most of the theoretical and experimental people involved with this reaction were present at the workshop. New data from LAMPF, IUCF, SATURNE and TRIUMF were presented as well as descriptions of theoretical progress in understanding the physics involved. Several messages came through clearly at the meeting a) there is as yet no clear systematic understanding of the observed nuclear effects or of the energy dependence of the analysing power; b) there is some experimental evidence that the total cross section for the (p,π⁺) reaction peaks near the Δ resonance region; c) none of the theoretical models developed to date have consistently fitted both the analysing power and dσ/dΩ simultaneously. Several groups (Dillig et al., Kisslinger et al.) are developing very ambitious microscopic two-nucleon model programs which are hoped will provide a better description; d) the theoretical models need to be guided by some better energy-dependent data in the range from 250 to 500 MeV: both selected transitions to coherent nuclear states and measurements of the π⁻ and π⁺ production in the continuum where the nuclear physics of the final state is not important.

TRIUMF is in a unique position to provide a major part of the data required for improving the understanding of the (p,π⁺) reaction. The experimental equipment and set-up have been described in previous annual reports. Beam line 1B is used and the main piece of equipment is a 65 cm Browne-Buechner spectrograph with a position-sensitive detector array at the focal plane for measuring the pion momentum. During the past year the operational characteristics of beam line 1B and spectrograph have been improved considerably. We are now able to routinely run with beam intensities in excess of 20 nA and have at times been able to run with 30 nA, with reasonable background levels.

\[ ^{12}\text{C}(p,\pi^{+})^{13}\text{C} \]

The group has now measured the angular distribution of A_\gamma and dσ/dΩ for the lab angular range 45 to 130° for incident proton energies of 200, 216, 225, 237 and 250 MeV. Part of the data is shown in Fig. 21(a) and (b). Figure 21(a) shows the differential cross section for T_p = 225 and 250 MeV. No significant energy dependence is seen. Figure 21(b), the values of A_\gamma for T_p = 200, 225 and 250 MeV, shows a dramatic energy dependence. Figure 22 shows the values of A_\gamma for the \(^9\text{Be}(p,\pi^+)\text{^{10}Be}\) reaction over the same energy range. Much less energy dependence is observed. These results have been submitted to Phys. Rev. C for publication. No further measurements need to be done on \(^{12}\text{C}\) at this time (within the energy region accessible with the present spectrometer).

\[ ^{10}\text{B}(p,\pi^{+})^{11}\text{B} \]

It is proposed to measure the angular distribution of the differential cross section and analysing power (A_\gamma) for this production reaction to the following states in \(^{11}\text{B}\): g.s., 2.12, 4.44 and 5.02 MeV, for incident proton energies from 200 to 270 MeV. Preliminary data have been taken at 225 and 250 MeV. The values for A_\gamma (Fig. 23) show an energy dependence somewhat similar to that for \(^{12}\text{C}(p,\pi^+)\). If the \(^{10}\text{B}\) reaction does show a similar energy-dependent effect as \(^{12}\text{C}\) this would lend some credence to the isobar-doorway model for nuclear reaction wherein the core nucleus of \(^{12}\text{C}\) and/or \(^{10}\text{B}\) is excited into a I = 1 state.

With the present resolution available from our experimental system the individual
Fig. 21(a). The differential cross section for the $^{12}\text{C}(p,\pi^+)^{13}\text{C}(\text{g.s.})$ reaction at 225 and 250 MeV incident proton energy.

Fig. 21(b). The energy dependence of $A_y(\theta)$ for the $^{13}\text{C}(\text{g.s.})$ transition in the 200-250 MeV incident proton energy range.

Fig. 21(c). The analysing power for the $^{13}\text{C}(\text{g.s.})$ transition at 225 and 250 MeV incident proton energy.

Table IV. Resolved final nuclear states accessible with the present spectrometer.

<table>
<thead>
<tr>
<th>State</th>
<th>J$^\pi$</th>
<th>Shell model</th>
</tr>
</thead>
<tbody>
<tr>
<td>A) $^{10}\text{B}(p,\pi^+)^{11}\text{B}$</td>
<td>g.s.</td>
<td>3/2$^-$</td>
</tr>
<tr>
<td></td>
<td>2.12</td>
<td>1/2$^-$</td>
</tr>
<tr>
<td></td>
<td>5.02</td>
<td>3/2$^-$</td>
</tr>
<tr>
<td>(see Fig. 21)</td>
<td>4.44</td>
<td>5/2$^-$</td>
</tr>
<tr>
<td>B) $^{12}\text{C}(p,\pi^+)^{13}\text{C}$</td>
<td>g.s.</td>
<td>1/2$^-$</td>
</tr>
<tr>
<td></td>
<td>9.5</td>
<td>9/2$^+$</td>
</tr>
<tr>
<td>(see Fig. 22)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>C) $^9\text{Be}(p,\pi^+)^{10}\text{Be}$</td>
<td>g.s.</td>
<td>0$^+$</td>
</tr>
<tr>
<td></td>
<td>3.37</td>
<td>2$^+$</td>
</tr>
</tbody>
</table>

$^a$ sp - single particle state.
Fig. 22. The analysing power dependence on incident proton energy for (a) the $^{10}\text{Be}(g.s.)$ transition and (b) the $^{10}\text{Be}^+_3$ transition. The solid circles are results obtained with the present spectrometer, the open circles are from Auld et al. [Phys. Rev. Lett. 41, 462 (1978)].

Fig. 23. Preliminary results of the analysing power $A_y(\theta)$ for the $^{10}\text{B}(p,p^+)^{11}\text{B}(g.s.)$ reaction at (a) $T_p = 225$ MeV and (b) $T_p = 250$ MeV.
transitions shown in Table IV can be separated. Our recent results show many other transitions to $^{13}\text{C}$ and $^{10}\text{B}$ for reactions B) and C), respectively, all of which are unresolved.

In a recent paper T.P. Sjoreen et al. could find no simple way of correlating their analysing power results with the properties of the nuclei involved nor did the shell structure provide any clue.

There have been two transitions measured to discrete states where either a single-step mechanism is prohibited, $^{10}\text{B}(p,\pi^+)^{11}\text{B}$ (2.12, 1/2$^-$), or the state is well described by a (2p-1h) configuration, $^{12}\text{C}(p,\pi^+)^{13}\text{C}$ (9.5, 9/2$^+$, 2p-1h). From our results [Fig. 21(c)] for $T_p = 225$ and 250 MeV the $^{13}\text{C}$ transitions show a consistent "pp $\rightarrow$ nπ"-like behaviour. The transition to the $^{11}\text{B}$ (2.12) state also shows indication of a similar behaviour at $T_p = 154$ MeV although the data are limited.

From this limited sample the measured values of $\Delta \gamma$ for transitions to (sp) states exhibit no common behaviour; however, transitions to other states show a "pp $\rightarrow$ nπ"-like behaviour.

$pp + \rightarrow n\pi^+$

A considerable amount of data on this reaction has been taken at proton energies of 400 and 450 MeV as a by-product of our measurements on $pp + \rightarrow n\pi$. The $pp + \rightarrow n\pi$ measurements were taken primarily to calibrate the solid angle of the spectrometer and the pion decay correction. We have also measured the line shape of the pion momentum distribution for this two-body reaction using a CH$_2$ target and a counter placed at small angles to provide the necessary coincidence signal from the associated deuteron. By taking data at various pion angles and various incident proton energies, the pion decay correction can be decoupled from the solid angle calculation. The results, still in a preliminary stage, strongly suggest an enhancement, due to a singlet final state interaction, between the undetected proton and neutron. The mean value of $\Delta \gamma$ is $-0.2 \pm 0.05$ over the range of pion energies shown.

The present data are limited to the angular range between $45^\circ$ and $90^\circ$ $\theta_{(\text{lab})}$ and the pion energy range for $T_\pi(\text{max})$ to $T_\pi(\text{max}) - 40$ MeV. It is intended to extend measurements to cover the back angle range $90^\circ - 135^\circ$ and to also cover a wider range of pion energies (down to $T_\pi \sim 20$ MeV).

$^{12}\text{C}(p,\pi^+)\pi^+$: Continuum pions; $^{12}\text{C}(p,\pi\gamma)\pi^+$: Coincidence measurements

As indicated above the theoretical efforts at describing the (p,$\pi$) reaction have encountered difficulties both in their ability to handle the nuclear form factors at the momentum transfers involved and the actual microscopic $N-N$ pion production vertex. The latter is complicated by the uncertainties regarding the $A$-nuclear interaction. A very useful constraint on the theories of the production process would be provided by measurements of the inclusive pion production over the (3,3) resonance region. These measurements (single arm and coincidence) would provide more data to test the production vertex components of the theories without the complication of the nuclear form factor.

In the process of doing the $pp + \rightarrow n\pi$ calibration with a CH$_2$ target we have accumulated some $^{12}\text{C}(p,\pi^+)\pi^+$ data. There is evidence of an enhancement in the kinematic range of the quasi-free $pp + \rightarrow n\pi$ production. Our data are limited to proton energies of 400 and 450 MeV, and to an angular range from $\theta(\text{lab})$ of $46^\circ - 90^\circ$, for the inclusive $(p,\pi)$ reaction. No data have been taken with the associated particle coincidence system in place.

Experiment 89: Interactions of muons with actinide nuclei

There has been recent theoretical interest in the excitation modes for prompt muon-induced fission in actinides. In particular, the knowledge of the specific atomic transitions resulting in prompt fission were shown to permit use of the muon as a "multipole meter" to investigate the giant resonance aspects of muon-induced fission. The electromagnetic excitation of actinides by negative muons has also been related to photofission in which giant multipole resonances are known to dominate. Preliminary measurements of $^{235}\text{U}$ and $^{238}\text{U}$ must be augmented by measurements of other actinide nuclei to confirm this theoretical approach. When a negative muon is captured by some heavy nuclei two processes may induce fission. First, during the cascade
de-excitation energy may be transferred to
the nucleus by a radiationless transition,
leaving the muon in the ls state. Only
prompt nuclear excitation results, with the
possibility of prompt decay by fission or
particle emission, etc. Due to the presence
of the muon in the ls state, the fission
barrier is increased by about 0.6 MeV, and
the prompt fission probability is reduced in
a muonic atom compared to a normal atom.
Approximately 1-2% of the atomically
captured muons produce prompt fission by
this process. Also, isomeric states may be
induced. The second process which induces
fission is nuclear muon capture, which
results in delayed fissions with a mean life-
time associated with the nuclear muon-
capture lifetime. Over the past two years
measurements at the meson facilities have
reconciled most discrepancies in lifetimes
measured via a number of decay-detection
modes.

In our experiment fissions induced by stop-
ning muons in 238U and 235U were observed in
a multiplate fission chamber. Coincidental
muonic X-rays were detected with an array of
NaI(Tl) counters. From this data we have
obtained absolute fission yields, prompt-to-
delayed yield ratios (both in singles and in
coincidence with K and L X-rays), and \( \mu \)
fission lifetimes. These results are given
in Table V. From our measurement of the
prompt fission yield in coincidence with L
X-rays, we are able to conclude that
(60 ± 13)% of the fissions are induced by
the 2p-1s dipole mechanism. A recent SIN
measurement found only (26 ± 15)% of the
fissions in 238U go via this channel, and
attributed the rest to 3d-1s transitions.
This discrepancy needs to be resolved in
order to clarify the role of the giant
quadrupole resonance in this process.

### Table V. Results of fission yields and lifetimes of 235U and 238U.

<table>
<thead>
<tr>
<th>Measurements</th>
<th>235U</th>
<th>238U</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean lifetime (ns)</td>
<td>71.6 ± 0.6</td>
<td>77.2 ± 0.4</td>
</tr>
<tr>
<td>Prompt fission yield</td>
<td>0.133±0.006</td>
<td>0.093±0.005</td>
</tr>
<tr>
<td>Absolute fission yield</td>
<td>14.8 ± 2.6</td>
<td>7.5 ± 1.0</td>
</tr>
<tr>
<td>Delayed fission yield</td>
<td>13.1 ± 2.6</td>
<td>6.9 ± 1.0</td>
</tr>
<tr>
<td>Prompt fission yield</td>
<td>1.74±0.36</td>
<td>0.64±0.10</td>
</tr>
<tr>
<td>Prompt fission * K_x ray</td>
<td>0 ± 14</td>
<td>9 ± 9</td>
</tr>
<tr>
<td>Prompt fission * L_x ray</td>
<td>60 ± 13</td>
<td>60 ± 10</td>
</tr>
<tr>
<td>Prompt fission * 2+1nr</td>
<td>1.04±0.31</td>
<td>0.38±0.09</td>
</tr>
<tr>
<td>Muon stop</td>
<td>2+1nr</td>
<td>2+1nr</td>
</tr>
<tr>
<td>where 2+1nr = [2p-1s(E1)]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Prompt fission * 3+1nr</td>
<td>0.70±0.27</td>
<td>0.26±0.08</td>
</tr>
<tr>
<td>Muon stop</td>
<td>3+1nr</td>
<td>3+1nr</td>
</tr>
<tr>
<td>where 3+1nr = 3d-1s(E2)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>3p-1s(E1)</td>
<td></td>
</tr>
</tbody>
</table>

### Experiments 113, 153
**Elastic scattering of protons from \(^3\)He**

Studies of the elastic scattering of protons
from very light nuclei have as main objec-
tives:

1) to provide a sensitive testing ground for
multiple scattering theories used in analys-
es of proton-nucleus scattering.

### Table VI. Cross sections for the \(^{12}\)C(\(\pi^\pm\),\(\pi\)N)\(^{11}\)C reactions.

<table>
<thead>
<tr>
<th>Energy (MeV)</th>
<th>(\pi^+)</th>
<th>(\pi^-)</th>
</tr>
</thead>
<tbody>
<tr>
<td>30</td>
<td>3.5 ± 0.3</td>
<td>1.8 ± 0.2</td>
</tr>
<tr>
<td>40</td>
<td>6.5 ± 0.4</td>
<td>3.1 ± 0.3</td>
</tr>
<tr>
<td>50</td>
<td>10.3 ± 0.6</td>
<td>6.1 ± 0.3</td>
</tr>
<tr>
<td>60</td>
<td>14.6 ± 0.8</td>
<td>10.6 ± 0.6</td>
</tr>
<tr>
<td>70</td>
<td>20.1 ± 1.0</td>
<td>16.4 ± 0.8</td>
</tr>
<tr>
<td>80</td>
<td>25.2 ± 1.3</td>
<td>24.5 ± 1.2</td>
</tr>
<tr>
<td>90</td>
<td>29.8 ± 1.5</td>
<td>30.0 ± 1.5</td>
</tr>
<tr>
<td>100</td>
<td>33.5 ± 1.7</td>
<td></td>
</tr>
</tbody>
</table>
2) to determine the sufficiency of the nucleon-nucleon scattering amplitudes, as extracted from nucleon-nucleon elastic scattering data, in analyses of proton-nucleus scattering using multiple scattering theories, and

3) to study specific nuclear structure and nuclear reaction mechanism information, e.g. the admixture of small components to the ground state wave function, the formation of intermediate Δ's.

With this aim measurements have been made of the \(^{3}\text{He}(p,p)^{3}\text{He} \) differential cross section and analysing power angular distributions at 200, 300, 415 and 515 MeV. The angular distributions cover the range from 20° to 150° c.m., except at 415 MeV where backward angles still need to be measured. The experiment is performed using the University of Manitoba L\(^{3}\text{He} \) cryostat placed in the MRS scattering chamber. Target thicknesses of 90 and 120 mg cm\(^{-2} \) were used. Both scattered protons and recoiling \(^{3}\text{He} \) particles were detected with the spectrometer. Differential cross section and analysing power angular distributions at 300 and 515 MeV are exhibited in Fig. 24. Multiple scattering theoretical analyses of the data are in progress.

In a second experiment a study is being made of the p-d relative momentum distribution in \(^{3}\text{He} \) through \(^{3}\text{He}(p,2p)d\) and \(^{3}\text{He}(p,pd)p\). In principle these two reactions should lead to the same momentum distribution in \(^{3}\text{He} \). As such it tests also the treatment of final-state interactions or distortions in the exit channel. To date the measurement of \(^{3}\text{He}(p,2p)d\) at 450 MeV has been completed. The scattered proton was detected using the MSR spectrometer while both the ejected proton and recoil deuteron were detected in range counter telescope (which included wire chambers) employing a triple coincidence technique. The University of Manitoba L\(^{3}\text{He} \) cryostat was placed at the MSR scattering chamber. The target thickness was 120 mg cm\(^{-2} \). Measurements of \(^{3}\text{He}(p,pd)p\) at 450 MeV are continuing.

**Experiment 114**

**Study of (p,2p) quasi-free scattering from \(^{3}\text{He} \):**

A study has been made of the relative momentum distribution of pn pairs in \(^{3}\text{He} \) through \(^{3}\text{He}(p,2p)pn\). Choosing kinematics such that the vector momentum of the recoiling pn

**Experiment 117**

**Fragments**

The high purity Ge detector telescope designed to measure the energy spectra of light fragments (A < 8) out to their...
kinematic limits was used for an in-beam experiment for the first time during 1981. This initial run served to test both the Ge system and the new PDP11/34-based data acquisition system. Minor technical problems were found in both and were solved for a subsequent run later in the year. The most significant problem was the inability of the electronics to handle the energy rate in the Ge detector for reasonable data collection rates. A new type of preamplifier for the Ge detector solved this problem.

The second set of experimental runs during the year provided one quarter of the data sought in this experiment. As an example of the detector, preliminary spectra (tentative energy calibration and no efficiency correction) for Ag(p, \(^3\)He)X and Ag(p, \(^4\)He)X reactions are shown in Fig. 26 for helium isotopes observed at 20° from a 300 MeV proton beam.

Supplemental information on Ag(p,p') and Ag(p,d) inclusive spectra was also obtained in conjunction with experimental measurements made for Expt. 142.

*Experiments 124, 165*

**Giant resonances**

Figure 27 shows a continuum spectra taken during a giant resonance run on \(^{208}\)Pb(p,p') in September. It is quite clear from the figure that the analysing power at 200 MeV is large at this angle. It is also expected that the additional information available from running both spin-up and -down spectra at each angle will allow a more reliable estimate of the background under the giant resonance "bumps" to be made. Asymmetry data were recorded at 6°, 8°, 10° and 14° with \(^{208}\)Pb during September. Spectra were also obtained for \(^{90}\)Zr.

**Fig. 25.** Relative momentum distribution for pn pairs in \(^3\)He.

**Fig. 26.** Helium isotope spectra (preliminary) from p + Ag reactions at 300 MeV for fragments observed at 20°.

**Fig. 27.** Raw asymmetry data for the giant resonance hunt, from MRS.
Experiment 127  
**Measurement of the strong interaction shift in pionic deuterium**

The accurate determination of the \( \pi N \) scattering lengths is fundamental to our understanding of their interactions. Measurement of the pionic K\( \gamma \) X-ray energy yields the scattering length \( a_{nd} = a_{np} + a_{nn} + \) higher-order corrections, which have been calculated to high accuracy. Our experiment aims at a measurement of this X-ray using the critical absorption foil technique. A high-pressure gas target is used to avoid Stark quenching of the X-rays in liquid H\(_2\). The X-rays are observed with Si(Li) detectors.

In a one-week run on the M13 channel stopping rates in our hydrogen target were studied as a function of gas pressure and beam properties. It was concluded that 60% of our registered stops occurred within the gas volume. An in-beam resolution of <350 eV and a low energy cut-off of ~2 keV was achieved, which is sufficient for the experiment to proceed. Figure 28 shows the observed X-ray spectrum in 10 atm of H\(_2\) gas. The low-energy structure is tentatively identified as the K X-rays, and its yield is consistent with our expectations. The group plans to verify this and to try to understand the backgrounds before proceeding with data collection next summer.

![Fig. 28. An X-ray spectrum, observed by Si(Li) detectors, from pions stopping in a high pressure hydrogen target.](image)

**Fig. 29.** A summary of the data accumulated in this experiment for the reaction \( 2\text{H}(p,\gamma)^3\text{He} \) at a laboratory beam energy of 500 MeV.

**Experiment 131.**  
\( 2\text{H}(p,\gamma)^3\text{He} \) and \( 3\text{H}(p,\gamma)^4\text{He} \)

No new data were taken during 1981. Analysis of the \( 2\text{H}(p,\gamma)^3\text{He} \) data is complete and the replay of the more copious, but harder to analyse, \( 2\text{H}(p,\gamma)^3\text{He} \) events accumulated in the same experiment is under way. Figure 29 displays the results for 500 MeV \( (p,\gamma) \) data. These data were taken in three separate runs. The points to note are the dip at forward angles seen previously at 200 MeV in the \( 2\text{H}(p,\gamma)^3\text{He} \) reaction and what appears to be a dip in the cross section at \(~105^\circ\) (corresponding to a momentum transfer of 790 MeV/c).

A short experiment in September, scattering 500 MeV protons from titanium tritide targets obtained from ORNL, verified that this batch of targets contains enough tritium to perform the \( 3\text{H}(p,\gamma)^4\text{He} \) experiment. We plan to request sufficient time in the next beam period to measure an angular distribution of the cross section and the analysing power from \(~18^\circ\) (lab) to \(140^\circ\) (lab) at one beam energy. The experiment will be performed as for the \( 2\text{H}(p,\gamma)^3\text{He} \) reaction, using counter telescopes and multi-wire chambers at forward laboratory...
angles to measure the energy and angle of the \(^{4}\)He particles, and lead glass Čerenkov detectors at backward angles to detect the coincident \(\gamma\)-rays. As before, this set-up will also allow us to measure the \(^{3}\)H\((p,\pi^{0})^{4}\)He cross section.

**Experiment 142**

**Non-evaporative fragment emission**

The data reduction for the 90° proton triggered \((p,2p)\) measurements on \(^{9}\)Be was completed in 1981. A gain stability problem in the NaI detector energy signal was solved by using the time-of-flight differences between observed proton and deuteron groups. These data, complete with efficiency corrections, are now tabulated awaiting final theoretical calculations. One means of displaying the data, suitable for cases with enough statistical accuracy, is illustrated by the case shown in Fig. 30 where contours of constant differential multiplicity (coincident protons/MeV*sr) are shown for protons in coincidence with a 70 MeV proton observed at 90° on the opposite side of the beam (all values in the laboratory frame). The values for these curves are derived from the summed energy spectra of the coincident protons for 90° trigger protons between 65 and 75 MeV; this removes the energy spread introduced by the binning.

In order to provide normalization information required for theoretical interpretation of the \((p,2p)\) data, 300 MeV protons were used to measure inclusive \(^{9}\)Be\((p,p')\) spectra at several angles between 20° and 160°. During these runs, \((p,p')\) and \((p,d)\) spectra were also measured on Ag at 300 MeV and on Al and U at 400 MeV to supplement Expt. 117 data and to provide comparison data for light ion induced reactions at 400 MeV/u. The theories involved in all of these reactions are tightly entwined and these supplemental measurements should help in their investigation by providing quantitative connections between the various reactions. The data reduction for these inclusive measurements is proceeding more smoothly than the previous \((p,2p)\) analysis since gains in the NaI detectors were stabilized using light pulsers.

**Experiment 143**

**A study by recoil detection of proton-induced reactions on \(^{9}\)Be**

The acquisition of data for this extensive study of reactions involving large, coherent momentum transfer is nearly complete following two series of measurements performed this year. Table VII summarizes the complete data set now available for the spectra of energetic recoil nuclei detected using semiconductor counter telescopes mounted in the 1.5 m diameter scattering chamber located on BL4A.

The observation of the lighter recoil nuclei over a wide kinematic range with protons incident at 225 MeV completes the study of the multiparticle final states, the simplest of which involve the reactions \(^{9}\)Be\((p,Nn)^{9}\)Be and \(^{9}\)Be\((p,2p)^{8}\)Li. These data define the dependence of the observed cross sections on the recoil momentum \((q, \text{typically } > 0.5 \text{ GeV}/c)\) and on the invariant mass of the unobserved light particles, as well as on the incident proton energy \((E_p)\). On this basis first assessments can be made of the influence of final state interactions (such as the formation of a \(\Delta\) in the \((p,Nn)\) reaction) and the possible role of sequential processes (such as contributions to the
Table VII. Experiment 143: Existing data set.

<table>
<thead>
<tr>
<th>$E_p$</th>
<th>Recoil nucleus</th>
<th>Angular range</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>225$^a$</td>
<td>$6, 7, 8\text{Li}, 7, 9\text{Be}, 8\text{B}$</td>
<td>$10^\circ \leq \theta_R \leq 98^\circ$</td>
<td>Studies of the multi-particle final states, particularly in the $(p,N\pi), (p,2N)$ and $(p,2N\pi)$ reactions</td>
</tr>
<tr>
<td>329$^b$</td>
<td>$3, 4, 5\text{He}, 6, 7, 8\text{Li}, 7, 9\text{Be}, 8\text{B}$</td>
<td>$10^\circ \leq \theta_R \leq 100^\circ$</td>
<td></td>
</tr>
<tr>
<td>499$^c$</td>
<td>$6, 7, 8\text{Li}, 7, 9\text{Be}, 8\text{B}$</td>
<td>$10^\circ \leq \theta_R \leq 100^\circ$</td>
<td></td>
</tr>
<tr>
<td>225$^a$</td>
<td>$9, 10\text{Be}, 10\text{B}, 10\text{C}$</td>
<td>$7^\circ \leq \theta_R \leq 12.5^\circ$</td>
<td></td>
</tr>
<tr>
<td>329$^a$</td>
<td>$9, 10\text{Be}, 10\text{B}, 10\text{C}$</td>
<td>$7^\circ \leq \theta_R \leq 17^\circ$</td>
<td></td>
</tr>
<tr>
<td>480$^a$</td>
<td>$9, 10\text{Be}, 10\text{B}, 10\text{C}$</td>
<td>$56^\circ \leq \theta_R \leq 71^\circ$</td>
<td></td>
</tr>
<tr>
<td>329$^a$</td>
<td>$9, 10\text{Be}, 10\text{B}, 10\text{C}$</td>
<td>$56^\circ \leq \theta_R \leq 71^\circ$</td>
<td></td>
</tr>
<tr>
<td>429$^a$</td>
<td>$9, 10\text{Be}, 10\text{B}$</td>
<td>$\theta_R = 15^\circ$, $19^\circ$</td>
<td></td>
</tr>
<tr>
<td>499$^c$</td>
<td>$9, 10\text{Be}, 10\text{B}$</td>
<td>$3.5^\circ \leq \theta_R \leq 20^\circ$</td>
<td></td>
</tr>
</tbody>
</table>

$^a$Data obtained during 1981.
$^b$Data limited to recoil energies $21 \leq E_R \leq 25$ MeV.

The observed yield of $^9\text{Be}$ from an initial $(p,\pi)$ reaction to nucleon-unstable states in $^{10}\text{Be}$ or $^{10}\text{B}$). Final analysis of the data will be completed soon and comparisons will be made where possible with specific calculations based on simple models of the processes involved.

The recent measurements for the heavier recoil products at $E_p = 225$, 329 and 480 MeV concentrated on completing the survey of the two-body final states produced in the $(p,p_0)$, $(p,\pi)$ and $(p,\gamma)$ reactions. This objective required the use of a thin beryllium target (0.4 mg/cm$^2$) and consequently higher beam intensities (up to 8 $\mu$A) to obtain good resolution of the peaks in the recoil spectra at near-optimum data rates. Improvements in the operation of the cyclotron permitted the use of these higher intensities despite the necessity to run at very forward angles. Typically the resolution was 1.2 MeV (FWHM) for the peak resulting from the $^3\text{Be}(p,\pi^0)^{10}\text{B}$ reaction. These data together with that obtained previously at $E_p = 429$ and 499 MeV complement the measurements made at TRIUMF with the pion spectrometer of the $^5\text{Be}(p,\pi^0)$ and $^{12}\text{C}(p,\pi^0)$ reactions at proton energies in the range $200 < E_p < 250$ MeV. The energy range spanned in a single experiment is unique to the present measurements and has been shown to be important to an understand-

ing of the mechanism involved in the $(p,\pi)$ reaction on complex nuclei. Also unique to this experiment is the opportunity to compare the dependence on $E_p$ and $q$ of the $(p,p_0)$, $(p,N\pi)$ and $(p,\pi)$ reactions.

Experiment 144

$(p,d)$ in nuclei

A series of measurements has been made to study the systematics of $(p,d)$ reactions at intermediate energies. The goal of these studies is to determine the major reaction mechanisms and to ascertain if such reactions still show a nuclear structure dependence which can be extracted in a quantitative manner. The TRIUMF MRS spectrometer and polarized proton beam were used to measure angular distribution for $\alpha(\theta)$ and $A(\theta)$ for target nuclei $^4\text{He}$, $^7\text{Li}$, $^{13}\text{C}$, $^{16}\text{O}$, and $^{40}\text{Ca}$. Measurements have been made at $E_p = 200$ MeV for all targets and, in addition, at 400 MeV for all except $^{16}\text{O}$. Recently Wharton et al. have reported that the $(\pi,p)$ cross section is well represented by an expression of the form $\sigma(\theta) = e^{-q/Q_0}$ where $q$ is the cms momentum transfer and $Q_0$ is a parameter varying from ~45-25 MeV/c for $A = 6-16$. We have found a similar $q$ dependence at forward angles for $(p,d)$ cross sections on nuclei in the range $7 < A < 40$. The resulting $Q_0$ values for the various targets are: $^7\text{Li}$ : 70; $^{13}\text{C}$ :
Fig. 31. Comparison between measured cross section for $^7$Li($p,d)^6$Li (ground state) and the predictions of the Wilkin model.

As an example of the coincidence neutron spectra Fig. 33 shows neutron spectra coincident with the gamma-ray transitions, $4^+_1 + 2^+_2$ and $8^+_1 + 6^+_2$ in the ground state bands, for the three different neutron multiplicities for $^{165}$Ho target. The high-energy peak can be best observed for the case of $8^+_1 + 6^+_2$ transition for $^{160}$Dy. For this isotope there is a large increase in intensity for $4^+_1 + 2^+_2$, especially in the region between the high-energy peak and the thermal region. This indicates that there is a large side-feeding to levels below $8^+_1$ which correlates to the intermediate-energy component of the pre-compound neutron spectra.

In contrast to the somewhat featureless cross sections the deuteron asymmetries show strong oscillatory patterns.

Experiment 145
The neutron-gamma ray correlation in $\pi^-$-capture in $^{165}$Ho and $^{181}$Ta

The neutron spectra in $\pi^-$ capture in medium-heavy nuclei are measured in coincidence with discrete nuclear gamma rays to exhibit correlation of the spectra to neutron multiplicity and nuclear states of residual isotopes. Discrete component in the pre-compound neutron spectra is resolved for the first time, and its correlation to population of high-spin nuclear states is observed.

Twelve large plastic scintillators (24 in. x 6 in. x 3 in.) were employed in a time-of-flight system with a flight path of 5 ± 0.25 ft. The counters were spaced to measure angular distribution at steps of 23 ± 5°. Both ends of each counter were viewed with phototubes in a mean-time mode, achieving overall timing resolution of better than 1 ns. A large Ge(Li) gamma-ray detector was placed 19 in. from the target in the plane defined by the neutron detectors.

Experiment 151
Interaction of muons with fissile nuclides

This work was undertaken with the prime intent of identifying shape-isomer back decay and measuring both the transition energy and the lifetime for such decay, thereby increasing significantly information on first-barrier structure. Observation of such back decay had been reported for both non-muonic and muonic $^{238}$U by others. The muonic $^{238}$U
results were, however, of marginal statistical significance and called for independent confirmation as much as for more precise quantitative values.

There have been two experimental runs in the past year. In November 1980 a rerun was made with our $^{238}$U target using two Ge(Li) detectors to detect back decay and three large NaI (5 in. x 5 in.) crystals with LBL-designed high current bases to suppress $\mu$-capture background. An earlier run with $^{238}$U had failed to show the gamma-rays reported by the Dubna group, at a yield level of approximately $1 \times 10^{-6}$ $\mu$-stop. (This number is to be compared with yields on the order of $(5\pm2) \times 10^{-3}$ that were reported from Dubna.) The purpose of the November run was to use the improved sensitivity detection set-up both to reconfirm our earlier negative results and to provide sufficient data for a detailed search, as a function of time and energy, for other possible back-decay candidates. In May 1981 there was a second run with an identical experimental set-up and plan, but using a 50 g $^{236}$U target obtained on loan from ORNL and LBL. As the first experimental measurement of muon capture on isotope separated $^{236}$U, in addition to the motivating measurements, new measurements were also obtained of the muonic X-ray spectrum.

Data analysis of the above two runs is still in progress. Preliminary results from the $^{238}$U data again fail to show the gamma-rays reported by the Dubna group. The search in $^{238}$U for other gamma-rays has thus far been concentrated in the 10-20 ns lifetime range, where the Dubna gamma-rays were reported. To ensure against bias and to establish a quantitative basis for gamma-yield limits a computerized peak-searching routine, GAMANL, is being used. The efficiency of this routine for finding true gamma-rays as well as for finding false gamma-rays is calibrated on each experimental spectrum using a Monte Carlo program that generates artificial spectra of peaks on a background that is statistically identical in shape and amplitude to the actual background. No isomer-decay candidates have yet been identified, but absolute yield limits as a function of energy and lifetime have not yet been set.

Experiment 152
Measurement of the spin rotation parameter R in $p-^4$He elastic scattering at 500 MeV

Measurements of the Wolfenstein R parameter in $p-^4$He elastic scattering have been completed at 500 MeV. The incident beam polarization was precessed into the scattering plane and transverse to the beam momentum direction by the JANIS solenoid. After scattering from a 140 mg/cm$^2$ liquid $^4$He target, the polarization in the scattering plane and transverse to the scattered beam direction was measured using a carbon target polarimeter mounted at the focal plane of the medium resolution spectrometer facility. The parameter R was then obtained from $P_{\text{scat}} = RP_{\text{inc}}$. Results are shown in Fig. 34. Error bars are due to counting statistics. An overall uncertainty of ±15% should be included due to the uncertainty in the effective analysing power of the polarimeter. An experiment to determine this analysing power has been completed by using unscattered polarized beam with the MRS at zero degrees. Three energies (350, 425 and 500 MeV) were used to obtain the energy dependence of the analysing power.
Fig. 34. Wolfenstein parameter at 500 MeV in p-^4He elastic scattering.

The analysis of these data are near completion and are expected to reduce the scale uncertainty.

Experiment 158
Pion production to 3-body final states on ^2H and ^3He

As a means of searching for deviations from the impulse approximation (IA), a study has been undertaken of a part of the final-state interaction effect which is important in the energy region of interest here, namely the part involving nN-rescattering by selecting reactions with a physical \( \pi \) in a final state. For this purpose we have obtained cross sections for the ^2H(p,\pi+)n and ^3He(p,\pi+)p reactions over a large region of the phase space of the final state but around small recoils of the single nucleon, including the (3,3) resonance region where the \( \pi \) and N interact strongly. Similar studies in the final-state interaction (FSI) region have been made before in ^2H(p,2p)n; here the FSI is between two nucleons.

The first reaction was chosen because isospin conservation requires the (\( \pi^+n \)) system to be in a pure I = 1/2 state (in free \( \pi n \) we have I = 1/2 and I = 3/2 contributions), which results in a very weak interaction at the energy considered. It was required to check, at the level of a few per cent, that in this case the IA works. A previous detailed study of this reaction by Lo et al. had revealed sizable departure from the IA for this same reaction at 800 MeV.

The second reaction was chosen because here the (\( \pi^+p \)) system must be in a pure I = 3/2 state as \( I_z^{\pi^+p} = +3/2 \), and thus the interaction is resonating at an invariant mass near \( m_\Delta = 1.23 \) GeV.

In both cases it was required to test the IA factorization

\[
d^5\sigma = k \cdot \phi^2(p_5) (d\sigma/d\hat{\Omega})_{16+34},
\]

where the indices are defined in the IA graph below, \( \phi^2 \) is the momentum space density at the vertex \( 2 + 65 \) and \( (d\sigma/d\hat{\Omega})_{16+34} \) is usually taken to be the free cross section leading to \( \pi(n\pi) \), at the invariant mass \( \sqrt{s} \) and p\( \pi \)-momentum transfer \( \sqrt{t} \).

In the two experiments we have performed recently, the pion and the deuteron (triton) were detected in coincidence and the kinematics of the final state was entirely determined.

The recoil distribution density \( \phi^2 \) extracted from Eq. (1) would be a function of only \( |p_5| \) in the limit of exact validity of the IA and of negligible error in replacing the amplitude squared at the 16 + 34 vertex by an on-shell cross section. The method to be followed here will consist in looking for possible variations of \( \phi^2(p_5) \) at constant \( p_5 \) but variable energies of the \( \pi \) relative to the nucleon (5) or of the d (or t) relative to the nucleon (5). Admittedly, the method is viable only if the off-shell effects are not dominant; that should most likely be the case for the ^3He reaction, and in any event restricts the study to small recoil momenta.

The deuterons (or tritons) were detected in the MRS in coincidence with \( \pi^+\)s in a 14-telescope array. MRS angles were between 11° and 17° in steps of 2°; a momentum range of 60% was scanned with three field settings. The data analysis for the ^2H reaction is nearing completion. Analysed in terms of the recoil momentum, the data cover a very large range of values for the two other variables of interest: \( \sqrt{t} \), the p\( \pi \) four-momentum transfer, and \( \sqrt{s} \), the d\( \pi \) invariant energy. Deviations from the IA
would be seen as a residual dependence of the momentum density obtained in standard manner upon t and s; such deviations have been previously seen in an 800 MeV experiment by Lo et al. Figure 35 shows that the nuclear matrix element squared for different deuteron angles and central momenta provides an internally consistent recoil spectrum. This result compares well with previous (p, 2p) and (e, e'p) results in this recoil range. Each data point shown is an average over a number of m-counters and therefore corresponds to an average over s and t.

We have encountered difficulties with the data in the region where \( \int d\Omega \) becomes very large; such a situation occurs when the solid angle available to the recoiling particle can become almost 4\( \pi \); this is the case when \( p_5 \) is parallel to the beam and/or \( |p_5| = 0 \). These data have not been included here; at the present time it does not appear that we have detected any deviation from the impulse approximation in \( ^2H(p, \alpha)n \), and of course, as explained above, we did not expect any. For \( ^3He(p, \alpha) \), however, we do expect deviations from IA but the results are not in yet.

The analysis at these two experiments will probably last to the end of 1982. How to (or whether to) continue this program will become apparent at a later time.

**Experiment 162**

Survey of X-ray production of high-energy protons

Proton induced K-vacancy production cross sections have been measured previously at \( E_p = 160 \) MeV and 4.88 GeV, but apparently there have been no measurements for L- or M-vacancy production at \( E_p > 40 \) MeV. To extend and complement these investigations, targets of Al, Ti, Fe, Mo, Sn, Ta, Pt, Pb, and U were bombarded with 500 MeV protons from the TRIUMF cyclotron. High-resolution semi-conductor photon detectors were used to measure X-ray production cross sections in the K-, L-, and M-shells of elements with 13 < Z < 82, 40 < Z < 82, and 73 < Z < 92, respectively. The total inner-shell vacancy production cross sections obtained for these shells will be compared with previous experimental results and available calculations.

