PROSPECTS FOR HIGH RESOLUTION STUDIES
WITH A PROTON BEAM BETWEEN $E_p = 200-500$ MeV

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UNIVERSITY OF VICTORIA
UNIVERSITY OF BRITISH COLUMBIA
PROSPECTS FOR HIGH RESOLUTION STUDIES
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This report is based mainly upon material discussed at a workshop on the same topic held at TRIUMF, October 5 and 6, 1979.

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Preface

The material which we have included in this report represents a rather personal editing of discussions held at the workshop on physics with high resolution spectrometers held at TRIUMF. The contributors to this workshop are given overleaf; to all of these we wish to acknowledge tribute. The material they presented will often appear here without reference; this has been done because of a wish to collect related topics and we hope no depredation will be felt.

In Appendix A we have appended recommendations from recent workshops held at LAMPF which seem often to overlap with our topic.

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Workshop on High Resolution Spectroscopy with Intermediate Energy Physics
TRIUMF, October 5 and 6, 1979

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1. INTRODUCTION

A fundamental goal of nuclear physics, not a new one but still an unattained one, is to relate nuclear structure and reaction dynamics to the underlying nucleon-nucleon (N-N) interaction. In fact, although we have made great strides in understanding the "microscopy" of physics at $10^{-15}$ cm (through QCD), we seem to have left a rather large gap around $10^{-13}$ cm! The QCD formalism is successful because the basic concept of the gluon exchange force as being weak at short distances ($10^{-15}$ cm) allows use of perturbation theory. Unfortunately the nature of the force is such that we cannot yet handle it in the macroscopic nuclear domain. Attempts to do this in the form of "bag" and "string" models have started to have some limited success and we hope we may yet succeed. It is perhaps in this context that we should try to set our goals in nuclear physics for the next ten years.

Within these broader goals it is our task now to attempt to outline the role which could be played by a high resolution spectrometer at TRIUMF. First we must face the reality that such an instrument could not metamorphose from our present device in less than three years. So we must redefine our task to read what role would a high resolution spectrometer play at TRIUMF three years hence? Now, if we knew exactly where we would be in three years, we could obviously save a lot of effort and jump directly to that point; alternatively we could go on a three-year vacation and again not miss anything! So we admit we really can never see clearly in our crystal ball exactly what is in store, and this uncertainty results in taking risks. In physics, as everywhere else, it is a rule that we can only make educated guesses and often it is in taking big risks that we can really make great breakthroughs.

In this document we have attempted to indicate a number of areas of intermediate-energy physics which today seem to be opening up new frontiers and which perhaps could be addressed best at TRIUMF energies. We note that in the series of workshops held at LAMPF in August 1979 of the eight panels making recommendations for the direction of intermediate physics for the next decade not less than three recommended that a high resolution spectrometer be funded at TRIUMF. We wish to emphasize that these recommendations were freely given and did not involve any coercion on our part! However, they were not accompanied by any funds so our position was not materially improved either.

2. THE UNIQUE POSITION OF TRIUMF

The TRIUMF accelerator continues to hold some unique advantages when one looks at what one would like to have for studies of nuclear structure at intermediate energies. We list some of the more obvious here.

(1) Energy continually variable between 185 and 515 MeV. It is worth noting that the time to change energy is about two hours for a major shift. Small changes, such as might be involved in searching for threshold effects, can be accomplished in perhaps one quarter of this time.
Primary beam resolution is already very good and is expected to improve (as reported by M. Craddock).

Present: 1 MeV @ 500 MeV normal operation
1980: 0.1-0.5 MeV medium beam resolution
Future (1982?) <0.1 MeV high resolution—but reduced current.

The last requires single-turn extraction from the machine. This will require the third harmonic added to the RF and possible improvement in magnet stability. In this mode maximum current from the machine would be 20 µA.

It is clear that such beam quality will be a major advantage in the design of any momentum-matching system and there can be considerable savings in scale by starting with a beam of good quality.

The polarized beam at TRIUMF continues to be a leader in intensity. It seems that the intensity could be increased, with fairly modest expenditure, to about 1 µA on target. This probably exceeds what would be required for most experiments using the spectrometer.

It is also possible that within the next three years techniques will become available to achieve appreciably higher polarized beam currents (≥20 µA). If so the polarized beam would be compatible with meson production for some experiments!

