

**MASTER**

**NUCLEAR STRUCTURE AT INTERMEDIATE ENERGIES**

**PROGRESS REPORT**

**G. C. Phillips**  
**G. S. Mutchler**

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**T. W. Bonner Nuclear Laboratories**

**April 1, 1978 through March 31, 1979**

**Prepared for the**

**U. S. DEPARTMENT OF ENERGY**

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RICE UNIVERSITY

PROGRESS REPORT

D.O.E. Contract No. EY-76-C-05-1316 "Task C"

### PROJECT ABSTRACT

During the contract year progress was made in data analysis and interpretation of a number of LAMPF experiments: E-80 ( $\pi^\pm$  scattering from nuclei), E-81 (pp and pd reactions), E-341 (pd $\rightarrow$ d $\pi^+$ n), E-82 ( $\pi^\pm$ d reactions), and E-197 (pd $\rightarrow$  $^3\text{He}\pi^0$ ). This analysis was aided by the start of operation of a new PDP 11/34 computer system.

During the year, one PH.D. degree in Intermediate Energy Physics at Rice was granted to a student member of the group. Four papers were published by the group and five papers were presented at meetings.

The principal collaborators for this work were the University of Houston Group under the direction of Professor John C. Allred.

PROGRESS REPORT

Contract No. EY 76 C 05 1316

"Task C"

Nuclear Structure at Intermediate Energies

Rice University, Houston, Texas 77001

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Physics Shop Personnel, Rice University

## INTERMEDIATE ENERGY PHYSICS

During the past contract year progress was made in consolidating and understanding past measurements as well as preparing for new thrusts.

The "mining" of the hundreds of data tapes from LAMPF E-81 was continued: so far five papers have been published and data analysis/paper preparation proceeds on five more. In addition, the data analysis and interpretation of several other experiments has advanced: LAMPF E-80, E-82, E-197 and E-341.

A major improvement of our technical capabilities occurred during the latter part of the past year that has enormously aided us: the purchase and initial usage of a new DEC PDP 11/34 computer system for data analysis. This computer, similar to and compatible with our portable laboratory based, on-line PDP 11/45 system, is beginning to allow a more reasonable turn around time in data analysis of our experiments. This new facility was jointly financed by our Intermediate Energy and High Energy D.O.E. contracts.

During the year a significant change of policy at LAMPF was effected which should be a significant help to our program in the future: a rededication of the LAMPF to variable energy proton beams (including polarization studies) was recommended by the LAMPF Users Group Long Range Planning Committee and was approved by Dr. Louis Rosen. G. C. Phillips served as Chairman of the Subcommittee on Nucleon-Nucleon Physics that made the variable energy/polarization recommendation.

Also during the past year a special D.O.E. review panel studied all the D.O.E. contractors who engage in basic research in nucleon-nucleon physics. This panel apparently endorsed our program. This, and the expected start of a variable energy/polarization program served to encourage us: in the past we had been somewhat confused by the reactions of some members of the LAMPF Program Advisory Committee to our proposals. We are confident that our medium energy program is

oriented in fruitful directions.

A principal high light of accomplishment of our group during the year is our contribution to understanding of the role of  $\pi$ -production mechanisms at intermediate energies. Two papers (see Publication 2 and 4) derived from E-81 measurements, have advanced this understanding. These papers, and on-going work (see below) continue our investigation of the importance of the  $\Delta(1236)$  to intermediate energy physics and develop, step-wise, a theoretical understanding of strong interaction particle physics to nuclear physics.

For several years we have been interested in the possibility that the N-N system might have resonances in the energy region near 1 GeV. Recent ZGS polarized proton experiments on  $\Delta\sigma_T = \sigma_{\text{tot}}(\uparrow\downarrow) - \sigma_{\text{tot}}(\uparrow\uparrow)$  by the Rice Group and on the  $\Delta\sigma_L = \sigma_{\text{tot}}(\uparrow) - \sigma_{\text{tot}}(\downarrow)$  by Yokosawa *et al* show remarkable energy structure and serve to encourage continued study of these problems.

A significant part of the Rice "high energy" work at ZGS during the past year was very german to "intermediate energy" research. For that reason some of the group participated in these measurements. This report does not describe the ZGS work in detail; instead, the report for our D.O.E. "high energy" contract is attached as a supporting document. While the two programs have distinctly different parts, we believe they also have strongly contiguous parts that complement and strengthen each other.

The year's results are discussed below under the following topics:

- A. Two Nucleons
- B. Three Nucleons
- C. Nuclei
- D. Theory
- E. Instrumentation
- F. Applied Physics

For each topic the experiment number and leader is indicated.

