



PROCEEDINGS OF THE DASS/SASP (DUAL ARM SPECTROMETER SYSTEM/ SECOND ARM SPECTROMETER) WORKSHOP

VANCOUVER MARCH 17-18, 1986

Editors: P.L. Walden, TRIUMF M.J. Iqbal, University of Alberta

MESON FACILITY OF:

UNIVERSITY OF ALBERTA SIMON FRASER UNIVERSITY UNIVERSITY OF VICTORIA UNIVERSITY OF BRITISH COLUMBIA

OPERATED UNDER A CONTRIBUTION FROM THE NATIONAL RESEARCH COUNCIL OF CANADA



TRI-86-1

PROCEEDINGS OF THE DASS/SASP (DUAL ARM SPECTROMETER SYSTEM/ SECOND ARM SPECTROMETER) WORKSHOP

VANCOUVER MARCH 17-18, 1986

Editors: P.L. Walden, TRIUMF M.J. Iqbal, University of Alberta

Organized by:	P.L. Walden, TRIUMF
Sponsored by:	Natural Sciences and Engineering Research Council of Canada
	TRIUMF
	TUEC

Postal address:

TRIUMF 4004 Wesbrook Mall Vancouver, B.C. Canada V6T 2A3



PREFACE

The DASS/SASP Workshop was held from March 17-18, 1986 at TRIUMF in Vancouver, British Columbia, Canada. The workshop was organized primarily by P.L. Walden (TRIUMF) with support from other members of the DASS/ SASP task force namely E.G. Auld (University of British Columbia) and C.A. Miller and S. Yen (TRIUMF). Funding for the workshop came from TRIUMF, TUEC, and NSERC (Canada).

Approximately 67 physicists and engineers attended this two day event which consisted of fourteen talks. The twelve main talks are presented in this volume. The objective of the workshop was to discuss the physics that could be done with a dual arm spectrometer system (DASS), which is a proposed nuclear physics facility for TRIUMF. As the TRIUMF physics community is well aware, one arm of this system is already in hand, the MRS. The main effort then of bringing the DASS facility on line is to design and manufacture a second arm spectrometer (SASP).

The hoped-for result of this workshop was to be a series of proposals submitted to the July 1986 session of the Experiments Evaluation Committee which specifically request use of the DASS/SASP facility. This goal was met with 3 proposals being submitted and accepted, all with high priority. The title and spokesman of each accepted proposal is given in Table I. Copies of these proposals are available from either TRIUMF or the spokesman.

EEC No.	Title	Spokesman
416	Neutron knockout with SASP	C.A. Miller TRIUMF
417	Survey of the (p, π^+) reaction in the Δ resonance region	P.L. Walden TRIUMF
418	Nucleon effective polarization in Ca, Zr and Pb	W.J. McDonald U. of Alberta

Table I. Accepted Proposals DASS/SASP.

A secondary goal of the workshop was to target members of the physics community who might be interested in using the DASS/SASP facility once it is finished. To accomplish this a questionnaire was handed out to workshop participants and also by post to a list of experimenters whose background made them likely candidates as users. At present there have been forty-three responses. It is hoped that this list will grow as SASP becomes more of a reality. The questionnaire was worded so as to commit people to expressing a desire to submit proposals if the DASS/SASP facility existed at the present moment. The distribution of interests is shown below in Table II. A complete list of the potential users is given at the end of these proceedings.

1. $(p, 2p)$		27
2. $(p, p'n)$		20
3. $(n,p)/(p,n)$		11
4. (p,π)		17
5. (p,πx)		23
x=p,n,d, etc.		
6. other		3
total manpower	43	

Cable	II.	Potential Manpower Commitments
		to DASS/SASP Programs

The organizers wish to thank all who contributed to the success of the workshop. Special thanks are due to Michael LaBrooy and Krish Thiruchittampalam of the Information Office who assisted in the registration and the video recording of the workshop. Special thanks are also due to Pat Stewart and Maureen White for their secretarial assistance. Finally acknowledgements and thanks must go to Ada Strathdee and Denise Mason for preparing these proceedings.

CONTENTS

	Page
Opening remarks P. Kitching	1
π PRODUCTION PHYSICS	
Pion physics using coincidence experiments G. Walker	4
Prospects for (p,π) physics in the Δ region using the SASP spectrometer P. Walden	13
(p,πx) experiments W. Falk	28
EXPERIMENTAL FACILITIES	
The IUCF/University of Maryland dual spectrometer facility P. Roos	41
DASS/SASP report of the conceptual design E.G. Auld	52
The DASS/SASP data acquisition system G. Ludgate	60
NUCLEON PHYSICS	
Nuclear reactions with intermediate energy protons R. Dymarz	64
<pre>(p,2p) scattering in nuclei W.J. McDonald</pre>	84
Neutron knockout measurements with DASS C.A. Miller	91
<pre>(n,p) and (p,n) reactions at TRIUMF S. Yen</pre>	105
Nuclear medium effects in quasi-free (p,2p) M.J. Iqbal	117
DASS/SASP users list	123



OPENING REMARKS

P. Kitching

TRIUMF, 4004 Wesbrook Mall, Vancouver, B.C., Canada V6T 2A3

Let me begin by welcoming you all to TRIUMF and to the DASS/SASP workshop. I hope that you will find the workshop a useful and productive one, and that those of you who have not visited TRIUMF before have the opportunity to look around the lab and see something of Vancouver.

The major purpose of this workshop for us is to stimulate ideas and proposals for the proposed second arm spectrometer which we are hoping to build here (Fig. 1). Let me now say something about how major projects like this are funded at TRIUMF.

The total annual operating budget is around 30 million Canadian dollars. The major part of that comes as a contribution from the National Research Council of Canada (\$25 million) which covers the operation of the basic TRIUMF facility. Included within this are some funds for building new facilities such as an DASS/SASP project, and I will say a little more about that later. Approximately \$2.5-3 million comes from the individual users, university researchers mainly, who apply to NSERC (the Canadian funding agency for university research) to do experiments at TRIUMF. This represents the money they obtain to do particular experiments at TRIUMF. Foreign users bring in around \$1 million per year from their countries of origin. There is also about \$1 million a year which comes from the four TRIUMF universities, particularly UBC.

So that is essentially the source of the funds. Let me now show you how long-term budget planning is developed. We have a rolling Five-Year Plan which is updated every year but which basically goes five years into the future. This identifies how we plan to spend the money. There are three components to that Plan; the first is the basic facility support and is determined essentially by the National Research Council. It amounts to about two-thirds of the \$25 million; its purpose is to keep the basic facility running. The other two components of the budget are



Fig. 1. Overall elevation view of the SASP (left) and MRS (right) spectrometers.



Fig. 2. Input structure of the Five-Year Plan.

FIVE YEAR PLAN

MAJOR PROJECTS

Increase proton beam intensity factor 3 (unpolarised beam) sound factor 10 (polarised beam) >5,4 Rebuild secondary channels increased meson fluxes (factor 2-3) H- extraction capability necessary for injection into any post accelerator Superconducting muon channel joint project with Japanese Longitudinal polarisation completion of present proton facility Second magnetic spectrometer exploits continuous Triumf beam New detector pion spectrometer ?? LASS

Fig. 3. Current list of projects on the Five-Year Plan.

experimental support (fixed amount, allowing for inflation) which is to provide the support for experiments, e.g. cryogenic targets, electronics, computing and so on, and facility development support. This latter is the money which is to be spent on building new facilities at TRIUMF, such as new beam lines and spectrometers. This fund is also held fixed at just over \$4 million per year.

The Five-Year Plan which indicates how money is to be spent is approved by the Treasury Board upon advice first from the National Research Council, which in turn is advised by the Director. Advice to the Director comes from his advisory committees, the Long-Range Planning Committee and Operating Committee, and by his administrators. Figure 2 The NRC Advisory Board on TRIUMF (ABOT) and the shows the structure. TRIUMF Board of Management must approve the Five-Year Plan but do not usually take an active part in generating it. Figure 3 shows new and continuing projects on the current Five-Year Plan. As you can see the second arm spectrometer is on there but with only a small amount of money to be spent in the coming fiscal year (April 1, 1986-April 1 1987). When we sought the advice of the Long-Range Planning Committee last summer, they gave the second arm spectrometer their endorsement and support, but said that it should have lower priority than completing the upgrade of the present MRS spectrometer. We have taken their advice and that is why the longitudinal polarization project, the last piece of the upgrade of the MRS facility, is intended to be completed before the start of major work on the second arm spectrometer. The TRIUMF Operating Committee considered the Five-Year Plan last fall. It was their feeling that management should urge the proponents of the second arm spectrometer to present experimental proposals which would use the facility to the next meeting of our Experiments Evaluation Committee (EEC). This procedure would enable a realistic evaluation of the scientific case for the facility to be made. A similar procedure was followed for a number of recent proposals for new facilities, most notably for the ISOL project and the charge exchange facility.

This, then, brings us back to the main purpose of this workshop. There is, of course, severe competition for funds at TRIUMF. Without a strong scientific case being made to the EEC the second arm spectrometer project is likely to languish. We need a number of good proposals for the new facility which will be essential. We hope that this workshop will play a major role in stimulating such proposals. The next meeting of the EEC takes place on July 9-11 and the deadline for submitting proposals is June 2.

PION PHYSICS USING COINCIDENCE EXPERIMENTS

G.E. Walker*

Nuclear Theory Center and Physics Department Indiana University, Bloomington, Indiana 47405

ABSTRACT

We briefly review selected inclusive (p,π) experimental results. A two-nucleon model of the (p,π) reaction is discussed. Recent applications of the model indicate it may be useful for interpreting future exclusive $(p,p'\pi)$ experiments. We discuss the advantages of exclusive $(p,p'\pi)$ studies for investigating the role of the Δ isobar in intermediate nuclear reactions. Connections between $(p,p'\pi)$ studies and other exclusive reactions such as $(e,e'\pi)$, $(\pi,\pi'N)$, and $(\pi,2\pi)$ are emphasized.

I. INTRODUCTION

In this discussion we stress the utility of combined studies of exclusive reactions such as (e,e' π), (π , π 'N) and (π , 2π) along with (p,p' π), on which we concentrate, for elucidating the role of the Δ isobar in intermediate energy nuclear reactions. One of the major opportunities afforded by intense-beam-current facilities dedicated to intermediate energy nuclear physics is to study the modifications of the A resonance in the nuclear many-body environment. While significant progress has been made, for example due to the development and application of isobarnuclear models, there is still much to learn. Thus while many of the reactions to be discussed may certainly have implications for quark-nuclear studies or the applications of relativistic quantum field theories, we concentrate on the possible role of the isobar in the reaction description. In the next section we review the basic characteristics of the (p,π) reaction as well as giving an overview of selected (p,π) experimental data near threshold. We also briefly review a microscopic two-nucleon model of the (p,π) reaction. This model includes an intermediate, propagating, interacting Δ and has given reasonable agreement with a recent (p,π) experiment at TRIUMF. Finally in this section we preview some of the possibilities afforded by exclusive (p,p'm) studies near 500 MeV. In Sec. IIIwe discuss other exclusive pion production reactions such as (e,e' π), (π , π 'p) and (π ,2p) data and discuss, in each case, how (p,p' π) data can be very helpful in further testing selected isobar mechanisms suggested as being important for each reaction. In the final section we review our main points regarding isobar studies involving theoretical and experimental work associated with exclusive electron, pion, and protoninduced pion production. Some of the material contained in the discussion below is also discussed in Ref. 1.

II. REVIEW OF PROTON-INDUCED PION PRODUCTION ON COMPLEX NUCLEI

There is considerable experimental data on the (p,π^{\pm}) reaction leading to bound or quasi-bound nuclear states in the proton projectile energy region 150 $\leq T_p \leq 800$ MeV.² Both analyzing power and cross section angular distribution data are available. Proton-induced pion production *Work supported in part by the U.S. National Science Foundation. results in a large momentum transfer $q \gtrsim 2k_F$ (~ 550 MeV/c) to the nucleus. The reaction allows study of a process (pion emission) that plays an important role in binding the nucleus. It also has the possibility of providing wave function and/or reaction mechanism information of interest for other high-momentum transfer medium energy reactions such as (p,γ) and $(e,e^{\cdot}\pi)$. Presently there does not exist a theoretical approach that has been shown to yield quantitative agreement with the wide range of high quality data available. However, the two-nucleon model of Iqbal and Walker³ has recently been shown to give good agreement with experiment for a stretched transition in ${}^{12}C(p,\pi){}^{13}C_{9/2}$ + at T_p^{1ab} = 354 MeV.⁴ The situation is complicated by such effects as a) the importance of multistep processes because of the large momentum transfer to the nucleus - (this may include an important two-nucleon mechanism involving a propagating intermediate Δ with medium corrections), b) relativistic corrections, and c) nuclear structure, distorting potential, and vertex form factor uncertainties at high momentum transfer.

Experimentally, there has been emphasis on energies below ~250 MeV and on targets of 90 Zr or lighter where the density of states is less and distortion effects are relatively reduced. The experimental results to date seem to have considerable lack of systematics (i.e., we have not yet recognized a pattern). In Figs. 1-4 we show some representative data. 5^{-8} In Figs. 1 and 2 a typical excitation function and angular distributions are shown for $T_p \leq 200$ MeV, ${}^{12}C(p,\pi^+){}^{13}C$. The excitation spectrum is apparently composed of "single particle" states [g.s. $(1p_{1/2})$, 3.09 MeV $(2s_{1/2})$, and 3.85 MeV $(d_{5/2})$] and two-particle one-hole (2p-1h) states [such as the 6.86 MeV 5/2⁺ and 9.5 MeV 9/2⁺ states]. Figure 1 illustrates that 2p-lh states can be as strongly excited as single particle states (depending on the nucleus). In the Δ resonance region, the reaction may be more selective, emphasizing 2p-1h stretched states.4 Figure 2 includes several angular distributions exhibiting dips near 90° (perhaps associated with a p wave, $\cos \theta$ dependence). The angular distributions for some single particle and 2p-lh states have the dip structure. The angular distribution associated with the analyzing power sometimes exhibits considerable energy dependence, as shown in Fig. 3.

The (p,π) reaction mechanism may, in fact, be several competing single nucleon and two-nucleon mechanisms. The (p,π^-) reaction is believed to result essentially from a two-nucleon mechanism. Arguments based on a two-nucleon model of the (p,π^-) reaction have resulted in correct predictions of the j dependence of the relative sign of the analyzing power.⁸ Recent studies of the (p,π^-) reaction indicate a selectivity presumably associated with the excitation of high spin 2p-lh states (see Fig. 4).⁹ This is consistent with a two-nucleon mechanism for a large momentum transfer process. This selectivity has been used to tentatively identify states reached via (p,π^-) in heavier nuclei.¹⁰

The first attempts to model the (p,π) reaction involved a DWBA single nucleon stripping model.² The fact that there is only one active nucleon in the model and the process requires evaluation of the final bound nucleon wave function at very high momentum transfer means there is considerable sensitivity to wave function and optical potential parameters. The observed strong excitation of 2p-lh states in the (p,π^{\pm}) reaction and an understanding of the (p,π^{-}) data are not naturally included in this model because such processes naturally involve two active nucleons. In addition it is known that single pion rescattering with an



Fig. 1. An excitation spectrum for the ${}^{12}C(p,\pi^+){}^{13}C$ reaction with 200 MeV incident protons showing the strong excitation both of states assumed to be of a single particle and two-particle hole nature. Figure taken from Ref. 5.



Fig. 2. Selected angular distributions for the ${}^{12}C(p,\pi^+){}^{13}C$ reaction for several incident proton energies. Figure taken from Ref. 6.

6





Fig. 4. An example of (p,π^+) and (p,π^-) showing the greater selectivity of the (p,π^-) reaction for the relative excitation of different states in the same final nucleus. Figure taken from Ref. 9.

Fig. 3. The energy dependence of $A_y(\theta)$ for the reaction ${}^{12}C(\dot{p},\pi^+){}^{13}C_{g.s.}$ for 200-250 MeV incident protons. Figure taken from Ref. 7.

intermediate Δ formation is an important ingredient of theories that fit the two-body NN $\rightarrow d\pi^+$ reaction. Some of this effect can be included in an average way in the many-body environment via pion distortions. One more recent example of a single nucleon mechanism is the <u>relativistic</u> calculation of Cooper and Sherif.¹¹ It may be useful to supplement the two-nucleon mechanism discussed below with a <u>plane wave</u> (to avoid possible double counting) single nucleon mechanism. Two-nucleon mechanism models incorporating Dirac phenomenology seem an especially attractive avenue for future theoretical research.

In the following we briefly summarize the approach we have taken in developing a microscopic two-nucleon model (TNM).³ We show in Fig. 5





Hys

Fig. 5. Some diagrams appearing in a two-nucleon mechanism of pion production. Diagram A (B) is referred to as a target (projectile) emission contribution resulting in intermediate Δ production. Diagrams C and D are nonresonant contributions.



Fig. 6. The differential crosssection contribution arising from projectile and target emission diagrams assuming harmonic oscillator (HO) or Saxon-Woods (SW) single nucleon bound orbitals. Full proton and pion distortions have been included in this TNM calculation. Figure taken from Ref. 3.

some typical (resonant and nonresonant) diagrams associated with the TNM under discussion. We utilize a TNM incorporating an intermediate propagating and interacting delta, virtual pion and rho exchange, and including the effects of realistic external proton and pion distortions. The details of the model, formulae, and calculational procedure are given in The results for a study of the ${}^{12}C(p,\pi^+){}^{13}C(g.s.)$ transition Ref. 3. $(T_p = 250 \text{ MeV})$ indicate that shapes of angular distributions are not qualitatively changed by modest variations in the A-nucleus optical potential, proton and pion optical potentials, and the choice of single particle orbitals (harmonic oscillator or Saxon-Woods). This relative insensitivity means that one can now carry out studies hopefully leading to a better understanding of the reaction mechanism(s) involved in pion pro-Calculations to date have shown that it is important to allow duction. for the propagation of the intermediate Δ and to include the energy transfer component in the intermediate meson propagator.³ The projectile emission piece (for the transition studied, see Fig. 6) dominates over the target emission term for the inclusive reaction. The exclusive $(p,p'\pi)$ reaction, where the momentum transfer to the target can be on the order of the Fermi momentum, may have kinematic regions where the target emission diagram is relatively important. Studies of the predicted relative importance of the target and projectile emission diagrams for various geometries is an important future area of theoretical investigation for the exclusive (p,p^{π}) reaction. This is of significance for comparative studies of (e,e^{π}) and (p,p^{π}) because it is the projectile emission "isobar" term in (p,p^{π}) that is similar to important intermediate Δ contributions to (e,e^{π}) , $(\pi,\pi^{*}p)$ and $(\pi,2\pi)$.

The exclusive $(p,p'\pi)$ reaction allows an exciting extension of the earlier (p,π) studies. By varying the energy and angle of detection of the final coincident particles, a broad range of momentum transfer to the nucleus can occur (from $|\vec{q}| \sim$ Fermi momentum to the GeV/c region). By carrying out broad continuum studies one can minimize the effect of nuclear structure uncertainties. By utilizing Dalitz plots one may be able to isolate the important isobar physics in the exclusive reaction. In this connection experimental studies in kinematic regions where isobar diagrams are predicted to dominate in $(p,p'\pi)$ and $(p,2\pi)$ along with isobar contributions in $(e,e'\pi)$, $(\pi,\pi'p)$ and $(\pi,2\pi)$ should provide useful insights into modifications of the isobar in the many-body environment (as well as the validity or fertility of reaction mechanism models which focus on isobar-hole diagrams).

In the next section we discuss other reactions closely related to the (p,p^{π}) reaction with a focus on using intermediate energy nuclear physics to study isobar formation and propagation in the nuclear environment.

III. RELATION OF (p,p'π) TO OTHER MESON PRODUCTION COINCIDENCE REACTIONS

Pion production using electromagnetic probes should involve an important contribution from an intermediate isobar term when the energy transferred to the hadronic system is approximately $M_{\Delta} - M_{N}$. Thus intermediate energy (γ, π) or $(e, e^{-}\pi)$ reactions are potentially important sources of information on Δ properties and propagation in nuclei. Tiator and Drechsel¹² have made a theoretical study of $(e, e^{-}\pi)$ including the isobar diagram shown in Fig. 7 in addition to the Born terms. They find



Fig. 7. An isobar contribution to the (e,e^{π}) reaction.

that those response structure function contributions to the cross section containing a transverse piece can be appreciably altered by the Δ "exchange current" term. For example they find typical enhancements of factors of two in the (e,e'\pi) cross section for 200 < ω_e < 400 MeV when the isobar terms are included. Although there is insufficient experimental data to test the predictions it is encouraging that there is satisfactory

agreement between the predictions in Ref. 12 and experiment for the reaction ³He(e,³H)e'π⁺. It is possible to arrange the experimental geometry so that the same three-momentum magnitude and energy is carried by the virtual boson [meson for (p,p'π), photon for (e,e'π)] leading to intermediate isobar formation for the projectile emission term in (p,p'π) and the isobar term in (e,e'π). An example is $T_e ~ T_p ~ 500$ MeV with projectile energy loss of ~200 MeV and $\theta_p^{\text{scat}} \simeq 1/5 \ \theta_e^{\text{scat}} ~ 10^\circ$. Detailed comparative studies of the (e,e'π) and (p,p'π) reactions in the continuum region where nuclear details are less important should be useful for Δ formation and propagation studies.

The $(\pi,\pi'p)$ reaction has already been useful in detailed studies of nuclear isobars. The simple application of the distorted wave impulse approximation for studies of quasi-elastic (π,π') has already been shown to be inadequate. There exists considerable theoretical research on the changes in the πN interaction due to the nuclear medium. Of special importance is the development of the isobar-hole model.¹³ Thies¹⁴ has shown, using the isobar-hole model, that below the resonance medium effects significantly reduce the πN interaction in the medium compared to the free space πN t matrix. Above the resonance the situation is reversed. The isobar-hole model, including these effects, yields much better agreement with quasi-elastic scattering data¹⁵ than prediction using the free space πN interaction.

The exclusive (π^+,π^+p) and (π^-,π^-p) reactions have been useful in demonstrating the limits of the first-order isobar-models.^{16,17} Large deviations from the predicted ratio of (π^+,π^+p) are observed in the small angle cross-section data for p-shell nucleon removal in ${}^{16}O(\pi,\pi^+p){}^{15}N$. Significant enhancements (reductions) are required to fit the ratios near (away) from the maximum of the π^+ cross-section data. There may be an additional term that interferes with the diagram included in the lowest-order isobar-hole calculation.^{17,18} One possible term, see Fig. 8(a,b), involves a second-order process where the intermediate Δ

N,

n (N2)

N₂

D(N.)



Fig. 8. (a) A second-order contribution to $(\pi,\pi'N)$; (b) A lowest-order contribution to $(\pi,\pi'N)$; (c) A similar contribution to (a) that should be important in $(p,\pi^{-}n)$. The exclusive $(\pi, 2\pi)$ reaction has already been the subject of several theoretical investigations.¹⁹⁻²³ One can expect experimental information on this reaction to substantially increase in the near future. An early DWIA investigation²⁰ stressed the sensitivity of $(\pi, 2\pi)$ cross sections to the nuclear spin-isospin Migdal parameter g'. A more detailed treatment²¹ of the elementary $\pi N \rightarrow \pi\pi N$ amplitude results in a substantial increase (~4 times) for the total $(\pi, 2\pi)$ cross section on free protons compared to that found in Ref. 20. For our purposes it is important to note that there exists an additional contribution to the $(\pi, 2\pi)$ amplitude

in nuclei. This contribution involves pion absorption on one nucleon leading to an intermediate Δ which by a subsequent $\Delta N \rightarrow \Delta \Delta$ interaction leads to double Δ formation.²² The two observed pions in $(\pi, 2\pi)$ could be produced in this mechanism via a $2\Delta 2N \rightarrow 4N2\pi$ or 2Δ \rightarrow 2N2 π mechanism. It has been predicted²³ that the ratio $R \equiv (\sigma(\pi^-, \pi^+\pi^-)/$ $\sigma(\pi^-,\pi^-\pi^-)$ is decreased by more than a factor of two, in the energy region $T_{\pi} \sim 300-400$ MeV, by the inclusion of the $\Delta\Delta$ mechanism. It appears that this reaction is sensitive to a variety of interesting effects associated with pions²⁴ and virtual intermediate Δ 's propagating in the nuclear medium. From our perspective an interesting feature is the connection between, as an example, the $(\pi, 2\pi)$ contribution shown in Fig. 9(a) and the $(p, 2\pi)$ diagram given in Fig. 9(c). Note that for the $(p,\pi^-\pi^-)$ reaction Fig. 9(b) cannot contribute. Note also that there is an interesting connection between $(p,2\pi)$ and $(e,2\pi)$.



Fig. 9. (a) A double isobar contributor to $(\pi, 2\pi)$. (b),(c) Contributions to $(p, 2\pi)$.

IV. SUMMARY

The proton-induced meson production coincidence experiments $(p, p'\pi)$ and $(p, 2\pi)$ have a close connection with coincidence experiments utilizing electron and pion projectiles such as (e,e' π), (e,2 π), (π , π 'N), and $(\pi, 2\pi)$. In this talk we have drawn selected diagrams to make this connection manifest. We have stressed the utility of combined coincidence studies in studying the role of isobars in intermediate nuclear reactions. There is the possibility that using the Dalitz plot technique one can determine whether a final coincidence nucleon and pion originated from a virtual isobar. The first job for experiment and theory is to determine whether, in fact, an isobar dominated two-nucleon mechanism is an adequate representation of the $(p, p'\pi)$ process. In this talk we briefly reviewed a microscopic two-nucleon model that has had some recent success in describing the inclusive (p,π) reaction near the resonance region. It is important to use models of this type supplemented with existing information from the isobar-hole model to theoretically study the $(p, p'\pi)$ reaction so that some guidance can be provided for experimentalists

planning concidence experiments. Our theoretical group at Indiana is in the process of developing the tools to make such initial theoretical (p,p^{π}) studies.

REFERENCES

- G.E. Walker, "Nuclear Physics Investigations using Medium Energy Coincidence Experiments". Lectures given at the NATO Advanced Study Institute on New Vistas in Electro-Nuclear Physics, Aug. 22-Sept. 4, 1985, Banff, Alberta, Canada (Institute Proceedings to be published by Plenum Press).
- 2. Some recent reviews of the experimental and theoretical situation include D.F. Measday and G.A. Miller, Annu. Rev. Nucl. Part. Sci. 29, 121 (1979); B. Hoistad, Adv. Nucl. Phys. 11, 135 (1979); H.W. Fearing, Prog. Part. Nucl. Phys. 7, 113 (1981), Pion Production and Absorption in Nuclei 1981, AIP Conf. Proc. No. 79, edited by R.D. Bent (AIP, New York, 1981); G.E. Walker, Comments Nucl. Part. Phys. All, 155 (1983).
- 3. M.J. Iqbal and G.E. Walker, Phys. Rev. C 32, 556 (1985).
- 4. G.M. Huber et al., submitted to Phys. Rev. Lett., March 1986.
- 5. F. Soga et al., Phys. Rev. C 22, 1348 (1980).
- 6. F. Soga et al., Phys. Rev. C 24, 570 (1981).
- 7. G.J. Lolos et al., Phys. Rev. C 25, 1086 (1982).
- 8. W.W. Jacobs et al., Phys. Rev. Lett. 49, 855 (1982).
- 9. S.E. Vigdor et al., Nucl. Phys. A396, 61c (1983).
- 10. M.C. Green et al., Phys. Rev. Lett. 53, 1893 (1984).
- 11. E.D. Cooper and H.S. Sherif, Phys. Rev. C 26, 3024 (1982).
- 12. L. Tiator and D. Drechsel, Nucl. Phys. A360, 208 (1981).
- M. Hirata, F. Lenz and K. Yazaki, Ann. Phys. 108, 116 (1977);
 M. Hirata et al., Ann. Phys. 120, 205 (1979);
 - Y. Horikawa, M. Thies and F. Lenz, Nucl. Phys. A345, 386 (1980)
 - F. Lenz, Spin Excitations in Nuclei, eds. F. Petrovitch et al. (Plenum, New York, 1984), p. 267.
- 14. M. Thies, Nucl. Phys. A382, 434 (1982).
- M. Baumgartner et al., Phys. Lett. 112B, 35 (1982);
 C.H.Q. Ingram et al., Phys. Rev. C 27, 1578 (1983).
- 16. E. Piasetzky et al., Phys. Rev. C 25, 2687 (1982).
- 17. G.S. Kyle et al., Phys. Rev. Lett. 52, 974 (1984).
- 18. M. Hirata, F. Lenz, and M. Thies, Phys. Rev. C 28, 785 (1983).
- 19. R. Rockmore, Phys. Rev. C 11, 1953 (1975).
- 20. J. Cohen and J.M. Eisenberg, Nucl. Phys. A395, 389 (1983).
- 21. R.S. Bhalerao et al., Phys. Rev. C 30, 224 (1984).
- 22. G.E. Brown, Phys. Lett. 118B, 39 (1982);
- B. Schwesinger et al., Phys. Lett. 132B, 269 (1983).
- 23. L.C. Liu (private communication).
- 24. E. Oset and M.J. Vicente-Vacas, Univ. of Illinois preprint 170 (1985).

PROSPECTS FOR (p,π) PHYSICS IN THE \triangle REGION USING THE SASP SPECTROMETER

P.L. Walden

TRIUMF, 4004 Wesbrook Mall, Vancouver, B.C., Canada V6T 2A3

ABSTRACT

The present experimental status of the (p,π) reaction is reviewed and interpreted within the framework of a NN \rightarrow NN π process. Reasons are given as to why (p,π) measurements in the Δ region (200 MeV $\langle T_p \langle$ 500 MeV) would yield new insights into the reaction mechanism. Several initial (p,π) experiments using the SASP spectrometer are suggested.

1. PRESENT STATUS OF (p, π^{-})

One of the initial experiments run on the QQSP spectrometer at IUCF was a survey of the (p,π^-) reaction with various nuclear targets at 200 MeV. The results of this survey revealed the previously unsuspected systematic of the final state nucleus preferring to be in a high-spin two-particle one-hole excitation with respect to the initial state nucleus.¹ Partial results of this survey are shown in Fig. 1. The feature to note is the concentration of the (p,π^-) strength into one or a few discrete levels near 3-7 MeV excitation. This concentration appears to be strongest for targets where a j> neutron subshell has just been filled and the corresponding p subshell is empty. The clue that these states are stretched two-particle one-hole high-spin states came from the



Fig. 1. Energy spectra from the (p,π^-) reaction on several targets showing the strong selectivity described in the text. The spectra were taken on the QQSP at IUCF at $\theta_{1ab} \sim 30^\circ$.