Some "basic" physics advantages:
- There is a window in nuclear absorption about 400 MeV, i.e. minimum in σₜ.
- The N-N interaction is well known both for p-p and n-p system (from BASQUE, Geneva).
- Direct reaction theories appear to work well down to Eₚ ≈ 300 MeV (DWIA, KMT, Glauber). (More on this in later sections.)
- Spin effects have clear, large signatures.

3. PROTON SCATTERING

3.1 Inelastic scattering

Inelastic proton scattering in this energy range must first be compared with electron scattering. For the latter our theoretical understanding of the process is, at least to first order, much better. However, recently the effects of meson exchange currents have created some uncertainty in our interpretation, especially for light nuclei.

The current situation for electron scattering at Bates was summarized. One must remember that with electron scattering we have so far measured only the lower moments. There are clearly areas where protons can play a role. In terms of today's theory the situation is also good (DWBA) but subject to corrections for:

1. distortion of electron waves (OK)
2. dispersion effects (nuclear polarization is small)
3. meson exchange currents.
The meson exchange currents are certainly important at high momentum transfer in $^2\text{H}(e,e')$ and for the total cross section for photodisintegration as shown in Fig. 1. The curves labelled A, B which include MEC effects are clearly a dramatic improvement over the impulse approximation. The effect on extraction of charge density is claimed to be small for heavier nuclei (generally <1%), but such seems not to be the case with the $^{16}\text{O}(\gamma,p)^{15}\text{N}$ results. Of course, MEC effects may be quite different for $(e,e')$ and $(\gamma,p)$.

Figures 2 and 3 show the disagreement between the density-dependent Hartree-Fock calculation of Negele (DDHF) and data for $^{208}\text{Pb}$. The second figure, showing percentage deviation between calculation and theory, indicates that quite large discrepancies still exist at large $q$. The dashed curve indicates again the marked improvement coming from inclusion of MEC. It was emphasized that "good" resolution at Bates today is 25 keV and better. The reason can perhaps be appreciated by a look at the $^{208}\text{Pb}$ spectrum taken at 180 MeV, Fig. 4. In fact there are about 200 states between 5 and 7 MeV excitation. Future directions of electron scattering program at Bates will include study of vibrators and rotators where high resolution will be a paramount need. They will also need 180° data to get M1 strengths.

Before we can use proton probes to explore areas not readily accessible to electrons, we first must have some confidence we can describe the reaction mechanism from a microscopic basis. The obvious choice here is DWIA. As discussed elsewhere, this seems to hold down to about $E_p \approx 300$ MeV. In DWIA we write

$$U(r_p) = \langle f | \sum_i V_{pi} (V_{pi})(1-P_{pi})|i\rangle$$

$$= \int V_{pp}(|\vec{r}_p - \vec{r}|)\rho_p^L(\vec{r})d^3\vec{r}$$

$$+ \int V_{pn}(|\vec{r}_p - \vec{r}|)\rho_n^L(\vec{r})d^3\vec{r}$$

where $V$ is a local form of the free two-nucleon $t$ matrix (e.g. of the type used by Love et al.) and $\rho(\vec{r})$ is the transition density.

To test that the effective interaction which we have constructed is satisfactory we can use selective transitions in light nuclei where selection rules and reaction dynamics often isolate a very few components of $V_{eff}$. Since the effective interaction is energy dependent, complementary studies at different energies will be required. These can perhaps be performed more meaningfully at $E_p \leq 300$ MeV as MEC effects in the reaction mechanism will be less of a complication in this range. In addition multi-step processes seem to increase as the energy increases. A compromise between the range of applicability of the impulse approximation and concerns due to enhanced meson effects would thus seem to dictate $E_p \approx 300$ MeV—a fortunate happenstance from our point of view!
The effective 2-nucleon interaction can be written

\[ V_{12}^{\text{eff}} = V_{12}^{\text{central}} + V_{12}^{\text{spin orbit}} + V_{12}^{\text{tensor}} \]

where

\[ V_{12}^{\text{C}} = V_0 + V_0 \sigma_1 \cdot \sigma_2 + V_{1T} \tau_1 \cdot \tau_2 + V_{2T} (\vec{r}_1 \cdot \vec{r}_2) (\vec{\tau}_1 \cdot \vec{\tau}_2) \]

\[ V_{12}^{\text{SO}} = (V_{LS} + V_{LS_T} \vec{\tau}_1 \cdot \vec{\tau}_2) \vec{\epsilon} \cdot \vec{s} \]

\[ V_{12}^{\text{ten}} = (V_T + V_{TT} \vec{\tau}_1 \cdot \vec{\tau}_2) S_{12} \]

and

\[ S_{12} = 3(\sigma_1 \cdot r_{12})(\sigma_2 \cdot r_{12}) - \sigma_1 \cdot \sigma_2 . \]