A more sensitive test of the predictions of FWBA and other theories for inner-shell ionization by high-velocity projectiles is the measurement of relative inner-subshell ionization cross sections. For example, variations in subshell intensity ratios as a function of projectile energy could be indicative of multiple ionization processes. With the good energy resolution of the detectors used (for the Si(Li) detector, full-width-at-half-maximum, FWHM = 180 eV at 6 keV, and for the intrinsic Ge detector, FWHM = 1.5 keV at 32 keV), individual K- and L-subshell cross sections were also measured. Typical X-ray spectra for the two detectors are shown in Figs. 36 and 37. Some results for relative subshell intensities are: Kg/Ka ratios of 0.14 ± 0.02 for Fe, 0.19 ± 0.02 for Mo, and 0.30 ± 0.04 for Pb, and Lg/La ratios of 0.82 ± 0.02 for Ta, 0.73 ± 0.02 for Pt, and 0.74 ± 0.04 for Pb. The Kg/Ka ratios are consistent with previous measurements at lower proton energies. The Pb Lg/La ratio is substantially higher than for 8-14 MeV protons, but it is in good agreement with equivalent-velocity electron data. These results extend the available L- and M-shell data for high-velocity protons and confirm

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the projectile velocity dependence of relative L-subshell intensity ratios.

Experiment 170
Fission evaporation competition in heavy nuclei at intermediate energies

The experiment aims to study the competition between evaporation and fission in excited heavy nuclei. The development of more sophisticated heavy ion detectors (parallel plate avalanche counters) at the Weizmann Institute enabled the angle between the two fission fragments to be accurately measured for the first time. In coincidence with the two fission fragments the angular distributions of both neutrons and light charged particles emitted in the reaction were measured. From these angular distributions it is expected that the numbers of evaporated particles emitted pre-and post-fission will be derived.

Our collaborators from the Weizmann Institute, Z. Fraenkel and A. Breskin, came to TRIUMF for the months of July and August. During this time the apparatus was set up and took beam (12 shifts were scheduled) toward the end of August. In this run it was possible to establish that the major part of the equipment worked well (the fission fragment detectors performed flawlessly and the neutron counters were able to distinguish neutrons from γ-rays by means of pulse shape discrimination). Some useful data on neutron-fission fragment coincidences from uranium were obtained. A second run is planned early in 1982, during which it is hoped to complete the first part of the proposal involving the use of intermediate-energy protons to excite the target nucleus.

Experiment 173
Measurement of pionic 4-3 X-ray transitions in heavy nuclei

Interest in pionic 4-3 X-rays was spurred by the recent observations of anomalously small strong interaction widths by Konijn et al. in Ta, Re and Bi. However, these widths are obtained from these data only after analysis of a complex hyperfine structure. Our experiment will attempt to measure the pionic X-rays in 208Pb and 209Bi, where these hyperfine complications are absent or minimal.

In attempting to extend the measurements of pionic atom transition to high Z one faces two difficulties. The increasing width of the 4f level due to pion absorption leads to a reduction in intensity, while the broadening of the lower level reduces the signal-to-background ratio. Konijn et al. have pioneered the use of a Compton suppression spectrometer to reduce the continuum background. However, his NaI(Tl) spectrometer has drawbacks in in-beam use: its bulkiness leads to shielding and geometry problems, while the high (n,n') cross section of 127I produces
contaminant lines in the detector. Bismuth germanate (Bi₄Ge₃O₁₂) offers advantages in both of these aspects.

**Experiment 178**  
**Nuclear radius studies in the Ca region**

The PISCAT group effort has been divided between completing experiments with existing apparatus and the development of new experiments. As can be seen from the new PISCAT proposals, extensive development is under way highlighted by the assembly of a QQD spectrometer as described in the Experimental Facilities Division section (p. 108). Our help in the commissioning of M11, has allowed the possibility of resonance energy experiments though the group emphasis is still low energy pion physics.

The analysis of $^{24}\text{Mg}/^{26}\text{Mg}$ elastic scattering cross-section ratios was presented at the spring CAP congress [Tacik et al., CAP Congress, Halifax, unpublished; Johnson, ibid., unpublished]. This is the first set of isotopes to be studied at low energies that are better described by a fermi matter distribution than a gaussian distribution. When the chi-squared comparisons between experiment and theory are plotted versus the fermi half radius and the diffuseness parameter of a fermi distribution, the minimum valley does not precisely follow a curve corresponding to a constant rms radius as shown in Fig. 38. If one plots the matter distributions that correspond to minima in these chi-squared comparisons between measured ratios and calculated ratios, though the skin thickness could be varied at will the distributions all passed through a common density at the same radius as shown in Fig. 39. This may indicate that a specific value for a single matter distribution parameter may be determined. Additional work on model-independent-type analysis is being performed.

After considerable effort a negative pion elastic scattering ratio experiment was performed on $^{32}\text{S}$ and $^{36}\text{S}$ as shown in Fig. 40. The targets were 1 cm in diameter and each 190 mg/cm² thick. The small size of the target and the current operating characteristic of M13 restricted the on-target pion rates to 1/100 of that which may be available for the channel. The ratio is consistent with a less than 100 mfm radius

![Fig. 38. Chi-squared contours for $^{26}\text{Mg}/^{24}\text{Mg}$ elastic scattering ratios.](image)

![Fig. 39. Normalized density distributions along the chi-squared valley.](image)

![Fig. 40. $^{36}\text{S}/^{32}\text{S}$ elastic scattering ratio compared with calculations that vary the neutron radius difference.](image)
difference between the $^{32}$S and $^{36}$S neutron radii but a more detailed analysis is under way. This work is complementary to an electron scattering experiment on the same targets to determine the proton radius distribution differences.

Experiment 184

\[ \beta + ^{2}H \rightarrow ^{3}H + n^{+} \]

The proposal to measure the analysing power in the $pd + \alpha$ reaction over the 350-500 MeV range of incident proton energies was predicated on upgrading the magnetic spectrograph ("Resolution") currently used for pion production studies from nuclei (Expt. 10). The existing spectrograph is capable of detecting pions of kinetic energies up to about 120 MeV ($p = 220$ MeV/c), whereas a 230 MeV ($p = 340$ MeV/c) capability is required for Expt. 184. The main change required involves new field coils capable of increasing the gap field from the current limit of about 1.1 T to 1.7. These developments have not yet been implemented. As a result, the group has been unable to pursue its primary objectives in Expt. 184 during this past year. Instead some runs have been performed at 400 MeV and 375 MeV using a CD$_2$ target with an additional associated particle arm mounted on the scattering chamber to enable detection of the triton in coincidence with the pion in the magnetic spectrograph.

These results were also required in order to determine the line shape profile of the magnetic spectrograph. An example of the pion line shape (with and without carbon background subtraction) is shown in Fig. 41. Further analysis of the results in order to obtain the angular dependence of the analysing power is currently in progress.

Experiment 189

$p,n^- \text{ radiochemical study}$

The principal objective of this experiment is to measure the total reaction cross section $\sigma_T$ as a function of proton energy (from 200 to 500 MeV at TRIUMF) for the group of reactions $^{209}$Bi($p,n^-x$n)$^{210-x}$At where $0 < x < 7$.

In essence radiochemical separations specific for astatine are applied to irradiated Bi foils, and the residual activity ($\alpha,\gamma$) of the heavy At reaction products measured to determine $\sigma_T$ for the specific reaction.

The first series of runs were performed in August and while some of these data are still under analysis, Table VIII presents some preliminary absolute cross sections at incident beam energies of 300 and 480 MeV. Data from BNL are also presented. The errors indicated include those from counting statistics, branching ratio uncertainties, chemical efficiency uncertainties, etc. Chemical efficiencies were measured by direct radioassaying of the irradiated Bi foil for the production of $^{211}$At and comparing this to $^{211}$At activity in the separated sample.

<table>
<thead>
<tr>
<th>Isotope</th>
<th>200 MeV*</th>
<th>300 MeV (TRIUMF)</th>
<th>480 MeV (TRIUMF)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{205}$At *</td>
<td>10.0 ± 1</td>
<td>112 ± 30</td>
<td>23 ± 8</td>
</tr>
<tr>
<td>$^{207}$At</td>
<td>14.1 ± 3.4</td>
<td>4.4 ± 0.6</td>
<td>3.4 ± 0.5</td>
</tr>
<tr>
<td>$^{209}$At</td>
<td>3.0 ± 0.8</td>
<td>1.0 ± 0.2</td>
<td>1.2 ± 0.3</td>
</tr>
</tbody>
</table>

*Secondary contributions have not been subtracted from data at 300 & 480 MeV.
**Values taken from J. Clark, Ph.D. thesis.
***Using a branching ratio for $^{205}$At of 0.10 ± 0.2 (NP 230, 380 (1974), for $^{207}$At of 0.115 (J. Clark, Ph.D. thesis), for $^{209}$At of 0.084 (J. Clark, Ph.D. thesis).

Fig. 41. The pion line shape observed by "Resolution" for the reaction $pd + \alpha$ (a) the raw data and (b) with carbon background subtracted.
Magnetism
(Experiment 71)

Spin glasses. $B_1$-μSR studies on AuFe, CuMn and AgMn have given an independent measure of the distribution of the local fields causing muon relaxation and spin glass behaviour, and have revealed a coexistence of fast and slow spin fluctuations just below $T_g$.

The amorphous spin glass Pd$_{75}$Fe$_5$Si$_{20}$ has been studied by ZF-μSR techniques and is found to affect the muon much the same as CuMn and AuFe spin glasses. The amorphous system should not be subject to the localized "clumping" of magnetic atoms which might obscure true spin glass behaviour in the more familiar systems. The modulation rate is plotted as a function of temperature in Fig. 42.

Magnetic superconductors. The crystal SmRh$_8$B$_4$ undergoes a transition from paramagnetic to superconducting states at $T_{c1} = 3$ K, followed by another transition to antiferromagnetic order below $T_{c2} = 0.8$ K; thus it permits superconductivity and magnetism to get as close as they can to simultaneous coexistence. This makes it an interesting system to study with some probe (like μSR) which doesn't mind zero applied field. The group has recently obtained the data shown in Fig. 43 using the separated surface muon beam of M9 (dc separator).

Above $T_{c2}$ there is a single "signal" whose $T1$ varies only mildly with $T$ (with a possible bump just below $T_{c1}$). Below $T_{c2}$ there are two distinct relaxation rates, each of which is almost independent of $T$. As far as one can tell, this transition is very sharp.

The behaviour of ErRh$_8$B$_4$ (a system with similar properties) is qualitatively comparable but much less distinctive.

Magnetic insulators. A large single crystal of CoCl$_2$·2H$_2$O was grown at UBC and studied in the antiferromagnetic phase with a 200 Oe field applied perpendicular to the muon polarization. As the orientation of the crystal was changed, up to 4 frequencies were observed, as shown in Fig. 44, whose orientation dependence indicates that the muons occupy two different sites with about equal probability. When the analysis is complete the orientation of the local magnetic field at these sites will be known.

Knight shifts in antimony alloys. A single crystal of SbBi(8%) was studied at 20 K with $B_1$-μSR as a function of orientation of the crystal and the strength of the applied field, as seen in Fig. 45. For $B_1 > 3$ kOe the Knight shift is large, positive and anisotropic but significantly reduced from that in pure Sb; the frequency shift, while linear in $B_1$, does not extrapolate to zero at $B_1 = 0$. Recent tests at fields of 100 and 200 Oe confirm that the Knight shift goes to zero below about 1 kOe. We suspect that this system is at the border between the conventional model of a screened positive charge in a metal and the extreme case of muonium formation where the Mu electron has rapid spin-exchange interactions with conduction electrons.

Antiferromagnets. A unique internal field (giving coherent muon precession) was measured at the muon in V$_2$O$_3$ below $T_n$. In MnF$_2$ and α-Mn, no such coherent precession was seen; these two antiferromagnets also differed in that a long $T_1$ (>10 μs) was seen in α-Mn even close to $T_n$ while in MnF$_2$ fast relaxation is observed in the paramagnetic phase.

Monte Carlo calculations. In 1978-9, TRIUMF experiments in zero magnetic field (ZF-μSR) gave the first direct observations of the stochastic relaxation functions predicted by Kubo and Toyabe. Since then the number of systems studied by this technique has been growing steadily; this is not surprising, since no other method can generate zero-field relaxation functions $G_{zz}(t)$, which contain a wealth of phenomenological information, including local field distributions and fluctuation rates and "hopping" rates for muon diffusion. As will be seen below, this technique has proved valuable in investigations of spin glasses, diffusion and magnetic superconductors. The range of applications is limited mainly by the facility with which one can calculate families of relaxation functions for different types of situations, to which the μSR data can be fitted to extract parameters of interest.

For certain classes of stochastic phenomena,
Fig. 42. Temperature dependence of the modulation rate (in ns$^{-1}$) of the local field at the muon in Pd$_{75}$Fe$_5$Si$_{20}$ amorphous spin glass.

Fig. 43. Temperature dependence of the ZF-$\mu$SR muon relaxation rate in the magnetic superconductor SmRh$_4$B$_6$. The crystal is paramagnetic above $T_{C1}$, superconducting between $T_{C1}$ and $T_{C2}$, and antiferromagnetic below $T_{C2}$.

Fig. 44. Dependence of muon precession frequencies in antiferromagnetic CoCl$_2$·2H$_2$O at 15 K as a function of the orientation of the crystal in a 200 Oe applied field.

Fig. 45. Field dependence of frequency shift (relative to copper in the same field) of muons in pure Sb and in SbBi(9%) at 9–20 K for crystalline c-axis parallel (circles) and perpendicular (triangles) to the applied field.

Fig. 46. ZF-$\mu$SR relaxation "signals" in Cu at low temperature. The loss of the characteristic "recovery to 1/3" at late times is obvious at lower temperatures. All fits give the same value of the static dipolar width, within statistical errors.
analytical expressions have been derived for the resultant $G_{zz}(t)$. However, such solutions can become rather difficult and in any case require certain assumptions or limitations on the model. This impediment has been removed by our development of a very general computer code capable of generating $G_{zz}(t)$ by Monte Carlo techniques for virtually any combination of random processes that can be described unambiguously. With TRIUMF's new VAX-11/780 computer it has become possible to generate a family of curves suitable for fitting in about one day of CPU time. It is expected that this will have far-reaching effects on our future research, and may also be valuable to people studying relaxation phenomena in other fields.

Muon diffusion and trapping in solids (Experiments 78 and 149)

Pure copper at low temperatures. Earlier reports have been confirmed that the relaxation rate of muons in pure Cu decreases as the temperature is lowered past about 10 K. In particular, there is a rapid decrease between 4 K and 0.5 K. By means of high-precision measurements in zero, longitudinal and transverse applied field, shown in Fig. 46, it has been ascertained that this phenomenon is definitely associated with a "motional narrowing" effect at lower temperatures. This is particularly exciting because it may indicate the onset of quantum tunneling processes in the best-studied system. An approximately constant difference has been found between the effective "hopping rate" in zero and transverse field. Since the motion of the muons themselves should not be affected by weak magnetic field, we believe that this difference is caused by the partial (but not complete) averaging of transverse components of the field produced by Cu nuclear dipoles due to their quadrupole interactions with the disturbance of the lattice by the muon.

Trapping at defects in aluminum. New high-precision measurements of $G_{zz}(t)$ at low temperatures in samples of pure Al quenched from near the melting point have shown that the muons must migrate to trap sites before they begin to relax. Detrapping from these sites is also observed at higher temperatures.

Fig. 47. Muon precession amplitude in $\text{SrTiO}_3$ as a function of temperature. The sudden decrease below about 38 K is due to muonium formation.

Muonium formation in solids (Experiment 154)

Strontium titanate. The evidence presented last year for Mu formation in this famous ferroelectric crystal has been reconfirmed, as has the strange behaviour of the resultant spin system, which is seemingly unaffected by applied magnetic fields as high as 15 Oe (normally enough to cause precession frequencies of 20 MHz). The temperature dependence of these phenomena seems correlated with the well-known electrical properties of the crystal, but in a surprising way: the sudden onset of Mu formation (evident in Fig. 47 as a drop in the muon asymmetry) takes place below about 37 K, which is the extrapolated Curie temperature for the Curie-Weiss law behaviour of the dielectric constant. There is apparently no other evidence for any sharp phase transition at this temperature.

Other insulators. Muon repolarization by strong $B_{\parallel}$ has been studied in a large sapphire ($\text{Al}_2\text{O}_3$) crystal; in pure $\text{TiO}_2$ there is (surprisingly) no evidence for Mu formation; Mu does form, however, in zeolites and in $\text{GeO}_2$ (of which we have borrowed two of the world's largest single crystals), although not nearly as efficiently as in quartz ($\text{SiO}_2$), which is remarkable inasmuch as the two crystals are nearly identical. Data on the muonium signal in $\text{GeO}_2$ are still being analysed.

Longitudinal field techniques. The $\text{ZF-\muSR}$ methods developed at TRIUMF in the past four years are augmented by measurements of the effect of magnetic fields applied parallel to the muon polarization ($B_{\parallel}$-$\mu\text{SR}$). Such studies can reveal the magnitude of the local fields causing the relaxation, for instance.
In addition, stronger parallel magnetic fields ($B_\parallel \sim 500-5000$ Oe) can quench the apparent depolarization of muons by muonium formation (the so-called "Paschen-Bach repolarization" effect), revealing the strength of the hyperfine interaction involved even in cases where transverse-field ($B^-\mu$SR) techniques fail due to fast relaxation by small local fields. This repolarization technique was actually the first widely used method of detecting muonium in solids, but has lapsed into disuse (outside of the Soviet Union) with the advent of new transverse-field techniques. Our studies of muonium formation have led us to an interest in many systems where Mu precession cannot be observed directly by $B^-\mu$SR methods, so we have revived the $B_\parallel-\mu$SR technique at TRIUMF. A preliminary study using general-purpose counters with the SFU $\mu$SR magnet (up to 4.25 kOe) indicates that the potential precision of this technique is extraordinary, with the main source of uncertainty coming from soluble systematic effects.

Muons and muonium on surfaces
(Experiment 191)

The experience of TRIUMF Expt. 60 (IEP-10) with muonium relaxation in oxide powders led last year to the conclusion that the relaxation mechanism at low temperatures involved interactions on the surfaces of the powder grains. This discovery prompted us to look for evidence of the nature and details of those interactions, with two motives in mind: (a) to learn whether Mu might make a good probe for the surfaces of these rather inelegant powders (most techniques for studying surfaces require ideally prepared surfaces, and those which work with "real" surfaces are usually not sensitive to dynamics on the nanosecond time scale of $\mu$SR); and (b) to evaluate the potential of $\mu$SR for studying the reactions of Mu (and by analogy, H) on catalytic surfaces like those actually used in industrial processes.

In silica powders of 3.5-nm radius grains which had been baked at high vacuum, a remarkable temperature dependence of the relaxation rate of Mu atoms has been found, apparently due to interactions with bare silica surfaces. The results for one sample are shown in Fig. 48 as an Arrhenius plot. At high temperatures the data seem to obey an Arrhenius law with an activation temperature of about 130 K. We believe this reflects the increasing time of stay of the Mu atoms on the powder surfaces, where they are depolarized by interactions with defects to which they quickly migrate once on the surface. Below about 25 K, the Mu atoms no longer escape from the surfaces. This accounts for the plateau region of the curve; there is no more depolarizing fate that can befall the Mu atoms.

The surprise comes at lower temperatures, where the depolarization rate actually decreases as the temperature drops. This we suspect is due to a retardation of the rate at which Mu migrates on the surface - and hence the rate at which it encounters the defects which cause relaxation.

Finally, at very low temperatures, the Mu atoms should actually begin to "freeze" in place; this may lead to depolarization via distortions of the hyperfine coupling. The results below 15 K are consistent with this expectation and obey an Arrhenius law with an activation temperature of about 7.5 K.

Thus we apparently have discovered a means of studying the dynamics of hydrogenlike atoms on catalytic surfaces in three distinct regimes with the same technique. We are very excited about these results and are anxious to see how far this technique can be taken.

Data were also taken on $\mu^+$ relaxation in microcrystalline Pt powder (a genuine industrial catalyst). The surprising result that addition of hydrogen to the Pt surfaces reduces the relaxation rate is still somewhat of a mystery. Preliminary results are shown in Fig. 49.
Fig. 49. Muon relaxation in Pt microcrystal powders as a function of temperature and hydrogen treatment.

Experiment 122
Dipole fields in ferromagnetic metals

A muon diffusing among the interstitial sites in ferromagnetic iron carries with it a cloud of electrons, the polarization of which can be extracted from the average precession frequency of the muon spin. This polarization changes when other elements are added to iron either substitutionally or interstitially. It is a challenge to theoretical physics to account for these changes. It is a challenge to experimental physics to extract the correct values. One problem is that dislocations affect the precession frequency. There is now evidence that the dislocation effect can be measured separately by comparing the precession in zero field where the magnetization lies along particular axes and in high fields where it lies along the field direction. In this it is necessary to know very accurately the internal field. It has been shown that this can be determined directly in a muon experiment by placing a thin piece of copper adjacent to the ferromagnetic sample and extracting two frequencies of precession. Preliminary results for 12 different solute elements in iron have been published.

Experiment 147
Muonium formation and reaction dynamics in the gas phase

$\mu^+$ charge exchange and muonium formation in pure gases

By measuring the amplitudes of "free" $\mu^+$ and of muonium (Mu) in transverse field $\mu$SR studies, the fractions $f_\mu$ and $f_{Mu}$ of muons thermalizing in diamagnetic environments or as muonium can easily be found. Using surface $\mu^+$ (from M20) we have completed a study of all the rare gases as well as the molecular gases, $H_2$, $N_2$, $NH_3$ and $CH_4$, as a function of stopping pressure (from 0.3 to 3.0 atm). In all cases, as reported in last year's annual report, the measured $\mu$SR (MSR) amplitudes are a strong function of pressure, changing approximately by a factor of two for a similar change in pressure. This pressure dependence can be interpreted in terms of the total time spent ($<0.1$ ns) by the $\mu^+$ during the charge exchange regime - at higher pressures this time is shorter and hence the depolarizing influence of the $\mu^+e^-$ hyperfine interaction has less time to act, thereby leading to a larger signal amplitude. The main effect causing $\mu^+$ charge exchange/slowing down is the (outer) electron density of the atom or molecule, but there are also inelastic contributions to the slowing down process, as evidenced, e.g., by the fact that the total amplitude ($A_\mu + 2A_{Mu}$) in $N_2$ is always larger than $A_\mu$, although both have the same charge density. Representative results are given in Table IX, along with the relative fractions ($f_\mu + f_{Mu} = 1$).

It is well known that the "absolute fractions" ($f_\mu + f_{Mu} < 1$) - i.e., normalized to 100% $\mu^+$ in $A_\mu$ - in condensed media generally sum to less than unity, defining the so-called "lost ($f_L$)" or "missing fraction," but in the gas phase our results strongly indicate that $f_L > 0$ at "high" (a few atm) pressure. Some corresponding results from condensed phase studies [Percival et al., Chem. Phys. 32, 353 (1978); Kiefl et al., J. Chem. Phys. 74, 308 (1981)] are compared with the gas phase results in Table X. For reference, the neutral fractions $f_H$ reported from proton charge exchange data [Tawara, Atomic & Nucl. Data Tables 22, 491 (1978)] are also given. The results in water are the best determined values and in a sense are also the most interesting since there has been a lot of controversy surrounding the mechanism of Mu formation in condensed media. The "spur model" [Percival et al., Chem.
Table IX. Pressure dependent $\mu^+$ and Mu amplitudes in different gases.

<table>
<thead>
<tr>
<th>Target gas</th>
<th>$P$(atm)</th>
<th>$A_{\mu^+}$</th>
<th>$A_{\text{Mu}}$</th>
<th>$A_{\text{TOT}}$</th>
<th>$f_{\mu}$ (%)</th>
<th>$f_{\text{Mu}}$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>He</td>
<td>1.2</td>
<td>0.154 ± 0.004</td>
<td>0.0</td>
<td>0.15</td>
<td>100</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>3.0</td>
<td>0.222 ± 0.002</td>
<td>0.0</td>
<td>0.22</td>
<td>100</td>
<td>0</td>
</tr>
<tr>
<td>Ar</td>
<td>1.1</td>
<td>0.071 ± 0.004</td>
<td>0.100 ± 0.003</td>
<td>0.27</td>
<td>23</td>
<td>77</td>
</tr>
<tr>
<td></td>
<td>2.8</td>
<td>0.095 ± 0.002</td>
<td>0.143 ± 0.003</td>
<td>0.38</td>
<td>24</td>
<td>76</td>
</tr>
<tr>
<td>Xe</td>
<td>0.40</td>
<td>0.046 ± 0.003</td>
<td>0.050 ± 0.003</td>
<td>0.14</td>
<td>0 c</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td>0.65</td>
<td>0.040 ± 0.010</td>
<td>0.089 ± 0.006</td>
<td>0.22</td>
<td>0</td>
<td>100</td>
</tr>
<tr>
<td>H$_2$</td>
<td>3.1</td>
<td>0.126 ± 0.008</td>
<td>0.086 ± 0.008</td>
<td>0.30</td>
<td>40</td>
<td>60</td>
</tr>
<tr>
<td>N$_2$</td>
<td>1.0</td>
<td>0.045 ± 0.003</td>
<td>0.125 ± 0.007</td>
<td>0.30</td>
<td>15</td>
<td>85</td>
</tr>
<tr>
<td></td>
<td>2.5</td>
<td>0.076 ± 0.002</td>
<td>0.171 ± 0.004</td>
<td>0.42</td>
<td>17</td>
<td>83</td>
</tr>
<tr>
<td>CH$_4$</td>
<td>1.2</td>
<td>0.037 ± 0.002</td>
<td>0.110 ± 0.004</td>
<td>0.26</td>
<td>12</td>
<td>88</td>
</tr>
<tr>
<td></td>
<td>2.9</td>
<td>0.058 ± 0.002</td>
<td>0.180 ± 0.005</td>
<td>0.42</td>
<td>13</td>
<td>87</td>
</tr>
<tr>
<td>NH$_3$</td>
<td>2.7</td>
<td>0.040 ± 0.004</td>
<td>0.182 ± 0.003</td>
<td>0.40</td>
<td>10</td>
<td>90</td>
</tr>
</tbody>
</table>

$A_{\text{TOT}} = A_{\mu} + 2A_{\text{Mu}}$, including wall contributions to $A_{\mu}$. These corrections are small (~5%) at high pressures but can be appreciable at low pressures, particularly in low charge density gases (~50% for 1 atm He).

$A_{\mu}$, $A_{\text{Mu}}$ and $A_{\text{TOT}}$ are corrected for wall contributions; $f_{\mu} + f_{\text{Mu}} = 1.0$.

Table X. Absolute fractions ($f_{\mu} + f_{\text{Mu}} < 1$) for different gases compared with results in condensed media.

<table>
<thead>
<tr>
<th>Target gas</th>
<th>Medium</th>
<th>$f_{\mu}$ (%)</th>
<th>$f_{\text{Mu}}$ (%)</th>
<th>$f_L$ (%)</th>
<th>$f_H$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>He</td>
<td>gas a</td>
<td>100</td>
<td>0</td>
<td>0</td>
<td>15</td>
</tr>
<tr>
<td></td>
<td>liquid b</td>
<td>&gt;90</td>
<td>&lt;2</td>
<td>&lt;8</td>
<td></td>
</tr>
<tr>
<td>Ar</td>
<td>liquid c</td>
<td>25 ± 4</td>
<td>75 ± 4</td>
<td>0</td>
<td>90</td>
</tr>
<tr>
<td></td>
<td>solid</td>
<td>1</td>
<td>91 ± 9</td>
<td>8 ± 9</td>
<td></td>
</tr>
<tr>
<td>Kr</td>
<td>liquid</td>
<td>0 ± 6</td>
<td>100 ± 6</td>
<td>0</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td>solid</td>
<td>7</td>
<td>57 ± 10</td>
<td>36 ± 10</td>
<td></td>
</tr>
<tr>
<td>Xe</td>
<td>liquid d</td>
<td>0 ± 3</td>
<td>100 ± 3</td>
<td>0</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td>solid</td>
<td>3</td>
<td>43 ± 9</td>
<td>54 ± 10</td>
<td></td>
</tr>
<tr>
<td>H$_2$O</td>
<td>liquid</td>
<td>5 ± 5</td>
<td>90 ± 10</td>
<td>0</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td>solid</td>
<td>48</td>
<td>52 ± 2</td>
<td>18</td>
<td></td>
</tr>
</tbody>
</table>

aFrom TRIUMF study, cf. Table IX.
dH$_2$O condensed phases from Percival et al., Chem. Phys. 32, 353 (1978).
Phys. 32, 353 (1978) and Percival, Hyp. Int. 8, 315 (1981)) maintains that the $\mu$+/μ fractions are decided as the result of recombination and diffusion in a radiation-induced process caused by the $\mu^+$ slowing down; whereas the "hot atom" model [Walker et al., J. Chem. Phys. 70, 4534 (1979) and Hyp. Int. 8, 329 (1981)] holds that Mu forms as a result of (epithermal) charge exchange, as in the gas phase, and then the $\mu^+$ signal is due to (inefficient) hot atom reactions exemplified by $\text{Mu}^* + \text{H}_2\text{O} \rightarrow \text{MuOH} + \text{H}$. Since we find essentially 100% Mu formation in the vapour phase, vs. only (at most) 40% in the liquid phase, it may suggest that there is indeed an additional mechanism operative in condensed media. Similar results are apparent in liquid rare gases (Table X). We are currently extending our $\mu^+$ charge exchange studies to include several vapours [Arseneau, M.Sc. thesis, Dept. of Chemistry, UBC], particularly those where the gas phase results can be directly compared with corresponding studies in liquids [Ito et al., Can. J. Chem. 58, 2395 (1980)]. Preliminary results though already indicate large differences - large (~100%) Mu formation fractions are seen in every case (H$_2$O, hexane, methanol) except CCl$_4$ (~50%).

Muonium and molecular ion formation in doped rare gases

Studies of Mu formation in different gas mixtures have also been undertaken, with results at several different partial pressures of Ar, Xe, CH$_4$, and NH$_3$ in a Ne moderator as well as Xe in a He moderator. In purified Ne or He there is essentially 100% $\mu^+$ (Table IX) but, upon the addition of an impurity gas at the 100's of ppm level, Mu formation competes favourably with the thermalization process of the $\mu^+$. In the cases of Xe, NH$_3$ and CH$_4$ in Ne, Mu formation is an exothermic process so that relatively little impurity gas is needed - Fig. 50 shows typical data and $\chi^2$ fits for Ne/Xe mixtures. Note the loss in signal amplitude for the "free" $\mu^+$ signal (bottom); there is a corresponding amount of muonium formed. The $\mu^+$ and Mu amplitudes as a function of added Xe concentration are plotted in Fig. 51. Similar plots have been obtained for Ne/NH$_3$ and Ne/CH$_4$ mixtures and also for Ne/Ar mixtures, although in the latter case relatively more Ar is needed to produce the same Mu signal since Mu formation is endothermic in $\mu^+$/Ar collisions. The data of Figs. 50 and 51 show conclusively that Mu formation is an epithermal process (the last charge exchange cycle occurring at a $\mu^+$ energy > 30 eV, depending on the moderator) since both the $\mu^+$ and Mu signals are clearly observable (at different magnetic fields).

If Mu formation were a thermal process in collisions of the $\mu^+$ with the (impurity) gas, then it would be formed at random times on a timescale much longer than the slowing down...
process itself (<30 nsec at 1 atm) and hence coherent Mu precession would not be possible. We have definitely established, however, that this process does indeed occur, i.e., in addition to epithermal Mu formation. The evidence for this comes from observation of the relaxation of the $\mu^+$ signal, which can actually be seen in Fig. 50; in pure Ne (top) the $\mu^+$ relaxation is $\approx 0.05 \mu s^{-1}$ while in the presence of 200 ppm Xe (bottom) it is twice this value. The results of many different runs are shown as a plot of muon relaxation $\lambda$ vs. Xe conc. in Fig. 52. The slope of the line ($\lambda = \lambda_0 + k[Xe]$) gives the bimolecular rate constant $k$ for the collision process $\mu^+ + Xe + Mu + Xe^+$, in exact analogy with Mu chemistry studies. The large error bars in Fig. 52 reflect the difficulty inherent in extracting very slow relaxations, near the edge of our present sensitivity as determined by field inhomogeneities. We are in fact currently constructing new coils to improve this by a factor of $\approx 100$. The data of Fig. 50 give a value for $k = (2.3 \pm 0.5) \times 10^{-11} \text{ cm}^3/\text{atom-1 s}^{-1}$, in good agreement with a much earlier determination based on relatively little data (1978 annual report). A survey of these values for different impurity gases is given in Table XI.

There are several interesting features which emerge from the values given in Table XI. First of all, note that there is no relaxation in Ne/Ar mixtures. This is expected since Mu formation is endothermic by 2.2 eV. Secondly, the relaxation rates differ considerably for different impurity gases, being largest for Ne/Ne mixtures. This is an immediate indication that one is not dealing with the collision of a free $\mu^+$ in the gas or the same "collision controlled" rate would be seen in every case. Hence, we must be dealing with a bound $\mu^+$ molecular ion, $\mu^+\text{Ne}$ or $\mu^+\text{He}$, as the case may be. In comparison with calculations of the ground state binding energies of the corresponding hydride ions, a simple zero-point energy correction predicts that the $\mu^+$ binding energies will be 1.7 eV in both cases. Thus, both would be endothermic for Mu formation ($\mu^+\text{Ne} + Xe + Mu + Ne + Xe^+$) by $\approx 0.2$ eV and no relaxation should be observed. The fact that we see relaxation in the case of $\text{Ne}^+\mu$ but not $\text{He}^+\mu$ is a third point of interest, suggesting that these molecular ions are formed in an excited vibrational state (which is expected to be long-lived relative to the 2.2 $\mu$s muon lifetime) and, in the case of $\text{He}^+\mu$, collisional de-excitation competes favourably with Mu formation. Another interesting idea which has recently emerged is the possibility of $\mu^+$ tunnelling through the rotational barrier, expected to be more favourable for $\text{He}^+\mu$ than for $\text{Ne}^+\mu$ [P. Fournier, Paris, Orsay].

These data described above form the basis of the Ph.D. thesis of R. Mikula (Dept. of Chemistry, UBC, August, 1981). A large paper on Mu formation has been written for submission to Phys. Rev. A while an additional paper describing the $\mu^+$ molecular ion data is in preparation.

Muonium chemistry and reaction dynamics

Significant progress has been made in 1981 in studying the $\mu^++\text{H}_2$ reaction as well as the $\mu^++\text{D}_2$ reaction. These were difficult and
time-consuming experiments in that the reaction rates are the slowest our group has ever measured, at the limit of the basic MSR technique in our present apparatus for temperatures below about 600 K. With a specially designed target can (up to ~5 atm pressure at 1000 K) it has been possible to measure the bimolecular rate constants for the reactions

\[
\begin{align*}
\text{Mu} + \text{H}_2 &\rightarrow \text{MuH} + \text{H} \\
\text{Mu} + \text{D}_2 &\rightarrow \text{MuD} + \text{D}
\end{align*}
\]

over the temperature range 600 to 850 K. The data, in the form of an Arrhenius plot is shown in Fig. 53. The upper solid line gives the (old) experimental results for the \(\text{H} + \text{H}_2\) reaction [Johnston, Reaction Rate Theory (Ronald Press, 1966)] while the middle and bottom lines are \(\chi^2\) fits to our data for \(\text{Mu} + \text{H}_2\) and \(\text{Mu} + \text{D}_2\), respectively. (The analysis of the \(\text{Mu} + \text{D}_2\) reaction is not yet complete.) The dots shown are the variational transition state theoretical calculations of Garrett and Truhlar et al. [Acc. Chem. Res. 13, 440 (1980) and preprint, submitted to J. Chem. Phys., 1981].

The present experimental results represent a real "tour de force" in muonium chemistry. We have long maintained that the availability of the lightest possible isotope of the H atom (\(m_{\text{Mu}} = 1/9 m_\text{H}\)) will be of unprecedented importance in establishing the validity of basic theories of (isotopic) chemical reaction rates [Connor, Hyp. Int. 8, 423 (1981)]. There are basically two ingredients in any theoretical study of reaction rates - the potential energy "surface" describing the interactions between atoms and molecules and the reaction theory describing the dynamics of the collision process on that surface. In general, it is difficult if not impossible to separate these two effects. However, in the one case of \(\text{H}_2\), an accurate "ab initio" potential energy surface exists (and hence, within the Born Oppenheimer approximation, for the isotopic variants of \(\text{H}_2\) also), and thus for the first time the reaction theory can be "tested" independently. The agreement seen in Fig. 53 is impressive. Within experimental error, the theory appears to be "exact" at high temperatures although there is some discrepancy, perhaps as much as a factor of two in the case of \(\text{Mu} + \text{D}_2\), at the lowest temperatures studied (~600 K). This discrepancy is a strong indication that there is not enough tunnelling included in the theory, which is manifest most dramatically at low temperatures and particularly in the case of muonium. This is again an indication of the impact that the study of muonium reaction rates can have on reaction rate theory. As noted above, the theoretical calculations shown in Fig. 53 are transition state calculations and in this case, unlike a more direct collision theory approach, the best way to include a tunnelling enhancement is not yet well established - the present data should certainly help to clarify this point. We are currently in the process of writing our \(\text{Mu} + \text{H}_2\) data up for publication (1982) in the J. of Chemical Physics.

Experiment 150
Utilization of backward muons to study muonium reaction intermediates

Previous work at SIN led to the suggestion that the chemical fate of the muon in aqueous systems is determined by reactions with transient species created in the terminal spur of the muon track. The model supposes that the muon comes to rest in the immediate neighbourhood (within a few nm) of the radiolysis products \(e^-\) (presolvated electron) and \(\text{•OH}\). If the muon and electron combine muonium is formed:

\[
\mu + e^- \rightarrow \text{Mu}
\]

Otherwise the muon will hydrate and end up substituted in a water molecule (within a few ps):
\[ \mu^+ + H_2O + \text{MuOH}_2^+ \]
\[ \text{MuOH}_2^+ + H_2O + \text{MuOH} + H_3O^+ . \]

The idea is borrowed from current theories of positronium formation, and if correct promises valuable insight into the structure and chemistry of the terminal spur.

However, Walker et al. [J. Chem. Phys. 70, 4534 (1979)] support an alternative hypothesis in which muonium is formed with sufficient translational energy to escape the radiation damage along the muon track. It is then able to undergo hot atom reactions in similar fashion to recoil tritium.

Last year the earlier results and new data from this experiment were subjected to quantitative analysis [Percival, Hyperfine Interactions 8, 315 (1981)], resulting in further refinement of the model. However, arguments counter to the spur model are still being brought forward [Walker, Hyperfine Interactions 8, 329 (1981)]. The extent of the controversy was clearly apparent at the IUPAC Symposium on Radiation Chemistry held in Vancouver, August, which included a discussion panel on the spur models of positronium and muonium chemistry. Nevertheless, one aspect of the spur model now seems to be generally accepted. This attributes the missing fraction of muon polarization in water to radiolysis effects. In this respect then, muonium cannot be correctly considered to be an unperturbed system at short times. During the past year a number of specific tests of the spur model were devised and applied. One such investigated the effect of hydroxide ions on the initial diamagnetic fraction, \( h_D \). This was chosen since the lack of effect of 0.2 M NaOH was reported by Walker et al. [J. Chem. Phys. 70, 4534 (1979)] as evidence against the model. They argued that \( h_D \) should be increased by virtue of the fast reaction

\[ \mu^+ + \text{OH}^- + \text{MuOH} . \]

In fact, our experiments showed just such an effect, from 0.63 to 0.75, as the concentration of \( \text{OH}^- \) was increased from 0.4 M to 10 M. As was found for Cd\(^{2+}\), the discrepancy between Walker's predictions for the spur model and the experimental results is merely a matter of degree, which has been explained in terms of the timescale of muonium formation [Percival, J. Chem. Phys. 74, 2901 (1980)].