Fig. 2. A graphic illustration of an A(p, π)A+1 process in which the subprocess NN \rightarrow NN π dominates. The directions of the initial nucleon i and the final state nucleons f are shown for minimum momentum transfer. The π is produced on the near side of the nucleus due to absorption.

 $^{18}O(p,\pi^{-})^{17}Ne$ reaction where the resultant state at 4.6 MeV was identified with a 2p-lh level of $J^{p} = (13/2)^{-}$.

This survey illustrates two basic merits of doing such experiments. This is especially true of surveys which probe new physics with new instruments. First, there is not a great need to justify the experiment beforehand with detailed predictions from sophisticated theories. The predictions would probably be wrong anyway. Second, the discoveries revealed in the survey are usually unexpected and usually shed light towards the correct formulation of the theory.

In the case of the QQSP survey, the light pointed to a possible NN \rightarrow NN π dominance being the driving mechanism behind the (p,π) reaction. This dominance would explain in a natural way the preference for (p,π^-) to go into 2p-lh final states, and the large momentum transfers associated with the (p,π) reaction would also explain a preference for final high-spin configurations.

This process was best described by Vigdor² using an illustration similar to the one shown in Fig. 2. It is assumed that the pion is produced on the near side of the nucleus with respect to a pion detector because of the preferential absorption on π 's produced on the far side of the nucleus. This means that pion production is a peripheral process associated with an impact parameter "b". In order to share the momentum transfer equally between the three nucleons involved the initial state nucleon must be headed towards the beam proton with momentum " P_i ", and the two final state nucleons must be headed along the direction of the beam proton with momentum " P_f ". With this directional constraint all three nucleons can have momenta which are close to the fermi level. Notice that for the (p,π) exclusive reaction the π has the highest possible energy which then constrains the relative momentum between the final state nucleons to be minimal. The angular momentum transfer is given by the equation:

$$\Delta J = |\vec{b} \times (\vec{P}_{f} - \vec{P}_{i})| + |\vec{s}_{f} - \vec{s}_{i}|$$
(1)

where " \vec{S}_i " and " \vec{S}_f " are the initial and final total spin projections of the reacting nucleons normal to the reaction plane. Note that for maximal angular momentum transfer " \vec{S}_i " should be aligned with the initial orbital angular momentum " $\vec{b} \times \vec{P}_i$ " (i.e., a reaction via j> subshell is preferred). Thus it should be well noted that the kinematics of the (p, π) reaction, if NN \rightarrow NN π dominance is envoked, severely constrains the directionality of the interacting nucleons, and peripherality along with large momentum transfer impart a large angular momentum kick to the final state nucleus.

It is proposed that NN \rightarrow NN π dominance also plays a major role in (p,π^+) , but this process is masked by the many reaction routes available for (p,π^+) to single-particle excitations, so that the dominance of the 2p-lh high-spin states over other transitions is not apparent. This is easily seen by the fact that (p,π^+) can proceed via $pp \rightarrow pn\pi^+$, or $pn \rightarrow nn\pi^+$, both of which can have the initial nucleon hole filled by a final state nucleon. Thus the initial nucleon orbital is not unique, and all orbitals can contribute to a single particle excitation. On the other hand 2p-lh transitions because of the creation of a hole can have only one initial state orbital contributing. It is to be noted that (p,π^-) is forced to create a hole because this reaction can only proceed via $pn \rightarrow pp\pi^-$ in which the final state protons cannot fill up the neutron hole. If NN \rightarrow NN π dominance is the reaction mechanism for (p,π) , then (p,π^-) has some clear advantages over (p,π^+) in gaining understanding about the reaction mechanism itself.

There are several substantiating pieces of evidence to back up this picture of NN \rightarrow NNm dominance, all of which come from the results using



the QQSP. The first piece of evidence comes from a theoretical model of Brown et al.³ They essentially predicted the relative strengths of the final state transitions from (p,π^{-}) on $(vlf_{7/2})$ subshell targets. The model used is basically simple, a plane wave zero-range reaction model combining 2-proton stripping with 1-neutron pickup (the basic ingredients of the NN \rightarrow NN π process). The success of this model is shown in Fig. 3, where the relative strengths of predicted final states are shown against the experimental evidence. The cases shown have varying amounts of $(\pi lf_{7/2})$ and (vlf_{7/2}) subshell fullness. For the results desired, the model succeeds remarkably well.

Fig. 3. Comparison of the experimental (p,π^-) cross sections with the calculated relative cross sections of Brown et al. for $T_p = 206$ MeV and $\theta_{1ab} = 30^\circ$.

A simple-minded corollary to Brown et al. would have the relative dominant 2p-lh strengths on different nuclear targets with the same interacting nuclear shell to be in the ratio of where F_{ν} is the number of neutrons in the subshell, E_{π} is the number of proton holes in the subshell, and 1 and 2 refer to the two different targets. For example in Fig. 1, the relative strength of ${}^{42}\text{Ca}(p,\pi^{-}){}^{43}\text{Ti}$ vs. ${}^{48}\text{Ca}(p,\pi^{-}){}^{49}\text{Ti}$ from (2) should be 1:4, and of ${}^{89}\text{Y}(p,\pi^{-}){}^{90}\text{Nb}$ vs. ${}^{90}\text{Zr}(p,\pi^{-}){}^{91}\text{Mo}$ should be 1:1. This is very close to being quantitatively correct.

The second piece of evidence comes from the study of the analyzing powers of the $^{12,13,14}C(p,\pi^-)^{13,14,15}O(g.s.)$ reactions.⁴ Here the final two protons from $pn \neq pp\pi^-$ are stuck into and fill the $(\pi l p_{1/2})$ subshell for all of the reactions. Thus it can be argued on the basis of fermion statistics that the final two protons are in a relative $^{1}S_{0}$ state. A simple analysis of $pn \neq pp\pi^-$ with this final state restriction requires the initial pn state to be in a spin triplet. The neutron subshells affected in these reactions are the $lp_{3/2}$ subshell in the case of ^{12}C and



the $lp_{1/2}$ subshell in the case of ^{13}C and ^{14}C . Referring back to Fig. 2, a $lp_{3/2}$ target would require \dot{S}_i to be pointing out of the page whereas a $lp_{1/2}$ target would require \dot{S}_i to be pointing into the page. In other words the nuclear target is effectively polarized. Coupling this fact with the requirement of an initial NN triplet state would predict that the analyzing powers between the ^{12}C and $^{13,14}C$ targets be equal and opposite. This simple prediction is dramatically substantiated by the experimental result shown in Fig. 4.

Fig. 4. The analysing powers and cross sections for the 12,13,14 C(p, π^{-})13,14,150 reactions. Note the polarity reversal mentioned in the text.

Vigdor² has argued that the preceding result can only be understood in the light of a NN \rightarrow NNm hypothesis. However, even though a polarity reversal is predicted, a strict application of the visual argument using Fig. 2 would require a reversal of the observed analyzing power signs shown in Fig. 4 (i.e. A_{no} for ${}^{12}C(p,\pi^{-}){}^{13}O$ should be positive and vice versa). This minor problem appears to be more substantial than a breakdown of a simple visual model. A sophisticated two-nucleon code for (p,π) reactions by Bent, Dillig, and Conte⁵ "ORCHID" predicts analyzing powers with the wrong signs as well. This failure to get the signs right is disconcerting especially in the light of other substantiating NN \rightarrow NNm evidence. It would be gratifying to have an explanation.

This failure is all the more puzzling because another visual model by Toki and Kubo,⁶ which is a third piece of evidence supporting a



Fig. 5. Analyzing powers for (p,π^-) into stretched 2p-lh highspin states. The solid line is a prediction from Ref. 6 based on a pn + pp(${}^{1}S_{0}$) π^{-} subprocess.

 $NN \rightarrow NN\pi$ hypothesis, gets the sign correct. Analyzing powers from (p, π^-) to stretched 2p-lh high-spin states7 shown in Fig. 5 show a generally positive sign pattern which is remarkably insensitive to the target mass. Toki and Kubo have argued, as was pointed out previously in describing Fig. 2, that the kinematics of (p,π) and the NN \rightarrow NN π hypothesis leave very little relative kinetic energy between the final state nucleons. This would favour the final state nucleons being in a relative ${}^{1}S_{n}$ state. Notice that this is the exact same requirement used to predict the A_{no} sign change for (p,π^-) on C targets going to 0 ground states. The analysis is therefore identical. For the example shown in Fig. 5, all targets involve a neutron from an initial j> subshell which requires S_1 in Fig. 2 to be aligned with the orbital angular momentum, $b \times P_i$, (i.e., \hat{S}_i points out of the page). The requirement of an initial triplet NN state requires the spin of the beam particle to be aligned with \hat{S}_i as well. This gives a positive Ano. Toki and Kudo's result is plotted as the solid line in Fig. 5. The curve is generated simply by the preferential absorption of π 's from different sides of the nucleus as a function of angle. The result is qualitatively correct. However, this success has been tempered somewhat by Vigdor⁸ who pointed out the sign reversal problem described above using the same model.

II. PRESENT STATUS OF (p, π^+)

In spite of a small problem of a sign reversal in one particular case, the qualitative evidence supporting NN \rightarrow NN π dominance in (p, π ⁻) reactions is nevertheless impressive. However, a successful sophisticated theory of the (p, π) reaction does not yet exist. There are two new

explicit 2-nucleon codes^{9,10} and a revamped 1-nucleon code using a delta-hole model¹¹ now in existence. None of these codes have yet been adequately tested as they all require the simplification of delta excitation to produce π 's which should be the dominating π production process in the 200 MeV $\langle T_p \langle 500 \text{ MeV energy range}$. Unfortunately not much data presently exist in this energy regime. It turns out that when data from this regime are finally forthcoming in sufficient quantity it will probably be better to compare the theories to (p,π^+) data in spite of the advantages inherent in the (p,π^-) reaction.

The disadvantages of using (p,π^+) to test reaction mechanisms compared to (p,π^-) has perhaps been overstated. A look at an excitation spectrum of ${}^{12}C(p,\pi^+){}^{13}C$ at 354 MeV (Fig. 6a) 12 reveals a dominant stretched 2p-1h high-spin 9/2⁺ state at 9.5 MeV. Similar pictures exist for two other (p,π^+) reactions; ${}^{13}C(p,\pi^+){}^{14}C$ at 354 MeV (Fig. 6b) 13 reveals a 5⁻ state at 14.87 MeV, 14 and ${}^{16}O(p,\pi^+){}^{17}O$ at 800 MeV 15 reveals a 11/2⁻ state at 7.75 MeV. Figures 6a and 6b are data from TRIUMF's MRS spectrometer and Fig. 6 is from the HRS at LAMPF. The point to notice about these figures is that the appearance of the spectra is similar to those of (p,π^-) at lower energies.

It seems that as the energy increases for fixed angle or equivalently as the momentum transfer increases, the (p,π^+) spectra take on the appearance of the (p,π^-) spectra observed at 200 MeV. In fact an analysis¹⁶ of the (p,π^+) reaction in the region of 200 MeV $\langle T_p \langle 260 MeV$ using the "Resolution" spectrometer data¹⁶ from TRIUMF reveals a global tendency for the differential cross section to have a simple statistical 2J+1 weighting for all states. This means that the reaction mechanism drives the final state into the state of highest possible angular momentum. These states just happen to be the stretched 2p-1h high-spin states mentioned previously.

The similarity of the (p,π^+) and (p,π^-) spectra warrants closer examination. The creation of a 2p-lh state via (p,π^+) can uniquely determine the initial nucleon subshell just as well as (p,π^-) . The problem with (p,π^+) is that it can go via two NN + NN π processes to (p,π^-) 's one $(pp + pn\pi^+ and pn + pn\pi^+ to pn + pp\pi^-)$. However, if one assumes that the NN + NN π process is dominated by intermediate Δ formation [NN + Δ N + NN π] for T_p > 200 MeV, the number of reactions can be effectively reduced to one, the pp + pn π^+ reaction. In fact this assumption further requires the final pn state to be in a relative T=0 3S_1 state. This state has the same quantum numbers as the deuteron. Thus the (p,π^+) reaction can be just as specific as the (p,π^-) reaction, and furthermore it has a fundamental pp + $d\pi^+$ reaction which is easy to measure experimentally.

To demonstrate this above claim we must again use the fact that the $A(p,\pi)A+1$ reaction and NN \rightarrow NN π dominance leave very little relative kinetic energy between the final state nuclear nucleons. Thus it is most probable that the final state nucleons are in a relative S-state, and this is what will be assumed. Next we consider the simplest intermediate ΔN state that can be created from an initial NN state, that of a ΔN in a relative S-wave. This state can have T=2, or 1 with $J_p = 2^+$, or 1⁺. It is impossible to reach T=2 from NN, so that the intermediate Δ amplitudes must have T=1. A $J_p = 1^+$ state can only be constructed from ${}^{3}S_1$ which is disallowed for pp by the Pauli principle. Furthermore the extended Pauli principle requires a ${}^{3}S_1$ NN state to have T=0 which cannot couple to an intermediate ΔN . Hence a ΔN S state can only couple to a T=1,



Fig. 6. Samples of A(p, π^+)A+1 spectra showing the dominance of 2p-1h high-spin states. (a) ${}^{12}C(p,\pi^+){}^{13}C$ (TRIUMF); (b) ${}^{13}C(p,\pi^+){}^{14}C$ (TRIUMF); (c) ${}^{16}O(p,\pi^+){}^{17}O$ (LAMPF).

a)

Ъ)

c)

 $J^{p} = 2^{+}$ initial NN amplitude. Note that this amplitude has natural parity. If the final state nucleons are in a T=1, ${}^{1}S_{0}$ state, only the unnatural parity amplitudes of 0⁻, 1⁺, 2⁻, ... are accessible to the final $\pi(NN)$ state because of the negative intrinsic parity of the π . Thus a T=1 final NN state cannot couple to a 2⁺ ΔN S state. The only NN \rightarrow NN π transition allowed under the above assumptions is a pp \rightarrow pn π^{+} reaction with the initial pp state in a ${}^{1}D_{2}$ singlet and the final pn in a T=0 ${}^{3}S$, triplet.

The analysis of the preceding paragraph is a restatement of the well-known fact that the ${}^{1}D_{2}[p-p] \rightarrow {}^{3}P_{1}[\pi-pn({}^{3}S_{1})]$ amplitude is by far the dominant amplitude for $pp \rightarrow d\pi^{+}$ in the delta region.¹⁷ It should be noted here that not only does the ΔN S-state amplitude, the ${}^{1}D_{2}$, only couple to $pp \rightarrow pn({}^{3}S_{1})\pi^{+}$ but also the dominant ΔN p-state amplitude, the ${}^{3}F_{3}$, only couple to $pp \rightarrow pn({}^{3}S_{1})\pi^{+}$ as well. The ${}^{3}F_{3}$ also has natural spin parity and thus cannot couple to T=1 final NN states. Hence the strongest Δ effects to be found in (p,π) above $T_{p} = 200$ MeV should be found in (p,π^{+}) , not (p,π^{-}) .



Fig. 7. Cross sections and analysing powers of the $pp \rightarrow pn\pi^+$ reaction at 450 MeV as a function of the pion kinetic energy. All quantities are in the laboratory frame. Vertical arrows indicate the pion threshold energies for the $pp \rightarrow pn\pi^+$ reaction. The solid curves are the analysing powers for the $pp \rightarrow d\pi^+$ reaction at the equivalent free energy E_F and 4-momentum transfer t. Experimental values of the $pp \rightarrow d\pi^+$ reaction at the corresponding angles are indicated by filled squares.

There is some experimental evidence to back up the above analysis. Figure 7 (Ref. 18) shows the analysing power " A_{no} " of the pp \rightarrow pn π^+ reaction. It is interesting to note that the A_{no} predicted from pp \rightarrow d π^+ data^{19,20} (solid line) matches that of the 3-body final state up to, in one case,40 MeV excitation of the pn system. This would suggest that the final state pn has a strong preference to be in a ${}^{3}S_{1}$ state. This result is in agreement with the assumption that a relative S state dominates the final NN pair in (p,π) .

Another piece of evidence to support this S state dominance comes from measuring the A_{no} of the ${}^{12}C(p,\pi^+)X$ reaction.²¹ The results are shown in Fig. 8. The predictions (solid line) are based on a pp +



Fig. 8. Cross sections and analysing powers of the ${}^{12}C(p, \pi^+)X$ reaction at 450 MeV. All quantities given are in the laboratory frame. The solid curves are the prediction from a plane wave ${}^{12}C(p, \pi^+pn({}^{3}S_1)){}^{11}B$ model with a pp $\rightarrow \pi^+({}^{3}S_1)$ subprocess. The calculated cross sections were multiplied by the factor indicated on each curve prior to plotting.

 $pn({}^{3}S_{1})\pi^{+}$ knock-out model for the reaction mechanism using measured pp + $d\pi^{+}$ data^{19,20} as input. The model is very naive and even uses plane waves. At small π angles where the use of plane waves should have the least effect the predicted A_{no} 's are in excellent agreement with the data. The shape of the cross section seems to be correctly calculated as well. At larger π angles the data fall below the prediction, but this could be the effect of using plane waves. Distorted waves would reduce the effective π angle and hence predict a more negative A_{no} . The results in Fig. 10 not only support the conjecture of S state dominance but also of NN \rightarrow NN π dominance of (p,π) as well.

A similar experimental result to Ref. 21 has been gathered from $^{13}\text{C}(p,\pi^+)^{14}\text{C}$ data²² at T_p = 200 MeV. The A_{no} has been plotted (Fig. 9) for $^{14}\text{C}(\text{Ex}{\sim}20$ MeV) which is in the continuum. The data show a strong similarity to the pp \rightarrow d\pi^+ A_{no} at an equivalent energy. Figure 9 also shows the A_{no} for $^{13}\text{C}(p,\pi^-)^{14}\text{O}(\text{Ex}{\sim}20$ MeV) as well. The conjecture, based on the (p,π^+) example, is that this A_{no} may reflect the A_{no} for the underlying pn \rightarrow pp(^{15}O) π^- process.

There is one more piece of supportive evidence which will bring us back to Fig. 2 and stretched 2p-lh high-spin states again. For the Ano of ${}^{12}C(p,\pi^+){}^{13}C(9.5 \text{ MeV},9/2^+)$ the data²³ show between 216 MeV $< T_p < 250 \text{ MeV}$ the behaviour plotted in Fig. 10. For comparison the pp $+ d\pi^+ A_{no}{}^{19,20}$ at an equivalent energy and identical 4-momentum transfer "t" are plotted as well. Note that the position of the peaks, dips and cross-overs between the fundamental NN $+ NN\pi$ process and the nuclear reaction are identical, but in the nuclear case the peaks and dips are enhanced. This feature could possibly have a simple explanation similar to the one given by Toki and Kubo⁶ and in Ref. 4. The ${}^{13}C(9.5 \text{ MeV},9/2^+)$ has a stretched configuration of $[\pi p_{3/2})^{-1}(\pi p_{1/2})^1](2^+)(vd_{5/2})^1$ so that



Fig. 9. Continuum analysing power distributions for ${}^{13}C(p,\pi^+)$ and ${}^{13}C(p,\pi^-)$. The A_{no} distribution for near-threshold pp+d π^+ , after tranformation to the nucleonnucleus frame is shown for comparison.



Fig. 10. The analysing power of ${}^{12}C(p,\pi^+){}^{13}C$ to the stretched 2p-1h state at 9.5 MeV and $J^P = 9/2^+$. The changes in A_{no} between beam energies 216 and 250 MeV are shown. The pp $\neq d\pi^+ A_{no}$ at the same equivalent free energy E_F and identical 4-momentum transfer are shown for comparison.

the target proton comes from the $P_{3/2}$ shell which requires \dot{S}_i to point out of the page (see Fig. 2). Since the intermediate Δ amplitude goes mostly via 1D_2 , a singlet, the incoming beam particle is required to have its spin pointing in the opposite direction which is into the page. The predicted A_{no} can then be as much as -1 which is close to what is observed at $T_p < 216$ MeV. Above this energy the 3F_3 and other partial amplitudes start to play a significant role in pp + $d\pi^+$ so that the predicted result is harder to ascertain without requiring a detailed calculation. However, the general features of the pp + $d\pi^+ A_{no}$ are still apparent at 250 MeV and it would be interesting to follow the energy behaviour of A_{no} to higher energies to see if this trend is followed.

If the above analysis holds correct, then the enhancement observed in the A_{no} of (p,π) is a detection of a spin-orbit coupling effect. Such an effect has been detected before in (p,2p) reactions²⁴ where the two final protons have been kinematically selected just to produce a kinematical configuration similar to the one shown in Fig. 2. However, the (p,π) reaction produces such a configuration naturally.

In summary, then, the (p,π^+) reaction can prove to be just as effective a probe for studying the reaction mechanism as the (p,π^-) reaction.

III. FUTURE PROSPECTS FOR (p, π)

It should be clear by now that in the light of the NN \rightarrow NN π hypothesis the (p,π) is a strongly directional and spin sensitive reaction. Hence the analysing power, A_{no} , can play a significant role in the interpretation of the data. For future progress in this field, spin sensitive measurements like A_{no} should always be measured, if possible, in addition to the usual cross section.

Also progress in this field will come where results can be compared to theory. As it was stated in Sec. II, these theories^{9,10,11} are expected to be most valid in the delta region 200 MeV $\langle T_p \langle 500$ MeV. There is a need for such data as not much currently exists and for reasons discussed in Sec. II, it should be (p, π^+) data. Figure 11 showing preliminary data from TRIUMF¹³ indicates as it was conjectured that (p, π^-) will be weak in the delta region. The (p, π^+) reactions for q = 600 MeV/c momentum transfer show clearly a peak at the expected delta resonance, ~350 MeV, whereas the (p, π^-) reactions show a falling cross section. What little data exist at 350 MeV¹² compares favourably to the theory of Iqbal and Walker.⁹ Figure 12 shows the cross section for the



Fig. 11. Preliminary results from E234 at TRIUMF. $q_{cm} \sim 572$ MeV/c. The 200 MeV data is from IUCF. For (p, π^+) , the reactions are o ${}^{13}C(p, \pi^+){}^{14}C(6.73; 3^-)$, and • ${}^{13}C(p, \pi^+){}^{14}C(11.67; 4^-)$. For (p, π^-) , the reaction is ${}^{13}C(p, \pi^-)$ ${}^{14}O(6.27; 3^-)$.



 $^{12}C(p,\pi^+)^{13}C$ reaction to the $9/2^+$ 2p-1h state at 9.5 MeV against the theoretical result. In view of this result, it is at present unfortunate that there are no analyzing power results either from experiment or from theory.

A plea should be made here for a continuing analogy of (p,π) with (p,2p) with regards to spin-orbit effects. The (p,2p) predictions use the fundamental pp elastic reaction partial wave analysis as input into a DWIA model.²⁴ The (p,π) theories, in contrast, are all built up from first principles. Seeing the difficulties "first principles" have with just pp + $d\pi^+$ (Ref. 17), it would seem a herculean task for theory to get $A(p,\pi)A+1$ even partially correct. Since $pp + pn({}^{3}S_{1})\pi^{+}$ could be the dominant fundamental (p,π^{+}) process in the delta region, as previously shown, it seems reasonable that a DWIA model using $pp + d\pi^{+}$ as input could succeed. This is all the more true as an adequate partial wave analysis of $pp + d\pi^{+}$ now exists.²⁵

It now comes to the time to discuss what (p,π) experiments in the energy region of 200 MeV $\langle T_p \langle 500 \text{ MeV}$ should be run on a spectrometer with a large solid angle such as the proposed SASP instrument. To return to the example of the QQSP at IUCF, the first experiment should be a survey, but this time with the (p,π^+) reaction. Although it is necessary to use some guidance from theory, experience should teach us to expect surprises with the (p,π) reaction, and hence some sort of blanket coverage of the field should be undertaken. The value of the SASP instrument would be that because of the large solid angle a reasonable survey could be completed in a reasonable time.

Thus for the first experiment, complete angular distributions of $d\sigma/d\Omega$ and A_{no} should be measured on many nuclear targets as a function of energy between 200 MeV < T_p < 500 MeV. The first targets chosen should be nuclei that have just filled a proton subshell such as:

1. ${}^{12}C$ ${}^{1P_{3/2}}$ $j_>$, 2. ${}^{16}O$ ${}^{1P_{1/2}}$ $j_<$, 3. ${}^{28}Si$ ${}^{1D_{5/2}}$ $j_>$, 4. ${}^{32}S$ ${}^{2S_{1/2}}$, and 5. ${}^{40}Ca$ ${}^{1D_{3/2}}$ $j_<$.

The targets have been chosen to exploit possible spin-orbit coupling effect between the j> and the j< subshells. The ³²S target should be interesting because the $2S_{1/2}$ shell should exhibit no spin-orbit effects. As an indication of such spin-orbit effects to be seen, there are some old data²⁶ on ${}^{16}O(p,\pi^+){}^{17}O$ which show a striking difference in A_{no} between the ${}^{17}O(g.s.)$ and the 0.87 1/2⁺ state (Fig. 13). One can conjecture that in the former case the reaction route is predominately from the $1p_{3/2}$ shell which enhances the normal pp $\rightarrow pn({}^{3}S_{1})\pi^{+} A_{no}$ whereas in the latter case the reaction route is predominately from the $1p_{1/2}$ shell which de-enhances the normal A_{no} giving the flat A_{no} .

Another feature that should be looked for in this survey is the excitation of very narrow highly excited states ($E_x > 20$ MeV) that have so far been seen in (p,π^+) on ¹²C and ¹³C.^{13,14} The ¹³C example is clearly shown at 23.6 MeV in Fig. 6b.¹³ At 200 MeV both known states have been shown to have almost identical cross sections²⁷ and A_{no}^{27} (Fig. 14). The amazing feature of the A_{no} is that they are zero, a surprising contrast to the negative A_{no} in the continuum around it



Fig. 13. Cross sections and analysing powers for ${}^{16}O(p,\pi^+){}^{17}O$ reaction at near-threshold energies. Data for the ground state $(5/2^+)$ and the first excited (0.87 MeV, $1/2^+$) are shown.



Fig. 14. Cross sections and analysing powers for ${}^{12}C(p,\pi^+){}^{13}C$ and ${}^{13}C(p,\pi^+){}^{14}C$ reactions to the very narrow high excitation ($E_X > 20$ MeV) states seen in both reactions. For the ${}^{13}C$ spectrum see Fig. 6(b).

(Fig. 9.). There has been speculation¹⁴ that these states represent $\Delta T=3/2$ transitions of (p,π) , and that the states seen are T=3/2 and T=2 states of ¹³C and ¹⁴C, respectively. Such a speculation has some difficulties as the dominant $pp \neq pn(^{3}S_{1})\pi^{+}$ process cannot generate $\Delta T=3/2$ excitations, as Ref. 14 pointed out. Furthermore this speculation would predict that (p,π^{-}) to mirror nuclei, such as $^{13}C(p,\pi^{-})^{14}O$, would have the same cross section as (p,π^{+}) to these states. This is not observed. These states represent somewhat of a mystery then, and the proposed survey would explore the extensiveness of this phenomenon and its energy behaviour.

As a second experiment the large solid angle of SASP should be exploited to further look at the small cross section (p,π^-) reaction. Although the analysis in Sec. II stated that Δ effects in (p,π^-) should be weak, they should nevertheless be looked for as the (p,π) reaction has been in the past a source of surprises. Preliminary data²⁸ on ${}^{18}O(p,\pi^-){}^{17}Ne$ (Fig. 15) indicate that the cross section to the ${}^{17}Ne(4.6, 13/2^-)$ stretched state rises with energy in contrast to the trend in Fig. 13. Since the statistics are very poor, such evidence cannot be conclusive. However, such statistics would justify an experiment using SASP, which would gather 10 times the statistics on this same reaction.





Finally in the interest of further testing spin-orbit coupling effects a (p,π^-) experiment should be done on a j_{\langle} subshell target to see if the A_{no} to a stretched state is reversed to the observed trend in Fig. 5. One candidate would be the ${}^{34}S(p,\pi^-){}^{35}Ar$ reaction looking at the j_{\langle} $ld_{3/2}$ subshell. If such a reversal of polarity would be seen, it would be analogous to the effect seen in Ref. 4 for (p,π^-) to the ground states of ${}^{13,14,15}O$.

REFERENCES

- 1. S.E. Vigdor et al., Phys. Rev. Lett. 49, 1314 (1982).
- S.E. Vigdor, Invited talk presented at the International Symposium on Nuclear Spectroscopy and Nuclear Interactions, Osaka, Japan, March 21 to 24, 1984.
- 3. B.A. Brown et al., Phys. Rev. Lett. 51, 1952 (1983).
- 4. W.W. Jacobs et al., Phys. Rev. Lett. 49, 855 (1982).
- 5. R.D. Bent, private communication.
- 6. H. Toki and K.-I. Kubo, Phys. Rev. Lett. 54, 1203 (1985).
- 7. M.C. Green et al., Phys. Rev. Lett. 53, 1893 (1984).
- 8. S.E. Vigdor, Phys. Rev. Lett. 54, 1204 (1985).
- 9. M.J. Iqbal and G.E. Walker, Phys. Rev. C 32, 556 (1985).
- 10. M. Dillig et al., IUCF 1985 Scientific and Technical Report.
- 11. E.D. Cooper and A. Matsuyama, Nucl. Phys. A460, 699 (1986).
- 12. G.M. Huber et al, submitted to Phys. Rev. Lett.

13. G.M. Huber et al., to be published.

- 14. E. Korkmaz et al., IUCF 1984 Scientific and Technical Report.
- 15. B. Höistad, AIP Conf. Proc. 79, 105 (1981), ed. R.D. Bent.
- 16. W. Ziegler, Ph.D. thesis, University of British Columbia (1985).