Clearly we must hope to demonstrate a one-to-one relationship between this effective interaction and the two-body force. To date some work has been performed at IUCF (J.R. Comfort et al.) which shows there is hope for this to be proven. An effective interaction consisting of three Yukawa terms (ranges 0.25 fm, 0.4 fm and 1.414 fm to reflect various meson exchanges) was constructed from N-N phase shifts. The resulting "fit" to \(^{12}\text{C}(p,p')\) data leading to the 14.11 and 16.11 MeV states are shown in Fig. 5. The wave functions used were those of Cohen and Kurath.

Having convinced ourselves that the effective interaction is well reproduced in the energy range of interest, where might we go? Some directions suggested at the workshop were to take advantage of:

1. increasing importance of spin-dependent interactions
2. selective excitation of nuclear states.

This in turn allows us to look for:

3. excitation of high spin states
4. large angular momentum transfer (\(\Delta J > 10\))
5. details of the transition density (as with electrons)
6. the selective nature of proton excitation in comparison with that of pions, electrons, etc.

As examples we consider natural and unnatural parity transitions in lead (see Fig. 6):

Natural parity transitions: \(^{203}\text{Pb} \ 3^-, 5^-; \ 2^+ \to 12^+\).

In DWIA one finds for \(J \leq 6\): Dominant central contribution

\[ J \geq 8\]: Dominant deformed \(\frac{3}{2} \cdot \frac{5}{2}\) contribution.

Unnatural parity states: At 135 MeV one seems to see rather pure \(l^p - 1h\) configurations, for example

\(^{160}\text{O}, \ 4^- \ as \ (p_{3/2})^{-1} (d_{5/2}) \)

and

\(^{208}\text{Pb} \ 14^- \ as \ (i_{13/2})^{-1} (j_{15/2}) \).

These stretched configurations seem to be excited more strongly as energy increases from 50 to 135 MeV but are very weakly excited at 800 MeV. The tensor interaction appears to be dominant in the excitation process. The physics interest lies in the
direct connection of spin-flip probability to spin transfer and hence to central and tensor spin-dependent interactions. Also one can see from IUCF work, that the addition of asymmetry data can often give greater sensitivity to selected portions of $\gamma^\text{eff}$ than the cross sections alone, as in the data for the $6^-$ state in $^{28}\text{Si}$ as seen with 135 MeV protons (shown in Figs. 7 and 8). An example of other new areas being planned is a search for pion condensate by looking at excitation of unnatural parity states as proposed by Ericson and Delorme\textsuperscript{3} and more recently detailed by Toki and Weise.\textsuperscript{4} The proposal is to search for precursors of pion condensate or "critical opalescence". The evidence may be increased cross section for excitation of unnatural parity states at high momentum transfer ($q \approx 1.5$ to $3 \text{ fm}^{-1}$), (Fig. 9). Such experiments will certainly be performed soon at other accelerators; however, they serve as an example of "novel" phenomena which we must expect. Can we also find similar phenomena which might be manifestations of gluon condensate? Are long-range effects due to the colour force detectable?

3.2 Giant resonances

Protons do have an inherent disadvantage in studies of giant resonances in that they excite equally isoscalar and isovector resonances in contrast to $T = 0$ probes such as deuterons and alphas. However, there are a number of compensating factors which may still result in proton probes playing an important role in our further understanding of giant resonance phenomena.

Firstly the basic interaction is better understood for protons than for other probes. Better optical model parameters exist, a necessary condition if we are to make quantitative estimates of the fraction of the EWSR exhausted. At intermediate energies the characteristic angular dependence for different $L$ values are more definitive. This is shown in Fig. 10 for the case of 200 MeV protons on lead. In addition we can use polarized protons and there may be additional selectivity in the asymmetry which also shows marked $L$ dependence as shown (Fig. 11) in DWBA predictions for $^{120}\text{Sn}$. Clearly, to know the exact form for different angular momenta it is necessary to establish the consistency of one's calculation by fitting transitions to low-lying states whose configurations are known. This will in general dictate high resolution.

Finally in this context we mention some recent measurements at Osaka. Measurements reported for $^{40}\text{Ca}(^{3}\text{He},^{3}\text{He}')$ in the giant resonance region\textsuperscript{5} have shown sharp structure in what were previously believed to be wide giant resonance states. More recent work with 60 MeV protons (resolution $\sim 20$ keV) shows that for $^{90}\text{Zr}$ the giant resonance region consists of many narrow states. Assignments of $L$ for these levels indicated that $L = 0,2,3$ states occur in this energy region.

