ORO-2972-3
(Task C)

EXPERIMENTAL MEASUREMENTS AT LAMPF

PROGRESS REPORT

MASTER

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No. EY-76-C-05-2972, Task C.

I. INTRODUCTION

The purpose of this report is to summarize our progress in Medium Energy Research at LAMPF during 1977. The research has been supported by U.S. Department of Energy Contract No. EY-76-C-05-2972, TASK C. The group, all from the University of Texas at Austin, consists of P. J. Riley, Professor of Physics, Charles Hollas, Research Scientist, and two Physics Graduate students, Charles Newsom, and Ron Ransome. Our LAMPF research is carried out as part of a collaborative research program involving, in addition to the University of Texas group, B. E. Bonner, J. E. Simmons, and J. Boissevain of P-Division, LASL, and T. S. Bhatia, G. Glass, J. C. Hiebert, and L. C. Northcliffe of Texas A & M University. M. McNaughton of Case-Western Reserve University has, in addition, made invaluable contributions to the fabrication of the polarized proton target. The progress reported here is not solely the progress of the University of Texas group, but progress involving the collaborative research program as a whole. We have tried to emphasize the research work that the University of Texas group was most concerned with.

Charles Hollas joined our University of Texas group in residence at LASL during November, 1976. He helped us complete data acquisition on the three experiments 262, 263, and 264 during the Spring of 1977, and since then has spent most of his time and efforts in the analysis of data for experiment 262, "Test of Isospin Invariance in the Reaction $np \to d\pi^0$". This analysis is now nearly complete, and he is spending at least 50% of his time assisting in preparations for experiments 65 and 66, expected to begin in February, 1978.

Charles Newsom has been in residence at Los Alamos during the past year; in May 1977, he was awarded an Associated Western Universities (AWU) Fellowship.

During the spring of 1977 Charles divided his time between work on the fabrication and testing of the polarized proton target, and help with data acquisition on experiments 262, 263, and 263. After the completion of data acquisition, Charles has spent full-time in preparations for experiments 65 and 66. Ron Ransome spent the summer of 1977, with the support of an AWU summer thesis parts program, at LAMPF, where he also assisted in preparations for experiments 65 and 66. Peter Riley visited LAMPF during the Spring of 1977 for help in data acquisition with experiments 262, 263, and 264. During the summer (spent in LAMPF) he assisted in data analysis, in the preparation of several manuscripts for publication, and wrote a new proposal, "The Measurement of the Polarization Transfer Coefficients D_t and A_t" at 800 MeV for the Reactions $d(\vec{p},\vec{n})2p$, $^{6}Li(\vec{p},\vec{n})^{6}Be$, and $^{9}Be(\vec{p},\vec{n})^{9}B$", (Proposal 360). This proposal is scheduled for presentation to the LAMPF Program Advisory Committee (PAC) in January, 1977.

The primary motivation of the collaborative research program has been a definitive determination of the n-p interaction, for energies up to 800 MeV. The required data include both elastic and inelastic experiments, and in addition the measurement of polarization and spin correlation parameters. The program is extensive and the results to date only represent the beginning of the project.

In all the experiments that we have performed to date we have used the multiwire proportional chamber spectrometer and the Medium Energy neutron facility which we have developed at LAMPF. Figure 1 shows a plan view of the facility. The proton beam delivered to our area from LAMPF is incident on a neutron production target then swept through 60° and buried some distance away. Neutrons emerging through the 0° collimator are first monitored, then cleared of charged particles before striking the radiator of either LH_2 or LD_2 placed at the focal point of the spectrometer. Charged particles leaving the radiator in the direction of the acceptance of the spectrometer are bent through a nominal 22° and their trajectories are determined from the wire chambers. The momentum of the particle is then calculated from the measured trajectory through the known fields. The overall efficiency of the system for a particle in the acceptance is better than 99.9% and the momentum resolution is on the order of 1% FWHM. Particle identification is achieved by simultaneous measurement of the time of flight of the particle through the spectromenter. The spectrometer can be moved about a pivot beneath the radiator and positioned at angles from 0° to 70°.

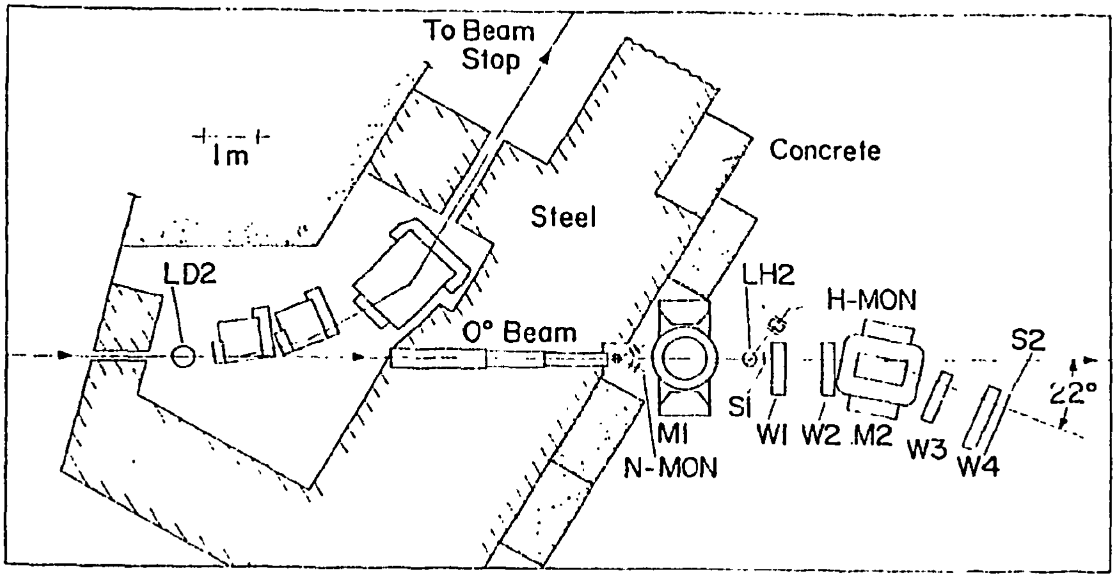


Figure 1. Schematic of the Medium Energy Neutron Facility at LAMPF.

During 1977 data acquisition was completed on three experiments, 262, "Test of Isospin Invariance in the reaction $np \rightarrow d\pi^0$," 263, "Measurement of the Energy and Angular Variation of the np Charge Exchange Cross Section," and 264, "Measurement of the Energy Variation of the nD Elastic Differential Cross Section near 180°." A very large amount of data was taken for these experiments: for experiments 262, 263, and 264, approximately 17 million, 36 million, and 57 million events respectively were written to tape.

In spite of the large amount of data, analysis is nearly completed -- this was made possible by the improvement in the computing efficiency of our code (TEWA) that calculates momentum from the measured coordinates at the entrance and exit of our spectrometer at LAMPF. Instead of integrating individual particle trajectories through the known magnetic field as in TEWA, the new program (TBEND) uses only the raw coordinates recorded for each event and from these, predicts the momentum to better than 1% for more than 99% of all events in the acceptance region of the spectrometer. The overall improvement in speed of TBEND over TEWA is about a factor of 8. This, combined with the packing of the output information by a factor of 20, has greatly facilitated the analysis of the very large amount of data taken for experiments 262, 263, and 264. Four abstracts based on these experiments were submitted to the Second International Conference on the Nucleon-Nucleon Interaction, June, 1977; the titles of these abstracts are "nD Scattering at 180° for Neutron Energies from 200 to 800 MeV", "The Inclusive Reaction, $np \rightarrow pX$ at 800 MeV", "np Charge Exchange Scattering for Neutron Energies 300-800 MeV", and "A Measurement of the Deuteron Spectrum in $np \rightarrow d(\pi\pi)^0$ at 800 MeV". In addition, a letter "nD scattering at 180° for Neutron Energies from 200 to 800 MeV" was submitted to and published by Physical Review Letters during 1977. Manuscripts based on the fully analysed data of experiments 262-4 are in preparation.

During 1977 we also either published or submitted for publication six manuscripts based on measurements carried out and completed before experiments 262, 263, and 264. The title pages of these manuscripts are given in Section V of this progress report. Analysis and publication of experimental measurements completed before 1977 is therefore now finished.

However, perhaps the largest effort during 1977, especially during the latter part of the year, has gone into preparations for experiments 65 and 66, "Neutron-Proton Polarization Measurements using a Polarized Target: Phase I. The n-p Polarization Observable", and "Neutron-Proton Polarization Measurements using a polarized target: Phase II. The n-p Spin Correlation Observable". In addition to work with the polarized target system, a large amount of new instrumentation has been necessary, partly because it is now expected that the incident proton beam current available for neutron production will not be more than 5 μamp. This is a factor of six less than projected in the original proposal. The implication is that counting rate must be regained by increasing the efficiency of the detection system. Consequently, a revised layout of the experiment was made, based on our experience with earlier measurements. A high efficiency neutron detector was designed and is being fabricated. The Multi-wire proportional counter spectrometer (MWPC) has been reworked so as to obtain a two-fold increase in solid angle in the magnetic spectrometer. New MWPC's have been designed and ordered; the electro-mechanical design has been modified to provide better reliability and greater flexibility in placement of chambers. A new PDP 11/60 computer has been procured through Texas A & M University; software development for the new computer system is proceeding rapidly. Finally, a trailer is being modified into an instrumentation trailer to provide greater space for the data acquisition hardware.

Most of the University of The University of Texas contribution to this effort during 1977 has been in the area of help with polarized target development (Charles Newsom), in help with the design and fabrication of the high-efficiency neutron detector, (Charles Newsom and Ron Ransome) and in the purchase of a VERSATEC Model 1100A printer/plotter by the University of Texas for use with the new PDP 11/60 computer system. A considerable effort was expended in the design of the bleeder string and base for the 12-stage Amperex XP 2230 photo multiplier tubes used in the neutron detector. Sixty bleeder strings and bases are now being fabricated at the University of Texas for the photomultipliers of the neutron and other counters for experiment 65.

Finally, during 1977, Los Alamos Scientific Laboratory acquired a second polarized target from Saclay, France (with the support of ERDA). This target is capable of longitudinal polarization in a geometry suitable for nucleon-nucleon experiments, and is expected to be operational at LAMPF in approximately one year.

II. EXPERIMENTAL RESEARCH

In the following we list and discuss briefly specific experiments and technical development work for experiments with which we have been involved during 1977. We do not include here descriptions of work either published or submitted for publication - the title pages of these manuscripts are given in Section V of this progress report.

1. Measurement of the Deuteron Spectrum in $np \to d(\pi\pi)^o$ at 800 MeV

The "ABC" effect in double pion production reactions was first observed[1] as an enhancement in the missing spectrum from reaction $pd \to {}^3He(\pi\pi)^o$. Since then various models have evolved to explain this effect in pD reactions and also in the simpler reaction $np \to d(\pi\pi)^o$. The two most extensively developed theories are the two nucleon exchange model of Anjos, Levy, and Santoro[2] and the one-pion exchange model with double delta ($\Delta\Delta$) excitation of Bar-Nir, Risser, and Shuster.[3] An interesting extension[4] of the latter model to allow for deep binding of the $\Delta\Delta$ system appears to account for the recent observation[5] of a peak in the polarization of the proton from deuteron photodisintegration as well as the measurements so far reported in double pion production.

These models yield predictions of the energy dependence and the detailed shape of the enhancements in the missing mass spectra. Data to test these models for $np \to d(\pi\pi)^o$ presently consist of the bubble chamber total cross section measurements[6] at eight momenta from 1.75 to 3.5 GeV/c and one deuteron momentum spectrum[7] at 4.5° and 1.88 GeV/c.

At LAMPF we have performed an experiment designed to measure the assymetry in the reaction $np \to d\pi^o$ at 800 MeV. The unexpectedly large cross section we observe for the $np \to d(\pi\pi)^o$ process means that we also obtained the momentum spectrum of the deuterons from this reaction over the entire angular range.

The 800 MeV proton beam from LAMPF was used to produce a nearly mono-energetic neutron beam using the d(p,n)2p reaction at 0 degrees. The momentum spectrum of the neutron beam is shown in Fig. 2. After being cleared of charged particles by a magnet, the 0° neutron beam strikes a liquid hydrogen radiator and then is buried in a beam dump. Charged particles emerging into the angular acceptance of our MWPC spectrometer are momentum analyzed, and their time of flight through the spectrometer is measured. We also measure the time of flight of the neutrons from the deuterium target to the hydrogen target. Our ∿.5 nsec timing resolution enables a rejection of events not due to neutrons in the sharp peak. Fig. 3 shows the kinematics at 0 degrees for deuterons associated with single and double pion production.

A dueteron momenta spectra over the angular range of .08 to .10 radians (laboratory) is shown in Fig. 4. The large peaks at 1575 MeV/c and 895 MeV/c deuteron momentum are associated with the $n + p \rightarrow d + \pi^{\circ}$ process. The higher momentum peak corresponds to deuterons traveling forward in the center of mass system; the lower momentum peak corresponds to deuterons traveling backward in the center of mass system. The presence of these deuterons provides a convenient method of obtaining the absolute cross sections for the $n + p \rightarrow d + (\pi\pi)^{\circ}$ process. The region between the two peaks is the kinematically allowed region for double pion production.