- 17. J. Niskanen, Nucl. Phys. A298, 417 (1978).
- 18. W. Falk et al., Phys. Rev. C 32, 1972 (1985).
- 19. G. Giles et al., Phys. Rev. C 28, 2551 (1983).
- 20. G. Giles, Ph.D. thesis, University of British Columbia (1985).
- 21. W. Falk et al., Phys. Rev. C 33, 988 (1986).
- 22. E. Korkmaz et al., IUCF Newsletter 37, 1 (1985).
- 23. G.J. Lolos et al., Phys. Rev. C 30, 574 (1984).
- 24. W.J. McDonald, these proceedings.
- 25. D.V. Bugg, J. Phys. G <u>10</u>, 717 (1984);
 H. Kamo and W. Watari, Prog. Theor. Phys. <u>62</u>, 1035 (1979);
 G. Jones, private communication.
- 26. T.P. Sjoreen et al., Phys. Rev. C 24, 1135 (1981).
- 27. S.E. Vigdor, private communication.
- R. Bent, Expt. 234 in TRIUMF 1983 Annual Report on Scientific Activities.

(p, πx) EXPERIMENTS

W. R. Falk University of Manitoba, Winnipeg, Man., Canada, R3T 2N2

ABSTRACT

The importance of coincidence experiments that investigate reactions of the type $A(p,\pi x)C$, where x is a nucleon or a deuteron, is discussed. Such studies provide the opportunity to understand how the fundamental pion production processes are modified by the nuclear medium and by momentum considerations in the initial and final states. New experimental facilities in the nature of large solid angle, large momentum bite spectrometers, are essential for such investigations.

INTRODUCTION

In the exclusive $A(p,\pi)B$ reactions discussed by the previous speaker the lack of freedom to vary a given dynamical parameter, without also varying other parameters at the same time, is severely restrictive. Reactions with three-particle final states provide much greater freedom to select dynamical parameters as, for example, the momentum transfer, the momentum sharing, or the relative energy between any two of the three final particles. Thus the possibility of examining different aspects of the pion production process and their sensitivities to other details in the interaction is provided. It must also be said at the outset that very few theoretical calculations of such reactions exist at the present time that provide specific predictions that can be checked experimentally. However, theoretical developments incorporated in current nuclear pion production models could be extended fairly easily to these reactions. Given the present situation this paper explores in rather broad and general terms what avenues of investigation may be most fruitful.

At proton bombarding energies in the energy range from 200-500 MeV many experiments point to the dominant role played by the intermediate formation of the $\Delta(1232 \text{ MeV})$. Indeed, it has been recognized for many years that this might be so. Current models of nuclear pion production all stress the centrality of intermediate \triangle formation (see refs. 2 and 3, for example). The intra-nuclear cascade model (INC) used to describe inclusive N-nucleus and nucleus-nucleus pion production has, as one of its main ingredients, the intermediate formation of the Δ (ref. 4). Figure 1 illustrates the potential role of the NN->N∆ process leading to three different final states. The first, Fig. la, represents the exclusive reaction, Fig. 1b, the emission of a nucleon along with the pion, and Fig. 1c, the emission of a deuteron (or two nucleons) together with a pion. Kinematically complete experiments for three-body final states of the kind represented by Figs. 1b and 1c have not been performed, except in few-nucleon experiments.

28

Work supported in part by the Natural Sciences and Engineering Research Council of Canada.


sections (ref. 6).

INCLUSIVE REACTIONS $A(p, \pi)X$

Some indication of the importance and feasibility of studying the three-body final state reactions of Fig. 1 can be obtained from examining the inclusive $A(p,\pi)X$ reaction. Only a small fraction of the total pion production yield in the interaction₅p+A is to be found in the exclusive reaction A(p, π)B. DiGiacomo et al. have measured inclusive pion yields from proton interactions with ¹²C and ²³⁸U at energies of 330, 400 and 500 MeV. At 400 MeV the total π cross section from ²C is 7.6 mb. An interesting comparison of this result can be made by summing the free $pN \rightarrow NN\pi$ isospin cross sections at this energy. A plot of these isospin cross sections, as given by Ver West and Arndt', is shown in Fig. 2. Summing the appropriate terms (σ_{01} is negligible at this energy)_yields a pp->d π +NN π cross section of 1.43 mb and a pn->NN π cross section of 0.04 mb. The total cross section for ^{12}C should thus be about 8.8 mb, in reasonable agreement with the experimental value of 7.6 mb. Thus the isospin cross sections seem to give a good account of the observations. This however, must be too simplistic, since the Fermi momentum of the struck nucleons, nuclear absorption, and other effects have been ignored. Indeed, in order to understand the high π^{-}/π^{+} yield ratio, which is about 1/8 for ¹²C and 1/2 for ²³⁸U, one is led to conclude that Δ rescattering, charge exchange and pion absorption play a major role in these processes .

A second important aspect of the inclusive reactions is the information provided by analyzing power measurements. We have recently reported such measurements on TC at 400 and 450 MeV bombarding energies. An unsophisticated model based on the elementary pp->d π and pN->NN π pion production processes was employed, where the incident proton interacts with a target nucleon, distributed in momentum according to the predictions from (e,e'p) experiments. Figure 3 illustrates this

29







Fig. 5. Cross sections and analyzing powers for the ${}^{12}C(p,\pi^+)X$ reaction.

30

model. Complete kinematic calculations were carried out for the collision of an incident proton with a target nucleon having energies E_1 and E_2 and momenta p_1 and p_2 respectively. The c.m. pion angle and momentum resulting from this collision were taken as the appropriate kinematical and dynamical parameters for calculating the corresponding pp->d π differential cross sections for the two_spin orientations. The angular and spin dependence of the pN->NN π channels was taken to be the same as that of the pp->d π reaction. Justification for this is obtained from the measured analyzing powers of the pp->pn π reaction at low relative np energies, and their successful interpretation in terms of the pp->d π analyzing powers. An example of these latter data and the calculated pp->pn π analyzing powers is shown in Fig. 4.

Cross sections and analyzing powers for the ${}^{12}C(p,\pi^+)X$ reaction at 450 MeV are shown in Fig. 5 together with the predictions of the above model (solid lines). The magnitude and energy dependence of the analyzing powers at forward angles is quite well predicted, while at the larger angles the magnitude of the experimental analyzing powers is considerably larger than predicted by this model. The cross section calculations in most cases exhibit the general shape of an inverted parabola, consistent with the trend of the data. The maxima of these parabola occur at pion energies close to the pion energy in the free pp->d π reaction, which in turn coincide quite well with the peak of the experimental differential cross sections.

Results of the model calculations also indicate that only 40-45 % of the total π yield arises from the pp->d π reaction, and the balance from the other pN->NN π channels. This can be understood from the effect of the Fermi motion of the target nucleons in shifting upward the effective interaction energies, since the cross sections for the latter channels increase rapidly with increasing energy.

COINCIDENCE $A(p, d\pi^+)C$ REACTIONS

The above discussion suggests that important insights might be gained by the kinematically complete studies of the reaction $A(p,d\pi^+)C$. The predicted strength of this channel - about 50% of the total pion production, barring extensive deuteron breakup - makes it particularly attractive for investigation. In the first instance the kinematic regime discussed above - the quasifree region, where the struck nucleon momentum is modest - would provide useful confirmation of the role of the basic processes considered. A measurement of the fraction of the pion events associated with the production of a free deuteron could be obtained. DWIA models have been developed for nuclear (p,π^+) reactions that incorporate the fundamental $pp > d\pi^+$ reaction as the basic pion production process. Such models could easily be extended to the case of a free deuteron in the final state.

An indication of the technical challenge of such experiments is illustrated in Fig. 6 where the deuteron intensity distribution (from the previously described model calculations) has been plotted for the reaction $C(p,d\pi)$ B, at 400 MeV, with the pion detected at 46 with respect to the beam direction. The deuteron distribution is strongly forward peaked, as expected, with most deuterons emitted at angles of less than 20°. Two spectrometers, one for the detection of the pion and the other for the detection of the deuteron, would provide



Fig. 6. Contour plot of the relative deuteron intensity distribution for a pion detected at 46° in the x-y plane.

excellent missing mass resolution in such experiments. On the other hand, the angular range to be investigated, together with the large momentum range of the detected particles at fixed angles (the deuteron kinetic energies range from 60-240 MeV in this case) make detailed investigations of this kind very tedious. Instead, initial survey measurements might most profitably be carried out using the large second arm spectrometer for detecting the pions, and an array of ΔE -E counters, providing particle identification and energy measurement, for detecting protons and deuterons. Indeed, one might also add neutron detection capability to these counters to provide a very versatile detection system. Such a detection system would greatly facilitate not only the $A(p,d\pi)C$ investigations, and extend the capability to detect neutrons and protons from deuteron breakup, but would also be applicable to the other experiments to be discussed presently. In fact, data for several different experiments could likely be collected simultaneously.

Simulation of some of the dynamical conditions pertinent to the exclusive $A(p,\pi)B$ reaction can be reproduced with the $A(p,d\pi')C$ reaction as one moves away from the quasifree region. As a reminder we note the c.m. energies, in Fig. 7, that can be attained in the head-on collision of two nucleons, where the target nucleon has a range of momenta and an assigned total energy of 920 MeV. Thus the collision of a 350 MeV proton with a target nucleon of momentum 200 MeV/c brings the c.m. energy into the lower domain of the NA system. Probing such momentum components in the nuclear wave functions results in momentum transfers $q=p_1-p_{\pi}$ which span a considerable range between the momentum transfers in the pp->d\pi and $A(p,\pi')B$ reactions. Figure 8 defines the relevant parameters in the collision and Fig. 9 shows the pion



Fig. 7. Center of mass energies attained in the head-on collision of two nucleons.



Fig. 8. Definition of parameters in the nuclear NN pion production collision.



Fig. 9. Pion momentum, and momentum transfer as a function of θ_{π} . All quantities are evaluated in the lab frame.



Fig. 10. Effective excitation energy of nucleus B, and the relative deuteron momentum.

Pr (MeVc)

momentum and the momentum transfer q as a function of the pion scattering angle for 350 MeV protons incident on H and C. Interestingly, at a pion angle of 80° the momentum transfer is about 870 MeV/c in all cases. The kinematics of the reaction also define the relative momentum of the deuteron and the residual nucleus C, as well as the internal energy of d+C (i.e. the equivalent excitation energy of B). Plots of these two quantities as a function of the pion scattering angle are shown in Fig. 10 for 350 MeV protons on C, and struck nucleon momenta of 150 and 300 MeV/c. The higher momentum target nucleon results in effective C excitation energies of 33-114 MeV and d-B relative momenta from 220-550 MeV/c. Thus the A(p,d π)C reaction is able to investigate much of the kinematical and dynamical regime of interest to the exclusive A(p, π)B reaction.

The $A(p,d\pi')C$ reaction is expected to exhibit a strong spin dependence, given the results discussed earlier. Such experiments should thus be performed using polarized protons since valuable signatures will be contained in the analyzing power information.

Kinematics for this reaction for essentially all cases of interest, indicate that the deuteron is emitted strongly in the forward direction (generally at $0-20^{\circ}$ with respect to the beam direction). Providing for the situation where the deuteron breaks up in the field of the nucleus, or where it is produced as an unbound np pair with some internal excitation, still has as consequence the forward emission of one or both nucleons in most cases. The detection of a deuteron or nucleon in the forward direction is thus a requirement in all situations.

As an example of the count rates expected in a coincidence experiment we consider 400 MeV protons incident on ¹²C, using a beam intensity of 1 nA and a target of 100 mg/cm². The second arm spectrometer with a solid angle of 10 msr is used as the pion detector, and an array of counters, each subtending a solid angle of 6 msr, placed in the forward direction for the detection of deuterons and nucleons. For an inclusive pion production cross section of 10 μ b/sr.MeV the singles pion count rate is about 30/s in a 10 MeV energy bin. The estimated coincidence count rate (see Fig. 6) is then about 1/s. However, the singles count rate in the forward-positioned counters would be in excess of 60,000/s, assuming an elastic cross section of 300 mb/sr at 10°. Random coincidence background will thus be the limiting factor in the data collection rates in these experiments. Four to five magnetic field settings of the pion spectrometer would be required to cover the range of pion momenta. An array of 5 to 10 counters would cover a large fraction of the angular range of the emitted deuterons and nucleons.

\triangle **PRODUCTION**

Given the dominant role that the intermediate \triangle is believed to play in all pion production at these energies it would seem important to look for direct signature of its presence. In NN experiments this dominant role of the \triangle has been confirmed in the pp->pn π reaction at 800 MeV as shown in the cross section measurements in Fig. 11. Only recently has such evidence become available for p-nucleus collisions where the reaction Li(p, \triangle) He was investigated at 1040 MeV. The experimental arrangement is shown in Fig. 12 where a He counter telescope was used to look directly for the 'two-body' signature of the final state. A scintillation counter hodoscope was used to provide





redundant information and reduce background contamination. An unambiguous signal for the reaction was seen which permitted the extraction of the differential cross section shown in Fig. 13. The solid curve in this figure represents a DWBA calculation for this reaction, performed by Jain 12 and Hasan and Jain 13 . Both the magnitude and shape of the differential cross section are reproduced remarkably well in this essentially parameter-free calculation. They conclude that this determines for the first time, in a direct way, that the effective spin-isospin coupling potential, V(NN->N∆), can be correctly described by the one-pion and one-rho exchange interaction. Because the Δ is produced in the free state such studies provide the opportunity to learn about the Δ -nucleus interaction potential and Δ propagation in the nuclear medium. The great importance of understanding this reaction in a comprehensive way has led the above authors to perform calculations for the ${}^{b}Li(p, \Delta^{++})^{b}He$ reactions at a number of energies in the range from 400 to 1250 MeV. Calculated angular distributions and total cross sections are shown in Figs. 14 and 15. At 500 MeV the differential cross section is about 4 μ b/sr at 0°, and the total cross section has dropped by an order of magnitude from its value at 1000 MeV. Nevertheless, such experiments should be feasible using the detection system previously described. The proton from the Δ^{++} decay is emitted strongly in the forward direction, while the pion is not so constrained. Other target nuclei on which the (p, Δ^{++}) reaction could be investigated are ¹⁰B and ¹²C, although the presence of several final nuclear states will and complicate the interpretation, unless these states can be resolved. Nuclear pion production via intermediate Δ formation in any two- or

36



three-body final state reactions should be characterized by a strong spin-dependence exhibiting different analyzing powers for interactions with j=1+1/2 and j=1-1/2 target nucleons. This follows from the fact that the T=1 10 initial NN state, in which the interacting nucleons are in the spin singlet state, dominates the interaction 10 . The situation is depicted in Fig. 16 which, when coupled with arguments about pion absorption, suggests opposite analyzing powers for j=1+1/2 and j=1-1/2 states. Similar predictions for the A(p, π)B reaction at lower energies by Vigdor 11 have indeed been borne out by experiment. Unfortunately, however, the observed analyzing power dependence is opposite to what this simple model predicts. Thus caution must be exercised in making specific predictions from such simple pictures.

NON-△ REACTIONS WITH THREE-BODY FINAL STATES

The $(p,n\pi^{+})$ reaction on T=0 target nuclei, proceeding to the low-lying final states of the same nucleus (T=0), occupies a rather special role in this general class of three-body final state reactions, in that this reaction cannot proceed via the intermediate formation of the Δ . Sherif et al. have suggested that this reaction may be used to answer certain specific questions regarding the NN π^{-} vertex function. They have performed calculations of the differential cross sections for the reactions He(p,n π^{+}) He and Ca(p,n π^{+}) Ca for specific neutron angles as a function of the detected pion angle. Figure 17 shows their results for the latter reaction at 500 MeV. While these cross sections are quite small - in the neighborhood of 1 μ b/sr⁻.MeV - they should be amenable to experimental investigation using the detection system discussed previously.

SUMMARY

This survey of potential $(p, N \pi^+)$ and $(p, d\pi^+)$ reactions has attempted to show that a rich field of experimentation is available that can shed much light on pion production processes in nuclei. All these studies would benefit from the use of polarized incident protons since the inherent spin-dependence of the NN->NN π reactions provides valuable signatures of the subprocesses involved. Specific results of these investigations would include a clearer picture of how the fundamental NN->NN π reactions are modified in the presence of the nuclear medium, an understanding of the role played by the intermediate formation of the Δ , and a better understanding of Δ -nucleus dynamics.

A fortunate aspect of most of the reactions discussed is that all have rather similar experimental characteristics in terms of the detection systems required and the typical angular and dynamic (momentum) ranges of the particles to be detected. Indeed, the combination of a large solid angle pion spectrometer together with an array of broad range nucleon detectors would provide an excellent tool for collecting data on a number of these reactions simultaneously. Very specific questions, where much better missing mass resolution is required, could then be addressed using the MRS and SASP in the dual arm configuration.

A clear need also exists for calculations to be carried out for the reactions discussed, that are firmly grounded theoretically, if the interpretation of these studies is to provide new insights into pion production.



Fig. 16. Spin-dependence in Δ -dominated interactions.



Fig. 17. Calculated cross section for ${}^{40}Ca(p,n\pi^+){}^{40}Ca$.

REFERENCES

- W.O. Lock and D.F. Measday, Intermediate Energy Nuclear Physics (Methuen, London, 1970), p.224.
- 2. B.D. Keister and L.S. Kisslinger, Nucl. Phys. A412, 301 (1984).
- 3. M.J. Iqbal and G.E. Walker, Phys. Rev. C32, 556 (1985).
- 4. Z. Fraenkel et al., Phys. Rev. C26, 1618 (1982), and references therein.
- 5. N.J. DiGiacomo et al., Phys. Rev. C31, 292 (1985).
- 6. B.J. VerWest and R.A. Arndt, Phys. Rev. C25, 1979 (1982).
- 7. W.R. Falk et al., Phys. Rev. C33, 988 (1986).
- 8. W.R. Falk et al., Phys. Rev. C32, 1972 (1985).
- 9. H.W. Fearing, Phys. Rev. C16, 313 (1977).
- 10. J. Hudomalj et al., Phys. Rev. C18, 2666 (1978).
- 11. T. Hennino et al., Phys. Rev. Lett. 48, 997 (1982).
- 12. B.K. Jain, Phys. Rev. Lett. 50, 815 (1983).
- 13. H. Hasan and B.K. Jain, Phys. Rev. C33, 1020 (1986).
- 14. D.V. Bugg, Nucl. Phys. A437, 534 (1985).
- S.E. Vigdor, International Symposium on Nuclear Spectroscopy and Nuclear Interactions, Osaka, Japan, 1984.
- 16. H.S. Sherif et al., Phys. Lett. 83B, 293 (1979).

THE IUCF/UNIVERSITY OF MARYLAND DUAL SPECTROMETER FACILITY*

P.G. Roos University of Maryland, College Park, MD 20742

ABSTRACT

This paper discusses the IUCF/University of Maryland Dual Spectrometer Facility -- the components of the spectrometers, their design parameters, the focal plane system and electronics, and the front end. Also discussed are a few initial experiments planned for this facility and other possible avenues of research.

INTRODUCTION

In this talk I will discuss not only the facility itself, magnets, focal plane system, etc., but also briefly discuss some of the physics planned when completed. Before beginning this discussion I would like to spend a couple of minutes discussing the history of this project, which provides some insight as to the eventual choice of the properties of the two spectrometers.

In 1979 the NSF held a review of all NSF supported university facilities. At this presentation we proposed the construction of a dual spectrometer facility for particle-particle correlation studies at the Maryland Cyclotron. These spectrometers were to have large acceptance (solid angle and momentum bite), but rather modest resolution. At about this same time IUCF was lobbying for a high resolution modern spectrometer, primarily for high resolution spectroscopy; e.g., inelastic scattering and transfer reactions.

In 1980 the Maryland Cyclotron ceased to exist (RIP). At that time we held discussions with IUCF and together with them submitted a joint proposal for a dual spectrometer facility to be operated at IUCF. To cover both the UM and IUCF interest, one spectrometer was to be capable of very high resolution with reasonable acceptance, while the other was to have large acceptance with modest resolution.

About one year later this proposal was funded by the NSF at a cost of approximately \$1.5 M. This cost represents essentially the hardware costs of the spectrometers. The power supplies and some beam transport magnets were donated by the University of Maryland Cyclotron; the beam line bender for dispersion matching is the IUCF QDDM spectrometer. Funds for the focal plane array were awarded in a separate proposal, and a new proposal for a dual sliding seal scattering chamber will soon be submitted. In addition, most of the costs for design and installation are being borne by the IUCF operating budget as one of their major equipment projects.

SPECTROMETERS

Figure 1 shows the design of the two spectrometers (designed by R. Pollock of IUCF). Their detailed properties are listed in Table I.

*Work supported in part by the U.S. National Science Foundation.

Table I. Parameters of the IUCF Dual Spectrometer System

	K=600 (3 dispersion modes)			K=300
	low	normal	high	
Maximum momentum (MeV/c)	860	1080	1005	760
Maximum proton energy (MeV)	334	493	437	269
Maximum magnetic rigidity (T-m)	3.00	3.60	3.50	2.55
Maximum dipole fields, D1/D2 (T)	1.23/1.64	1.64/1.64	1.64/1.23	1.70/1.70
Nominal bend radius (m)		2.1		1.3
Nominal bend angle		115°		70°
Maximum solid angle		6.0		14
$\Delta \theta \Delta \phi \text{ (msr)}$				
Maximum radial acceptance		±44		±66
Maximum axial acceptance $\Delta \phi$ (mrad)		±44		±68
Momentum range pmax/pmin	1.131	1.097	1.063	1.357
Resolving power p/ Sp		~30,000		~2,000
Momentum dispersion (cm/%)	6.2	8.1	9.8	2.4
Energy dispersion (keV/mm) (for 200 MeV protons)	65	50	40	170
Mininum scattering angle θ	4.5° (at 1 msr)			20°
with external beam stop	top 12° (at 6 msr)			sector of



Fig. 1. Basic designs of the K-300 and K-600 spectrometers.



The K-600 consists of two dipoles and an entrance quadrupolehexapole combination. An aberation correction coil (H) and a kinematic correction coil (K) are included in the dipoles. The solid angle of the spectrometer is a quite respectable 6 msr. The K-600 design has some very special features. By operating the two dipoles independently, three focal plane positions with varying dispersion can be used. (The properties of the three dispersion modes are listed in Table I.) As a result one can use the high dispersion mode (~6% momentum bite) for high resolution spectroscopy, or use the low dispersion mode (~13% momentum bite) for coincidence work where generally coverage of phase space is a more important consideration. A second feature is that the K-600 spectrometer can be operated at angles as small as 4.5° with an external Faraday cup using a special septum magnet. This small angle mode, along with the normal mode, are pictured in Fig. 2.



Fig. 2. Normal and small angle modes of the K-600 spectrometer.

The K-300 spectrometer is a much simpler magnet with an entrance quadrupole and single dipole. However, the pole piece of the dipole is split to provide additional focusing and aberation corrections. Also the quadrupole, identical in basic design to that of the K-600, contains higher multipoles for aberation corrections. From Table I we see that this spectrometer is optimized for solid angle (14 msr) and momentum bite (~35%) at a cost of momentum resolution ($p/\delta p \sim 2000$). The K-300 spectrometer is primarily intended for coincidence measurements, but also would probably be the spectrometer of choice for some inclusive reaction studies.

To maximize the range of angle pairs which can be covered in coincidence measurements, the K-300 will be mounted vertically. This has the undersirable feature that dispersion matching to the beam (horizontal dispersion) cannot be done. In addition, definition of the inplane scattering angle is more difficult. However, considering the high quality of the beam at IUCF, the intrinsic resolution of the K-300 spectrometer, and the requirements of presently conceived experiments, we believe that the flexibility in angle is the overriding consideration.

Presently, the installation of the spectrometers is proceeding at the north end of the original IUCF building. This location, in addition to the rest of the facility, is shown in Fig. 3. Eventually, when the IUCF Cooler Ring is operation, the spectrometers will be moved to the site on the ring shown in Fig. 3. The angular range covered by each of the spectrometers at these sites are the following:



Fig. 3. IUCF floor plan showing the two location of the dual spectrometer facility.

	North End of Bldg.	Cooler Ring
к-600	105°L → 29°R	$14^{\circ}L \rightarrow 102^{\circ}L$
K-300	75°L → 135°R	$14^{\circ}R \rightarrow 156^{\circ}R$
Minimum Separation	≳ 30°	≥ 30°

The focal plane detector systems for both spectrometers will consists of two sets of wire chambers to measure position and angle and two to three plastic scintillators. To achieve the K-600 design goal of $p/\Delta p \simeq 3 \times 10^4$, position and angle must be measured very accurately ($\Delta x < 0.2 \text{ mm}, \Delta \theta < 3 \text{ mrad}$). This dictates the use of vertical drift chambers¹ for the 2 x-planes. The y-direction is less critical, the information primarily being utilized for background suppression. Therefore, drift chambers of the Los Alamos type² will be used for the y-planes. In addition, a diagonal drift chamber (U chamber) will be included to aid in the identification of multiple-hit events. The much more modest requirments of the K-300 ($\Delta x < 0.75 \text{ mm}, \Delta \theta < 15 \text{ mrad}, \Delta y < 2 \text{ mm}, \Delta \phi < 50 \text{ mrad}$) allow the use of Los Alamos type drift chambers for all planes.

Behind the wire chamber a stack of two or three plastic scintillators will be used for timing, particle identification, and generating event triggers. Information from phototubes on each end of the scintillators will provide additional consistency checks. We plan to have a selection of scintillator thicknesses to allow optimization for the various experiments. An example of the focal plane system for the K-600 is shown in Fig. 4.



Fig. 4. Focal plane detectors for the K-600 spectrometer.

Before turning to a discussion of the electronics, let me mention that considering the recent importance of the measurements of spintransfer information, a focal plane polarimeter will be available in the early stages of operation. A design which has an efficiency of $\sim 1.5\%$ and an analyzing power of ~ 0.5 for 200 MeV protons has been proposed.

To take maximum advantage of the dual spectrometer facility and the scarce beam time available at IUCF, it was deemed essential that the focal plane electronics and readout be capable of handling a singles rate of at least 10^5 cts/sec and an event rate of $5 \times 10^3 - 10^4$ cts/sec. This requires individual wire readout and TDC's and ADC's with conversion times in the few microsecond range. Furthermore, a smart front end with parallel processors capable of some preprocessing of events is essential.

The adopted scheme is shown in Fig. 5. To keep the costs at a reasonable level, 20 to 25 wires from each plane (separated sufficiently so that they are not triggered by the same hit) are or'd by means of a multiplexor (MUX) to the individual TDC's. Each event is then passed through a buffer to a set of 10 parallel processors where partial analysis of the event can proceed and bad events rejected. After preprocessing the events are passed on to a VAX where they can be analyzed in a sample mode.



Fig. 5. Schematic block diagram of the proposed readout and event processing system.

As probably most of you know, this project has suffered a number of delays, and continues to proceed slowly due to the pressures of the Cooler Ring construction. However, events are proceeding: the beam transport system is essentially complete; the K-600 spectrometer has been shimmed and mapped and is being installed; the K-300 spectrometer has been mapped once and shims are being fabricated; the focal plane electronics and front end are designed and largely completed; and the wire chambers and plastic scintillators are in various stages of construction. As of now (3/14/86) the schedule calls for tests of the beam line in April and initial beam tests of the K-600 (with complete focal plane) in early August. We would, therefore, expect the K-600 to be available this fall for singles experiments.

The schedule for the K-300 is less well defined and is at the mercy of the Cooler Ring, IUCF's top priority project, as well as the normal operation and maintenance of the Cyclotron. We are hopeful that the K-300 will be installed and available for testing in the summer of 1987. However, this schedule will depend on all other laboratory projects.

Eventually, both spectrometers will be moved to the site on the cooler ring. With respect to the schedule for completion of the ring and the movement of the spectrometers, I would not even hazard a guess.

A SAMPLE OF PROPOSED AND POSSIBLE EXPERIMENTS

There are a variety of experiments possible with the K-600 alone utilizing the high resolution. For example, there is already an approved experiment³ to study inelastic proton scattering from calcium isotopes. Others will use a focal plane polarimeter to measure spintransfer properties. Rather than discuss such experiments, I will concentrate on some coincidence experiments. For coincidence measurements, the dual spectrometer facility is capable of providing data of a quality three orders of magnitude better (in terms of resolution, count rate, and background) than previously available. Many previously impossible studies become possible with this facility.

$A(\vec{p}, 2p)B$

An approved experiment⁴ will measure the $(\vec{p}, 2p)$ reaction at 200 MeV on ¹²C, ⁴⁰Ca, and ⁹⁰Zr obtaining high statistics for transitions to lowlying states in the residual nucleus. The experiment will measure the cross sections and analyzing power ($\Delta A \leq 0.02$) for a number of angle pairs, both symmetric and asymetric.

This experiment utilizes the predicted⁵ and confirmed⁶ feature that the struck target nucleon is effectively polarized for situations in which the final state protons have either unequal angles or energies due primarily to different attenuations. A primary motivation of this experiment is an attempt to study the nucleon-nucleon interaction in the nuclear medium under conditions of differing density and distance offshell. To clarify the motivation, we write the factorized DWIA cross section,⁷ neglecting spin-orbit terms, for an incident beam with polarization P_0 as

$$\frac{\mathrm{d}^{3}\sigma}{\mathrm{d}\Omega_{1}\mathrm{d}\Omega_{2}\mathrm{d}E_{1}} (\vec{P}_{0}) \propto \frac{\mathrm{d}\sigma}{\mathrm{d}\Omega} (0) \left[1 + (\vec{P}_{0} + \vec{P}_{eff}) \cdot \vec{A} + \vec{P}_{0} \cdot \vec{P}_{eff} C_{nn}\right] |\phi_{DW}|^{2}$$

where ϕ_{DW} is the distorted momentum distribution of the struck nucleon, P_{eff} is the polarization of the struck nucleon caused by distortion effects, and $\frac{d\sigma}{d\Omega}(0)$, \vec{A} , and C_{nn} are the two-body p-p unpolarized cross section, analyzing power, and spin correlation coefficient.

Assuming this expression to be correct, measurements of $(\vec{p}, 2p)$ cross section and analyzing powers allow the extraction of the p-p scattering observables $(d\sigma/d\Omega, A, C_{nn})$ in the nuclear medium. By appropriate choice of angles and residual states one can isolate the various terms in a manner which is almost independent of the distorted wave parametrization. In particular, some of the obvious choices and considerations are as follows:

(a) For knockout of an S-state (l=0) P_{eff}=0, and one focuses on A;
 (b) For l≠0 and symmetric angles (θ₁=-θ₂) we find θ_{pp} ≃90° so that
 A≈0 and one focuses on C_{nn}. However, in this case C_{nn} appears only as a product with P_{eff} so one must use the DWIA to extract C_{nn};

(c) For the knockout of spin-orbit partners, there is an approximate relationship between P_{eff} which is well satisfied, namely $P_{eff}(j = l + l/2) = - \frac{l+1}{l} P_{eff}(j = l - l/2);$

(d) Measurements of spin-orbit partners at asymmetric angle pairs where both A and C_{nn} contribute should allow the separation of these various terms.