3.3 Elastic scattering

A major aim of elastic scattering measurements at medium energies has been the mapping out of nuclear matter densities. For charge densities the primary probes are electromagnetic (electron scattering and muonic X-ray measurements) but hadronic
probes such as protons can complement the electromagnetic probes in two important ways:

1. large cross sections permit rapid systematic surveys,
2. neutron densities and currents can be probed more accurately and completely.

Up until now medium energy proton elastic scattering measurements have been interpreted in terms of either the Glauber formalism or the KMT optical potential formalism. A vital part of the hadron-nucleus scattering program over the next five years will be addressed to testing the accuracy of these approaches, but already the indicators are that things begin to go wrong below 300 MeV. Fits to IUCF data at 135 and 182 MeV are not of comparable quality to that obtained at ~1 GeV, while serious discrepancies with the experiment arise below 400 MeV in calculations of \( \sigma_{\text{TOTAL}} \) and \( \sigma_{\text{REAC}} \) based on the KMT formalism and the impulse approximation. This can be seen in Fig. 12 where calculations in DWIA can be compared with the world data set. At energies above 500 MeV analyses are rendered ambiguous by lack of knowledge of the N-N amplitudes. The TRIUMF energy range is thus of particular interest in the extraction of neutron densities from elastic scattering data.

This energy range is also of interest in the way the optical potentials themselves show structure. In particular the energy dependence of the real part of the spin orbit potential undergoes a change of slope at 200 MeV, while that of the imaginary part goes through a minimum of the same energy and goes through zero at 500 MeV (Fig. 13). Another recent interesting discovery is the strong damping of the oscillations in the differential cross section at intermediate angles (Fig. 14) which is apparent at 185 and 200 MeV and has disappeared at 400 MeV. This phenomenon appears to arise from interference between spin-flip and non-spin-flip amplitudes (Fig. 15) and is a manifestation of spin dependence in the proton-nucleus interaction.

4. PICKUP REACTIONS

In the last two years a considerable body of data has appeared for \((p,d)\) reactions from IUCF, TRIUMF, and LAMPF to add to the pioneering work at Uppsala and Saclay. These measurements, however, continue to be mainly for light nuclei. Our primary goal for these reactions continues to be (i) to extract information about the high momentum components of the single particle wave function and (ii) to extract information on "deep-hole" states. However, before we can do this we must demonstrate an understanding of the reaction mechanism.

The \((p,d)\) reaction mechanism at intermediate energies continues to be the subject of much spirited discussion. This discussion has, as its two main themes, the continued contribution of one-nucleon exchange which dominates at low energies and the increasing importance of reactions involving the formation of intermediate baryon resonances. Complexities of this latter type will clearly impede our primary goals as outlined above; however, they may provide an important tool to aid in our eventual understanding of mesonic degrees of freedom in nuclei.
The $^4$He(p,d)$^3$He reaction has remained one of the enigmas in this area. Here it was felt we "knew" the nuclear structure rather well from electron scattering, yet calculations in exact finite range (EFR) DWBA have failed rather dismally. These calculations\(^7\) use a deuteron wave function generated from the Reid soft-core nucleon-nucleon potential, deuteron D state is included, and spectroscopic factors are taken from calculations of Norton and Goldhammer. A key element in the analysis was the n-$^3$He wave function generated from the $^4$He charge form factor which has a deep minimum near $q \approx 2.2$ fm\(^{-1}\). This in turn results in a node in the $^4$He(p,d)$^3$He angular distribution about $\theta = 15^\circ$ c.m. which in large part caused the poor agreement with experiment. It has now been shown that if one subtracts the pion exchange contributions from the $^4$He electron scattering data before extracting the $^4$He nucleon density, one gets a filling-in of the hole in the configuration space n-$^3$He wave function. Then, when one calculates the (p,d) cross section for the 770 MeV Saclay data, one finds that the minimum at $\theta \approx 15^\circ$ has disappeared and the calculation is now below the data by a factor 2-3 as shown in Fig. 16. This discrepancy could possibly be accounted for by including more terms such as

![Diagram](https://example.com/diagram.png)

This correction also results in a very reasonable fit to the excitation function data at 22.5\(^\circ\) (TRIUMF) as shown in Fig. 17. From these recent calculations we must conclude that, at least for light nuclei, meson exchange effects play an important role at 770 MeV. Data to be taken at TRIUMF will, however, be required before we can answer the questions for energies between 200 and say 400 MeV.