## A. Two Nucleons

1. "Production of the  $\Delta^{++}$  in the Reaction  $pp \rightarrow p\pi^+n$  at 800 MeV" LAMPF E-81, J. Hudomalj-Gabitzsch *et al.*

Kinematically-complete data for the reaction  $pp \rightarrow p\pi^+n$  at 800 MeV have been accumulated at four proton lab angles ( $15^\circ$ ,  $20^\circ$ ,  $25^\circ$ , and  $30^\circ$ ) where the cross section  $d^5\sigma/dp_1 d\Omega_1 d\Omega_2$  is dominated by  $\Delta^{++}$  production. The data, spanning four momentum transfers  $t_{\Delta^{++}}$  between 0.07 and 0.3  $(\text{GeV}/c)^2$ , have been compared to the predictions of a pion and rho exchange model with various baryonic intermediate states. The best agreement between the theoretical and experimental cross sections was obtained with the form factor range parameters  $\Lambda_\pi = 0.78 \text{ GeV}/c$  and  $\Lambda_\rho = 1.8 \text{ GeV}/c$ . The integrated  $pp \rightarrow n\Delta^{++}$  cross section was calculated to be 13.4 mb, which, in agreement with isospin predictions of the isobar model, accounts for 75% of the estimated experimental  $pp \rightarrow N\Delta$  cross section of  $19 \pm 3$  mb.

This work has been accepted for publication in the Physical Review (scheduled for winter 1978-79) (Publication No. 4).

2. "The  $pp \rightarrow pp\pi^0$  Reaction"

LAMPF E-81, G. P. Pepin

Data from three reactions studied using the LAMPF 800 MeV External Proton Beam during Experiment E-81,  $pp \rightarrow p\pi^+n$  ( $np$  FSI),  $pp \rightarrow d\pi^+(1)$ , and  $pp \rightarrow p\pi^+n$  ( $\Delta^{++}$  production) <sup>(2)</sup> are being re-analyzed to study  $\Delta^+$  production in the reaction  $pp \rightarrow pp\pi^0$ .

The experimental setup, explained more fully in reference (1), included a spectrometer arm which measured momentum ( $P_s$ ),  $\theta$ , and  $\phi$  of one proton and a time of flight arm which measured  $\theta$  and  $\phi$  of the other proton. The angular settings at which data were taken are listed in Table I along with the reaction originally being studied, and the central momentum ( $P_c$ ) accepted by the spectrometer magnet. The range of momentum transfer to the  $\Delta^+$  covered by these angles was from 0.20 to 0.47  $(\text{GeV}/c)^2$ . The angular

settings for the FSI and  $d\pi^+$  experiments are the same with only the magnet setting,  $P_c$ , being different. Both sets of data were analyzed to obtain  $\Delta^+$  data at all possible momentum values,  $P_s$ , since at each setting the magnet accepted only a portion of the proton momentum range.

It is easily seen from the kinematically corrected time of flight spectra (DFOB) for the TOF arm that two separate reactions were being measured. The two peaks, shown in Fig.1, correspond to pions from the reactions  $pp \rightarrow p\pi^+n$  and  $d\pi^+$ , and protons from the reaction  $pp \rightarrow pp\pi^0$ . The data desired were thus easily separated out by accepting only those events with a proton time of flight. This was usually sufficient to remove events due to competing reactions.

The cross section  $d^5\sigma/d\Omega_s d\Omega_t dP_s$  is being calculated. A plot of the typical cross section versus  $P_s$  is shown in Fig.2. The peak in the cross section at about 1000 MeV/c corresponds to the  $\Delta^+$ . This peak is most pronounced at small momentum transfers, decreasing in size as the momentum transfer increases. The peaks at the high and low ends of the spectrum are phase space effects due to tangency at the ends of the kinematically-allowed locus.

The cross sections will be compared to theoretical calculations due to Furić and Duck<sup>(2)</sup> using a peripheral model of pion production (see Section D.8).

#### References:

- (1) R. D. Felder, Ph.D. Thesis, Rice University (1976), unpublished.
- (2) J. Hudomalj-Gabitzsch *et al.*, accepted for publication in Phys. Rev. C.

### 3. "The $pp \rightarrow d\pi^+$ and $pp \rightarrow d^*\pi^+$ Reactions"

LAMPF E-81, R. D. Felder

This reaction has been analyzed and the interpretation and write up has continued during the year.