In other work muonium was sought and found in the liquid and solid phases of ammonia. This work forms the first part of a collaboration with the metal-ammonia researchers at Arizona State University and Salford University (U.K.), but is also relevant to the present project in that ammonia is chemically very similar to water. It is interesting, therefore, to compare the observed muonium fractions in the two substances in their various phases:

<table>
<thead>
<tr>
<th></th>
<th>solid</th>
<th>liquid</th>
<th>gas(^a)</th>
</tr>
</thead>
<tbody>
<tr>
<td>water</td>
<td>0.52</td>
<td>0.20</td>
<td>~1.0</td>
</tr>
<tr>
<td>ammonia</td>
<td>0.21</td>
<td>0.21</td>
<td>0.91</td>
</tr>
</tbody>
</table>

\(^a\)Fleming et al.

The large differences between the results for gaseous and condensed phases suggest that it is not relevant to apply to condensed matter the theory and experimental data for muon thermalization in the gas phase. Water and ammonia, together with some of the inert gases [Warren et al., J. Chem. Phys. 74, 308 (1981)] are the only substances tested in all three phases, so the plans of Fleming et al. (Expt. 147) to measure muon and muonium fractions in the vapour phase of many substances already studied as liquids are especially timely.

Parallel to the muonium formation studies an investigation of the reaction of muonium with the thiosulphate ion (\( S_2O_3^{2-} \)) was undertaken. This is a good example of the use of muonium as a substitute for hydrogen atoms. Although much work has been done at the Univ. of Saskatchewan on the radiation chemistry of aqueous solutions of \( S_2O_3^{2-} \) and other sulphur-containing systems [Kabachia, Ph.D. thesis, 1972] no data are available on \( \text{H} \) reactions, only on \( e_{aq}^- \) and \( \text{\cdot OH} \):

\[ e_{aq}^- + S_2O_3^{2-} \rightarrow \text{\cdot S}^- + SO_3^{2-} , \]

\[ k = 3.8 \times 10^7 \text{ M}^{-1} \text{ s}^{-1} \]

\[ \text{\cdot OH} + S_2O_3^{2-} \rightarrow \text{OH}^- + S_2O_3^- , \]

\[ k = \sim 2 \times 10^9 \text{ M}^{-1} \text{ s}^{-1} . \]

The hydrogen atom is a reducing species, so it will not react like \( \text{\cdot OH} \). Instead, the S-S bond is expected to break. The analogous reaction to that with \( e_{aq}^- \) would be

\[ \text{H} + S_2O_3^{2-} + \text{\cdot OH} + SO_3^{2-} . \]

An alternative that leaves the \( \text{H} \) atom in a diamagnetic product is
From measurements of the muonium decay rates in dilute solutions of $S_2O_3^{2-}$ in the $10^{-4}$ M range we determined the rate constant for the muonium reaction to be $(1.4 \pm 0.1) \times 10^{10}$ M$^{-1}$ s$^{-1}$. This is close to, if not already at, the diffusion controlled limit for reactions in water. So far the only classes of muonium reactions found to be so fast are oxidation of $\mu$ to $\mu^+$ (not possible here) and addition. Measurements of the muon polarization at high $S_2O_3^{2-}$ concentrations clearly demonstrate a diamagnetic product for the reaction since the muon polarization from muonium is recovered as part of the diamagnetic signal. The results, shown in Fig. 54, were analysed according to a simple model based on the direct conversion of $\mu$ to diamagnetic product (such as $\mu S^{-}$). The best fits are shown as solid lines for each thiosulphate concentration. An optimum value of $k_{\mu} = 2.4 \times 10^{10}$ M$^{-1}$ s$^{-1}$ was found for most of the solutions, but at 0.01 M and 0.02 M higher values resulted. It is not clear if the deviations from the directly measured value of $k_{\mu}$ are significant. Further analysis is under way to investigate the possibility of a short-lived radical intermediate. It could be that an addition reaction occurs prior to bond fission:

$$H + S_2O_3^{2-} \rightarrow SH^- + SO_3^-.$$  

Alternatively, the $\mu S$ radical may form and then undergo fast reduction to $\mu S^-$. 

**Experiment 157**

*The chemistry of muonium atoms in condensed media*

Muonium ($\mu^+e^-$) continues to be of considerable interest as a highly reactive chemical reagent and light isotope of $H$. It is a product of intermediate energy physics research and can only be studied at meson facilities using the $\mu$SR techniques. These particular experiments are devoted to the study of chemical kinetics in solutions – with the main emphasis being on water because life is aquo-centred. They provide basic information on three matters: (i) the mass-dependence of diffusion, activation and quantum mechanical tunneling, when compared with $^1H$, $^2H$ and $^3H$; (ii) the reactivity and mechanism of hydrogen-like atom reactions which cannot be studied for 'normal' $H$ atoms; and (iii) the chemistry and mechanism of formation of these 'exotic' chemical species, for comparison with positronium atoms and solvated electrons.

During 1981, Expt. 157 was assigned 49 shifts on M20. This enabled three investigations to be completed. In the first of these, muonium radicals were observed in several vinyl monomers, at relatively large transverse magnetic field using both 'backward' and 'surface' muons. The Fourier transform of the muon spin rotation time histogram is shown as Fig. 55 at two fields for the case of styrene ($C_8H_8CH=CH_2$). The observation of a single pair of radical frequencies shows that only one radical is formed when muonium attacks this molecule. Furthermore, the hyperfine coupling constant obtained proves that this radical arises from addition of muonium to the vinyl bond rather than to the benzene ring. This finding is of significance to polymer science.

In a second study, it was shown that $\mu$SR can reveal the spin-state of a species through its muonium reaction rate constant. This study involved utilising the unique properties of nickel cyclam which transforms from the paramagnetic (octahedral, $d^8$) state to the diamagnetic (square planar) state merely by the addition of an inert salt (sodium perchlorate, in this case). Sure enough, there was a marked transition in the muon spin...
relaxation rate as the $p + d$ transition was induced by the inert salt progressively drawing off the axial solvent ligands.

In a third study, the muonium reactivity was measured as a function of temperature in both formate and deuteroformate solutions. This will now permit a complete intercomparison of isotope effects involving muonium, $^1H$ and $^2H$ as attacking atoms, and $^1H$ and $^2H$ as the abstracted atoms. It is planned to extend these studies next year to non-polar (hydrocarbon) solutions and to a wider temperature range.

**Experiment 140**

*Transfer effects for stopping $\pi^-$ in $H_2$-$D_2$ mixtures*

In preliminary runs it has been shown that if a $\pi^-$ stops in a mixture of $H_2$ and $D_2$ gas, then there is a slight preference for the $\pi^-$ to be captured on a deuteron. This has been interpreted as a net transfer of pions from protons to deuterons, although transfer occurs in both directions.

Quite large transfers have been observed in liquid targets but there the deuterium is in the form of HD molecules and there is ample evidence that small differences in the environment create large differences in the capture ratio. In the last year we have been able to manufacture several litres of HD with the co-operation of the Chemistry Department at UBC. A frustrating problem has been that there was no compressor at TRIUMF capable of reaching the high pressures that we normally use in this experiment (≈100 atm), and so two special pumps had to be purchased specifically for this experiment (although clearly available for general use). We anticipate that a run with HD will be possible fairly soon.
Theoretical Program

Introduction

The theory group was established at TRIUMF some years ago to provide a core group of theoretical physicists who are actively involved in research in the areas of medium-energy nuclear and particle physics which are under experimental investigation at TRIUMF. The intention is then that such a group will provide both a centre for high quality theoretical research and resource people for the various experimental groups and that the laboratory program as a whole will benefit from the interaction between theorists and experimentalists. Generally such benefits are being realised, despite the fairly small size of the group relative to the large variety and number of experimental programs underway. The theorists have taken an active part in various activities of the laboratory and are involved in a number of research programs, some of which are detailed below.

Currently there are three permanent staff in the group: H.W. Fearing, A.W. Thomas and R.M. Woloshyn. J. Ng holds an NSERC University Research Fellowship. Research associates, some of whom are supported jointly with UBC, include M. Betz, B. Blankleider, R. Ellis (from September), J. Niskanen (to September), A. Rosenthal and O. Shanker. Graduate students are M. Beaudry, G. Brookfield (M.Sc. 1981), J. Johnstone, P. Kalyniak, N. Shrimpton (M.Sc. 1981), S. Thébèrge, R. Workman and P. Zakaracos. Others who have actively participated in group activities and in some of the projects listed below include E. Vogt, TRIUMF Director; R. Barrett, L. Dodd, A. Gal, A. Gersten, A. Rinarat, all visitors to TRIUMF or UBC; and various theoretical faculty and research associates at member universities including D. Beder, M. McMillan, N. Weiss (UBC), J. Greben, A. Kamal, H. Sherif (Univ. of Alberta), C. Picciotto, C. Wu, M. Zahir (Univ. of Victoria), and D. Boal and M. Soroushian (SFU).

During the year members of the group have helped with the organization of a workshop on kaon physics and have participated in study sessions and prepared reports on physics possible with a kaon factory at TRIUMF. Others have been involved with planning for a CAP Summer School for 1982 and with the Long-Range Planning and Experiments Evaluation Committees for TRIUMF. Several have taught courses at UBC and given lectures at others of the member universities and a number are supervising graduate students.

Members of the theory group have represented TRIUMF at a number of external meetings, including:

9th International Conference on High Energy Physics and Nuclear Structure, Versailles, France
IUCF Workshop on the (p,n) Reaction, Bloomington, Indiana
CAP Annual Meeting, Halifax, Nova Scotia
APS Division of Nuclear Physics, Asilomar, California
LAMPF Workshop on Physics Below 31 GeV, Los Alamos, New Mexico
LBL Heavy Ion Summer Study, Berkeley, California
CAP-Banff Summer School on Particle Physics, Banff, Alberta
1981 International Symposium on Lepton and Photon Interactions at High Energies, Bonn, Germany
Univ. of Washington Workshop on Grand Unification and Supersymmetry, Seattle, Washington
Workshop on Pion Production and Absorption, Orsay, France
International Conference on Pion Few Nucleon Systems, Prague, Czechoslovakia
Nuclear and Particle Physics Vacation School, Melbourne, Australia
Nucleon-Nucleon Workshop, Saclay, France

The group made its third annual visit to Edmonton in the spring for discussions with the experimental group there. Regular weekly theory meetings have continued, providing opportunities for informal presentation of work in progress. Organization of the regular TRIUMF seminar series has been another responsibility and it, together with the theoretical visitor program, has made possible visits to TRIUMF of a number of theorists including:

R. Amado  
M. Baker  
R. Barrett  
G. Bhamath  
E. Borie  
G. Branco  
V. Chohan  
J. Comfort  
E. Cooper  
L. Dodd  
C. Dominguez  
T. Donnelly  
C. Dover  
P. Hwang  
R. Freedman  
Y. Fujiwara  
A. Gal  
J. Germond  
J. Ginocchio  
R. Goldflam  
T. Goldman  
J. Greben  
S. Gurvitz  
W. Haxton  
M. Huber  
N. Isgur  
F. Khanna  
C. Kim  
L. Kisslinger  
M. Kohn  
M. Krell  
C. Lam  
R. Landau  
T-S.H. Lee  
F. Levin  
L. Li
Some specific areas and topics of research which have been of interest during the past year include the following.

**Pion production and \((p,\gamma)\) reactions**

**Polarization parameters in \(pp + d\pi^+\)**

There has been an increasing interest recently, both theoretical and experimental, in the reaction \(pp + d\pi^+\). Undoubtedly this interest has been spurred not only by the fundamental nature of the reaction, but also by the unexpected structure seen both in N-N and \(\pi-d\) elastic scattering with consequent speculations about dibaryon resonances. Although at present little is known about the spin dependence in \(pp + d\pi^+\), there are now experimental programs both here at TRIUMF and elsewhere to determine the various polarization parameters. Encouraged by this we have used the few-body model of the \(\pi NN\) system [Blankleider and Afnan, Phys. Rev. C 24, 1572 (1981)] to investigate correlation parameters \(A_{1j}\) in \(pp + d\pi^+\) and the spherical-tensor polarizations \(t_{11}, t_{20}, t_{21}, t_{22}\) in \(pp + d\pi^+\).

Our results for the \(A_{1j}\) are similar to those of other models and therefore some large theoretical discrepancies with the new SIN data still persist. For the polarizations \(t_{kj}\) we have used the Madison Convention choice of axes (previous predictions do not appear to use this standard) and our results are shown in Fig. 56. As yet there are no experimental data. The results for the tensors \(t_{20}, t_{21}, t_{22}\) are to a large extent model independent and in addition do not vary greatly over a large energy region. In contrast the vector \(t_{11}\) is sensitive to the choice of input and therefore its measurement might be the most useful.

**Pion production in nucleon-nucleon collisions**

The excitation of \(\Delta\) isobars in NN interactions is known to play an important role in many areas of medium-energy physics and nuclear structure. Single-pion production in NN collisions, which is dominated by the process \(NN + N\Delta + NN\pi\), constitutes a unique tool for the study of the \(NN + N\Delta\) transition ampli-

---

**Fig. 56.** The vector polarization (a) and tensor polarization parameters (b) for \(pp + d\pi^+\) calculated using a few-body model of the \(\pi NN\) system. The proton laboratory energies are (o) 335, (•) 383, (△) 567, (unlabelled) 751 and (x) 799 MeV.
Fig. 57. Differential cross sections for kinematically complete LAMPF measurements of \( p p + p n\pi^+ \) at \( T_L = 800 \) MeV. The various curves illustrate the sensitivity of the results to different choices of \( \rho \) and \( \omega \) cut-offs in the \( NN + NA \) interaction, and the effects of initial state interactions:

a) \( \lambda_\pi = 1200, \lambda_\rho = 1600 \) (MeV/c);

b) \( \lambda_\pi = 700, \) no \( \rho \)-exchange; and

c) same as b) but no initial state interactions.

Fig. 58. Analysing power for kinematically complete measurements of \( p p + p n\pi^+ \) at \( T_L = 800 \) MeV at LAMPF. The meaning of each curve is the same as in Fig. 57.

[Betz et al., TRIUMF preprint TRI-PP-81-59]. Sample results, corresponding to an approximate solution in which multiple rescattering of the \( \pi \) between \( N \) and \( \Delta \) is neglected, are shown in Figs. 57 and 58. The model is fairly successful in reproducing the magnitude and shape of the differential cross section, whereas for the analysing power the discrepancy between theory and experiment is appreciable. The figures illustrate the essential equivalence (as far as \( d^5\sigma \) and \( A_Y \) are concerned) of a model including \( NN + NA \) transitions through both \( \pi \) and \( \rho \) exchanges with hard vertices, and one including only \( \pi \) exchange, with soft vertices. Also shown in Figs. 57 and 58 is the role played by initial state \( NN \) interactions, which suppress the cross section by roughly 30%. This effect can be attributed to the loss of flux into the inelastic channel and demonstrates the need to treat the coupling to \( NN\pi \) states consistently to all orders.

The amplitudes generated by the approximate calculations described above are probably reliable for those partial waves corresponding to sufficiently large \( \Delta \) orbital angular momentum. They can therefore be used as constraints in a phenomenological analysis from which the low-\( \ell \) partial-wave amplitudes could be extracted, once enough data are available. The theoretical amplitudes for small \( \ell \) are likely to be significantly affected by multiple rescattering of the pion between \( N \) and \( \Delta \) and by \( NN \) interactions in the presence of a spectator pion. In particular, the coupling to the \( \pi d \) channel should be important at TRIUMF energies. The extension of the numerical calculations to include these effects is
in progress.

A particularly intriguing and controversial issue pertaining to the two-baryon system is the existence of dibaryon resonances. Although much of the speculation about these objects was triggered by the observation of phenomena which can now be explained by standard NN* dynamics, the possibility that exotic dibaryon states (e.g., six-quark states with 'hidden colour') might show up in experiments cannot be ruled out at the present time. In order to isolate their eventual signature, it is desirable to construct models which incorporate them together with the more mundane aspects of the NN* system in a consistent fashion. One possibility is to generalize the model discussed above to include a coupling of the NN and NA channels to an 'elementary' dibaryon. Scattering equations for the NN* NN* and NN* NN* amplitudes in this extended model have been formulated, and preliminary calculations have been performed to study the sensitivity of various observables for the pp* pnir + reaction. These calculations indicate that all analysing powers at 800 MeV, with the exception of Ann*, would be significantly affected by the presence of a dibaryon in the 3- channel. A more detailed study will be performed once the improvements of the background calculation have been completed.

The nNA coupling and the Δ(1232) resonance width

We have calculated higher-order mesonic effects contributing to the Δ(1232) width and shown that the quark model value for \( f_{nNa} \) can be consistent with the experimental width. These contributions are very sensitive to the vertex form factors and to avoid drastic exaggeration of the Δ width we need very long-range cutoffs even for the \( p \) meson. Details are summarized in TRI-PP-81-31.

Energy dependence of (pπ) and (p,γ) reactions in a DWIA model

As suggested earlier, a comparison of (p,π) and (p,γ) reactions has recently been made [Fearing, Proc. 9th Int. Conf. on the Few Body Problem, Eugene, Vol. I, paper II-11 (1980)] for the reaction pd + tπ and pd + \( ^3\)He using a DWIA model [Fearing, Phys. Rev. C 16, 313 (1977)]. For both cases the model reproduces \( d\sigma/dΩ \) and the normalization near the resonance rather well. Above about 600 MeV, however, cross sections fall too rapidly with increasing energy. One possible explanation for this discrepancy is the following. In such calculations one factorizes the input two-body amplitude and evaluates it at some average on-shell point, usually one corresponding to the maximum of the rest of the integrand. Thus at high energies the impulse amplitudes used here tend to be evaluated far out in the tail where the amplitudes are strongly suppressed.

To estimate possible effects of a calculation without factorization, several different prescriptions were tried. First, input amplitudes were simply evaluated at an energy giving the maximum contribution consistent with on-shell constraints. Alternatively the average of this choice and the original one was taken. For (p,γ) above 600 MeV both approaches increase the cross section by a factor of 1.3-2.0 with little change in the angular distribution. For (p,π) the increase is larger at intermediate angles, but zero at 0° and 180° because of the on-shell constraint. Hence the angular distribution is changed and so for the (p,π) case it appears one must relax the on-shell constraints as well.

Thus these rather crude estimates indicate that the choice of kinematic point for the amplitude can be important. Clearly efforts should be made to include these effects exactly by avoiding the factorization assumption completely.

Applications of the cloudy bag model

Last year we reported on the first stage of a long-term program, whose aim is to eventually unify our understanding of nuclear and particle physics. Of course, this is a noble aim, and the first steps must necessarily be more modest. Nevertheless, substantial progress has been made in the past year, and our early optimism has not faded in the least!

Our approach (the cloudy bag model, or CBM) begins with the observation that one quite successful phenomenological approach to hadron structure, namely the MIT bag model, badly violates chiral symmetry. In order to restore chiral symmetry we are necessarily led to introduce a pion field coupled to the surface of the bag. The appropriate Lagrangian density is (without a pion mass term)
\[ \mathcal{L}_{\text{CBM}}(x) = (i \bar{q}(x) \gamma \gamma S q(x) - B) \delta_{\nu} + \frac{1}{2} (\partial_{\mu} \phi)^2 - \frac{1}{2} \bar{q}(x) \Delta_{S} + \frac{1}{2} (\partial_{\mu} \phi)^2 , \]  

(1)

where \( \phi \) is the three-component compensating (pion) field and \( D_{\mu} \phi \) is a covariant derivative

\[ D_{\mu} \phi = \partial_{\mu} \phi - [1 - \xi \frac{\phi}{f}] \gamma_{5} \phi \]  

(2)

As usual \( q(x) \) is the quark field, \( B \) the phenomenological energy density of the bag, \( \delta_{\nu} \) is one inside the bag and zero outside, and finally \( \Delta_{S} \) is a surface delta function.

Notice that in the absence of (unobserved) \( \sigma \)-mesons Eq. (1) is necessarily non-linear. To lowest order in the pion field the conserved axial current associated with Eq. (1) is

\[ A_{\mu}^A(x) = \frac{1}{2} \bar{q}(x) \gamma_{\mu} \gamma_{5} \gamma_\tau q(x) \delta_{\nu} - f \partial_{\nu} \phi \]  

(3)

If we add a pion mass term to Eq. (1), thereby breaking chiral symmetry, we find that \( A_{\mu}^A \) obeys the PCAC relationship

\[ \partial_{\mu} A_{\nu}^A = f m_{\pi}^{2} \phi + o(\phi^{2}) , \]  

(4)

with \( f \) the pion decay constant (93 MeV).

At this stage \( f \) is the only indication that the pion has structure. Of course, one would eventually hope to derive something like \( \mathcal{L}_{\text{CBM}}(x) \) from QCD, with the pion being a Goldstone boson associated with some dynamical symmetry-breaking mechanism. The work of Goldman and Haymaker is very suggestive in this regard.

In order to obtain a practical theory of pion-baryon dynamics, we have chosen to expand Eq. (1) in powers of \( \phi \). Essentially this amounts to saying that the MIT bag is a good starting point for a quantised field theory - a minimum in the classical action, in the path integral formulation. Keeping only terms of lowest order in \( \phi \), Eq. (1) becomes

\[ \mathcal{L}(x) = (i \bar{q} \gamma \gamma S q - B) \delta_{\nu} + \frac{1}{2} (\partial_{\mu} \phi)^2 - \frac{1}{2} \bar{q}(x) \gamma_{\mu} \gamma_{5} q \Delta_{S} . \]  

(5)

From this we can easily write down a Hamiltonian for a pion interacting with any hadron describable in the bag model. If we restrict the space of bag states to non-exotic hadrons [e.g. three-quark baryons (a similar analysis could and should be carried out for non-exotic mesons, \( qq \) states, which couple strongly to pions, e.g. the rho-meson)], denoted \( (a, \beta, \ldots) \), this Hamiltonian is:

\[ H = H_{\text{MIT}} + H_{H} + H_{\text{int}} , \]  

(6)

\[ H_{\text{MIT}} = \sum_{a} m_{a}^\text{bag} a^\dagger a , \]  

(7)

\[ H_{H} = \sum_{k} \alpha_{k}^{\text{bag}} a_{k}^\dagger a_{k} w_{k} , \]  

(8)

and

\[ H_{\text{int}} = -\frac{1}{2f} \sum_{a, \beta, k} \int dx q(x) \gamma_{\mu} \phi(x) \gamma_{5} x q(x) \Delta_{S} |a \rangle \delta^{\alpha \beta} a_{k} + h.c. . \]  

(9)

In the limited space of \( N \) and \( A \), which is of most interest in low and intermediate energy nuclear physics, \( H_{\text{MIT}} \) contains \( \Delta \pi, \Delta N \) and \( NN \) vertices. The ratio of the bare coupling constants can be calculated in terms of the bag model wave functions. There is also a form factor, or high momentum cut-off, because the pion is no longer coupling to a point, but to the surface of a large object. If we neglect the small difference between the \( N \) and \( A \) bag radii, this form factor is identical for all three vertices, that is

\[ u(k) = j_{0}(kR) + j_{2}(kR) = 3j_{1}(kR)/kR . \]  

(10)

For some justification of the linearization of Eq. (1) we refer to the review submitted to the International Conference on Pion Few Nucleon Systems, Prague (TRI-PP-81-19, to appear in Czech. J. Phys.) and to the lectures presented at the NUPP Vacation School at the University of Melbourne (UM-P-81/29) in May. For the present we merely observe that once the equations are linearized [Eqs. (6)-(9)] the resulting model is ideally suited to applications in low and medium energy physics. In particular the theory is renormalizable, and the renormalizations are finite and small!

Pion-nucleon scattering

Last year we reported on the successful application of the CBM to pion-nucleon scattering in the \((3,3)\) channel. In the past year Rinat has applied our model to the \( P_{11} \) channel (containing the Roper resonance). A reasonable understanding of the small \( p \)-waves has been obtained by Musakhanov et al.
From the theoretical point of view the most interesting new result for pion scattering concerns the s-waves. By applying a unitary transformation to the Lagrangian of Eq. (1) we have obtained a generalization of the Weinberg effective Lagrangian for pion-nucleon scattering [Thomas, J. Phys. G 7, 283 (1981)]. This new Lagrangian incorporates the Weinberg-Tomoza result

$$a_T = \left( \frac{B}{2m} \right)^2 \left( \frac{B_V}{B_A} \right)^2 \frac{m_T}{2n} \left( 1 - m_T/m_\pi \right)^{-1} \times \left[ T(T+1) - T_t(T_t+1) - 2 \right], \quad (11)$$

for low energy s-wave scattering of a pion from any hadronic bag (total isospin $T$, target isospin $T_t$).

**Formal proof of convergence**

The nucleon bag will of course be dressed by its interaction with the pion field, but the nucleon does remain as the one discrete eigenvector of the Hamiltonian (6), satisfying

$$H|N> = m_N|N> . \quad (12)$$

In the old meson source theories such as Chew-Low one could also write an equation like (12), but $H$ would not include the $\Delta$. The convergence properties of these old source theories were very poor. For example the ratio of bare to renormalized coupling constant squared was about three; the average number of pions in the cloud about the nucleon was large. Finally the properties of the core itself were completely unknown.

For the CBM, on the other hand, the convergence properties have been shown to be excellent. The renormalization of the $NN\pi$ coupling constant has been shown by explicit calculation to be of order 10% [Théberge et al., Can. J. Phys. (in press)]. More formally, starting with Eq. (12), it has been proven by Dodd, Alvarez-Estrada and Thomas [Phys. Rev. D 24, 1961 (1981)] that one can place rigorous bounds on the number of pions present in the physical nucleon. Indeed, for $R = 0.82$ as found in $nN$ scattering, the average number of pions is rigorously less than or equal to 0.9, and this seems to be a generous upper bound. This should be compared with Chew-Low where the same bound is 2.2 pions. It is this fantastic convergence property, which is unique to the CBM, that is most encouraging for applications to many-body systems.

The implications of this model for proton decay are under investigation [McKellar and Thomas], but it is clear that in lowest order it justifies the usual assumption that the nucleon consists of just three quarks.

**Magnetic moment of the nucleon octet**

The first calculations of the pionic corrections to hadronic properties were for the neutron and proton. Indeed we saw that there was a significant improvement in the predictions of the MIT model when pion cloud effects were included [Thomas et al., Phys. Rev. D 24, 216 (1981)]. In view of its significance we repeat again that the model has very definite predictions for the charge density of the neutron. In fact, a good measurement of $G_{EN}$ is probably the least model-dependent method to determine the size of the bag.

In the past year we have extended the calculation of pion corrections to the other members of the nucleon octet. The coupling of the quark and pion fields to the photon occurs through the usual minimal coupling. For simplicity we take $SU(6)$ wave functions for all octet members in order to calculate both the ratio of the coupling constants (e.g. $\Sigma\pi$, $\Xi\pi$, etc.) to the $NN\pi$ coupling constant, and the magnetic coupling to the bag ($\gamma\Sigma$, $\gamma\Sigma^0$, etc.). The $NN\pi$ coupling constant itself was fixed at the usual value of $f^2/4\pi = 0.081$, and the radius of the bag for all hyperons was taken to be 1 fm - in agreement with the MIT analysis.

At this stage the model has no free parameters! For the $\Sigma$, for example, we calculate all the graphs shown in Fig. 59 in exactly the same way as for the nucleon. We observe that although there are a large number of graphs in which the photon couples to the bag with the pion 'in the air', these are usually small, and in any case there is considerable cancellation. The results of the calculation are summarized in Table XII.

![Fig. 59. Contributions to the magnetic moment of the $\Sigma$-hyperon, including pionic corrections to $O(\alpha^2)$](image-url)
Table XII. Comparison of the magnetic moments of the members of the nucleon octet calculated in the CBM, in comparison with the most recent data (all numbers in nuclear magnetons).

<table>
<thead>
<tr>
<th></th>
<th>CBM</th>
<th>Experiment</th>
</tr>
</thead>
<tbody>
<tr>
<td>p</td>
<td>2.60(^a)</td>
<td>2.793</td>
</tr>
<tr>
<td>n</td>
<td>-2.01(^a)</td>
<td>-1.913</td>
</tr>
<tr>
<td>Λ</td>
<td>-0.58</td>
<td>-0.614±0.005</td>
</tr>
<tr>
<td>Σ(^-)</td>
<td>-1.08</td>
<td>-1.41±0.27</td>
</tr>
<tr>
<td>Σ(^+)</td>
<td>2.34</td>
<td>2.33±0.13</td>
</tr>
<tr>
<td>Σ(^-)</td>
<td>-0.51</td>
<td>-0.69±0.04(^b)</td>
</tr>
<tr>
<td>Σ(^0)</td>
<td>-1.27</td>
<td>-1.25±0.014</td>
</tr>
</tbody>
</table>

\(^{a}\) Using R = 0.82 fm as determined from pion-nucleon scattering [Théberge et al., Phys. Rev. D 22, 2838 (1980)].

\(^{b}\) F. Myhrer, private communication.

\(^{c}\) G. E. Brown, private communication.

Clearly the overall agreement with experiment is excellent. One remarkable feature of the calculation not shown in Table XII is that once pionic corrections are included there is little sensitivity to a small change in the bag radius. For example, arbitrarily reducing R from 1.0 fm to 0.9 fm changes \(\mu(\Sigma^+)\) and \(\mu(\Sigma^-)\) to 2.21 n.m. and -1.07 n.m. (i.e. by 5% and 1%), respectively. To some extent, therefore, the extra pion contribution for a small bag compensates for the decrease in the contribution from the core.

Nucleon-nucleon scattering

Some work has already been carried out on the long-range N-N force in the CBM. At least as long as the bags do not overlap, the standard one- and two-pion-exchange potentials (including delta excitation) should be a good approximation. At shorter distances (that is inside about 1.6 fm) the quarks will play a critical role, and unhappily there is, as yet, no reliable calculational technique. In a very interesting piece of analysis, Gersten [TRI-PP-81-2, 2nd Int. Conf. on Recent Progress in Many-Body Theories, Oaxtepec, Mexico] has been able to set limits on the value of \(R\), appearing in the \(NN\) form factor (3.6), on the basis of N-N phase-shift analysis alone. His limits of \(R\) between 0.60 and 0.90 fm are quite consistent with the CBM result of 0.82 fm (±10%).

In another attempt to get some insight into the form factor at the NN\(ω\) vertex, we have looked at N-N scattering in partial waves for which the two-pion-exchange contributions are well approximated by the box diagram [Gersten and Thomas, TRI-PP-81-28]. For these partial waves we have used the quasipotential equation approach by which the ladder diagrams are generated in an approximate way. We have selected only the partial waves for which the first iterated Born term was a good approximation to the box diagram. This led us to consider the \(3\Sigma_2\), \(\varepsilon_3\), \(3\Sigma_3\), \(\Sigma_4\) partial waves as the best candidates. Next we used the one-pion-exchange potential modified by the form factor of Eq. (10). The results for \(\varepsilon_3\) and the \(3\Sigma_2\) phase shift are in best agreement with the data for a bag radius of \(R = 0.8\) fm. The determination of the phases \(3\Sigma_3\) and \(3\Sigma_4\) in the phase-shift analysis is still not accurate. Of course, at the present time we have considered only uncorrelated and correlated two-pion exchange. At the present stage of the art it is impossible to calculate the contributions of exchanges of a higher number of mesons. Therefore, we cannot estimate how sensitive the result \(R = 0.8\) fm is to the inclusion of 3 or more uncorrelated (irreducible) and correlated pion exchanges.

In the absence of a theory which connects the nucleon-nucleon force with the substructure of the nucleon, there has never been an estimate of the direct effects on NN scattering of the violation of SU(2) x SU(2) at the quark level. In particular, in order to explain the mass splittings within multiplets such as the nucleon, \(Σ, Σ, Λ\) and so on, one expects a splitting of the \(u\) and \(d\) quark masses. Within the framework of the bag model we recently obtained a value of \((m_u - m_d)\) of \((4-5)\) MeV [Bickerstaff and Thomas, TRI-PP-81-64]. Of course it is common to calculate the effects of \(n-p\) mass differences (an indirect inclusion of effects of \(m_u \neq m_d\)). In the CBM we have recently shown that such a mass difference leads to a charge-symmetry violating difference between the \(ω_{pp}\) and \(ω_{nn}\) coupling constants [Thomas et al., Phys. Rev. D 24, 2539 (1981)]. One of the most attractive features of this result is that it is associated with the longest range piece of the N-N force, and should survive in even the most recent models of N-N scattering which take into account the large size of the nucleon bag. (A pessimist might doubt whether \(ρ-ω\) and \(ω-η\) mixing will survive, since they are of short range and the bags overlap at \((1.5-2.0)\) fm.) The effect of this violation should be seen at an appropriate level in many systems. In par-
ticular we think of different widths for $\Delta$ decay to $\pi^0$, of forward-backward asymmetry in $np + \Delta^0$ (which may be enhanced in polarization measurements), and so on.

**Recoil corrections to $\pi N$ scattering in the CBM**

Calculations of $\pi N$ scattering in the CBM have until now relied on the static baryon approximation. Although this is sufficient at low energy for most purposes, it is sometimes desirable to do better. In particular, scattering in the $P_{11}$ channel, which is relevant to the construction of models for $\pi$ production, is governed by a delicate cancellation between the repulsion due to the nucleon pole and the attraction due to the Roper resonance of mass 1470 MeV. At energies in the neighborhood of the latter, recoil corrections are expected to be significant. Improving upon the static approximation involves the use of three-body techniques in the solution of scattering equations, as well as the construction of CBM form factors taking into account baryon recoil. Both of these problems are being studied.

**Pion-nucleus interactions**

$\pi$-nucleus scattering, charge exchange and quasielastic scattering

Our interest in pion-nucleus scattering and reactions continues. A review of the current status of the theory was presented at the Versailles meeting [Thomas, Nucl. Phys., to be published]. As reported elsewhere in this report the attempts to extract reliable information on nuclear matter distributions using low energy pions continue to be an important concern at TRIUMF. In addition, we are presently involved in calculations of low energy single and double charge exchange. Indeed, the calculations of Landau and Thomas (unpublished) are in rather good agreement with recent LAMPF data for the $^{15}N(\pi^+,\pi^0)^{15}O$ reaction at 50 MeV.

In past years we have discussed the possibility of examining the $\pi N$ interaction inside nuclear matter by using the $(\pi,\pi N)$ knockout reaction. In fact, Jackson, Ioannides and Thomas [Nucl. Phys. A322, 493 (1979)] proposed a specific experimental geometry which was expected to reduce theoretical ambiguities to a minimum. These ideas have recently been tested in much more detail by Shrimpton [UBC M.Sc. thesis, Oct 1981] and Thomas.

By examination of the contributions to the DW matrix element, it has proven possible to isolate which part of the nucleus contributes most significantly to the $(\pi,\pi N)$ reaction at each angle and energy setting. From this it has become clear that Jackson et al. were a little too optimistic. In fact, there is only one window, at about 116 MeV, where it is reasonable to expect to see large effects of the medium (Pauli principle). At lower energies its effect is too small, while in the resonance region the pions do not penetrate far enough into the nucleus for the effective fermi momentum to differ significantly from zero. Of course, this result has rather important consequences for programs of quasielastic scattering measurements. Figure 60

![Fig. 60. Five-fold differential cross section of the knockout of a $^{1}P_{1/2}$ proton from $^{16}O$ by $\pi^+$ at 116 MeV, as a function of the recoil angle of the nucleus $\theta_R$. The lines give the cross sections calculated for various fermi momenta, and include the off-shell effect and the effective polarization of the nucleon. The solid line gives the cross sections calculated with the fermi momentum determined by the localization of the knockout reaction. In this case $K_f$ local = 0.7 fm$^{-1}$. The dotted lines gives the cross sections calculated with $K_f$ = 0.0, the dashed line with $K_f$ = 0.7 fm$^{-1}$, the dash-dot lines with $K_f$ = 1.0 fm$^{-1}$ and the dash-two dot line with $K_f$ = 1.36 fm$^{-1}$. The geometry is fcg A of Jackson et al. (op. cit.)](image-url)
shows several calculations of the cross section for removing a $p_{1/2}$ proton in the $^{16}_0\alpha(x^+,\pi^+p)x^{15}_N$ reaction at 116 MeV. The solid curve is the best prediction including medium effects, whereas the dotted curve would be obtained by using the $\pi N$ t-matrix in free space. There is a clear qualitative difference between the two curves.

Strong-absorption signature of giant-resonance excitation in pion-nuclear reactions

Predictions of the eikonalized strong-absorption model for the small-angle excitation of isovector giant-resonance states, as well as for analog states, are given for pion-nuclear single-charge-exchange reactions. Spin-flip excitations are treated, particularly in connection with the recent observation of the giant dipole resonance in $(\pi^-,\pi^0)$ on $^{40}$Ca. The results trivially generalize to excitation of isoscalar resonances.

Electromagnetic interactions

$n+p \rightarrow D+\gamma$

The sensitivity of the cross section and various polarization observables in the radiative neutron capture by protons to phase-equivalent unitary transformations of the two-nucleon Hamiltonian is being studied for energies below pion production threshold. This work is motivated in part by suggestions that small discrepancies between previous calculations and cross-section data may be due to exotic chromodynamic effects. Preliminary results of the present calculations show that small changes (10-15%) in the cross section may be induced by transformations which would not lead to conflict with other reactions, e.g., electron-deuteron elastic scattering. The neutron and proton analysing powers have been found to be remarkably insensitive to a wide class of transformations. A failure of the potential model to reproduce these quantities could be highly significant. It has been proposed that the neutron analysing power be measured at TRIUMF [Cameron and Wilson, Expt. proposal No. 190].

A relativistic gauge invariant model for N-N bremsstrahlung

Recent measurements of the p-p bremsstrahlung (pp$\gamma$) cross section and a proposal being considered [Kitching, Expt. 208] at TRIUMF to measure, for the first time, the asymmetry in pp$\gamma$ have stimulated a new look at the theoretical situation. Historically most calculations have used non-relativistic potential models which allow direct connection with off-shell information, the main motivation for looking at pp$\gamma$. They are, however, generally not gauge invariant and are non-relativistic whereas it is now known that even very simple relativistic corrections are important at 200 MeV. An alternative, the soft photon approximation (SPA), is relativistic and gauge invariant, but has no off-shell information. Somewhat surprisingly the SPA fits the data as well or better than the potential calculations [Fearing, Phys. Rev. C 22, 1388 (1980); Rogers et al., Phys. Rev. C 22, 2512 (1980)].

Kaon and hypernuclear studies

$\mathbf{KN}$ scattering lengths

Theoretical work on $\mathbf{KN}$ scattering has been stimulated by the discrepancy between kaonic hydrogen measurements and dispersion calculations of the low energy scattering parameters. This question is also clearly of importance for low energy reactions to be performed at a future kaon factory.