The situation for heavier nuclei seems quite different. Already at 800 MeV the EFR-DWBA has done a creditable job in reproducing the measurements on $^{12}$C(p,d)$^{11}$C. So perhaps our conclusion should be that light nuclei, where reactions are dominated by meson exchange effects, are just not a useful area to test what may be applicable in general (say for $A \geq 12$). This, of course, means more high resolution studies, even for reaction mechanism tests.

Other interesting aspects of the recent data on (p,d) reactions include the strong excitation of a group of states at around 13 MeV excitation seen at 800 MeV in the $^{12}$C(p,d)$^{11}$C reactions as shown in Fig. 18. [These states are also seen in ($\pi^+$,p); see discussion in the next section.] These states were, however, not excited in low energy (p,d) studies and their configurations are still not understood.

Another interesting feature of (p,d) reactions at intermediate energies has been pioneered at TRIUMF. This involves the measurement of asymmetries using a polarized proton beam. In the $^{13}$C(p,d)$^{12}$C reaction a completely new countenance is shown...
in that one finds very marked nuclear structure dependence in the shape of the angular distribution, in contrast to the somewhat insipid form of the differential cross sections. The pickup to the ground state and 4.4 MeV level of $^{12}\text{C}$ are shown in Fig. 19 together with EFR-DWBA calculations. It is hoped that this new complexion, once we have refined our ability to interpret it, will serve as a powerful tool in spectroscopy of deep hole states, and in assignment of j-values to new excitations such as mentioned for the $^{12}\text{C}(p,d)^{11}\text{C}$ reaction.

5. $(p,\pi)$ REACTIONS

The $(p,\pi)$ reaction is expected to show the same sensitivity to nuclear structure as $(p,d)$ reactions and thus should also be a good probe of high-momentum components in the nuclear wave function. This expectation has not yet been realized because of great difficulty in separating nuclear structure effects from reaction mechanism effects. At present the bulk of $(p,\pi)$ data on nuclei are near threshold; recent studies of IUCF comparing cases in which final nuclear states could be reached in $(p,\pi)$ by a 1-step process with cases in which 2-step processes are required were described at the workshop. The need for good energy resolution to study "interesting" nuclear excited states was apparent.

The $(p,\pi)$ data indicate that in general single-particle states are strongly excited in comparison to core-excited states. Excitation of 2p-1h states also seems to be relatively weak. This would seem to favor a one-nucleon reaction model.

A comparison of Indiana data on $(p,\pi)$ at $\sim 200$ MeV, where $q \approx 460$ MeV/c, with low energy $(d,p)$ data shows the same states populated (at least for s-p shell). However, the $(d,p)$ reaction does seem to favor higher-shell filling in contrast to $(p,\pi)$ results.

Such similarities also exist at higher energies. This is seen in Fig. 18 for pickup from $^{12}\text{C}$ (LAMPF data). Again one finds the different states are populated at about the same level for the two reactions. This is perhaps seen more quantitatively when one compares a large range of $(\pi,p)$ and $(p,d)$ data as has been done by Keister and Wharton. They show that angular distributions scale as

$$\frac{d\sigma}{d\Omega} = \text{const.} \cdot e^{-q/\lambda}$$

and that $\lambda$ has an almost unique value for a given nucleus for a large range of pion energies over the range for which the nucleus is almost opaque to where it is almost transparent to the pion. Values of $\lambda$ found for $(p,d)$ reactions for $E_p \approx 200-700$ MeV yield the same value of $\lambda$ to within 10%. We still have to find out why! Could it be, after all, that we are sensitive to a common feature of both reactions, i.e. the single-particle momentum distribution? Another possibility, of course, is that both reactions are dominated by common reaction vertices. Such a viewpoint has recently been proposed. In this approach the triangle graph used to explain the backangle peak in $p+d$ elastic scattering (which can, of course, be viewed as the basic $(p,d)$
process] is applied. It is found that for a variety of nuclei the stripping \((d,p)\) reaction in the intermediate energy region can be estimated in terms of the cross section for pion production \((p,\pi)\) at half the laboratory kinetic energy. In Fig. 20 the \(^{12}\text{C}(p,d)^{11}\text{C}\) cross section at 740 MeV is compared to the prediction (circles) based on the \(^{12}\text{C}(\pi,p)^{11}\text{C}\) measured at an equivalent proton energy of 350 MeV.