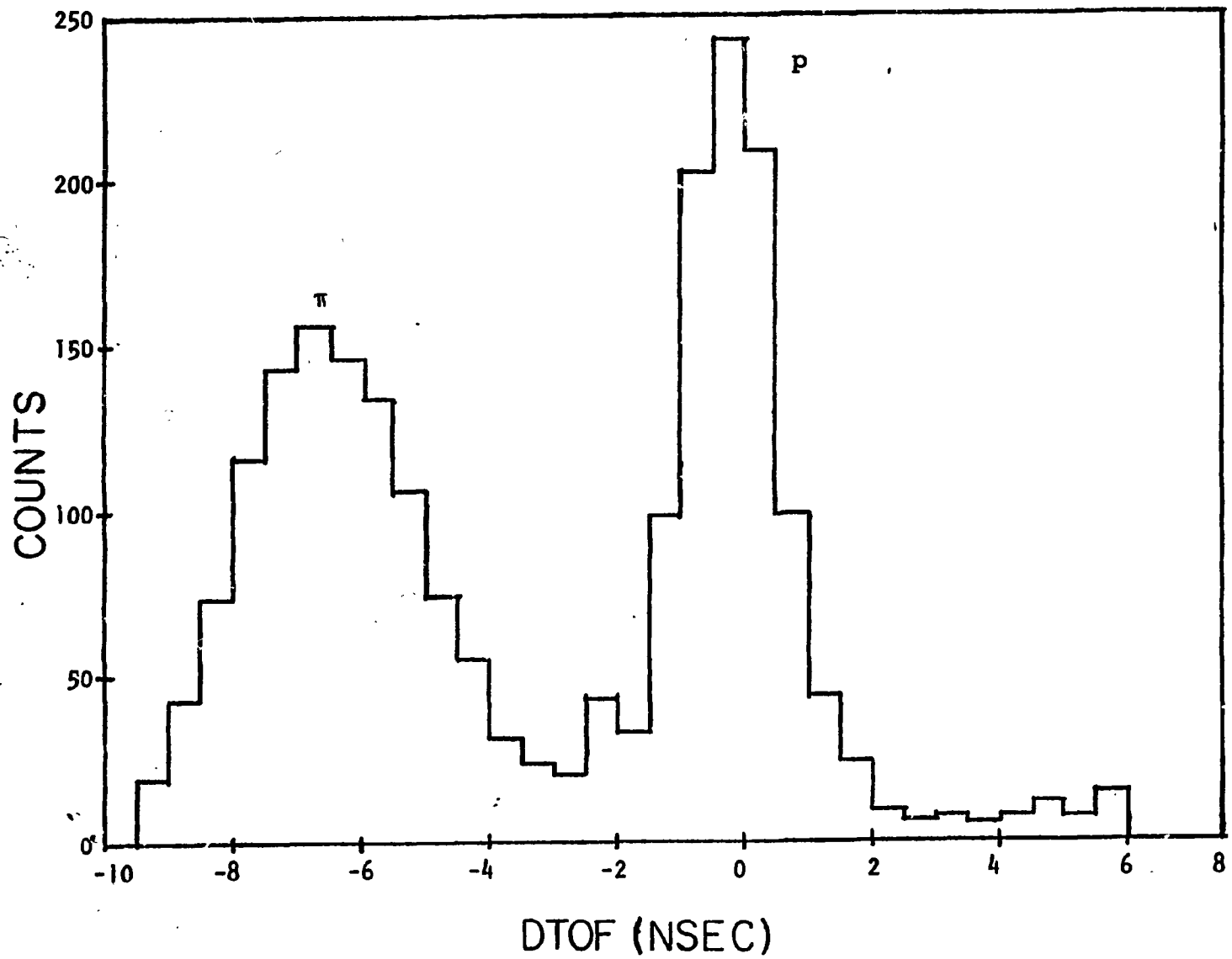


Figure 1:  $pp \rightarrow pp\pi^0$  DTOF Spectrum [see text]