The cloudy bag model can be extended in a straightforward way to flavour SU(3) and provides a useful tool for examining low energy $\mathbf{KN}$ scattering and reactions. For the I=0 channel, it is assumed that the $\Lambda(1405)$ and $\Xi$ states are the most important inelastic
intermediate states, in which case the set of coupled equations for $\bar{K}N$, $\Sigma\pi$ and $\Lambda(1405)$ can be solved analytically to first order in the meson-baryon interaction potential. The $\Lambda(1405)$ has been assumed to be a pure 70 of SU(6) and a singlet of SU(3); however, no wave function corrections for centre-of-mass motion have been made. The results for massless quarks are shown in Fig. 61; the introduction of a massive strange quark ($m_s = 300$ MeV) does not change these results by more than 10%.

The results of these calculations confirm the expectation that the subthreshold $\Lambda(1405)$ resonance induces a repulsive $\bar{K}N$ interaction. The renormalization of this interaction due to the effects of coupling the $\Lambda(1405)$ to the $\Sigma\pi$ system are strong and tend to reduce the real part of the $\bar{K}N$ amplitude but no reasonable choice of the parameters (the averaged meson octet weak decay constant and the bag radius) will change the sign of the interaction. However, our $I=0$ scattering lengths are smaller than those calculated by most other workers in the field and tend to lie between the atomic measurements and the dispersion calculations. We feel that this result, together with the calculations of other authors, reinforces the need for new low energy experiments.

Future work will deal with the effects of centre-of-mass motion and of the $I=1$ channel.

Photokaon reactions

The possibility of forming hypernuclei in the radiative reactions ($\gamma, K^+$) or ($K^-, \gamma$) promises to give rewarding insights into hypernuclear structure. In particular the low-lying unnatural parity states of light $\Lambda$ or $\Sigma$ hypernuclei can be excited in these reactions but not by the common ($K^-, \pi^+$) production mechanism. The structure of these states is sensitive to the spin dependence of the $AN$ forces, a quantity of considerable recent interest. Before recommending a set of experiments it will be necessary to understand the two-body reaction mechanism $\gamma + K^+\Lambda$.

Unlike $\gamma + \pi N$ there is no strongly resonating intermediate state but rather a distribution of more or less equally excited resonances. For application to hypernuclear physics it is desirable to represent these resonances by Feynman diagrams so that the recoil structure of the nuclear amplitude may be at least approximately taken into account. In this model the hyperon polarization is generated by the finite lifetime of the resonating states.

The simplest amplitude which is capable of giving a reasonable description of the data from threshold to $K_Y = 1.4$ GeV contains $K^*(890)$ and $K^*(1420)$ t-channel exchange, $N^*(1470)$ and $N^*(1710)$ s-channel exchange and $\Sigma$ and $\Sigma^*(1660)$ u-channel exchange. The coupling constants were taken from data where available leaving 7 adjustable parameters for 119 cross-section data points. The 1.05 GeV results are shown in Fig. 62. The 90° polarization, which is not fitted in the parameter search, is given as -0.26 as compared to the experimental value of -0.39 ± 0.15. The cross-section fit has the same quality at other energies, being generally too small at back angles. Inasmuch as the forward angle amplitude is the more important for hypernuclear photoproduction (because of nuclear form factor effects) we are confident that we have a workable amplitude at the 15% level.

This amplitude differs from the $\bar{\omega}\pi$ form assumed by Bernstein et al. [MIT preprint] in two important ways:

1) There are angle-dependent terms which represent the momentum-transfer behaviour of the actual amplitude.

2) There is a term proportional to $(\vec{q}_K \times \vec{K}_Y) \cdot \epsilon$ which allows for the excitation of natural parity states such as the $\langle \bar{n}S_{1/2}, p S_{1/2}^{-2} \rangle$ of $^{12}C$. 

Fig. 61. $I=0$ $\bar{K}N$ scattering amplitude. Dashed curves are Im $f$ and solid curves are -Re $f$. The lowest and highest curves are for a bag radius of 1 fm and the two central curves for 0.8 fm.
Fig. 62. Differential cross section for yp + K+Λ at \( P_{LAB} = 1050 \text{ MeV/c} \).

The University of Pittsburgh photoproduction computer code is being adapted for use with this amplitude.

Study of the \( T = 3/2 \) ΣN interaction

One-boson-exchange models of the ΣN interactions have been studied, preparatory to a full investigation of Σ-hypernuclei. The simplest channel is \( T = 3/2 \) where the strong decay EN + AN is isospin forbidden and in which there is the outstanding problem of a possible Σn bound state. Standard analyses [Nagels et al., Phys. Rev. D 20, 1633 (1979)] proceed by fitting meson coupling constants to NN and the small amount of AN and EN data, a procedure which involves a large number of free parameters. This analysis has used the OBEP with recent parameters derived from meson-baryon scattering, an independent source of information [Bradford and Martin, Z. Phys. C1, 357 (1979)]. The couplings are in many cases quite different from the fitted values of Nagels et al. We find that at low energies all EN channels are repulsive except for the \( ^1S_0 \) whose depth depends strongly on \( ^1\!\!K^+ \) meson exchange. Two models have been considered:

A) A single \( ^1\!\!K^+ \) nonet with masses at the

Particle Data values. There are two free parameters, the eNN coupling and the F/D ratio. The former is fixed in fits to S-wave NN scattering and the latter has been varied to the EN data.

B) A pair of \( ^1\!\!K^+ \) nonets, one (called \( 0_1^+ \)) at \( \sim 800 \text{ MeV} \) including the \( S^* \) and \( \delta \), and another (\( 0_2^+ \)) at \( \sim 1400 \text{ MeV} \) including the ε and \( \kappa \) as suggested by bag models. There are five free parameters: \( \epsilon_{1\!\!NN} \), \( \kappa_{1\!\!NN} \), \( \epsilon_{2\!\!NN} \) and the two F/D ratios.

With model B one can fit the low energy data in more than one way and predictions are ambiguous. In model A, however, adequate fits to data are possible only in a very restricted parameter range. None of these fits allows a bound \( ^1\!\!Σn \) and they all predict a strongly repulsive \( ^3S_1 \) channel so that such a model is unlikely to bind the \( ^1\!\!Σ\text{nn} \) system. These results lead us to expect that even for the lightest Σ-hypernuclei one will be concerned with the full complications of a coupled channels problem.

In the ground state, Λ-hypernuclei can only decay via the weak interaction. Such states therefore have long lifetimes, and their properties have been studied experimentally for many years. The Σ-hyperon, on the other hand, is some 80 MeV heavier than the Λ, and since both have \( S=-1 \), the conversion EN + AN (with the release of 80 MeV) can happen via the strong interaction. Thus for many years it was believed that Σ-hypernuclear states would be very broad (\( \Gamma \sim 25 \text{ MeV} \) in nuclear matter). It was therefore a great surprise when relatively narrow Σ-hypernuclear levels were reported from CERN in 1979.

Over the past eighteen months we have attained a fair understanding of these states, and particularly their long lifetimes, at the microscopic level. This involved the construction of a set of non-local separable potentials describing the coupled EN-AN systems. From this we have calculated the Brueckner single-particle potential for the Σ in a light nucleus — the density of which is described by the harmonic oscillator model. This potential includes nucleon recoil effects exactly (technically we do not need to factorize to the tp form), in a three-body model, as well as the effects of the Pauli exclusion principle. The eigenvalues for the resulting non-local single-particle potential
were obtained self consistently by solving the Schrödinger equation in momentum space. The results of these calculations for the $s$-states of a number of light $\Sigma$-hypernuclei are shown in Table XIII [Johnstone and Thomas, TRI-PP-81-70].

The momentum transfer in present $(K,\pi)$ experiments does not favour the formation of $s$-state $\Sigma$-hypernuclei. In fact, only one such level has so far been reported - for $^{12}_\Sigma^0$. Our calculation is in rather good agreement with both its position and width. Further confirmation of that result, and new measurements in (say) $^{16}_\Sigma^0$, would be very valuable. Finally we note that the only information hitherto available on the $\Sigma$-nucleus interaction came from $\Sigma$-atoms. It is a remarkable result of the present calculation that we not only find narrow $ls$ levels in $\Sigma$-hypernuclei but that we also obtain the same volume integral for the $\Sigma$-nucleus interaction as found in Batty's phenomenological analysis of the $\Sigma$-atom data.

Table XIII. $S$ state binding energies in $I^0$ hypernuclei.

<table>
<thead>
<tr>
<th>Nucleus</th>
<th>$K_F$ (MeV/c)</th>
<th>$B_N$ (MeV)</th>
<th>$E + I/2$ (MeV)</th>
<th>$I$ (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^5_\Sigma^0$He</td>
<td>245</td>
<td>7.5</td>
<td>+2.49-0.881</td>
<td>1.75</td>
</tr>
<tr>
<td>$^7_\Sigma^0$Li</td>
<td>250</td>
<td>10</td>
<td>+0.81-0.991</td>
<td>1.98</td>
</tr>
<tr>
<td>$^9_\Sigma^0$Be</td>
<td>260</td>
<td>10</td>
<td>-0.46-1.951</td>
<td>3.89</td>
</tr>
<tr>
<td>$^{12}_\Sigma^0$C</td>
<td>260</td>
<td>10</td>
<td>-2.06-4.911</td>
<td>9.81</td>
</tr>
<tr>
<td>$^{16}_\Sigma^0$O</td>
<td>260</td>
<td>10</td>
<td>-4.22-6.261</td>
<td>12.51</td>
</tr>
<tr>
<td>$^{13}_\Sigma^0$C</td>
<td>260</td>
<td>10</td>
<td>-2.65-5.301</td>
<td>10.60</td>
</tr>
</tbody>
</table>

Weak interactions and particle physics

Effects of the $\Lambda$ in radiative muon capture

The radiative muon capture process, $\mu + Z + (Z-1) + \gamma + \nu \gamma$ is particularly sensitive to $g_\mu$, the induced pseudoscalar coupling constant of the weak interaction and has been used as a way of measuring this coupling. The most recent experiment [Hart et al., Phys. Rev. Lett. 39, 399 (1977)] when interpreted using the theory available at that time gave good agreement with the value of $g_\mu$ predicted via the Goldberger-Treiman (GT) relation. The same data interpreted using a more modern theoretical analysis [Sloboda and Fearing, Nucl. Phys. A340, 342 (1980)], which includes some new effects, as well as all those previously considered except one, suggests very poor agreement with the GT prediction. The one effect left out, namely the effect of the nuclear Coulomb field on the muon propagator, is controversial with some finding it small and others finding it large [Rood et al., Nucl. Phys. A228, 333 (1974); Christillin et al., Nucl. Phys. A345, 317 (1980)]. It is thus of interest to look for other effects which might influence the extracted values of $g_\mu$.

One such possible effect is that due to a $\Delta$ intermediate state. Such diagrams arise from, say, a proton-gamma-delta vertex followed by a delta-weak-neutron vertex. Thus the $\Delta$ replaces the intermediate proton (or neutron) of the dominant contributions. We have evaluated such diagrams for the simple process $\mu + \pi + \nu + \gamma$ using standard relativistic Feynman graph techniques. The couplings at the nucleon-gamma-delta and delta-weak-nucleon vertices were evaluated using CVC, PCAC and information from pion photo- and electro-production. For this simple reaction the effects generated by the delta are small, but non-negligible and should be included in accurate calculations. They, however, seem to have the wrong sign to resolve the discrepancy in the value of $g_\mu$.

However, in a nucleus additional effects enter arising from the interactions of the $\Delta$ propagating in the nuclear medium. Such effects may be very important and clearly must be examined in detail before one can say whether the results obtained so far on a proton carry over to the nuclear case.

Massive neutrinos in $\mu$ and $\pi$ decays

We have analysed the effects of intermediate mass neutrinos on precision measurement of the Michel parameters in muon decays. Under the assumption that the effective interaction at low energies is predominantly left-handed, the effects of massive neutrinos and neutrino mixings will be too small to be detected by current experiments. Lowest-order radiative corrections are also taken into account. A global analysis of neutrino oscillation experiments and $\pi^0_2$ branching ratios was used to constrain the possible range of a massive $\nu_T$ mixing into $\nu_\mu$ and $\nu_\tau$. We found that a mass of $m_{\nu_T} < 2$ MeV with Cabibbo mixing is not ruled out by current data. Improved data certainly will help in lowering the mass of $\nu_T$ and its mixing.
Phenomenology of flavour violation

The phenomenology of flavour violation in different extensions of the standard model that are presently of interest was studied. Mass bounds were derived from different processes on the masses of flavour-violating particles in horizontal gauge models, models with flavour-violating neutral Higgs particles, technicolour models and the Pati-Salam type of grand unified models. The possibility of getting information on the mechanism of flavour violation by looking at the z dependence of the coherent \( \mu e \) conversion rate or at the ratio of the rates for \( K_L + ee \), \( K_L + \mu e \) and \( K_L + \mu \mu \) was noted.

Leptonic decay widths for \( L=1 \), \( J^{PC}=1^{--} \) T-baryonia

The leptonic decay widths of the \( J^{PC}=1^{--} \) T-baryonia in the 1-5 GeV region have been estimated using the Van Royen Weisskopf technique within the framework of the QCD potential model [Ellis et al., UMP-81/43]. In this work the diquark and antidiquark are assumed to have a finite extent, a more realistic approximation than previous calculations in which the diquark and antidiquark were assumed pointlike [Ellis et al., Phys. Rev. D 22, 2832 (1980)].

Our calculations indicate that T-baryonia have very small leptonic widths, generally of the order of 10 eV. Consequently, with current experimental resolution, they are unlikely to be observed in \( e^+e^- \) annihilation experiments which are such a clean source of vector mesons. However, a recent calculation [Ellis et al., Lett. Nuovo Cimento 30, 455 (1981)] indicates that M-baryonia are more likely to be observed in \( e^+e^- \) experiments than T-baryonia. Therefore, it will be of interest to extend detailed calculations of the leptonic widths to M-baryonia.

High energy nuclear reactions in quantum chromodynamics

Perturbative quantum chromodynamics (QCD) can be applied to hadronic reactions that take place at short distances. It has been shown that the structure functions of lepton-nucleus can be analysed within a QCD framework in the same way as the structure functions of more elementary hadrons. The logarithmic \( Q^2 \) scaling violations of proton and deuteron structure functions were found to be target independent as predicted by QCD.

Perturbative QCD predicts that a quark carrying a large fraction of a hadron's total momentum should be polarized. This polarization can be measured in deep inelastic polarized electron scattering. A study of polarized electron scattering on \( ^3\text{He} \) has indicated that quark polarization in this nucleus may be visible at momentum transfers above about 10 GeV\(^2/c^2\).

Electroproduction of W-bosons in ep colliders

We have calculated the production rates of W\(^\pm\)-bosons in electron proton collisions using the Weinberg-Salam model and the quark parton model in the Weizsäcker-Williams approximation. It is found that this approximation is quite reliable. Several parameterizations with quantum chromodynamic corrections to the quark distributions are used and the W-boson production rates are found not to be too sensitive to the difference. We conclude that W-boson production is at a detectable level for the next generation of colliders.

Many-body theory

Fermi liquid interactions in neutron matter

We have calculated Landau's Fermi liquid parameters for neutron matter. Our calculations, which include the tensor force and polarization effects of the neutron medium, agree qualitatively, but not quantitatively, with those of Bäckman, Källman and Sjöberg. Our calculated Landau parameters also suggest that superfluid transition temperatures (\( ^1S_0 \)) for neutrons and protons in neutron star matter are enhanced at low density by neutron density fluctuations, but are suppressed by neutron spin fluctuations at high density. Details are given in TRI-PP-81-55.
VAX COMPUTER CENTRE

Following considerable discussion during the latter part of 1980 the decision was made to purchase a VAX-11/780 to give TRIUMF a more powerful computer for analysis, etc. The computer was installed in the top floor of the chemistry annex and a system manager, D. Schumacher, was hired to oversee the system and its future development.

The VAX-11/780 has been running with the following configuration for the last half of the year:

- 4 MB memory with battery backup
- 256 MB disk with removable media
- 2 tape drives, 125 ips, 800/1600 bpi
- line printer/plotter
- 3 VT640 graphic terminals
- 3 VT100 terminals
- 8 asynchronous EIA ports
- 1 VS11 graphics terminal with joystick

and with the following software:

VAX/VMS Ver. 2.3 Operating System
VAX FORTRAN PLUS Ver. 2.3
FORTRAN IV VMS/RSX Cross-compiler Ver. 2.5
VAX/VMS DECNET Ver. 2.0
IMSL Library
MINUIT, FIOWA, VAX MULTI
BCPL
editors - EDT, SOS, TECO, WYLBUR

System usage has been steadily increasing from June 1 to the present, as shown below.

<table>
<thead>
<tr>
<th>Location</th>
<th>Data lines</th>
</tr>
</thead>
<tbody>
<tr>
<td>Office building, 2nd floor</td>
<td>48</td>
</tr>
<tr>
<td>Proton extension, 2nd floor</td>
<td>32</td>
</tr>
<tr>
<td>Service extension, 2nd floor</td>
<td>32</td>
</tr>
<tr>
<td>Control room</td>
<td>24</td>
</tr>
<tr>
<td>Meson mezzanine, elev. 264</td>
<td>32</td>
</tr>
<tr>
<td>Chemistry annex, elev. 276</td>
<td>40</td>
</tr>
</tbody>
</table>

The STC tape drives (1600/6250 bpi) have not been used yet since one hardware problem after another has arisen. An AVIV controller is being purchased and hopefully it will resolve the hardware problems.

A second UNIBUS has been installed along with an additional 16 asynchronous EIA ports. An RP07 (516 MB) drive which was substituted for the second RM05 has a projected delivery date of December at this time.

The Gandalf PACX system arrived and was installed during November. The PACX system allows any user device (e.g. a terminal or a computer) attached to its "terminal" side to select a particular class of service on its "port" side. The classes of service will initially be the VAX and the UBC Computing Centre but could be enlarged to include other computer systems both local and remote.

A request for the installation of data lines throughout TRIUMF has been made to the Plant Group and should allow users to have remote terminal connections to the VAX.

VAX use statistics

<table>
<thead>
<tr>
<th></th>
<th>Number of active users</th>
<th>Logins</th>
<th>CPU seconds (x 000)</th>
<th>Connect time (h)</th>
<th>Tape mounts</th>
<th>Print jobs</th>
</tr>
</thead>
<tbody>
<tr>
<td>June</td>
<td>42</td>
<td>1941</td>
<td>376</td>
<td>878</td>
<td>284</td>
<td>335</td>
</tr>
<tr>
<td>July</td>
<td>61</td>
<td>2479</td>
<td>776</td>
<td>1386</td>
<td>250</td>
<td>1202</td>
</tr>
<tr>
<td>August</td>
<td>64</td>
<td>4442</td>
<td>890</td>
<td>1799</td>
<td>435</td>
<td>1848</td>
</tr>
<tr>
<td>September</td>
<td>79</td>
<td>6633</td>
<td>850</td>
<td>2271</td>
<td>661</td>
<td>3823</td>
</tr>
<tr>
<td>October</td>
<td>86</td>
<td>5382</td>
<td>1224</td>
<td>2547</td>
<td>459</td>
<td>3005</td>
</tr>
</tbody>
</table>
The year 1981 saw some successes in the Applied Program as well as some disappointments. The latter occurred in most cogent form in the areas of TRIUMF's collaboration with external commercial enterprises (such as AECL and Novatrack) where continuity of service is essential. Unreliability of operation of the TRIUMF cyclotron, together with extended shutdowns, have a catastrophic impact on such operations, as well as on others in the medical field where patient scheduling is closely keyed to availability of beam. Failure of the supplier to deliver the CP42 cyclotron on schedule also adversely affected the program.

Highlights of the Applied Program in 1981 included the eventual delivery of the same CP42 at year's end, and the good operating characteristics achieved in that machine prior to delivery. The installation in the TRIUMF cyclotron vault of components for the completed beam line 2C for radioisotope production was achieved with hard work and capitalization on the availability of some unexpected working time in the vault. Construction of a PETT VI positron emission tomograph was on schedule and close to budget at year's end, with mechanical assembly of the gantry complete. Progress and publications are reported from the related program of development of brain-scanning agents, and from the TRIM program on $^{123}$I-based radiopharmaceuticals. The FERFICON program of measurements related to spallation breeding is close to completion. A cost estimate has been developed for installation at TRIUMF of a high-flux pion channel for the Biomedical Program.

BIOMEDICAL PROGRAM

The year 1981 has been a relatively frustrating year for the biomedical users who require high intensity and stability over an extended period of time (over two weeks). Most of the biomedical experiments had to be compromised or aborted due to cyclotron failure.

The only patient π⁻ treatment experiment conducted during this period was in June and involved three patients. It was aborted after 9 daily fractions were received out of 10 intended. The last fraction was delivered using conventional X-rays and the patients are still under observation.

After two unsuccessful attempts in March and June, a 10-fraction experiment for pig skin irradiation was successfully completed in September before the long shutdown. Several mouse experiments had been scheduled during the March and June runs. They were, however, cancelled due to unexpected failure in the cyclotron.

Several cellular experiments were completed during short periods of high intensity runs. These included investigations of the effect of field size, split dose, presence or absence of oxygen, and radiosensitizers.

The extended period of shutdown for the year, however, has greatly facilitated the installation of the computerized treatment couch and other necessary modifications in the biomedical experiment cave, which has now been converted into a π⁻ treatment room. The couch is ceiling mounted and was designed at TRIUMF. The couch is now operational under computer control. With the installation of an electronic safety interlock system, which should be completed in spring 1982, the group will be able to treat patients early next year. The couch is shown in Fig. 63 and its specifications in Table XIV.

The installation of this couch has been an important step in the development of the π⁻ radiotherapy program because it will enable the patient to be scanned relative to the π⁻ beam to produce the large uniform field required for routine radiotherapy. Together with the range shifter that has been installed, it will be possible to deliver tumoricidal dose to any 3-dimensional volume.

Another major requirement for radiotherapy is the development of high π⁻ flux. Significant progress has been made in this direction in the last year. Following the report by the TRIUMF High Flux Channel Committee recommending the development of a large acceptance superconducting pion channel similar to the SIN piotron for radiotherapy at TRIUMF, a detailed cost estimate of $12 million was made. On the other hand, since the TRIUMF piotron will take several years to develop, the group is also actively pursuing a relatively minor modification to the existing π⁻ channel to improve the flux by a factor of two.
Table XIV. General specifications of the biomedical treatment couch.

<table>
<thead>
<tr>
<th></th>
<th>Linear movement</th>
<th>Rotational movement</th>
<th>Positioning in x, y, z</th>
<th>Rigidiry (with 175 kg on centre of table)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>x direction (east-west) 233 cm</td>
<td>main column rotation 180° (in 15° steps)</td>
<td>accuracy within 0.025 mm</td>
<td>vertical deflection 1 mm ± 0.2 mm</td>
</tr>
<tr>
<td></td>
<td>y direction (up-down) 52 cm</td>
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<td>z direction (along beam axis) 92 cm</td>
<td>table tilt ±20° (continuous)</td>
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Fig. 63. The biomedical treatment couch.

In July an International Workshop on Pion and Heavy Ion Radiotherapy: Preclinical and Clinical Studies was held on the UBC campus. This was sponsored by the B.C. Cancer Foundation and subsidized by the Federal Department of Health, Education and Welfare. Over 40 invited speakers coming from Switzerland, Germany, the Netherlands, the United Kingdom, Japan, the United States and Canada participated in the three-day sessions.

RADIOISOTOPE RESEARCH

TRIM program

Production of $^{123}$I from the cesium spallation target in beam line 4A was scheduled for only 12 runs this year to finish a series of myocardial studies at Vancouver General Hospital (VGH) with iodinated fatty acid labelled in the TRIUMF radiopharmaceutical lab. Three of the twelve runs were unsuccessful due to cyclotron failures. Excess $^{123}$I from these runs was distributed to research groups outside of B.C.

In addition to the myocardial studies some radiiodine was used to label a renal diagnostic agent named Hippuran. Hippuran is already much used in western Europe, where it accounts for a significant fraction of the $^{123}$I used in medicine. The TRIM group developed a labelling method which results in $>99\%$ tag. It is likely the TRIM Hippuran can be approved as a radiopharmaceutical. Excellent results were obtained in scanning three kidney patients using TRIM Hippuran at VGH. Figure 64 shows an example. Each patient also received $^{99}$Tc-DTPA, the best alternative agent, so that the Hippuran results could be examined critically. We feel that Hippuran has much potential, through proven applications, with exceptionally high specificity for kidney structure, and provision of more functional information than can be obtained with DTPA.

Fig. 64. Scintiphoto obtained with Hippuran ($^{123}$I) shows smaller defective kidney on the right in a case of renal vascular hypertension.
Production runs in 1981 are expected to bring to a close the use of the cesium spallation facility. It is estimated that the TRIM group has produced and shipped more than 40 Ci of $^{123}$I to some 18 institutions in Canada since the beginning in 1978. The goals of exercising a complete production, delivery and clinical testing program have been achieved. In addition, several scientific papers have been published and there have been many conference presentations. We finally wish to express our gratitude to the Nuclear Medicine community for the opportunity to work with them and to the funding agencies: Health and Welfare Canada, the Vancouver Foundation and TRIUMF for much support.

Positron emission tomography

Administration. The TRIUMF/UBC program on positron emission tomography (PET) became during the year a component of the program of the UBC Imaging Research Centre. B.D. Pate was appointed the Director of the PET component of that program.

Tomograph. Following cancellation of an order for a positron tomograph with a commercial supplier, it was decided to construct at TRIUMF a PETT VI tomograph, following the prototype constructed at Washington University in St. Louis by the group under the direction of Dr. M. Ter-Pogossian. The TRIUMF tomograph features improved design in some areas, particularly in control and diagnostics, coupled with a much more powerful computer system (the TRIUMF VAX 11-780 system) for reconstruction calculations.

Starting in April, a PET construction team was assembled and a PERT diagram and budget produced. By year's end the tomograph mechanical assembly was complete, as was the fabrication of the components of the electronic and microprocessor-CAMAC data acquisition and control systems. The 288 cesium fluoride gamma-detectors required for the tomograph were ordered and received from Harshaw Chemical Company, together with 8 spares. These were completely tested for amplitude, resolution and timing performance, and installed in to the gantry assembly. Reconstruction software was written, following the general procedure of the St. Louis material, but adapted for the TRIUMF VAX computer. At year's end testing was beginning of the integrated tomograph systems, leading onto the first measurements with phantoms.

PET chemistry. The design proceeded this year of gas targets for the CP42 cyclotron, for production of positron emitters via the reactions $^{20}$Ne$(p,p2n)^{18}$Ne + $^{18}$F, $^{16}$O$(p,pn)^{15}$O, $^{14}$N$(p,d)^{11}$C and $^{18}$O$(p,n)^{18}$F.

During this year techniques were established at TRIUMF for the production of conventional PET scanning agents, including $O_2$, $CO$, $CO_2$ and $H_2O$ based on $^{15}$O and $^{11}$C, plus 2-fluoro-2-deoxy-D-glucose labelled with $^{18}$F (FDG). Particular attention was paid to the design of synthesis apparatus for these materials, capable of complete remote control by means of electrical solenoid valves controlling the flow of reagents.

In addition, new synthetic techniques were developed for the rapid incorporation of positron-emitting labels into more complex organic molecules. The techniques involved the cleavage of metal-carbon bonds in metalated precursors of the compounds desired, by means of the action of radiohalogens. A first publication on this technique appeared in the literature [Adam et al., Chem. Commun. 1981, 733], and two papers were presented at conferences.

Some attention was paid to the synthesis of positron-labelled analogs of spioperidol and haloperidol, while the labelling of dopa, both in the ring and in the carboxyl position with $^{18}$F and $^{11}$C, respectively, was pursued, for application in proposed studies of movement disorders and particularly Parkinson's disease.

An application for a Program Grant to the Medical Research Council of Canada was formulated this year, for funding to support the activities in the TRIUMF/UBC PET program.

RADIOISOTOPE PRODUCTION

AECL operations

The development of processes to produce $^{67}$Cu, $^{68}$Ge, $^{82}$Sr, $^{109}$Cd and $^{127}$Xe have been completed and these isotopes are available in commercial quantities. The Cyclotron Corporation CP42 (42 MeV cyclotron) will be installed and operating by June 1982. Process development for $^{57}$Co, $^{67}$Ge, $^{111}$In, $^{123}$I and $^{201}$Tl is complete. These isotopes will be available in commercial quantities from the CP42 in the second half of 1982.
Fig. 65. TRIUMF's PET scanner nears completion. Detectors are arranged in the slots on the periphery of the scanner. The patient's head is inserted in the central aperture during a scan.

Fig. 66. The PET scanner is able to execute a slow "wobble" about its centre line to improve the resolution obtainable from the finite sized detectors. The patient's head remains stationary.

Beam line 2C

The beam line as shown in the 1980 annual report was installed in April this year. Individual components were comprehensively tested in an external assembly area before final positioning in the vault so that the radiation dose to personnel could be minimized. The total dose received was 0.97 man rem compared with 2.3 predicted by the results of a vault dose study.

Since the spring shutdown, access has been limited to a few maintenance days and a short unscheduled period in September. This time was used to extend four of the "target beam pipes" to their final length and to install three target radiation shields. One of the lines was equipped with a wire monitor at the target position which was used in a short test to view the spot at 100 MeV and 1 \(\mu\)A. The size was slightly larger than expected, but it is anticipated that it can be improved when beam is again available.

Almost all of the facility controls hardware is in place but the executive software for coordinating several microprocessors with the minicomputer has not been completed.

The first target will be a \(^{127}\text{Xe}\) generator composed of liquid cesium. A model has been built and tested.

Progress on the variable energy extraction mechanism, necessary for the exploration of new production processes, has been at a virtual standstill for lack of manpower. As soon as the line begins regular operation at 70 and 100 MeV it is hoped that efforts will be renewed.

The 42 MeV cyclotron

Delivery of The Cyclotron Corporation's CP42 cyclotron took place in December. Installation was started immediately, and it is expected to have the machine ready for radioisotope production by the middle of 1982.

The machine passed most of the in-plant acceptance tests specified in the contract. A severe test, in May, was a 100 h run at 200 \(\mu\)A on an external target, without having to open the machine to replace ion source components or stripping foils. During this run the beam current was stable within 1\%. Two stripping foils were used up, but since the remotely operable stripping foil carousel contains four foils, this did not disqualify the test. The need for operator intervention during this run was well below the specified value of less than once per hour.

The test to produce two simultaneous beams of the same energy also exceeded the
The Cyclotron Corporation's 42 MeV cyclotron ...

and the 42 MeV cyclotron vault - in waiting - for the "baby cyclotron" ...

The "baby" was delivered in December.
specifications: a 50% split ratio, stable within 20%. What was achieved was a 1% split ratio stable within 1%!

There is still some question whether the 100 h test was actually run at 42 MeV. The emittance of the variable energy beam has not yet been measured, but so far preliminary tests with the variable energy beam tend to indicate some difficulty in meeting the specifications near the lower end of the energy range. However, beams variable from 11 to 42 MeV were extracted with ease and simplicity, as compared to what it would take to do this with a positive ion machine.

The two pneumatic target transfer systems (rabbits) were almost ready for their implant acceptance tests in December. Each system is capable of remotely and automatically dispatching a target from the cyclotron target station to the radiochemistry hot cells and vice versa. The specifications call for 50 consecutive runs without failure, a severe but necessary test, since the irradiated targets will be very radioactive. Their power dissipation capability is 6 kW (200 µA at 30 MeV), which is still to be tested.

500 MeV isotope production facility

During the second year of its operation the facility received approx 51.2 mAh of beam current, a little less than last year's 55.7 mAh. Fifty-three radioisotope targets were irradiated, and 38 were delivered to AECL. For last year these numbers were, respectively, 40 and 26. Table XV lists the various isotopes produced.

The CsCl targets were the only ones that initially failed during 50 µA irradiations. They appeared to swell and obstruct the passage of cooling water, causing window failure. The contents then dissolved in the cooling water. The CsCl collected in the demineralizer, but the isotope product, $^{127}$Xe, stayed in solution. It was effectively removed by bubbling air through the thimble and disposed of below the MPC. After improving the target manufacturing process, by better drying of the CsCl and tighter quality control, no further failures occurred.

The irradiation facility's hot cell (Fig. 67) that is used to transfer the targets from the beam into a lead flask had to be disassembled twice this year, to gain access to the TNF cave. The first disassembly was necessary to install a new NAA thimble for Novatrack in January and the second to remove the radio-gas target, which had developed a leak.

500 MeV gas target

The gas target, commissioned in 1980, produced $^{18}$F, $^{15}$O and $^{11}$C during 1981 in preparation for the PET project. It has two target chambers, each 7 cm long, with a target gas pressure of 10 atm. The yield for $^{18}$F was 1.7 mCi/µA at the end of an 180 min irradiation at 54 µA on 0.1% F₂/Ne target gas. The yield for $^{11}$C was 3.4 mCi/µA at the end of a 45 min irradiation at 54 µA on N₂ target gas. For both gases this is approximately 33% of the theoretical value.

![Fig. 67. The hot cell assembled above the 500 MeV irradiation facility on the TNF shielding.](image)
Early in 1981 the target developed a leak in both target chambers. The target was removed during the July shutdown and inspected in a hot cell. The leaks are probably due to corrosion as a result of imperfect nickel-plating of the inside of the chambers. A new target has been designed using monel for the chamber walls and inconel for the windows, thus avoiding the nickel-plating problem.

FERTILE-TO-FISSILE CONVERSION (FERFICON)

Two sets of detector system sensitivity calibration measurements were carried out during the year. The purpose of these measurements was to compare our assaying sensitivity with standards assayed at Chalk River Nuclear Laboratories and Los Alamos National Laboratory to ensure that the experimental yields for the $\Delta\Delta(p,x)^{24}\text{Na}$ proton beam monitor reactions and the $^{197}\text{Au}(n,\gamma)^{198}\text{Au}$ neutron capture reactions in the gold foils used to map the thermal flux in the water bath experiments were on a common basis. The measurements were done as a function of separation distance between the activated foil and the Ge(Li) detector to determine the effect of the $\gamma$-energy sum losses due to the coincident detection of photons from a single decay event. Similar measurements were performed with manganese, uranium and thorium foils at TRIUMF only to establish the assaying sensitivity for neutron capture reactions on these foils. Manganese was used in some of the water bath measurements reported in the 1979 annual report, and the uranium and thorium foils were used in measuring the conversion reactions in depleted uranium and thorium targets.

These measurements essentially complete the water bath experiments to determine the neutron leakage source strengths from targets of various materials and sizes. The data analysis of the conversion experiments which map the neutron capture rates in bare uranium and thorium targets is continuing.

NOVATRACK

Neutron activation analysis has grown in popularity in 1981. The number of samples analysed in 1981 (October 1980-September 1981) amounted to 60,254, an increase of more than 100% over 1980. Unfortunately only about 22% of the samples could be irradiated at TRIUMF; the remainder of the samples were irradiated at the University of Washington (26%), Washington State University (50%) and the University of Alberta (2%).

Sending samples elsewhere for irradiation became a necessity because of the absence of any useful beam at TRIUMF for most of the year. Since the neutron activation analysis program at TRIUMF has to be fully self-supporting, continuity of the service is of utmost importance. Many industries in B.C. have come to rely on neutron activation analysis as a means of obtaining data that was previously not available.

Revenue generated from neutron activation analysis is used to support research in unique new applications of neutron activation analysis which utilize the high energy component of the TRIUMF neutron flux. One such application is the analysis of oxygen via the $^{17}\text{O}(n,p)^{17}\text{N}$ reactions. $^{17}\text{N}$ is a delayed neutron emitter with a short half-life, which can be measured with an array of BF$_3$ detectors. The detection limit that can be achieved depends on the beam current produced at TRIUMF. When a beam current of 100 $\mu$A is extracted from the cyclotron, the detection limit can be as low as 0.001% oxygen (10 ppm), provided that no targets are inserted in the 500 MeV isotope production irradiation facility.

A new 44 sample rotating irradiation facility was installed in the thermal neutron facility. The device has proven to be reliable and was used for doing the bulk of the irradiations at TRIUMF this year.

Although there is optimism that the TRIUMF neutron flux will eventually produce neutron fluxes for more than just a few months per year, it is essential for the continuation of the neutron activation analysis program that another more reliable neutron source is available locally. To this end, Novatrack in collaboration with Simon Fraser University is contemplating the installation of a SLOWPOKE reactor at Simon Fraser University.
Most operational and developmental activities concerning the cyclotron were incorporated within the Cyclotron Division as a result of the TRIUMF reorganization which took place at the beginning of July. The cyclotron was defined as the whole system delivering beam to the primary targets and included the primary beam lines. The Division was structured into five sections corresponding to major areas of activity consisting of cyclotron proper, the injection system, primary beam lines, controls and operations. The beam development effort was organized within the Accelerator Research Division with both divisions collaborating in maintaining and upgrading the beam capabilities of the machine.

A series of unscheduled interruptions in beam production which started toward the end of 1980 and continued through 1981 necessitated a shift in priority toward machine reliability. Developments aimed at increasing machine reliability were given higher priority relative to other developments. The resonator system, a major cause for beam schedule interruptions in the past, was given highest priority. Construction of a new resonator segment prototype and the preparation of a vacuum chamber for RF testing were expedited. The redesign of resonator-related tank components such as cooling headers, wireways, etc. is in progress. Higher emphasis was also given to the investigation, with model studies and improved RF diagnostics, of the nature of the RF leakage in the "field-free" regions of the tank. The Cyclotron Development Group is collaborating with the RF Group on this project.

High priority was also given to improvements in the ion sources and the control system where greater reliability will allow more stable beam production on a day-to-day basis. A more detailed analysis of faults and of their frequency was performed by the operation section to allow selective action in terms of improvements and maintenance. Communications between the various groups within the Cyclotron Division were improved.

The beam production schedule had to be interrupted twice during the year for unscheduled emergency shutdowns. The first emergency shutdown, lasting four weeks during July-August, was necessitated by a series of component failures produced mainly by RF leakage. After the resonator panels had been readjusted, to be aligned under RF load, the RF leakage was closely monitored during operation and the RF problem was kept well under control. The second unscheduled shutdown at the end of November was due to inflector arcing problems. This occurred during a period when the 24 one hundred ton jacks of the magnet lifting system had been removed for modifications after bearings were found to be ruptured. The tank could not be opened for the inflector repair forcing an earlier than anticipated winter shutdown, previously scheduled for January.

It is remarkable that even with these problems the total beam production time and the total charge delivered were only 12% less than in 1980. A more serious consequence of the emergency shutdowns was the disruption to the experimental programs caused by the rearrangements of the production schedule. A further consequence was the increase of the fraction of polarized beam time from 26% in 1980 to 47% in 1981. The Polarized Source Group was able to cope well with a higher demand and substantially improve the reliability of the source.

Several developments achieved during the first part of the year were reported during September at the 9th International Cyclotron Conference in CAEN, France, where TRIUMF was well represented with nine papers. The Cyclotron Division contributed with six papers on the following subjects:

- Developments toward higher intensity
- Developments toward separated turns
- Higher intensity for $^+$ polarized sources
- Model measurements for a higher intensity unpolarized $^+$ source
- Improvements on the machine control system
- Non-intercepting cyclotron phase probes.

A highlight in the steps toward 400 $\mu$A intensity was the extraction at 500 MeV of a peak current of 205 $\mu$A, in a 10% pulsed mode. A result of the fivefold increase in current due to high bunching efficiency is an instantaneous current in the injection line of the order of 2 mA at which space charge effects are significant. The limiting factor for peak currents higher than 200 $\mu$A now seems to be the need for improved tunes in the vertical injection line and in the cyclotron central region. Further beam studies
which take into account the longitudinal space charge are required. To allow extraction of currents in excess of 150 μA in a dc mode the TNF target and moderator tank are being redesigned and reconstructed as described in the report on the thermal neutron facility.