This type of similarity also extends to \((\gamma,p)\) reactions. This was recently pointed out by Källne who showed that the momentum distribution extracted was essentially the same for \((\gamma,p)\) \((p,d)\) and \((\pi,p)\) reactions, even when data are analyzed in plane wave approximation! This may be simply coincidence, and it seems that additional work must be carried out to verify the observations and to try to account theoretically for the similarities.

The small cross section of typical \((p,\pi)\) reactions and short lifetime of the pion mean a pion spectrometer should be compact and have large solid angle, properties which could not easily be accommodated in a spectrometer designed for high resolution detection of protons or deuterons. However, assuming that an unravelling of nuclear structure and reaction mechanism effects in \((p,\pi)\) will require study of its energy dependence, it will be necessary to do some high resolution \((p,\pi)\) at energies \(T_p > 350\) MeV. In favourable circumstances an HRS might be the only facility at TRIUMF able to give adequate energy resolution. The reduced detection efficiency may limit its application to higher energy pions and to small angles where the cross section is highest. It would be complementary to the "Discovery" spectrometer which will be more compact but which will not be capable of going below \(\theta = 20^\circ\).

6. CONCLUSIONS

6.1 Prospects for high resolution studies with an intermediate-energy proton beam

In the past five years significant advances in studying interactions of hadrons in nuclei have been achieved. There is cause for (guarded) optimism that comparison of \(e,p,\pi\) probes will lead to an understanding of the interaction of baryons and mesons in nuclear matter, because of their quite different spin and isospin dependence. Excited states of nuclei provide the "nuclear laboratory" in which various spin-isospin components of the hadronic interactions may be studied. Examination of nuclear level schemes reveals that the present MRS resolution (~400 keV FWHM at 200 MeV) permits study of but a handful of nuclear excited states, and that better than 50 keV resolution is needed to gain access to most of the excited states of interesting spin or isospin composition. (However, even 100 keV resolution could be useful in studying some aspects of reaction mechanisms on light nuclei.)

One of the keys to understanding the hadron-nucleus interaction will certainly be a study of the energy dependence of reactions. TRIUMF, covering the energy region in which the onset of pion production affects all reactions, is in a position to make a vital contribution to the field. The combination of high-intensity polarized proton beam, easily varied beam energy, and absence of pressure to operate at high (>1 GeV) beam energies would enable TRIUMF to play a leading role in these studies, provided a high resolution spectrometer were available.
(2) Nuclear spectroscopy at intermediate energies will not simply be a rehash of work at lower energies—new kinds of states may be emphasized; for example, high spin states or giant resonance states in inelastic scattering. In addition, new types of experiments will be required to elucidate subtle effects such as predicted due to pion precondensation. As these might involve measurement of spin-flip probabilities and other Wolfenstein parameters of $p +$ nucleus scattering, they become much more feasible at intermediate energies. High-momentum components of nuclear wave functions may be probed by reactions such as $(p,2p)$, $(p,d)$ and $(p,\pi)$. In all spectroscopy studies it is of great advantage to have good energy resolution; when the states of interest are narrow and discrete it permits them to be seen above the background of nearby "uninteresting" states; when the feature of interest is broader, such as a giant resonance, it allows one to look for finer structure. For spectroscopy studies it is fair to say that 600 keV is hopeless and 100 keV may often be inadequate.

(3) The time required to build an HRS (the order of three years) makes it difficult to predict what experiments one would be doing after it was built. However, whatever new subfields have opened up, high resolution will probably be essential. As an example, there is a lot of recent interest in the interacting boson model of rotational and vibrational nuclei, where one needs $\sim 20$ keV resolution just to resolve the ground states.

6.2 Future measurements

An outline for future proton measurements might be:

(1) Isolate reaction mechanism effects from nuclear structure effects.
   - This requires resolution of "test states" of high purity,
   - hence good resolution ($\leq 100$ keV) is required,
   - energy dependent studies.

(2) Having completed above, use the knowledge to study nuclear structure, taking advantage of the complementary nature of probes.

(3) Exploit the importance of spin dependence to probe both the mechanism and structure.