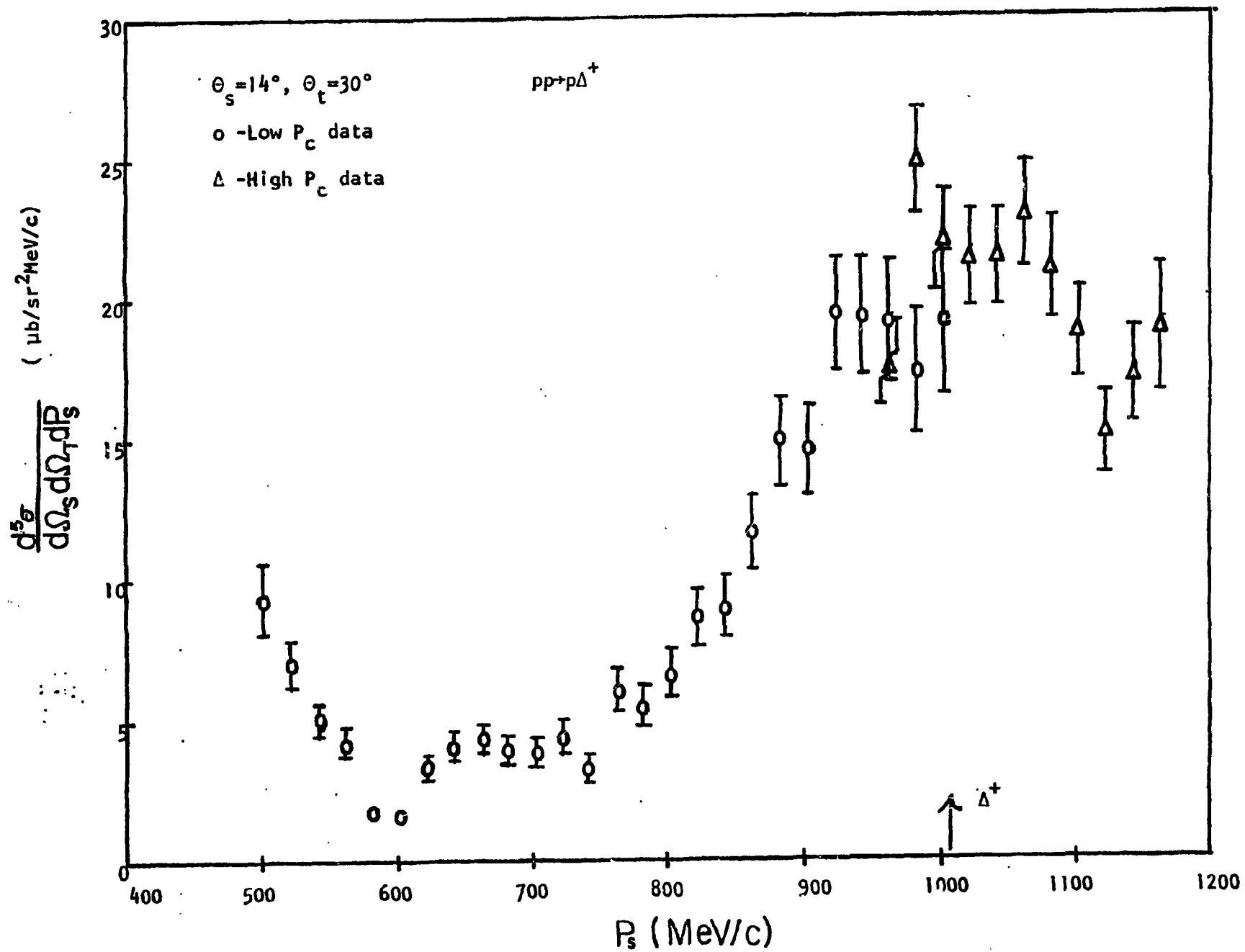


Figure 2: Cross Section vs.  $P_s$

TABLE 1  
 $pp \rightarrow pp\pi^0$  Angle Pairs

$\theta_s$	$\theta_T$	$P_c$ (MeV/c)	Principle Reaction
14°	22.8°	950	$d\pi^+$
14°	22.8°	485	FSI
14°	25°	1002	$d\pi^+$
14°	25°	500	FSI
14°	30°	1002	$d\pi^+$
14°	30°	520	FSI
15°	22.8°	600	$\Delta^{++}$
15°	41°	1022	$d\pi^+$
15°	41°	560	FSI
20°	22°	600	$\Delta^{++}$

#### 4. "The $\pi^{\pm}d \rightarrow \pi^{\pm}pn$ and $\pi^{\pm}d \rightarrow \Delta^{++}n$ Reactions"

LAMPF E-82, J. H. Hoftiezer

Kinematically-complete experimental studies have been carried out to compare various pion-induced deuteron breakup mechanisms. Specifically, the quasi-free scattering (QFS) reactions  $\pi^{\pm}d \rightarrow \pi^{\pm}pn$  and the production reaction  $\pi^{\pm}d \rightarrow \Delta^{++}n$  were studied. These mechanisms have identical Feynmann diagram neutron vertices, as shown in Fig.1. Thus, one should be able to factor out this vertex and study the  $\pi p \rightarrow \pi p$  and the  $\pi p \rightarrow \Delta$  vertices in a simple nucleus.

This work was performed in the LAMPF P<sup>3</sup> channel. The experimental arrangement is shown in Fig.2. Scattered reaction products were detected coincidentally in the system. Data was collected over a wide range of neutron momenta (see Tables I and II).

Analysis of this data is in the final stages. Computer reconstruction of the scattering events allows one to project back to the target (see Fig.3a and 3b) to verify that the event comes from the reaction of interest. Cuts placed on these histograms, and time of flight histograms (3d) allow one to reject accidental events and background reactions. A typical proton momentum spectrum for the reaction  $\pi^{-}d \rightarrow \pi^{-}pn$  following such cuts is shown in Fig.3d. The spectrum shows a peak at 420 MeV, corresponding to a minimum in the spectator neutron momentum as expected from the QFS model.