Improvements to the primary beam lines to enable higher average intensities were made by the Beam Lines group. Urgent modifications for radiation hardening and remote handling beam line components were introduced in the vault section and BLA region between 1AT1 and 1AT2. More modifications are planned for the next shutdown.

The effort toward separated turns was highlighted by the implementation, in an operational mode by a microprocessor, of a feedback loop on the magnet field. The feedback of the RF sequency, which had been demonstrated to keep the phase constant within ±1.5°, is being engineered for routine operation. The amplifiers for the provision of a third harmonic RF component were tested at full power on a dummy load. Work continued on the cyclotron beam phase probes, in spite of the difficult RF leakage environment in the cyclotron. The results are reported in the cyclotron section.

A great deal of interest at the Cyclotron Conference was generated by the paper presented by the Ion Source Group on plans for increasing the beam intensity of the polarized source. Accordingly, in the first phase of these plans, the duoplasmatron in the Lamb shift source will be replaced by an electron cyclotron resonance type proton source. In a second phase a high intensity optically pumped polarized ion source, theoretically capable of extracted currents (50 μA) useful for meson users, would be installed. A model for experimental studies of this source is being assembled, with most of the components already on site.

The upgrading of the central control system as described in last year's annual report is being implemented. The Controls Group has been very successful in keeping the downtime and disruptions for these modifications to a minimum. The multiport memory was upgraded with three new prototype ports. This system once completed will allow all computers to have access to the conversion system tables.

Further information about the above systems is given in this report under the relevant section headings.

BEAM PRODUCTION

This year saw a considerable change in the operation of the cyclotron. The hours of polarized operation grew to 1717 h compared with 1094 h in 1980 and 1061 h in 1979. The total hours of unpolarized beam operation decreased from 3154 h in 1980 and 4060 h in 1979 to just 1699 h in 1981.

Even with this reduction in unpolarized running hours a total integrated current of 97 mAh was delivered in 1981 compared with 110 mAh in 1980 and 83 mAh in 1979. The hours of operation on a weekly basis are shown in Fig. 68. Figure 69 shows the integrated current produced compared with other years. The number of shifts scheduled to individual experiments is shown in Table XVI.

The primary reason for the reduction in total operating hours (from 4248 to 3686) was the failure of cyclotron equipment requiring two unscheduled shutdown periods in addition to the scheduled ones. The total shutdown time for 1981 was 16 weeks.

The April-May shutdown was a scheduled one with work being carried out to improve reliability. Although the radial flag in the cyclotron central region failed shortly after startup, the cyclotron nevertheless remained operable until the last week in July when failures in some of the correction plates and probes forced a three-week unscheduled shutdown. In most instances the failures were due to RF heating. A hole melted through the tip of one of the outer resonator panels. Details of the failure can be found later in the specific reports. The resonators were aligned with reference to their location in their hot, or operating, position for the first time. Later operation was more reliable with some reduction in RF leakage.

In the few weeks following, the operation of the cyclotron was plagued with various faults. A most spectacular electrical storm, of a magnitude never before seen in Vancouver, seemed to cleanse many of the problems, with some help from the Electronics Group. Operation was quite reliable up to the scheduled shutdown of October 7.

The October shutdown was scheduled mainly to enable construction to begin on a new remote handling building. The building connects with the vault service bridge tunnel.
The cyclotron jacking system, which had been giving some problems over the past few years, was inspected. The lower bearings under the nut on the screw were found damaged with their raceways broken. Since these pieces of metal could quite readily become enmeshed in the gears it was decided to remove the jacks, repair them in the proton hall extension and reinstall them during the scheduled January shutdown.

Operation was resumed with polarized beam for about three weeks. One week of 30 μA running and four weeks of 100 μA running were scheduled before Christmas. However, a problem with holding voltage on the negative inflector electrode again made operation precarious. It was decided to begin the January shutdown in the third week of November before any high intensity running could increase the residual activity in the vault. By then the jacks were repaired and ready for installation. The installation was completed two weeks ahead of schedule and the lid was raised on December 2.

At year’s end all groups had almost completed their shutdown activities scheduled for this period in the vault area. These include: (1) a series of measurements by the RF Group to determine distortions and misalignments of the existing resonator panels and the establishment of proper geometrical references for the installation of the new resonators; (2) probe repairs to bring back all systems to proper operating conditions; (3) improvements to the inflector insulators; (4) installation of a new wireway prototype for the correction plates; (5) Improvements on beam line 4B to make it compatible with higher beam currents in the cyclotron. Most shutdown activities outside the vault area were proceeding well.

The cyclotron tank lid was lowered before New Year's Eve for the final commissioning phase. Beam commissioning is scheduled for mid-January and high intensity beam production, which we hope will be more reliable than in the past year, is scheduled for February 1, 1982.

CYCLOTRON SYSTEMS

Cyclotron development

Developments and improvements to the cyclotron during 1981 reflected both the increased emphasis on machine reliability and performance, and the long-term goals of improved beam quality and higher beam intensity for both unpolarized and polarized beam. New developments in extracted beams included the construction of a vault beam line for the 70-100 MeV beam, the testing of beam quality defining stripping foils, and the extraction of two simultaneous beams down beam line 1A with a unique two-finger stripping foil. New records in peak beam intensity and transmission were achieved. The stability of the magnetic field has been improved by a factor of three. Progress has been made in the measurement and stabilization of the beam phase, and the required stability for single turn extraction has been demonstrated.

The RF resonator replacement programs received top priority during the year, with the prototype resonator in an advanced stage of construction as described below. In parallel, studies of the existing RF system continued, with the aim of explaining the nature of the RF leakage in the beam gap which has been plaguing the diagnostic probes, correction plates and vacuum elements.
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<td>( ^{13} \mu ) parameter in muon decay</td>
<td>K. Crowe</td>
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<td>( ^{13} \text{p} ) in ( ^{2} \text{H}-^{2} \text{D} )</td>
<td>D. Measday</td>
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<td>( ^{13} \text{p} ) capture</td>
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<td>G. Jones</td>
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<td>( ^{13} \text{P} ) production</td>
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<td>( (^{12} \text{p},^{3} \text{He}) ) at backward angles</td>
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<td>( (^{12} \text{He}) ) and ( ^{13} \text{L} )</td>
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<td>5 1/3 + 14</td>
<td>P</td>
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<td>174</td>
<td>pp + pm( ^{3} \text{He}^{+} ) spin dependence</td>
<td>D. Axen</td>
<td>18 + 60</td>
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in the cyclotron tank during last year's operation. Work on new broadband RF voltage probes for studies of the fundamental and 3rd harmonic has begun, along with the design of a 1:10 aluminum and copper model of the full cyclotron tank and resonator system. Special equipment, including a network analyzer and a spectrum analyzer, have been ordered for these studies.

The effort of the probes and diagnostics groups was mainly toward improved reliability. Increased use is being made of the high level language (HLL) control computer for acquisition and analysis of accelerator parameters, for software feedback loop tests and for communication with the UBC Computing Centre. New peripherals and more memory have been added to the HLL to extend its storage and execution capabilities.

Main magnet stability

During 1980 initial results of improved stability of the main magnet field were demonstrated, using a software feedback loop in the HLL computer. This loop uses the digitized reading of the main field as measured with an NMR probe located in one of the magnet hills, to provide the primary loop error signal. This loop has now been implemented in firmware in a local TRIMAC processor, located in the magnet control crate (Crate #76). Two modes of magnet operation are now available from the console. In the first, the adjusted point for the main magnet M106 control unit is set directly from the console but the magnetic field variations due to thermal or hysteresis effects have to be manually corrected using the beam tune. In the second mode, the operator selects, instead, the desired magnetic field which is then kept constant by the feedback loop.

The overall stability of the field as shown in Fig. 70 is now ±3 ppm for periods of several hours. A non-magnetic X-Y traversing table to be used for positioning the NMR probe in the main magnet field has been designed and constructed. This will be used for optimizing the position of the NMR probe as well as for local field map studies.

Beam phase stability

Two software loops have been used to stabilize the phase of the extracted beam to ±1.5°. In the first loop, fast fluctuations in the magnetic field are determined by integrating the voltage induced in an outer trim coil (#54). This integration is done digitally in a local TRIMAC processor located in the RF control CAMAC crate. A second feedback loop derives its input from the measured phase of the extracted beam, and applies corrections at 0.3 Hz to reduce fluctuations not taken care of by the NMR and the trim coil 54 loops. The beam phase loop requires extracted beam currents of 5 µA in beam line 1. Efforts are being made to reduce this requirement, as described below, particularly for polarized and medium resolution operation.

Non-intercepting phase probes

During 1980 emphasis was placed on obtaining internal beam phase information, using 7 internal non-intercepting capacitive phase probe pairs. Cables were run from the lower fixed phase probes to give a total of 14 probe signals. Analysis of stray RF pickup from all the probes showed both even and odd harmonics present. The beam phase measurement technique was demonstrated at peak currents of 15 µA with a 50% duty cycle. A comparison of the beam phase measured with one of the internal probes and the magnetic field fluctuations measured with trim coil #54 is shown in Fig 71. The sensitivity was improved with a switched capacitor filter which correlates the detected beam signal with the external ISIS beam modulation.

While this technique improves the system sensitivity it also uncovered a new problem, namely that the stray RF field picked up by the phase probe is modulated by the beam as it travels through the cyclotron. This RF pickup, which is highly correlated with real beam, can introduce errors into the phase measurement when the pulsed beam modulation
is less than 30%. However, the phase information can be easily achieved during operational tuning periods, by setting the duty cycle around 50%. The electronics for simultaneous phase measurements at seven different radii are being constructed and the signals will be displayed for operational purposes.

For external counter derived phase measurements, a phase locked loop which produces an RF timing signal locked onto scattered beam pulses has been tested. This provides a usable phase signal at currents of a few nanoamperes.

High intensity developments

The maximum current which can be extracted from the cyclotron is presently limited to 150 µA by the TNF target. This limit was reached at the beginning of 1980; in order to explore higher currents tests were continued in a pulsed mode. Improvements in both source operation and high intensity ISIS and cyclotron tunes led to the achievement of records in both peak extracted current and beam transmission. Early in the morning of September 2, 205 µA peak extracted current, in a 10% duty cycle mode, was achieved (20.5 µA average current). This occurred for an ISIS transmission of 75% and a cyclotron transmission of 45%. Later the same month during a 100 µA production run, 102 µA was extracted from an initial beam entering the injection line of only 211 µA. The injection line transmission was 91% and the cyclotron transmission was 53%, both new records. Tests for higher extracted peak currents and for reliable production at the 150 µA level were planned but were delayed due to unscheduled shutdowns.

Vacuum studies

During the April shutdown a controlled leak system was installed in order to allow input of a known flow rate of a particular gas into the cyclotron tank. This system has proven very useful in calibrating tank vacuum gauges, measuring pumping speeds for different gases and for determining gas stripping in the cyclotron. The tank ion gauges were found to be ~3 times less sensitive to H₂ than to N₂. In the mass spectrometer the sensitivity to the two gases was approximately equal. The tank pumping speeds for N₂ and H₂ were measured to be 60,000 l/s and 5700 l/s, respectively. The current loss due to gas stripping was found to be (12 ± 2)% for 9 × 10⁻⁷ Torr of H₂. This gives us a rough rule that a N₂ equivalent stripping pressure of 1 × 10⁻⁷ Torr is responsible for 10% current loss. In December an additional leak system was added to increase the sensitivity of the analysis of residual gases in the opposite side of the tank and to reduce the effects of the low conductance of the resonator gap. To this end, it was decided that another quadrupole mass analyzer be purchased so that we have a partial pressure measuring device on each side of the cyclotron. An analysis of the design and performance of the liquid He cryopump led to the conclusion that further laboratory tests are required. However, in view of more urgent priorities given to reliability in other areas, and because of limitations in manpower, these tests have been temporarily postponed.

RF system

Resonator replacement program

Prototype resonator. The development and manufacturing of the prototype resonator in the machine shop is finally under way with substantial effort being put into the assembly, development and testing program in the proton hall extension.

The 16 ft × 24 ft levelling table platform, which was initially set up on the vault roof, has now been moved into the proton hall extension. The "hot table" for soldering cooling channels to the resonator panels is set up on the platform and test pieces are being
The stretch form fixture is complete and set up to stretch and prebend the I beams for the strongback structure. Two unsuccessful attempts were made at developing a clamping joint for stretching the I beam, and a third one is being manufactured in the machine shop. Although the first two attempts were unsuccessful valuable information was obtained.

The strongback assembly fixture was manufactured by an outside contractor but the attachments were made in the machine shop. The assembly fixture has been anchored to the floor for stability and the attachments safely packed away for use during strongback assembly.

RF test facility. The vacuum tank which was initially used to bake out the original set of resonators was sandblasted and cleaned. All vacuum ports and vacuum seals were ground down and a rough vacuum of tens of microns successfully maintained. Design work is being carried out on the mounting frame, flux guides and RF coupling system.

The 25 kW RF amplifier to test the new resonator prototype is being designed by HN Engineering and will be assembled and tested in house.

RF model work. A one-half scale model of the beam gap in the area of resonators #7 and #8 was built using copper-covered plywood. Test results agreed with the theoretical calculations reported in the paper presented at the 1979 Particle Accelerator Conference in San Francisco on the RF beam gap impedance of the TRIUMF cyclotron. RF field maps were also plotted in the beam gap, but the measurements were very sensitive to external capacities and coupling feed lines. The model was modified to represent resonators #8 and #9, and a third structure added to simulate #10 resonator plus its flux guide. This drastically changed the field configuration as did electrically connecting the upper and lower flux guide in order to simulate the situation in the tank. Since the proximity of an adjoint resonator and the mode of coupling drastically changed the results, it is felt that TRIUMF must now proceed with a 1/10 scale model of the complete array of resonators in the vacuum tank. The model will be constructed of aluminum. A series of measurements in the RF and beam gaps are planned.

RF resonators

The disaster of melting resonator tips was rectified by realignment of the hot arm panels and retuning the ground arm panels. The resonators were tuned for a compromise between the resonator strongback temperatures and the pressure in the vacuum tank, without too much regard to RF pick-up on diagnostic probes. A further refinement of the tip tuning program was carried out prior to the shutdown. It was found that the best tune for minimum strongback temperatures and lowest vacuum pressure approached a symmetrical ground arm tip adjustment. A non-symmetrical tune, however, gave lower RF leakage and less RF pick-up on diagnostic probes.

The following changes were made to the resonators during the spring shutdown:

1) New tip-to-tip tulips were installed to give good mechanical coupling between resonators as well as good electrical coupling.
2) The new resonator tip supports, installed in the previous shutdown, were modified with a hinged hook attachment to allow for better thermal expansion.
3) New alignment targets were installed at the centre of the resonator tips to eliminate any alignment errors due to twisting of the resonator panels.
4) Levelling arm adjusting hooks were replaced on all resonators except the centre ones to allow for a larger range of adjustment and to improve the remote handling capability of the resonators.

An extensive alignment program was carried out on the resonator hot arms using the new targets and the new periscope prisms. For the first time it was possible to perform a hot arm adjustment with the RF and magnet on which revealed some surprising results. It had always been assumed that the effect of electrostatic and electromagnetic forces with the RF on would be uniform and the resonator hot arms would be deflected uniformly and symmetrically. However, the latest periscope measurements indicate that this is not the case. Due to the different friction forces acting on each resonator due to "M" foils, mechanical latching of #1 resonator, flux guides, flux guide tulips, etc., the deflection of the resonator tips on resonators in the centre of a quadrant (i.e., #3,4,5,6) is greater than the deflection of the resonator tips at either end (i.e., #1,2,7,8,9,10). By adjusting the ground arm panels to compensate...
for hot arm tip misalignment, it was possible to obtain more reliable operation.

**RF amplifiers**

The major causes of downtime due to the amplifiers system were:

1) Three-way valve oscillations due to a broken temperature sensing bulb.
2) Fine tuning return valve mechanical linkage loosened, causing backlash and confusion to the control system.
3) Loss of nitrogen blanket on input smoothing tank for resonator cooling.
4) Various RF control problems.
5) Tube socket in one of the amplifiers (PA1) was damaged by RF arcing and was replaced.
6) DC knife switch which feeds DC power to the PA1 amplifier was improperly engaged and caused it to melt.
7) Loop tuning capacitor on the transmission line failed.
8) Vacuum capacitor in final combiner failed.

The majority of the failures were due to components reaching the end of their expected life. When the problems in PA1 were encountered the RF system was switched to operating with three amplifiers only. This was the first time the system had operated in this mode at 100 μA. The amplifiers handled the extra power without problems.

**Third harmonic**

The third harmonic amplifier work was contracted out to HN Engineering Inc. They were successful in producing 100 kW continuously into a resistive load for 8 h without any parasitic or heating problems. No third harmonic work has been done with the resonators.

**Probes and diagnostics**

During 1981 there have been many problems with the cyclotron probes, and although many are attributable to distortion caused by RF heating others have been caused by general aging and wear and tear on the systems. Many of the problems were rectified completely, but others will require further redesign efforts.

Improvements have been made to several systems. These included a vacuum interlock system to facilitate extraction foil cartridge changes, the fabrication of a new radial flag mechanism, and slit mechanism modifications to better accommodate thermal changes.

During the April shutdown the extraction probe 4 cyclotron tank valve was removed for replacement of its gate sealing surface. This had been damaged when the valve was closed on broken probe control cables. The valve is located in a high radiation area, and most of the removal and reinstallation work was done remotely by the Remote Handling group. The corresponding extraction probe 1 valve was also removed at the same time to repair a vacuum leak in a bellows seal within the valve and the radial flag mechanism was also worked on since it had seized. New pickup heads, designed for better RF rejection, were added to the low energy probes; however, problems experienced in moving these probes after the shutdown have prevented their further use, and a redesign of these probes is planned for early 1982.

After the April shutdown the vertical flag, radial flag and water cooled pop-in probe movements all failed, most likely due to RF heating, and a further shutdown in July was necessary to restore them to operation. As a result of the problems, the radial flag was redesigned, and plans made to replace the plain bearings in the slit and vertical flag mechanisms with ball bearings which are more suitable for operation in high temperature and vacuum.

A longstanding problem with coupling between the longitudinal and vertical motions on both extraction probes, experienced during beam tuning, was finally rectified after it was traced to magnetic coupling of the control cables moving the probe head.

The periscope system used to view components inside the cyclotron under vacuum is being upgraded, with modifications under way to the position control mechanism and lighting system. The prototype of this system operating within the cyclotron tank was tested and showed a marked improvement in illumination level and ease of use over the old external system. The design and fabrication of the final version is currently under way.

In the middle of the year under the new TRIUMF organization, responsibility for maintenance of beam line diagnostic systems has been integrated into the Probes Group, which is now also responsible for implementing new monitor designs originating from the Accelerator Research Division.
Cyclotron vacuum

The pressure in the vacuum tank was high \((2.2 \times 10^{-7} \text{ Torr})\) during the early months of this year due to two leaks in sidewall flanges. These leaks were repaired during the spring shutdown, the west "window box" being replaced with a blank flange. The operating pressure after the spring shutdown varied from \(8 \times 10^{-8} \text{ Torr}\) to \(1 \times 10^{-7} \text{ Torr}\), depending on beam intensity and RF tune. The interaction between RF leakage and cryopanels was monitored through the temperature of the cryogenerator 20° head.

Typical spectra of the tank residual gases are shown in Fig. 72. The tenfold increase in the hydrogen partial pressure with the RF on is caused by dissociation of some of the residual water vapour. The stripping cross section for hydrogen is \(\sim 7\) times smaller than for air and thus the partial pressure of hydrogen is responsible for \(\sim 40\%\) of the vacuum losses. The liquid helium cryopump tested in the vacuum tank last year would produce a reduction of the hydrogen partial pressure by a factor of three. At 450 MeV and with these vacuum conditions this pump would reduce the vault activation by 15%.

Cyclotron central region

The spiral electrostatic inflector at the centre of the TRIUMF cyclotron operated successfully in 1981 except for some sparking problems with the negative inflector prior to the December shutdown. These were temporarily solved by lowering the negative voltage and compensated by running the positive voltage higher. During the shutdown the inflector was removed and the problem was traced to a defective support insulator on the negative inflector. A new type of insulator was designed and installed and it is felt that the present modification will substantially reduce insulator breakdown problems.

The operation of the electrostatic correction plates in the central region is complicated by RF leakage. The leakage fields cause problems with feedthroughs and the wireways which supply voltage to the plates. A new wireway prototype was designed and installed in the December shutdown. The wires sit in stainless steel tubes which both shield the wires from leakage fields and add physical strength to the wireway assembly. Metallic covers were designed and installed on the unshielded portions of the present wireways.

ION SOURCES AND INJECTION SYSTEM

This year has seen a number of important developments take place in ISIS and POLISIS. Temporary wiring, installed to permit the initial machine commissioning, was finally replaced. A long overdue interlock system was installed in the polarized source. Developments with a model source have permitted record currents to be extracted from the cyclotron. Exciting new ideas and experiments with polarized ion sources have given rise to the expectation of much higher polarized \(\text{H}^-\) currents within the next few years.

Normal \(\text{H}^-\) injection

The ion source HV terminal 480/208/120 V distribution system and 120 V logic control system have been replaced with a proper distribution system and a low voltage control system (developed by the Electronics/Controls group). Along the injection line a new TRIMAC-based control system for the ISIS RF devices (bunchers, chopper, 1:5 selector) was installed and commissioned during the spring. The 1:5 selector slit in the horizontal beam line has been replaced with a compact unit combining the 1:5 selector slit in the same diagnostic box with a second slit for regulating beam intensity. These new slits were designed to allow the current to be varied.

Fig. 72. Cyclotron tank vacuum mass spectra with RF off and on. \(P_{\text{NeEQ}}\) is the nitrogen equivalent stripping pressure.
quickly to meet the demands of the cancer irradiation program. In addition, the positions of both slits can now be adjusted and monitored remotely from the control room.

The electronics and display system for the wire scanners has been completed. Eight wire scanners have been installed along the injection line. Useful profiles can be obtained with low polarized currents (~100 nA) as well as high unpolarized currents (1 mA) and with duty cycles varying from 2 to 99%. The complete system, which will have sixteen wire scanners, will be installed as soon as the present system has been commissioned.

Experiments with an ion source on the test bench resulted in an optimized ion source which reliably produced 1 mA within a normalized emittance of $0.21 \times 0.07 \left( \pi \text{mm-mrad} \right)^2$. When this source was installed in the ISIS terminal only 600 µA could be transported to the 300 kV acceleration stack. Measurements were made of the beam profile in the 12 keV optics box to determine where the beam loss was occurring. Analysis of the data resulted in three minor changes to the optics. Subsequently, it was possible to transport 900 µA through the 12 keV optics box. As a bonus, the three operational sources also yielded higher current. In addition, the 300 kV acceleration stack sparking rate was significantly reduced.

There have been a number of developments on the ion source. A source, without water seals in the vacuum region, has been successfully tested and is operational. Work is progressing on determining the critical tolerances required to make two "identical" sources. An "identical" source would eliminate the tuning that presently follows each source change and consequently reduce the beam-off time after filament failures.

The ISIS reliability would be considerably higher with a high current ion source on standby in a third high voltage terminal. A study was made on the possible locations for a future ion source terminal, and preliminary drawings were prepared of a proposed building extension.

A study of the vertical beam line was begun. It is realized that there could be a lengthy shutdown if the existing vertical sections were to be removed for repair. A new design of an electrostatic beam line section which is much less likely to fail and which will allow easier access for repair has been prepared and is being evaluated.

**Polarized $H^{-}$ injection**

A new interlock system was installed in April within the polarized source terminal. The system is comprised of eight four-channel DICON modules, a local control panel and an interface break-out panel. In addition, the Controls group have prepared telterm pages indicating the status of the vacuum system, the status of the power supplies and the status of each interlocked device.

The source has been modified to improve the polarization and to permit the installation of an RF spin filter which will make possible more rapid spin reversal. The vacuum chamber surrounding the polarization region was constructed from mild steel to shield out the cyclotron fringe magnetic field (~5 G). In addition, a mu-metal shield was placed inside the vacuum chamber. This combination reduced the transverse magnetic field to less than 50 mG. Cryopumps were installed on both sides of the argon charge exchange solenoid to decrease the probability of $H^{-}$ forming outside of the required axial magnetic field region. As expected, the result has been higher beam polarizations.

The RF spin filter has been assembled and is being tested in the laboratory. The magnetic field is sufficiently uniform ($600 \text{ G} \pm 0.05 \text{ G}$) within the RF cavity but work is still required to reduce the field gradient at the entrance and exit of the solenoid. The RF cavity has a measured Q of 4000. Installation is planned for February 1982.

**IPHIS (Intense polarized $H^{-}$ ion source)**

Development of a more intense polarized ion source is planned to take place in two stages. The first phase involves upgrading the existing source to increase currents by a factor of 2 to 5. Polarized beam currents will become less marginal and substantial currents (50 nA or more) will be available also in the medium energy resolution production mode ($\Delta E/E < 1/1000$). The second phase involves developing a high intensity polarized source which could be used for meson production. The design goal for this phase is to provide an extracted current of 30 µA. This would substantially increase the amount of beam time available for both polarized proton and meson users and as well for the applied programs.
The existing polarized ion source - a Lamb-shift type source - appears to be limited to ~1.5 pA of H\(^+\) current. This limit was believed to be due to either space charge or self-quenching (decreased metastable H\(_2\)S lifetime due to internal electric fields). Measurements with the TRIUMF source indicated that, at 1.5 μA, self-quenching was not a problem. Therefore, work was begun on solving the space charge problem (i.e., transporting more than ~500 μA of 500 eV H\(^+\) through the 1.2 cm diameter cesium canal). An electron-cyclotron-resonance (ECR) proton source at Grenoble has achieved greater than 99% space charge neutralization. A quick attempt to convert the Grenoble source into a Lamb-shift type polarized source, performed in collaboration with groups from Grenoble, Karlsruhe and North Carolina, failed to produce the anticipated currents but did help to formulate the essential design parameters. An ECR proton source is now being constructed in the development laboratory and it will replace the duoplasmatron in the TRIUMF source terminal for a series of tests. If successful, this change will increase the source availability since the ECR source requires less servicing. Next, using the experience gained from the Grenoble experiment, the axial magnetic field will be extended over the cesium charge exchange cell. The space charge neutralization should improve with this change and, as a result, the polarized current should increase by a factor of ~2 to 5.

None of the existing polarized H\(^-\) sources provides adequate current to satisfy the phase II requirements (i.e., ~30 μA extracted). Various schemes for obtaining higher currents have been proposed. One of the most promising is a technique involving optical pumping. A sodium vapour is polarized using a laser and the polarization is transferred through charge exchange in a magnetic field to a proton beam. The optimal parameters for polarizing the sodium vapour and for the polarization transfer process need to be investigated. Various components to carry out this study are being assembled in the development lab. A sodium vapour target, vacuum chamber and solenoid are ready to be tested. A broad band dye laser is in operation. Results on sodium polarization are expected during the coming year.

**PRIMARY BEAM LINES**

**Vault upgrade**

Because of the higher currents extracted in beam line 1 and of the general increase in the residual radiation level around the cyclotron tank, an upgrade program was begun in 1981 for the vault sections of beam lines 1 and 4. This program will replace '0' ring seals with radiation-resistant double indium joints. Vacuum connections and beam line components will be installed so as to have the capability of being handled remotely.

Replacement of all '0' ring seals between the combination magnet and first dipole magnet has been accomplished in the vault sections of beam lines 1 and 4. This required that two monitors, the fast valves and the ion pumps be repositioned.

The upgrade program also involves the replacement of the combination magnet stand and vacuum box in each beam line. A vacuum 'C' seal at the entrance to each magnet will be eliminated by welding the vacuum box to the cyclotron exit horn. A magnet stand has been designed which will allow the magnet to be moved for coil repair without requiring a major realignment. The new stands and vacuum boxes will be delivered early in the new year. These components will be installed as part of future shutdown activities.

When complete, the upgrade program will give improved reliability and remote handling capability to the vault beam lines.

**Beam line 1A**

Several improvements have been made in beam line 1A external to the vault. A beam blocker was installed which permits access to the beam line with (polarized) beam operation in beam line 1B. A water target has been installed on the 1AT1 target ladder. The alignment of target 1AT1 with respect to the 1AT2 target has been checked. At 1AT2 collimator 'B' was replaced and aligned to ±0.015 in. with respect to the beam line.

During the year quadrupoles 1A10 and 1A15 experienced cooling blockages which caused magnet overtemperature trips. Both magnets were backflushed with an acid solution; the procedures cleared the blockages. The quadrupoles are in high radiation areas and the cooling problems seem to correlate with beam current. Similar problems have been
encountered at LAMPF and CERN. At LAMPF, a portable backflushing station has been built. The unit can be used to quickly clear blocked cooling circuits of a magnet. This approach will be used at TRIUMF.

The region between targets 1AT1 and 1AT2 is one of relatively high radiation. Vacuum and beam line components in this section are being revised to allow easier remote handling. Quadrupoles 1AQ12 and 1AQ13 are to be replaced by radiation-hard components. The design of new stands and vacuum couplings at this point has been completed and the components are being fabricated.

**Beam line 1B**

The main accomplishment this year was successful operation of the refurbished power supplies for dipoles 1BB2 and 1BB3. This allowed commissioning of the beam line at 500 MeV. A University of Alberta type polarimeter was also installed in the line.

The notorious steering problem of this line was traced to a slight misalignment of dipole 1BB2. Addition of a new monitor upstream of dipole 1BB3 has made it possible to properly tune the beam line.

**Beam line 4**

During the year beam line 4C was reconfigured. This included the installation of new 4Q14/8 quadrupoles.

A conceptual design for the stand for the beam line 4B twister was proposed for budgetary and planning purposes. The design will also permit an assessment of the layout changes which are required in the MRS upgrade.

No major problems were encountered in the operation of beam line 4A. The line was operated at a maximum current level of 10 μA for the production of $^{123}$I. Occasionally tuning problems were encountered because of a beam halo which seems to originate in the cyclotron.

**THERMAL NEUTRON FACILITY (TNF)**

**Analysis of the first target**

The first neutron target, which had been in operation from January 1978 until June 1979, was examined at AECL Chalk River Nuclear Laboratories for radiation damage. The target has been exposed to 50 mA of beam. It took more than one year to obtain a shipping licence from the Atomic Energy Control Board.

The examination consisted of cutting the target longitudinally in a hot cell. Subsequently, the target was inspected visually and photographed to determine migration of the lead into the vacuum tubes. Samples were then taken of the lead and the stainless steel container in several locations. The container samples were subjected to transmission electron microscopy, scanning electron microscopy and energy dispersive spectrometry. Both the container samples and the lead samples were analysed by means of gamma spectrometry.

The examination did not reveal any damage to the container due to radiation or due to exposure to the molten lead. While this confirmed our expectations, it also provided us with the necessary evidence to support our request to the Atomic Energy Control Board for renewal of our operating licence. We requested renewal to include permission to expose the present target up to 350 mA. (Exposure to date is approximately 200 mA.) The licence renewal was granted and allows us to use the present target until the end of 1982.

**Operational aspects**

The TNF radiogas storage system, which accumulates gaseous effluent from the target until it can be released safely, depends on a two-stage refrigerator that keeps a cold trap at $-100^\circ$C to trap $^{194}$Hg. This refrigerator, which had been in continuous operation for two years, broke down and the second-stage compressor had to be replaced. A new unit was installed, side by side to the old one, to give us improved reliability. In the past, back-up refrigeration was provided by an arrangement for filling the trap with liquid nitrogen - a rather cumbersome operation. However, soon after this installation the old refrigerator broke down completely and a liquid nitrogen arrangement had to be reinstalled. We are planning to redesign the
trap refrigeration system so the refrigerators can be exchanged more easily, since these low temperature refrigerators appear to be unreliable.

During the overhaul of the gas storage system we were able to measure the radioactivity of the holding tanks. The mercury trap was approximately 2 rad/h on contact, and it appeared to effectively collect all $^{134}$Hg in the system. The $^{134}$Hg will probably have to be stored indefinitely. The trap can be valved off.

Only one of the two inert gas storage tanks had been used for the last year or so. It measured about 45 mrad/h on contact and 90% of the contents consisted of $^{127}$Xe. The $^{127}$Xe can be released below the MPC without any problems.

New developments

The design of an upgraded target and moderator tank to accept higher beam currents is proceeding approximately on schedule. The new, waterjacketed target has been ordered and will be ready for testing early in 1982. The whole assembly is to be installed early in 1983.

Engineering studies have shown that it will not be possible to completely meet the design criterion of 200 kW dissipated beam power. This, however, should not limit ultimate cyclotron operation at 400 μA, as long as some other targets in beam line 1A, such as the 500 MeV irradiation facility, share the load.

During the January shutdown the neutron activation analysis thimble, used by Novatrack, was replaced by a new one including a 5 cm diameter rabbit tube. This new tube has not yet been used.

CONTROL SYSTEM

The main effort during 1981 has been to fully implement the system configuration described in the 1980 annual report and shown in Fig. 74. This effort has been frustrated by a number of computer system problems, both with the aging Supernovas and with the newly acquired Eclipse S130's. As a result of manpower limitations and logistic problems related to keeping the existing control system running, it was only in the last month of 1981 that the problems appeared to be understood and the solutions close at hand.
Nonetheless, some progress has been made. The "D1" (display processor #1) computer - removed nearly one year ago after the failure of a Supernova chassis - is again installed and running in the system. Floating point hardware was installed in both new Eclipses. This made possible the use of the old "data interface" Eclipse S200 as the program development system, with its former tasks being taken over by the "HLL" (high level language) Eclipse S130. Most importantly, three prototype ports of the new multiport memory - an essential element in the system expansion - were installed in September. Final tests were performed in October, and installation of the complete seven-port system, which is described in more detail below, is now scheduled for January 1982.

The program to replace all multiplexed analogue-to-digital converter systems to be autonomously scanning was completed in 1981. The object of this endeavour had been to reduce the number of CAMAC cycles required to read an analogue value, and it has resulted in much improved system performance. A second major installation was of the microprocessor-controlled ISIS RF system, which is described in more detail below. The TRIMAC-based extraction probe interlock system has demonstrated its flexibility by being reprogrammed to accommodate changes in the vacuum system configuration. Another advance - of particular value for debugging - was the installation of system select panels at each REMCON station. This allows easy access to all parameters from any REMCON panel.

Numerous smaller improvements have also been made. The spin flipper program has been improved to eliminate beam bursts between spin states, and to permit spin state programming by integrated current rather than time. A microprocessor-controlled main magnet loop closure based upon an NMR signal has been added to the system. The loop becomes active on pushing a console button, whereupon the console set point becomes the desired field (in gauss). Safety neutron and air monitors - both integrated and current values - have been added to the system and are routinely scanned. The safety system display program has been completely rewritten to facilitate changes. In addition, a complete new safety program for the 42 MeV cyclotron has been generated. To assist with the understanding of problems in the RF system, routine logging of a large number of RF parameters has been instituted. A loop for on-line centring of the beam on BL4A using steering magnets and signals from SEM's has been successfully tested. This system is to be extended to provide on-line centring and straightening.

A start was made in 1981 on two major new projects - the beam line 2C control system and the extension of the microprocessor-based
safety system to include control of beam spill trip and warning levels and an independent display. The former uses a PDP 11/34 and a serial CAMAC branch, both innovations for the central control system, and the latter introduces multiple processors and new communications paths to the safety system. The basic system programming for the PDP 11/34 part of the BL2C system is complete, and FORTRAN applications remain to be written. A decision has been reached to use the real-time monitor AMX in the new safety system. This will be the first application of a true multi-tasked real-time microprocessor system.

**Electronics**

As is usual, the Electronics group has made major contributions to control system progress in 1981. Two representative projects are the improved and expanded multiport memory and the new ISIS RF system.

**Multiport memory.** It had been known for several years that the "temporary" multiport memory shared by the CCS Supernova computers was inadequate and potentially unreliable. Design of a new unit had been started but proceeded slowly until this year when manpower was available to complete it. The new unit has 8 ports, 2 K of PROM and up to 64 K of RAM. Data can be written to or read from the memory by either programmed I/O or data channel transfers. In addition CPU's can interrupt each other to facilitate message passing. By comparison the old unit had 3 ports, programmed reads & writes, no PROM and only 16 K of RAM.

**ISIS RF control.** Four TRIMAC's sharing a single CAMAC crate and common I/O modules provide sampled-data closed loop control of amplitude and phase for the ISIS main phase, buncher, chopper and 1:5 selector. Amplitudes are measured via a multichannel analog-to-digital converter and phases via time-to-digital converters. Measured values are compared to set points provided from the central control system and error corrections are applied to attenuators and phase shifters via digital-to-analog converters. One TRIMAC monitors the system parameters, passing them to the CCS via a CAMAC-to-CAMAC link and displaying them on a local CRT. Operating and display modes can be entered on a numeric pad. Each TRIMAC is capable of independent operation and has its own self-checking diagnostics for rapid troubleshooting. Software changes are made off line and new PROM's installed in a few minutes.

**Reliability**

An attempt at improved reliability has been made in the ISIS system with the installation of stiffened crates, octal DACs and new interlocking digital controllers "DICONS". Continued problems with the RF thermocouple system resulted in yet another reworking, with one diode removed from each circuit.

In spite of our efforts towards improved reliability the summer and early fall of 1981 brought the most serious reliability problems ever - all in areas where problems had been long anticipated. The CY computer failed intermittently; a replacement computer had been budgeted. The crate 71 power supply failed several times in the summer heat; level 264 cooling is being installed, and another crate has been added to distribute the load. The most severe problem, however, was the failure of the multiport memory (MPM) throughout July, August and September, resulting in over 50 h of downtime. The silver lining is that progress on the new MPM was expedited, and prototype installation took place ahead of schedule in September. The programmed I/O feature of three ports of the new system has worked reliably since then.

Finally, it should be noted that it has been necessary to retire two Supernovas, and a third, "CY", has been misbehaving and is scheduled for replacement. The anticipated end of the road may be at hand, and a full-scale replacement program necessary. Moreover, the present system relies heavily on punched cards. This equipment is becoming more and more difficult to have serviced. A change to more modern methods and media may be indicated; however, such a development would involve considerable expense as well as significant procedural and philosophic changes.
OPERATIONAL SERVICES

Plant

All equipment generally operated very well throughout the year. One 50 ton overhead bridge crane had a gear box on the hoist replaced. This was the first major replacement of a component on the cranes.

At year-end an order was placed to air condition the service annex. This building contains a large number of power supplies and RF equipment, and it is hoped that the previously experienced warm weather summer failures will be reduced by improving the environment.

In the fall the cyclotron jacking system was found to be faulty. This system consists of 24 one hundred ton jacks. It was necessary to remove the jacks from the vault for their repair. It was found that the raceways on the bearings under the jack screws were broken. Ball bearings were replaced with taper roller bearings to increase their ability to take side thrust. Some nuts were very hard to turn on the screws and some machining was required. One nut was found to have some cracks in it and a new nut was made to replace it. Several of the lubrication holes were found to be plugged; however, wear was considered to be at a minimum. A new lubrication system was designed and installed to prevent grease spillage and to ensure the grease is applied where required. A special team was found within TRIUMF to redesign and repair the jacks. Engineers and technicians were allocated from various groups and the repairs were carried out in excellent time. The cooperation and workmanship in this special endeavour were excellent and a tribute to those involved.