In Fig. 5 are deuteron momenta spectra over the angular ranges 0.00 to 0.02, 0.04 to 0.06, 0.08 to 0.10, and 0.10 to 0.14 radians. The solid lines are proportional to the three body phase space with a single normalization and are calculated at the average angle. The main enhancements appear in the central region near the maximum missing mass value. No clear evidence of enhanced peaks at two-pion mass value is observed, such as were seen at Pn = 1880 MeV/c by Bizard et al.[7] The magnitude of the cross sections decrease

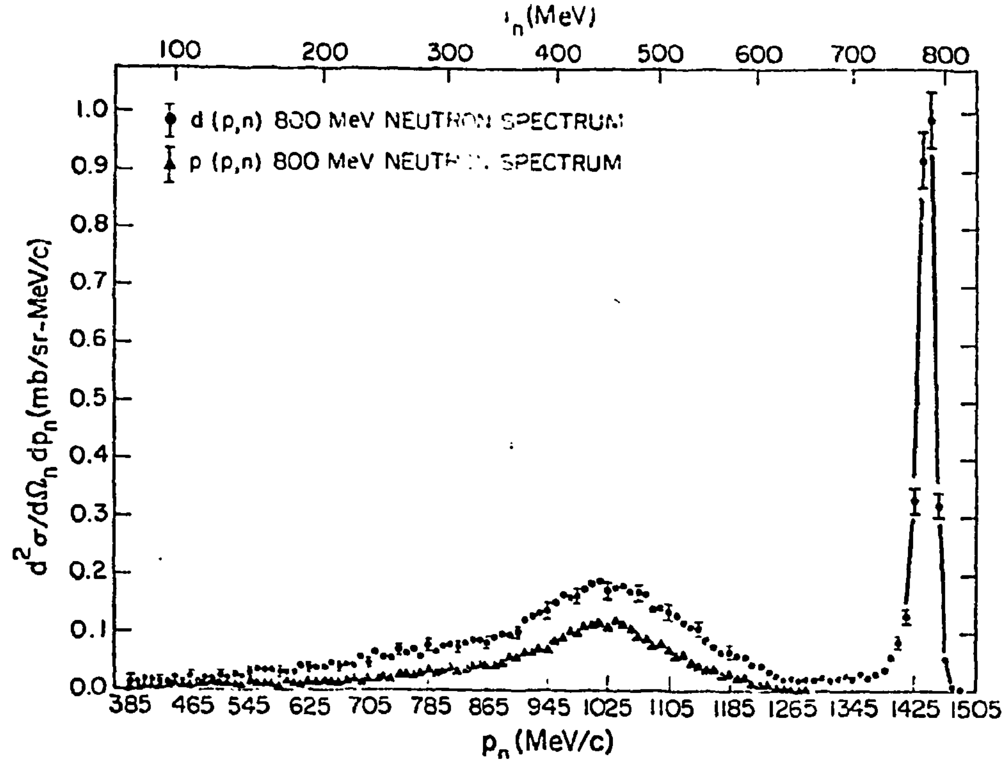
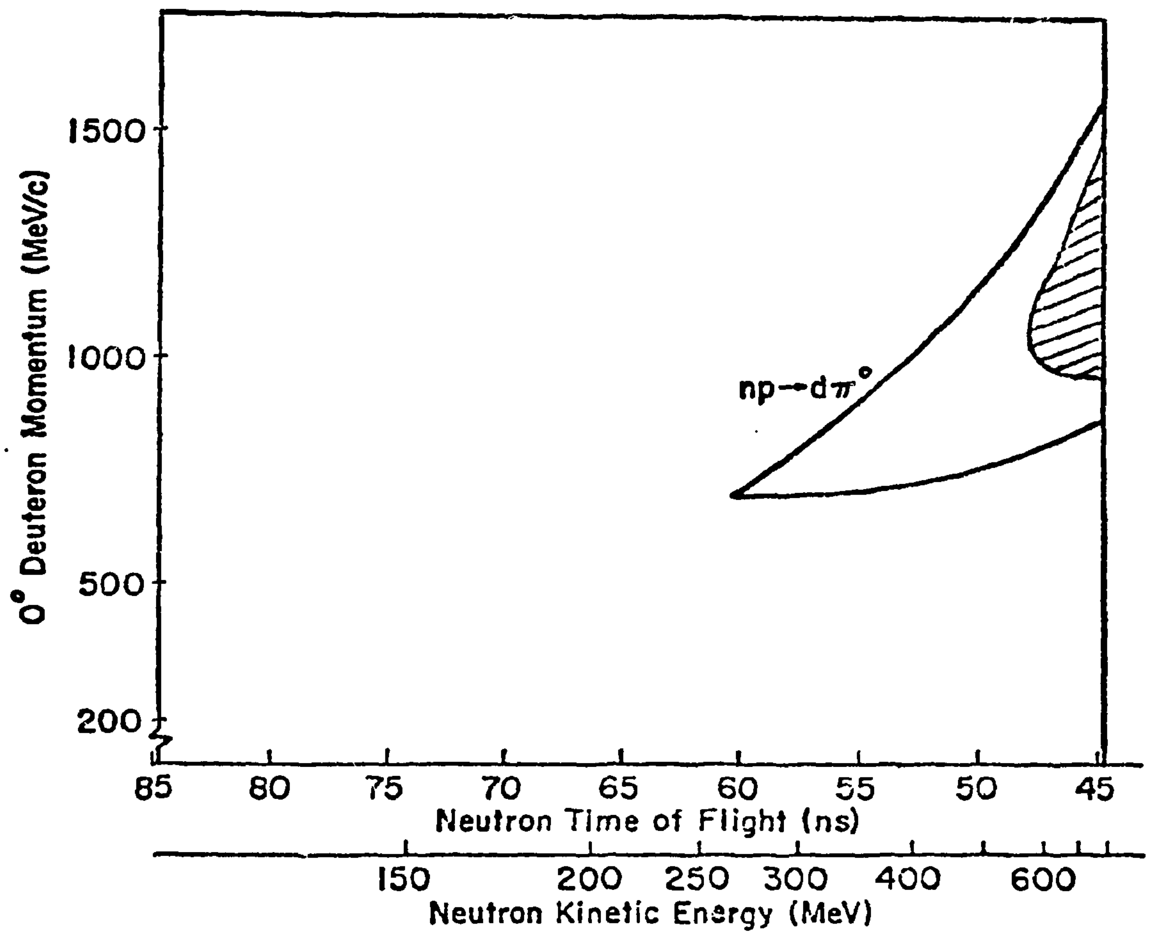


Fig. 2. Momentum spectrum of the neutron beam.

Fig. 3. Kinematics at 0^o for deuterons associated with single and double pion production in the reaction $np \rightarrow d\pi^0$.



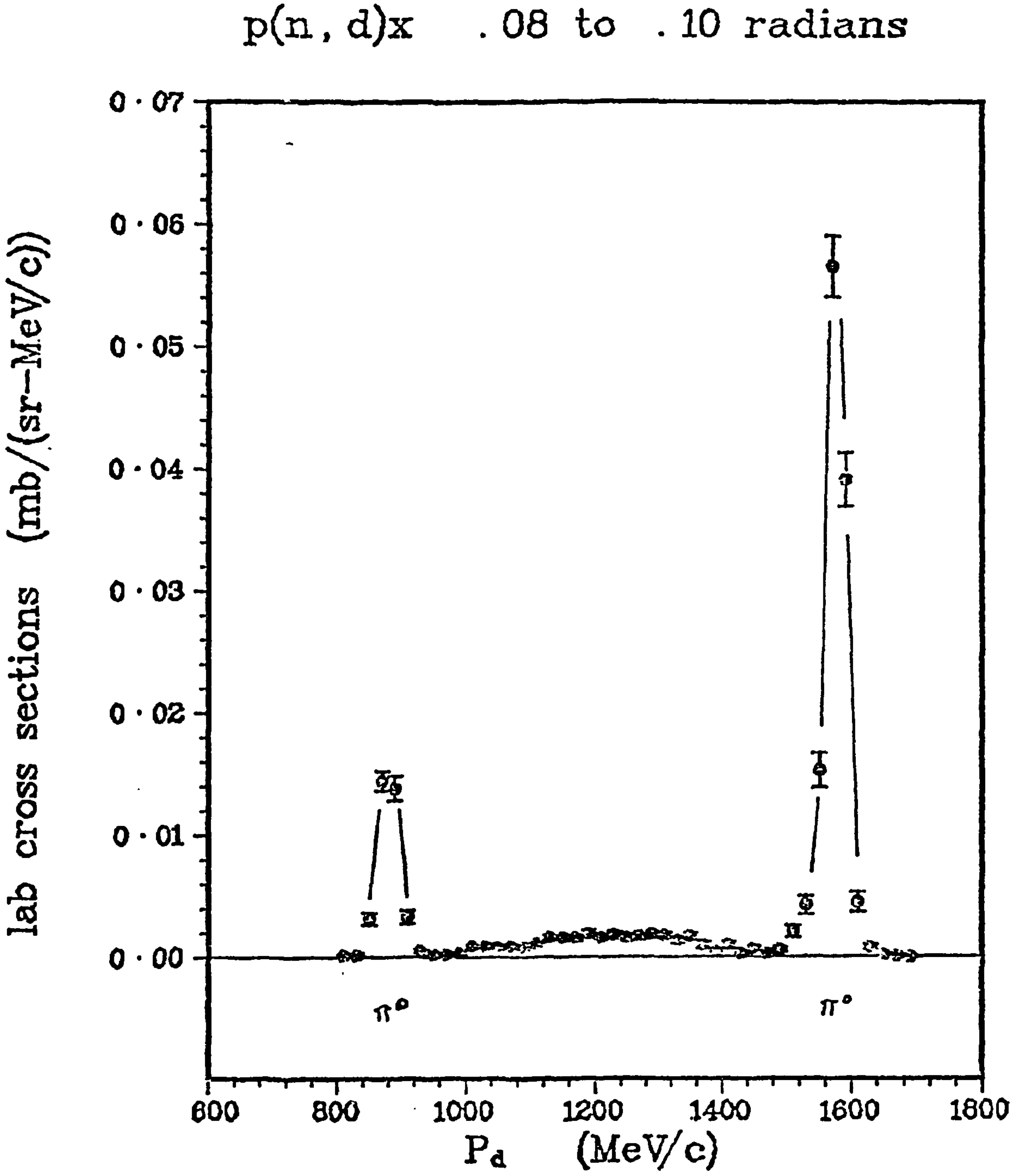


Fig. 4. p(n,d)X momentum spectrum.

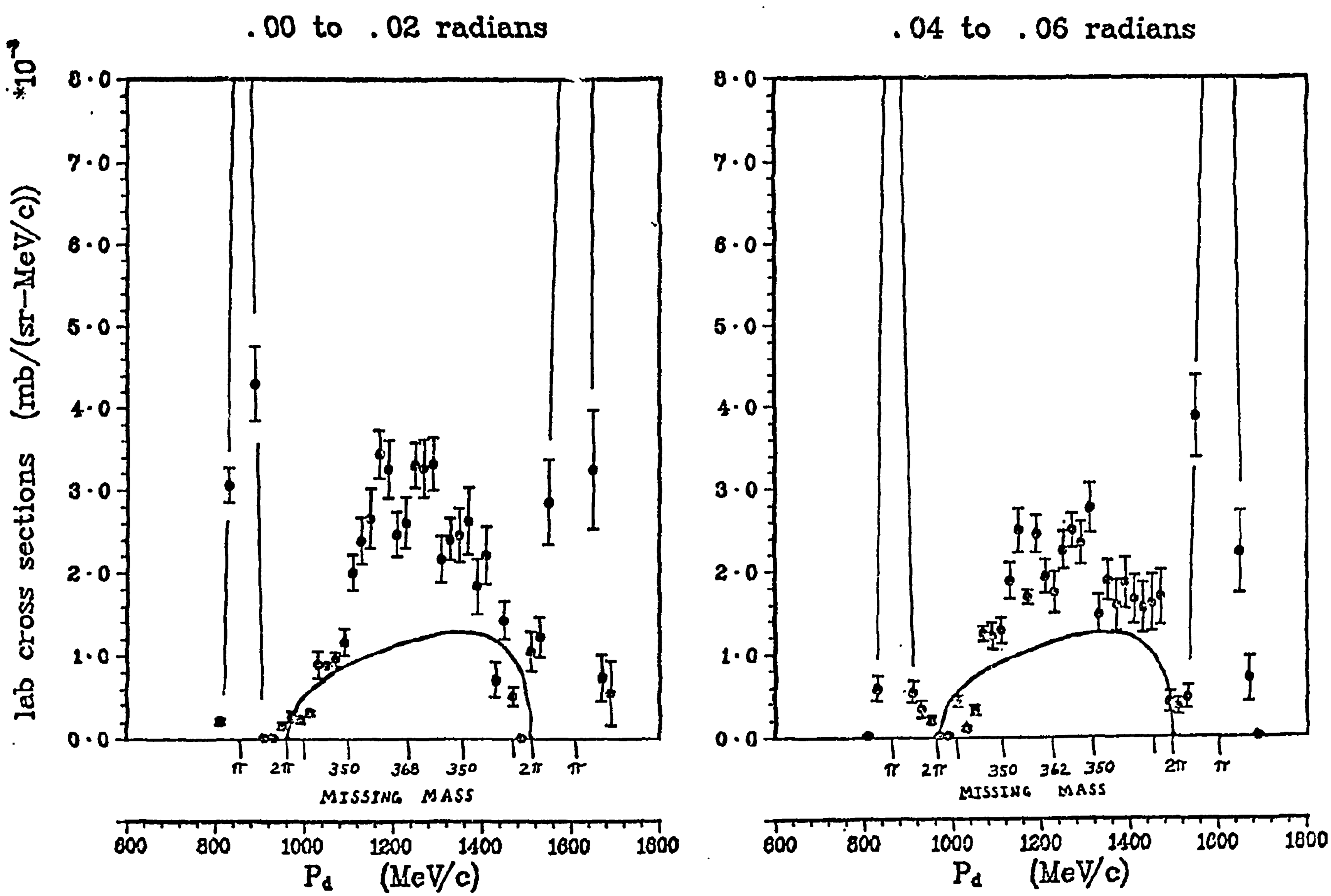


Fig. 5(a). p(n,d)X spectra.