Although my discussion, and thinking about the experiment, has clearly been largely based on the equation presented above, we are cognizant of the uncertainties and impact introduced by reaction mechanism and nuclear structure. In the proposed experiment the choice of targets, nuclear levels, angles and energies will allow for interrelated studies of reaction mechanism (factorization, distorted wave treatment), nuclear structure, and the nucleon-nucleon quantities discussed above.

This experiment promises to produce very interesting results. Work here at TRIUMF already indicated difficulties with the analysis of $(\vec{p}, 2p)$ data with conventional DWIA calculations. For a review of the present status of (p,2p) studies, as well as a more detailed discussion, see Ref. 8. The most exciting possible explanation is that the spin dependence of the nucleon-nucleon interaction is strongly modified in the nuclear interior. However, it may well be that the reaction model is too simple. In either case the extensive data provided by the proposed experiment should indicate the source of difficulty.

Before continuing to the next experiment I would like to point out that the Dual Spectrometer Facility will provide count rates such that the error in analyzing power in a 5 MeV bin for 40Ca(\vec{p} ,2p)39K($3/2^{-}$,g.s.) will be < 0.02 in a one-hour run. This rate is comparable to many singles measurements. In addition, the rate is sufficient to allow reasonable measurements of the polarization of one of the outgoing protons. These measurements will not be considered until after the initial measurements of cross section and analyzing power, to determine if there is any reason to make this more difficult measurement.

Studies of the (p,2p) Continuum

A second approved proposal for the dual spectrometer facility is that of Segal et al.⁹ This work is oriented toward a study of reaction dynamics by detailed measurements of the continuum (> four-body phase space) produced in (p,2p) reactions. The choice of experimental configuration is based on the hypothesis that one high energy proton is produced directly in an initial nucleon-nucleon collision. A second proton is then produced by the multiple scattering of the target (or projectile) nucleon in the nucleus. In a simplistic treatment the data then allow extraction of the mean free path of the proton in the nucleus. A more formal treatment¹⁰ attributes most of the continuum yield to initial p-p interactions with valence nucleons followed by multiple scattering, described by the experimental (p,p') data. These calculations provide a good description of ⁵⁸Ni(p,2p) at 100 and 200 MeV.

The experiment will measure (p,2p) cross sections on a light, medium, and heavy nucleus at a variety of angle pairs. These data will be used to test reaction models, such as that of Ref. 10. If the original hypothesis is correct, one will be able to extract quantities related to the classical mean-free-path. An interesting, and utilitarian, sidelight is that confirmation of the model would then allow estimates of the continuum yield due to valence particles, and place limits on the yields from deeper-lying hole states. Based on the scant results to date, we doubt that the (p,2p) reaction will be a useful tool in the study of deep-hole states.

Cluster Knockout Reactions

With the expected improvement in count rate $(\sim 10^2)$ and energy resolution (~1/5-1/20) new or greatly improved studies of cluster knockout reactions become possible. For example, (p,pa) cross sections can be measured with a factor of 10 improvement in the statistical error compared to presently available data. To date most experiments have concentrated on ground-state transitions, which are about a factor of ten stronger than excited states. In addition, analyzing power data with excellent precision is possible. With these new measurements both ground state and excited state data will provide precision tests of the DWIA treatment of the reaction, and assuming the applicability of the DWIA should better define the bound cluster wave function, and thereby the spectroscopic factor. In addition, one will be able to look for transitions forbidden by the simplest cluster knockout DWIA treatment, such as the excitation of unnatural parity states. Observation of these states will place limits on the importance of multistep processes and/or the presence of excited states of the clusters in the target nucleus.

Similar experiments can be envisaged for other cluster knockout reactions. In any event the facility opens many new avenues of research into the cluster structure of nuclei.

Pion Production

The experiment which I personally find most interesting is the study of pion production using the $(p,p\pi)$ and $(p,d\pi)$ reactions. These reactions were discussed at this meeting by W. Falk. Unfortunately for me, work with the dual spectrometer facility at IUCF will have to await the completion of the cooler ring, which will allow the beam energy to be ramped to energies higher than 200 MeV. Several year ago we attempted a measurement of ${}^{12}C(p,p\pi^{\pm})$ at 205 MeV and found the cross sections to be too small to obtain an acceptable real to accidental ratio. That experiment gave R/A < 1/10. However, that situation will improve rapidly with increasing energy.

The experiment I would like to do is to measure all allowed reactions of $(p,p\pi^{\pm})$ and $(p,d\pi^{\pm})$ on a series of targets ¹,²H, ³,⁴He, and ¹²C starting at T₀ \simeq 500 MeV and working down toward threshold. This series provides the following:

(1) A measurement of the fundamental processes for production of π^+ and π^- using ${}^{1}\text{H}(p,p\pi^+)n$ and ${}^{2}\text{H}(p,p\pi^-)2p$;

(2) A measurement of the $(p,p\pi^{\pm})$ production as the number of nucleons, density, distance off the energy shell, and Fermi motion change dramatically;

(3) A measurement of the $(p,d\pi^+)$ reaction $(e.g., {}^{4}\text{He}(p,d\pi^+)t)$ isolates, to a large extent, the effect of Fermi motion on the production mechanism; and

(4) Measurements of $(p,d\pi^{-})$ should define the importance of final state interaction charge exchange.

There are a variety of other aspects to these studies and I believe that such a series of experiments has tremendous potential in terms of improving our understanding of pion production, particularly near threshold where to produce the pion one not only needs Fermi motion, but also an additional interaction to put the reaction on-shell.

Having thought about this experiment several years ago (in sufficient detail that it reached the level of a draft proposal to TRIUMF), I carried out some DWIA calculations of the ${}^{12}C(p,d\pi^+){}^{11}B(g.s.)$ reaction by factorizing the p+p+d+ π^+ vertex. The predicted cross sections are shown in Fig. 6 for 3 energies. Clearly the count rates will be very good with a dual spectrometer facility.



Fig. 6. Energy sharing cross sections for ${}^{12}C(p,d\pi^+){}^{11}B(g.s.)$ predicted by a factorized DWIA calculation. Calculations are shown for three bombarding energies (T_p = 300,400, and 500 MeV), a fixed outgoing deuteron angle 25° and two pion angles (-25° and -50°).

SUMMARY

I have reviewed the design and progress of the IUCF/UM Dual Spectrometer Facility and indicated several coincidence measurements that will be carried out when construction is complete. We are confident that the tremendous enhancement in the quality of data provided by this facility will lead to new and exciting physics discoveries, and look forward to its completion.

I would like to acknowledge the efforts and dedication of Prof. Peter Schwandt in his role as project manager. I would also like to acknowledge the technical staff at IUCF who have done an excellent job on this project in spite of the numerous competing demands for their time and expertise.

REFERENCES

- 1. W. Bertozzi et al., Nucl. Instrum. Methods 141, 457 (1977).
- e.g., C.L. Morris, Nucl. Instrum. Methods <u>196</u>, 263 (1982), and references therein.
- 3. J. Kelly and A. Saha, spokesmen, "Microscopic Structure of the Calcium Isotopes" (6/85), approved experiment at IUCF.
- H.L. Chen, N.S. Chant, and P.G. Roos, spokesmen, "Measurement of the (\$\vec{p}\$,2p) Reaction at 200 MeV with the Dual Spectrometer Facility" (12/85), approved experiment at IUCF.
- V.E. Herscovitz, Th.A.J. Marris, and M.R. Teodoro, Phys. Lett. <u>69B</u>, 33 (1977); Th.A.J. Maris, M.R. Teodoro, and C.A.Z. Vasconcellos, Nucl. Phys. <u>A322</u>, 461 (1979).
- e.g., P. Kitching et al., Phys. Rev. Lett. <u>37</u>, 1600 (1976); P. Kitching et al., Nucl. Phys. A340, 423 (1980); see also Ref. 8.
- e.g., N.S. Chant, "Knockout Reactions with Hadronic Probes," IUCF Workshop on Nuclear Structure at High Spin, Excitation, and Momentum Transfer, Bloomington, IN (1985).
- P. Kitching, W.J. McDonald, Th.A.J. Maris, and C.A.Z. Vasconcellos, <u>Advances in Nuclear Physics</u>, edited by J.W. Negele and E. Voyt (Plenum Publishing Corp., 1985), Vol. 15, p. 43.
- 9. R. Segal, spokesman, "Coincidence Study of Quasifree (p,2p) Reactions" (12/85), approved experiment at IUCF.
- 10. G. Ciangaru et al., Phys. Rev. C 29, 1289 (1984).

DASS/SASP REPORT OF THE CONCEPTUAL DESIGN

E.G. Auld Department of Physics, University of British Columbia Vancouver, B.C. V6T 2A6

SASP is a Second Arm SPectrometer designed for use in single arm high resolution experiments like (p,π) and for use in a Dual Arm Spectrometer System (DASS) in conjunction with the MRS Spectrometer for experiments like (p,2p). The present funding schedule calls for its completion at TRIUMF to be in late 1989.

SECOND ARM SPECTROMETER FEASIBILITY STUDY

The feasibility study of the Second Arm Spectrometer was completed in the 1985/86 fiscal year. A detailed report of the study was presented to the TRIUMF Long Range Planning Committee (LRPC) in July 1985. This submission described the spectrometer details and some of the interesting physics that could be done with SASP or with SASP and the MRS in a dual arm spectrometer arrangement (DASS).

This paper describes the basic characteristics of the SASP as presented to the LRPC and indicates the progress made to the design since then.

The SASP is intended for use both as a large solid angle device for low cross-section single arm experiments, such as (p,π) and (n,p) and as a second arm in conjunction with the existing MRS spectrometer for coincidence experiments such as (p,2p) and $(p,\pi x)$. The configuration of the optical elements consists of two multipoles followed by a vertical bend clam-shell dipole. The preliminary design sketches of the system are shown in Figs. 2, 3 and 4.

The expected performance characteristics are shown in the following table:

Central momentum
Momentum bite±10%
Solid Angleat 594 MeV/c9.3 msr
at 627 MeV/c11.3 msr
at 660 MeV/c11.5 msr
at 693 MeV/c11.5 msr
at 726 MeV/c11.5 msr
Resolution.(with 2 mr multiple)
(scattering at focal plane)0.02%
D/M4.56 cm/%
Flight pathat 660 MeV/c6.70 m
Angular acceptance.(bend plane)±85 mr
(non-bend plane)±43 mr
Focal plane tilt
Total bend angle
Angular range
Angular resolution. (1 mm beam spot)
(with no front end chamber)
with no front one onemotion of the

Table I. SASP Specifications.

The first order transport calculations produced the following transfer coefficients:

R(11) = -0.6149	R(12) = 0.0000	R(16)=2.8047
R(21) = +4.1438	R(22) = -1.6307	R(26)=5.8482
R(33) = -4.0609	R(34) = -0.2000	
R(43)=-12.7623	R(44) = -0.8743	

The details of the intrinsic resolution as a function of the momentum is shown in Fig. 1. Folded into this calculation is 2 mr of multiple scattering in the focal plane proportional chambers. This type of resolution implies that for the pion production experiments, as an example, the energy resolution on the detected pion would vary from 46 keV to 165 keV for the (p,π) reaction on 28 Si. The better resolution occurring at 200 MeV incident proton energy and the other for 500 MeV incident energy.

The preliminary design of the spectrometer indicates no insurmountable engineering tasks. What we want to build requires standard engineering solutions to all the design problems. Figure 2 shows the general layout and dimensions of the spectrometer, including an initial idea for the support frame, the detector array support and the shielding.

The general features to point out are the fact that the 90° bend and the low position of the focal plane will make it quite easy to shield the direct target background radiation. The focal plane detector array will consist of vertical drift chambers with both x and y sensitivity (as per the MRS), segmented plastic scintillators and a Cherenkov counter for pion coincidence (and to reject the protons of the same momentum). The "beam dump" location for operating the spectrometer at zero degrees is sketched in at its approximate location. The first quadrupole will be removable to allow the insertion of the (n,p) target for recoil measurements.





Fig. 2. Overall layout of the Second Arm Spectrometer (SASP).

There are three magnetic elements: a multipole doublet followed by a clam shell dipole. The maximum central momentum for the high resolution design will be 660 MeV/c; however, all the coils and power supplies for the dipole and the multipoles will be designed to be capable of producing 10% more magnetic field than is necessary for the 660 MeV/c. The overall assembly of the SASP system will allow easy transfer of the spectrometer to other experimental areas within the present and future areas of TRIUMF.

The multipole element nearest to the target chamber and hence the one that will come nearest to the beam line will have to be specially designed to allow as close an approach to the beam line as possible. If a design similar to that of the MRS open sided quadrupole (shown in Fig. 3) is adopted then a minimum angle of 20° seems possible. The closest angle of approach between the MRS and the SASP must be less than 60° ; therefore, care must be taken in making sure the first MRS quadrupole does not require the same space that either of the SASP quadrupoles might require. The present layout indicates that an approach angle of 40° is feasible.

The characteristics of the multipole nearest the target chamber are the following: The maximum quadrupole strength at the pole will be 8.50 kG and the sextupole will be 1.01 kG. Its effective length will be 30 cm and its aperture will be 20 cm. The minimum angle of approach it will have to the beam pipe will be 20° .

The second multipole will have a maximum quadrupole strength of 8.5 kG and a sextupole field of 0.10 kG. Its aperture will be 20 cm and



Fig. 3. Sketch of the MRS open sided quadrupole. This could be a first order design for the SASP front end quadrupole. its effective length will be 38 cm. The pole pieces will be detachable and will be shaped to provide the higher multiple components.

The drift lengths from the target to the dipole are the following:

target to first quad(FEQ)=0.70 m
first quad to second quad(BEQ)
 = 0.32 m
second quad to dipole = 1.20 m

There may be some magnetic coupling between the two elements, because of the short drift length from the first to second quadrupoles. The aperture of both quadrupoles is 20 cm.

There will not be sufficient room between the two elements to place a vacuum connection, hence the pipe should be inserted through both quads during assembly. Both elements will be separately mounted on a rail system that will allow them to be moved radially, with extra positional adjustments both vertically and

transversely. The vacuum system will be designed in such a way that either quadrupole can be removed from the assembly to allow the insertion of special targets or chambers.

The clamshell dipole has a tapered magnet gap ranging from 10 cm at the inside radius (with a maximum field of 1.6 T) to 15 cm at the outside radius (with a field of 1.07 T). Figure 4 shows a copy of a sketch that H. Enge prepared for this design. The dipole will weigh 90 tons, and the power supply will require 150 kW. The design will allow the coil power to be increased so as to produce fields 10% higher than those mentioned above. This would cause the magnet to go into saturation where the gap is approximately 10 cm, but would still provide a useful albeit lower resolution operation for momenta beyond 720 MeV/c. How far we go is obviously going to be determined by cost considerations. The bottom of the dipole comes within 20 cm of the floor, thus placing some special constraints on the support frame design.

The coils of the dipole will have to be saddle shaped at the entrance and exit to allow the insertion of field clamps to ensure that the magnetic field conforms to the concave shape of the pole edges.

The spectrometer should be able to operate at zero degrees in the laboratory, but at lower beam intensities. There is enough room to insert some shielding to shadow the beam spot from the focal plane detector.

The vacuum chamber will not be self-contained in that the magnet poles will form part of the chamber wall, hence putting the pole pieces inside the vacuum. This has the advantage that the full magnet gap can be utilized, with no dead space due to vacuum chamber walls. The connections between the spectrometer vacuum and the scattering chamber vacuum





Fig. 4. Sketch of the Clam dipole, prepared by H. Enge.

is to be via a sliding seal. Provision will be made for the insertion of a front end low pressure wire chamber if certain special experiments require it. A couple of access ports for magnetic field probes for the dipole are also required.

Figures 5 and 6 show views of the MRS and SASP in combination with a conceptual design of the SASP frame. A free standing frame is preferable but the vertical dimensions of the dipole may not allow this. The concept of having the dipole built into the frame structure is acceptable. The centre post connection and drive wheels will be attached directly to the magnet. The drive mechanism and angular readout will be controllable remotely. The support frame and drive must match with the centre post on the MRS and allow a mutual approach angle between the MRS and SASP of less than 60° for the (p,2p) requirements. The present design allows this angle to be as small as 40° . The drive mechanism will be designed to minimize positional hysteresis and to avoid correlated errors between



Fig. 5. Overall layout of the MRS and the SASP. Elevation view.



Fig. 6. Overall layout of the MRS and the SASP. Plan view.

components of the motion (i.e., vertical motion from air pads should not cause a shift in theta).

The 90° bend of the dipole allows us to employ a compact support structure for the shielding and the focal plane detector array, which will not impinge on a large area of the proton hall. The design can be made in such a way that different experimental detectors can be

interchanged easily and accurately, a philosophy that was successfully applied with the Resolution Spectrometer that the (p,π) group used on beamline 1B.

Good personnel access is essential. The basic detector support should be easily removable from the area to allow preassembly of specialized detectors. The cable access will be designed in such a way as to allow full rotation of the system without fouling the lines.

The detector array will consist of three types of counters: vertical drift chambers, for trajectory information; plastic scintillators for dE/Dx, TOF and trigger information; and a Cerenkov counter for fast pion identification and rejection of the high momentum but low velocity protons. The focal plane angle is about 45°, with the lower end nearer the target.

About 20 cm thickness of iron shielding will be used to shadow the focal plane detectors from particles emanating directly from the target. Experience with the MRS has shown that the remaining particles hitting the focal plane detectors do not originate directly from the target, but are neutral particles in the proton hall. Shielding from this background would require enclosing the detectors in a shielded box, an expensive proposition which we do not consider at the present time. We would rely instead on a stringent event trigger to eliminate unwanted background, hence the need for the multiple layers of focal plane detectors.

The data acquisition system must be capable of operating in a single channel mode with the SASP spectrometer on its own or in a two channel mode with the SASP and MRS in coincidence. Both the MRS and SASP must be operated independently at the same time and the acquisition system must allow such a mode with ease and transparency. Given the present CAMAC hardware constraints, this would seem to imply a separate crate controller system for each spectrometer in which the fast trigger logic of each spectrometer would both define an event. If these events were from single arm experiments, then there would be no further logic. If these events had to be in coincidence, then one more level of logic would be required in order to set both CAMAC systems into the transfer mode to the computer.

There should be some effort to make the SASP system from the latest state of the art electronics. There is every indication that the data and singles rates in the focal plane detector could be quite high.

The software support for the SASP should consist of the following types of programs:

a) A basic introduction to the system. This program would be a menu driven program, which would provide the new or inexperienced user with all the information he would need to know in order to prepare for, perform, and analyze a SASP or SASP/DASP type of experiment. This program would also help him initiate and operate the data acquisition and any local analysis he might want to do.

b) The data acquisition program. This program should be callable from the "Introduction" program or directly callable by a simple terminal command. It must perform several functions as well as being user friendly (i.e., jargon free, easy command structure, changeable on line). Its two main subfunctions would be:

 diagnostics: real time analysis of a portion of the data. This process must be changeable easily during a shift. ii) data taking and storage: high speed, tape or disk storage with a format structure compatible for all major computer systems on which the final analysis may be done. The technical details should not have to be dealt with by the "average experimenter" (i.e., the default choices must be well chosen), but the technical details should be well described so that the average experimenter can understand.

In order to do the coincidence experiments between the SASP and the MRS, two major items of the present MRS system will have to be changed.

The scattering chamber: To allow reaction products into both spectrometers, a window subtending 160° on both sides of the beam will be required, as will independent angular adjustments of the spectrometers. This probably means the construction of a completely new scattering chamber.

The MRS support frame: In its present form, the MRS support frame will not allow the two spectrometers to be set any closer than 90° apart in angle. A preliminary design has shown that the front end of the MRS frame could be modified to allow a much closer angle of approach for the two spectrometers. However, the work represents a considerable amount of reconstruction at the front end of the present frame.

In summary, the objectives of the feasibility study have been fully met. A Second Arm Spectrometer can be built which in combination with the MRS will provide TRIUMF with a world class dual spectrometer facility for studying proton-nuclear interactions.

The present funding schedule for the project calls for the major items to be delivered in the fiscal years 87/88 and 88/89. This schedule is contingent upon getting strong support from the TRIUMF EEC meeting to be held in July of 1986.

THE DASS/SASP DATA ACQUISITION SYSTEM

G. Ludgate

TRIUMF, 4004 Wesbrook Mall, Vancouver, B.C., Canada V6T 2A3

INTRODUCTION

When discussing the data acquisition and analysis system for DASS/ SASP one can afford to be a little speculative as time is on our side and a few months can see dramatic changes in price/performance for hardware. The SASP is basically another spectrometer, and TRIUMF already has one successful example of a large spectrometer and its data acquisition system, the MRS. But let us continue as though we were starting afresh.

USER REQUIREMENTS

The basic requirement of all data acquisition systems in nuclear and particle physics is to gather events of physics interest, with a minimum of "background", as fast as possible. Do we have anything to learn from the large particle physics experiments in exploiting the natural concurrency of this problem and can it be applied to help DASS/SASP? We will return to the question later.

DASS/SASP can, as the full name implies, operate in conjunction with the MRS or stand alone. The required operating modes are therefore:

- MRS independently, alone
- SASP independently, alone
- Subdetectors of MRS or SASP independently and concurrently
- MRS and SASP independently and concurrently
- MRS and SASP dependently and concurrently as DASS

These modes are easily justified. The MRS (SASP) may be required for an experiment which precludes the operation of the SASP (MRS) due to experimental conditions or physical space requirements. It must be possible to switch quickly between these two independent modes.

Likewise it is not hard to envisage that during a period of setting up equipment physicists may wish to trigger one or more subdetectors (called partitions) of the MRS and/or SASP independently and at the same time. Event trigger hardware and data acquisition software must both accommodate rapid changes into and out of this mode. The triggers from each partition must not interfere with each other and the event-data must find its way back to the correct analysis or logging process on the controlling host computer.

There may be times when both spectrometers wish to run independently but at the same time. Essentially one would then need to duplicate the present MRS system. The most interesting requirement is when MRS and SASP are to be run in concert as DASS.

The complexity of these modes coupled with the "inner working" of each mode led to the requirement that a computed-aided instruction (CAI) program be produced for those users who were just starting to use the system for the first time or else were infrequent users. Regular users would expect to interact more directly with the system in a more traditional manner.

TRIUMF DA PLANS

The "standard" data acquisition system at TRIUMF has been, for several years, a DEC PDP-11 running a modified version of MULTI/DA. Other data acquisition systems are in use on DEC and Data General computers but they all suffer from the same limitation, namely:

- The 16-bit vertical address space limits the size of programs and data structures.
- The computers are based on a single bus architecture connecting memory, the CPU and all peripherals, which has a bandwidth closely matched to the normal requirements of the CPU. Any activity on the bus therefore leads to a slowing of the CPU and thus the ability to analyse data.

The next generation system will be one that supports both data acquisition and data analysis concurrently. It will be based on the DEC VAX-11 family of computers, and each system will come equipped with a 6250 bpi tapedrive, a disc of the order 450 Mb, to provide a firm base for both of the primary functions. The new systems will initially be connected to CAMAC data acquisition hardware. The System Crate architecture has been selected for systems carrying out event-by-event experiments. Its advantages are:

- supports up to 7 CAMAC branches each with up to 7 crates.
- supports a multiprocessor architecture a CES 2180 STARBURST will be located in the System Crate to perform the real-time task of acquiring data from CAMAC modules and buffering it for transfer to the VAX.
- supports a DMA device that can autonomously perform CAMAC commands and transfer the results directly into VAX memory.

Other data acquisition hardware systems, such as VME or FASTBUS, could also be easily interfaced.

On the software side the intention is to provide support for easily programming data acquisition and real-time event rejection in the STARBURST and to provide a framework wherein these data are transferred to the VAX transparently. Once on the VAX, analysis programs having an interest in the data must be able to obtain the data quickly and with a minimum of users programming and, similarly, output from these programs should be made available to a further set of analysis programs, etc. One or more of these programs would likely write the data to tape, as convention dictates.

Of increasing interest in the data acquisition world is the use of networks, both local and continental in scope. The use of these networks will be promoted.

In summary TRIUMF intends to support a number of software tools for which a data acquisition system could be built and tailored to the needs of a facility or a particular experiment, and to document these tools on paper or, more importantly, on line.

The progress to date can be quickly listed as:

 the purchase of a VAX-11/750, 6250 bpi tapedrive and 400 Mb disc, targetted for MRS

- the purchase of a MicroVAX II
- the purchase of a System Crate CAMAC system complete with STARBURST and DMA controller
- the completion of the software architecture and about 50% of its implementation
- the start of documents, in earnest

DASS/SASP HARDWARE

If you consider data acquisition to be mainly a communication problem then the discussion of the hardware breaks down into:

- the micro-area network, the traditional data acquisition computer and front-end electronics
- the local area network
- the wide area network

The micro-area network for the MRS is CAMAC and NIM, but it may make good sense for some or all of DASS/SASP to be in FASTBUS. This is economical if the fast readout of a large number of channels is required, and after all it is the total cost that matters for the detector, its output electronics and the digitizing electronics. A detector with more channels read by FASTBUS may be cheaper than one with fewer, perhaps more sophisticated, channels read by CAMAC.

For the MRS and SASP to run concurrently as DASS one host VAX computer with two tapedrives may not be adequate if the users require sophisticated reconstruction algorithms for a good percentage of the acquired events. A MicroVAX II may well be required to handle the computation load (probably not the data transfer load). In fact it would be too difficult to incorporate the MicroVAX II into the System Crate as an analysis-only computer and allow another computer to record the data onto tape. In general the MRS and SASP data acquisition systems should be characterized by incorporating multiple microprocessors into their design to enrich the final datastream being written to tape.

The word 'tape' used in the previous paragraphs can be regarded as standing for 'tapedrives' or 'as yet to be purchased data-recording devices' such as optical discs, now available in 1, 2 and 4 gigabyte write-once varieties.

The local area network at TRIUMF is based on DECNET carried over Ethernet. This network allows VAX users such features as remote log-in, file transfer, remote printing, messaging, etc. Users of the DASS/SASP system should not, therefore, feel restricted to the host computer for that system. It would be just as easy to perform real-time analysis of data on the 8600 cluster as on the host itself. As long as the event analysis time is longer than the event copying time (over the network) a factor of 4 in speed could be expected by using the 8600.

For the wide area network several choices exist and more may be on the horizon. It is possible today to obtain 9600 bits-per-second network links into and out of TRIUMF over BITNET, DECNET, HEPNET, DATAPAC and COLOURED BOOK. The software packages that 'drive' these networks allow you some of the functionality available in the local area network. This picture will change in the near future due to the computer protocol standardization work of the CCITT and ISO bodies. Full functionality between any two vendors' computers is nearly here. The new technology and software developed for the ISDN telephone exchanges will make 65 kb per second a standard speed for data (and voice) communications. Higher speeds of 1.5 Mb per second will be more easily available as all switching and transmission move to become fully digital. One may be able to ship data home - in real time.

DASS/SASP SOFTWARE

A computer-aided instruction program will be made available to help new users and remind infrequent users of the operating principles of the DASS/SASP data acquisition and analysis system. The program could be driven by menu commands, light pen, touch screen, mouse, track ball or by voice command. Colour terminals will be heavily in use. The program will lead users through trails of their interest showing how to configure programs for analysis and start the system acquiring data. The tutorial program would invoke a command-driven control program for users to test their knowledge before continuing.

The command-driven program would be for more experienced users and would be the means by which the front-end electronics are initialized and a run started. The aim of the software system is to both acquire data and to allow its easy analysis before being stored. Multiple microprocessors could be employed in the front end to examine raw events in real time and filter out those events that would be normally rejected by offline analysis. This enriching of the datastream reduces the processing load of re-examining the data off line. Well planned experiments may have the software systems complete before an experiment begins and be able to record useful physical parameters of interest rather than the results of digitization as is often the rule today.

SUMMARY

The recent speed increases in both acquisition hardware and analysis computers have opened up the possibility of significantly reducing the amount of data stored for an experiment by converting it to information in real time (information is processed and summarized data). This reduces the off-line workload and leaves more time for extracting physics from the information and for planning future experiments. The step required to embrace this is to ensure software systems for experiments are ready and tested before the experiment begins, as are the hardware systems. This is not always possible for every experiment, but it should be possible for most facilities constructed at TRIUMF and for a series of experiments of a similar nature.

NUCLEAR REACTIONS WITH INTERMEDIATE ENERGY PROTONS*

R. Dymarz Theoretical Physics Institute, University of Alberta, Edmonton, Alta. and TRIUMF, Vancouver, B.C.

ABSTRACT

Nuclear reactions initiated by the intermediate energy protons in which only nucleons are identified in the exit channel are addressed. First the effective nucleon-nucleon interaction and the optical model potential is defined and next exclusive and inclusive (p,N) and (p,p'N) reactions are discussed.

1. INTRODUCTION

The nucleon is one of the most powerful probes to study a nuclear structure and nuclear forces. The interaction of nucleons with nucleus should be, in principle, treated within many-body theory of finite systems. At present such treatment is possible only with several drastic approximations and in practical calculations we rely on simple models which, fortunately, become more and more "microscopic". The common feature of these models is the separation of reaction mechanism from the nuclear structure effects and from the problem of nucleon-nucleon (NN) interaction in the nuclear environment. In my talk I will cover the first and third aspect of the problem. The arrangement of my talk is following: In section 2 I will describe briefly both the construction of the effective NN potential from free NN scattering matrix (t_{NN}) and in the nuclear matter and the construction of the microscopic optical potential. In section 3 I will comment on elastic scattering, inelastic scattering and on charge exchange reactions (p,n) leading to the discrete, excited states in the final nucleus. In section 4 I will talk about reactions (p,p'N) in the quasi-free region which also lead to well defined states in the residual nucleus. The reactions with the state of final nucleus well defined are generally called exclusive reactions. In contrast in section 5 I will discuss inclusive (p,p') and (p,p'N) reactions where states of the final nucleus is not identified. Conclusions are presented in section 6.