We expect to present the results of this experiment at the Houston Meson-Nuclear- Physics Conference to be held during March 1979.

#### 5. "Studies of the Spin-Dependence of $pp \rightarrow \pi X$ "

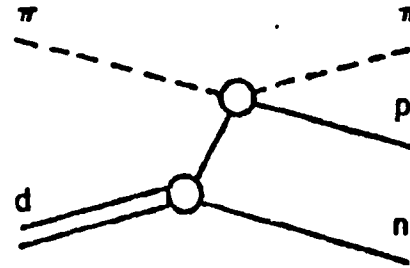
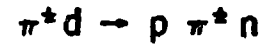
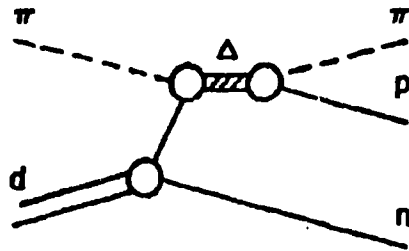
LAMPF E-336, G. S. Mutchler *et al.* in collaboration  
with Case-Western Reserve University

The startup of this experiment has been delayed and postponed due to the severe illness of our principal collaborator, Phillip Bevington. It is hoped that the Rice-University of Houston Group can assume the lead on this work in 1979.

FIG. 1

Exp. 82 DATA

350 Mev/c

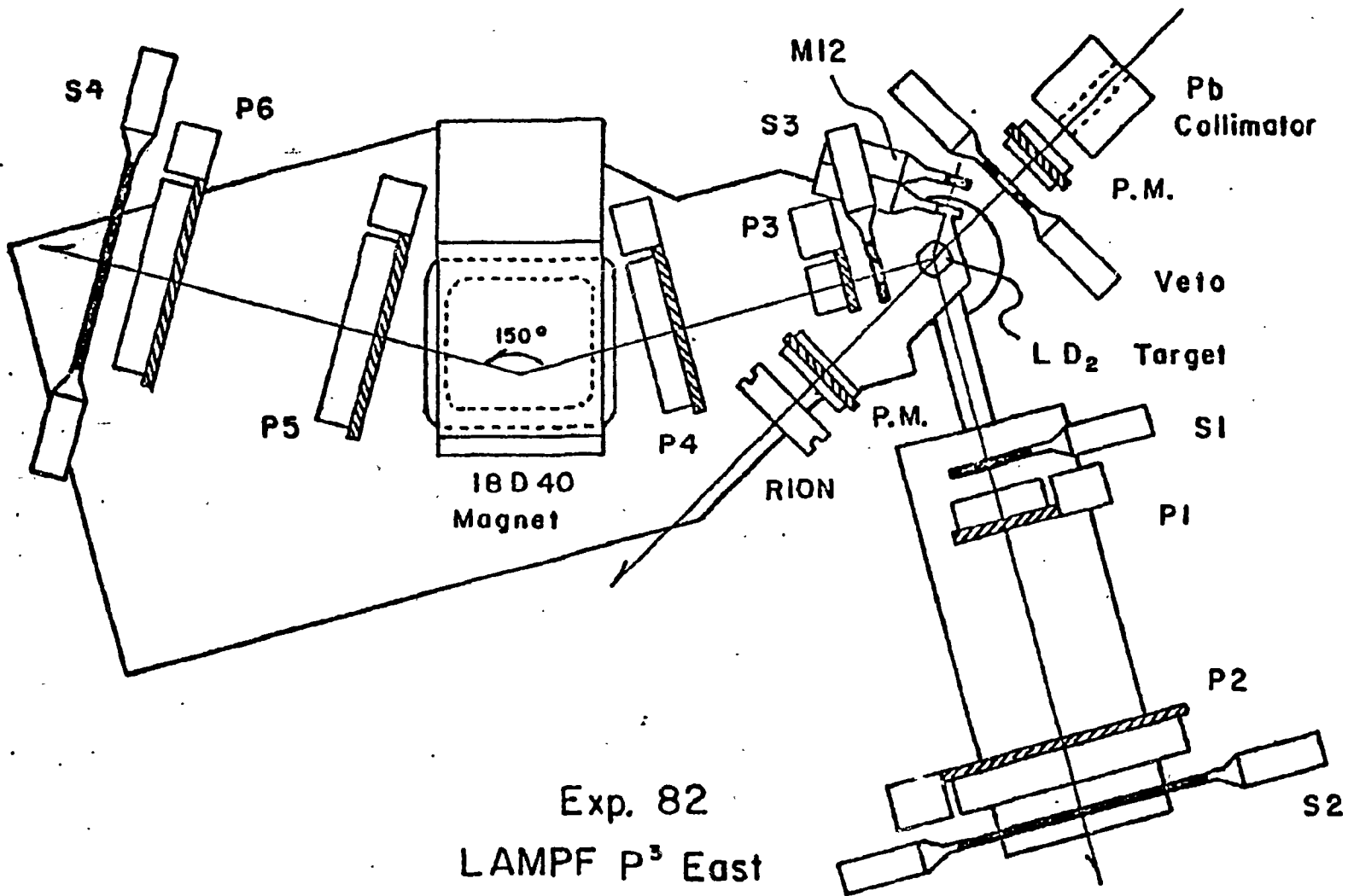


Angle		Momentum $\Delta$ c.m.	Events		
p	$\pi$		n	$\pi^+$	$\pi^-$
30	80	4	95	16.	4.
40	70	21	112	20.	5.
50	60	36	139	20.	2.6
60	50	50	173	3.4	.5
70	40	62	209	.5	

( $10^3$ )

Angle		Momentum n	Events	
p	$\pi$		$\pi^+$	$\pi^-$
30	105	15	33.	8.6
40	95	55	27.	9.7
50	85	88	13.	2.2
50	95	129	5.	1.2
50	105	171	2.5	1.2
60	100	223	1.	.5

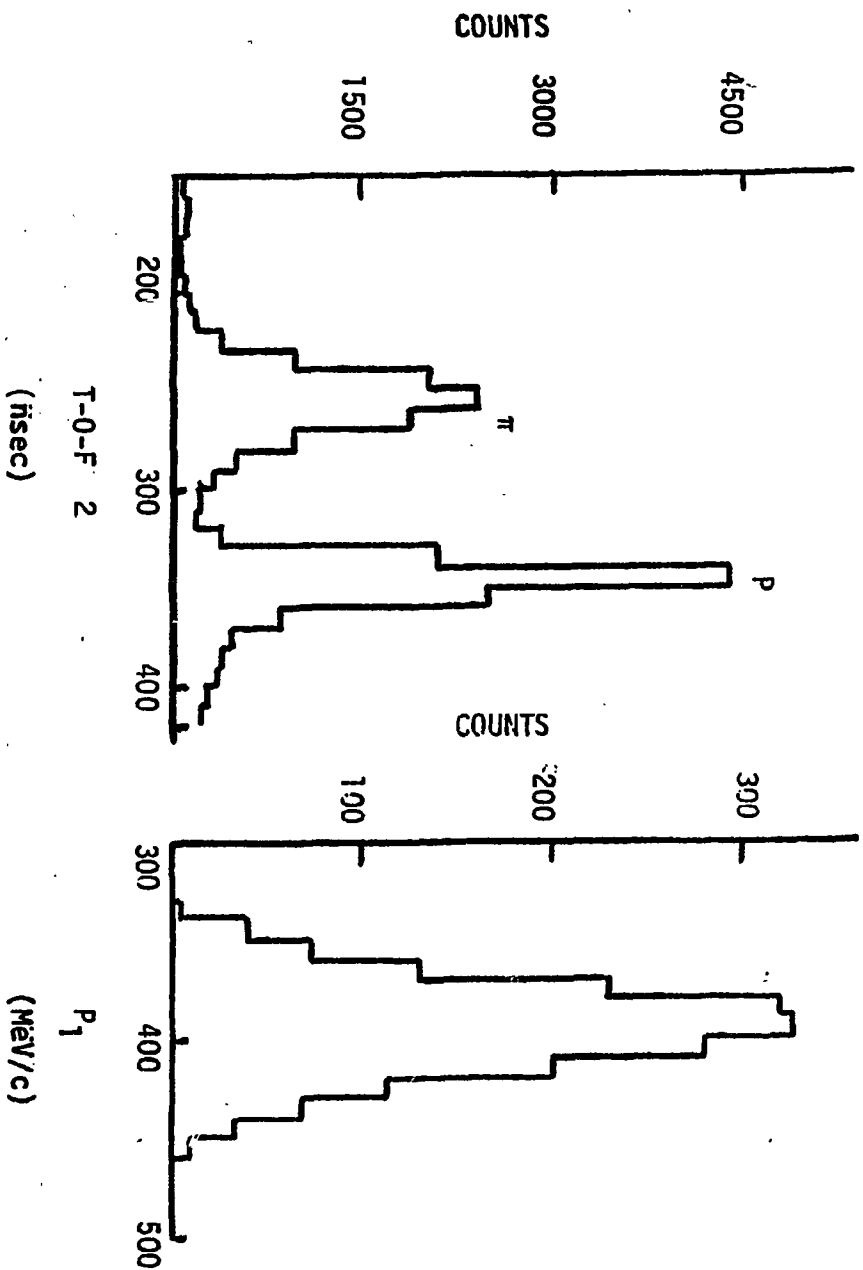
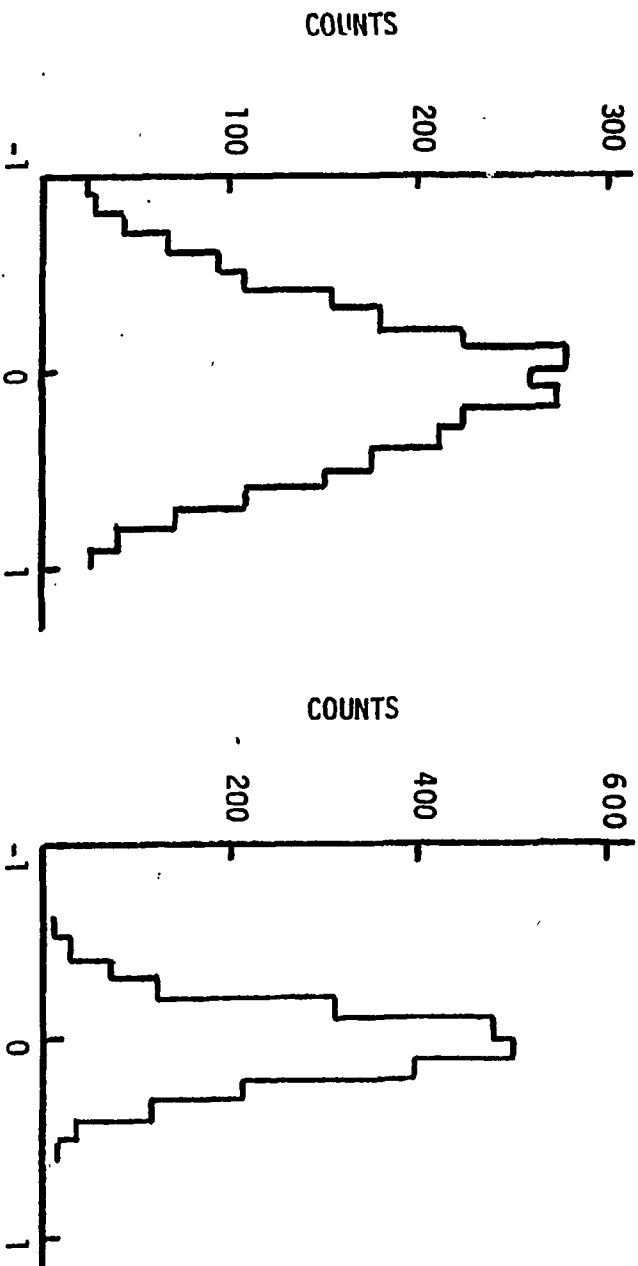
( $10^3$ )