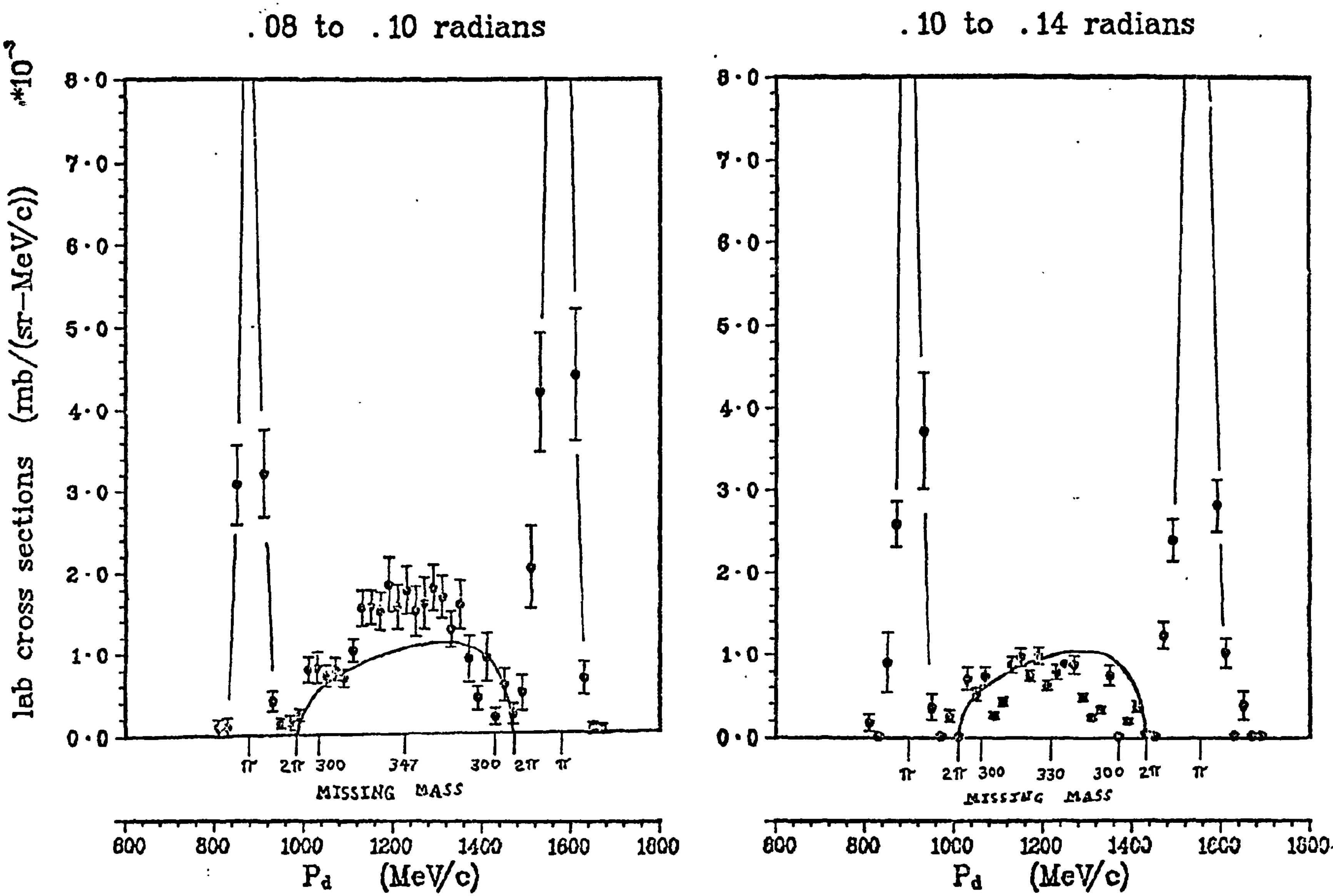


Fig. 5(b). p(n,d)X spectra.

almost monotonically as a function of angle from the maximum near zero degrees to zero at the phase space boundary near 0.15 radians.

Detailed published calculations for $n+p \rightarrow d+(\pi\pi)^\circ$ at our incident neutron momentum do not exist. However, our data can be compared to Fig. 4 of Bar-Nir, Risser, and Shuster[3] and with Fig. 11 of Anjos, Levy, and Santora[2] to obtain a rough idea of how their calculations predict the data. At Pn = 1.5 GeV/c, Ref. 3 predicts a maximum cross section for the central region of ∿0.6 μb/(sr-MeV/c). From the graph in Fig. 11 of Ref. 2, the maximum value of the cross section in this region is ∿1.8 μb/(sr-MeV/c). Our measured value is ∿1.5 μb/(sr-MeV/c). No calculations are published on the angular dependence of the cross sections.

From our data we extract a value for the total cross section of 28.23 μb for the process $n + p \rightarrow d + (\pi\pi)^\circ$. This value is plotted in Fig. 6 with the $n + p \rightarrow d \pm (\pi^+\pi^-)^\circ$ data of Bar-Nir et al.[6]

[1]A. Abrashian et al., Phys. Rev. Letters 5 (1960) 258.
[2]J. C. Anjos, D. Levy, and A. Santoro, Nuovo Cimento 33A (1977) 471.
[3]I. Bar-Nir, T. Risser, and M. D. Shuster, Nucl. Phys. 87B (1975) 109.
[4]T. Kamae and T. Fujita, Phys. Rev. Letters 38 (1977) 471.
[5]T. Kamae et al., Phys. Rev. Letters 38 (1977) 468.
[6]I. Bar-Nir et al., Nucl. Phys. B54 (1973) 17.
[7]G. Bizard et al., Proc. 5th Int. Conf. on High-Energy Physics and Nuclear Structure, Uppsala, Sweden, 1973.

2. The $np \rightarrow d\pi^\circ$ Reaction at 800 MeV

We have carried out differential cross section measurements for the $np \rightarrow d\pi^\circ$ reaction at 800 MeV. The motivation for making the measurement stems partly from the need for providing data for deuteron-associated pion production in nucleon-nucleon collisions, but primarily from an idea apparently first observed by Yang in 1952 that a comparison of the two reactions

$$n + p \rightarrow d + \pi^\circ$$

$$p + p \rightarrow d + \pi^+$$

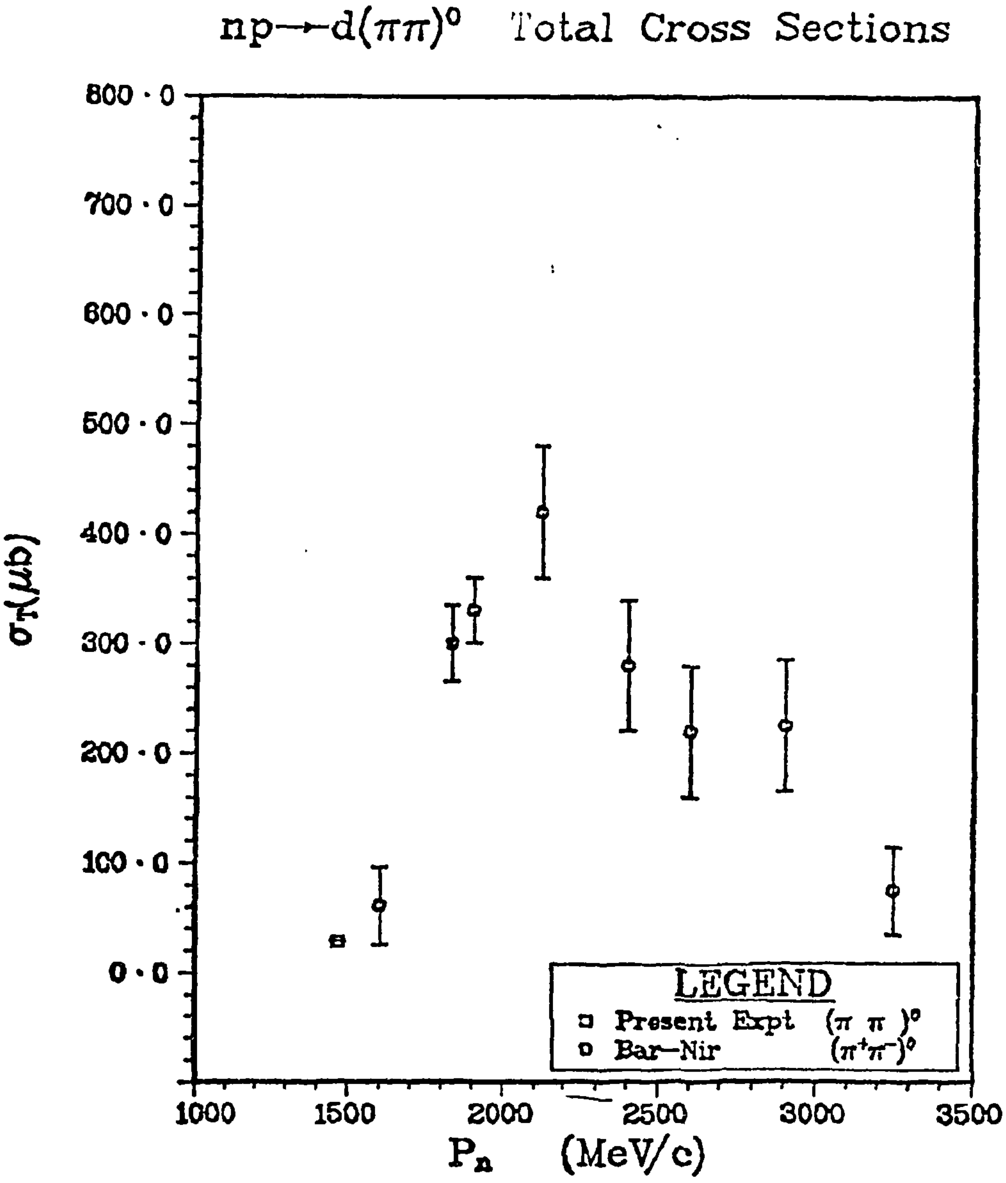


Fig. 6. The total cross section from the present experiment shown together with the data of Bar-Nir *et al*.

should provide a severe test of the hypothesis of charge independence in meson-nucleon interactions. This test and further tests were discussed by several authors soon afterwards; the first experimental measurement of $np \to d\pi^{\circ}$ was reported by Hildebrand at Chicago in 1952[1] with 400 MeV neutrons. This test requires that the differential cross sections at the same center-of-mass energy and angle have the ratio 1:2 for the two reactions, neglecting $\pi^{+}-\pi^{\circ}$ and n-p mass differences. As discussed by Wilson et al[2], this ratio can be obtained by expressing the initial and final states as eigenstates of total isospin as follows:

$$\frac{d\sigma(np \to d\pi^{\circ})}{d\sigma(pp \to d\pi^{+})} = \frac{|1/\sqrt{2}\,\langle 1,0|S|1,0\rangle + 1/\sqrt{2}\,\langle 1,0|S|0,0\rangle|^2}{|\langle 1,1|S|1,1\rangle|^2}$$

If isospin is conserved

$$\langle 1,0|S|0,0\rangle = 0$$

If the strong forces are independent of T_3

$$\langle 1,1|S|1,1\rangle = \langle 1,0|S|1,0\rangle$$

Thus, charge independence requires that

$$\frac{d\sigma(np \to d\pi^{\circ})}{d\sigma(pp \to d\pi^{+})} = \frac{1}{2}$$

There are three possible experimental observations. First, the $np \to d\pi^{\circ}$ agnular distribution in the center-of-mass system must be symmetric about 90°. This follows from the identity of the particles in the initial state in the $pp \to d\pi^{+}$ reaction. This consequence allows a test for the $np \to d\pi^{\circ}$ reaction which is independent of any other measurement. Second, the angular distributions observed for the two reactions at the same c.m. energy must have the same shape. This test requires accurate measurements of both the $np \to d\pi^{\circ}$ and the $pp \to d\pi^{+}$ reactions. Finally, the magnitude of the cross sections for the two reactions at the same c.m. energy must have the ratio of 1:2. Again, accurate measurements for both reactions are essential.

Hildebrand[1] obtained six data points in the $np \to d\pi^\circ$ angular distribution, and found no asymmetry about 90°. In addition, a fit to comparable $pp \to d\pi^+$ data passed through his data points. Hildebrand also observed that this measured cross sections were of the same order of magnitude as those obtained for the $pp \to d\pi^+$ reaction. Since then the accuracy of the measurements has improved. However, in 1970, Bartlett et al.[3] were not able to detect the need for a $\cos^4\theta$ term to fit their $np \to d\pi^\circ$ data; such a term is required to fit the most accurate $pp \to d\pi^+$ data.

With the development here at LAMPF of an intense, nearly monoenergetic neutron beam in area B, it was felt that a new measurement of $np \to d\pi^\circ$ could be made with greater precision than had previously been obtained. In addition, in experiment 201 here at LAMPF, Minehart et al. have proposed a careful measurement of the reaction $\pi^+ d \to pp$, the inverse of $pp \to d\pi^+$, which could be used to compare with our work.

The $np \to d\pi^\circ$ measurements were carried out using the LAMPF 800 MeV p(d,n)2p 0° neutron beam and the MWPC spectrometer in area B of LAMPF. The accelerator was operated in a chopped beam mode, providing 40 nsec between micropulses. Using neutron time-of-flight measurements, we were able to select events which were initiated only by neutrons within the sharp high energy peak of the neutron momentum spectrum. Charged particle mass identification was provided by simultaneous measurement of momentum and flight time through the spectrometer, allowing a direct rest mass calculation for each event. Figure 7 shows a typical mass spectrum. The experiment consisted of the measurement of deuteron momentum only in the $np \to d\pi^\circ$ reaction.

Because of kinematic considerations, all the deuterons are emitted in the forward direction into a cone of half angle of approximately 15°. For a given angular setting of the spectrometer we observe two groups of deuterons. Figure 8 shows the deuteron momentum spectrum measured at the average angular setting of about 5°. (The spectrometer has an angular acceptance of approximately 4°.) The higher momentum deuteron group near 1580 MeV/c consists of deuterons emitted in the forward direction in the center-of-mass, and those near 800 MeV/c correspond to those emitted backward in the center-of-mass. The kinematics for the reaction are indicated by the central line in Fig. 9 for an incident neutron eneary of 800 MeV. The two outer lines are obtained by folding in approximate resolutions for our angle and momentum determinations and the spread in the incident neutron beam. An interesting feature in the spectra is indicated by the events appearing between the two peaks; we attribute these events to deuterons associated with double pion production.

Using five angular settings of the spectrometer, we have obtained a complete angular distribution for the $np \to d\pi^{\circ}$ reaction. The most recent angular distribution cross section data are shown in Fig. 10. The errors shown are statistical only; the cross sections have been normalized by means of existing $\pi^{+}d \to pp$ data.[4] Fig. 11 shows cross sections for the $\pi^{+}d \to pp$ reaction taken from the work of Richard-Serre et al.[4] The pion energy of this measurement corresponds to a proton energy for the inverse $pp \to d\pi^{+}$ reaction of 810 MeV, very close to our neutron energy of 800 MeV. The solid line shown in Fig. 10 is a fit to this $\pi^{+}d \to pp$ data of Fig. 11.