2. THE EFFECTIVE NN INTERACTION

The NN potential can be written in a general form

$$V_{eff}(r) = V_{C}(r) + V_{LS}(r)L + S + V_{T}(r)S_{12}$$
(1)

where S is a total spin, L - angular momentum of relative motion and $S_{1,2}$ is the tensor operator. The central part of the interaction can be

[&]quot;Work supported by the Natural Sciences and Engineering Research Council of Canada.
decomposed in the spin $(\sigma)/isospin (\tau)$ space as follows

$$V_{c}(\underline{r}) = V_{o}(\underline{r}) + V_{\sigma}(\underline{r})(\underline{\sigma}_{1} \cdot \underline{\sigma}_{2}) + V_{\tau}(\underline{r})\underline{\tau}_{1} \cdot \underline{\tau}_{2} + V_{\sigma\tau}(\underline{r})(\underline{\sigma}_{1} \cdot \underline{\sigma}_{2})(\underline{\tau}_{1} \cdot \underline{\tau}_{2}).$$
(2)

The spin-orbit part $V_{LS}(\underline{r})$ and tensor part can also be decomposed into isoscalar/isovector components. The above representation is in the form of the transferred quanta and is convenient in analysis of inelastic scattering. The relations with other representations is given in Ref. 1.

The local representation of the effective NN interaction is a drastic approximation to the realistic situation and is motivated rather by practical reasons (simplicity of using it in the nuclear reaction calculations) than on physical ground². This local form of the V_{eff} is usually related to the experimental free NN t-matrix (t_{NN}) when used in the impulse approximation calculations or to the nuclear matter g-matrix when medium effects are expected to be important.

The procedure of deriving V_{eff} from t_{NN} is, unfortunately, not unique. The most popular one seems to be the one developed by Love and Franey³. In Ref. 3 the $t^{NN}(E,q)$ is expressed by a local coordinate space interaction with antisymmetrization included explicitly in NN system (and in N- nucleus system when V_{eff} is used in nuclear reaction calculations):

$$t_{NN}(E,q) = \int d^{3}r \ e^{-ik' r} \ V_{eff}[1 + (-1)^{L}p^{x}]e^{ik \cdot x} .$$
(3)

Here P^{X} is the space exchange operator and $(-1)^{L}$ ensures antisymmetrization. For computational simplicity $V_{O}(r)$ and $V_{LS}(r)$ in Eq. (1) are taken to be a sum of the Yukawa (Y(r)) functions and $V_{T}(r)$ is taken to be Y(r)*r². The strengths of the potentials and ranges of the Yukawa function are searched such that the right hand side of Eq. (3) reproduces experimental t_{NN} on the left hand side of Eq. (3). The parameters are tabulated for proton laboratory energies 50-1000 MeV.² There are many uncertainties in these parameters. They come, for example, from errors connected with experimental t_{NN} , from representing V_{eff} by Yukawa functions, or from procedure of searching for "best" parameters. The errors introduced to N-nucleus calculations can be significant especially at higher momentum transfer.

The medium effects (like Pauli blocking or Fermi motion) are incorporated into the nuclear matter g-matrix which satisfy the Bethe-Goldstone equation

 $g(\omega, k_F) = V + VG_O^+(\omega, k_F)g(\omega, k_F) , \qquad (4)$

where V is an NN bare potential, ω is the total energy of the interacting nucleons and k_F is the Fermi momentum. The Green's function $G_0^+(\omega, k_F)$ obeys the outgoing boundary conditions and contains medium effects which arise from the requirement of propagation in unoccupied intermediate states under the influence of the average potential in the nuclear medium. There are several calculations along this line reported⁴⁻⁶ but in analyses at intermediate energies the most frequently used is the so called "Hamburg potential"⁶. The Hamburg potential is the g-matrix calculated with Paris NN-potential and approximated by a sum of Yukawa functions as was described earlier for the Love and Franey potential³. The parameters of this potential are tabulated for several k_F and for several proton laboratory energies between 60 and 400 MeV.⁶

The Brueckner g-matrix is commonly interpreted as an effective interaction and used in analysis of elastic and inelastic scattering. The advantage of using g-matrix instead of V_{eff} derived from t_{NN} was demonstrated in some cases. However, while using the g-matrix in the microscopic construction of the optical potential has been justified by Hufner and Mahaux⁷ within the hole-line expansion theory, no derivation or justification of the use of the Brueckner g-matrix for inelastic transitions exists. Rather—as was shown recently⁸—this assumption is not quite correct when density dependence of g-matrix is strong. In addition to this basic problem there are uncertainties in g-matrix connected with the approximations adopted in numerical calculations. These uncertainties can already be seen in elastic scattering, where g-matrix enters through the optical potential only.

The optical potential for finite nuclei is usually calculated in the folding model which can be interpreted as a first-order (single scattering) approximation within multiple scattering formalism. The optical potential can be written in this approximation as a sum of the local direct (D) and non-local exchange (EX) terms which both are energy dependent (see Ref. 9 for discussion and further references)

$$U^{\text{NL}}(\underline{r}_{1},\underline{r}_{1}',E) = \delta(\underline{r}_{1}-\underline{r}_{1}')\int d\underline{r}_{2}\rho(\underline{r}_{2})V^{\text{D}}(\underline{r}_{1},\underline{r}_{2},E) + \rho(\underline{r}_{1},\underline{r}_{2})V^{\text{EX}}(\underline{r}_{1},\underline{r}_{2},E), \quad (5)$$

where $r_1(r_2)$ is a coordinate of incident (bound) nucleon. One can define local equivalent optical potential

$$U(\underline{r}_{1}, E) = \int U^{NL}(\underline{r}_{1}, \underline{r}_{1}', E) \psi(\underline{r}_{1}') d\underline{r}_{1}' , \qquad (5')$$

where ψ is the scattering wave function of the incident nucleon. Certainly, the approximation of nonlocal potential by local one may well be a source of significant errors. The next approximation is to replace nonlocal interaction $v^{D(EX)}$ by the corresponding local and energy- (and density- in the case of g-matrix) dependent effective interaction

$$V^{D(EX)}(r_1, r_2, E) \approx g^{D, EX}(|r_1 - r_2|, \rho, E)$$
.

To eliminate $\psi(r')$ from Eq. (5') usually a local momentum approximation is used giving a final expression for the potential

$$U(\underline{r}, E) = \int \rho(\underline{r}_2) g_C^D(\underline{s}, \rho(\underline{R}), E) d\underline{r}_2 + \int \rho(\underline{r}_1, \underline{r}_2) g_C^{EX}(\underline{s}, \rho(\underline{R}), E) j_O(k|\underline{s}|) d\underline{r}_2 ,$$

where $s = r_1 - r_2$ and $R = (r_1 + r_2)/2$ and C refers to central part. The nuclear matter density is $\rho(r)$ and $\rho(r_1, r_2)$ is the mixed density matrix, while j_0 is the Bessel function of zero order. The evaluation of mixed density involves further approximations and not being unique is a source of additional uncertainties. Comparing calculations with the experimental data it should be remembered that all these approximations

are made for the purpose of simplifying calculations and may not be correct in a particular reaction.

In the relativistic approach a parallel development of models follows. However, for example, the optical potential is usually calculated¹⁰ in the so-called "tp" approximation with t being the experimental free $t_{\rm NN}$ matrix. In this approximation exchange is taken into account implicitly and only recently the relativistic analogue of the Love and Franey³ potential (exchange treated explicitly) has been constructed and used in p-nucleus calculations¹¹.

Due to the approximate treatment of exchange the " $t\rho$ " is not quite correct in elastic scattering (see discussion in section 2) and is erroneous in inelastic scattering where sometimes the contribution from knock-out exchange term is of the same order of magnitude as a direct term. (See Ref. 12 for detailed discussion of the relativistic approach to inelastic scattering and further references).

The relativistic Brueckner-Hartree-Fock calculations in nuclear matter were initiated by the Brooklyn group¹³ and have been reported by other authors¹⁴. However, the resulting relativistic g-matrix was not used systematically in constructing the optical potential or in the inelastic scattering calculations.

3. THE ELASTIC AND INELASTIC (p,N) SCATTERING 'NO BOUND STATES

3.1 Elastic scattering

In the context of the problems discussed in the preceding section a few observations can be made:

(a) A differential cross section is not very sensitive either to the medium effects or to the relativistic effects. However, it is essential in both the nonrelativistic and relativistic approach that exchange is taken explicitly in N-nucleus scattering (see Ref. 15). In Fig. 1 we show the differential cross section as a function of the momentum transfer squared. In part (a) of the figure the experimental data are compared with the relativistic impulse approximation calculations in the "tp" approximation and in part (b) comparison is made with the nonrelativistic folding model calculations in which nuclear matter g-matrix was used. One can see that energy dependence of the cross section at relatively small momentum transfer is not reproduced well in relativistic "tp" model while it is well reproduced in the nonrelativistic model where exchange is taken explicitly into account.

(b) A large momentum transfer cross section can be reproduced neither within relativistic approach nor nonrelativistic models with nuclear matter g-matrix. The diffraction pattern of the calculated cross section is shifted towards smaller q in comparison with the experimental one. The mechanisms other than those included in the models discussed probably are important at large q.¹⁶

(c) Even with nuclear matter g-matrix the experimental cross section in scattering on light nuclei is reproduced only qualitatively (see Fig. 2).

(d) The total reaction (σ_R) and total $(\sigma_T = \sigma_R + \sigma_{ELASTIC})$ cross sections are too large when calculated within nonrelativistic model (IA or with g-matrix) (see Fig. 3). The relativistic models work well but probably medium effects have to be taken into account at low energies (see Ref. 16).

- see next page -

Fig. 1. The differential cross section for p^{-208} Pb elastic scattering. The solid lines represent the results of (a) relativistic impulse approximation calculations and (b) nonrelativistic folding optical model with medium modified effective NN interaction. The upper momentum transfer squared scale is for the upper curves and the bottom one is for the lower curves.



Fig. 2. The elastic scattering cross section of proton on ^{16}O at E_p =135 MeV. The solid line (G) and dashed line (G₀) represent the results of the calculation with the full g-matrix and with the g-matrix at ρ =0, respectively.



Fig. 1.





Fig. 3. The total reaction (σ_R) and total (σ_T) cross sections. The curves RIA and RMM represent relativistic impulse and relativistic medium modified calculations respectively. The curves NRIA and NRMM represent nonrelativistic impulse approximation and medium modified (with nuclear matter g-matrix) calculations. See Ref. 15 for details and references to experimental data.

3.2 Inelastic and charge exchange scattering

The inelastic and the charge exchange scattering of protons probes different components of the V_{eff} . Below are shown the transitions with transferred spin (Δ S) and isospin (Δ T), the corresponding components of the central part of the effective NN interaction and the states (or resonances) excited:

Interaction:	vo	ν _τ	Vσ	Vgt	
(ΔS,ΔT):	(0,0)	(0,1)	(1,0)	(1,1)	
State or	GQR	GDR	2-,3+	ML	
Resonance:	first 2+,3	IAR		GT	

where GQR (GDR) refers to the giant quadrupole (dipole) resonance, IAR is the isobaric analogue resonance and GT and MI refer to Gamow-Teller and magnetic dipole resonances respectively. The spin-orbit and tensor part of the $V_{\rm eff}$ contribute also to some of the transiton indicated above but this contribution is significant at large momentum transfer.

The excitation with (0,0) transition is strongest; about 10 times stronger than excitations with other terms of interaction involved. Because of this the transitions to the natural parity states $(\pi = (-)^J)$ and GQR have large cross section. Usually these transitions are analysed within collective model with transition potential proportional to the derivative of the optical potential which although contains also other pieces of NN interaction is dominated by V_o component.

The analysis of experimental data on (p,n) reaction suggests that all the Fermi strength (V_{τ}) is collected in the IAR. In contrast to to this in the Gamow-Teller transition ($\Delta S=\Delta T=1$), mediated by spinisospin component of the force $(V_{\sigma\tau})$, only about half of the strength was found¹⁷. It was suggested that this missing strength is hidden in the background even at high excitation energies or the transition is quenched by the intermediate Δ formation¹⁹ (see also Ref. 20 for discussion of quenching). Details will be discussed in the talk by S. Yen.

A similar quenching to that measured in the GT transitions was found in ML transitions in many nuclei both with $\Delta T=1$ and $\Delta T=0$ and it gave impetus for searching this missing strength in background as $\Delta T=0$ transition cannot be quenched by virtual Δ excitation.

A quenching is defined as a ratio of experimental cross section to the calculated one. Usually the cross section is evaluated in the DWIA or with g-matrix as a transition potential. It is obvious that both the transition potential and the distorting optical potential should be calculated correctly before any firm conclusion can be drawn about correct value of quenching.

4. EXCLUSIVE QUASI-FREE PROTON SCATTERING

The quasi-free reactions (p,p'N) and (e,e'p) were from the beginning designed to study one-particle aspects of nuclear structure. The mechanism of quasi-free scattering was supposed to be simple: incoming particle knocks out nucleon in the nucleus which remains in a one-hole state. The experimental data are analysed usually in the impulse approximation (IA) with the formula exhibiting this simplicity (see Ref. 21 for references)

$$\frac{d\sigma}{d\Omega_1 d\Omega_2 dE_1} = KC^2 S \left[\frac{\gamma}{M} T^{\alpha \Lambda M} \right]^2 \sigma(\theta_{pN}) , \qquad (6)$$

where K represents kinematical and phase-space factor C^2S is the spectroscopic factor of the struck nucleon and $\sigma(\theta_{\rm pN})$ is the off-shell differential pN cross section. The scattering matrix T has the form

$$T^{\alpha LM} \sim \int \chi_{2}^{(-)*} \chi_{1}^{(-)*} \phi_{L\Lambda}^{\alpha} \chi_{0}^{+} d^{3}r$$
(7)

where χ 's are the scattering wave functions of the incoming (o) and outgoing (1,2) nucleons and ϕ is overlap of the initial and final nucleus wave functions. In the distorted wave impulse approximation (DWIA) χ 's are calculated in the optical potential in the proper channel and $\sigma(\theta_{\rm DN})$ is taken on the energy shell. The function ϕ is calculated usually as a single particle bound state wave function in a Woods-Saxon potential.

The Eqn. (6) is derived from the full lowest order distorted- wave Born approximation formula for the amplitude²²

$$T = \int d^{3}\mathbb{R} d^{3}\mathbb{r} d^{3}\mathbb{r}' \chi_{1}^{(-)*}(\underline{k}_{1}, \underline{R} + \frac{1}{2}\underline{r}) \chi_{2}^{(-)*}(\underline{k}_{2}, \underline{R} - \frac{1}{2}\underline{r}) \times V(\underline{r}, \underline{r}') \chi_{0}^{+}(\underline{k}_{0}, \underline{R} - \frac{1}{2}\underline{r}') \phi(\underline{R} + \frac{1}{2}\underline{r}') , \qquad (8)$$

where $V(\mathbf{r},\mathbf{r}')$ is NN effective interaction, R is the centre of mass coordinate of the interacting nucleons and \mathbf{r} and \mathbf{r}' are their relative coordinate in the initial and final states. This derivation is based on many approximations and simplifications and recently with more precise experimental data available, it became obvious that some corrections to the factorized formula (6) are necessary²²,²³. In particular the measurements of the analysing power required that spin orbit distorting potential be taken into account and the cross-sectionfactorized formula be replaced by the amplitude-factorized one²⁴. Such replacement, unfortunately, does not assure the correct description of measured A, for large and/or asymmetric scattering angles²⁵.

In Fig. 4 we compare our DWIA calculations with experimental data for the quasi-free scattering of protons on ¹⁶O at an energy of 200 MeV. The shared energy cross-section and analysing power were measured for the reaction ¹⁶O(p,2p)¹⁵N at angles $\theta_1 = \theta_2 = 47^{\circ}$ (TRIUMF) and for the ¹⁶O(p,p'n)¹⁵O reactions at $\theta_1 = \theta_2 = 45^{\circ}$ (Indiana); both the transitions to the ground (j=1/2) and excited state (j=3/2) were identified. The DWIA calculations were performed as described in Ref. 26 and the cross sections in the figure are plotted with the spectroscopic factors as indicated (i.e. half of the values of simple shell model prediction). The following observations concerning the comparisons presented in Fig. 4 can be made.

(a) The experimental cross section is reproduced only qualitatively within DWIA model.

(b) The spectroscopic factors are too small in comparison with the results of (e,e'p) (see Ref.26 for discussion and further references).

72



Fig. 4. Energy sharing cross section and analysing power for the quasifree reactions (p,p'N) on ${}^{16}O$ at proton laboratory energy of 200 MeV. The curves are DWIA calculations (see text for details).



Fig. 5. The ratio of the (p,2p)/(p,p'n) reactions on ^{16}O with 500 MeV protons. The solid (dashed) curve represents full (with distorting spin-orbit potential neglected) DWIA calculations. The dotted curve is the free scattering (p,p)/(p,n) cross section ratio (taken from Ref. 26).

(c) The analysing power is not reproduced even qualitatively within DWIA model.

In Ref. 26 we have analysed the same reactions as those discussed above but for an incident proton energy of 500 MeV and for asymmetric angles (θ_1 = 21.5° and θ_2 = 35°-75°). The overall conclusions were similar to those mentioned in comment (a) and (b) (A, was not measured). In Ref. 26 we also analysed in details the ratio of the (p,2p)/(p,p'n) cross sections and we have found that this ratio is reproduced neither by free scattering cross section (p,p)/(p,n) ratio nor by the full DWIA calculations (see Fig. 5). I have to mention that in Ref. 26 we used amplitude-factorized formula with the distorting optical potentials (central and spin-orbit) calculated microscopically with the nuclear matter g-matrix as an effective NN interaction. The failure of our attempt to reproduce experimental data satisfactorily convinced us that more precise evaluation of the amplitude (8) is needed. Unfortunately, numerical evaluation of Eq. (8) is difficult to perform and only qualitative estimates²⁷ have been made.

The (p,2p) and (p,p'n) will be discussed in details by W.J. McDonald and C.A. Miller in this workshop. Now I would like to discuss some problems connected with (p,p'N) reactions on ³He and deuterium. As we mentioned earlier the scattering wave functions in Eq. (7) are calculated in the optical model potential. This approach still works for the reaction ⁴He(p,2p)³He²⁸ but the (p,pN) reactions on ³He²⁹,³⁰ and on deuterium³¹⁻³³ are usually analysed in the plane wave approximation (PWA) and the final state interaction is taken into account only occasionally and in an approximate way. In the PWA the expression for T (Eq. (7)) simplifies and the cross section becomes proportional to the momentum distribution of the struck nucleon

$$\frac{d\sigma}{d\Omega_1 d\Omega_2 dE} \sim |\phi(\mathbf{k})|^2 \sigma(\theta_{\rm pN}) \qquad (9)$$

For the deuteron, for example, $|\phi|^2 = u^2(k) + w^2(k)$, where u(k) and w(k)are Fourier transforms of the S and D wave components. It was known for a long time³¹, ³² that the Eq. (9) breaks down for a deuteron momenta k>200 MeV/c. The measured cross section is an order of magnitude larger than that given by Eq. (9) already at k=300 MeV/c. In the recent experiment³³ momentum k=650 MeV/c has been reached and measured cross section was found to be almost constant at large k (see Fig. 6). The enormously large cross section at large k (corresponding large scattering angles $\pm \theta_D$) was explained by production of virtual A. However, the role of Δ 's seems to diminish at large k^{34} and the experiments at large θ_p could determine if mechanisms other than production of virtual Δ is important at large k. A sudden breakdown of formula (9) is in apparent contradiction with the results of (e,e'p) experiments³⁵ where contributions from Δ , meson exchange currents (MEC) and final state interaction are moderate and they are only corrections to the formula (9) (see Fig. 7). The other mechanisms which are missing at large k are multiple scattering effects. Although the multiple scattering corrections when calculated³⁶ were found to be small it seems that the method of Ref. 36 was not accurate at energies where it was applied. The multiple scattering effects are suggested to be



Fig. 6. The differential cross section for d(p, 2p)n reaction at $T_p = 509$ MeV. The dashed curve is the PWIA prediction with the Paris potential. The solid curve is the cross section for virtual Δ -excitation (Ref. 34) and the dotted curve is the incoherent sum of the two (figure taken from Ref. 33).



Fig. 7. Differential cross section for d(e,e'p) reaction. The calculations (with Reid soft core potential) are as follows: BA - with nucleon plane wave functions; N = BA+FSI (final state interaction); IC - isobar configurations; MEI meson exchange current (figure taken from Ref. 35).

important in explaining the experimental results (particularly A_y) in the inclusive reactions (see section 5).

The role of the Λ in the reactions like (p,p'N) or (e,e'p) depends strongly on the amount of energy transferred (ω) to the system by the projectile, i.e. on the kinematical conditions of reaction. The large momentum transfer and small energy transfer in the inclusive electron scattering (e,e') is weakly dependent on the Λ excitation and MEC and (see discussion in Refs. 37 and 38) unlike the inclusive (p,p') scattering (see section 5), it is free of multiple scattering effects. As such it is an ideal process to probe large momentum components of the nuclear wave function through formula similar to Eq. (9). It was shown³⁹ that the cross section for inclusive electron scattering under the above mentioned conditions (large q, small ω) scales (i.e. depends not on q and ω separately but on some combined variable) in variable $y=q\cdot k/|q|$

$$\sigma(\omega,q)d\omega = (Z\sigma + (A-Z)\sigma)F(y)dy ,$$

where $\sigma_{ep(en)}$ are elementary e-N cross sections and F(y) measures the

probability to find a nucleon with momentum k =y. The scaling hypothesis has proved to be correct for both ${}^{3}\text{He}(e,e'){}^{37}$ and ${}^{2}\text{H}(e,e'){}^{38}$ reaction. In both cases the momentum distribution was tested up to k=800 MeV/c and in both cases the substantial underestimation of experimental values of $|\phi(k)|^{2}$ at large k was obtained when the "most reliable" wave functions for ${}^{3}\text{He}$ and deuteron were used.

Recently we have obtained a deuteron wave function with $\Delta\Delta$ components⁴⁰. The presence of $\Delta\Delta$ components in the deuteron wave function has enormous impact on large momentum behaviour of the deuteron wave function $\phi(k)$. As a consequence we are able to correctly reproduce the scaling function F(y) up to y corresponding to k=800 MeV. As we see here and as we will discuss later (section 5) the study of the large momentum components in the nucleus seems to be of great importance. It appears that the cross section in the inclusive scattering of nucleons scales also in a variable related to y and reconciliation of electron and nucleon data appears to be a serious challenge for future experimental and theoretical studies.

5. INCLUSIVE REACTIONS WITH PROTONS

By inclusive reactions we understand all reactions in which the final state of the nucleus is not identified. Those can be the reactions with one (p,x) or more (p;x,y,z) particles in final state detected: the secondary particle can be any particle or light ion $(x,y,z=\pi,N,d,{}^{3}\text{He}...{}^{12}\text{C})$. We will be interested here only with nucleons as secondary particles. The detection of particles in coincidence is experimentally difficult and because of this most inclusive experiments reported are with only detection of one particle in the final state. However, the coincidence experiments are crucial for understanding the mechanism of production of particles in N-nucleus and nucleus-nucleus collisions. (See for a recent review, Ref. 41).

5.1 Inclusive A(p,N) reactions

The shape of the spectrum of the secondary nucleons in inclusive A(p,N) reaction depends strongly on the energy of incident protons and on the scattering angle. Generally at lower energies a broad peak at forward angles is observed as can be seen in Fig. 8. At large angles the peak disappears and eventually at backward angles cross sections fall exponentially as a function of energy (see Fig. 8). At higher energy the peak is not so broad and is followed by a broader one connected with virtual production of Λ isobar (see Fig. 9). As can be seen in Fig. 9 the angular dependence of the cross section at higher energies is very similar to that at lower energies.

(a) Small angle scattering

The broad peak corresponding to not very large energy losses observed at forward angles exhibits a kinematical behaviour expected for the scattering of the incident proton by a bound target nucleon. The energy at the maximum is $\sim q^2/2m$ where q is the momentum transfer and m is nucleon mass. The detailed study of this quasi-free (QF) peak is crucial for understanding the mechanism of the early stage of the nuclear cascade developing in the nucleus in N-nucleus reactions. For



Fig. 8. Comparisons of neutron and proton spectra (solid circles) from the bombardment of an ²⁷Al target by 90 MeV protons with the predictions (solid lines) of a PWIA calculation for quasi-free scattering (taken from Ref. 42).



Fig. 10. Giant resonance spectra at 8° and 16° for a ²⁰⁸Pb target. The heavy arrows indicate the maxima in the broad continuum peaks (taken from Ref. 44).



Fig. 9. Single proton inclusive spectra for 800 MeV protons. Solid curves are drawn for guiding the eye. Arrows indicate the proton momenta for protonnucleon quasi-elastic scattering (taken from Ref. 43).



Fig. 11. Plot of $A_y(\theta)$ versus scattering angle for the region near the centroid of the proposed quasi-free peak and for regions of excitation 10 and 15 MeV above that for the quasi-free peak. The curves show the phase shift predictions for pp and np scattering (taken from Ref. 44). heavier targets where the QF peak composes a great amount of background for the giant resonances (see Fig. 10) a precise knowledge of QF peak would allow a calculation of this background unambiguously.

Although it seems now to be well established that the QF peak originates from single NN collision, a detailed comparison with experiment suggests that other mechanisms (multiple scattering, higher multiple resonances) can contribute to the cross section in this region. The additional information about the reaction mechanisms contributing to the cross section in QF region can be obtained from measurements of spin observables. A few such measurements were reported for analysing power A₄⁴⁴⁻⁴⁶, spin flip S_{NN}^{45,47,48} and other spin transfer coefficients⁴⁹. Although there are some discrepancies between different experiments^{46,47} the general conclusion is that the measured spin observables are in better agreement with free pN values in QF region than off this region. (See Fig.11). The existing discrepancies can be attributed to the distortion effects or to some relativistic effects. The A_i in the Δ region is well reproduced within the nuclear cascade model with intermediate production of Δ^{50} .

(b) Large angle scattering

The inclusive scattering at large and backward angles (with large momentum transfer) is even more interesting than the region of forward angles. The interest in this type of reaction started with the experiment by Frankel et al.⁵¹ where inclusive cross sections of p,d and t production were measured at $\theta=180^{\circ}$ in reactions with intermediate energy protons (600 and 800 MeV) on several targets from beryllium to lead. The measured cross section for secondary particles was fitted by simple expression $\sigma(p) \sim \exp(-ap^2)$ (see Fig. 12). The explanation for production of fast protons at backward direction was first offered by Amado and Woloshyn⁵² in the so called direct knock-out model(DK). The argument of the model is based on the observation that because of large energies and short time involved this should be direct reaction and not statistical. The simplest direct mechanism in the reaction discussed is single pN scattering. Because protons observed at angles θ >90° are in the region kinematically forbidden for free pN scattering, the proposed mechanism requires that the struck nucleons be moving backward with high virtual momentum before the collision. If the model were correct the type of measurements reported in Ref. 51 would be useful in studies of high momentum components of the wave function. The proposed model flourished in several papers and in the so called "quasi-two-body scaling" hypothesis⁵³ which states that in the reactions of the general type A(x,y) where x and y can be N,d or light ions and A is any nucleus the backward cross section is governed by quasi-two-body kinematics with the scaling variable k_{\min} being the minimal momentum of residual recoil nucleus. Later^{54a} it was shown for the (p,p') reaction that this scaling can be interpreted quite differently with the two-body kinematics corresponding to the on-shell scattering before and after collision. The interpretation of experimental data within this simple single-scattering model requires a great amount of the large momentum components in the one-nucleon wave function in apparent contradiction with the results of inclusive scattering of electrons and calculations



Fig. 12. Differential cross section for 180° production of protons. The fits are made with $B_p \exp(-\alpha_p p^2/2m_p)$ (taken from Ref. 51).



Fig. 14. The integrated onenucleon momentum distribution for inclusive scattering of 200 protons, 0.6-1 GeV protons (high energy data fit), electrons and alpha particles (180 MeV/nucleon) (taken from Ref. 54b).



Fig. 13. Analysing power in d(p,p')x reaction at $\theta_p = 120^\circ$ is compared with the free pp scattering and with the values of A_y reported for Li and Ta in Ref. 61 (taken from Ref.64).



Fig. 15(a) The observed experimental coincidence cross section between the forward- and backward-going protons (Ref. 69). The numbers on the curves denote the contour line of the cross section. (b) The calculated coincidence cross section using the deuteron-like cluster model. (c) The calculated coincidence cross section using single scattering mechanism (taken from Ref. 70). with standard models⁵⁵. The differences between the proton and electron data seem to reduce substantially for low incident proton energy^{54b}. In Fig. 14 the so called integrated one-nucleon momentum distribution

$$G(k_{\min}) = \int_{k_{\min}}^{\infty} n(k)k \, dk$$

is shown for inclusive scattering of 200 MeV protons and compared with high energy proton data fit^{54a}, inclusive scattering of electrons and alpha particles. While agreement with electron data is quite satisfactory, the large differences between low and high proton energy data are surprising. It is argued^{54b} that the final state interaction of nuclear fragments is responsible for these differences as at higher energies the multiple scattering effects are much larger than at low energies. The unphysical amount of the large momentum components is necessary to mock up this effect within single scattering model.

There were many other models proposed which fitted the experimental data of Ref. 51 equally well as DK model. Those models ranged from the so called multi-nucleon transfer model⁵⁶ through correlated cluster model⁵⁷ to the equilibrium models⁵⁸,⁵⁹. To falsify at least some of the models new kind of experiments are needed. One of the possibility is to measure "less inclusive" reactions like A(p,p'N) and this subject will be addressed shortly in the next section. The other possibility is to measure some spin observables. Analysing power A, measurements has been reported for few targets⁶⁰⁻⁶⁴. The results of all experiments generally are compatible swith nonzero A,. This suggests that the mechansim of reaction is not statistical and then all models based on statistical arguments should be ruled out from further consideration (and also model or Ref. 56). However, the measured analyzing power also differs from the A, in free pN scattering even at scattering on deuteron 64 (see Fig. 13), suggesting that model like DK is also not quite correct. The multiple scattering effects play probably a major role in determining the A_{v}^{65} but unlike for forward angles no reliable calculations of A, at backward scattering angle exist up to now.