References

8B.D. Keister and W.R. Wharton, in Abstracts of Contributed papers, 8th Int. Conf. on High-Energy Physics and Nuclear Structure, Vancouver, 1979, p. 82.
APPENDIX A. Excerpts from Report on LAMPF Workshop (August 1979)

Panel N-1

IV. SUMMARY

The recommendations of panel N-1, which have been discussed in the previous sections, are summarized in Table VI-IV. The top priority is to obtain nucleon-nucleon amplitudes at HRS and at Saclay from studies of $\bar{p}p$ and $\bar{p}d$ elastic scattering and $\bar{p}d$ quasi-elastic scattering. It should be emphasized that high-intensity polarized neutron beams obtained from stripping vector polarized deuterons will be available at Saclay early in 1980. At LAMPF, there is need for a polarized deuterium ($d$) target. The panel recommends an accelerated effort on the part of the users and urges the support on the part of LAMPF to complete the Saclay $d$ target and to build a copy of the CERN target. Another recommendation includes a complete set of elastic measurements of $1s$-shell nuclei as a test of the multiple-scattering interpretation. Measurements of $Q$ are strongly urged for closed-shell nuclei, as well as a complete study of the energy dependence of cross sections and polarizations.

Completion of the spectrometer at TRIUMF is urged to extend new measurements to lower energies. Spin-flip excitation studies including $d\sigma/d\Omega(0)$ at zero degrees, $P(0)$, and triple-scattering parameters will add new dimensions.

TABLE VI-IV

<table>
<thead>
<tr>
<th>NN Immediate Needs: (1-4 years)</th>
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<tbody>
<tr>
<td>$\bar{p} + \bar{p}$ at 800 MeV, $\theta_{lab} \leq 35^\circ$, complete determination of Wolfenstein amplitudes.</td>
</tr>
<tr>
<td>$\bar{p} + \bar{d}$ elastic and quasielastic at 800 MeV, $\theta_{lab} \leq 35^\circ$, to further constrain $n + p$ amplitudes.</td>
</tr>
<tr>
<td>Development of polarized deuterium target at LAMPF, refurbish old Saclay target, build copy of the CERN target.</td>
</tr>
<tr>
<td>$n + \bar{p}$ at Saclay, full set of amplitudes.</td>
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<th>Eventual Needs: (1-10 years)</th>
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<tr>
<td>The full $n-p$ and $p-p$ amplitudes between 500 and 1000 MeV, energy step size contingent upon possible NN energy-dependent structures.</td>
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<tr>
<th>Light Nuclei: (1-4 years)</th>
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<tbody>
<tr>
<td>$\bar{p} + ^4H, ^4He, ^3He, ^3H, d\sigma/d\Omega, Q$, spin-spin correlations to test reaction theories, and to investigate correlation, spin effects, and intermediate isobar states.</td>
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<th>Heavy Nuclei</th>
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<td>$\bar{p} + ^{16}O, ^{40,48}Ca, ^{90}Zr, ^{208}Pb, d\sigma/d\Omega, P, Q$, from 100 to 1000 MeV in steps of 100 MeV. Test of the energy dependence of the reaction theory and approximations.</td>
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<th>Reactive Content</th>
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<td>Proton and pion inclusive scattering from a few nuclei from 100 to 1000 MeV to test reaction theory and reactive content of optical model and multiple-scattering theory.</td>
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Continued on next page.
Closure Cross Section

Proton inclusive scattering from a few targets at 800 MeV.

Isotopic and Isotonic Density Studies in Heavy Nuclei

In particular, the nickel and tin isotopes and the N = 28,82 isotones.

Transition Densities

Test cases for T = 0 nuclei, ΔT = 0 transitions.

Spin-Flip Transitions

dσ/δΩ(0°), P(θ), triple-scattering measurements, spin-flip probabilities.

Completion of a High-Resolution Proton Spectrometer at TRIUMF

Variable Beam Energy at LAMPF

Pion Probes (1-10 years)

a. Theoretical advances needed.
b. 1-2-GeV pion beam with magnetic spectrometer;
   Resolution 100 KeV
   Solid angle 15 msr
   Angular resolution 1 msr

Magnetic spectrometer for the AGS.

Panel N-8

Recommendations

The measurement of (p,d) cross sections and analyzing powers on 4He and 11,12C at 200 ≤ T_p ≤ 800 MeV in 100-MeV steps. These measurements would fill the gap between the existing low-energy (T_p ≤ 200 MeV) measurements and the 700- to 800-MeV Saclay and LAMPF data, and provide analyzing powers at all energies. These data are important because they cover the energy range where the meson-exchange processes indicated in Fig. XIII-7 are expected to "turn on," and should therefore be extremely useful in testing various reaction models. Care should be taken to choose energies which will allow comparison with (π^+,p) results. The completion of the TRIUMF spectrometer is required in order to cover the 200-400-MeV region.