The shape of the $np \to d\pi^{\circ}$ angular distribution is clearly in very good agreement with the $\pi^{+}d \to pp$ data. Further, the $np \to d\pi^{\circ}$ data is clearly rather symmetric about 90° c.m. Although analysis of our data is nearly complete, some further corrections, such as corrections for the dissociation of deuterons in the MWPC spectrometer, must still be made. However, it does appear that the $np \to d\pi^{\circ}$ cross section will be symmetric about 90° c.m., and in excellent agreement (shape) with the best presently available $pp \to d\pi^{+}$ data. We hope that our measurements

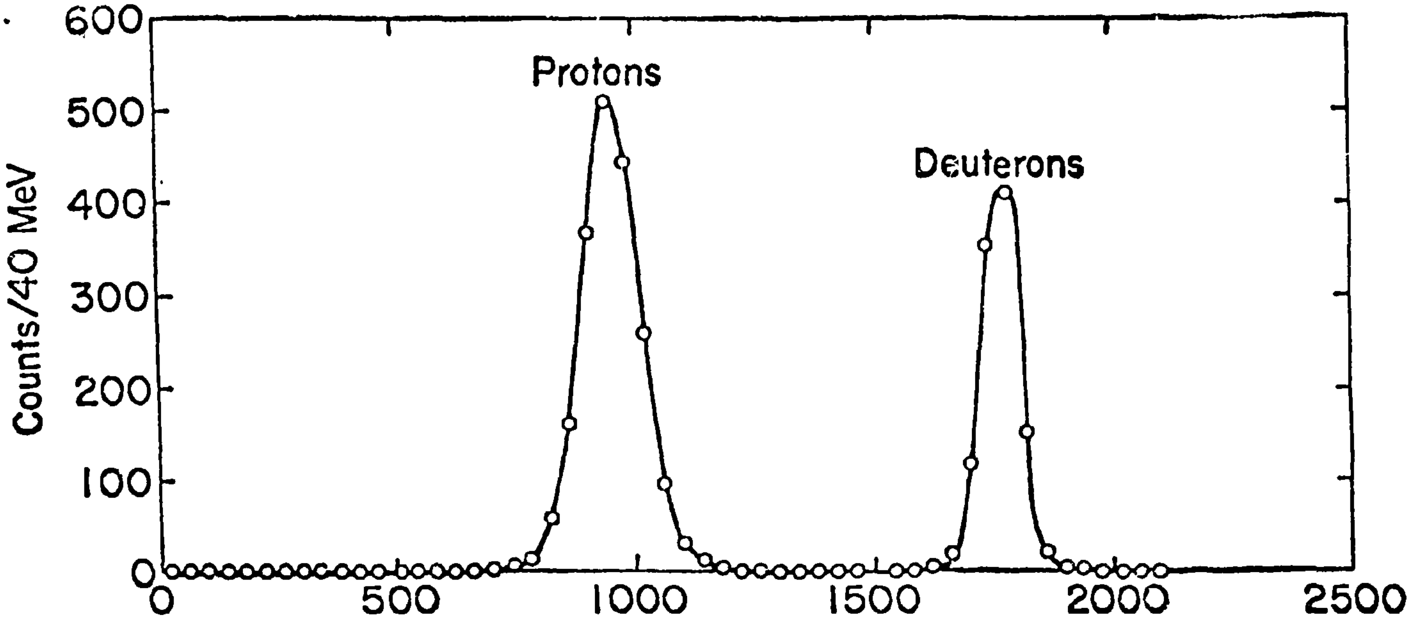


Fig. 7. Typical n + p mass spectrum.

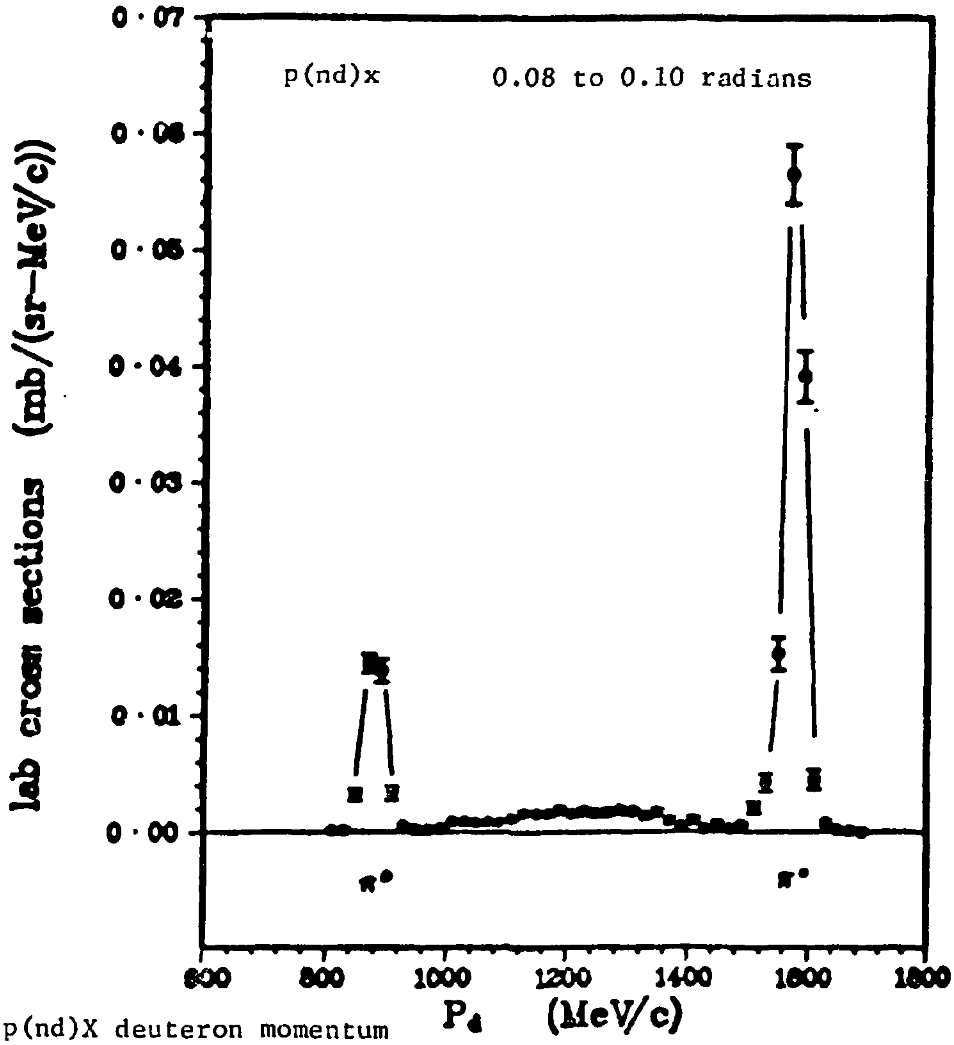


Fig. 8. p(nd)X deuteron momentum spectrum.

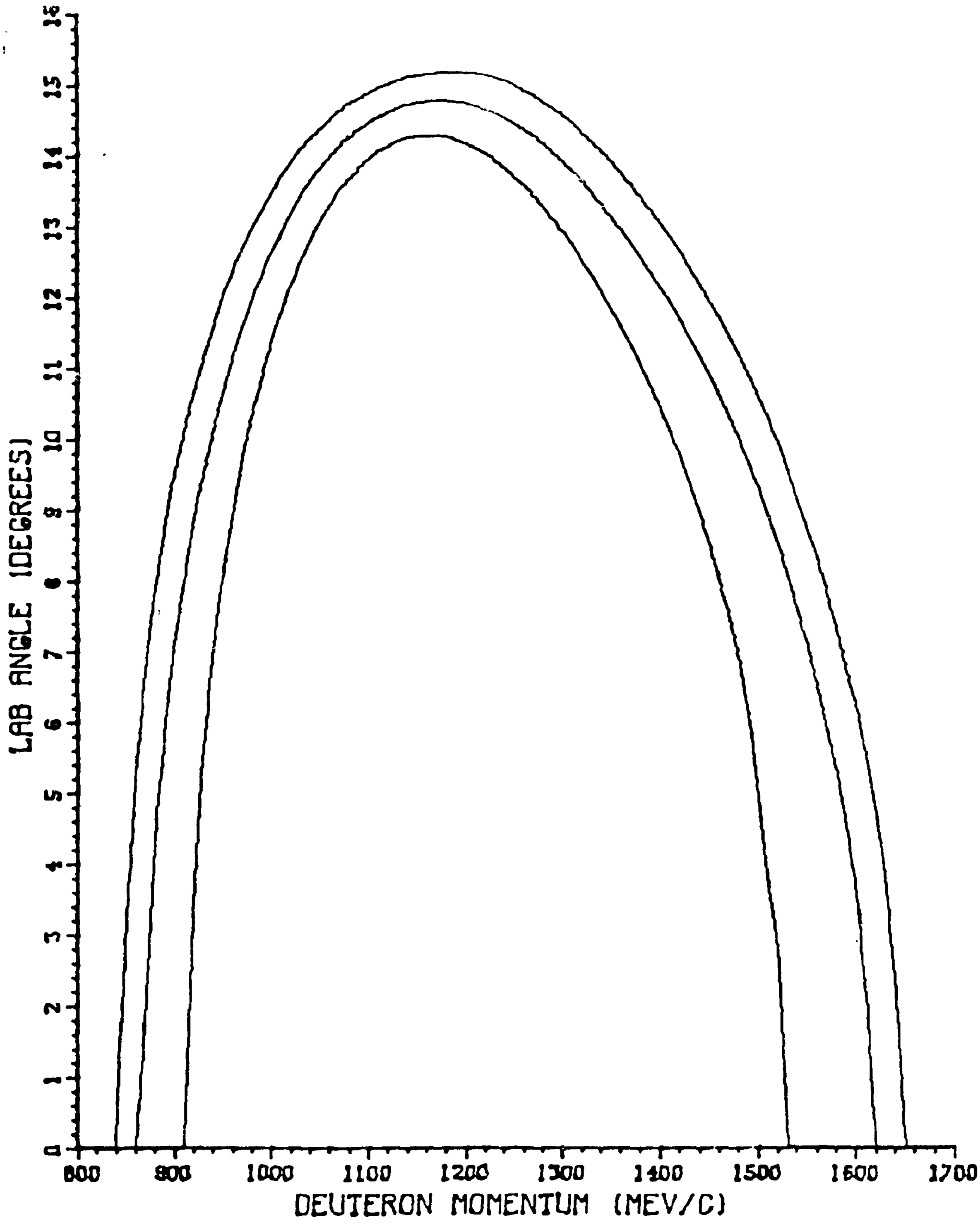


Fig. 9. np → $d\pi^0$ Kinematics. The central line represents two-body kinematic calculations for E_n = 800 MeV. The upper and low lines indicate the spreading of the observed spectra due to an angular error of 0.006 radians, a neutron momentum error of 30 MeV/c, and a deuteron momentum error of 30 MeV/c.

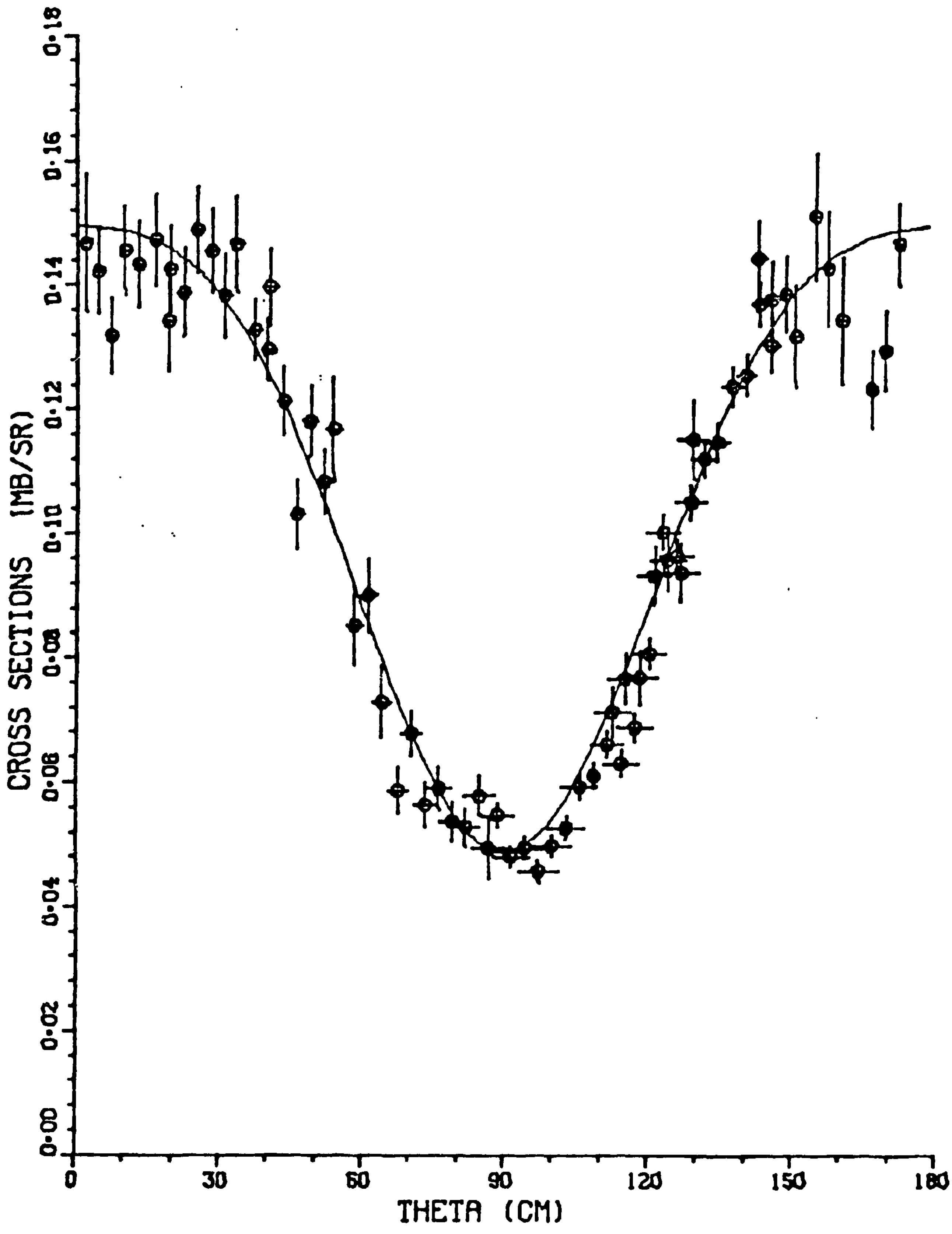


Fig. 10. np → $d\pi^0$ cross section data normalized to the solid line. The solid line is a fit to the $\pi^+ d \to pp$ data shown in Fig. 11.