5.2 Inclusive A(p,p'N) reactions

In the inclusive (p,p'N) reaction at least one of the outgoing nucleons is far removed from the kinematic region accessible in the quasi-elastic (p,p'N) reaction discussed earlier, where excitation energy and recoil momentum of the final nucleon are measured. Contrary then to quasi-free (p,p'N) reaction, where both the outgoing nucleons are detected at forward angles (θ_f) , in inclusive (p,p'N) reaction one of them is detected at large angle $(\theta_g > 90^\circ)$. The experiments were performed with the light targets to minimize the rescattering effects of the outgoing nucleons. At energy of 800 MeV reaction (p,2p) was studied on $^{6}\text{Li}^{66}$, at 640 MeV on $^{12}\text{C}^{67}$, at 300 MeV on $^{9}\text{Be}^{68}$.

Recently the results of the most extensive study of the inclusive (p,p'x) experiment have been reported⁶⁹. In this experiment the 800 MeV protons were scattered on C, KCL and Pb targets. The forward $(\theta_f = 15^\circ)$ protons or deuterons were detected in coincidence with the backward protons $(\theta_g = 118^\circ)$ in both the in plane (in pl.) and out of

plane (out pl.) configurations. In the subtracted ($\sigma_{in} pl. \sigma_{out} pl.$) cross section a strong correlation of the maximum of the cross section in both the channels (p,2p) and (p,p'd) was observed. This region of momenta of the two outgoing particles, where the correlation has been seen is well separated from the region of momenta, where the single scattering mechanism in the p-p scattering is expected to dominate and it gives evidence that the production of backward protons comes partly from scattering on deuteron-like clusters. The calculations⁷⁰ within the correlated cluster model reproduce the experimental data quite well (see Fig. 15). It seems that more coincidence experiments along the line of the experiment reported in Ref. 70 are necessary for understanding the mechanism of production of backward protons in inclusive scattering.

6. CONCLUSIONS

The aim of my talk was to give a brief review of topics connected with the reactions induced by the intermediate energy protons and to underline some problems encountered when interpreting the experimental data within the currently acceptable models of nuclear reactions and nuclear forces. The models I discussed were nonrelativistic and I only listed those developed in relativistic approach. It is obvious that in constructing the models the approximations are made for the purpose of simplifying calculations and not on physical grounds. As was pointed out in Ref. 2 the local representation of effective NN interaction is one of the examples of this procedure. The obvious problems with describing data in quasi-elastic (p,pN) reactions as discussed in section 4 seem to support the arguments developed in Ref. 2.

In connection with the discussion of the d(p,2p)n reaction it seems obvious that the relative importance of multiple scattering effects and more exotic mechanisms like the intermediate- Δ formation has yet to be established in reactions in off-quasi-free scattering region. The inclusive scattering of protons in quasi-free scattering region can be qualitatively reproduced in the single scattering approximation. However, understanding the details of the cross section, the spin observables and, in particular, the backward angle scattering require more complicated mechanism to be considered.

I would like to thank Drs. F.C. Khanna and D.M. Sheppard for reading the manuscript.

REFERENCES

- 1. G. Bertsch et al., Nucl. Phys. A 284, 399 (1977).
- 2. E.F. Redish, in: Antinucleon- and nucleon-nucleus interactions, ed. G.E. Walker, Ch.D. Goodman and C. Olmer (Plenum Pub. Corp. 1985).
- W.G. Love and M.A. Franey, Phys. Rev. C 24, 1073 (1981); ibid. C 31, 488 (1985); A. Picklesimer and G.E. Walker, Phys. Rev. C 17, 237 (1978).
- 4. J.P. Jeukenne et al., Phys. Rev. C 16, 80 (1977).
- 5. F.A. Brieva and J.R. Rook, Nucl. Phys. A 291, 299 (1977).

H.V. von Geramb in: The interaction between medium energy nucleons 6. in nuclei (1982) ed. H.O. Meyer (AIP, New York, 1983). 7. J. Hufner and C. Mahaux, Ann. Phys. 73, 525 (1972). T. Cheon et al., Nucl. Phys. A 445, 227 (1985). 8. G.R. Satchler, Direct Nuclear Reactions (Oxford University Press, 9. 1983). 10. J.A. McNeil et al., Phys. Rev. Lett. 50, 1439 (1983). 11. C.J. Horowitz, Phys. Rev. C 31, 1340 (1985); C.J. Horowitz and D. Murdock, Phys. Lett. 168B, 31 (1986). 12. J.R. Shepard et al., Phys. Rev. C 33, 634 (1986). 13. M.R. Anastasio et al., Phys. Rep. 100. 327 (1983). 14. R. Machleidt and R. Brockmann, Phys. Lett. 160B, 364 (1985). 15. R. Dymarz, Phys. Lett. 152B, 319 (1985); ibid. 155B, 5 (1985). 16. R.D. Amado and D.A. Sparrow, Phys. Rev. C 29, 932 (1984). 17. C. Garde et al., Nucl. Phys. A 369, 258 (1981). 18. G.F. Bertsch and I. Homamoto, Phys. Rev. C 26, 1323 (1982). 19. I.S. Towner and F.C. Khanna, Nucl. Phys. A 399, 334 (1983). 20. F. Osterfeld et al., Phys. Rev. C 31, 372 (1985). 21. P. Kitching et al., Adv. Nucl. Phys., ed. J.W. Negele and E. Vogt (Plenum, N.Y., 1985), p. 43. 22. N. Austern, Phys. Rev. Lett. 41, 1696 (1978). 23. D.F. Jackson, Physica Scripta 25, 514 (1982). 24. N.S. Chant and P.G. Roos, Phys. Rev. C 27, 1060 (1983). 25. P. Kitching et al., Nucl. Phys. A 340, 423 (1980). 26. W.J. McDonald et al., to be published in Nucl. Phys. 27. P.C. Wright et al., Phys. Rev. C 17, 473 (1978). 28. W.T.H. van Oers et al., Phys. Rev. C 25, 390 (1982). 29. L.T. Myers et al., Phys. Rev. C 28, 29 (1983). 30. A. Bracco et al., Phys. Lett. 137B, 311 (1984). 31. C.F. Perdrisat et al., Phys. Rev. 187, 1201 (1969). 32. T.R. Witten et al., Nucl. Phys. A 254, 269 (1975). 33. C.F. Perdrisat et al., Phys. Lett. 156B, 38 (1985). 34. A.F. Yano, Phys. Lett. 156B, 33 (1985). 35. S. Turck-Chieze et al., Phys. Lett. 142B, 145 (1984). 36. J.M. Wallace, Phys. Rev. C 5, 609 (1972). 37. I. Sick et al., Phys. Rev. Lett. 45, 871 (1980). 38. P. Bosted et al., Phys. Rev. Lett. 49, 1380 (1982). 39. G.B. West, Phys. Rep. 18C, 264 (1975). 40. F.C. Khanna et al., to be published. 41. D.H. Boal, Adv. Nucl. Phys., ed. J.W. Negele and E. Vogt, in press (also Michigan State University preprint MSUCL-451). 42. B.D. Anderson et al., Phys. Rev. Lett. 46, 226 (1981). 43. R.E. Chrien et al., Phys. Rev. C 21, 1014 (1980); I. Tanihata et al., Phys. Lett. 100B, 121 (1981). 44. J. Lisantti et al., Phys. Lett. 147B, 23 (1984). 45. J.M. Moss et al., Phys. Rev. Lett. 48, 789 (1982). 46. J.A. McGill et al., Phys. Lett. 134B, 157 (1984). 47. S.K. Nanda et al., Phys. Rev. Lett. 51, 1526 (1983). 48. T.N. Taddeucci et al., Phys. Rev. C 33, 746 (1986). 49. T.A. Carey et al., Phys. Rev. Lett. 53, 144 (1984). 50. Y. Tzeng and T. Tamura, Phys. Lett. 129B, 379 (1983). 51. S. Frankel et al., Phys. Rev. Lett. 36, 642 (1976).

52. R.D. Amado and R.M. Woloshyn, Phys. Rev. Lett. 36, 1435 (1976). 53. S. Frankel, Phys. Rev. Lett. 38, 1338 (1977). 54. (a) S.A. Gurvitz, Phys. Rev. Lett. 47, 560 (1981). (b) M. Avan et al., Phys. Rev. C 30, 521 (1984). 55. Y. Alexander et al., Phys. Rev. C 16, 526 (1977); J.V. Van Orden et al., Phys. Rev. C 21, 2628 (1980). 56. H.J. Weber and L.D. Miller, Phys. Rev. C 16, 726 (1977). 57. T. Fujita, Phys. Rev. Lett. 39, 174 (1977). 58. J. Knoll, Phys. Rev. C 20, 773 (1979). 59. T.F. Hoang, Phys. Rev. D 15, 2533 (1977). 60. J. Kallne et al., Phys. Lett. 74B, 170 (1978). 61. S. Frankel et al., Phys. Rev. Lett. 41, 148 (1978). 62. H. Sakai et al., Phys. Rev. Lett. 44, 1193 (1980). 63. G. Roy et al., Phys. Rev. C 23, 1671 (1981). 64. H. Brody et al., Phys. Rev. C 24, 2157 (1981). 65. S. Frankel and W. Frati, Phys. Rev. C 24, 2739 (1981). 66. S. Frankel et al., Phys. Rev. C 24, 2684 (1981). 67. V.I. Komarov et al., Phys. Lett. 80B, 30 (1978); V.I. Komarov et al., Nucl. Phys. A 326, 297 (1979). 68. R.E.L. Green et al., Nucl. Phys. A 405, 463 (1983). 69. Y. Miake et al., Phys. Rev. C 31, 2168 (1985).

70. V. Haneishi and T. Fujita, Phys. Rev. C 33, 260 (1986).

(p,2p) Scattering in Nuclei

W.J. McDonald University of Alberta, Edmonton, Alberta, Canada T6G2E9

ABSTRACT

The potential of the (p,2p) reaction for studying properties of the NN interaction and states of bound nucleons in nuclei has been long recognized and many pioneering experiments have been done. However, the several conditions required for systematic study of this process are only now on the threshold of being realized. The necessary ingredients include:- a) proton accelerators with good energy resolution, high duty factor, and polarized beam capability in the energy range of 200 to 600 MeV, and b) dual arm spectrometer systems capable of isolating discrete nuclear states and covering the kinematical regions of interest both in and out of the reaction plane.

INTRODUCTION

The concept of quasi-free scattering of protons by nucleons in a nucleus came in 1952 at the Berkeley 350 MeV Cyclotron when pairs of protons were observed emerging from a Lithium target bombarded by protons 1,2. The proton pairs were correlated in angle with a spread that was later shown to be consistent with the Fermi momentum distribution of nucleons confined to a nuclear volume 3. It appeared that an incoming proton was being scattered from an individual nucleon moving in the target and that nucleons other than the struck one were not strongly affected. This was an exciting result because physicists now had a way to observe the momentum states of nucleons within the nucleus and examine their momentum distributions. The parallel between this story and the recent discovery of quark-gluon jets emerging from collisions of high energy protons is interesting. Both discoveries represent extensions of Rutherford scattering, one to see the substructure of nuclei and the other to see the substructure of the nucleon constituents.

In subsequent studies of (p, 2p) processes summed energy spectra of the proton pairs were used to determine binding energies of the ejected protons. The results provided direct evidence of shell structure in nuclei by resolving the individual shells predicted by Mayer ⁴ and Jensen et al ⁵ and even demonstrated the expected spin orbit splitting of nuclear orbits ^{6,7}. In the period since these pioneering experiments much experimental and theoretical work has been done and is summarized in several reviews (see for example reference ⁸ for a complete listing).

PRESENT STATUS

To illustrate the present status of (p, 2p) data and interpretation in terms of model calculations I will use some of the results from TRIUMF. Fig. 1 shows some representative missing energy spectra for the $^{16}O(p, 2p)$



fig 1.Separation energy spectrum for 505 MeV ¹⁶O(p, 2p)

These data were obtained for a 500 MeV proton beam with a time of flight spectrometer operating in coincidence with the TRIUMF MRS spectrometer. The resolution is not adequate to separate final states although it does allow a rough separation of $p_{1/2}$ and $p_{3/2}$ groups. The inability to resolve individual states is a serious limitation when one attempts to do spectroscopy, but some studies of the NN interaction in the nuclear medium are possible. Better resolution can be obtained at lower energies but it is highly preferable to do experiments over the energy range where the nucleus is most transparent, ie ~ 200 to 600 MeV.

In fig. 2 cross section and asymmetry data are shown for ¹⁶O(p, 2p). These data were obtained at 200 MeV with scintillation counters but the resolution was not significantly better than that shown in fig. 1. They demonstrate strong spin-orbit dependence and show that asymmetries of the outgoing protons are roughly consistent with expectations based on the the Shell Model and the Distorted Wave Impulse Approximation (DWIA). In this model, it turns out that the struck proton is, in general, polarized and depending on the kinematics, the degree of polarization can be quite large in agreement with experiment. It comes about as a result of distortion of the outgoing channel waves by the optical potential in combination with spin-orbit coupling in the target nucleus and the sensitivity of the pp interaction to the relative spin directions of the colliding protons⁸.

The ability of the DWIA Model to predict the cross sections and asymmetries is not outstanding, as shown in fig. 2 but the main features of the spin dependence are

85



fig 2.¹⁶O(p,2p) cross sections and asymmetries for 200 MeV incident protons

is possible to obtain the effective reproduced. It polarization of the struck nucleon from measured asymmetries and thus test to see if we get the same result for $p_{1/2}$ and This kind of comparison P3/2 states as one would expect. test should be reasonably independent of the details of the DWIA calculation. As shown in ref. 9 and fig. 3, the results are fairly good for symmetric kinematical situations but not for all geometries. It has been noted 9 that agreement is greatly improved if one sets the pp scattering polarization, $P(\theta)$ equal to zero (fig. 4). Similar results have been obtained for the 1d states in 40 Ca (ref. 10 and Several possible explanations for this figs. 5 and 6). phenomena have been proposed, including medium effects on the NN vertex ⁸ and changes in the effective pp scattering angle in the nucleus 11.

FUTURE POSSIBILITIES

Before attempting to discuss future experiments it is useful to consider again the original reasons for optimism about the potential of (p,2p) measurements. The "window into the nucleus" that the Berkeley results suggested has provided some important confirmations of our ideas about nuclear structure and reactions. However, progress toward the

86



fig 3. p_{eff} from ¹⁶O(p, 2p) data

development of an effective "microscope" which would let us examine the specimen closely has been slow. The nucleus is not very transparent to hadron probes and the lack of a solid theoretical footing for hadron interactions is a serious problem. For both of these reasons the (e,e'p) reaction has proven to be more effective for studies of nucleon separation energies and momentum distributions. Nevertheless, the (p,2p) reaction has some advantages which can be exploited using present technology.

What are these advantages and how could we make use of them? Perhaps the most important feature of the hadron probe is the opportunity to control the spin and isospin parameters on the NN interaction. By using polarized proton beams we can control the spin, and by detecting coincident pn or pp particle pairs in the exit channels we have a handle on the C. A. Miller will discuss the (p,pn) isospin as well. measurement possibilities later in this workshop. A second important advantage is the large cross section. Next to elastic scattering, quasi-free scattering is the most probable way for a proton to interact with a nucleus and, given a good detection system, a variety of exclusive experiments are possible. Finally, (p,2p) shares with (e,e'p) the considerable advantage of kinematic control. The momentum of the struck nucleon (which equals minus the recoil momentum) can be controlled independently of the NN interaction kinematics and this makes it possible in principle to separate nuclear structure from reaction mechanism effects.

With these ideas in mind it is possible to examine some experiments which would be possible with a dual arm spectrometer system and the TRIUMF polarized proton beam. With a pair of good spectrometers it would be possible to do some detailed spectroscopic studies of the nucleon orbitals as a function of atomic mass, A. For example, measurements of p_{eff} could provide a sensitive test of nuclear structure models and give useful information about the structure of filled shells ⁸. Of course more work is necessary on the theoretical side too so that the reasons for the present lack of agreement between predicted asymmetries and experiment are understood.



fig 4. p_{eff} from ¹⁶O(p,2p) data with P(θ)=0

From the point of view of reaction mechanisms, it would be interesting to investigate the dependence of $P(\theta)$ on the effective density of the nucleus where the reaction is localized and this could be done by controlling the reaction kinematics appropriately. This would be a nice way to begin a search for medium effects on the NN interaction. The possibility also exists to include isotopic spin dependence in the search by comparing $P(\theta)$ determinations from (p,pn) and (p,2p) reactions in the same kinematic situations.

88







fig 6. p_{eff} from ⁴⁰Ca(p,2p) data with P(θ)=0

89

Most of the necessary ingredients already exist at TRIUMF. A polarized proton beam is available with high duty factor and covering the energy region where the nucleus is The Indiana University least absorptive to protons. Cyclotron Facility is likely to have a complementary facility which will permit studies at the lower end of the energy range of interest but the TRIUMF energy range is ideal and probably necessary. The presently available reaction models are less reliable at lower energies and in any case it will be necessary to study the energy dependence in order to establish that any reaction model can be believed. The MRS is an appropriate detection system for one of the exit channels and has < 100 keV energy resolution. It may also be suitable for neutron detection to observe (p,pn) reactions. If approved, the proposal to build a complementary second arm spectrometer would provide a very good facility for extending the TRIUMF (p,2p) program. One feature which is not part of the present proposal is a way to reach out-of-plane kinematical situations. While it is certainly true that many experiments can be done without such a capability it would be very advantageous to have the kinematic flexibility. This is particularly true when one attempts to separate the nuclear structure from the NN interaction effects. Frequently one would like to follow a kinematic locus in which the parameters of one or the other of these is kept constant. Invariably, this means going out of the reaction plane to some extent.

In summary, the addition of a second arm spectrometer to the TRIUMF facility would provide a unique opportunity for finally exploiting the potential of quasi-free scattering of protons. Consideration should be given to a support structure for the second arm which would permit out-of-plane measurements.

REFERENCES

- 1. Chamberlain, O., and Segre, E., Phys. Rev. 87, 81 (1952).
- Cladis, J. B., Hess, W. N., and Moyer, B. J., Phys. Rev. 87, 425 (1952).
- Wilcox, J. M., and Moyer, B. J., Phys. Rev. 99, 875 (1955).
- Haxel, O., Jensen, J. H. D., and Suess, H. E., Phys. Rev. 75, 1766 (1949).
- 5. Meyer, M. G., Phys. Rev. 75, 1969 (1949).
- 6. Tyren, H., Maris, Th. A. J., and Hillman, P., Il Nuovo Cimento 6, 1507 (1957).
- 7. Tyren, H., Hillman, P., and Maris, Th. A. J., Nucl. Phys., 7, 10 (1958).
- Kitching, P., McDonald, W. J., Maris, Th. A. J., and Vasconcellos, C. A. Z., in Advances in Nuclear Physics, vol 15, Plenum pub., 43 (1985)
- 9. Veit, E., Ph. D. dissertation, Universidad Federal do Rio Grande do Sul, Brazil (1981)
- Antoniuk, L., Kitching, P., Miller, C. A., Hutcheon, D. A., McDonald, W. J., Neilson, G. C., and Olsen, W. C., Nucl. Phys., A370, 389 (1981).
- 11. Miller, C. A., Nucl. Phys., A353, 157c (1981).

NEUTRON KNOCKOUT MEASUREMENTS WITH DASS

C.A. Miller TRIUMF, 4004 Wesbrook Mall, Vancouver, B.C., V6T 2A3

ABSTRACT

We propose that the Second Arm Spectrometer now being designed will be very useful as part of a facility for the study of neutron knockout from nuclei. Although the momentum distribution and separation energies of nuclear protons are now best studied at the modern (e,e'p) facilities, such is not the case for neutrons. Uncertainties in the theoretical interpretation of the (p,pn) data due to strong distortions can be reduced through the comparison of (e,e'p) and (p,2p) measurements on the same target. In this way the proton probe can be "calibrated". We present two distinct experimental approaches with complementary capabilities. On the basis of count rate estimates, we anticipate modest beam time requirements for this type of experiment. An example of a possible first measurement is suggested.

INTRODUCTION

Kinematically complete measurements of nucleon knock-out reactions exciting nuclear hole states provide the most direct information about momentum distributions and separation energies of nucleons. The threebody final state is determined experimentally by measuring the momenta of the scattered probe particle and ejected nucleon, from which the energy and momentum of the recoiling nucleus can be inferred. If a suitable kinematic regime is chosen so that the nucleus is reasonably transparent to the probe and ejectile, the recoil momentum is closely related to the initial momentum of the struck nucleon. The quantitative extraction of nuclear momentum distributions and occupation probabilities for shell model orbitals require the introduction of the nuclear optical model to account for the interaction with the nucleus of ejectile and the probe if it is hadronic.

Some decades ago, such measurements using protons as the probe provided dramatic qualitative confirmation of the shell model picture of the nucleus. Since then the application of this reaction as a quantitative probe of the details of nuclear structure has been retarded on the one hand by experimental difficulties, especially in the case of the electromagnetic probe and on the other by inadequacies of the reaction model especially in the case of the strongly absorbed hadronic probe. However, fundamental information about the momentum distributions and separation energies of nuclear protons has been obtained. The (e,e'p) results are reviewed in Ref. 1 and (p,2p) results in Ref. 2.

We are now experiencing the beginning of what promises to be a renaissance in the field because of some recent developments. There are being commissioned dual-spectrometer facilities capable of high resolution in recoil nucleus excitation. As well, there are becoming available higher duty factor electron beams and polarized proton beams at energies best suited for penetrating nuclei. Finally, the reaction model so crucial for interpreting the data from hadronic probes is being improved. We will return to this point.





Proton hole state spectroscopy is being led by (e,e'p) facilities such as the new dual-spectrometer system at NIKHEF-H in Amsterdam. Although the interpretation of (e,e'p) data is complicated by the one strongly-interacting particle in the final state, there is evidence that reliable spectroscopic information can be extracted.³ For example, the fragmentation of 1f strength in ⁹⁰Zr has been studied, leading to the distribution shown in Fig. 1. The total 1f strength from 0 to 20 MeV amounts to 8.9 compared with the shell model sum rule limit of 14, indicating a substantial depletion of shells just below the Fermi surface.

In spite of the clear advantage of the electron probe, (p,2p)experiments still have at least two roles to play. One is the detailed investigation of the effect of the nucleon medium on the nucleon-nucleon interaction. Here spin-transfer observables which are relatively insensitive to nuclear structure offer a way of disentangling the different aspects of the reaction mechanism.⁴ The other role is based on the demonstrated sensitivity of $(\vec{p}, 2p)$ analyzing powers to the J-value of the struck nuclear proton.⁵ Spectroscopic information obtained in this way could complement that from (e,e'p) experiments if a suitable high-resolution (p,2p) facility were available in the best energy range near 400 MeV. Here both initial and final state particles have the lowest possible interaction probabilities so that two-step processes are suppressed. Such a facility will exist when the dual spectrometer facility now under construction at IUCF is installed on the cooler/tripler ring now also being constructed. However, a schedule for this does not exist at present. Figure 2 shows the quality of separation energy spectra even for deep hole states that can be obtained with a hadronic probe of sufficiently high energy.

For obvious instrumental reasons, neutron hole-state spectroscopy has lagged far behind that of protons. Although there is some hope that the next generation of high duty factor electron accelerators will make (e,e'n) experiments feasible,¹ it remains that the (p,pn) reaction is





the only practical probe with direct access to the bulk of the momentum distributions of neutrons in nuclei. Other reactions such as nucleon pick-up are sensitive only to the high-momentum tail.

In the foreseeable future, knockout reaction data will be interpreted in the context of the distorted wave impulse approximation (DWIA). In this model, the transition amplitude is taken to be

$$T_{fi} = \int d\underline{r} \chi^{(-)*}(\underline{k}_{aC},\underline{r}) \chi^{(-)*}(\underline{k}_{bC},\underline{r}) \langle \underline{k}_{ab}^{(f)} | t_{NN}(\rho(\underline{r})) | \underline{k}_{ab}^{(i)} \rangle$$

$$\times \chi^{(+)}(\underline{k}_{aA},\alpha\underline{r}) \phi_{JL}^{m}(\underline{r}) \qquad (1)$$

where the χ 's are optical model scattering wave functions describing the interaction of the probe particle a and the ejectile b with the target nucleus A or recoil nucleus C. The spin indices have been suppressed. The optical potentials are constrained by nuclear elastic scattering and total reaction cross section data and are increasingly influenced by guidance from microscopic calculations of the optical potentials based on the density-dependent nucleon-nucleon interaction.⁶ ϕ_{JL}^{m} is the initial bound state wave function of the struck nucleon which for protons is strongly constrained by electron scattering data. The matrix elements of t_{NN} represent the two-body scattering amplitude for the probe-ejectile interaction. Its momentum dependence within the range of momentum-smearing introduced by the distorted waves is normally ignored in the "factorization" or "zero-range" approximation. We have written the amplitude with explicit density-dependence.

Will it be possible to obtain convincing spectroscopic information from a strongly absorbed proton probe? We expect the key to this problem will be in the comparison of the results from (e,e'p) and (p,2p) measurements of comparable quality on the same target to be studied using the (p,pn) reaction. Since the difference between neutron and proton optical potentials in a neutron-rich nucleus are expected to be modest and predictable by microscopic calculations of the optical potentials, such comparisons can be used to "calibrate" the proton probe for each target For example, the existing medium-energy (p,2p) cross section nucleus. data are fitted by the best presently available DWIA calculations with spectroscopic factor 1.5 to 2 times smaller than those obtained from (e,e'p) data.⁵⁻⁷ There are plausible reasons for this trend such as the so-called Perey-damping effect¹⁶ of the neglected non-locality of the optical potentials. In order to apply this "normalization correction" derived from the (p,2p)/(e,e'p) comparison to the derivation of neutron spectroscopic factors, it would be necessary to show that it is independent of the subshell in a particular target nucleus from which the nucleon is ejected. Hence the (p,2p) facility which supports the (p,pn) program in this way should be capable of resolving all the states that are distinguished in the (e,e'p) measurements. A dual-arm spectrometer system is a necessity.

Our confidence in information about bound neutrons derived in this way depends on our confidence in the DWIA reaction model. The application of the DWIA to nucleon knockout is subject to more critical tests than for (e,e'p) in that $(\vec{p},2p)$ analyzing powers for knockout from known orbitals near the Fermi surface can be easily measured and compared with predictions that are relatively insensitive to details of the struck particle wave function. The J-dependence of these analyzing powers arises entirely through the distorting potentials experienced by the final state proton. Hence they are good tests of the model. Until recently, the existing data for knockout of 1p and 1d shell protons with known J-values were in agreement with DWIA calculations only in certain kinematic conditions. However, new calculations using the Love-Franey interaction are in fair agreement with the analyzing power data over a wide range of kinematic conditions.⁷ Some examples are shown in Fig. 3. If a similar improvement is observed in the present poor agreement of DWIA calculations with the existing (\vec{p}, pn) analyzing power data,⁸ we will have reason to hope that this J-dependence will become a useful spectroscopic tool.

Confidence in the DWIA would be firmer if the factorization approximation were eliminated. Progress in the area has been slow in large part because of the practical numerical difficulties caused by the high dimensionality of the phase space associated with the three-body final state. However, there are some recent encouraging developments. In some calculations, the factorization approximation has been weakened to the extent that the effects of nuclear-density dependence of the nucleon-nucleon interaction can be investigated. The types of density-dependence associated with the Hamburg interaction were found to have only modest effects on (p,2p) cross sections and analyzing powers.⁷ The study of



Fig. 3. $(\dot{p}, 2p)$ data from Ref. 5 with DWIA calculations from Ref. 7.

other types of density-dependence is the subject of other TRIUMF proposals. Most exciting, however, is the work now underway to develop an unfactorized finite range calculation in the Dirac framework.⁹ This will be the first self-consistent (p,2p)/(p,pn) calculation in the sense that the same covariant direct-plus-exchange model of the nucleon-nucleus interaction is used both to generate the optical potentials and to describe the primary quasi-free scattering process. Such optical potentials generated by this interaction have recently been shown to give rise to nuclear elastic scattering observables in remarkably good agreement with experiment.¹⁰

In spite of the above-mentioned possibility of using the (p,2p)/(e,e'p) comparison to "normalize" the DWIA cross sections it will be important to use the best calculations possible in interpreting the

(p,pn) data. This is because, in terms of percentages, the cross sections are more sensitive to the rms radius of the wave function of the struck nucleon than to the spectroscopic factor. 11 Hence, careful examination of the shape of the cross sections in a variety of kinematic conditions will be necessary to constrain the rms radius of the neutron wave functions since they will not be determined by electron scattering This also emphasizes the need for 500 MeV beam energy to ensure data. that the energies of the final state nucleons remain in the energy region of optimal nuclear transparency for all experimental kinematic conditions, including variation of their energy sharing at fixed angles. However, it is likely that the best-determined spectroscopic quantity will be the composite parameter $C^2S \times R^n_{rms}$ for some power n. n has a value near 4 for 150 MeV beam energy but it lies between 1 and 2 for energies above 300 MeV and kinematic conditions which avoid low energy This again illustrates the importance of higher final state nucleons. energy. Studying the energy dependence should help resolve this potential ambiguity btween spectroscopic factor and rms radius.

THE (p,pn) EXPERIMENTAL PROBLEM

What experimental facilities are needed to support the next generation of (p,pn) experiments at intermediate energy? The obvious choice is a large solid angle, broad momentum acceptance magnetic spectrometer in coincidence with a neutron time-of-flight spectrometer with a long flight path. The proton hall at TRIUMF allows flight paths up to only 10 m. Figure 4 shows a possible experimental layout using the proposed second arm spectrometer as the proton detector. There are presently no plans at IUCF to provide for long flight paths in association with their new spectrometers. Based on the resolution of 1 MeV in 80 achieved at IUCF with large $1m^2$ neutron detectors at 19 m we expect a neutron energy resolution of 5 MeV at 200 MeV. The time reference for the time-of-flight



measurement will be derived from the proton spectrometer focal plane trigger counters with extensive corrections for flight path through the spectrometer scintillator and spatial non-uniformity using the drift chamber information. Such a resolution is useful for the investigation of relatively deep neutron hole states which are broad anyway but require a facility with large acceptance to cope with the relatively low yield spread over more phase

Fig. 4. A (p,pn) configuration using SASP in coincidence with a neutron time-of-flight detector.