The jacks were reinstalled and commissioned in a two week period in November.

Magnet power supplies

The downtime attributed to power supplies was reduced considerably this year due to extra effort being placed in this area.

Twenty new power supplies were purchased this year. Ten were installed on the cyclotron trim and harmonic coils for improved polarized beam and medium energy resolution operation. The other ten were installed on experimental beam lines. The two dual LBL power supplies on M20 were replaced and the controls improved. This is the first phase of the planned M20 upgrade. Two Brentford power supplies were rebuilt. One is being used on M11B2 and one for magnet measurements.

Vacuum and liquid helium services

Vacuum

No major changes to the pumping system were made during the year. Numerous small improvements to reliability and aid in servicing were made. The efforts made last year have resulted in reasonable if not outstanding service intervals of 1500 h for the Phillips cryogenerators used in the cyclotron vacuum system.

Liquid helium facility

A total of 24,423 l of liquid were delivered.

The purifier arrived in mid-June, incomplete but usable in a manual mode. It appeared to function reasonably well, but its use has been curtailed by problems with the recovery compressor.

Gas was recovered from experiments in the main building during the summer.

Remote handling

Cyclotron

Detail drawings for a new lift trolley have been completed, and design work has begun on a new series of tank shadow shields and related handling system. The existing lift trolley was used for three cycles of shadow shield operations during the spring shutdown.

The tool trolley actuating head has been provided with an angle drive attachment and is being equipped with a torque limiting over-ride clutch. A retrieval system for multiple separable in-tank fasteners has been commissioned.

Extraction probe number 4 gate valve was removed on a trial basis using the tool and lift trolleys with appropriate attachments. An initial run of the remote tank vacuum cleaner equipment was made for the purpose of gaining experience as was a remote tank seal inspection operation.
Photographic equipment has been purchased to incorporate into a remote inspection/documentation system. A video graphics display unit has been received to visually illustrate the geometry of trolley relationships when properly interfaced to the system control microprocessor.

**Beam lines**

Using equipment specifically designed for the job, the old collimator "B" at 1AT2 was removed as a remote operation. The new collimator was installed and aligned in the same operation. A new cooling line feedthrough beam tube section downstream of 1AT2 and a vacuum beam tube section through 1AQ14, 15 and 16 were reinstalled.

Assistance was given with the radiation resistant vacuum flange seals during the installation of the "front end" of beam line 2C in the vault.

The M1l septum magnet was removed from and later reinstalled in the beam line and made available for repair in the warm cell.

A portable beam line work station has been completed to serve as a base of operations during beam lines area repair jobs.

**Hot cells**

Routine target cassette changes were made on the 1AT1 and 1AT2 target ladders. A damaged 1AT1 protect monitor was also replaced. A water-cooled test chamber was installed on 1AT2 to test the effects of high radiation levels on cobalt/samarium permanent magnets. The applied program radiogas target was sectioned for failure mode analysis.

A variable level work table and adjustable height/rotation work support frame was built into the hot cell. Layout has been completed for the reassembly of the warm cell, pending M20 beam line extension.

**Dose study**

The Dose Study Group continued its efforts in trying to estimate radiation doses for shutdown jobs. The total man-dose estimated for work to be done in the spring shutdown was 16 man-rem whereas the total man-dose incurred was 14.5 man-rem. A series of measurements of gamma-ray spectra and decay curves were carried out in the higher radiation areas in order to improve the calculations of residual radiation fields.

A program to perform the accounting for the pencil chamber dosimeter readings has been written on the new VAX-11 computer. The program gives up-to-date information on various kinds of dose statistics for individuals as well as groups. Implementation needs only a direct communications link between the VAX-11 and the situation room.
This report describes the work of the Beam Development, Beam Line Diagnostics, Kaon Factory and Computing Services Groups, formed into the Accelerator Research Division in July 1981. The topics covered thus correspond closely to those headed "Beam Research and Development" in previous reports.

In the cyclotron the major achievement has been the acceleration of a record 205 \( \mu \)A (at 10% duty factor). This has partly been made possible by a better understanding of space charge effects in the injection line – particularly the apparently complete space charge neutralization in the 12 keV region in the HT terminal. At the other extreme, beams as weak as 10\(^3\)/s have been provided. Spill and radiation measurements have confirmed that running at 450 MeV reduces the radiation levels in the vault by roughly the expected factor of 2 (normalized to the same pion flux). The magnetic perturbations caused by removing the elevating jacks for repairs and adding stainless steel cooling tubes in the new rf cavities have each been measured and found to be acceptable.

Studies of resonance depolarization in the cyclotron have enabled the acceleration to 300 MeV to be completely corrected; attempts have also begun to accelerate and extract beams with horizontal polarization.

The high intensity proton line (1A) has been retuned to give circular beam spots on the new carbon targets and to be compatible with operation of the fast pion channel M11. Beam line 1A has also been used to demonstrate that a double beam can be transported from a two-component stripping foil and focused to two spots sufficiently transversely separated for the use of a magnetic septum. A beam line design (1C) has been prepared which would transport the lower intensity (40 \( \mu \)A) portion of such a split beam to a Piontron located next to the Biomedical Annex.

With more powerful power supplies available beam line 1B has now been commissioned from 400 to 500 MeV; its tuning problems at lower energies have also been clarified. For beam line 4B the five-quadrupole twister will be mechanically rotatable, permitting dispersed tunes in both planes at 4BT2, even with a solenoid operating upstream. Many new beam line monitors have been built, including some successful new ionization chamber spill monitors.

The major event on the secondary channels has been the initial commissioning of the fast pion channel M11. On M20 a small dc separator has been designed to produce clean surface muon beams. On the M8 biomedical channel tests have begun to determine the feasibility of adding permanent quadrupole magnets at the front end to enhance the pion flux.

Links to the UBC Computing Centre have been increased by the addition of two further multiplexers (providing 12 more lines) – though all 31 terminals will have been converted to dedicated 4800 Bd lines by the end of the year. Other improvements include a third printer station, additional graphics terminals and the provision of a "block mode" terminal. Many of the interactive terminals may be switched to either MTS or the VAX via PACX. On the software side this year's major effort has been the conversion of MTS programs to operate on the VAX.

Kaon factory activities have been dominated by the Kaon Factory Physics Workshop held in August and attended by about a hundred physicists. A clear consensus emerged that a strong case exists for the construction of kaon/neutrino factories. The main topics to benefit would be CP violation, rare kaon and hyperon decays, baryon spectroscopy, kaon-nucleus interactions and hypernuclei.

Kaon and antiproton production cross sections have been the object of a collaborative experiment with LAMPF and CERN at the CERN PS. Preliminary results for higher momenta secondaries show a generally linear dependence on proton energy so that no particular accelerator energy is favoured. Work on secondary channel design for a kaon factory has so far concentrated on low momentum K\(^+\) channels. Two 550 MeV/c designs have been looked at in some detail, with the object of achieving low pion contamination.

The question of accelerator design remains open for the moment. For the synchrotron a three-ring design (accumulator, accelerator, stretcher) is favoured for ease of construction and flexibility in performance. For multiturn injection \( H^+ \) ions would be easier than protons, but require both beam stacking and \( H^+ \) extraction from TRIUMF. An
alternative is to strip in two stages, extracting neutral atoms from TRIUMF and stripping to protons for synchrotron injection.

For the CANUCK cyclotron option conceptual designs now exist for 9, 12 and 15 GeV. Magnetic fields have been computed for the 9 GeV design and confirm the static orbit properties previously found for an artificial field. A study has begun of passage through some of the more serious resonances and shows that a significant fraction of the beam may be lost if the energy gain per turn is too low. The accelerator feasibility studies should be completed, allowing the optimum design to be chosen, by mid-1982.

BEAM DEVELOPMENT

Cyclotron

ISIS beam optics

12 keV optics. The most significant result of these studies was the appreciation of the high degree of space charge neutralization existing in this region. In the case where all electrostatic elements were grounded, i.e. a drift length, measurements made with a 1 mA beam agreed with SPEAM calculations only by assuming complete charge neutralization. As lens voltages were increased, e.g. on the einzel lens, the space charge neutralization appeared to decrease and the effective beam current used in the calculations had to be increased. Apparently the low energy positive charges in the vicinity of the lens are being removed.

A tune was therefore developed for the 12 keV region constraining electrostatic components to the lowest voltage possible with the aim of transporting the maximum amount of beam. 850 μA were obtained at the end of the E-W section, which includes acceleration to about 300 keV. The transmission from the middle of the 12 keV region to the end of the E-W section was close to 100%.

300 keV optics. A record current of 660 μA has been obtained at the fast target, just above the cyclotron inflection system, from 780 μA at the exit of the acceleration tube. This tune has no immediate application since the bunchers were off and only about 10% would be accepted by the cyclotron. While the bunchers increase the beam at the exit of the cyclotron, they also increase space charge effects and decrease the ISIS transmission.

During a recent high intensity test a maximum peak current of 205 μA (at 10% duty factor) was extracted from the cyclotron at 500 MeV from 440 μA at the fast target. The major limitation in achieving more extracted current was not the source but rather the difficulty matching the injected beam to the acceptances (both longitudinal and transverse) of the inflector and cyclotron.

Studies have been begun to determine methods of improving the bunching efficiency. A program, SPUNCH, has been written to calculate the bunching efficiency for any number and configuration of bunchers in the presence of longitudinal space charge. The method of this program is similar to that used by Tronc; it is to divide a given bunch and its nearest neighbours into a specified number of slices. The beam is assumed to be circularly cylindrical with a specified constant radius. The slices are approximated in infinitesimally thick circular discs of uniform charge density. Forces between discs are explicitly calculated with the approximation that the electric field felt by a given slice is constant over its surface and equal to the value calculated for its centre. SPUNCH results compare well with simple analytic situations and calculations made by Joho using the LANL program BUNCH.

At present, bunching in ISIS is performed by two bunchers: a first harmonic buncher at 21.1 m from the inflector and a second harmonic buncher at 16.6 m from the inflector. Figure 75 shows contour plots calculated by SPUNCH of bunching efficiency as a function of the voltages of the two ISIS bunchers for the currents < 1 μA (i.e., no space charge), 200 μA and 500 μA. The acceptances assumed for these calculations were 40° of phase and ±0.4% in energy, and the ISIS beam diameter was assumed to be 7.5 mm. These values are based on the most recent measurements and are accurate to 25%. The calculated optimum bunching efficiencies of 53%, 77% and 58% for the three currents compare well with the best measured cyclotron transmission from inflector entrance to 500 MeV of 55%, 67% and 58%, respectively (corrected for the 20% loss due to gas and electromagnetic stripping).

SPUNCH actually overestimates space charge effects because space charge neutralization and the shielding effects of the beam pipe have been neglected. It is noteworthy, however, that the program correctly predicts a maximum in bunching efficiency between zero
and 500 μA. This effect is due to the de-bunching tendency of space charge forces and shows in particular that bunching efficiencies for currents greater than ~200 μA can be improved by installing a second fundamental frequency buncher in the vertical section of ISIS. Also, by using this proposed buncher as a debuncher, bunching efficiencies for very low currents (e.g., from the polarized source) can be improved. Work is continuing to determine the ideal parameters for such a scheme.

Internal beam losses

Last year's report gave the results of measurements of losses due to gas stripping and electromagnetic stripping. The secondary emission detectors used have been augmented with one that measures the H° current by stripping the electrons from the neutral atoms. These detectors monitor loss directly and avoid the need to allow for the differing response of ion gauges to different gases.

The use of a Tylan electronic flow controller has improved the accuracy of leak rate measurement, resulting in a revision of the figure for gas stripping loss between injection and 500 MeV for $1 \times 10^{-7}$ Torr of nitrogen to 10% from 14%. This result, together with flux measurements in secondary channels reported last year, leads to the conclusion that extraction at 450 MeV of a beam intensity sufficient to preserve the $\pi^{-}$ flux in M8 will give a factor of 2 reduction in beam power loss and tank activation.

Spill and radiation measurements taken (respectively) during and after a week of 450 MeV running in March confirmed that beam spill in the vault was considerably lower than is usual for 500 MeV. A proton current of 120 μA was run in beam line 1A, resulting in ~80% of the pion and muon fluxes usual for 100 μA at 500 MeV.

The vault spill monitors distant from the beam lines, averaged over three days, indicated a reduction in spill/μA by a factor of 2.5, or in spill/pion by a factor 1.8. For vault monitors viewing the beam lines the corresponding figures were 1.75 and 1.25. Along beam line 1A the spills/μA were comparable for the two energies, except near Q7 and Q8 where there was an (acceptable) factor 4 increase at 450 MeV.

Radiation surveys of the vault taken 24 h after running 120 μA at 450 MeV indicated residual levels comparable to those found 24 h after running 30 μA at 500 μA.

Depolarization in the cyclotron

Direct evidence has been obtained linking the 3% drop in polarization observed near 300 MeV to the $3.796\gamma = 5$ resonance, and corrective action has resulted in recovery of the lost polarization. Two resonances are possible candidates:

$$3.796\gamma = 6 = \nu_r + \nu_z$$
$$3.796\gamma = 5$$

(Here 3.796 stands for $1 - g/2$ where $g$ is the H⁻ g-factor.) The former depends on the intrinsic sixth harmonic of the magnetic field (~2400 G) but only through its radial derivatives, and it is further weakened by being only of second order in the betatron oscillation amplitudes; the resulting
depolarization is expected to be <<1%. The latter is an imperfection resonance driven only by fifth harmonic horizontal field components, but is of zero order. Computations indicate that the fifth harmonic $B_r$ and $B_q$ components measured during the 1974 field survey (~2 G) would produce 1.5% depolarization; in fact a 3% loss is observed. To correct this, harmonic coil set #12 was powered in "first harmonic" $B_r$ mode. Each coil set consists of six 60° wide coils, #12 giving a maximum $B_r$ near 300 MeV. In this mode the relative currents are arranged to maximize the first harmonic component and zero harmonics 0, 2 and 3; however, the $(6n \pm 1)$th higher harmonics - including the fifth - remain non-zero. Scans were made for different current amplitudes at fixed phase and vice versa. It was found possible to increase the polarization $P$ at 400 MeV by 3% to its 200 MeV value or to lower it by as much as 13% - a much larger effect than has been observed with any other cyclotron control parameter. Moreover, the form of the variation (Fig. 76) agrees well with that expected theoretically for small changes:

$$\Delta P = A|\vec{I} - \vec{I}_0|^2$$

where $\vec{I}$ stands for the vector current in HC 12 (assumed proportional to the field it produces) and $\vec{I}_0$ for that needed to correct the existing imperfection. The curve is a quadratic fit to the data with $A$ and $\vec{I}_0$ as free parameters.

The immediate post-resonance spin motion consists in general of slow precession $\omega_e$ about a near-vertical axis ($B_e$ - see Fig. 77) together with rapid precession of that axis about the vertical at the resonance frequency (here 5 times the ion orbit frequency). The vertical spin component $S_z$ exhibits a damped oscillation with frequency proportional to the resonance defect in field $\Delta B$ (or energy $\Delta E$) and amplitude proportional to the strength of the driving field $\delta B$ divided by $\Delta B$ (or $\Delta E$). Numerical calculations indicate that several of these oscillations should remain observable even for a beam of ~30° phase width. Measurements taken at 1 MeV intervals around the 300 MeV resonance with harmonic coil HC 12 powered in a depolarizing sense in order to amplify the effect show the first oscillation clearly (Fig. 78). This is believed to be the first observation of this effect. The curve is a fit to the spin-up data < 306 MeV with the theoretical shape for a constant amplitude fifth harmonic driving field $\delta B$.

A similar resonance ($3.796\gamma = 4$) occurs at 51 MeV, driven by fourth harmonic imperfection fields. Because this is below the extractable energy range it is not possible to observe a loss in polarization directly as the resonance is crossed. Therefore attempts have been made to drive the resonance using harmonic coil set HC 7 and observe polarization changes at higher energy. For this purpose HC 7 was wired in "second harmonic" $B_r$.

Fig. 76. Polarization of a 400 MeV extracted beam as a function of the deviation of the harmonic coil #12 current from its optimum value $\vec{I}_0$. The current $\vec{I}$ was scanned in amplitude at fixed phase (triangles) and vice versa (circles).

Fig. 77. Post-resonance precession: spin and magnetic field vectors in a frame rotating at the resonance frequency.
Fig. 78. Polarization measurements near the 3.796γ = 5 resonance with HC 12 detuned. The curve is a fit to the spin-up data < 306 MeV.

mode, which zeroes its contributions to harmonics 3n and 6n±1 and maximizes those to harmonics 6n±2, in particular harmonics 2 and 4. So far, however, our attempts have not succeeded in provoking any significant change in polarization, either in the normal vertical component (observed at 400 MeV), or in the normally zero horizontal component (observed at 200 MeV).

Particles tracked numerically through 51 MeV with the horizontal fourth harmonic components observed during the 1974 magnetic field survey show <1% depolarization (Fig. 79) - the sense of field rotation being opposite to that of spin precession. The figure also shows how the depolarization may be very much larger if the field and spin rotate in the same sense.

Horizontal polarization in the cyclotron

Recently an Osaka group has reported the acceleration of horizontally polarized protons to 65 MeV. The provision of extracted beams from a cyclotron with polarization available in any direction is of interest, as it would obviate the need for precession magnets and solenoids upstream of the experimental targets. Initial attempts have therefore been made to accelerate horizontally polarized H− ions through the TRIUMF cyclotron. The horizontal polarization was produced by adjusting the fields in the Wien filter in the injection line, which normally precesses the spin to maximize the vertical polarization (E=240 in Fig. 80), to zero it instead (E=1000). The Wien filter could also be physically rotated to rotate the spin in the horizontal plane. To keep the spin precession as coherent as possible the cyclotron was run in separated turn mode and beam was extracted at 200 MeV.

In a first attempt a superconducting solenoid was used to precess any surviving horizontal polarization to the vertical, and the MRS was used as a single-arm polarimeter. When neighbouring turns in the cyclotron were extracted and analysed there were some indications of the survival of horizontal polarization, consistent with the expected angular precession between turns (4 turns ∓ 220°). Because of the danger of systematic errors with this technique, a second experiment was

Fig. 79. Depolarization through the 3.796γ = 4 resonance for various fourth harmonic imperfection fields: (A) 3 G rotating with spin, (B) 3 G against spin, (C) measured (~1.6 G).

Fig. 80. Vertical polarization as a function of Wien filter electric field for spin up (P+) and down (P−). The curves are sinusoidal fits to the data.
mounted using a vertically scattering polarimeter (provided by the BASQUE group). This time no significant polarization could be observed. The coherency requirement for H\textsuperscript+- ions is twice as hard to satisfy as for protons, and for both the difficulty increases with kinetic energy. Further trials are planned.

The coherency requirement is a lot easier to maintain over a few turns than all the way from injection. Thus some experimental groups have had indications of a coherent spin component in the horizontal plane at 300 MeV and 500 MeV just at or past depolarization resonances where a loss in vertical polarization is accompanied by the appearance of a coherent horizontal component. The direction of this component, when extracted, will depend on the number of turns made from the resonance. To maximize the polarized beam intensity TRIUMF normally operates with a wide, 45\degree phase acceptance and a radial amplitude equivalent to several times the radius gain per turn from the rf voltage. Consequently at extraction there will be a spread in the number of turns made from the resonance and a spread in the direction of the horizontal spin vectors resulting in a reduced horizontal polarization amplitude.

Several particles were tracked by GOBLIN through the 3.796\gamma = 5 resonance at 300 MeV. The starting phases were spread over 40\degree and the maximum radial amplitude was 6 mm. The spin vectors in the horizontal plane had rms spread in angle of 6\degree, 30\degree and 50\degree at simulated extractions 10, 20 and 30 MeV beyond the resonance; thus some coherence may remain as high as 330 MeV. Calculations made across the 3.796\gamma = 6-\nu\gamma resonance from 450 to 515 MeV show a correlation between horizontal spin direction and particle height above the beam plane. A stripping foil lowered partially into the beam will perform a vertical selection and some coherence in the horizontal plane would be expected. This is a common mode of operation which facilitates a change in the beam current shared between two beam lines by altering the relative heights of the foils. This coherence should be reduced as the foil is lowered further into the beam. The fairly strong correlation predicted between height and horizontal direction is probably due to the extended nature of the resonance.

The new resonators planned for 1983 will be water cooled using stainless steel tube that will have undergone a variety of flattening, bending and soldering procedures. It is well known that such procedures render stainless steel slightly magnetic, and it was thought desirable to measure the induced permeability and estimate the field perturbation.

A piece of tube was suspended from one arm of a standard balance in the non-uniform fringe field of a dipole magnet. The force exerted on the specimen when the magnet was powered was obtained from the change in the weights in the other pan of the balance necessary to restore equilibrium. The susceptibility and permeability may be obtained from a knowledge of the same force, the sample dimensions and the field variation along the sample. The precision of the apparatus was tested using tubes containing samples of inorganic components of known susceptibility. The permeability of the stainless steel tubes ranged from 1.003, for the unprocessed tube, to 1.05. It was found that flattening and bending the tube had a greater effect than heating it to soldering temperatures. It should be possible to compensate any effect on the beam by means of trim coils.

The screw jacks, bearings, etc. associated with the elevating system were dismantled and removed from the vault for mechanical repair during the year. The mass of material removed constituted 0.3\% of the mass of the entire system, and it was guessed that the effect in the field might range from 0.1 to 1.0 G. The actual change in B\textsubscript{r} field was inferred from the changes in trim coil current necessary to restore the beam to the mid-plane and render it isochronous and was found to be <0.1 G.

**Very low intensity beams**

The proton radiography group has long used a 5 cm long, 1 cm diameter aperture brass collimator to reduce nanoampere beams to a rate of typically 10\(^5\) p/s. The BASQUE nucleon-nucleon experiments have more recently successfully used a similar collimator in beam line 4A to prepare beams of 10\(^5\) p/s for beam line 4C (see frontispiece). The giant resonance group is interested in states many tens of MeV removed from the ground state and
operate the medium resolution spectrometer (MRS) to take data over a 40 MeV bite. They wished to check that the regular beam had no low energy satellite that could elastically scatter into their inelastic spectrum.

By using the bunchers to debunch the beam in the injection line, and by using an einzel lens to defocus the beam on a slit in the ion source, it was possible to obtain a stable beam with intensities as low as $10^3$ p/sec while preserving the cyclotron and beam line tunes. The MRS was rotated to $0^\circ$ and the primary beam examined at the focal plane. The rate was compatible with their detectors and no evidence was observed for any low energy peak larger than $2.5 \times 10^{-5}$ of the main component.

**Primary lines and spectrometers**

**Beam line 1A — 450/500 MeV tunes**

Circular spot tunes at both 1AT1 and 1AT2 have been developed for 450 and 500 MeV. The observed beam spot sizes (FW at 90%) were:

- 450 MeV: $1.5 \times 2$ mm
- 500 MeV: $1.0 \times 1.5$ mm

For 500 MeV the circular spot tune spills were similar to the "operator" tune, except, as expected, monitor #16 read about four times higher with the former. For 450 MeV the beam line spills/µA were ~20% lower than for 500 MeV.

Commissioning and operation of the M11 channel have required powering beam line 1A quadrupole 1AQ9 for the first time. This is located immediately downstream of the M11 septum magnet and must be run negative (vertically focusing) for $\pi^+$ and positive for $\pi^-$. The effect on the primary line tune can be compensated by adjusting quadrupoles 1AQ10-Q14. For $\pi^+$ in M11 the polarity of these quadrupoles remains the same, but for $\pi^-$ they must be reversed, otherwise the spills near 1AQ11 become unacceptably high for thick targets at 1AT1. Reversing switches for these quadrupoles are to be installed during the winter shutdown.

**Beam line 1A — Two-component beam**

A theoretical study has shown that the stripping foil structure shown in Fig. 81 would produce two beams which could be transported down a single beam line with no measurable increase in spill. After installing such a foil the beam profile (solid curve of Fig. 81) was measured at 1AT1. Experimental data were obtained by steering the composite beam across a 1 mm grid of wires. The fraction of the total beam in the "tooth" part could be varied from 0 to 50% by simply adjusting the height of the stripping foil.

Further studies showed that a separation >1 cm could be attained at a location 1 m downstream of 1AM5. (This is the proposed location of the beam splitter for the Piotron, see next page.) The beam line was retuned to form a focus at the multi-wire ion chamber closest to the proposed 1A/1C splitter location. Figure 82 shows a series of profiles at this location at different relative heights of beam and foil. It can be seen that the separation between the two components is close to 1 cm, which should be
adequate for the introduction of a magnetic septum. Calculations show that it would be necessary to add additional quadrupoles to the main beam line to transport the beam to the dump. It was not possible to run more than a few nanoamperes in the absence of these quadrupoles.

**Beam line 1C — Design**

This line is designed to feed the proposed high flux pion channel (Piotron). Using a split stripping foil it is possible to image a double spot about 1 m downstream of 1AM5 with sufficient separation (1 cm) to allow the clean insertion of a septum magnet which would deflect the beam 10° into beam line 1C (Fig. 83). The line would consist of the septum followed by two quadrupoles (1CQ7, 1CQ8), a 40° bender, two more quadrupoles (1CQ9, 1CQ10) and another 40° bender. The target would be 14.8 m from the vault wall and 12.2 m from beam line 1A. An extra pair of quadrupoles (1AQ6.1, 1AQ6.2) would need to be inserted into the existing beam line 1A just following the 1BV2 bender. These are required to maintain the present optical capabilities of beam line 1A.

**Beam line 1B**

The main achievement this year has been the successful commissioning of beams at 400, 450 and 500 MeV, the rebuilt Daresbury power supplies having been available for the first time. In addition, with the help of an extra monitor (1BM5.5) between the 1BB2 and 1BB3...
achromatic operations at location 4BT2. Operation in a horizontally dispersed mode at 4BT2 was impossible because the second and fourth quadrupoles of the twister required too large pole-tip fields. If the twister array is rotated into the standard quadrupole orientation (Fig. 85), the problem is eliminated. Since it is planned to rotate the twister ±8° (to account for phase space rotation with the solenoid turned on), a support will be designed which is capable of rotation through 45° + 16° = 61°. This would allow use of the solenoid with a horizontal dispersed beam as well as all aspects of twisted operation.

![Twister Quadrupole Yokes](image)

Fig. 85. Orientation of the twister quadrupole yokes.

**Secondary channels**

**M8 upgrade**

Survey work during the spring shutdown confirmed that it is physically possible to install a permanent magnet quadrupole in the 1AT2 housing. A small piece of SmCo$_5$ has been placed within 10 cm of the pion production target 1AT2 to study the neutron radiation damage.

**M9 channel**

There are presently 1 mil kapton windows at the entrance and exit of the dc separator. A study has been made of the effect of window thickness on the luminosity of the surface muon beam. When the window thickness is increased from zero to 0.001 in. the flux decreases 25%, the beam spot area increases a factor 2 and the luminosity decreases a factor 2.7. The conclusion is that to give twice the present luminosity the window thickness should be decreased to 0.00025 in.

When the dc separator in the M9 extension is replaced by the rf separator, the M9 extension cannot be used any longer for experiments with surface muons. The dc separator will eventually be placed in the new M20. The possibility has therefore been suggested of installing temporarily an extra leg on M9, as follows: place a small bending magnet near F2, bend the beam 45° anticlockwise and follow with a doublet, dc separator and triplet. In the "longitudinal polarization mode" (low voltage on dc separator) the luminosities of M9, M9 dogleg and new M20 are 3.55×10$^5$, 2.65×10$^5$ and 1.35×10$^5$/s/cm$^2$ for 100 µA on a 10 cm Be production target at 1AT2. The difference is mainly due to a difference in momentum acceptance, respectively 11, 7 and 5% Δp/p FWHM. In the "transverse polarization mode" the high voltage and magnetic field for the dc separator cause a severe restriction of the momentum acceptance. In all three cases the FWHM is 3.4% Δp/p and the luminosity is 0.87×10$^5$/s/cm$^2$.

**M11 channel performance**

During the year tuning of the M11 pion channel has been started and carried through to a point (0.84 cm x 0.72 cm FWHM spot for 66 MeV π$^+$) where the experimental program could be initiated.

Tuning was begun using $^{246}$Cm and $^{212}$Pb (ThC) α-sources. Predicted and measured parameters at the mid-plane are tabulated below:

<table>
<thead>
<tr>
<th>Predicted</th>
<th>Observed</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M_x$</td>
<td>-0.43</td>
</tr>
<tr>
<td>$D_x$ (cm/°)</td>
<td>+1.88</td>
</tr>
<tr>
<td>$M_y$</td>
<td>-6.43</td>
</tr>
</tbody>
</table>

These values were obtained with all but 1AQ9 at their nominal values. It was necessary to increase the field of 1AQ9 by 5.9%. During these measurements a vertical magnification of -4 was observed with M11Q2 increased 14% and all other elements at their normal settings. TRANSPORT calculations agreed with the observed data. The data in the above table were obtained by allowing 1AQ9 to vary while holding M11Q1 and M11Q2 at their nominal values. The good agreement between measured and predicted values is taken to
indicate that TRANSPORT models the front end of the channel very well.

Because of the low α-source intensity it was extremely difficult to obtain data at the achromatic focus and the tuning was therefore continued with 66 MeV α⁺. Initially a small spot was obtained (0.84 cm × 0.72 cm FWHM) — at the expense of a loss in flux — by allowing two elements to deviate from their theoretical settings. With the theoretical tune the flux was in agreement with expectations; the spot was larger than expected, but should be reducible to under 1 cm × 1 cm FWHM with further tuning.

M20 channel

A small crossed-field dc separator is being constructed to obtain a clean surface muon beam from the present M20 channel. The luminosity will be 2–3.5 × 10⁴ a/cm² for a 100 μA proton beam on a 10 cm Be target. The parameters of this separator have been determined in an optics study. The vertical gap is 14 cm, the width is 20 cm, the length is 80 cm and the electric gradient is 10 kV/cm. It will also be possible to use the separator on M13.

M20 redesign with clean muons. In addition to the operational modes described previously it is also possible to tune the quadrupoles Q2, Q3 and Q4 for a clean forward muon beam in the 37.5° leg without turning on the separator, at the expense of 30% backward muon flux in the 75° leg. The contaminating electrons, pions and unpolarized cloud muons from the production target are shifted off axis horizontally after the 37.5° bend and can be readily removed with a slit 1.5 m after the separator. In that case there will be 4 × 10⁵/s/100 μA backward μ⁺ in the 75° leg and simultaneously 5 × 10⁵/s/100 μA forward μ⁺ in the 37.5° leg in a 4 × 4 cm² spot for a 10 cm Be production target.

BEAM LINE DIAGNOSTICS

More of the standard proportional chamber, ion chamber and secondary emission profile monitors have been built, together with some of the protect monitors for the new isotope line 2C and a total current monitor for 1B. New air ionization chamber spill monitors have been built in conjunction with the Safety Group. They have proved to be successful downstream of the 1AT2 production target and more are planned for the vault and other locations where photomultiplier tubes have a reduced life. The limited amount of high intensity operation has meant that it has not been possible to properly test new non-intercepting monitors that measure overall intensity and charge distribution within the bunch.

Serious damage has been seen on Raychem insulated wire used on devices within 0.5 m or so of the production targets. This material is rated at 5 × 10⁸ R and has been in place during 250 mAh of beam. Ceramic bead insulation will be used in future.

A major development during the year was the assignment of a new mechanical engineer whose major responsibility will be the detailed supervision of all diagnostic work. This should result in more efficient operation and further improved reliability.

COMPUTING SERVICES

The asynchronous communication system between TRIUMF and UBC has continued to expand. With the installation of third and fourth multiplexers there are 12 more lines available (making 31 altogether), each line having its own port. Seven of these lines provide MTS terminal support in the chemistry annex; six terminals are located in the VAX terminal room and will have access to both MTS and the VAX via the PACX multiplexer. A third Printronix printer/plotter has also been installed there to provide readily accessible hard copy output from MTS.

The long-awaited extra telephone circuits to TRIUMF have finally been installed by BCtel (400 pairs, of which 200 pairs are for data lines to the outside world). We are therefore in the process of demultiplexing the 28 lines that have been limited to 1200 baud to provide at least 4800 Bd to all the interactive terminals.

The second Comterm station, located adjacent to the main control room, has been replaced by a Printronix printer/plotter and an "attached device" card reader. This requires using another terminal to initiate the reading process, but this restriction will be removed soon and the card reader will revert to the normal batch entry mode.

"Block mode" support is now available on one terminal line. This is specifically designed
to support low rate data exchange with another computer. Whereas regular terminal support is restricted to a maximum input rate of ~30 characters/second, the block mode support, due to the fact that each input character no longer generates an interrupt, can support input rate of ~120 characters/second.

At the end of the year the office building (CRM) terminal was moved to larger rooms next to the new library. Some of the interactive terminals at this station will have access to either MTS or VAX via a PACX.

A major project next year will be installation of a high speed (>1 megabaud) link to MTS. The program was as follows:

|------|------|------|------|

- Telephone circuits
- TRIUMF stations
- Multiplexed lines
- >4800 Bd terminals
- Printers

With the acquisition of the VAX one of our major concerns has been the conversion of existing MTS software. REVMOC, TURTLE, RELAX3D, CYCLOPS and TRINHEEL are some of the programs now implemented on the VAX. In addition, a great number of service routines have been written, the most useful being a plot package for simple x,y plots, 2D histogramming (with hidden line removal) and contour plots on the VT640-Printronix combination and a library [KOST.LIBRARY] including many routines to ease the writing of interactive programs and data manipulation.

KAON FACTORY STUDIES

Kaon Factory Physics Workshop

The second TRIUMF Kaon Factory Physics Workshop was held on August 10-14. About a hundred physicists participated in the meeting, which consisted of 15 invited talks and four afternoon workshop sessions and proved to be a stimulating and productive event. The invited speakers reviewed the present state of the art of kaon and neutrino physics. The workshop discussions centered on identifying the most important physics areas that could be studied with a machine providing an increase in intensity of two orders of magnitude in primary proton beam over present accelerators in the energy range 8-20 GeV and on establishing some preliminary guidelines on the desirable properties of secondary beams at such a machine. The program was as follows:

**Monday, August 10**

- Introduction
- Time reversal violation in kaon decay
- The physics of CP violation
- \(K^0\) physics at Fermilab
- Measuring \(|\eta_{00}/\eta_{44}|\)
- Kaon production and neutral kaon workshop

**Tuesday, August 11**

- Neutrino-nucleus interactions
- Neutrino scattering at LAMPF
- Neutrino scattering and oscillation experiments at BNL
- Neutrino physics workshop

**Wednesday, August 12**

- Nucleon-hadron interactions
- Quark structure of hadrons
- Dibaryons with strangeness
- Hadron-nucleon interactions workshop

**Thursday, August 13**

- Kaon-induced nuclear reactions
- Nuclear scattering at kaon factory energies
- Hadronic atoms
- K-nucleus interactions and hypernuclei workshop

**Friday, August 14**

- Hypernuclear physics: theoretical
- Hypernuclear physics: experimental
- Summary

Overall it appeared that a very good case could be made for building kaon/neutrino factories; 8-10 experimental set-ups could be identified, each of which would make possible a several-year program of important experiments needing the extra beam intensity or purity which such a machine could provide. The main topics which would benefit are CP violation, rare kaon and hyperon decays, baryon spectroscopy, kaon-nucleus interactions and hypernuclei.

The most obvious area of study for a kaon factory is CP violation. The kaon system is still the only one in which this phenomenon
is observed and in spite of recent progress in constructing gauge theories of fundamental interactions it has not yet been satisfactorily explained. More precise measurements of CP-violating parameters, particularly $e'$ and $\eta_{+-0}$, could help clarify the origin of CP violation as well as test ideas of grand unification and competing alternatives of extending the standard Glashow-Weinberg-Salam model, as well as gluon corrections in QCD.

The study of rare kaon decays would also be greatly aided by increased intensity beams. Rare decays can be divided into two categories. First those which involve transitions between families and thus probe physics at mass scales not directly accessible with accelerators. An example is $\bar{K}_L + \mu e$ which provides a crucial test of technicolour schemes. Second are those which are allowed as higher-order electroweak interactions such as $K^+ + \pi^+\nu\bar{\nu}$ and $K + \mu e e^+$. Improved measurement of these processes would help reinforce the standard model or discern deviations from it.

Neutrino physics was also discussed at the workshop. For experimental reasons a useful neutrino beam would require the addition of a proton storage ring to the facility. With a primary beam in the 10 GeV range a useful $\nu_\mu$ beam of a few hundred MeV, not available at present, could be obtained. Important experiments to be done with such a facility include a precise determination of the Weinberg angle through neutrino scattering and measurements on neutrino oscillations and masses.

The baryon spectrum up to 2 GeV is not very well known, particularly for $Y^*$. Better measurements of both masses and branching ratios would enable a more stringent comparison to be made with the promising QCD-based predictions. Polarization measurements in $K^-p + K^0n$ and in $K^-n$, $K^-p$ and $K^-n$ scattering are particularly important.

Because of the weak $K^-n$ interaction $K^+$-nucleus scattering should be free of the distorting effects that confuse $N$-nucleus and most $\pi$-nucleus scattering. Positive kaons may therefore prove to be as useful a nuclear probe as very low energy pions, but over a broader energy range and with shorter wavelengths.

Improvements in $K^-$ beam intensity and purity will make possible systematic measurements on hypernuclei and their excited states—perhaps allowing the study of $\gamma$-rays in coincidence—in the same way that is taken for granted for ordinary nuclei. A systematic study of $\Lambda$, $\Sigma$, $\Xi$ and $\Lambda\Lambda$ hypernuclei—from the deuteron up—will provide crucial information on both the $Y-N$ interaction and on many-body effects.

$K$ and $\bar{K}$ production

In collaboration with colleagues from LAMPF and CERN an experiment has been mounted on the CERN proton synchrotron to investigate the dependence of $K^-$, $\bar{p}$ and $\pi^-$ production on incident proton energy, target material and thickness, and secondary particle momentum. The PS was run at 10, 18 and 24 GeV to span the range of possible kaon factory energies. The primary measurements were taken on the K24 channel using 3 and 10 mm C, Cu and W targets for $K^-$, $\bar{p}$ and $\pi^-$ at 1.0 and 1.4 GeV/c and for $\pi^-$ only at 0.4 GeV/c. The new $\bar{K}26$ channel was used for 0.4 GeV/c $K^-$, $\bar{p}$ and $\pi^-$ measurements with a 3 mm Cu target.

Low momentum kaon beam lines

Low momentum kaon beams (700 MeV/c down to perhaps 400 MeV/c - 363 MeV to 142 MeV) are of considerable interest. A 700 MeV/c kaon has a decay length of 5.26 m, resulting in 15% surviving a 10 m drift and 5.8% surviving a 15 m drift; the corresponding figures for 400 MeV/c are 3.01 m, 3.6% and 0.7%. To produce a desired angular separation of a pion beam relative to a kaon beam, an electrostatic separator for a 400 MeV/c beam need be only 22% as long as the separator that would be needed for a 700 MeV/c beam. For 700 kV
across 10 cm producing a 5 mrad angular separation of the two beams a 0.54 m long separator is needed for 400 MeV/c beams, while a 2.45 m separator is needed for 700 MeV/c beams. For these reasons, a channel will have its optimum properties at its design momentum and will not have optimum performance over the entire 700 to 400 MeV/c range.