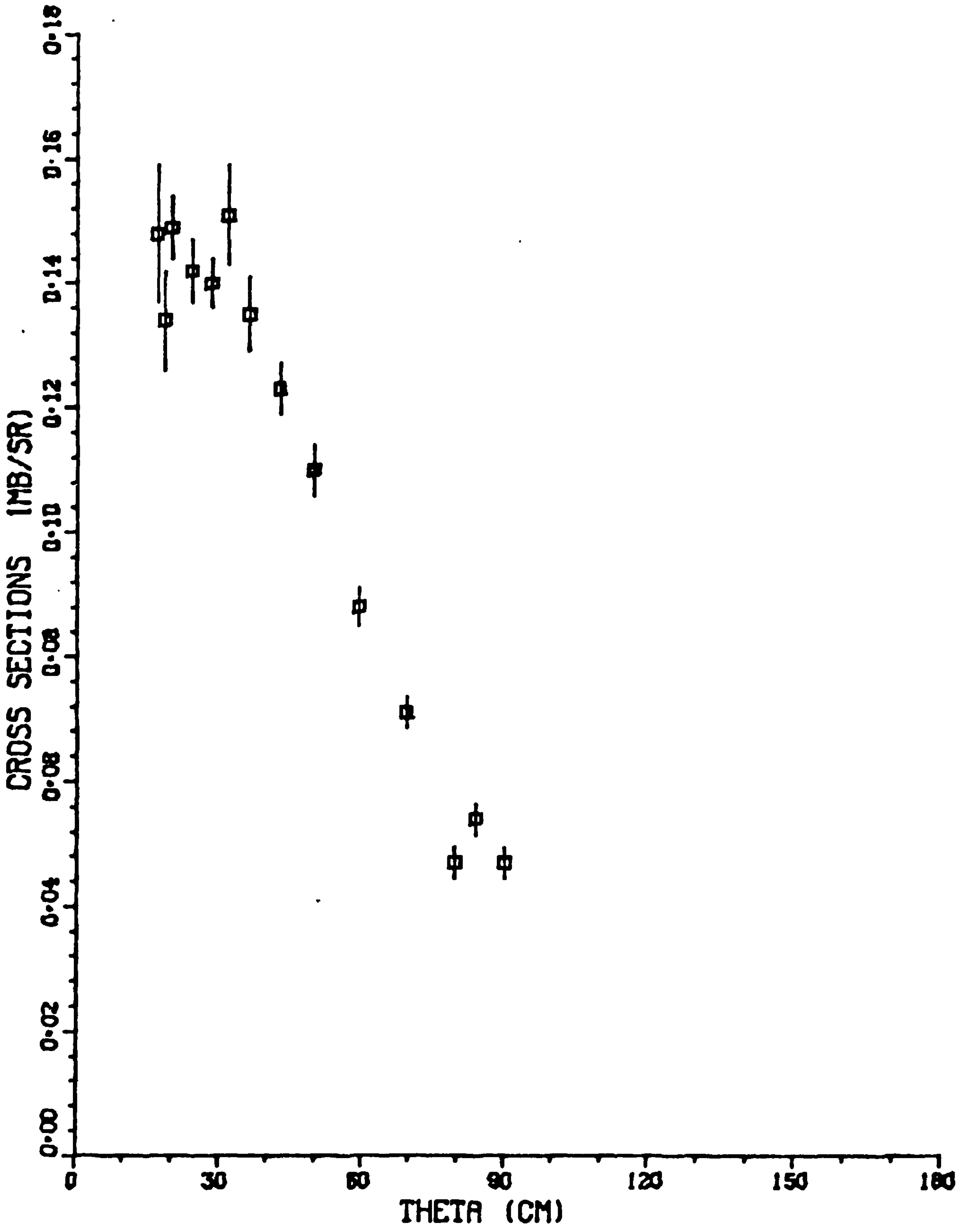


Fig. 11. $\pi^{+}d \rightarrow pp$ cross section data taken from Richard-Serre et al.

will encourage more precise $pp \to d\pi^+$ data to be taken for comparison with our $np \to d\pi^\circ$ work.

[1]R. H. Hildebrand, Phys. Rev. 89, 1090, (1953).
[2]S. S. Wilson, et al., Nucl. Phys. B33, 253, (1971)
[3]D. F. Bartlett et al., Phys. Rev. D1, 1984, (1970).
[4]C. Richard-Serre et al., Nucl. Phys. B20, 413, (1970).

3. Polarized Target Development Work

During the early part of 1977 the thermometry for the polarized target was put in its final form with the installation of new wiring, the replacement of the leaking feedthrough connectors, and the installation of brass plugs in the two unused connector holes. In the ^4He region there are six type E thermocouples and thirteen 200-ohm 1-watt Allen Bradley carbon resistors. In the ^3He region, there are three E thermocouples, nine 100-ohm 1/8-watt Allen Bradley resistors, one 10-ohm 1/8-watt Allen Bradley resistor, and one 100-ohm 1/8-watt Speer resistor that is used as a target heater.

Data from our first polarization run indicated that the propanediol was low in paramagnetic spin centers thus causing long polarization times and rather low polarizations. Using the electron paramagnatic spin resonance apparatus, we tested eight different batches of target material and kept those batches with a peak to peak width of the differentiated absorption signal near 6 gauss. This width, representing about 1.4×10^{20} spin centers per cm^3, is considered to be optimum and is a factor of three to four more than our first sample.

A substantial amount of effort was spent to improve the magnetic field stability of the 22-in. Varian magnet. Personnel from E-1 maintenance assisted us in this work. The trouble was finally traced to the Hall probe, which is the sensor for the Fieldial controller. Such sensors must be maintained at constant temperature and should be turned on for a long period before actual use. With proper attention to these points, the field stability has been improved to the point where the drift is less than 1 gauss per hour at 25000 gauss central field.

With the help of personnel from MP-13, magnetic field measurments were also performed on the magnet. Measurements of fringe field versus radius were made to establish the bending of charged particles through the magnet. In addition, detailed homogeniety measurements were made of the central field. In this a 2-mm-diam NMR probe was fabricated following a design by MP-7. The general field shape corresponds rather well to the information provided by Varian seven years ago. The object of such measurements is to determine how large a volume of polarized material may be employed in this target. The measurements indicate there to be a 10 gauss maximum deviation in a volume of 50 cm^3. This appears to be a feasible condition.

The setup of the polarized target system was completed at the external proton beam line at LAMPF during the first part of July. This effort culminated in the first measurements at Los Alamos of the scattering of a polarized proton beam by a polarized proton target. The measurement of the p-p spin correlation parameter $A_{yy}(\theta)$ at 800 MeV was one of the objects of this collaboration. The scattering of an unpolarized beam from the polarized target represents a method by which an independent measurement of target polarization can be made and thereby verify the accuracy of the NMR polarization measurement. Both of these objects were accomplished in runs that occupied the latter part of July and most of August.

A number of annoying problems were encountered during the first part of the run. Most importantly, there included failure of the Varian magnet power supply which was hastened by operator error, excessive liquid helium usage from stock dewars, and a tendency for the evaporator valve to become blocked. The blocking problem was partially cured by installing a filter on the intake tube in the storage dewar. Helium usage was reduced by installing a filter on the intake tube in the storage dewar which cooled appropriately the transfer tube and usage could undoubtedly be reduced to low levels by redesign of the transfer system. In the latter part of the run in August, the system ran reliably for many days at a time with polarizations near 80% in a target of 8 cm^3 volume. The polarized target assembly has now been moved to the 0° neutron beam line in area B and should be available for experiment 65 by the end of January, 1978.

4. Instrumentation for Experiment 65

It is now expected that the incident proton beam current available for neutron production on this experiment will be not more than 5 μA. This is a factor of six less than projected in the original proposal. The implication is that counting rate must be regained by increasing the efficiency of the detection system. These questions were studied, and a revised layout of the experiment was made. A critical element in these considerations is concerned with the neutron detector array. The design consists of 18 bar-shaped NE 110 detectors arranged in two vertical rows facing the polarized target, and placed at distances of from 1-4 m from the target. Position information relating to polar angle is obtained from the identification of the struck detector, and information relating to azimuthal angle is obtained from the vertical position along each bar. This latter parameter is obtained from end-to-end timing to an expected precision of 10 cm (FWHM). Each bar is 40 in length and has a cross section of 2.7 x 4 inches.

Efficiency and momentum resolution (by time-of-flight) are more favorable at lower neutron energies than at higher ones. For example, at 40 MeV the efficiency is ~50% and $\Delta P/P$ (momentum resolution) is 4%. At 400 MeV the efficiency has fallen to ~12% and $\Delta P/P$ has degraded to ~9% (FWHM) for a distance of 4 m between target and detector. Nevertheless, these efficiencies are improvements over the original projections. Taken together with increased spectrometer solid angle, the least favorable signal rates are projected to be 1 count per second. This is adequate for good data.

A study was made of possible PMT's for use with the neutron counter array. At an earlier stage, inexpensive 10-stage tubes were investigated with the idea of conserving funds. It was finally decided that the loss of performance outweighed the economic benefit. Attention was turned to the class of 12-stage higher performance PMT's. These included the old standby RCA8575 that we have used for many years, the EMI9814B, and the Amperex XP2230. Information was gathered and specifications were compared. The choice went to the XP2230 on the basis of fast time response and generally good performance. An order of 55 units was placed of which all have been received. Our initial tests look good; for scintillator pulses closely coupled from ^{137}Cs gamma rays, the risetime is about 2 ns with 6 ns FWHM. For single electron noise pulse, the rise-time is observed to be near 1.4 ns with FWHM of about 3 ns. For these highfrequency pulses, a definite ringing is excited at the anode. We have investigated and implemented damping procedures. The XP2230 and the RCA 8575 have the same pin configuration.

A prototype bleeder string for the 12-stage Amperex XP2230 PMT was designed and tested. Careful study of existing RCA and EMI bases being used by us and by LAMPF personnel indicated several design problems. Heat dissipation was poor. Impedance matching on the anode line could be improved. Construction, alterations, or replacement of existing components was difficult at best.

The new base is constructed on two printed circuit wafers. Components are widely spaced minimizing heating between adjacent parts. Construction of the PC boards is simple and allows more reliable soldering of the components. High-voltage wires are more safely positioned. A different type of BNC plug allows impedance matching to be accomplished between the anode pin and the external BNC cable. Special care has been taken to minimize the inductance at the last dynode and the anode. Sixty new bases are presently being fabricated at the University of Texas.

A magnetic shield design has been made for the photomultipliers of the neutron and other counters for experiment 65. It incorporates a 2.75 inch o.d. by 1/8-inch-thick wall soft-iron outer cylinder with a 0.040-inch-thick inner mumetal cylinder. The design is compatible with the new bleeder string assembly.

Considerable effort has been invested in a light pulser system for the neutron scintillation detectors. The method is similar to that described by McFarlane.[1] Light pulses are created by current pulses driven through light emitting diodes (LED) and transmitted to the detectors by optical fiber bundles. The form for the system is as follows. Current pulses are created by switching a charged capacitor to ground through the action of three avalanche transistors (2N 3700) in series. The load consists of three each LED's (HP-5082-4984, green). Each LED provides light to four optical fiber bundles of 1.2 mm diam, and each bundle goes to one end of the neutron bar scintillator. Therefore each such electronic module services six scintillator bars, and three modules will be required for the eighteen scintillators of the neutron detector array. It is expected to introduce the light into the lightguide of the scintillator near the intended photomultiplier (PMT). Pulse output from the XP 2230 PMT as generated from light pulses as sketched above is approximately as follows. With the PMT at negative 2500 volts, the pulse risetime is 4 nsec, the full withd at half maximim is 12 nsec, and the amplitude is near minus one volt into 25 ohms. This represents a very adequate amount of light, at 10-MeV electron equivalent, but part of this may be lost in the detailed coupling method to the light guide.

[1]W. K. McFarlane, R.S.I. 45, 286, (1974).

5. <u>The Inclusive Reaction $np \to pX$ at 800 MeV</u>

The problem of the unique determination of the nucleon-nucleon amplitude remains unsolved both because of the lack of a viable theory and sufficient data to test such. In a recent treatment D. Brayshaw[1] attempts to construct a consistent dyanmical model of NN scattering using the results from inelastic channels $NN \to NN\pi$ and $NN \to \pi D$ as well as the results of $\pi D \to \pi D$ and $\pi D \to NN\pi$ to pin down the ambiguities inherent in any treatment using only the elastic channels. Thus, the importance of single pion production lies not only in knowledge of the $NN\pi$ interaction itself but possibly also in the way that it can be used to determine the NN scattering amplitude, especially above pion production threshold.

In conjunction with an experiment designed to study the reaction $np \to d\pi^{\circ}$, we have obtained data on the inclusive process $np \to pX$, which will provide a measure of the combined cross sections σ_1 $(np \to pn\pi^{\circ})$ and σ_2 $(np \to pp\pi^{-})$. The proton is the detected particle having momentum between 500 and 1300 MeV/c with angles between 0° and 16°.

The data for the above reactions have been arranged as averaged cross sections in bins of θ_p and P_p where θ_p is the proton lab angle and P_p is its lab momentum. The bins are 0.01 rad x 20 Mev/c wide and range from 0.0 rad to 0.65 rad and 500 MeV/c to 1500 MeV/c. The coverage in this experiment is almost complete for $0.0 < \theta_p < 0.3$ rad and about 50% complete for $0.3 < \theta_p < 0.65$ rad. The statistical precision in each bin is for the most part approximately 5%. By generating 50 cross sections with P_p and θ_p randomly selected within each bin and interpolating between neighboring bins, we have effectively constructed a continuum of cross section values over the entire covered range as specified above. Having this continuum we are able to make cuts on the (P,θ) space with respect to other variables such as momentum transfer and invariant missing mass. Some rather interesting patterns have been obtained as a result of choosing as the independent variables, t and M, defined as

$$t = (q_n - q_p)^2$$

where q_n and q_p are the four momenta of the incident neutron and detected proton respectively and

$$M^2 = (q_n + q_H - q_p)^2$$

where q_H is the target proton four momentum. Plots of $d\sigma/dtdM$ versus t for cuts in M reveal a surprising regularity for values of $|t| \lesssim 0.25\ (\mathrm{GeV/c})^2$.

On a semilog plot all mass cuts show a straight line t dependence with the same slope except for very small t ($|t| \lesssim 0.06\ (\mathrm{GeV/c})^2$) where as $|t|$ decreases the cross section starts to fall away from the straight line and starts to dip at $|t| \sim 0.04\ (\mathrm{GeV/c})^2$. Of course not all mass cuts have $|t|$ values as low as $0.04\ (\mathrm{GeV/c})^2$, but the tendency to break from the straight line is at about the same value of t for all mass cuts! One pion exchange calculations which have been quite successful in predicting the overall shape of the momentum spectra at 0° cannot possible give a dip in $d\sigma/dt\, dM$ at such a large value of $|t|$. A possible explanation has been brought to our attention by R. Weiner[1,2] which is a statistical model of virtual pions as a cloud of bosons surrounding a bare nucleon. The incident nucleon (which can be thought of as the target nucleon in the c.m. system) creates a pion by simply breaking only the binding energy link between one of these virtual pions leaving its three-momentum intact. Thus the knowledge of the pion's original momentum distribution is preserved in the variable t given that only one of the four possible single pion exchange diagrams contributes significantly, which is the case for $|t|$ small (i.e., $|t| \lesssim 0.02\ (\mathrm{GeV/c})^2$).