Exp. 82  
 LAMPF P<sup>3</sup> East

FIG. 2

FIG. 3



RUN #158  $\pi^+d \rightarrow p\pi^+n$   
 $P_0 = 350$  MeV/c  $\theta_n = 50^\circ$   $\theta_\pi = 95^\circ$

## 6. Non-Resonant $\pi$ -Production in $np \rightarrow \pi^- pp$

LAMPF E-366, G. S. Mutchler *et al.*, B. W. Mayes *et al.*,  
University of Houston, and B. E. Bonner (LASL)

This experiment is ready to go but beam time has not yet been scheduled.

## 7. Spin Dependence and Energy Dependence of Two-Nucleon Systems

Several studies by the Rice Group have been carried out during the last year at ZGS as part of Rice's high energy physics program. Some of these studies, are, in fact, very germane to our on-going medium energy physics program. The progress report of that contract is submitted as supporting information. Of special interest is the possibility that N-N resonances may occur in the LAMPF energy range.

### B. Three Nucleons

#### 1. "Study of the $pd + d\pi^+ n$ Reaction at 800 MeV"

LAMPF E-341, D. M. Judd

The pion production reaction  $pd + d\pi^+ n$  was studied in a kinematically-complete experiment at 800 MeV. Since the deuteron has zero isospin, a pion-nucleon final state in the (3,3) resonance is isospin forbidden. This allows the study of  $\pi^+ d$  interactions without a pion nucleon resonance background. Previous experiments by this group have studied this reaction at small momentum transfers to the neutron for 800 MeV incident protons<sup>(1)</sup> and large momentum transfers for 585 MeV incident protons.<sup>(2,3)</sup> This experiment was designed to make a detailed study of the  $pd + d\pi^+ n$  reaction at all accessible momentum transfers.