It is likely that the most important channel property will be a pion-to-kaon ratio as low as possible. This will require small vertical plane (non-bend plane) phase space and good vertical optics in order to separate the pion beam spot from the kaon beam spot cleanly at an intermediate vertical focus. If a longer channel length is acceptable, two vertical foci can be produced between bending magnets to reject particles originating near the primary beam spot on the production target ("cloud" pions). Since there seem to be no stringent requirements on momentum resolution, channels can be designed with a large bend plane angular acceptance. A short channel has very few possible locations for sextupole elements and, in general, these locations are not optimal. First-order designs have been produced that have small second-order geometric aberrations; with a limited momentum transmission (±2%) vertical plane chromatic aberrations have been found to be tolerable.

Two 550 MeV/c channel designs are currently under investigation. In both cases the channels accept ±125 mrad horizontally and ±15 mrad vertically. TRIUMF channel K is a 11.1 m channel with two 60° uniform field bending magnets, 5 quadrupoles and a 1 m long separator. TRIUMF channel KD is a 15.0 m channel with two 60° uniform field bending magnets, 10 quadrupoles and a 1.2 m long separator. This latter channel features vertical and horizontal foci before and after the separator with very good rejection of particles produced outside the primary beam spot on the production target.

TRIUMF channel K could be designed for 400 MeV/c particles. Shorter bending magnets and quadrupoles plus a reduction in the separator length could result in a 9.1 m channel with 4.9% of the 400 MeV/c particles surviving compared to 6.8% of the 550 MeV/c particles that survive a 11.1 m drift.

TRIUMF channel KD could be designed for 700 MeV/c particles by increasing the bending magnet fields, by using longer quadrupoles and by increasing the separator length. In a longer 16.3 m channel, 4.5% of the 700 MeV/c kaons survive compared to the 2.7% of the 550 MeV/c kaons that survive in a 15.0 m channel.

Possible neutral kaon beams at future kaon factory

For the recent Kaon Factory Physics Workshop a literature search was made in order to study the possibility of future neutral kaon beams. The following tentative conclusions can be drawn:

1) The flux of long-lived kaons K is 10^10 to 10^11 s^-1.

2) The neutron contamination can be reduced by letting channels take off at a large angle.

3) Monoenergetic K^0 beams at 550 MeV/c (1350 MeV/c) can be obtained with 1 GeV/c π^- (K^-) beams on a liquid hydrogen target.

4) Short-lived kaons Κ^0 are not available directly from the production target but can be made by placing regenerators in 4-8 GeV/c K^0 beams;

5) A tagged K^0 beam can be produced by using Primakoff excitation of a K^0 beam.

Finally, a high proton energy (>20 GeV) is recommended because of the fairly high kaon momenta and because it is necessary to enhance the flux for points 2) and 4) and especially for points 3) and 5).

Synchrotron design

While the technology of building 10-20 GeV proton synchrotrons for low current beams is well established, some problems do arise when the acceleration of high currents is considered (10 µA is the present record), and when injection is provided by a cw machine (isochronous cyclotron). To avoid the effects of coherent beam instabilities the charge per cycle must be limited; thus for 100 µA operation a rapid-cycling synchrotron with a repetition rate of about 30 Hz is required. But to utilize the cw injector efficiently beam must be collected over a large fraction of the cycle. One way of achieving this for a fast-cycling machine would be to build a separate accumulator ring (Fig. 87); at 450 MeV, and with dc magnets, this would be relatively inexpensive and could be installed in the same tunnel with
Fig. 87. Timing between accumulator and synchrotron.

The mechanics of collecting the cw beam from the TRIUMF cyclotron for acceleration in the pulsed synchrotron is also under study. Two schemes are under consideration, one using charge exchange injection, the other not. In both cases it is advantageous to stack the beam with high turn compaction in TRIUMF and extract packets of, say, 100 turns at a time. For a 30 Hz synchrotron there will be 1540 of these packets to be collected—say 16 around the ring times 96 in transverse and synchrotron phase space. If the beam is extracted from TRIUMF in the normal way by stripping H ions to protons, these 96 strings of 16 packets have to be steered into non-overlapping regions of phase space. Some success in this direction has recently been achieved at the TARN project in Japan, where about 200 turns have been injected—although only for low currents and relaxed time scales and with an efficiency of 35%.

An alternative is to save the stripping process for injection into the synchrotron, allowing multiple turns to be injected into the same region of phase space. To avoid multiple scattering in the foil on subsequent turns fast kicker magnets would be used to deflect the beam immediately before and after stripping. The only problem with this scheme is the extraction of H or H from the TRIUMF cyclotron with high efficiency.

Pulsed beam extraction from TRIUMF

To transfer beam efficiently from the TRIUMF cyclotron (accelerating 23 million bunches/s) to a synchrotron (accelerating <50 bunches/s) it is advantageous to extract it in pulses of as many turns as possible. Even for injection into a high energy cyclotron (normally run cw) it is important to consider the option of pulsed operation for neutrino physics.

One possible way of achieving this type of operation is to stack approximately one hundred turns of beam near the extraction radius in TRIUMF and then to apply an axial electric field so that the hundred turns are deflected vertically and then extracted. If TRIUMF is also operated so that only one of the five radial bunches rotating around the cyclotron's centre is filled with beam, the result would be a 7 ns pulse of extracted beam every 25 μs. While the beam pulse is being accelerated through the 3 GeV booster cyclotron, the dee voltage rising with radius would compress the pulse to a width of some 2 ns. Thus the net duty factor from the cyclotron facility would be about 1/10⁴, which is suitable for many neutrino experiments.

There are two techniques which have been investigated for stacking the beam in TRIUMF. One is magnetic, requiring a field which falls below isochronism so the ions get out of phase and start back towards the centre (Fig. 88). Consider a field which is 1.9 G below isochronism at a radius of 7600 mm and drops to 2.1 G below isochronism at 7625 mm. Ions which start out at the centre with a phase spread of 5° can be spread over the phase interval of 57.6° to 68.5° at R = 7600 mm by tailoring the magnetic field. Approximately 100 turns of the accelerated and decelerated beam will be concentrated in the above radial interval and can be extracted as one packet.

The second technique for stacking the beam depends upon the expansion of the phase of the beam with reduction in the accelerating voltage according to the relation \( \alpha V \sin \alpha = \text{constant} \). The effective dee voltage could be reduced by a ground plane starting at \( R = 7500 \text{ mm} \) to \( V = 0 \) at 7650 mm. For the TRIUMF example with \( V_p = 80 \text{ kV} \) and the ions spread in phase from \( \alpha = 5° \) to \( \alpha = 10° \) at \( R = 7500 \), there is a compaction of 150 turns in the radial interval of 25 mm at \( R = 7600 \text{ mm} \).
Fig. 88. The phase history of the ions starting at 57.6° and 68.5° for beam stacking between 7600 mm and 7625 mm radius. All the ions in the cross-hatched area are collected in one packet. The lower curves give the turn density for the two extreme values of the phase.

According to our preliminary investigations it appears to be possible to produce a density of turns which is somewhat higher with the falling rf voltage technique, but the magnetic stacking appears to have some advantages in ease of application.

Neutral beam transfer

Charge exchange extraction from TRIUMF obviates the difficulties of extracting H+ ions from the cyclotron's magnetic field. Charge exchange injection into a synchrotron reduces the problems of multturn injection to a triviality by permitting repeated injection into the same phase space. Conventional H+ to H° charge exchange can only use one or other of these advantages. The possibility has therefore been looked into of using a two-stage charge exchange process, retaining both advantages: H+ to H° for extraction from TRIUMF, followed by H° to H+ for injection into the synchrotron.

A carbon foil <20 μg/cm² would provide >70% H° at 450 MeV, the remaining H+ being transported to an experimental target or beam stop as desired. Such foils are available supported all round but would need development to leave one edge free. Possible alternatives are gas jets or lasers. A study of the beam optics has shown that stripping locations allowing the H° beam to leave through the exit horns would lead to beam spots <10 cm horizontally × 6 cm vertically 100 m away, or if the exit horns were not used, <6 cm × 3 cm. These spot sizes would be quite acceptable for synchrotron injection although the transfer line would probably not need to be as long as 100 m.

CANUCK cyclotrons

12 GeV and 15 GeV cyclotron designs are being looked into. The maximum practical cyclotron energy is essentially set by the difficulty of extracting orbits which lie closer and closer together - and therefore by the energy gain which can be achieved per turn. With the realization that the RF cavities proposed for 9 GeV were rather conservative (0.6 MV), more powerful (1 MV) and more numerous cavities are employed for higher energies. A uniform criterion has been used that the radius gain per turn at maximum energy must equal one-quarter of the radial beam diameter. Resonant effects will be used to effect complete separation of the final orbit.

<table>
<thead>
<tr>
<th>Maximum energy</th>
<th>8.5 GeV</th>
<th>12 GeV</th>
<th>15 GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum radius</td>
<td>20.6 m</td>
<td>41.2 m</td>
<td>51.7 m</td>
</tr>
<tr>
<td>Number of sectors</td>
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<td>42</td>
<td>54</td>
</tr>
<tr>
<td>Number 1 MV cavities</td>
<td>28</td>
<td>35</td>
<td>45</td>
</tr>
<tr>
<td>Energy gain/turn</td>
<td>25 MeV</td>
<td>33 MeV</td>
<td>45 MeV</td>
</tr>
<tr>
<td>Radius gain/turn</td>
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<td>0.6 mm</td>
</tr>
<tr>
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<td>115 MHz</td>
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<tr>
<td>RF power</td>
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<td>3.6 MW</td>
<td>4.6 MW</td>
</tr>
</tbody>
</table>

Magnetic field design. In order to calculate the field produced by the superconducting magnets we have used a modified version of the COILS code developed by Heighway. Like Westcott's code MAGHILL and that of Gordon and Johnson, COILS computes the field on the horizontal mid-plane of a symmetric magnet on the assumption that the iron is fully saturated and can be replaced by a current sheet around its vertical sides. These codes have been very successful in reproducing the fields of the Chalk River and MSU superconducting cyclotron magnets. COILS is restricted to magnets shaped from arcs of circles, for which the field on the mid-plane can be computed directly in terms of elliptic integrals, without explicit integration along the arc or up the side of the current sheet. In order to deal accurately with the non-circular coils of the high energy cyclotrons a modified version (COILX) has been developed in which integration along the coil is carried out numerically (although the analytic vertical integration is retained). The
Fig. 89. Magnetic field contours and proton orbits computed for the second-stage 8.5 GeV cyclotron. The field contours are plotted at 1 T intervals from 0 to 5 T and the orbits at 0.5 GeV intervals from 3 to 8.5 GeV.

Circular arc framework of the code nevertheless remains useful, for instance for the geometrical problem of sectioning a thick coil into thin current sheets.

COILX has been implemented on the TRIUMF VAX computer operating under VMS. For a grid of 120 × 120 points on the mid-plane the computing time is 1 h. The fields produced are then run on the equilibrium orbit code CYCLOP to determine the orbit properties. The optimum coil and pole shape is determined by an iterative process, starting from the shape found for the Woods-Saxon field edge.

Figure 89 shows the field contours for one of the second-stage magnets for the 8.5 GeV design together with selected orbits. To keep the field edge sharp a polegap of 2.5 cm is used. The coil width is 8 cm, the coil current 2.1 MA and the maximum field ~5 T. The focusing properties of this field were found to be very similar to those previously reported for a simulated field.

Dynamics of the second-stage cyclotron. A study of the beam stability and field tolerances associated with the 3 to 8.5 GeV ring has been begun using our equilibrium orbit code CYCLOP. The field is 30-fold symmetric and the intrinsic resonances 30/3 and 30/4 will be met at 7.45 and 5.68 GeV; the former is of lower order. Figure 90 shows how the unstable fixed points converge on and diverge from the equilibrium orbit fixed point near 7.45 GeV. Also shown is the area of phase space expected to be occupied by the beam. The shape was obtained from the Twiss parameters calculated by CYCLOP, the size by scaling the measured TRIUMF extracted emittance of 2 π mm-mrad at 0.5 GeV to account for adiabatic damping. We expect that for the particles of larger amplitude the radial motion will be non-linear or unstable for 4 or 5 turns. Even fewer turns are spent traversing the 30/4 resonance.

As an example of imperfection tolerances we chose to make calculations at νr = 8. The
motion appears to be non-adiabatic for a few turns in the integer resonance for an 8th harmonic field imperfection $\Delta B_8/B$ of $\sim 10^{-5}$. The half-integer resonance, gradient of the 16th harmonic, gives unstable motion over one turn with a gradient of $d(\Delta B_{16}/B)/dR$ of $3 \times 10^{-5}/\text{cm}$. Although the amplitude increase is very small for this imperfection, perhaps 3%, the gradient tolerances will be of this order since there are 15 such resonance crossings in this ring and we wish to keep the overall growth to less than 10%.
In July of 1981 the new administration under Dr. E.W. Vogt organized TRIUMF management into five technical divisions. The Experimental Facilities Group of the previous administration expanded into the Experimental Facilities Division under E.W. Blackmore with the following primary responsibilities:

- To provide assistance to experimental groups to enable them to carry out their experimental programs efficiently. Areas of assistance include development of special equipment, such as cryogenic targets and magnets, and support in nucleonics, detectors and data acquisition facilities.

- To implement new facilities such as secondary channels and spectrometers.

- To provide general site services available to all divisions.

The Experimental Facilities Division is organized into three sections with L. Robertson responsible for experimental support, A. Otter coordinating facility and beam line engineering, and I. Thorson overseeing site services.

During the summer a reassessment of site priorities and allocation of resources was carried out which resulted in several changes to the existing Five Year Plan. In the Experimental Facilities Division emphasis has been placed on the completion of a number of major projects while others have been delayed or suspended for future consideration. The relevant projects in Facilities and Experimental Support are shown in Table XVII. The M20 improvement program has been assigned high priority after a brief hiatus, and engineering has started on this project. The MRS upgrade program, which includes a new scattering chamber, new wire planes and a dispersion plane twister, is being pushed for completion in 1982. The development of frozen spin polarized targets is also being pursued with renewed vigour.

As for progress during 1981, three major projects made significant advances towards completion. The Mil channel was completed, a preliminary tune was achieved and the first experiments were run on this channel in June. The septum magnet problems mentioned in last year's report were successfully repaired and the magnet reinstalled in the beam line in April. Initial tuning of the Mil channel produced a good beam spot at the final focus but at a reduced flux. Later tuning just prior to the cyclotron shutdown in November resulted in a factor of two increase in flux but with a larger beam spot. Further tuning shifts are obviously required to remedy this situation.

Beam line 2C, the 70-100 MeV high current facility located in the cyclotron vault, was installed in April and during several test runs during the year a low current beam was transported to a target station located in the cyclotron vault wall. Most of the effort during the year was concentrated on the development of the controls and interlock system for the beam line and targets. The first target will be a $^{127}$Xe generator of liquid cesium running at 100 MeV.

The RF separator was assembled and installed in the meson hall mezzanine for final tests before installation in the M9 channel. The new control system was completed and available in November for the testing program. Except for water leaks in the separator cooling lines, the separator has not presented any problems other than higher X-ray fields than anticipated. By December the separator was run at full power and installation in M9 is planned for January.

At the end of 1980 the PISCAT group at TRIUMF proposed the installation of a low energy pion spectrometer (QQD) which together with the excellent performance of the M13 channel would result in a facility unmatched elsewhere at this time. The availability of a magnet from Jülich and collaboration with that group enabled this project to advance quickly. By late summer the magnet and quadrupoles were assembled on a stand for field mapping. It is expected that the assembly will be installed on the Mil channel early in 1982 for commissioning.

Another major experimental support activity was the assembly and field mapping of the Sagane magnet for Expt. 185. It will be installed on the M13 channel together with a large solenoid magnet fabricated at LBL early in 1982.

Other support activities involving nucleonics development, data acquisition systems, the detector facility and cryogenic and polarized...
<table>
<thead>
<tr>
<th></th>
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<th></th>
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<td>M20 improvements</td>
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<td>MRS upgrade</td>
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<td>Liquid methane target</td>
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<td>65</td>
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<td>300</td>
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<td>942</td>
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<td>Secondary channel upgrading</td>
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<td>300</td>
<td>600</td>
<td>600</td>
<td>Completed</td>
<td>2000</td>
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<tr>
<td>Superconducting muon channel</td>
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<td>---</td>
<td>50</td>
<td>700</td>
<td>700</td>
<td>600</td>
<td>2550</td>
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<td>200</td>
<td>400</td>
<td>1000</td>
<td>1400</td>
<td>3000</td>
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<td>---</td>
<td>---</td>
<td>100</td>
<td>300</td>
<td>500</td>
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<td>1600</td>
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<td>Suspended for future consideration</td>
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<tr>
<td>Polarized H&amp;D target</td>
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<td>150</td>
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<td></td>
<td>572</td>
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<tr>
<td>Frozen spin target</td>
<td>240</td>
<td>440</td>
<td>Completed</td>
<td></td>
<td></td>
<td></td>
<td>693</td>
</tr>
</tbody>
</table>

Targets are described later in this section, along with further details of the projects mentioned above.

A significant improvement in experimental set-up has been the completion in mid 1981 of the proton hall building extension. This has provided much needed floor area with crane access for the assembly of large pieces of experimental equipment. In addition to the staging area, the extension also includes a laboratory workshop and office wing, and three permanent counting rooms for proton hall experiments. During the November shutdown the data acquisition system for both 4BT1 experiments and MRS experiments were moved to these new counting rooms.

As mentioned previously a new Five Year Plan has been written and submitted to NRC after active discussion with TRIUMF users. While the priorities for next year's activities are reasonably firm, several options exist for expanding experimental capabilities in subsequent years. In the proton hall there is active discussion of a second arm spectrometer to be located on BL4B, and pivot on the opposite side of the beam line from the medium resolution spectrometer. This facility would satisfy the needs of the (p,π) program and allow (p,2π) studies to be made in the two spectrometer mode.

In the meson hall several options are being considered. The most important goal is to relieve the experimental pressure on the M13 channel which is both an excellent low energy pion scattering channel and a high luminosity surface muon channel. One possibility is to use the 150° vertical takeoff from the 1AT1 target (the M15 channel) and install a surface muon channel to an experimental area north of the meson hall. Another option is to construct a larger experimental hall in this location and provide a proton beam line into this area. A third option, which has been discussed for some time, is to locate a third experimental hall north of the meson hall fed by BL2A and to provide several secondary channels around a single target station. Other possibilities which have been discussed previously involve the replacement of target 1AT2 with a new target shield which would enable improvements to be made to the front ends of channels M9, M20 and M8.
A meson facility working group is collecting these proposals and a report will be available early in 1982. A major factor which enters into a decision on whether to proceed with any of these options is the kaon factory proposal. Before planning any major new experimental hall it will be necessary to know the proposed layout of the accelerator and experimental areas for the kaon factory. This information should be available by mid 1982.

**EXPERIMENTAL SUPPORT**

TRIUMF has increased the amount of support to experiments in the development of detectors, targets, nucleonics and data acquisition systems, both by establishing a number of new professional and technical positions as well as by significantly increasing the budgets for equipment and services in these areas. To coordinate this increased support, groups working in these areas have been organized under the Experimental Support Section of the Division. Scientific group leader positions newly established include:

- **Nucleonics** (M. Comyn)
- **Data Acquisition Systems** (J. Macdonald)
- **Detector Systems** (M. Salomon)

Advice for the nucleonics support is provided by the Instrumentation Advisory Committee (IAC) and for data acquisition system support by the Computing Facilities at TRIUMF (CFAT) Committee.

Developments of importance to users instituted during the year include the removal of Pool rental charge on a large fraction of standard modules used in many experiments, the establishment of data acquisition systems assigned to channels and facilities shared by many experimental groups, the consolidation of MWPC chamber gas distribution systems in the meson and proton halls, and the provision of test and repair facilities for MWPC chambers on site to augment the MWPC construction facilities based at TRIUMF/Univ. of Alberta.

**Data acquisition systems**

In recognition of the fact that several of the data acquisition systems at TRIUMF are shared by several experiments and/or groups, an effort has been made over the past year or so to coordinate various aspects of these facilities. Excluding the applied program facilities, there are nine experiments' data acquisition systems in use, of which four now conform closely to a standard configuration recommended by the CFAT committee. This is a PDP 11/34 (or 11/60) based system on which a general purpose software package (MULTI) is implemented and supported. The remaining systems are presently used in specialized configurations to support particular facilities or experiments. Plans exist to upgrade one of these to the standard, and to acquire an additional system for the meson hall counting rooms.

**CFAT Committee**

Membership in the Standing Committee on Computing Facilities at TRIUMF (CFAT) was augmented somewhat in 1981 to provide needed overlap with the Instrumentation Advisory Committee (IAC). Meetings were held regularly each month and minutes distributed to those interested. Discussions were held on all aspects of the published mandate of the committee and a standard acquisition system specified.

The CFAT committee oversees scheduling, hardware improvements and maintenance of these data acquisition systems, as well as their interaction with other instrumentation and with the TRIUMF Data Analysis Centre (VAX). To assist with this task, a "system consultant" was named for each acquisition system. As no budget was provided to augment or upgrade the TRIUMF data acquisition facilities in 1981, no major improvements were made.

Again in 1981 CFAT oversaw the support provided by TRIUMF to standard data acquisition software. One programmer was available for this task, providing approximately nine man-months of support. The standard acquisition program (DA) was enhanced to support multiple crates, allow variable length records, and speed up list processing. The analysis phase (MULTI) was modified to incorporate the "Seattle" enhancements for speed (compilation), increase available histogramming area (store 20 histograms in memory), support hard copy plotting, and provide a "COMMON" area for user-written tasks. Performance measurements were made and published. Assistance was also given for the adaptation of a pulse height analysis program to the standard system. A manual on available data acquisition and analysis software is in preparation, and draft versions have been made available.

CFAT has recognized the need for TRIUMF to provide more programming help in this area, as well as to assist users with data analysis on the VAX.
In April L.P. Robertson took over from E.G. Auld as Chairman of the Instrumentation Advisory Committee. At the same time M. Comyn assumed the role of Technical Administration Officer to assist with the operation of the Equipment Pool. To ensure complete overlap of jurisdiction between the IAC and CFAT committees, two members of each committee will be ex-officio members of the other in future. The membership of the IAC for 1981-82 is as follows:

L.P. Robertson  Chairman
M. Comyn  TAO
R. Green  SFU, Secretary
J.H. Brewer  UBC
A. Olin  UVictoria
W.C. Olsen  UAlberta
J.V. Cresswell  TRIUMF, Electronics
D.P. Gurd  CFAT ex officio
J.A. Macdonald  CFAT ex officio

During the year the majority of user requests for standard Pool rentable items were satisfied. The IAC conducted evaluations of HV single- and multi-channel power supplies, spectroscopy amplifiers and constant fraction discriminators in order to establish new Pool standards. Improvements in the inventory of asseted equipment have been made. The nucleonics inventory database was modified to include a site location code to help searches for equipment. A technician is now available to maintain this database and extend its scope to include all nucleonics and data acquisition equipment. Standard Pool-owned equipment continues to be repaired free of charge, all other categories of asseted equipment being repaired at the owner's expense.

The Nucleonics group performs, as part of its function, the routine maintenance and repair of Pool equipment and DEC-based data acquisition systems. Through the purchase of spare components and test equipment, plus the development of better diagnostics, TRIUMF is now able to perform a substantial part of the repair and maintenance previously allocated to external companies. This has led to increased equipment reliability and reduced downtime for experiments. External maintenance contracts are still held for Decwriters and out-of-hours servicing of data acquisition systems.

The manufacture of scintillation counters for TRIUMF experiments has increased by about 20% from last year. As there is now a large number of counters a repository is being organized for users to keep their spare detectors.

Research work on position-sensitive phototubes is continuing and a new design is presently being built at SRC Laboratories. TRIUMF has recently started to evaluate avalanche silicon photodiodes as possible replacement of photomultipliers in some specific applications.

The Amperex XP2230 was recommended to the Instrumentation Advisory Committee to be adopted as site standard for 2 in. phototubes to replace the RCA 8575.

Further testing and development of the prototype 60 cm × 60 cm aperture chamber for Expt. 121 was carried out during the year. The chamber uses a delay line readout and, with constant fraction discrimination of the delay line pulses, a position resolution of ±0.3 mm was obtained with the chamber. Several versions of flat solenoidal delay lines and amplifier boards were tested with this chamber. Currently the electronics for this chamber consists of a flat solenoidal delay line with a delay of 17.2 ns/cm and an MVL100 amplifier board. Constant fraction timing is achieved by summing the signal from the end of the delay line with the signal from a tap 2.5 cm from the end of the delay line in the MVL100 amplifier. The MVL100 is used as an amplifier only and an external discriminator circuit is used instead of the on-chip discriminator. This is because the on-chip discriminator is leading edge triggered, but a zero cross detector instead was needed for constant fraction timing.

A wire tension tester was constructed which enabled the wire tension to be tested by vibrating the wires in an electrostatic field, the frequency of vibration depending on the wire tension. Using this device two loose anode wires were identified and replaced. A second 60 cm aperture chamber is being assembled which uses stretched foils with etched copper strips instead of wires for the cathode planes. The two chambers are tentatively scheduled to be ready for beam tests by mid December.
In response to comments about the difficulty of servicing the 5" x 5" and 8" x 8" aperture chambers in current production, the group is designing them to make them easier to maintain. It is also clear that the current 5" x 5" and 8" x 8" chambers have an unacceptably short lifetime before they need cleaning. This appears to be due to having to operate the chambers at higher voltages than are typical for chambers with this plane spacing in order to get a large gas amplification. This results in polymers forming on the wires from the organic quencher gases, rapidly degrading the chamber performance.

To overcome this it is planned to redesign the chamber electronics so that less gas amplification is needed, allowing the chambers to operate at a lower voltage. This should increase chamber lifetime significantly.

MESON HALL

M11 channel

An interim tune was found in June for M11 and some experiments were carried out. This tune is listed in Table XVIII. The fluxes of p's, π's, μ's and e's measured for this interim tune are shown in Figs. 91 and 92 for +ve and -ve particles, respectively. Note that these fluxes were measured using the polarized proton beam with an approximately 20% uncertainty in the nanoampere currents. The surface muon flux was found to be very low, ~0.026 Hz/nA. Figure 93 shows the beam spot measured for this interim tune with Δp/p = 2%.

This tune is referred to as interim because of discrepancies between it and TRANSPORT predictions. Limited measurements were carried out in September, again with polarized beam, using the TRANSPORT tune. An increase of 70% was found in the π⁺ fluxes but as yet the beam spot is large.

The highest energy available in M11 at present is (~200 MeV). This limitation is due to cooling and insulation problems in the present septum. A new septum is being built and should be ready for installation in the summer of 1982 after which pions to the highest possible energies (~350 MeV) will be available.

During the November shutdown the stand for the last two elements in the channel, Q6 and the sextupole, were modified to accommodate the use of the QQD spectrometer. All the steel and special shielding to M11Q5 has been installed.

M13 channel

The beam line was upgraded by replacing Q4 so that the line can now be used reliably for pions up to 50 MeV, using the standard tune.

Relative measurements have been made, using standard μSR techniques of the polarization of the muon beam around surface muon energies. Assuming that "surface muons" at 29.6 MeV/c have a polarization of unity we found that, at 32 MeV/c, the polarization was (−0.973±0.024). The slits at the first focus (F1) have been modified so as to reduce the effect of slit scattering on the polarization of the surface muon beam.

NMR probes have been installed in the first bending magnet (B1) and are due to be installed in the second bending magnet (B2). These probes will enable easier tuning of the line for momenta above 27 MeV/c.

The M13 Q6 and Q7 stand was replaced with a modified version to accommodate the QQD spectrometer track in the M13 experimental area.

Table XVIII. Sample achromatic tune at P = 206.9 MeV/c.a.

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</tr>
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<td>1IS1</td>
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<td>760</td>
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<tr>
<td>1IQ1</td>
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<td></td>
</tr>
<tr>
<td>1IQ2</td>
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<td></td>
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<td>1ISX1</td>
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<tr>
<td>1ISX5</td>
<td>311</td>
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</table>

aLocation of focus is 203.5 cm downstream from geometric midpoint of Q6.
Fig. 91. Positive particle fluxes per nanoampere on the Mll channel from a 28 mm H₂O target.

Fig. 92. Negative particle fluxes per nanoampere on the Mll channel from a 28 mm H₂O target.

Fig. 93. Horizontal beam spot at final focus for interim tune with Δp/p = 2%.
QQD spectrometer

A magnetic spectrometer for low energy pion experiments was proposed [TRI-DN-10-81] late in 1980. Its assembly began in January. At the close of 1981 it is complete except for the focal plane wire chambers which are scheduled to arrive in January 1982. Modifications to the experimental areas of M13 and M11 have also been completed. These modifications consisted primarily of changing the stands under the final beam line components of these channels to accommodate the spectrometer.

The spectrometer consists of a dipole and quadrupole loaned to TRIUMF by KFA Jülich and a new quadrupole built at TRIUMF. The stand on which the spectrometer rotates is also a loan from Jülich and the scattering chamber is on loan from MPI Heidelberg.

Table XIX shows the design parameters of the QQD spectrometer compared to the existing TRIUMF low energy pion spectrometer (QD) and to the spectrometers proposed at LAMPF and SIN for this purpose.

Table XIX. Comparison of the QQD spectrometer design parameters with the TRIUMF low energy spectrometer (QD) and proposals under consideration at SIN and LAMPF.

<table>
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<tr>
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<th>TRIUMF</th>
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<td>Δp/ρ</td>
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<td>±20</td>
<td>-15,+20</td>
<td>±15</td>
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<td>D(=R₁₀)</td>
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<td>1.1</td>
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<td>1.2</td>
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<td>M(=R₁₁)</td>
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<td>D/M</td>
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<td>2</td>
<td>5</td>
<td>2.2</td>
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<tr>
<td>P_max (MeV/c)</td>
<td>250</td>
<td>300</td>
<td>250</td>
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</table>

*proposals

A study [TRI-DN-81-11] of the M13 channel indicates that the insertion of sextupoles will eliminate aberrations and increase the channel's luminosity. The mechanical design changes necessary to accomplish these improvements were under study in December. The accomplishment of these improvements will make it possible for the spectrometer and channel to be operated in a matched mode, and for the spectrometer to reach its design resolution.

RF separator

The RF separator was designed to produce a clean cloud muon beam of 77 MeV/c (±5%) in M9 of approximately twice the intensity possible from the electrostatic separator now in use. The major fabrication of the separator components was completed in the spring of this year.

Since then activity has centred around the assembly and testing of the device, the development of a control system and the building of a new set of slits from components of the old M9 slits to be used downstream of the separator to achieve optimum particle separation. Both the slits and controls are now complete and are undergoing tests.

During the course of the tests of the separator itself a number of minor defects in the construction and design which lead to vacuum problems were found and repaired. Many low and medium power RF tests have been carried out to verify the basic design and to fine tune the resonant characteristics. Some problems have been encountered in the power amplifier and power supplies salvaged from the old cyclotron central region model. While the various difficulties have all been solvable, they have contributed to a rather longer commissioning period than had been hoped for.

In July the separator was moved from the CRM lab to a final testing and staging area on the mezzanine of the meson hall where there was more space and better flexibility in providing X-ray shielding during sustained high power tests.

Thus far the separator has been tested to approximately 1/2 its design power. It is now in the process of final testing with the new controls. Once full power has been achieved and reliability demonstrated the separator will be installed in M9 during the year-end shutdown.

M20 improvements

At the beginning of 1981 a great deal of effort was being put into the M20 improvement project and a large number of conceptual plans and channel optics studies had been completed. Detailed designs were initiated. Unfortunately it became clear in March that there would be insufficient money in fiscal 81/82 for this project to continue as
anticipated. The design effort was therefore substantially reduced. Sufficient money was made available to allow the installation of the power supplies purchased early in 80/81. The result was the complete replacement of the old and unreliable LBL dual 90 power supplies, the removal of the necessity of switching power supplies for surface muon tunes, the provision of a well regulated 60 kW power supply for Helmholtz coils in the experimental area and the provision of remote channel control in the M20 counting room. These improvements have led to a much more reliable and convenient operation of the existing M20 channel.

In September high priority and an additional $50,000 of reserve funds were allocated to the M20 improvement project. This allowed design and construction efforts to return to pre-April I levels. All major purchases had to be deferred to fiscal 82/83; however, sufficient funds were available to allow reasonable progress toward the channel construction. A new PERT was drawn which indicates that an installation date near January 1, 1983 is entirely feasible, and work is continuing with this expectation.

Neutron spectrometer

Powder neutron diffraction turns out to be quite feasible even with the very low flux (up to $10^{11}$ neutrons per square centimetre per second at the source) by using large samples in the large cross-section beam extracted from the thermal neutron facility. A furnace has been constructed that will accommodate large samples without having excessive temperature gradients. Work has commenced on the temperature dependence of Mn$_4$N and Mn$_{4-x}$Ti$_x$N where T stands for various transition metal atoms. Ferromagnetic Mn$_4$N has a lattice structure in which one out of four Mn has a large volume available to it in a cubic environment. The questions being asked are how does the magnetic moment on a transition element change with the volume of the site in which it resides and how strongly is its magnetic moment coupled to its neighbours.

The general purpose spectrometer has been completed and fully automated. The microprocessor has been programmed to collect data in the background while presenting a fully usable computer to the experimenter for handling data and developing instructions for the background operation. The spectrometer is telephone addressable from remote terminals and can as well call for assistance in event of failures. The computer itself can be remotely rebooted.

PROTON HALL

MRS operation and upgrade

Operations

The spectrometer continued to be used in a number of experiments:

86,169 Elastic scattering of $^{40}$Ca and $^{16}$O
124,165 Giant resonances
152 Spin rotation parameter in elastic scattering on $^4$He
113 Elastic scattering on $^3$He
158 Quasi-free p+d $\rightarrow t+n$ on $^3$He
114 Quasi-free scattering of protons in $^3$He

For the moment, the energy resolution remains at the 0.5 to 1.0 MeV level.

The only significant operational change was rearrangement of the plumbing at the centre port to permit movement of the spectrometer to $-12^\circ$. In conjunction with the small angle configuration target chamber horn extension, this allows detection of deuterons from p+p $\rightarrow d+t$ on both sides of the beam. The resulting accuracy in measurement of absolute scattering angle will be useful in determining the absolute beam energy.

Upgrade

The goal of the MRS upgrade program is to achieve a momentum resolution of better than $\Delta p/p = 10^{-3}$ over the full acceptance. As of October the status of this program is as follows:

New scattering chamber. The design is complete for a new scattering chamber which eliminates vacuum foils in the beam by rotating with the spectrometer and coupling to the beam pipe via large flexible bellows. Engineering drawings for the chamber itself are finished and tender has been awarded for construction at Ebco Industries, Ltd. Delivery is expected in January 1982. It remains to complete engineering drawings for the support post and bellows support assembly. The TRIUMF Design Office started on this in November. It is planned to have the chamber system ready for installation in a proton hall mini-shutdown which is expected to occur in late spring or early summer 1982.
This large angle configuration (LAC) chamber will accommodate scattering angles larger than 15°. A conceptual design exists for a small angle configuration (SAC) horn extension to the chamber which will allow operation down to 3° with the beam stopped in a blocker inside the horn. Detailed design will begin when personnel become available in spring 1982.

**Focal plane detectors.** A small-scale prototype for new high resolution multi-cell drift chambers of the Bates "vertical drift" type has been designed and is under construction in the wire chamber shop in Edmonton. A sample amplifier/discriminator card (7791) has been ordered from LeCroy for testing with the prototype. If the tests are successful, a full-scale chamber will be constructed and further electronics purchased. It is likely that the readout system will be the LeCroy 4290 drift chamber digitizing system.

**Front-end wire chamber.** Frames have been constructed for a new low-pressure MWPC for measuring the scattering angle (and establishing the spectrometer "object" when the beam line is operated in untwisted mode). Thin metallized foils are being mounted and a special gas supply system has been assembled.

**Dipole shims.** Pole-edge shims for the exit end of the MRS dipole are under construction in the TRIUMF machine shop. These shims are intended to untilt the focal plane from its present angle of 66° to approximately 45°. An attempt will be made to mount them during the first major shutdown in 1982.

**Beam line quadrupole Hall probes.** Temperature-stable Hall probes in special jigs have been installed on the pole tips of all of the quadrupole magnets in beam line 4B. Cabling is complete and control system software changes have been made to permit readout in the control room. This system is intended to facilitate accurate reproduction of existing beam line tunes and possibly establishment of new computed tunes.

**Beam line dispersion twister.** Optimum operation of the upgraded spectrometer requires (vertical) dispersion matching at 4BT2. Optics design is complete for a 5-quadrupole dispersion twister which will be installed between target locations 4BT1 and 4BT2 (G.M. Stinson and D.A. Hutcheon). A redesign of this beam line in the proton hall is in progress.

There has been produced a conceptual design for a mounting frame which allows physical rotation of the 5-quad assembly through 60°. This is necessary to accommodate all conceivable operating modes of the beam line, including those with a spin precession solenoid. Since the twister is longer than the existing triplet, there may be some encroachment on target location 4BT1. Counter experiments at that location which require access to small angles may be impacted. Also, the beam pipe aperture between 4BT1 and 4BT2 will be reduced from 8" to 4". The 4" quadrupoles for the twister are on hand. Two of the existing 8" quadrupoles will be installed downstream of 4BT2 to accommodate the larger beam divergence with dispersed operation. It may be possible to make these beam line modifications during summer 1982. However, horizontal dispersion will be adequate for measuring the momentum resolution afforded by the new wire chambers and scattering chamber.

**TARGETS AND CRYOGENICS**

**Polarized targets**

**Liverpool polarized proton target.** The improvements to the NMR system for this target, begun at the end of last year, have been completed and the target was run for Expt. 174 during March, August, September and November. The program to convert this target to frozen spin mode is continuing, in collaboration with Dr. G.R. Court of the University of Liverpool, U.K. All the TRIUMF components for one dilution refrigerator have been sent to Liverpool for assembly. A similar set of components for a TRIUMF refrigerator is about 75% completed.

**Large frozen spin target.** The design of the cryostat has been completed and some parts have been produced by the machine shop. The design of the dilution refrigerator is about 50% complete. The principal components of the 3He circulation pumping stand have been received and assembly is about 30% complete.

**Cryogenic targets**

**Liquid deuterium neutron production target.** The renovation program for the neutron production target is reaching its final stages. The items completed include

1) moving the gas storage and dump tanks outside the experimental hall
2) building a new gas handling system
3) installing a new hydrogen ventilation hood
4) reconstructing the target vacuum pumping system
5) installing a thermal radiation shield around the 80 K jacket in the target vacuum vessel
6) fabrication and installation of a new target flask, with improved cooling capabilities.

The remaining items are
1) repairs and maintenance for the A-20 cryogenerator
2) the microprocessor-based control system.

Manitoba LHe target. The target was set up and operated in the MRS scattering chamber for an experimental run during March. Following the run extensive maintenance was carried out on the control system, with most of the old electrical wiring on the cryostat being replaced.

Hydrogen targets. A liquid hydrogen target was installed in M11 and run for Expt. 9 during September. Following the run, the two target flasks were modified to suppress boiling in the target.

Miscellaneous items

Superconducting solenoids. The new Janis superconducting solenoid was received and tested satisfactorily, following replacement of a leaking bellows in the cryostat. Both this and the old BASQUE solenoid were operated at various times throughout the year in beam lines 4A, 4B and 4C.