The pion momentum (P_π) distribution is given by the Bose-Einstein form

$$\frac{dN_\pi}{dp_\pi} = \frac{P_\pi^{\;2}}{e^{E(P_\pi)/kT}-1}$$

where $E(P_\pi)$ has been assumed to take on the high energy (temperature) form $E = \sqrt{P_\pi^{\;2} + \mu^2}$ with a free parameter representing the virtual pion's effective mass. These data indicate that kT will be approximately 150 MeV whereas the high energy results[1] are fit with kT $\sim$ 80 MeV. It has been suggested by Weiner that this higher temperature at 800 MeV indicates the break from peripherality which dominates at higher energy. However, in his model of the interaction he had used a different diagram as the dominant one than what we have used, which could perhaps account for our differing values of kT. Further investigation of this point will be pursued.

The cross section dependence on other variables such as the nucleon-nucleon invariant mass has also been investigated and indicates definite structure at the limiting mass value of 1877 MeV where one expects to see the effect of the strong S state low-energy nucleon-nucleon final state interaction. A hint of some structure around 2080 MeV has also been seen, but is beclouded by the indefiniteness of the nucleon-nucleon invariant mass for this experiment where only one particle is detected. Further study is suggested in experiments which detect two particles for these reactions or where only the pion is detected.

[1]K. F. Galloway, A. Mann, and R. M. Weiner, Lettere Al Nuovo Cimento 2, 635 (1971).
[2]Ibid, 1295 (1971).

6. N-p Charge Exchange Scattering for Neutron energies 150-800 MeV

This experiment (Proposal 263) was designed to concentrate on the charge exchange region of np elastic scattering, measuring the cross section in a continuous fashion for incident energies from 150 to 800 MeV and proton angles from 0° to 30° lab. A rather striking feature of the np charge exchange cross section was noted in the 1960's.[1] When the cross sections are plotted versus the square of the invariant momentum transfer, −u, then a very simple shape is apparent -- a sum of two exponentials fits the data very well:

$$d\sigma/d\mu = \alpha_1 e^{\beta_1 \mu} + \alpha_2 e^{\beta_2 \mu}$$

The present data have been binned in steps of 30 MeV/c for neutron momenta from 575 to 1429 MeV/c; the data in each bin have been fitted to the above double exponential formula. The resulting data and fit for p_n = 1429 meV/c are shown in the Fig. 12 - the data were fitted out to only −u = 0.20. Excellent fits have been obtained for all momentum bins.

In 1969 a Phys. Rev. Letter[2] was published showing a large bump in the logarithmic slope of the np charge exchange cross section as a function of energy. This data, and subsequent calculated theoretical fits, are shown in Fig. 13, which is taken from the work of Londergan and Thaler.[3] The logarithmic slope is

$$\beta = \lim_{\mu \to o} \frac{\frac{d}{d\mu}\left(\frac{d\sigma}{d\mu}\right)}{d\sigma/d\mu} = \frac{\sigma_1\beta_1 + \alpha_2\beta_2}{\sigma_1 + \alpha_2}$$

Note that the extraction of β (as well as β_1, β_2 and α_1/α_2) is independent of absolute normalization. The results from Expt. 263 are shown in Fig. 14. The current results are consistent with a constant value of β equal to $\sim 80 (\mathrm{GeV/c})^{-2}$ instead of a value which peaks near 800 MeV/c and falls by a factor of 4 for P>1000 MeV/c.

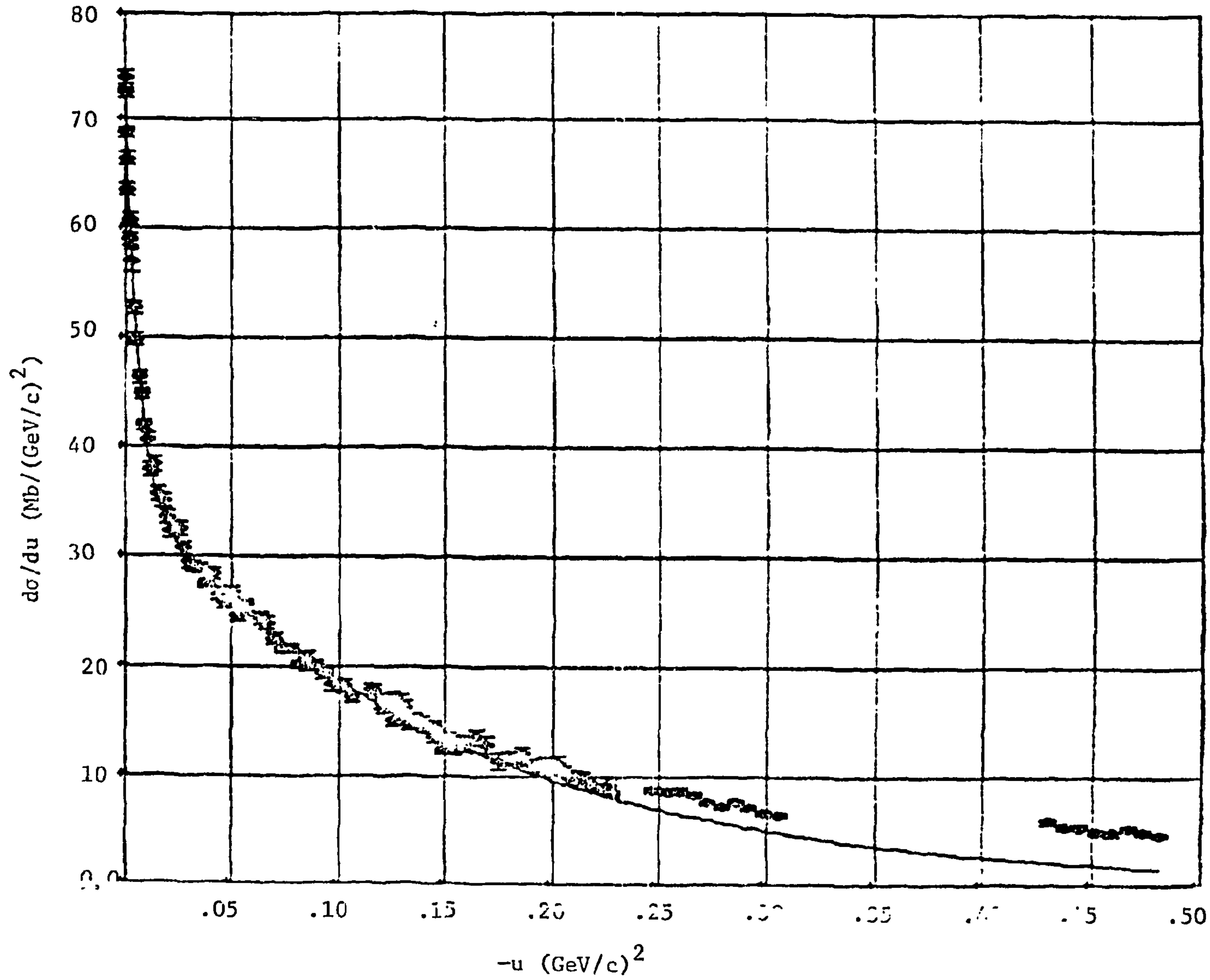


Fig. 12. Double exponential fit to np charge exchange scattering data for P_n = 1429 MeV/c.

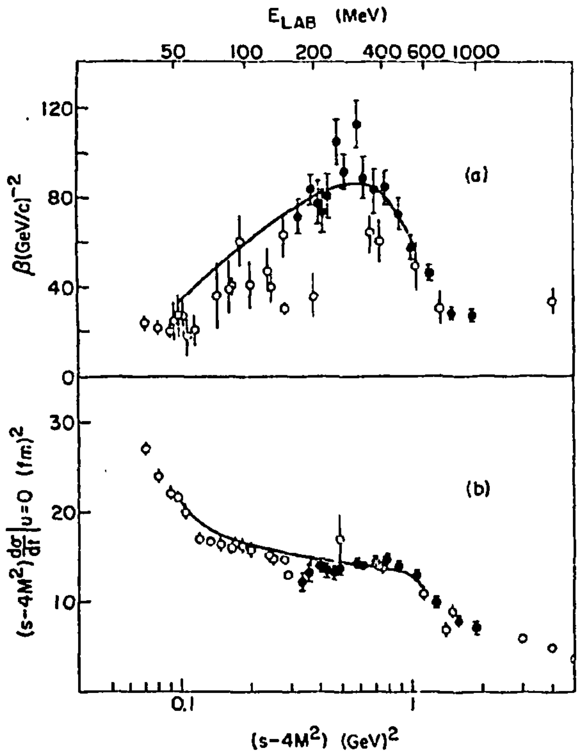
Absolute normalization for these data are obtained from the deuteron in the accompanying reaction $np \to d\pi^{\circ}$. The reaction is available for $P_n > 825$ MeV/c. Figure 14 also shows a plot of the quantity $P_{Lab}^2 \left.\frac{d\sigma}{d\mu}\right|_{\mu=0}$ which is shown to have an approximately constant value of 160 mb. This value is also in disagreement with previous measurements[1,2,4].

In addition $\beta_1 \simeq 160(\text{GeV/c})^{-2}$ $\beta_2 \simeq 6.8(\text{GeV/c})^{-2}$, and $\alpha_1/\alpha_2 \simeq 1$. Therefore one can write

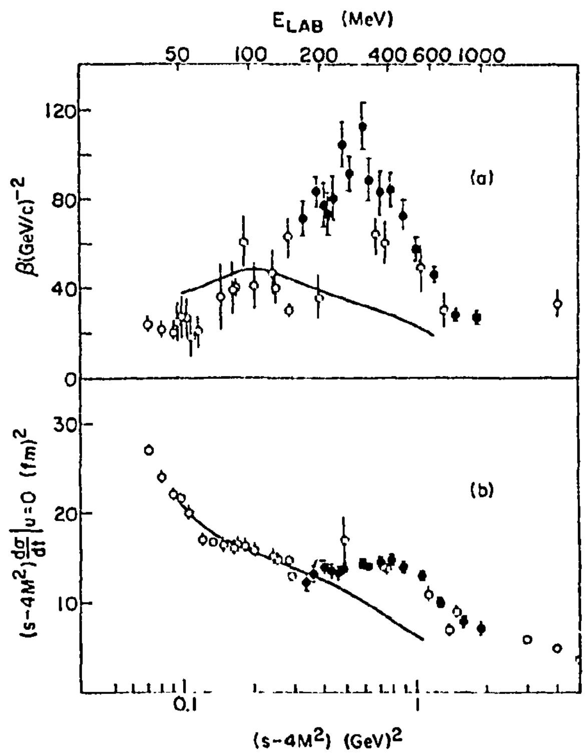
$$\frac{d\sigma}{d\mu}(s,u) = \frac{80}{P_L^2}(e^{160u}+e^{6.8u})\,\text{mb}(\text{GeV/c})^2,$$

for $0.8 \leq P_L^2 \leq 1.5$ GeV/c and $0 < -u < 0.2$ $(\text{GeV/c})^2$. Errors on the various quantities at this point are about 15%.

[1]J. L. Friedes et al., Phys. Rev. Letts. 15, 38 (1965); R. Wilson, Ann. Phys. 32, 193 (1965).
[2]R. E. Mischke, P. F. Shepard, and T. J. Devlin, Phys. Rec. Letters 23, 542 (1969).
[3]J. T. Londergan and R. M. Thaler, Phys. Rev. Letts 25, 1065 (1970).
[4]G. Bizard et al., Nucl. Phys. B85, 14 (1975).



(a) A plot of the logarithmic slope $\beta \equiv [-(d/dt)\ln(d\sigma/dt)]_{u=0}$ as a function of incident kinetic energy, for *n-p* scattering. (b) A plot of the differential cross section at $u=0$ as a function of kinetic energy. The experimental data are taken from Mischke, Shepard, and Devlin; see Ref. 3. The solid curves represent the quantities as calculated with the Livermore phase shifts, using OPE phases for $l > 5$ with $g_\pi^2 = 14.4$.



Fits to the data when the peripheral ($l > 5$) OPE phase shifts are set equal to zero. (a) A plot of the logarithmic slope β as a function of kinetic energy. (b) A plot of the backward cross section as a function of kinetic energy.

Fig. 13. Previous n-p charge exchange scattering data and theoretical fits, as taken from Londergan and Thaler.[3]

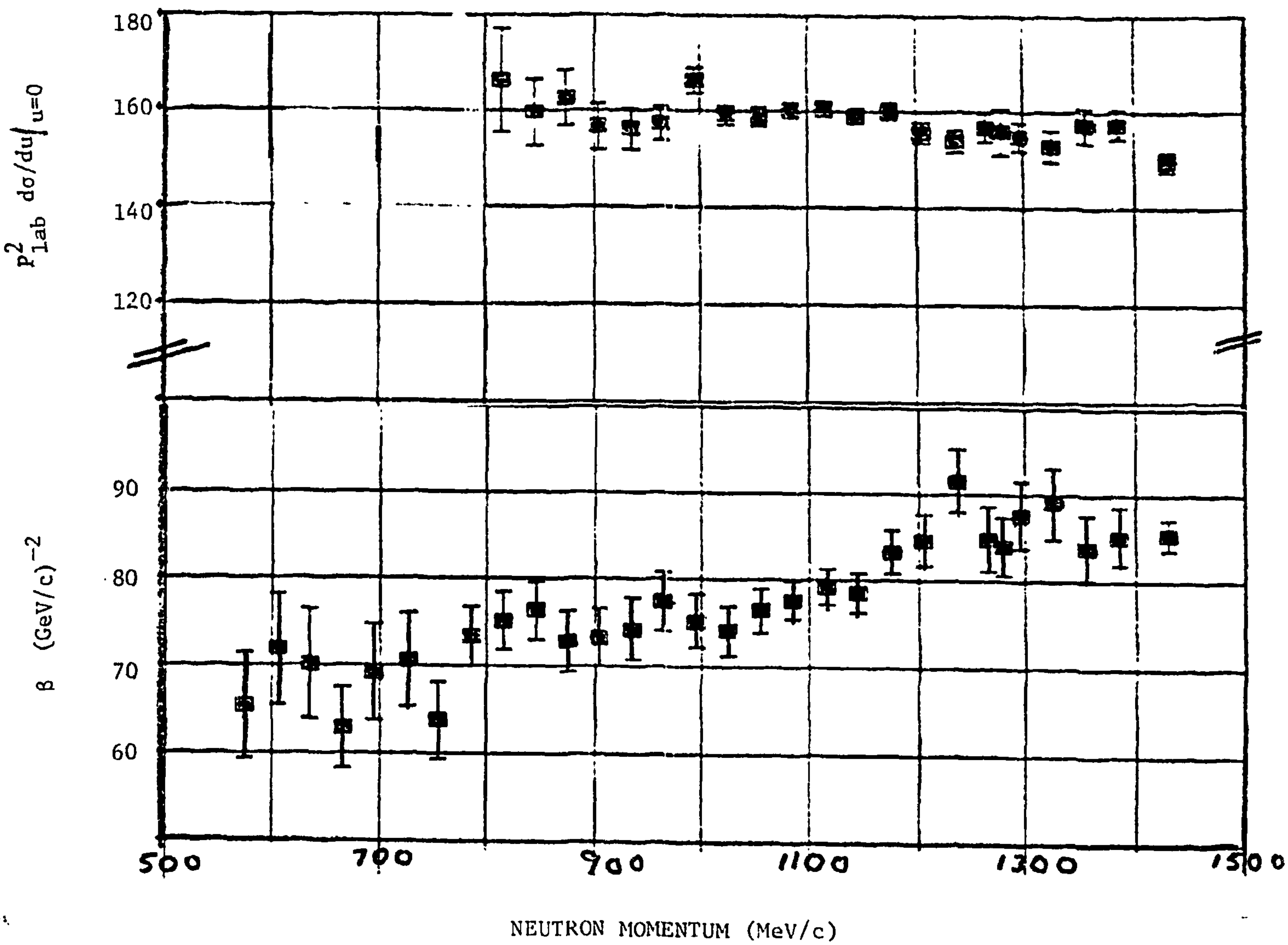


Fig. 14. Results from Experiment 263.