The determination of the A-dependence of (π^+,p) and (p,d) cross sections. Targets should have A > 40. This program may be quite limited. Time has already been allocated at LAMPF for wZr(p,d) measurements at T_p = 800 MeV. After these results become available, the need for more measurements, perhaps on wPb, can be assessed. Such a measurement could most readily be done at LAMPF or Saclay.

An extension of (e, ep) measurements to check consistency with the (γ,p) results. This may allow a check of the (γ,p) mechanism. In conjunction with these experiments, more (γ,n) measurements should be encouraged, again because comparison with (γ,p) will likely give information about the reaction mechanism. Measurements of angular distributions
for the inverse reaction \((p,\gamma)\) currently under way at Indiana University Cyclotron Facility can be expected to provide a more stringent test of the theoretical models for these processes. Some further \((\gamma,p)\) measurements, either on new targets or with improved resolution, should be undertaken (see report of panel N-5).

A study of the "new" levels seen in \((p,d)\) and \((\pi^+,p)\) reactions. The multiple-energy measurements contained in our first recommendation will be very useful in this regard, since the strength of these levels as a function of energy is likely to give some indication of their nature. Analyzing powers may also provide useful information. These efforts should be coordinated, if possible, with the measurement of conventional low-energy reactions which excite these states.
Fig. 1. Total cross section for deuteron photodisintegration. Solid curves show improved agreement with data resulting from adding meson exchange current effects to a conventional impulse approximation calculation (dashed curve).

Fig. 2(a). Cross section for elastic scattering on 208Pb as a function of momentum transfer. (b). Deviation between the data and DDHF calculation of Negele.

Fig. 3. Blow-up of Fig. 2(b). Dashed curve shows improvement obtained when MEC effects are added. (Note break in vertical scale).
Fig. 4. Inelastic electron scattering spectra from $^{208}\text{Pb}$.

Fig. 5. Inelastic proton scattering to $T=1$ states in $^{12}\text{C}$. Curves are DWIA calculation using force mixtures as indicated.

Fig. 6. Excitation of high spin states in inelastic proton scattering at I.U.C.F.
Fig. 7. Angular distribution for 135 MeV protons exciting the 6⁻, T=1,0 states in ²⁸Si. Contributions from various parts of the effective interaction to the calculated strength for this transition are shown.

Fig. 8. Asymmetry for the T=1 case shown in Fig. 7.

Fig. 9(a). see Fig. 5(b).

FORM FACTORS

Fig. 9(b). M1 form factor for 1⁺, T=1 states in ¹²C measured in inelastic electron scattering. Note in both cases that calculations fail to reproduce the measured cross section in region of momentum transfer q ≥ 2 fm⁻¹.
Fig. 11. Analyzing power of angular distributions for different partial waves for excitation of the giant resonance region in $^{120}$Sn using 104 MeV protons.

Fig. 10. Cross section of angular distributions for different partial waves for excitation of the giant resonance region of $^{208}$Pb using 200 MeV protons.

Fig. 12. Proton total cross sections for $^{12}$C and $^{16}$O compared to an impulse approximation calculation. Barred area is estimated uncertainty due to input parameters used in the calculation.

Fig. 13. Energy dependence of real and imaginary spin orbit part of the optical potential obtained by fitting proton elastic scattering.
Fig. 14. Recent measurements of elastic scattering of protons from $^{208}$Pb at intermediate energies.

Fig. 15. Interference of spin flip and spin non-flip amplitudes resulting in observed damping of oscillations at intermediate angles in proton elastic scattering.

Fig. 16(a). $^4$He single particle wave function extracted from electron scattering showing effect of subtracting meson exchange currents.

Fig. 16(b). $^4$He($p,d)^3$He differential cross section at $E_p = 770$ MeV calculated in DWBA using wavefunction shown in (a).
Fig. 17. \(^4\text{He}(p,d)^3\text{He}\) excitation function calculated for wavefunctions of Fig. 16 (a) compared to measured cross sections.

Fig. 18. \(^{12}\text{C}(p,d)^{11}\text{C}\) and \(^{12}\text{C}(\pi^+,p)\) spectra for \(T_p = 800\text{ MeV}\) and \(T_\pi = 180\text{ MeV}\) measured at LAMPF.
Fig. 19. $^{12}$C$(p,d)^{11}$C cross section and analyzing powers measured at TRIUMF. Curves are EFR(— ) and ZR(-- ) DWBA calculation.

Fig. 20. Measured $^{12}$C$(p,d)^{11}$C cross section (•) compared to prediction (••) of Wilkin based on $^{12}$C$(\pi,p)$ cross section data.