Fig. 5. Schematic layout of a (p,pn) facility consisting of the Second Arm Spectrometer in coincidence with the MRS as a neutron recoil spectrometer.

space. On the other hand, the study of valence hole states requires much better resolution. This can be achieved at some considerable cost in efficiency by using the proposed TRIUMF dual-arm spectrometer system (DASS), with the neutron undergoing 0° charge exchange in an active hydrogenous converter (organic scintillator) at the entrance to one of the spectrometers. Such an arrangement is shown schematically in Fig. 5. The neutron detection system is similar to that used in the TRIUMF nucleon charge exchange facility (CHARGEX) except that instead of the primary beam being deflected, the hydrogenous converter is protected from the intense charged particle background flux from the target by an intervening compact, saturated pole tip dipole. This small magnet constitutes the only significant cost of this (p,pn) facility beyond the construction of SASP itself. The design requirements for this dipole are very simple since no region of uniform field is required; merely the highest possible peak field along the collimated edge of the converter acceptance. Charged particles directed toward this point require the largest deflection to clear the converter and multi-wire chambers which track the recoil protons entering the spectrometer. Rather than clamp the field to prevent deflection of the primary beam by the dipole fringe field, it will be more efficient to shield the beam with a thick-walled steel pipe. The compactness of the dipole is crucial since it determines the distance to and hence the solid angle acceptance of the converter. It appears that a dipole length of 30 cm will be adequate so that the converter may be 60 cm from the target. The converter scintillator is preceded by a thin veto counter to eliminate any charged particles leaking through the dipole by scattering from the poles, for example.

Experience with the existing CHARGEX facility indicates that such a recoil spectrometer has a resolution well below 1 MeV. The contribution of the beam energy spread will be less in this (p,pn) mode because the beam momentum dispersion can be matched to the proton spectrometer, obviating the need to accept the energy spread over some finite strip target width. Also, a thinner primary target combined with correspondingly higher beam intensity should be possible because the primary beam is transported out of the area to the well-shielded external dump. For these reasons, a neutron energy resolution of 0.5 MeV or better should be possible, probably limited by the energy resolution of the recoil scintillator. For a time-of-flight system, this would require a flight path of at least 100 m, giving rise to more accidental coincidence events from many different beam burst/velocity combinations.

Of course, the central problem with the recoil spectrometer system is the small conversion efficiency of neutrons into recoil protons. In the CHARGEX facility, with a 2 cm thick scintillator of chemical composition CH, the efficiency is 10^{-5} . This can be doubled by changing to a commercially available liquid scintillator with approximate composition The thickness of 2 cm was chosen to maintain the maximum energy CH2 . loss in the scintillator to be small compared to the MRS momentum acceptance at 200 MeV so that the system acceptance would be constant over a substantial momentum range. If (p,pn) kinematics are chosen with the neutron energy in the vicinity of 300 MeV, the maximum energy loss is reduced and the MRS energy acceptance increases. Also, it is an inessential convenience to have a flat momentum acceptance; it will have to be calibrated anyway using the D(p,pn)p reaction, for example, for which the cross section shape is quite well known. Hence, the converter thickness can be increased to at least 5 cm, resulting in a conversion efficiency of 5×10^{-5} . The thickness will be ultimately limited by the increased contribution to the neutron energy resolution by the converter energy loss resolution.

The above argument illustrates one reason for choosing the MRS rather than SASP as the recoil spectrometer: the converter is more efficient at the higher momentum accommodated by the MRS. The other reason is that the SASP optics design does not require a front end chamber in order to provide good resolution. If the MRS was the proton detector, its front end chamber would be exposed directly to the primary target and would severely limit the beam intensity. The only disadvantage to SASP as a proton detector is that its focal plane instrumentation must cope with the larger background fluxes transmitted by its large solid angle acceptance. However, assuming the SASP focal plane instrumentation is similar to that presently installed on the MRS, it will accommodate fluxes in the several MHz regime; as will be seen below, this is adequate to reach beam intensities beyond which statistical uncertainties will not reduce significantly.

The carbon content of the converter scintillator will generate background from $^{12}C(n,p)$ for residual nuclear excitation energies larger than the 12 MeV Q-value for this reaction. The relative size of this background can be estimated from the $CH_2(n,p)$ spectrum obtained with the CHARGEX facility which is shown in Fig. 6. This relatively small contamination in the (p,pn) data can be subtracted by successive deconvolution from lower excitation. In any case, the primary purpose of this facility is not the study of deep hole states.



Fig. 6. Recoil proton energy spectrum from (n,p) on CH₂.

We now compare the event rate capabilities of the recoil spectrometer versus the time-of-flight spectrometer in coincidence with the SASP as a proton detector. The values provided for the experimental parameters are those appropriate for the recoil spectrometer. The "true" (p,pn) event rate is

$$R_{t} = \sigma_{t} b t \Omega_{p} \Omega_{n} \Delta_{p} \varepsilon$$
⁽²⁾

where $\sigma_t = 10$ to $100 \ \mu b/(sr^2 MeV)$ is a typical cross section for valence subshells, b is the beam flux and t is the target thickness $(10^{21} \text{ cm}^{-2})$. The effective solid angle acceptances are $\Omega_p = 0.01$ sr for SASP and $\Omega_n = 0.003 \text{ sr } \times 5 \times 10^{-5}$ for a "CH₂" converter 2 cm wide by 5.5 cm tall by 5 cm thick 60 cm from the target, and Δ_p is the proton energy bin chosen to be small enough not to unduly smear the recoil momentum distribution - say 10 MeV. ε is the efficiency of the entire detector system which we take to be 0.5. The "accidental" event rate is

$$R_{a} = \tau \sigma_{p} \sigma_{n} b^{2} t^{2} \Omega_{p} \Omega_{n} \Delta_{p} \Delta_{n} \varepsilon$$
(3)

where τ is the beam burst period $(44 \times 10^{-9} \text{s})$ unless the coincidence resolving time can be less than the beam burst width (~3 ns). In calculating the accidental <u>trigger</u> rate, we must use the beam period but in calculating the statistical error, we assume that accidentals in the same beam burst can be rejected during data reduction by applying comprehensive time-of-flight and scintillator response corrections to the SASP focal plane trigger time using its drift chamber data. The neutron timing signal can be derived from the recoil scintillator, corrected for spatial variation using the front end chambers of the MRS. In this case the effective resolving time will be taken to be

$$\tau = \frac{P}{w} \tau' = \frac{44}{3} \ 0.5 \times 10^{-9} = 7.3 \times 10^{-9} s \tag{4}$$

where P is the beam period, w is the burst width and τ' is the time resolution (2 σ). σ_p and σ_n are the inclusive cross sections generating background fluxes of protons and neutrons, respectively. σ_p has been measured to be 1 mb/(sr MeV) near the quasi-free scattering peak¹² and (p,n) measurements at IUCF indicate that the (p,n) continuum is similar to (p,p').¹³ An is the neutron energy bin width over which the yield must be integrated for each residual nuclear state and for fixed proton energy. It is essentially the resolution in missing mass. We take it to be 1 MeV.

Assuming that we subtract accidental events from only one adjacent beam burst, the fractional statistical error in one proton energy bin is

$$E^{2} = \frac{N_{t} + 2N_{a}}{N_{t}^{2}} = \frac{1}{N_{t}} + \frac{2N_{a}}{N_{t}^{2}}$$
(5)

where $N_{\rm t}$ and $N_{\rm a}$ are the number of true and accidental events accumulated over the running time T. Hence the contribution from the accidentals is

$$E_{a}^{2} = \frac{2N_{a}}{N_{t}^{2}} = \frac{2R_{a}T}{(R_{t}T)^{2}} = \frac{2\sigma_{p}\sigma_{n}\tau\Delta_{n}}{\sigma_{t}^{2}\Omega_{p}\Omega_{n}T\Delta_{p}\varepsilon}$$
(6)

which is independent of beam flux and target thickness. For $\sigma_t=30 \mu b/(sr^2 MeV)$,

$$E = \frac{50}{\sqrt{T}} (\text{seconds})^{1/2} . \tag{7}$$

It requires a 2 day run ($\simeq 2 \times 10^5$ s) to achieve $E_a=.08$ or 8%. It would be desirable to choose the beam intensity to make $E_t^2=1/N_t$ half as large as E_a^2 . This occurs when $R_t=R_a$. Hence

$$b = \frac{\sigma_t}{\sigma_p \sigma_n \tau t \Delta_n} \quad . \tag{8}$$

Again for $\sigma_t = .03 \text{ mb}/(\text{sr}^2 \text{ MeV})$, $b=8 \times 10^{12}$ Hz or 1.3 µA. At this beam flux, the SASP focal plane total proton flux would be 9 MHz. At this rate, almost half the events would have two tracks through SASP in the same beam burst. If the SASP focal plane is instrumented like that of the MRS, this will not be fatal. Each drift chamber contains two wire planes, one (X) with wires perpendicular to the bend plane and the other (U) rotated only 30°. Since the flux dispersal along the wire length is thereby kept short compared to the length of the chambers in the bend plane, only the minority of dual tracks which are close together in the dispersion coordinate will suffer from ambiguity in X/U association, requiring both of them to be discarded. Also the trigger scintillator hodoscope above the drift chambers is sufficiently granular that coincident tracks are likely to hit different scintillators, allowing many of the extraneous ones to be rejected on the basis of sub-beam-burst time resolution. For these reasons, together with our experience regarding
the severity of indirect background flux in the existing MRS instrumentation, we expect to be able to operate the proposed (p,pn) system with beam intensities in the neighbourhood of 1 μ A.

It appears that this dual spectrometer (ppn) facility can generate good quality energy-sharing spectra for moderately deep neutron hole states at a few angle pairs for one target nucleus in approximately a week of beam time. However, it is clear that it would be a struggle to extend this to deep hole states for which the cross sections will be smaller and spread over more final state phase space and hence much more vulnerable to accidental coincidence background. As has been pointed out previously, excellent energy resolution is not necessary for the study of relatively broad deep hole states, whereas good statistics are necessary. This leads us to propose the time-of-flight spectrometer in coincidence with the relatively large acceptance SASP as a complementary part of the TRIUMF (p,pn) facility. As in the case of the recoil spectrometer there need be little additional cost beyond the construction of the SASP since the large 1 m² neutron detector arrays used for experiments 121 and 182 are still available. Some possible external users have similar arrays with potentially better time resolution. To estimate the event rate performance of this system, we replace the neutron detector effective solid angle acceptance Ω_n with the value appropriate to the time-of-flight spectrometer with a detection efficiency of 25%:

$$\Omega_{\rm m} = 1 \ {\rm m}^2/(10 \ {\rm m})^2 0.25 = 0.0025 \ {\rm sr}$$
.

Also, the energy resolution Δ_n becomes 10 MeV and ε increases somewhat to approximately 0.7. The resolving time, τ , increases to 44 ns, one beam burst. It is difficult to estimate the indirect background flux to which the neutron counters will be sensitive but it should be minimized by the relatively high pulse height threshold that the efficiency of 25% implies in conjunction with a total scintillator thickness of 30 cm. Finally, we take 10 μ b/(sr² MeV) as a typical deep-hole-state crosssection σ_t . Inserting the values into Eq. (6), we obtain

$$E_a = \frac{7.6}{\sqrt{T}} \text{ (seconds)}^{1/2} .$$

One shift of beam time will then produce statistical errors from accidentals per 10 MeV bin less than 4%. The beam intensity required to bring the intrinsic statistical error E_t below this is then given by Eq. (8) to be 50 nA. However, this would yield an event trigger rate integrated over 100 MeV in both neutron and proton energy of several kHz, mostly accidentals, and proton singles fluxes into the neutron detector of 5×10^5 which might lead to phototube stability problems because of the large energy loss in these thick scintillators. A practical choice of beam intensity might be 10 nA on the nominal target thickness of 10^{21} cm⁻². Then in two shifts of beam time, the intrinsic statistical error will dominate at the level of 5% per 10 MeV bin. This compares very favourably with the results of past (p,2p) or (p,pn) experiments at lower energy.

The general scenario we propose, then, for the study of neutron hole states in a particular target nucleus includes high-resolution

 $(\dot{p}, 2p)$ measurements with the dual spectrometer system in the same kinematic conditions as those planned for the (p,pn) measurements. The normalization for spectroscopic factors can be established and the J-dependence of the analyzing powers can be studied by examination of the data for a few well-resolved hole states near the Fermi surface which have been characterized by (e,e'p) measurements. Then good resolution (p,pn) measurements using the recoil spectrometer system can provide spectroscopic factors for the prominent neutron hole states at low excitation as well as confirmation that the J-dependence of the analyzing powers for states of known J is consistent with the predictions of the DWIA. Finally, (p,pn) measurements with the time-of-flight spectrometer will probe deeper hole states with good statistics with the interpretation of the missing mass spectrum being assisted by the analyzing power signatures together with the recoil momentum dependence. It seems to us that only such a coordinated approach is likely to yield the spectroscopic information about neutron single particle properties that is needed to complement the growing body of such data about protons from the (e,e'p) facilities.

SAMPLE EXPERIMENT

Although it is not possible to predict what will be the most urgent (p,pn) measurements when SASP could become available in about two years time, it is useful to offer an example of one of the first experiments if the facility were available now. An aspect of nuclear structure that can



Fig. 7. Neutron separation-energy spectra (a) for the 40 Ca (p,pn)³⁹Ca reaction at 149.5 MeV with (θ_p, θ_n) = (44.3°,36.1°); and (b) for the 48 Ca(p,pn)⁴⁷Ca reaction at 149.5 MeV with (θ_p, θ_n) =(47.3°,36.1°).

be studied systematically with neutron knockout but is not accessible via proton knock-out is the effect on the energy distribution of strength in the orbitals below the Fermi surface as the one at the surface is filled. This possibility has already been exploited in the first good resolution (p,pn) experiment done at energies as high as 150 MeV.¹¹ By comparing knockout spectra in 40 Ca and 48 Ca (Fig. 7) the shift in the energies of the $2s_{1/2}$ and $1d_{3/2}$ hole states was observed as the $1f_{7/2}$ orbital is filled. Tentative conclusions were reached regarding the differences in neutron matter distributions in the two nuclei. In view of the uncertainty involving matter distributions in the calcium isotopes, 15 it is important to repeat these measurements at higher energy such as 500 MeV where the nucleus is more transparent to the final state particles. If a J-dependent analyzing power signature can be confirmed at the higher energy, it will help in confirming the interpretation of the separation energy spectra based on their momentum distributions.

Data are needed from both the high resolution recoil spectrometer system to resolve the $lf_{7/2}$, $2s_{1/2}$ and $ld_{3/2}$ states as well as from the time-of-flight system to obtain good statistics for the broad $ld_{5/2}$ and lp distributions. As an initial stage, it would be adequate to obtain one energy sharing spectrum with the recoil spectrometer system at an angle pair chosen to allow zero recoil momentum at moderate separation energy (13 MeV) and two angle pairs using the two available neutron detector arrays, one positioned to reach zero recoil momentum at 22 MeV for the $d_{5/2}$ state and the other for the lp region of excitation near 35 MeV.

Based on the count rate estimates presented earlier, to be sure of better than 10% statistics in each of 10 MeV wide bins in the detected proton energy for each of the two targets, we need four shifts of beam time in recoil spectrometer mode and two shifts in time-of-flight mode for a total of twelve shifts. This should be polarized beam if it can be shown that there is a reliable J-dependent analyzing power signature at 500 MeV and in the mass 40 region. To test this, we would require two shifts of polarized beam in the dual spectrometer (\vec{p} ,2p) mode at each of two angle pairs to study the analyzing powers for knockout of protons from the 2s and 1d orbitals of 40 Ca. This estimate is based on the observation that the effective acceptance of the MRS is very similar to that of the time-of-flight spectrometer.

The $(\vec{p}, 2p)$ measurement would be scheduled first to determine if polarized beam is useful for the (p, pn) measurements. If indications are positive, polarized beam would be used for the high resolution measurements on 40 Ca to confirm that the analyzing powers behave as expected for neutron knockout from the same orbitals. If this result also is positive, polarized beam would be indicated for all measurements.

The total beam time for the entire study is estimated to be 16 shifts. Of course, this could be modified by experience during commissioning of the facilities.

REFERENCES

- 1. S. Frullani and J. Mougey, Adv. in Nucl. Phys. 14 (1984).
- 2. P. Kitching et al., Adv. in Nucl. Phys. 15, 43 (1985).

- 3. G. van der Steenhoven et al., Phys. Lett. <u>156B</u>, 151 (1985); J.W.A. den Herder et al., Phys. Lett. <u>161B</u>, 65 (1985); P.K.A. de Witt Huberts, Proc. XIth Eur. Div. Conf. on Nuclear Physics with Electromagnetic Probes, 1985, Nucl. Phys. A446, 301c (1985).
- 4. C.J. Horowitz and M.J. Iqbal, Relativistic effects on Spin Observables in Quasielastic Scattering, Phys. Rev. C 33, 2059 (1986).
- P. Kitching et al., Nucl. Phys. <u>A340</u>, 423 (1980).
 L. Antonuk et al., Nucl. Phys. <u>A370</u>, 389 (1981).
- 6. W.J. McDonald et al., Nucl. Phys. (in press).
- 7. Y. Kudo and K. Miyazaki, Analyzing powers for (p,2p) Reactions with Effective N-N Interactions, Preprint (1986), 6th International Symposium on Polarization Phenomena in Nuclear Physics, Osaka, Japan, 1985, contributed paper 1.34.
- "The ²H(p,pn) and ¹⁶O(p,pn) Reactions at 200 MeV", J.W. Watson, W. Parisuwan, B.S. Flanders, P.J. Pella, R. Madey, N.S. Chant, P.G. Roos, and M. Ahmad, Bull. Am. Phys. Soc. <u>29</u>, 716.
- 9. E.D. Cooper and B. Jennings, private communication.
- C.J. Horowitz and D. Murdock, Bad Honnef Conf. preprint (1985); Phys. Lett. <u>168B</u>, 31 (1986).
- 11. M. Ahmad et al., Nucl. Phys. A424, 92 (1984).
- R.E. Segel et al., unpublished; H. Esbensen and G.F. Bertsch, Phys. Rev. C 34, 1419 (1986).
- R.E. Segel et al., Phys. Rev. C 26, 2424 (1982);
 J.W. Watson et al., Phys. Rev. C 23, 2373 (1981).
- 14. S.L. Belostotskii et al., Sov. J. Nucl. Phys. 41, 903 (1985).
- 15. What do we know about the radial shape of nuclei in the Ca region? Proc. Karlsruhe Int. Discussion Meeting, 1979, ed. H. Rebel, H.J. Gils and G. Schatz.
- 16. F.G. Perey and B. Buck, Nucl. Phys. 32, 353 (1962).

(n,p) AND (p,n) REACTIONS AT TRIUMF

S. Yen

TRIUMF, 4004 Wesbrook Mall, Vancouver, B.C., V6T 2A3

INTRODUCTION

This paper deals with the nucleon charge-exchange program at TRIUMF and its possible impact on the proposed Second Arm Spectrometer (SASP). First I will present the reasons for studying (p,n) and (n,p) reactions at TRIUMF. I will then describe the present facility based on the Medium Resolution Spectrometer (MRS). I will then discuss in some detail the question of the apparent quenching of Gamow-Teller strength in (p,n)reactions and the role of the Δ -isobar in this quenching. Finally, I will outline a few possible avenues of future research in this area employing the SASP.

WHY CHARGE-EXCHANGE AT TRIUMF?

Why should we investigate nucleon charge-exchange reactions at TRIUMF? The 200 to 500 MeV energy range accessible with the TRIUMF cyclotron is the energy region where the nucleon-nucleon interaction is the weakest, so that the impulse approximation is expected to work best in this energy range. This greatly simplifies the reaction mechanism and makes for reliable comparisons between experimental data and calculations based on standard DWIA codes. In this energy range, the ratio of isovector spin-flip to isovector non-spin-flip interaction potentials $V_{\text{OT}} / V_{\text{T}}$ is the largest,¹ so that the TRIUMF energy range is ideal for looking at spin excitations of the nucleus. In addition, (p,n) and (n,p) reactions pick out the Δ T=1 excitations, so that the experimental spectra are free of the background of isoscalar excitations present in (p,p'). All this means that TRIUMF's energy range is ideal for exploring spin isovector excitations of the nucleus.

The (p,n) reaction from 80 to 200 MeV has been explored for a number of years at the Indiana University Cyclotron Facility.^{2,3} Why should we be interested in (n,p) reactions? The first, and perhaps most compelling, reason is that it offers a way of disentangling the various factors that may contribute to the apparent quenching of the GT strength in (p,n) reactions. This will be discussed in detail later. Secondly, (n,p) has a different isospin selectivity than does (p,n). For N > Znuclei, (n,p) populates only states with final isospin $T_f = T_0 + 1.4$ This is in contrast to (p,n), which preferentially excites $T_f = T_0 - 1$, and (p,p'), which preferentially excites $T_f = T_0$. Thus, (n,p) can be used to explore, for example, the $T_f = T_0 + 1$ components of isovector giant resonances. Thirdly, in N >> Z nuclei, the Gamow-Teller excitation is strongly Pauli blocked, so that we can observe the other isovector giant resonances such as the spin isovector monopole, without interference from the strong GT strength present in (p,n) reactions. Fourthly, the (n,p) reaction results in a final nucleus of lower Coulomb energy than does the (p,n) reaction. The lower energy means that there is less spreading of the lp-lh strength due to mixing with 2p-2h configurations, so that the lp-lh strength will be more concentrated and more visible. Lastly, the (n,p) reaction can be used to give information on important

weak interaction rates, e.g. on the distribution of GT strength in 56 Mn, important for the rate of the 56 Fe(e,v) 56 Mn reaction which is the final step before the collapse of the core in supernova explosions.

THE TRIUMF CHARGEX FACILITY

Motivated by the considerations discussed in the last section, we began in 1983 to design a facility based on the existing Medium Resolution Spectrometer (MRS) at TRIUMF to investigate (p,n) and (n,p) reactions. W.P. Alford of the University of Western Ontario and K.P. Jackson of TRIUMF were initially the principal instigators of this project. By the summer of 1985 we had a working facility and the first experiment, ${}^{14}C(p,n)$, was performed during that summer.

Figures 1 and 2 illustrate the principle of the TRIUMF nucleon charge-exchange facility (called CHARGEX). In the (p,n) mode (Fig. 1), the primary proton beam hits the target under study. The primary beam is bent 21° by a clearing dipole magnet into a beam dump. Neutrons produced by the (p,n) reaction in the target travel forward and strike a recoil scintillator, which converts the neutrons into knockon protons via the ${}^{1}\text{H}(n,p)$ reaction. These knockon protons are then momentum analyzed in the MRS. A veto scintillator located before the recoil scintillator vetoes any charged particles hitting the recoil scintillator. The neutron to proton conversion efficiency is about 10^{-5} . The proton

(n,p) Mode

(p,n) Mode







Fig. 2. (n,p) mode of CHARGEX.

blocker prevents protons which are elastically scattered to the left in the primary target from being bent by the clearing magnet into the recoil scintillator. By measuring the energy loss in the scintillator and adding it back to the energy measured in the MRS, we can use a relatively thick (2 cm) scintillator without substantially degrading the overall energy resolution.

In the (n,p) mode (Fig. 2), the primary proton beam hits a ⁷Li neutron production target. The clearing magnet again bends the primary beam into a beam dump. The 0° neutron beam from the ⁷Li(p,n) reaction travels straight forward, through a veto scintillator which vetoes charged particles, and into the (n,p) target stack. Protons produced by (n,p) reactions in the target stack are then momentum analyzed in the MRS.

The system of detectors used in the (n,p) mode is shown in Fig. 3. First is a veto scintillator VS which vetoes events induced by charged particles in the target stack. Then follows the (n,p) target stack. This consists of 6 target layers, sandwiched between multi-wire proportional counter planes marked A-F. The idea is that by examining the hit patterns in the 7 MWPC planes, one can deduce which target layer the (n,p) reaction occurred in, and thereby make a correction for the energy loss of the outgoing proton in all subsequent target layers. This considerably improves the energy resolution of the whole system. It is also possible to run different target materials in different layers; it is usual to place a CH, target in the last position to obtain cross sections relative to the known np cross section. The target system is called "Robert's Box" after its designer, Robert Henderson, of the University of Melbourne. Then follows a set of X and Y position-sensitive drift chambers labelled FECM, a trigger scintillator FES, and another set of drift chambers FECO. The MRS spectrometer itself consists of the quadrupole Q and dipole D, of 2.6 m bend radius and capable of bending 1500 MeV/c. The focal plane detectors consist of two sets of vertical drift chambers (X1, U1) and (X2, U2) spaced 1 m apart, followed by an



Fig. 3. Detector system for (n,p),



Fig. 4. Time-of-flight spectrum of neutrons from ⁷Li(p,n) reaction at 160 MeV taken at IUCF. From Ref.21.

Fig. 5. Neutron spectrum from ⁷Li(p,n) reaction at 200 MeV, using TRIUMF CHARGEX facility.

array of 10 plastic scintillators, followed by two large-area plastic scintillators S1 and S2.

I will now show some figures illustrating the performance of the CHARGEX system. Figure 4 shows the spectrum of neutron energies from the ⁷Li(p,n) reaction measured at 160 MeV at Indiana using a time-of-flight system. The neutron energy increases to the right. The energy distribution consists of a sharp peak due to the population of the g.s. and 430 keV states in 'Be, and a tail of lower-energy neutrons due to excitation of higher states in ⁷Be. If we set CHARGEX up in the (p,n) mode and look at the neutrons from the $^{7}Li(p,n)$ reaction at 200 MeV, we get the spectrum of Fig. 5. Here, the neutron energy increases to the left, backwards from Fig. 4. We see a large peak due to neutrons converting to protons on the hydrogen in the recoil scintillator, and a second peak about 15 MeV lower in neutron energy due to neutrons converting on the The events between the two peaks correspond to the continuum carbon. seen in Fig. 4, and are not due to instrumental background. Obviously, the events to the right of the second peak are due to (n,p) on both hydrogen and carbon, so the response function of the system to a monoenergetic neutron source is somewhat complicated at high excitation energies.

Figure 6 shows a neutron spectrum from the ${}^{14}C(p,n)$ reaction. The FWHM is 0.7 MeV after off-line software corrections. The ratio of the areas of the 0⁺ 2.31 MeV Fermi transition and the 1⁺ 3.95 MeV Gamow-Teller transition can be used to deduce the ratio of volume integrals of the isovector spin-flip to non-spin-flip parts of the effective NN interaction. We have done this measurement at 200, 300, 400 and 450 MeV. The results are shown in Fig. 7, where the solid curve is the ratio predicted



Fig. 6. Neutron spectrum from ¹⁴C(p,n) reaction at 200 MeV, using TRIUMF CHARGEX facility.

Fig. 7. Ratio of squared volume integrals of spin-flip to nonspin-flip parts of isovector interaction strengths, as derived from (p,n) experiments.



Fig. 8. Proton spectrum from ${}^{12}C(n,p)$ reaction, TRIUMF.

by the Franey-Love NN interaction,¹ and it can be seen that the data lies considerably above the prediction.

Figure 8 shows a spectrum of protons from the ${}^{12}C(n,p){}^{12}B$ reaction, with CHARGEX operating in the (n,p) mode. The ${}^{12}B$ ground state peak has a FWHM of 1.0 MeV. The peak to the left of it is due mainly to (n,p)reactions in the hydrogen in the argon-isobutane gas mixture used in "Robert's Box". We now use an Ar-CO₂ mixture which eliminates this peak almost completely.

Table I summarizes the performance of the TRIUMF CHARGEX system. It is obvious that the 11 msr solid angle of the Second Arm Spectrometer will allow a 5.5-fold increase in event rate over the present 2 msr MRS, for energies up to 260 MeV.

The world competition in (n,p) is as follows. The upgraded Uppsala cyclotron will have an (n,p) facility which will permit experiments in the 80 to 185 MeV range. The design parameters call for 2.5 million

Energy range	200-450 MeV with MRS 200-260 MeV with SASP
θ _{lab}	0° - 32°
Resolution	~ 700 keV in (p,n) ~ 1 MeV in (n,p)
$\Delta\Omega$ spectrometer	\sim 2 msr with MRS \sim 11 msr with SASP
Neutron flux	~ 10 ⁶ neutrons/s on a 2×4 cm ² target in (n,p) mode at 200 MeV
Neutron flux	~ 10 ⁶ neutrons/s on a 2×4 cm ² target in (n, mode at 200 MeV

Table I. CHARGEX Facility Performance

neutrons/s on target, and a 10 msr magnetic spectrometer with 1.1 MeV resolution. First extraction from the upgraded cyclotron is planned for early 1986.

Los Alamos, starting in 1988, will have the capability of studying (n,p) reactions up to 800 MeV bombarding energy. Their system will be based on a 15 msr Medium Resolution Spectrometer which is now under construction. A long flight path between the production and secondary targets will allow spin precession solenoids to provide polarized neutron beams of various orientations. Event rates are expected to be similar to those at TRIUMF.

QUENCHING OF GAMOW-TELLER STRENGTH

Figure 9 shows a neutron time-of-flight spectrum from the 90Zr(p,n) reaction, obtained at IUCF. The shaded peaks are identified from their angular distributions as 1⁺ strength. The dotted line shows the assumed "background" that the experimentalists subtract off.

The 1⁺ strength in (p,n) or (n,p) is essentially a measure of the squared matrix elements of the σt_{\pm} operators:

$$s_{\beta\pm} = \sum_{f} |\langle f| \sum_{k=1}^{A} \sum_{\mu} \sigma_{\mu}(k)t_{\pm}(k)|i\rangle|^{2}$$

For free nucleons, $S_{\beta\pm}=3$. If nucleons in a nucleus behave like free nucleons, then we have the Gamow-Teller sum rule^{5,6}

$$S_{B-} - S_{B+} = 3(N-Z)$$



spectrum from ⁹⁰Zr(p,n) reaction at 200 MeV, IUCF. From Ref. 21. over the periodic table. From Ref. 21.

In the absence of (n,p) experiments, $S_{\beta+}$ must be estimated in some way. For heavy nuclei, the $S_{\beta+}$ strength is largely Pauli blocked and may be approximated by zero. Alternatively, in some cases, $S_{\beta+}$ may be computed from a shell model calculation. In any case, 3(N-Z) provides a lower limit on $S_{\beta-}$. Using the background subtraction procedure described above, it was found that the GT strength measured in (p,n) is only about 60% of the sum rule. This is true for a range of nuclei spanning the periodic table (Fig. 10).