III. PUBLICATIONS DURING 1977

1. G. Glass, Mahavir Jain, M. L. Evans, J. C. Hiebert, L. C. Northcliffe, B. E. Bonner, J. E. Simmons, C. Bjork, P. Riley and C. Cassapakis, "Neutron Spectra at 0° from Proton-Proton Collisions between 647 and 805 MeV", Phys. Rev. D, 15 (1977) 36.

2. P. J. Riley, C. Bjork, C. R. Newsom, M. L. Evans, G. Glass, J. C. Hiebert, Mahavir Jain, R- A. Kenefick, L. C. Northcliffe, B. E. Bonner, J. E. Simmons, Nelson Stein, and C. Cassapakis, "Measurement of (p,n) and (n,p) Reactions on ^{6}Li and ^{7}Li at 800 MeV", Phys. Letters B68 (1977) 217.

3. B. E. Bonner, G. Glass, C. L. Hollas, C. R. Newsom, and P. J. Riley, "nD Scattering at 180° for Neutron Energies from 200 to 800 MeV", Proceedings of the Second International Conference on the Nucleon-Nucleon Interaction, June, 1977, to be published by the American Institute of Physics.

4. G. Glass, M. Jain, B. E. Bonner, C. L. Hollas, C. R. Newsom and P. J. Riley, "The Inclusive Reaction, np → pX at 800 MeV", Proceedings of the Second International Conference on the Nucleon-Nucleon Interaction, June, 1977, to be published by the American Institute of Physics.

5. B. E. Bonner, J. E. Simmons, G. Glass, C. L. Hollas, C. R. Newsom and P. J. Riley, "np Charge Exchange Scattering for Neutron Energies 300-800 MeV", Proceedings of the Second International Conference on the Nucleon-Nucleon Interaction, June, 1977, to be published by the American Institute of Physics.

6. C. L. Hollas, C. R. Newsom, P. J. Riley, B. E. Bonner, and G. Glass, "A Measurement of the Deuteron Spectrum in np → $d(\pi\pi)^{\circ}$ at 800 MeV", Proceedings of the Second International Conference on the Nucleon-Nucleon Interaction, June, 1977, to be published by the American Institute of Physics.

7. P. J. Riley, C. W. Bjork, B. E. Bonner, J. E. Simmons, J. Wallace, M. L. Evans, G. Glass, J. C. Hiebert, M. Jain, L. C. Northcliffe, and C. G. Cassapakis, "Quasi-Elastic Charge Exchange in nd → pnn at 800 MeV", Proceedings of the Second Internation Conference on the Nucleon-Nucleon Interaction, June 1977, to be Published by the American Institute of Physics.

8. B. E. Bonner, J. E. Simmons, M. L. Evans, G. Glass, J. C. Hiebert, Mahavir Jain, L. C. Northcliffe, C. W. Bjork, P. J. Riley, and C. G. Cassapakis, "Extreme Back Angle nD Elastic Scattering at 794 MeV", Phys. Rev. C, in press.

9. B. E. Bonner, J. E. Simmons, J. M. Wallace, M. L. Evans, G. Glass, J. C. Hiebert, Mahavir Jain, L. C. Northcliffe, C. W. Bjork, P. J. Riley, and C. G. Cassapakis, "Quasi-Elastic Charge Exchange in nD → pnn at 794 MeV", Phys. Rev. C, in press.

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11. B. E. Bonner, J. E. Simmons, C. R. Newsom, P. J. Riley, G. Glass, J. C. Hiebert, Mahavir Jain, and L. C. Northcliffe, "Systematics of 0° Neutron Production by 800 MeV Protons on Targets with $27 \leq A \leq 238$", Phys. Rev. C, submitted for publication.

12. P. J. Riley, C. W. Bjork, C. R. Newsom, R. A. Kenefick, M. L. Evans, G. Glass, J. Hiebert, Mahavir Jain, L. C. Northcliffe, B. E. Bonner, J. E. Simmons, Nelson Stein, and C. G. Cassapakis, "Neutron Induced Deuteron Production from Light Nuclei at 800 MeV", Phys. Rev. C (Communications), submitted for publication.

IV. CURRENT LAMPF PROPOSALS

No. 262 "Test of Isospin Invariance in the Reaction $np \rightarrow d\pi^{\circ}$" B. E. Bonner, Spokesman. Data acquisition and preliminary data analysis were completed during 1977.

No. 263 "Measurement of the Energy and Angular Variation of the np Charge Exchange Cross Section" B. E. Bonner, Spokesman. Data acquisition and preliminary data analysis completed during 1977.

No. 264 "Measurement of the Energy Variation of the nD Elastic Differential Cross Section near 180°" B. E. Bonner, Spokesman. Data acquisition and approximately 70% of the preliminary data analysis were completed during 1977.

No. 65 "Neutron-proton Polarization Measurements Using a Polarized Target: Phase I. The n-p Polarization Observable" J. E. Simmons, Spokesman. Data acquisition on this experiment will begin in February, 1978.

No. 66 "Neutron-Proton Polarization Measurements Using a Polarized Target: Phase II. The n-p Spin Correlation Observable" J. E. Simmons, Spokesman. Data acquisition on this experiment is expected to begin after the completion of experiment 65, probably during the late Spring of 1978.

No. 360 "The Measurement of the Polarization Transfer Coefficients D_t and A_t' at 800 MeV for the Reactions $d(\vec{p},\vec{n})2p$, $^6Li(\vec{p},\vec{n})^6Be$, and $9Be(\vec{p},\vec{n})9B$" P. J. Riley and J. E. Simmons, Spokesmen. This proposal will be considered by the PAC in January, 1978. We propose to schedule this experiment for August-September, 1978.

No. 366 "Non-Resonant Pion Production in the Reaction $np \rightarrow \pi^- pp$" B. W. Mayes and G. S. Mutchler, Spokesmen. The proposal will be considered by the PAC in January, 1978. A realistic date for the experimental runs would be fall, 1978.

V. TITLE PAGES OF PUBLISHED AND SUBMITTED PAPERS

PHYSICAL REVIEW D VOLUME 15, NUMBER 1 1 JANUARY 1977

Neutron spectra at 0° from proton-proton collisions between 647 and 805 MeV*

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Momentum spectra of neutrons at 0° from the process $pp \to np\pi^+$ have been measured at 647, 771, and 805 MeV. Absolute cross sections $d^2\sigma/d\Omega dp$ and $d\sigma/d\Omega^*$ are given for all three energies. A phenomenological calculation using only *S*- and *P*-wave πN phase shifts and an *NN* final-state interaction appears to account for the shapes and magnitudes of the spectra quite well. Comparison with the process $np \to pX$ indicates a non-negligible contribution from nonresonant amplitudes.

I. INTRODUCTION

The nucleon-nucleon (*NN*) interaction, although not elementary from a particle-physics point of view, is fundamental and extremely important to nuclear physics. The determination of an unambiguous and accurate scattering matrix for *NN* collisions must perforce overcome the obstacles presented by the effects of pion production. Therefore, insights to be gained from a study of pion production in *NN* collisions would contribute toward a better understanding of the *NN* interaction, as well as furthering our knowledge of the πN interaction.

In the present experiment momentum spectra have been measured for 0° neutrons from the reaction

$$pp \to np\pi^+ \tag{1}$$

for $T_p = 647$, 771, and 805 MeV. The quantity of accumulated data and the momentum resolution (~1%) are sufficient to provide ~5% statistical precision in 20-MeV/*c* bins, which until now has not been available in this kinematic region and in this incident energy range. These data allow for critical tests of theories on pion production at these energies, and since at each neutron momentum, P_n, the value of the πp invariant mass, $M_{\pi p}$, is uniquely determined, the cross section $d^2\sigma/dpd\Omega$ directly reflects the effects of the $\Delta(1232)$ resonance. This latter feature helps one to deduce the contribution from nonresonant amplitudes for which the πN isospin equals $\frac{1}{2}$. Although extensive studies both theoretically[1-9] and experimentally[10-24] have been conducted, no single phenomenological model has yet been shown to quantitatively explain the results in this energy region. However, we make use of a modified version of a code developed by Stephenson, Gibbs, and Gibson[5] (referred to as SGG) and find that by appropriate adjustment of four parameters rather good fits are obtained at all three energies investigated here. Some further discussion of the parametrization of these fits is given in Sec. V. Other treatments have been quite successful in other energy regions. The peripheral model with absorption[6] does fairly well from 1.3 to 9 GeV, but the influence of many baryon resonances [especially the $\Delta(1232)$] in the region from 800 to 1300 MeV makes necessary a phenomenological treatment such as the one-pion-exchange (OPE) model.[2] Below 650 MeV, where the only significant resonant contribution comes from the $\Delta(1232)$, and where the *NN* final-state interaction (FSI) plays an important role, Mandelstam's treatment[1] has been successful. However, in the region between 650 and 800 MeV neither the low-energy[1,4] nor the higher-energy[2,3] models are valid, which makes the measurements presented here interesting especially in view of the potentially viable treatment of SGG.[5]

Previous measurements of neutron spectra from the process in Eq. (1) have been made by Guzhavin *et al.*[11] and Bugg *et al.*[11] from bubble-chamber measurements of the proton and pion momenta. However, since the number of events was small (430 and 1414, respectively) their spectra necessarily had to include integration over the neutron solid angle, $\Delta\Omega_n = 4\pi$. More detailed information in this energy region is furnished by recent experiments at the Clinton P. Anderson Meson

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MEASUREMENT OF (p,n) AND (n,p) REACTIONS ON ^{6}Li AND ^{7}Li AT 800 MeV *

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The measured ^{7}Li(p,n), ^{6}Li(p,n), and ^{6}Li(n,p) cross sections at 0° show a high-energy peak (≈ 25 MeV, FWHM) which we attribute primarily to nuclear charge exchange leading to final states in ^{7}Be, ^{6}Be, and ^{6}He, respectively. By contrast, the ^{7}Li(n,p) cross section at 0° shows a broad weak high-energy peak believed due mostly to break-up processes. At 16°, the ^{6,7}Li(n,p) cross sections are dominated by quasi-elastic scattering.

At energies in the neighborhood of 100 MeV, the ^{7}Li(p,n) reaction has been recognized as one of the best sources of monoenergetic neutron beams [1, 2]. We report in this letter the results of high-resolution measurements of the neutron spectra at 0° produced by 800 MeV protons on ^{6}Li and ^{7}Li. These results, together with previously reported [3] cross sections for (p,n) reactions on ^{12}C and ^{27}Al, suggest that ^{7}Li remains an excellent source of monoenergetic neutrons up to 800 MeV. Proton spectra at 0° and 16° produced by 800 MeV neutrons incident on ^{6}Li and ^{7}Li have also been measured and are compared to the 800 MeV (p,n) data.

For incident energies up to 155 MeV, peaks have been observed in (p,n) spectra at energies corresponding to $\Delta T = 0$ isobaric transitions [1, 4, 5]. Above about 100 MeV, quasi-elastic scattering also becomes important in the production of high-energy neutrons via the (p,np) reaction [6]. In this process an incident nucleon collides with a single particle in the target nucleus. The observed scattering reflects jointly the elastic nature of proton-nucleon encounters and the distribution of nucleon momenta in the target nuclei. However, the concept of (p,np) quasi-elastic scattering may not be applicable at 0° because of the very strong final-state interaction between the slowly moving nucleon and the spectators [7].

The experimental arrangement at LAMPF for the (p,n) measurements has been described previously [3]. After passing through the Li target the proton beam was deflected through 60° into the beam stop. The neutrons were collimated to 0.1° half-angle, and after passing through a sweep magnet they impinged on a liquid-hydrogen radiator located at the pivot point of a multiwire proportional chamber (MWPC) spectro-

* Work performed under the auspices of the U.S. Energy Research and Development Administration.

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Physical Review C, Jan., 1978

Extreme Back Angle nD Elastic Scattering at 794 MeV*

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ABSTRACT

The cross section for elastic scattering of 794-MeV neutrons by deuterium has been measured for neutron center of mass angles from 139° to 179°. The angular distribution is fit very well both by an empirical function $\alpha e^{\beta(u-u_{180°})}$ and by a calculation that uses the one parameter Craigie-Wilkin triangle diagram technique.

[NUCLEAR REACTION nD→Dn, E = 794 MeV; measured σ(θ). Calculated σ(θ) with triangle diagram techniques.]

*Work supported under the auspices of the U. S. Energy Research and Development Administration.

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Quasielastic Charge Exchange in nD → pnn at 794 MeV*

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ABSTRACT

The proton spectrum resulting from 794-MeV neutron bombardment of deuterium was measured at several angles. The angular distribution of the integral of the quasielastic charge exchange peak is fit very well by the two exponential form $d\sigma/dt = \alpha_1 e^{\beta_1 t} + \alpha_2 e^{\beta_2 t}$ as has previously been found for the np elastic case. The ratio of the two cross sections at $t = 0$ is 0.56 ± 0.04. A modified impulse approximation calculation accounts for most features of the observed angular distribution.

[NUCLEAR REACTION nD → pnn, E = 794 MeV; measured σ(0). Calculated σ(0) with modified PWBA.]