High pressure argon gas target for TPC. A commercially fabricated fiberglass vessel for use in this target failed to pass a hydrostatic pressure test. An equivalent aluminum vessel was fabricated and was successfully tested hydrostatically with oxygen gas. The gas handling and support system for this target are also complete.

EXPERIMENTAL FACILITIES ENGINEERING

Magnets and beam lines

Procurement of magnets and assistance to experimenters have increased this year. The Sagane magnet was refurbished and field mapped. The QCD spectrometer has been assembled and a modified "Jülich quadrupole" designed and fabricated. Stands and vacuum chambers have also been made for both these projects. A superconducting solenoid from American Magnetics was delivered and commissioned. The beam line 2A combination magnet is being made. The new spin precession dipole which will use the original M11 B1 coils is out for bid and the detailed designs for the upgraded M20 B1 and M20 B2 dipoles have been completed. Three new quadrupoles, 120/2/5's, have been ordered for the A leg of the new M20.

Experimental area support

During the past year there have been various activities for support of the meson hall. Additional space for experimental set-up is available now due to relocating the Beam Lines group. A shack has been made available for a quasi-clean area for experimenter wire chamber or scintillator set-up.

The workshop area has been enlarged to provide better access. An old lathe from the machine shop is now in place and operating. A new complement of tools has been stocked for the workshop area and, as well, a set of tools and tool cabinet for each of the experimental areas.

A chemical target separation room is now functional. This lab is for approved experiments. It is not to be used for the handling of any radioactive substance.

SITE SERVICES

In the restructuring of the organization following the change of Director at mid year most of the service groups providing technical support for all divisions on a site-wide basis were grouped as a semi-autonomous section of the Experimental Facilities Division. These groups included all of the previously established "Cost Centres", namely, Electronics Group and Shop, the Design Office and the Machine Shop. It also includes the TRIUMF Safety Group, Stores and Security, Buildings and Construction, Mechanical Engineering, and Planning/Scheduling groups. These groups have responsibilities that inherently extend over the whole site, such as Safety Group, or were previously established to maintain viable-sized specialist groups, such as Electronics, that facilitate maintenance of design and equipment compatibility across the TRIUMF site. This structure is also intended to accommodate some of the smaller projects within the various divisions which may require resources not available within that division.
The projects reported below are mostly continuations of work under way from the previous administration. Much of the work for such groups, such as the Design Office and Machine Shop, is an integral part of the progress reported by other sections and divisions.

Safety program

Facility licensing

The TRIUMF Accelerator Safety Report, a two-volume document supporting TRIUMF's accelerator licence application, was submitted to the Atomic Energy Control Board (AECB) in the spring. Approval was obtained from the AECB to continue running with the present lead target at the TNF for a total integrated charge delivered of 440 mAh.

In June TRIUMF was visited by two compliance inspectors from the AECB. No items of non-compliance were found, and TRIUMF was complimented on the quality of its radiation safety program.

The TRIUMF Safety Group gave a safety orientation course consisting of five two-hour lectures and demonstrations. The course was repeated three times and in total about 75 staff members attended. The lectures were temporarily suspended during the summer shutdown and will be resumed in the new auditorium.

Radiation protection

Figure 94 shows a frequency distribution of the accumulated gamma/beta dose for 1981 (to November). Out of 485 individuals 128 had non-zero readings for a total man-dose of 21 man-rem and an average non-zero dose of 164 mrem. The neutron badges again did not record a single reading. This fact together with a large increase in the cost of the service resulted in the decision to discontinue the neutron badge service except for individuals who work in known neutron fields on a regular basis. The neutron area monitoring capability has been increased so that there are now nine Anderson-Braun neutron monitors in place. In addition 20 passive monitors consisting of pairs of thermoluminescence dosimeters (TLD-600/700) in paraffin moderators have been built and installed.

Several of the scintillator beam spill monitors in the high spill regions have been replaced with air ionization chambers. Radiation damage to the photomultiplier tube bases had resulted in lifetimes of only a few months.

Work on a new CAMAC-based radiation monitor readout and display system has progressed slowly. The system will accept a variety of inputs from various types of radiation monitors. There will be two microprocessors in the system, one to perform the warning and trip logic and the other to display radiation levels on a CRT. Software development for the trip logic was near the testing stage by year's end.

Safety interlock

The central safety system (CSS) logic was modified twice in 1981 to facilitate changes and additions to beam lines and experimental areas. One of the major alterations was made to accommodate BL2C. Changes were made to several of the lock-up areas. The radioactive storage area in the service annex tunnel is now a separate lock-up area from the rest of the service annex. This change limits unnecessary exposure and reduces lock-up time. Controlled access to the vault, BL1B and BL4B has been modified such that the door must remain open during controlled access. This allows for easier communication between those entering the area and the person pressing the deadman button.

The area safety unit (ASU) for the M9 experimental area was converted to a microprocessor-based system. The micro (a Cremenco single card computer) electronic buffering and front panel layout is the same as that

![Fig. 94. Frequency distribution of accumulated gamma/beta dose.](image-url)
used in M1. After some teething problems were resolved the ASU now runs reliably.

Other changes and additions have also been made. A new beam blocker has been installed in BL1A which allows full access to BL1A, TNF cave and the meson channels when running polarized beam to BL1B.

A new explosive gas monitoring system has been built and partially installed. The system consists of a metering rack and plug-in modules and heads calibrated for hydrogen, isobutane or methane. At present a rack and 7 modules are installed in the meson hall. A second rack and modules will be installed in the proton hall in the next two months.

The BL2C safety system is unique in that the basic machine protect logic is carried out by an independent microprocessor which gives the central safety system a BL2C Enable signal. The CSS does not directly monitor values, magnets, etc.

The BL2C shine blockers, which are personnel protect devices, are also controlled by an independent microprocessor, although source drive signals pass through Safety's independent hard-wired logic, providing additional protection.

Industrial safety

At the close of the year TRIUMF continues to enjoy low accident frequency and severity rates. The median frequency rate has almost doubled to 0.7 injuries/100 workers/month over last year's rate of 0.37. However, it is believed that this increase is a result of staff diligence in reporting all injuries, as required by WCB regulations. This belief is supported by the fact that the severity rate of these reported injuries is down to a median rate of 0.33 days lost/100/workers/month as compared to a median rate of 0.49 last year. Secondly, the severity trend last year predicted increases in time lost due to injuries. However, this year that trend is now decreasing.

A demonstration was given by the UEL Fire Department on the use of Scott Air Paks to approximately 30 staff members. The session was well received and videotaped for future training needs. Two fire inspections were held in conjunction with the UEL Fire Dept. These inspections included the semi-annual audit of all fire extinguishers on site. The quota of extinguishers has been upgraded and documented. Key plans and accompanying emergency procedures have been continually revised to meet the changing needs at TRIUMF.

The meson hall gas handling system (MAGHS) facility has been completed. A similar facility for the proton hall is nearing completion. Two new 13-channel dedicated gas detection systems were designed and built by TSG and are calibrated for a variety of flammable gases, adding to the comprehensive list of gas detection/industrial hygiene equipment now available at TRIUMF.

Radiochemistry operations

The routine radiation survey program was expanded and intensified throughout 1981 to meet the demands of escalating radiochemistry operations. Laboratory air sampling became a daily routine in addition to the surface and swipe surveys. The stack monitoring system for the chemistry annex and the 70 MeV trailer laboratory became functional in the second half of 1981. This system consists of an air sampling unit with a shielded NaI(Tl) detector whose output pulses are fed to the datalog system in the 500 MeV cyclotron control room. The data is stored and once a week a survey is produced as a print-out. In addition, the stack exhaust air is continuously sampled through fibreglass and charcoal filters. Once a week the filters are removed and subjected to γ-spectroscopy for quantitative and qualitative evaluation. From this data the radioactive air concentrations in the labs can be established.

The liquid effluent control in the chemistry annex is a well established routine. All releases are carefully analyzed and released within the limits of TRIUMF's radioisotope operating licence.

In the first half of 1981 a radioactive source loan service was implemented at TRIUMF. Six standarized shielded storage boxes were conveniently distributed on site, providing source loans with a minimum of administrative inconvenience.

The "Accelerator Facility Construction Approval" for a facility comprising a 42 MeV cyclotron was issued by the AECB at the end of 1980. Since then the CP-42 safety interlock system has been completed and tested.
Electronics and controls development

With the change in administration the Electronics group reported to the Site Services section of the Experimental Facilities Division, and a more formal secondment was made of group members to the Divisions they historically supported. At year's end the group consisted of:

- 2 Board-appointed engineers (2 - 1980)
- 9 P&S engineers (10 - 1980)
- 13 Technicians (14 - 1980)
- 6 Assemblers/installers (6 - 1980)
- 1 Part-time buyer/expediter (1 - 1980)

The increased experience and skill of the staff, particularly in the use of the TRIMAC microprocessor system, has resulted in the successful completion of many projects. Program development for TRIMAC systems is now simplified and standardized by the use of an ever-growing software library (TRILIB) developed by the group over the past two years. It contains mathematical functions, logical functions, code conversions, CAMAC drivers, TRIMAC initialization routines and handlers for several CAMAC modules. Most of the software is designed for assembly language use but is compatible with FORTRAN programs. It is now possible to produce custom interlock systems in a fraction of the time previously required to hard-wire relay logic. Thus the goal of "going microprocessor" has been realized. Major TRIMAC systems completed during the year include:

Polarized target NMR. TRIMACs control the swept frequency generator, measure the absorption response, compute and display the polarization curve on an oscilloscope. This system was first used in 1980; final enhancements were added in 1981. Conceptual designs for the frozen spin target employing TRIMACs and LSI-11s have commenced.

RF Separator Control. Similar to the ISIS RF system in concept, this system has the additional feature of sequenced pulse start (to overcome multipactoring in the resonators). It has been partly commissioned and awaits final installation of the separator.

Beam line 2C controls. The control system for BL2C includes many "firsts" for TRIUMF. It is the first to use serial CAMAC highway, the first to use a PDP-11 as a control computer and the first to have all vacuum and monitor controls handled by TRIMAC. The TRIMAC provides all interlock protection and actuation of all valves, pumps, monitors and shine blockers. It shares a CAMAC crate with an L-2 serial controller connected to the PDP-11. Requests to activate devices originate with either a local control panel or the PDP-11, but in both cases the TRIMAC ensures conditions are valid and safe before acting upon a request. Because the vacuum system will be reconfigured for different operating conditions, the system accepts keyboard entry, by an authorized operator, of interlock bypass commands. Such commands cause the program to ignore the state of the bypassed parameter in computing permissives. The TRIMAC routinely reports the state of all interlocks including the fact that they are bypassed to the CCS for logging. This procedure reduces the probability that unreported terminal-block jumpers will be left on interlocks when the need for bypassing does not exist.

At year's end the TRIMAC portion of BL2C was operational except for the monitor control.

Liquid deuterium target controls. A TRIMAC system provides the complete control for the new LD_2 target. The system is 90% complete and will undergo final commissioning in early 1982. Features of the system include:

- Continuous surveillance of all pressure and temperature parameters to ensure safe operations. Automatic shutdown procedures are initiated if required.
- Automatic pumpdown sequence initiated from local panel commands.
- Closed-loop temperature control of target.
- Motion control of target in response to local panel.
- Target flask pumpout or pressurize sequences from local panel commands.
- Target fill or empty sequences.
- Generation of local display on CRT.
- Communication of target status to CCS via CAMAC-to-CAMAC link.

Each of the projects described above was implemented by a mixed software-hardware team. Fabrication of electronics hardware and cables was done in the Electronics Shop.

Non-TRIMAC projects of note that made significant progress during the year were:

POLISIS and ISIS interlock systems. A new CAMAC digital control module with interlock capability (the DICON) was debugged and manufactured in sufficient quantity to completely rework the POLISIS and ISIS interlock system.
The scheduled installation in the winter shutdown was delayed when it was found that the DICON had a propensity to turn off devices when the 300 kV source acceleration potential sparked down. Installation of RFI filters on the inputs reduced this effect sufficiently that POLISIS was fitted with the units in the spring. Experience with POLISIS operation has been successful and the units are now being installed in ISIS in preparation for the first beam in 1982. In addition to sanitizing the wiring in the sources, the new system provides more complete reporting of momentary or intermittent interlock failures and a local control facility. This second feature will decouple ISIS from the control system on maintenance days, thus relieving scheduling conflicts.

Medical bed control. Also nearing completion at this time is a 3 motion, dc motor control and absolute encoder readback system for the B.C. Cancer Foundation treatment bed. The system includes hard-wired protection interlocks utilizing programmed array logic (PAL) integrated circuits. The control system is interfaced to the existing Nova 1200-CAMAC system used to control the medical channel.

PETT electronics. A team of two technicians and an engineer (part-time) has been formed to construct the electronics for the PETT VI scanner. The design follows the St. Louis design except for a change to commercial histogramming memories; the use of a CAMAC LSI-11 microcomputer to control motion and provide diagnostics; and the use of a serial CAMAC system connected to the TRIUMF VAX. The project started in April, is roughly 1/2 completed and has to date utilized ~1/2 man-year of Electronics shop assembly effort. Testing of front-end amplifier/discriminator circuits, memories and memory interface is underway, in keeping with a tight schedule calling for a June completion date.

TPC electronics. The major effort in nucleonics design has been directed to providing front-end amplifiers and discriminators for a chamber trigger system for the TPC.

FASTBUS. TRIUMF continued its participation in the FASTBUS specification development by sending representatives to most hardware working group meetings in 1981. At the August and November meetings in Boulder, Colorado, all technical details except possibly the board height were frozen. The next meeting at Edmonton in March 1982 will be devoted to final editorial revision of the specification. Publication should follow soon after that. The commitment of major labs like SLAC, Fermilab and CERN to the FASTBUS indicates that it will be the CAMAC of the 1980s.

Conceptual studies have been started on a serial segment, fast pre-processor, and some ADC-memory modules for TPC. However, TRIUMF will have to rely on other laboratories or manufacturers to produce the key devices such as host interfaces, segment interconnects and diagnostic modules.

On the brighter side, two tangible uses of FASTBUS can be found in our lab. The TPC front-end amplifier/discriminators are being built in FASTBUS mechanics, and a simple input-output register FASTBUS interface (IORFI) purchased from SLAC has been interfaced to the PDP-11. It can generate cycles on a FASTBUS segment for development and test purposes.

Building program

Two major construction projects were completed during 1981.

Proton hall and service annex extension. An 80 ft westward extension of the main accelerator building at ground level (proton area) provided approx 8000 ft² of open space serviced by the two existing 50-ton cranes. Two mezzanine floors were installed along the west wall of this extension yielding eight new offices with a total floor area of 1500 ft² on the first level and 2000 ft² of storage area on the second level.

A two-floor westward extension of the service annex provided 3000 ft² of set-up area for experiments on its ground floor. The second floor accommodated six local control rooms with a total area of approx 1300 ft² and nine offices with a combined floor area of 1300 ft².

This building was completed in September.

Office building extension. In November construction of the office building expansion was completed with a total gross gain of approximately 10,500 ft². The expansion comprised a two-floor eastward extension of the existing office wing, a second floor addition over the existing laboratory building, and a two-level connecting wing between both structures. The building extensions provided office space for the Theory
group, computer rooms, the entire Business Office, a new and expanded library, a conference room and an auditorium.

At year-end excavation work was in progress for the construction of a remote handling building. This facility will be located north of the vault section of the main accelerator building. The structure will consist of two 44 ft x 48 ft floors of reinforced concrete below ground with a connection to the existing service bridge tunnel at beam level for direct access into the cyclotron vault. A metal-clad steel frame superstructure with crane will serve as maintenance shop. Attached to the superstructure will be a 20 ft x 40 ft two-floor office annex consisting of a metal-clad wood frame structure on concrete slab on grade. This building is scheduled to be completed in autumn 1982.

Preparation of architectural drawings is proceeding for the construction of a new workshop building. This facility will be located on land immediately south of the present TRIUMF site which was recently obtained from UBC. The 10,000 ft² building, with crane service, will be a metal-clad steel frame structure with attached service bay on concrete slab at grade level. The new workshop with its adjacent assembly yard will be connected to an extended perimeter road. Construction is scheduled to commence in spring 1982.

Planning

The PERTable activities (approx 1000) at TRIUMF are organized into four major PERTs related to various systems. PERT #1A and #1B deal with the activities related to cyclotron systems and PERT #2A and #2B include the experimental facilities and experimental support activities. These PERTs are updated monthly and distributed to the personnel involved. Overall manpower distribution reports are similarly prepared. Several new PERTs have been prepared this year.

PETT PERT. This detailed PERT with more than 300 activities for the PETT construction has been reviewed every two weeks since April. The project seems to be well on schedule and within budget. It is being effectively used as a planning manpower analysis and cost control tool and proved quite helpful to the team members in managing the project. The details for the tail end of the PERT have been added to reflect the stages of tests, etc.

RF resonator plan. In order to achieve the primary objective of increasing the reliability of the machine, the RF resonator replacement program was given a high priority. A preliminary Five Year Plan was prepared with an aim of installing all standard and central region resonators by the end of fiscal 1984/85. However, the realization of this plan is subject to the completion of mechanical and electrical tests on a prototype standard resonator by August 1982 which is optimistic. The detailed PERT (with approx 300 activities) has been drawn to help in proceeding in an organized manner, and progress is being reviewed every week.

M20 improvements PERT. Due to the higher priority on this project during 1981/82, a detailed PERT for M20 (with approx 300 activities) has been drawn with the manpower analysis and cashflow forecasts and is being reviewed every two weeks. It is planned to install M20 improvements with dc separator in the January 1983 shutdown.

The overall analysis of Experimental Facilities projects indicates a heavy demand on the Beam Lines group for installation of various facilities in the 1982/83 fiscal year, and some solutions will have to be sought to meet the schedules.

Shutdown schedules. The October 1981 shutdown was scheduled to start on October 6 with beam to be delivered by November 3. The elevating system repair job was found to be more complicated than anticipated, and it was decided to keep the tank lid down until repairs could be completed in the January shutdown. Unfortunately, the inflector problems forced the January 1982 shutdown to start one and a half months earlier. Some of the planned activities, e.g. stand and vacuum box modifications for combination magnet #4, etc., could not be ready and were deferred until the next shutdown in 1982. However, many of the planned activities were able to proceed and to take advantage of the low radiation levels in various areas.

Five Year Plan. The first iteration of the Five Year Plan for major projects was prepared with the cash flow forecasts for presentation to NRC, ABOT and EEC. The overall long-term plans are under continuous review.
ORGANIZATION

Board of Management

The Board of Management of TRIUMF manages the business of the facility and has equal representation from each of the four universities. At the end of 1981 the Board comprised:

University of Alberta
Dr. J.G. Kaplan
Dr. G.C. Neilson
Dean K.B. Newbound
Hon. Secretary

Simon Fraser University
Dr. B.P. Clayman
Dr. W. DeVries
Dean J.M. Webster

University of Victoria
Dean J.M. Dewey
President H.E. Petch
Chairman
Dr. C.E. Picciotto

University of British Columbia
Dr. K.L. Erdman
Dean P.A. Larkin
Mr. D. Sinclair

Non-voting members: Dr. R.A. Foxall, National Research Council
Dr. E.W. Vogt, Director, TRIUMF
Dr. G.A. Ludgate, TRIUMF
Secretary

Changes in board membership were: Dr. J.G. Kaplan replaced Dr. H.E. Gunning, and Dr. K.L. Erdman replaced Dr. E.W. Vogt. Dr. E.W. Vogt was selected as the next Director of TRIUMF, from July 1, by a selection committee.

The board met three times during the year.

Administration

In July, under the directorship of Dr. E.W. Vogt, all TRIUMF personnel were organized into five divisions, with division heads and the administration branch as follows:

Division Head, Science Division
Dr. D.A. Axen

Division Head, Applied Program Division
Dr. B.D. Fate

Division Head, Cyclotron Division
Dr. G. Dutto

Division Head, Accelerator Research Division
Dr. M.K. Craddock

Division Head, Experimental Facilities Division
Dr. E.W. Blackmore

Chief Financial Officer
Mr. C.W. Bordeaux

Personnel Officer
Ms. P. Adams

Information Officer
Dr. G. Ludgate

All report to the Director.

Operating Committee

The Operating Committee of TRIUMF is responsible for the operation of the facility. It reports to the Board of Management through its chairman, Dr. E.W. Vogt. It has four voting members, one from each of the four universities. The Associate Director is a non-voting member. The members of the committee (alternate members in parentheses) at the end of 1981 were:
Changes in 1981 were: Dr. E.W. Vogt was appointed Director replacing Dr. J.T. Sample. Dr. D.A. Axen was appointed Associate Director replacing Dr. K.L. Erdman. Dr. B.D. Pate was appointed Division Head of Applied Program and left the committee. Dr. G.A. Moss replaced Dr. J.M. Cameron as senior member for the University of Alberta, with Dr. P. Kitching being appointed alternate. Dr. J.H. Brewer replaced Dr. M.K. Craddock as senior member for UBC, with Dr. R.R. Johnson being appointed alternate.

TRIUMF Safety Advisory Committee

The TRIUMF Safety Advisory Committee (TSAC) has four standing subcommittees with membership as defined below. The main TSAC consists of all standing subcommittee members as well as:

Mr. I.N. Thorson Chairman
Dr. G.A. Ludgate Secretary
Dr. G.D. Wait
Dr. R.T. Morrison

Operation Radiation Hazards Subcommittee:

Mr. A.J. Otter Chairman
Dr. J.A. Macdonald
Mr. L. Moritz
Mr. J.W. Carey
Dr. H.W. Greene

Induced Radioactivity Hazards Subcommittee:

Dr. G. Dutto Chairman
Mr. J.W. Carey
Dr. B.D. Pate
Mr. W. Rachuk

Mr. F. Szlavik
Mr. R. Thaller

Chemical Toxicity and Flammability Hazard Subcommittee:

Mr. J.J. Burgerjon Chairman
Mr. A. Bishop
Dr. D.R. Gill
Dr. P. Percival
Dr. J.B. Farmer

Industrial Hazards Subcommittee:

Mr. A. Johnson Chairman
Mr. L. Crozier
Mr. A. Hurst
Ms. Y. Langley

Mr. T.D. Bulger (Observer)
Mr. S. Frazer (Observer)

TRIUMF
TRIUMF
Head, TRIUMF Safety Group
Director of Nuclear Medicine, VGH

TRIUMF
TRIUMF
Radiation Protection and Pollution Control Officer, UBC

TRIUMF
AECI

TRIUMF
TRIUMF
TRIUMF
Dept. of Chemistry, UBC

Workers' Compensation Board of B.C.
Workers' Compensation Board of B.C.
A TSAC meeting consists of the first group above, together with the chairman of each of the subcommittees and as many of their subcommittee members as is required for the particular agenda in hand.

**Experiments Evaluation Committee**

- **Dr. A.W. Thomas** Chairman, TRIUMF, University of Pennsylvania
- **Dr. R.D. Amado**
- **Dr. D.A. Axen**
- **Dr. A.D. Bacher** (ex officio)
- **Dr. J.H. Brewer**
- **Dr. R.L. Burman**
- **Dr. J. Domingo**
- **Dr. E.P. Hincks** Associate Chairman, Carleton University
- **Dr. K.P. Jackson** (ex officio)
- **Prof. A.E. Litherland**
- **Dr. C.A. Miller** Secretary, TRIUMF
- **Dr. L.D. Skarsgard** (ex officio)
- **Prof. A. Turkevich**
- **Dr. M.B. Walker**

**Biomedical Experiments Evaluation Committee**

- **Dr. L.D. Skarsgard** Chairman, B.C. Cancer Foundation
- **Dr. M.J. Ashwood-Smith**
- **Dr. H.C. Johns**
- **Dr. R.R. Johnson**
- **Dr. A.E. Litherland**
- **Dr. T.R. Overton**
- **Dr. J.T. Sample**
- **Dr. A.W. Thomas**
- **Dr. D.C. Walker**
- **Dr. G.F. Whitmore**
Appendix A

PUBLICATIONS

Journal publications:


Analysing power measurements for the $^{13}\text{C}(p,d)^{12}\text{C}$ reaction at 200 and 400 MeV, Phys. Lett. 99B, 311 (1981).


K.R. Shortt and R.M. Henkelman, Ionization chamber measurements of a pion beam, *ibid.*, 419.

TRIUMF reports:

Proceedings of the TRIUMF Muon Physics/Facility Workshop, Vancouver, August 8-9, 1980, eds. J.A. Macdonald, J.N. Ng, and A. Strathdee. [TRI-81-1]


Conference proceedings:

A. Gersten, Search for basic properties of the nucleon-nucleon interaction, Proc. 2nd Int. Conf. on Recent Progress in Many-Body Theories, Oaxtepec, January (to be published). [TRI-PP-81-2]


P.L. Walden, Meson production reactions by $p,d,o$ ... on nuclei, *ibid.*, [TRI-PP-81-29]


G.J. Lolos, E.L. Mathie, P.L. Walden, E.C.
Auld, G. Jones and R.B. Taylor, The \((p, \pi^-)\) reaction on \(^3\text{Be}\) with 200–500 MeV polarized protons, *ibid.*, 191.

E. Vogt, On multiple pion production in nuclei by intermediate energy nucleons, *ibid.*, 205.


D.F. Measday, J.M. Poutissou, M. Salomon and B.C. Robertson, Study of the reactions \(\pi^- p + \gamma n\) and \(\pi^- p + \pi^0 n\) at low energy, *ibid.*, 332.


M.K. Craddock, G.H. Mackenzie and P.W. Schmor
Depolarization of H⁻ ions in the TRIUMF
cyclotron, ibid. [TRI-PP-81-37]

C.J. Kost and G.H. Mackenzie, Extraction of a
beam spot made up of two spatially separate
components, ibid. [TRI-PP-81-38]

E.W. Blackmore, D.A. Dohan, G.H. Mackenzie
and R. Poirier, Developments toward separated
turns at TRIUMF, ibid. [TRI-PP-81-39]

R. Baartman, G. Dutto, R. Laxdal,
G. Mackenzie, L. Moritz, P. Schmor and
M. Zach, Developments toward higher beam in-
tensity at TRIUMF, ibid. [TRI-PP-81-40]

R. Burge and R. Vader, A beam phase measuring
system for the TRIUMF cyclotron, ibid.
[TRI-PP-81-46]

R. Baartman, P. Bosman, R.E. Laxdal, D. Yuan
and P.W. Schmor, The H⁻ ion source for the
high intensity beam at TRIUMF, ibid.
[TRI-PP-81-47]

M.K. Craddock, C.J. Kost, G.H. Mackenzie and
J.R. Richardson, High energy superconducting
cyclotrons, ibid. [TRI-PP-81-49]

K. Sakamoto, S. Okada, G.K.Y. Lam and
J. Howard, Biological properties of particle
radiations, Proc. IAEA Conf., Kyoto, Japan,
September (in press).

M. Betz, B. Blankleider, J.A. Niskanen and
A.W. Thomas, Theories of pion production in
nucleon-nucleon collisions, Proc. Workshop on
Pion Production and Absorption in Nuclei,
Bloomington, October (AIPCP, in press).

H.W. Fearing, Models for (p,π) reactions,
ibid. [TRI-PP-81-59]

H.W. Fearing, Summary of discussion on con-
nections among models of pion production,
ibid. [TRI-PP-81-74]

G.J. Lolos, New data and plans for exper-
iments - TRIUMF, ibid. [TRI-PP-81-60]

G. Jones, NN + πd and NN + NNπ; A review of
experimental results, ibid. [TRI-PP-81-62]

Proceedings of 1980 conferences published in
1981 included the following papers:

J.A. Niskanen, Polarization phenomena in
(p,π) reactions, Proc. 5th Int. Symp. on
Polarization Phenomena in Nuclear Physics,

J.A. Edgington, The interpretation of recent
measurements of np and pp cross sections,
ibid., 84.

E.G. Auld, Polarization analyzing power
measurements in coherent pion production by
protons, ibid., 93.

G. Roy, L.G. Greeniaus, G.A. Moss, D.A.
Hutcheon, R. Liljestrand, R.M. Woloshyn,
D. Boal, A.W. Stetz, K. Aniol, A. Willis,
N. Willis and R. McCamis, Inclusive scatter-
ing of protons on helium and nickel at
500 MeV, ibid., 158.

R. Abegg, J.M. Cameron, D.A. Hutcheon, R.P.
Liljestrand, W.J. McDonald, C.A. Miller, L.E.
Antonuk, C.E. Stronach, J.R. Tinsley, Search
for the dibaryon bandhead, ibid., 188.

D.A. Hutcheon, J.M. Cameron, R.P. Liljestrand
P. Kitching, C.A. Miller, W.J. McDonald, D.M.
Sheppard, W.C. Olsen, G.C. Neilson, H.S.
Sheriff, R.N. MacDonald, G.M. Stinson, D.K.
McDaniels, J.R. Tinsley, L.W. Swansen,
P. Schwanand, C.E. Stronach and L. Ray, Elas-
tic scattering of polarized protons at 200 to
500 MeV, ibid., 454.

G.J. Lolos, E.L. Mathie, P.L. Walden, E.G.
Auld, G. Jones and R.G. Taylor, New aspects
of the TRIUMF (p,π) program, ibid., 550.

P. Kitching, L. Antonuk, C.A. Miller, D.A.
Hutcheon, W.J. McDonald, W.C. Olsen, G.C.
Neilson, G.M. Stinson and A.W. Stetz, Quasi-
elastic ⁴⁰Ca(p,2p) scattering at 200 MeV at
TRIUMF, ibid., 568.

Cameron, L.G. Greeniaus, D.A. Hutcheon, C.A.
Miller, G.A. Moss, R.P. Liljestrand,
H. Wilson, A.W. Stetz, M.B. Epstein and D.J.
Margaziotis, The reaction ²H(p,π)π⁺ at 470
and 500 MeV, ibid., Part 2, 1205.

M.P. Epstein, D.J. Margaziotis, R. Abegg,
D.K. Hasell, W.T.H. van Oers, J.M. Cameron,
G.A. Moss, L.G. Greeniaus and A.W. Stetz,
Asymmetries from the ⁴He(p,2p)³H reaction at
250 and 500 MeV using polarized protons,
ibid., 1287.


C.A. Miller, The (p,2p) and (p,pn) reactions, ibid., 157c.


P.W. Percival, Muonium formation in water and aqueous solutions, ibid., 315.

P.W. Percival, The missing fraction in water, ibid., 325.

D.C. Walker, Arguments against a spur model for muonium formation, ibid., 329.


Y.C. Jean, B.W. Ng, Y. Ito, T.Q. Nguyen and D.C. Walker, MSR applications to muonium reactivity in cyclodextrins, ibid., 351.

Y. Ito, B.W. Ng, Y.C. Jean and D.C. Walker, Effect of external electric fields on the $\mu$SR of liquid hydrocarbons and fused quartz, ibid., 355.

R.F. Kiefl, Thermalization of muonium in oxide powders at low temperatures, ibid., 359.

J.H. Brewer, Muonium in quartz, ibid., 375.


J.H. Brewer, D.P. Spencer, D.G. Fleming and J.A.R. Coope, Muonium hyperfine matrix in quartz, ibid., 405.


J.H. Brewer, E. Koster, A. Schenck, H. Schilling and D.L.I. Williams, $\mu^+$SR studies in antiferromagnetic CoCl$_2$·2H$_2$O, ibid., 619.

J.H. Brewer, E. Koster, A. Schenck, H. Schilling and D.L.I. Williams, $\mu^+$ diffusion in single crystal AlCu(2%), ibid., 671.

M. Doyama, Comparison between positive muon research and positron annihilation in the study of crystalline effects, ibid., 701.


Y.J. Uemura, Probing spin glasses with zero-field $\mu$SR, ibid., 739.

Y.J. Uemura, C.H. Huang, C.W. Clawson, J.H. Brewer, R.F. Kiefl, D.P. Spencer and A.M. de Graff, Zero-field $\mu$SR in an insulator spin glass (CoO)$_{40}$(Al$_2$O$_3$)$_{10}$(SiO$_2$)$_{50}$, ibid., 757.


J.H. Brewer, $\mu^+$SR with surface muon beams, ibid., 831.

M. Strovink, Possible deviations from (V-A) charged currents: Precise measurement of muon decay parameters, Weak Interactions as Probes of Unification, Blacksburg, December, AIPCP #72 (AIP, New York, 1981) p. 46.
Preprints and in press:


A.W. Thomas, The cloudy bag model: Or, bag models, chiral symmetry and all that. [Univ. of Melbourne UMP-81/29]


O. Shanker, Present status of muon number (submitted for publication). [TRI-PP-81-10]


R.E.L. Green, K.P. Jackson and R.G. Korteling, Analysing powers in inclusive Ag(p,3He) and Ag(p,4He) reactions at intermediate energies (Phys. Rev. C, in press). [TRI-PP-81-50]


Y.C. Jean, B.W. Ng and D.C. Walker, Muonium spin rotation applications to model biological systems, in "Applications of nuclear and radiochemistry", ed. R. Lambrecht (Pergamon, in press).


### Appendix B

#### USERS GROUP

<table>
<thead>
<tr>
<th>University of Alberta</th>
<th>University of Victoria</th>
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<tr>
<td>R. Abegg*</td>
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*at main site Vancouver

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<td>G.A. Ludgate</td>
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†B.C. Cancer Control Agency

Visiting experimentalists based at main site:

- G. Azuelos, R. Poutissou, Université de Montréal
- A. Bracco, H.P. Gubler, D.K. Hasell, W.-P. Lee,
  W.T.H. van Oers, University of Manitoba
- J. Tinsley, University of Oregon
- M. Moinester, Tel-Aviv University
Other institutions:

Canada

C.Y. Kim, S. Rowlands, University of Calgary
T. Walton, Cariboo College
A.L. Carter, Carleton University
G.A. Bartholomew, M. de Jong, J.S. Fraser,
O.F. Häusser, F.C. Khanna, H.C. Lee,
A. McDonald, Chalk River Nuclear Laboratories
J.W. Scrimger, S.R. Usiskin, Cross Cancer
Institute, Edmonton
P.A. Egelstaff, University of Guelph
B.S. Bhakar, J. Birchall, N.E. Davison,
W. Falk, J. Jovanovich, R. McCamis, J.P. Svenne, University of Manitoba
S.D. Hanham, MacMillan Bloedel Research
B. Margolis, S.K. Mark, L. Yaffe, McGill
University
P. Depommier, J-P Martin, Université de
Montréal
M.S. Dixit, C. Hargrove, National Research
Council
H. Blok, Novatrack Analysts Limited
G.T. Ewan, B.C. Robertson, Queen's University
J.T. Sample, Research Secretariat of B.C.
Y.H. Shin, University of Saskatchewan
M. Krell, Université de Sherbrooke
T.E. Drake, University of Toronto
R.T. Morrison, Vancouver General Hospital
W.P. Alford, University of Western Ontario

Overseas

D.V. Bugg, R. Gibson, Queen Mary College, London
N.M. Stewart, Bedford College, London
A.S. Clough, University of Surrey
A.N. James, University of Liverpool
G. Marshall, Rutherford Laboratory
C. Amsler, A. Astbury, R. Keeler, CERN
R. Engfer, Universität Zürich
J. Domingo, S. Jaccard, E.L. Mathie,
A. Schenck, SIN
L. Antonuk, Université de Neuchâtel
R. Grynszpan, CNRS Vitry
R. van Dantzig, IKO Amsterdam
J. Niskanen, University of Helsinki
M. Furic, Inst. R. Boskovic
C. Cernigoi, N. Orion, University of Trieste
and INFN
J. Alster, Tel-Aviv University
B.K. Jain, Bhabha Atomic Research Centre
R. Hayano, A. Ito, K. Nagamine, K. Sakamoto,
T. Yamazaki, University of Tokyo
I.R. Afna, Flinders University of South Australia

United States

D. Ashery, Argonne National Laboratory
K.W. Jones, Brookhaven National Laboratory
F.P. Brady, University of California, Davis
B.M.K. Nefkens, J.R. Richardson, University
of California, Los Angeles
M.P. Epstein, D.J. Margaziotis, California
State University
B. Bassalleck, Carnegie-Mellon University
J.J. Kraushaar, T. Masterson, University of
Colorado
H.S. Plendl, Florida State University
M.E. Rickey, F. Schwandt, T. Ward, Indiana
University
Y.K. Lee, Johns Hopkins University
P. Tandy, Kent State University
C. Clawson, K.M. Crowe, G. Gidal, S. Kaplan,
R.H. Pehl, V. Perez-Mendez, S. Rosenblum,
H. Steiner, M.W. Strovink, R. Tripp,
Lawrence Berkeley Laboratory
J.W. Blue, Lewis Research Center, NASA
L.E. Agnew, H.L. Anderson, R.M. deVries,
C.A. Goulding, C.Y. Huang, R.J. Macek,
T. Suzuki, Los Alamos National Laboratory
R.P. Redwine, Massachusetts Institute of
Technology
H.B. Willard, National Science Foundation
B. Dieterle, University of New Mexico
J.K. Chen, State University of N.Y. Geneseo
K.K. Seth, Northwestern University
F.E. Bertrand, Oak Ridge National Laboratory
B.C. Clark, Ohio State University
D.K. McDaniels, University of Oregon
K.S. Krane, R. Landau, A.W. Stetz, L.W.
Swenson, Oregon State University
R.F. Carlson, University of Redlands
G.S. Mutchler, Rice University
R. Dubois, Stanford Linear Accelerator Center
R. Bryan, R.B. Clark, Texas A&M University
V.G. Lind, R.E. McAdams, O.H. Otteson, Utah
State University
M. Blecher, K. Gotow, D. Jenkins, Virginia
Polytechnic Institute and State University
I. Halpern, E.M. Henley, F. Wooton, Univer-
sity of Washington
A.S. Rupaal, Western Washington University
W.C. Sperry, Central Washington University
M. Eckhause, R.T. Siegel, College of
William and Mary
H. Michael
T.C. Sharma
Users Executive Committee

At the Users Annual General Meeting November 12-14 the following Executive Committee was elected:

L.G. Greeniaus  Chairman   University of Alberta
D. Garner       Assoc. Chairman  University of British Columbia
A. Olin         University of Victoria
A.W. Stetz      University of Alberta
G. Roy          University of Alberta

P.W. Schmor     TRIUMF Liaison Officer

Long Range Planning Committee

D.F. Measday  Chairman   University of British Columbia
J.M. Poutissou Secretary   TRIUMF
D.V. Bugg
K.M. Crowe
D.A. Hutcheon
K.P. Jackson
J.R. Richardson
A.W. Thomas
T. Yamazaki

Queen Mary College, UK
Lawrence Berkeley Laboratory, USA
TRIUMF/University of Alberta
TRIUMF/Simon Fraser University
University of California, Los Angeles, USA
TRIUMF, EEC Chairman
University of Tokyo, Japan
EXPERIMENT PROPOSALS

The following lists experiment proposals received up to the end of 1981 (missing numbers cover proposals that have been withdrawn, replaced by later versions, or combined with another proposal). Page numbers are given for those experiments which are included in this annual report.

1. Low-energy π nuclear scattering  
R.R. Johnson, University of British Columbia [Completed]

2. The study of fragments emitted in nuclear reactions  
R.G. Korteling, Simon Fraser University [Completed]

3. Studies of the proton- and pion-induced fission of light to medium mass nuclides  
B.D. Pate, University of British Columbia [Completed]

4. A study of the reaction π⁻ + p → γ + n at pion kinetic energies from 20-200 MeV  
D.F. Measday, University of British Columbia [Active]

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* deceased