Where has all the GT strength gone? There are basically 3 competing explanations. (1) Mixing of the lp-lh configurations with 2p-2h configurations may spread and shift the lp-lh strength from the low-lying, strong peaks into regions of higher excitation energy where the strength is not observed.⁷ (2) Some of the "background" under the major peaks subtracted off by the experimentalists may in fact be actually GT strength, so not all the GT strength is observed.8,9 Mechanisms (1) and (2) are obviously closely related. (3) In addition to the p-h degrees of freedom, the (p,n) reaction may also excite ∆-hole components.¹⁰,¹¹ In other words, subnucleonic degrees of freedom are excited, so that the nucleons involved in the GT excitation no longer behave like free nucleons. The classical Gamow-Teller sum rule is thus violated. Some of the excitation strength is shifted to excitation energies in the vicinity of the A-isobar. The possibility that subnucleonic degrees of freedom were manifesting themselves in low-energy nuclear physics phenomena such as GT transitions excited many nuclear

physicists, and this was the topic of the Telluride II conference in $1982.^{12}$

Since Telluride II, belief in the role of the Δ has decreased. Models of the NA coupling based on π and ρ exchange¹³ and microscopic Gmatrix calculations¹⁴ seem to indicate that the Landau-Migdal parameter g'_{AN} , which describes the short-range part of the Δ -N interaction potential, is closer to 0.4 rather than to 0.6, as had been originally assumed on the basis of "universality" of NN and NA interactions. This would mean that the NA coupling is much weaker than had been previously assumed, so that the Δ would play a much smaller role in the quenching. Also, several large-basis RPA calculations^{15,16} allege to be able to substantially reproduce the entire 90Zr(p,n) spectrum without resorting these calculations indicate that substantial amounts of GT to A's; strength are located at high excitation energies away from the most prominent peaks, so that when the total GT strength is added up, there is really no quenching at all. However, these RPA calculations ignore ground-state correlations and treat 2p-2h admixtures in only a rough phenomenological fashion. A definitive experimental test is still lacking. It is our intention at TRIUMF to use (n,p) to directly measure S_{R+} , and together with S_{R-} from the available (p,n) results, directly test the Gamow-Teller sum rule.

UPCOMING (p,n) AND (n,p) EXPERIMENTS

I would now like to describe a few experiments which have or will soon be taking data on the CHARGEX facility at TRIUMF.

Experiment 265, a study of the ¹⁴C(p,n) reaction proposed by Parker Alford, has already been completed¹⁷ and was discussed earlier. The significant result, shown in Fig. 7, is that the ratio of the volume integrals of the spin-flip to non-spin-flip isovector interaction strengths $|J_{\sigma\tau}/J_{\tau}|^2$ is significantly higher than predicted by the Franey-Love¹ interaction, which is parametrized from free NN scattering phase shifts. The culprit is suspected to be the J_{τ} component, which may be poorly constrained by existing NN data.

Experiment 266, a study of the ${}^{6}\text{Li}(n,p)$ and ${}^{12}\text{C}(n,p)$ reactions for which Peter Jackson is spokesman, is a study of the (n,p) reaction in N=Z light nuclei where the (n,p) strength should be the same as the (p,n)strength by charge symmetry. A spectrum is shown in Fig. 8. Preliminary results indicate that the quenching factor for (n,p) is about the same as for (p,n).

Experiment 267/383, a study of the 54 Fe(p,n) and 54 Fe(n,p) reactions proposed by 0. Häusser, took some data in December 1985 and will be taking more shortly. The idea is to measure both $S_{\beta+}$ and $S_{\beta-}$ in a nucleus where both are non-zero and explicitly test the Gamow-Teller sum rule.

Experiment 376, a study of the 90Zr(n,p) reaction, is a collaboration between the TRIUMF group, the University of Melbourne, and Tel-Aviv University. It will take data in May 1986. It aims to search for S_{β+} strength in this neutron-excess nucleus where the GT strength in the (n,p) direction is completely Pauli blocked to first order. The occurrence of significant S_{β+} strength would invalidate the conclusions of Refs. 15 and 16 that no Δ 's are needed to explain the apparent quenching observed in (p,n). A secondary objective of this experiment is to search



Fig. 11. Enhancement mechanism for 1^+ states in ${}^{208}\text{Pb}(n,p)$. a) $0-\hbar\omega$ (p,n) is allowed in a neutron-excess nucleus like ${}^{208}\text{Pb}$; b) But $0-\hbar\omega$ (n,p) is blocked by the neutron excess, and can occur only via groundstate correlations; c) If the neutron can be excited to become a Δ , then (n,p) is no longer Pauli-blocked.

for giant isovector spin resonances; the 90Zr(n,p) reaction is a favourable case because the GT resonance which normally dominates the spectrum in (p,n) reactions is Pauli blocked in (n,p), providing a window through which to look for other multipolarities.

Experiment 268, a study of the 208 Pb(n,p) reaction, aims to measure the cross section for exciting discrete 1⁺ states in 208 Tl. The idea originated from Brown, Krewald and Speth, 18 and is illustrated in Fig. 11. These authors predict an 0° enhancement by a factor of 3.5 in the presence of Δ -hole admixtures, an enhancement which would not occur if 2p-2h spreading were the cause of the quenching observed in (p,n). This experiment will also take data in May 1986.

Experiment 384, "Abysmal Astrophysics", is a proposal by Peter Jackson et al. to study the 56 Fe(n,p) and 58 Ni(n,p) reactions. The objective is to map out the GT strength distributions for electron capture rates relevant in supernovae; the electron capture by 56 Fe and 58 Ni are principal reactions which deplete the electron gas pressure and allow the supernova to undergo collapse.

Experiment 378, for which Parker Alford is spokesman, aims to study the 48 Ti(n,p) reaction, as a test of important matrix elements relevant for calculations of 48 Ca double beta-decay.

Experiment 344, for which John Watson and his Kent State collaborators are principal investigators, is a study of the ${}^{28}Si(p,n)$, ${}^{28}Si(n,p)$, ${}^{88}Sr(p,n)$, and ${}^{120}Sn(n,p)$ reactions. The aim is to search for concentrated 1M ω stretched state strength in heavy nuclei; the reactions on ${}^{28}Si$ provide a well-known benchmark to prove that things are working as they should be.

Last, but certainly not least, is experiment 411, a study of ${}^{48}Ca(n,p)$ led by Otto Hausser and Ron Jeppeson. The doubly closed structure of ${}^{48}Ca$ admits no GT strength to zeroth order, so a search for GT strength provides an excellent test of ground-state correlations. This experiment will be a real tour-de-force, involving over \$2 million worth of ${}^{48}Ca$ metal target material on loan from Los Alamos.

FOR THE FUTURE

As the review of the present activities indicates, the nucleon charge-exchange program at TRIUMF is a vigorous and growing program, especially in the area of (n,p) studies. Apart from the initial program of selected nuclei, we will eventually want to systematically study many nuclei, analogous to what has been done in (p,n). The counting rate for (n,p) is low, since the incident neutron flux is only of order 10^6 per second on a 2×4 cm² target. To obtain useful counting rates, it is necessary to use thick targets (of order 1 g/cm²), and for separated isotopes it is often prohibitively expensive to obtain this much target The 5.5-fold increase in solid angle obtainable with SASP material. would therefore not only mean much higher counting rates, but would make possible some experiments which would otherwise be impossible simply because of the cost of the target material. Alternatively to obtaining a higher counting rate, one could choose to use thinner targets and enjoy better energy resolution. We will certainly need to go in this direction to improve the resolution from the present ~1 MeV.

The suspected role of Δ 's has been a major motivation for the (n,p) program at TRIUMF. Two-arm experiments such as $(p,p'\pi)$ may give better understanding of Δ -dynamics and the NN \rightarrow N Δ interaction in nuclei. One may, for example, pick out specific parts of the NN \rightarrow N Δ interaction by exciting specific final states of the target nucleus in a (p, Δ^{++}) reaction. The Δ^{++} may be via its decay products, $p + \pi^+$. Only one such reaction has been studied, the ${}^{6}\text{Li}(p, \Delta^{++}){}^{6}\text{He}$ reaction.¹⁹ The analysis by Jain²⁰ indicates a small Landau-Migdal parameter of $g'_{N\Delta} < 0.4$ for large momentum transfers.

In addition to the first-generation (p,n) and (n,p) cross-section measurements, one may look forward to difficult second-generation experiments which the large solid angle of the SASP would make possible. One such experiment would be to measure spin transfer coefficients in a (n,p) reaction. Assuming an incident proton beam polarization of 75%, one can achieve 25% neutron polarization with a ⁷Li neutron-production target, which is quite low. One can do better with a liquid deuterium target; the (p,n) reaction on deuterium at 9° would yield a neutron polarization of 67%. The poor energy resolution obtained with deuterium may not matter much for continuum measurements. With such a setup, one could search for isovector spin-flip strength in the continuum, to see if the GT strength "missing" from low excitation energies is spread to higher energies. It must be admitted that count rates will be very low, and LAMPF's (n,p) setup, with its longer flight path, will be more suitable for inserting solenoids and other devices necessary to provide neutron beams of various spin orientations.

It would also be interesting to explore the decay modes of isovector giant resonances. To separate out the various multipolarities, one would measure the angular distributions from the decay protons and/or neutrons from these giant resonances, in coincidence with the SASP. The protons and neutrons would be detected in a semiconductor telescope array or liquid scintillator array which would constitute a "third arm spectrometer". The large solid angle of the SASP would be of enormous benefit in such coincidence experiments. To conclude, (p,n) and (n,p) are unique probes of spin isovector excitations in nuclei. As I have indicated in my presentation, there are lots of interesting things to do. The Second Arm Spectrometer would greatly enhance our capabilities in this field.

ACKNOWLEDGEMENTS

It is my pleasant duty to acknowledge the many people who have contributed to the development of the TRIUMF (n,p) facility. These include: Rudi Abegg, Parker Alford, Anna Celler, Dieter Frekers, Peter Green, Otto Hausser, Robert Henderson, Richard Helmer, Ken Hicks, Peter Jackson, Andy Miller, and Mike Vetterli. The research reported in this paper was supported in part by the Natural Sciences and Engineering Research Council of Canada.

REFERENCES

- 1. M.A. Franey and W.G. Love, Phys. Rev. C 31, 488 (1985).
- C. Gaarde, J.S. Larsen and J. Rapaport, in Spin Excitations in Nuclei, eds. F. Petrovich, G.E. Brown, G.T. Garvey, C.D. Goodman, R.A. Lindgren and W.G. Love (Plenum Press, New York, 1984), p. 65.
- 3. C.D. Goodman, in The (p,n) Reaction and the Nucleon-Nucleon Force, eds. C.D. Goodman, S.M. Austin, S.D. Bloom, J. Rapaport and G.R. Satchler (Plenum Press, New York, 1980), p.149
- 4. F.P. Brady, C.M. Castaneda, J. Romero, V.R. Brown and C.H. Poppe, in Ref. 2.
- 5. C. Gaarde, J.S. Larsen, M.N. Harakeh, S.Y. Van der Weuf, M. Igarashi and A. Muller-Arnke, Nucl. Phys. A334, 248 (1980).
- C. Gaarde, J. Rapaport, T.N. Taddeucci, C.D. Goodman, C.C. Foster, D.E. Bainum, C.A. Goulding, M.B. Greenfield, D.J. Horen, E. Sugarbaker, Nucl. Phys. A369, 258 (1981).
- 7. G.F. Bertsch and I. Hamamoto, Phys. Rev. C 26, 1323 (1982).
- 8. F. Osterfeld, Phys. Rev. C 26, 762 (1982).
- 9. F. Osterfeld and A. Schulte, Phys. Lett. 138B, 23 (1984).
- 10. M. Ericson, A. Figureau and C. Thevenet, Phys. Lett. 45B, 19 (1973).
- 11. E. Oset and M. Rho, Phys. Rev. Lett. 42, 47 (1979).
- Spin Excitations in Nuclei, eds. F. Petrovich, G.E. Brown, G.T. Garvey, C.D. Goodman, R.A. Lindgren and W.G. Love (Plenum Press, New York, 1984).
- A. Arima, T. Cheon, K. Shimizu, H. Hyuga and T. Suzuki, Phys. Lett. <u>122B</u>, 126 (1983).
- 14. H. Sagawa, T.-S.H. Lee and K. Ohta, Phys. Rev. C 33, 629 (1986).
- 15. Amir Klein, W.G. Love and N. Auerbach, Phys. Rev. C 31, 710 (1985).
- 16. F. Osterfeld, D. Cha and J. Speth, Phys. Rev. C 31, 372 (1985).
- W.P. Alford, R.L. Helmer, R. Abegg, A. Celler, O. Hausser, K. Hicks, K.P. Jackson, C.A. Miller, S. Yen, R.E. Azuma, D. Frekers, R.S. Henderson, H. Baer, and C.D. Zafiratos, Phys. Lett. <u>179B</u>, 20 (1986).
- 18. V.R. Brown, S. Krewald and J. Speth, Phys. Rev. Lett. 50, 658 (1983).

- T. Hennino, D. Bachelier, O.M. Bilaniuk, J.L. Boyard, J.C. Jourdain, M. Roy-Stephan, P. Radvanyi, M. Bedjidian, E. Descroix, P. Poessel, S. Gardien, J.Y. Grossiord, A. Guichard, M. Gusakow, R. Haroutunian, M. Jacquin, J.R. Pizzi, and A. Garin, Phys. Rev. Lett. <u>48</u>, 997 (1982).
- 20. B.K. Jain, Phys. Rev. C 29, 1396 (1984).
- 21. J. Rapaport, in Studying Nuclei with Medium Energy Protons: University of Alberta/TRIUMF Workshop, July 1983, ed. J.M. Greben. (TRIUMF Report TRI-83-3).

NUCLEAR MEDIUM EFFECTS IN QUASI-FREE (p,2p)

M.J. Iqbal

TRIUMF, Vancouver, B.C., V6T 2A3, Canada, and Physics Department, University of Alberta, Edmonton, Alta., T6G 2J1

Recently it has been shown¹ that in a relativistic approach to quasi-elastic proton scattering, from closed shell nuclei, the most important medium effects on the nucleon-nucleon (NN) interaction, due to the enhancement of the lower components of the nucleon wave function, can be characterised by assigning an average effective mass M^* to the nucleons. The M^* dependence of the NN interaction was taken from relativistic impulse approximation (RIA) calculations.² One of the consequences of this M^* dependence of the NN interaction is a decrease in the analysing power (A_y) compared to free NN scattering ($M^* = M$, M is free mass of nucleon). There is a strong experimental evidence for this decrease in the analysing power in single arm (p,p') quasi-elastic experiments.³ There are certain advantages in looking for medium effects on the NN interaction in single arm (p,p') experiments. For example, one is averaging over all the nuclear states and hence is not sensitive to the details of the nuclear structure.

The advantage in considering the double arm experiments is that one can look at the observables, e.g. nucleon-nucleon analysing power, at different regions of nuclear density and hence map out the density dependence of these observables. This will put a strong constraint on the models which try to investigate medium modifications on free nucleonnucleon interaction. At present the (p,2p) and (p,pn) experiments which have been performed have looked at the regions of lower nuclear densities. However, the medium effects observed in quasi-free (p,p')should also be present in (p,2p) and (p,pn) on nuclei. This point has been discussed in a recent review of (p,2p) experiments by Kitching et al.⁴ Their observation is based upon the following analysis. The effective polarisations of two nucleons bound in orbits j = l + 1/2 and j = l - 1/2 respectively, satisfy, for any kinematics and distortions,

$$P_{\ell-1/2} = - \frac{\ell+1}{\ell} P_{\ell+1/2}$$

They observed, from the analysis of experimental asymmetries for 16 O and 40 Ca, that this relation can only be satisfied if one assumes that the pp analysing power is zero inside the nucleus, compared to its free value of 0.3 - 0.4 at 200 MeV. This observation can be directly tested provided one considers proton scattering from those nuclear protons which have zero effective polarisations. This is the case for $1S_{1/2}$ and $2S_{1/2}$ protons in 40 Ca and $1S_{1/2}$ protons for 16 O. In this case measured experimental asymmetry is equal to the NN analysing power, as can be seen from the formula

$$A(\theta) = \frac{P(\theta) + P_{\ell} j D_{nn}(\theta)}{1 + P_{\ell} j P(\theta)} .$$

where P_{ℓ} is the effective polarisation of a nucleon bound in an orbit $(n\ell j)$, $P(\theta)$ and $D_{nn}(\theta)$ are the usual spin observables in NN scattering and $A(\theta)$ is the experimentally observed asymmetry. However, their (p,2p) experiment on ${}^{40}Ca$ at 200 MeV, where one of the nucleons from $2S_{1/2}$ orbit is knocked out, gave null result. The measured analysing power was very close to the free analysing power. They correctly pointed out that this may be due to the fact that the nuclear medium effects are small when a $2S_{1/2}$ nucleon from ${}^{40}Ca$ is knocked out. We will analyse their result in the M* model and show where one expects to find large medium effects in (p,2p) experiments.

Most of the formalism given below is described in detail in Ref. 1. However, there are some important modifications for the (p,2p) reaction. We will assume that the basic (p,2p) interaction goes through a single scattering event and that the multiple scattering effects are well reproduced by distorted waves. This is a good approximation for light nuclei and works well in forward angle scattering. Consider the incoming proton under the influence of scalar (S) and vector (V) optical potentials. In an eikonal approximation, the wave function is

$$\psi_{ks}^{\pm} = \sqrt{\frac{E+M}{2M}} \begin{pmatrix} 1 \\ \sigma^{\bullet} p \\ \sim \gamma \\ \overline{E+M+S-V} \end{pmatrix} e^{ik \cdot x} e^{iS^{\pm}(x)} \chi_{s}$$

where k is the particle momentum, χ_{S} the Pauli spinor. The phase factor S(z) is given by

$$S^{\pm}(z) = \int_{\pm\infty}^{z} \frac{M}{k} dz' \{ V_{c}(b,z') + V_{so}(b,z')(\sigma \cdot b \times k - ikz') \}.$$

where the effective central V_{C} and spin-orbit V_{SO} potentials are

$$V_{c} = S + \frac{E}{M}V + \frac{1}{2M}(S^{2}-V^{2})$$
$$V_{so} = -\frac{1}{2Mr}\frac{\frac{\partial}{\partial r}(S-V)}{E+M+S-V}$$
$$r = \sqrt{b^{2}+z^{2}}$$

As a first approximation let us drop V_{so} . The effects of spin-orbit distortions on (p,2p) will be discussed in a later paper. Then the transmission probability for going through the nucleus at an impact parameter b is

$$T(b) = \left| e^{i \widetilde{S}^{+}(b) \right|^{2}} \right| = \exp \left\{ \frac{4M}{k} \int_{0}^{\infty} dz \operatorname{Im} V_{c}(b, z) \right\}.$$

We choose to define the average density for scattering from a nucleon in

a state Rnl j as

$$\rho_{eff} = \frac{\int_{0}^{\infty} bdb T^{3/2}(b) |R_{nlj}(b)|^2 \rho(b)}{\int_{0}^{\infty} bdb T^{3/2}(b) |R_{nlj}(b)|^2}.$$

Here $\rho(b)$ is nuclear density at an impact parameter b

$$\rho(b) = \frac{\int_0^\infty dz \ \rho^2(z,b)}{\int_0^\infty dz \ \rho(z,b)}$$

and $R_{nlj}(b)$ is the effective nuclear wave function at an impact parameter b

$$R_{nlj}(b) = \int_{-\infty}^{\infty} dz R_{nlj}(\sqrt{b^2+z^2}).$$

In the present work we have chosen to use harmonic oscillator wave functions. The extra factor of $T^{1/2}(b)$ compared to Ref. 1 takes care of absorption of the outgoing extra proton.

One can define an effective impact parameter \mathbf{b}_{eff} at which the interaction takes place, by

$$b_{eff} = \frac{\int_{0}^{\infty} bdb (b) |R_{nlj}(b)|^2 T^{3/2}(b)}{\int_{0}^{\infty} bdb |R_{nlj}(b)|^2 T^{3/2}(b)}$$

Given an effective density ρ_{eff} for (p,2p) reaction one can estimate an effective mass M^{*} by

$$\frac{M^*}{M} = 1 - 0.44 \rho_{eff}$$
.

Here ρ_{eff} is measured in units of nuclear matter saturation density and 0.44 is a result of mean field theory.

In Fig. 1 we have plotted harmonic oscillator 1S, 1P, 1D and 2S wave functions for 40 Ca. We used a value of β ($\beta = m\omega$) parameter of .28. In Fig. 2 phenomenological scalar (S) and vector (V) optical potentials are shown for 40 Ca at 200 MeV, obtained by fits to proton elastic scattering data.⁵ In Tables I and II the values for ρ_{eff} , M^{*} and b_{eff} are given for 1S, 1P, 1D and 2S states of 40 Ca and 1S and 1P states of 160 at 200 MeV. A comparison of Fig. 1, Fig. 2 and Table I yields some very interesting information. Consider first proton knock-out from 2S_{1/2} orbit of 40 Ca. Let us assume that the interaction takes place at z = 0. (It turns out to be a very good approximation for (p,p') but our general



Fig. 1. 1S, 1P, 1D and 2S wave functions for 40 Ca. We use β =.29 where β =m ω , m being the nucleon mass.



Fig. 2. Scalar and vector optical potentials for ${}^{40}Ca$ at 200 MeV. The potential strengths are in F^{-1} .

in south and the	15	1P	1d	25
	Margaren -	70000 10000 8100	en ganne en Rigannetig	<u>The second</u> p. offer ge
$\rho_{eff} (\rho_0)$.64	.50	.29	.21
м*/м	.72	.78	.87	.91
b _{eff} (F)	2.4	3.1	4.0	4.3

Table 1. Medium effects for (p,2p) on 40Ca at 200 MeV

argument is not affected by relaxing this approximation.) The beff for 2S orbit is about 4.3 F. We see that at impact parameter the S and V potentials have appreciably died down and effective density at which interaction takes place is only about 20% of nucleon matter density. Thus the medium effects are small. The M* is .91 in nuclear mass units. In Table III we have given analysing power as a function of scattering angle for different values of M^* . We see that for $M^* = .91$ the analysing power is very close to its free value. Thus the results of Kitching et al. are expected. Let us consider now the knock-out of the nucleons 1D, 1P and 1S orbits of 40 Ca. As expected, as we move to inner shells the beff decreases, Peff increases and hence M* decreases. The medium effects become larger. For protons knocked out from 1S orbit of 40Ca we see that $M^* \simeq .72$. The analysing power at this value of M^* is about half its free value. Thus strong medium effects should be seen in (p,2p) on 40 Ca when a nucleon is knocked out from the $1S_{1/2}$ shell. Knocking a proton out of $1S_{1/2}$ is understandably much more difficult. However, the NN interaction at medium energies is large and high flux beams are available at TRIUMF. This is definitely an experiment one could perform

	15	1P	
^ρ eff (ρ ₀)	.40	.28	
м*/м	.82	.87	
b _{eff} (F)	2.2	2.7	

Table II. Medium effects for (p,2p) on ¹⁶0 at 200 MeV

Θ _{cm}	$\frac{M}{M}^{*}=1.0$	$\frac{M^*}{M}$ =.91	$\frac{M^*}{M} = .88$	$\frac{M^*}{M} = .82$	$\frac{M^*}{M} = .72$
10	.14	.11	.10	.08	.05
20	.23	.27	.26	.23	.15
30	.28	.30	.28	.25	.16
40	.30	.28	.26	.22	.15
50	.27	.24	.22	.28	.13
60	.22	.28	.27	.24	.10
70	.16	.23	.11	.20	.07
80	.08	.06	.06	.05	.03

Table III. M* dependence of analysing power at 200 MeV

with a two arm spectrometer. In Table II we have also given b_{eff} and M^* values for knocking out a proton from 1S or 1P orbits of ${}^{16}O$ at 200 MeV. Again we see that the M^* effect is large for protons knocked out from 1S orbit of ${}^{16}O$. The analysing power for protons knocked out from 1S orbit is about 60% of the free value. This is certainly an easier experiment compared to knocking $1S_{1/2}$ protons out of ${}^{40}Ca$. Also the spin-orbit distortion effects are smaller compared to ${}^{40}Ca$. It is better to consider those (p,2p) experiments where the second proton is knocked out from S-shell orbits because in this case the effective polarisation of the struck proton is zero and hence experimentally measured asymmetries are directly related to in-medium NN analyzing power.

In Table IV we have given the energy dependence of M^* and beff for 1D state of ${}^{40}Ca$. It is seen that the medium modification effects are largest at 400 MeV. Thus we suggest that the most suitable experiment to measure medium effects in (p,2p) is to measure asymmetries on ${}^{16}O$ at 400 MeV when a proton is knocked out from $1S_{1/2}$ orbit.

Similar medium effects are seen in other spin observables in (p,2p) experiments. Since we have not discussed the effects of spin-orbit distortions on the spin observables in (p,2p) we will not discuss them at

T _{lab} (MeV)	м*/м	b _{eff} (F)	
160	0.87	3.9	
200	0.88	4.0	
300	0.89	4.1	
400	0.87	3.9	
500	0.91	4.3	
800	0.93	4.5	

Table IV. Energy dependence of medium effects for 1d state of 40Ca

this point. Asymmetries are relatively insensitive to spin-orbit distortions; hence our results discussed in this section are affected little.

For other spin observables in (p,2p) a more careful analysis of spin-orbit distortions is needed. This work is in progress.

Useful and stimulating discussions with Professor W.J. McDonald are greatly appreciated.

REFERENCES

1. C.J. Horowitz and M.J. Iqbal, Phys. Rev. C 33, 2059 (1986).

2. C.J. Horowitz and B.D. Serot, Nucl. Phys. A368, 503 (1981).

3. T.A. Carey et al., Phys. Rev. Lett. 53, 144 (1984).

- P. Kitching, W.J. McDonald, Th.A.J. Maris and C.A.Z. Vasconcellos, Advances in Nuclear Physics 15, 43 (1985), edited by J.W. Negele and Erich Vogt (Plenum, New York, 1985), p. 43.
- 5. A.M. Kobos, E.D. Cooper, J.I. Johansson and H.S. Sherif, Nucl. Phys. A445, 605 (1985).

DASS/SASP USERS LIST

R. ABEGG, TRIUMF, Vancouver, B.C., Canada (p,2p), (p,pn) W.P. ALFORD, University of Western Ontario, London, Ont., Canada (p,2p)(p,n)(n,p) E.G. AULD, U.B.C., Vancouver, B.C., Canada \dots (p, π)(p, π x) R.D. BENT, IUCF, Bloomington, IN, USA \dots (p, π)(p, π x) N.S. CHANT, University of Maryland (p,2p)(p,πx) College Park, MD, USA $(p,p\alpha)(p,pd)$ E. COOPER, TRIUMF, Vancouver, B.C., Canada Theory(p,2p) $(p,pn)(p,\pi x)$ T. DRAKE, U. of Toronto, Toronto, Ont., Canada (p,2p)(p,pn)(p,πx) F. DUNCAN, U.B.C., Vancouver, B.C., Canada \dots (p, π)(p, π x) R. DYMARZ, U. of Alberta, Edmonton, Alta., Canada Theory(p,2p)(p,pn) J. ERNST, Institut für Strahlenund Kernphysik, Bonn, W. Germany (p,π)(p,πx) W. FALK, U. of Manitoba, Winnipeg, Man., Canada $(p,\pi)(p,\pi x)$ D. FREKERS, TRIUMF, Vancouver, B.C., Canada ... $(p, \pi x)(\mu, \pi)(p, d2p)(p, \pi dp)$ L.G. GREENIAUS, University of Alberta, (p,2p)(p,p'n) Edmonton, Alta., Canada G. HUBER, U. of Regina, Regina, Sask., Canada $\dots (p, \pi)(p, \pi x)$ D. HUTCHEON, TRIUMF, Vancouver, B.C., Canada (p,2p)(n,p) M.J. IQBAL, U. of Alberta, Edmonton, Alta., Canada Theory(p,π) $(p, \pi x)(p, 2p)$ K. ITOH, U. of Saskatchewan, Saskatoon, Sask., Canada (p,2p) K.P. JACKSON, TRIUMF, Vancouver, B.C., Canada (n,p) G. JONES, U.B.C., Vancouver, B.C., Canada (p,π)(p,πx) P. KITCHING, TRIUMF, Vancouver, B.C., Canada (p,2p) J. LISANTTI, TRIUMF, Vancouver, B.C., Canada (p,2p) G.J. LOLOS, U. of Regina, Regina, Sask., Canada $(p,\pi)(p,\pi x)$ E.L. MATHIE, U. of Regina, Regina, Sask., Canada $(p,\pi)(p,\pi x)$ W.J. McDONALD, U. of Alberta, Edmonton, Alta., Canada..(p,2p)(p,n)(p,pn) C.A. MILLER, TRIUMF, Vancouver, B.C., Canada (p,2p)(p,pn) G.A. MILLER, U. of Washington, Seattle, WA, USA .. Theory(n,p)(p, π)(p, π x) A. MOALEM, Ben-Gurion University, Israel (p,pn)(p,πx) W.C. OLSEN, U. of Alberta, Edmonton, Alta., Canada ... (p,2p)(p,pn)(p,πx) S. PAGE, U. of Manitoba, Winnipeg, Man., Canada (p,2p)(p,pn)(p,πx) W.D. RAMSAY, TRIUMF, Vancouver, B.C., Canada (p,2p)(p,pn) E.F. REDISH, IUCF, Bloomington, IN, USA Theory, all P.G. ROOS, U. of Maryland, College Park, MD, USA (p,2p)(p,πx) P. SCHWANDT, Indiana University, Bloomington, IN, USA (p,2p)(p,pn) D.M. SHEPPARD, U. of Alberta, Edmonton, Alta., Canada .. (p,pn)(p,2p)(p,n) W. SHIN, U. of Saskatchewan, Saskatoon, Sask, Canada (p,2p) G. STINSON, U. of Alberta, Edmonton, Alta., Canada (p,2p)(p,pn) L.W. SWENSON, Oregon State U., Corvallis, Oregon, USA..(p,py)(p,2p)(p,pn) M. VETTERLI, TRIUMF, Vancouver, B.C., Canada (p,2p)(p,n) P.L. WALDEN, TRIUMF, Vancouver, B.C., Canada all T.E. WARD, Brookhaven National Lab, Upton, NY, USA all except (p,2p) S. YEN, TRIUMF, Vancouver, B.C., Canada all

Interests

A DESCRIPTION OF THE PARTY OF THE

(Land) (19, 1) A rain (1) month (Land) (1) and (2)

Harrison, Tedran Vancontres and Annalds and An