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cles produced in a direct reaction and those which result from a hot spot produced in a sequential process. The out-of-plane spectra as well as a generalization of our model with respect to the initial conditions will be presented in a forthcoming paper.[8]

We acknowledge discussions with R. Albrecht, H. Ho, and J. P. Wurm, and the help of T. Ledergerber in the early stages of programming.

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nd Scattering at 180° for Neutron Energies from 200 to 800 MeV

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We have measured the cross section for neutron-deuteron elastic scattering over the incident energy range 200–800 MeV. Preliminary results for the extreme back angles ($\theta_n^* \geq 175°$) show a striking shoulder in the excitation function for neutron energies 300–600 MeV. Comparison is made with calculations using the Craigie-Wilkin triangle-diagram technique.

Near the end of the last decade, *pd* elastic scattering experiments demonstrated that the angular distributions were characterized by a strong backward peak in the neighborhood of 1 GeV.[1] Kerman and Kisslinger,[2] in an attempt to understand this behavior, found that simple one-nucleon exchange failed to fit the backward peak, the calculation being low by a factor of 2. They postulated the existence of isobars in the deuteron, finding that a 1% admixture of the $N^*(1688)$ sufficiently augmented the calculated cross section to bring it into agreement with the 1-GeV data of Bennett *et al.*[1] Since then, several experiments and calculations have been performed relating to backward *pd* elastic scattering at medium energy and isobars in nuclei.[3] Alternative explanations of the observed peaking were proposed. One was the calculation of Craigie and Wilkin[4] in which triangle diagrams were used to relate the cross sections for *pd* elastic and $pp \to d\pi^+$. Many authors have pursued this technique with success in fitting backward *pd* scattering. Another recent calculation[5] takes account of the fact that *np* angular distributions also are backward peaked and incorporates this into an extended Glauber multiple-scattering calculation plus one-nucleon exchange. With this approach, backward *pd* scattering is fitted over a wide range of energies above 660 MeV when a radically different form factor for the deuteron is postulated for the large momentum transfers encountered. Recent measurements[6] at the Stanford Linear Accelerator Center tend to verify the postulated shape of the deuteron form factor.

There are several plots in the literature of the extrapolated 180° cross section as a function of

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Systematics of 0° Neutron Production by 800 MeV Protons on Targets with $27 \leqslant A \leqslant 238$*

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ABSTRACT

The 0° neutron spectra resulting from 800 MeV proton bombardment of targets of Al, Ti, Cu, W, Pb, and U have been measured for neutron momenta above 500 MeV/c. Integrated cross sections for the quasielastic charge exchange peaks and the broad pion associated peaks at lower momenta show a remarkably smooth dependence on atomic mass of the target, varying as $A^{2/3}$ and $A^{1/2}$ respectively.

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Neutron Induced Deuteron Production from Light Nuclei at 800 MeV*

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ABSTRACT

The deuteron spectra from (n,d) reactions at 800 MeV near 0° are characterized by a high energy quasielastic (QE) scattering peak, and at lower momentum, a quasifree (QF) scattering peak. The ratio of the QF to QE cross sections is approximately 10:1. Both cross sections exhibit a $A^{1/3}$ mass dependence over the range of target nuclei studied. Comparisons are made with corresponding proton-induced QE and QF deuteron production.

NUCLEAR REACTIONS n + X › d . E_{lab} = 800 MeV. Measured deuteron quasielastic and quasifree cross sections near 0°.

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nD SCATTERING AT 180° FOR NEUTRON ENERGIES FROM 200 to 800 MeV*

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THEORETICAL BACKGROUND

Near the end of the last decade, Kerman and Kisslinger,[1] in attempting to understand the backward peaking that had been observed in pD elastic scattering at 1 GeV, found that simple one-nucleon exchange failed to fit the backward peak, the calculation being low by a factor of two. Taking a bold step, they postulated the existence of Isobars in the deuteron, finding that a 1% admixture of the N* (1688) sufficiently augmented the calculated cross section to bring it into agreement with the 1-GeV data of Bennett et al.[2] In intervening years, many experiments and calculations have been performed relating to backward pD elastic scattering at medium energy and Isobars in nuclei.[3] Alternative explanations of the observed peaking were proposed. One was the calculation of Craigie and Wilkin[4] in which triangle diagrams were used to relate the cross sections for pD elastic and $pp \rightarrow d\pi^+$. Many authors have pursued this technique with success in fitting backward pD scattering. Another recent calculation[5] takes account of the fact that np angular distributions also are backward peaked and incorporates this into an extended Glauber Multiple Scattering calculation. With this approach, backward pD scattering is fit over a wide range of energies when a radically different form factor for the deuteron is postulated for the large momentum transfers encountered. The fact that the recent SLAC measurements[6] tend to verify the postulated shape of the deuteron form factor brings us back to the original hope that information on the high-momentum components of the deuteron wave function can be obtained from the scattering of hadrons of modest energy.

EXPERIMENTAL BACKGROUND

In the last few years, several angular distributions have been reported[2] for pD backward elastic scattering at medium energies. In each of these measurements, the backward peak is observed. Representative results between 600 and 1000 MeV are shown in Fig. 1. The data of Boschitz[7] and of Alder[8] near 600 MeV and the three measurements[2,9,10] at 1000 MeV are shown. Two observations can be made:

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nD SCATTERING AT 180° FOR NEUTRON ENERGIES FROM 200 TO 800 MeV.*

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The failure of the one nucleon exchange mechanism to fit the backward peak observed in pD elastic scattering at medium energy led to the postulation[1] of excited nucleon states (NN*) and double delta (ΔΔ) components in the deuteron wave function. Many experiments designed to search for such components have yielded conflicting and inconclusive results.[2] The energy dependence of the backward cross section has been the subject of much speculation since a change of slope around 500 MeV in the exponential decrease of the (extrapolated) 180° cross section with increasing energy was suggested by several measurements.[3] In addition some measurements[3] indicated a shoulder in the otherwise smooth decrease of the cross section from low energies up to a few GeV. This behavior cannot be explained in terms of isobar components in the deuteron.

At LAMPF we have measured the variation with energy of the backward nD elastic cross section over the incident energy range from 200-800 MeV using the technique mentioned in Ref.[4]. The resolution on the incident energy was about 15 MeV and the data were binned according to incident momentum in 30 MeV/c wide bins. The measurement is free of extrapolation errors since the angular range covered was 140° to 180° c.m. Based on the analysis of a small fraction of our data, the peak that was previously hinted at around 500 MeV is indeed present and is mapped out very well in the present measurement. The dramatic change in the slope of the 180° cross section occurs at about 350 MeV and the peak is centered about 525 MeV.

The data appear to be consistent with calculations incorporating the so-called triangle diagrams,[5] which give rise very naturally to such an energy dependence of the cross section. The explanation in this case is that the peak is merely a manifestation of the Δ in the intermediate state, and it is not necessary to invoke isobar components in the deuteron wave function.

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THE INCLUSIVE REACTION np → pX AT 800 MeV*

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The age-old problem of the unqiue determination of the nucleon nucleon amplitude remains unsolved both because of a lack of a. viable theory and sufficient data to test such. In a recent treatment D. Brayshaw[1] attempts to construct a consistent dynamical model of NN scattering using the results from the inelastic channels NN → NNπ and NN → πD as well as the results of πD → πD and πD → NNπ to pin down the ambiguities inherent in any treatment using only the elastic channels. Thus, the importance of single pion production lies not only in knowledge of the NNπ interaction itself but possibly also in the way that it can be used to determine the NN scattering amplitude, especially above pion production threshold.

In conjunction with an experiment designed to study the reaction np → $d\pi^\circ$, we have obtained data on the inclusive process np → pX, which will provide a measure of the combined cross sections σ_1 (np → $pn\pi^\circ$) and σ_2 (np → $pp\pi^-$). The proton is the detected particle having momentum between 500 and 1300 MeV/c with angles between 0° and 16°. These measurements will be compared to the Saclay[2] data which cover the incident energy region between 600 and 1000 MeV for these reactions. When compared with the pure I-spin initial state for pp → $np\pi^+$,[3] the np → pX results will reveal the extent of the contribution from I = 0 initial states.

Interest in these reactions also stems from a calculation by Stephenson, Gibbs, and Gibson,[4] which has proven to be reasonably successful for pion production from proton proton collisions and can easily be generalized to handle the I = 0 component of the initial state in neutron proton collisions. Their theory has been applied to previous measurements[3] of pp → $np\pi^+$ for detection of the neutron at 0° and the present data will allow an extensive test of the theory at other angles.

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np CHARGE EXCHANGE SCATTERING FOR NEUTRON ENERGIES 300-800 MeV*

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In the 1960's it was noted[1] that the shape of the np angular distribution for backward neutron c.m. angles could be fit very well by a sum of two exponentials in the square of the invariant momentum transferred between the incoming neutron and recoil proton: $d\sigma/dt = \alpha_1 e^{\beta_1 t} + \alpha_2 e^{\beta_2 t}$. It was somewhat surprising when the data from the PPA[2] in 1969 showed a very striking peak around 800 MeV/c in the logarithmic slope of this cross section as well as a sharp decrease in the cross section at $t = 0$ beyond about 1 GeV/c. That this behavior was already evident in the phase shifts of MacGregor et al.[3] was claimed by Londergan and Thaler[4] in 1970. More recent data from Saclay[5] indicated that the $t = 0$ cross section did not decrease so sharply, but their measurement of the logarithmic slope was consistent with a peak as reported by the PPA.

At LAMPF we have measured the np charge exchange cross section from 300-800 MeV using a continuum neutron beam in conjunction with a liquid hydrogen radiator and multiwire proportional chamber spectrometer. Time-of-flight measurement on the incident neutron in conjunction with momentum determination in the spectrometer sufficed to separate elastically scattered protons from other processes. Good resolution on the proton momentum determination (~ 1%) then allowed the events to be binned according to the incident neutron momentum calculated from two-body kinematics. Absolute normalization in the range 300-800 MeV was obtained from the deuterons detected simultaneously from the reaction $np \to d\pi^0$. Data have been analyzed for angles 0°-16° and incident energies 300-800 MeV at the present time.

Our results indicate that over the entire range the logarithmic slope $\beta = (\alpha_1\beta_1 + \alpha_2\beta_2)/(\alpha_1 + \alpha_2)$ is constant and equal to ~ 80 $(GeV/c)^{-2}$. In addition the quantity $P_L^2\, d\sigma/dt(t=0)$ is constant (~ 160 mb), the ratio α_2/α_1 falls from about 1.4 at 300 MeV to 1 at 800 MeV, β_1 is constant (~ 160 $(GeV/c)^{-2}$), and β_2 falls smoothly from 8 to 6 over the range 300 to 800 MeV. The present results are in good agreement with our previously reported results[6] at 650 MeV where a single energy measurement was made. These results will be compared to those mentioned previously as well as calculations using one boson exchange potentials.[7]

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A MEASUREMENT OF THE DEUTERON SPECTRUM IN $np \rightarrow d(\pi\pi)^{\circ}$ AT 800 MeV*

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The "ABC" effect in double pion production reactions was first observed[1] as an enhancement in the missing mass spectrum from the reaction $pD \rightarrow {}^{3}He(\pi\pi)^{\circ}$. Since then various models have evolved to explain this effect in pD reactions and also in the simpler reaction $np \rightarrow d(\pi\pi)^{\circ}$. The two most extensively developed theories are the two nucleon exchange model of Anjos, Levy, and Santoro[2] and the one-pion exchange model with double delta ($\Delta\Delta$) excitation of Bar-Nir, Risser, and Shuster.[3] An interesting extension[4] of the latter model to allow for deep binding of the $\Delta\Delta$ system appears to account for the recent observation[5] of a peak in the polarization of the proton from deuteron photodisintegration as well as the measurements so far reported in double pion production.

These models yield predictions of the energy dependence and the detailed shape of the enhancements in the missing mass spectra. Data to test these models for $np \rightarrow d(\pi\pi)^{\circ}$ presently consist of the bubble chamber total cross section measurements[6] at eight momenta from 1.75 to 3.5 GeV/c and one deuteron momentum spectrum[7] at 4.5° and 1.88 GeV/c.

At LAMPF we have performed an experiment designed to measure the asymmetry in the reaction $np \rightarrow d\pi^{\circ}$ at 800 MeV. The unexpectedly large cross section we observe for the $np \rightarrow d(\pi\pi)^{\circ}$ process means that we also obtained the momentum spectrum of the deuterons from this reaction over the entire angular range. At this time we have analyzed only a small fraction of this data however.

Although detailed comparison of our results with the published calculations has not been made yet, the magnitude of the cross sections appear to be about a factor of four larger than that given in Ref. 3 and in rough agreement with the calculation of Ref. 2.

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QUASI-ELASTIC CHARGE EXCHANGE IN nd → pnn AT 800 MeV*

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We have measured the proton spectrum at lab angles from 0° to 18° resulting from 800-MeV neutron bombardment of deuterium. The LAMPF 800-MeV neutron beam and the multiwire proportional counter spectrometer system in the Nucleon Physics Lab. at LAMPF were used.[1] Particle separation was unambiguous with contamination less than 1%, and the momentum resolution $\Delta P/P$ was 1% FWHM. Absolute normalization of the cross sections was obtained from a separate measurement of the np CEX cross section at 800 MeV and has an overall uncertainty of ±7%. Measurements were made with the spectrometer at angles of 0°, 4°, 8°, and 16° to the incident neutron beam. The angular resolution of the spectrometer was about ±2 mrad. The sharp peak in the proton spectrum observed at 0° gradually broadens with increasing angles. At 16° the width of the peak is consistent with that calculated from the Fermi momentum distribution of the struck nucleon in the deuteron folded with kinematic broadening due to the finite acceptance of the spectrometer. At smaller angles $^1S_0$ final state interaction between the two unobserved neutrons sharpens the peak dramatically. For free np CEX the t variation of the cross section is described over a wide range of incident energies by a sum of two exponentials: $d\sigma/dt = \alpha_1 e^{\beta_1 t} + \alpha_2 e^{\beta_2 t}$.[2,3] The present quasi-elastic np CEX data are also fit very well by this function. We obtained the following values for the four parameters: $\alpha_1 = 12.58$ mb/(GeV/c)^2, $\beta_1 = 121.7$ (GeV/c)$^{-2}$, $\alpha_2 = 24.52$ mb/(GeV/c)^2, and $\beta_2 = 5.37$ (GeV/c)$^{-2}$. The ratio of the quasi-elastic CEX cross section at t = 0 to the corresponding elastic cross section is 0.56 ± 0.04 at 800 MeV. A plain-wave-impulse-approximation analysis of the quasi-elastic CEX cross section provides a good fit to the data.

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