Table I lists the available data by angle pairs and gives the minimum spectator (neutron) momentum allowed. All of the data, except the 80° angle pairs have been analyzed. The preliminary results from the analysis are shown in Fig. 1a-b. The curves shown are calculated using the One Nucleon Exchange model (ONE). This model has been shown to reproduce the data for small

ANGLE PAIRS FOR  
PD-D  $\pi^+$ N REACTION

$\theta_D \backslash \theta_\pi$	20°	30°	35°	40°	80°
15°				0	83
20°	142			96	208
25°			188		338
30°			285		478
35°		389			626

TABLE I

Table of available data by angle pairs from E-341. The numbers are the minimum spectator (neutron) momentum allowed.

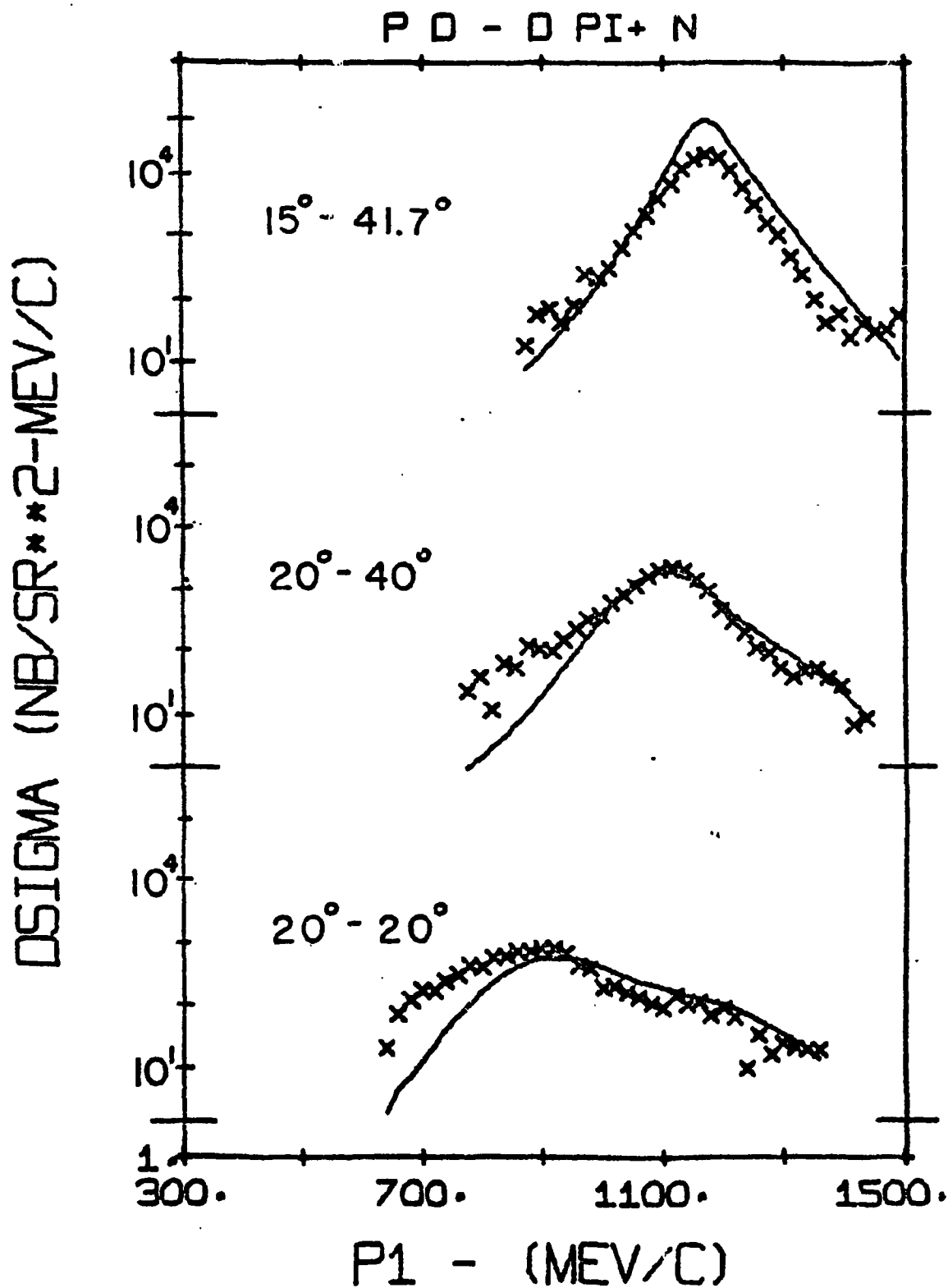


Fig.1a: Preliminary results from the analysis of E-341. The x represents the data points. The solid lines are calculated using the One Nucleon Exchange Model. The angle pairs for each curve are shown.

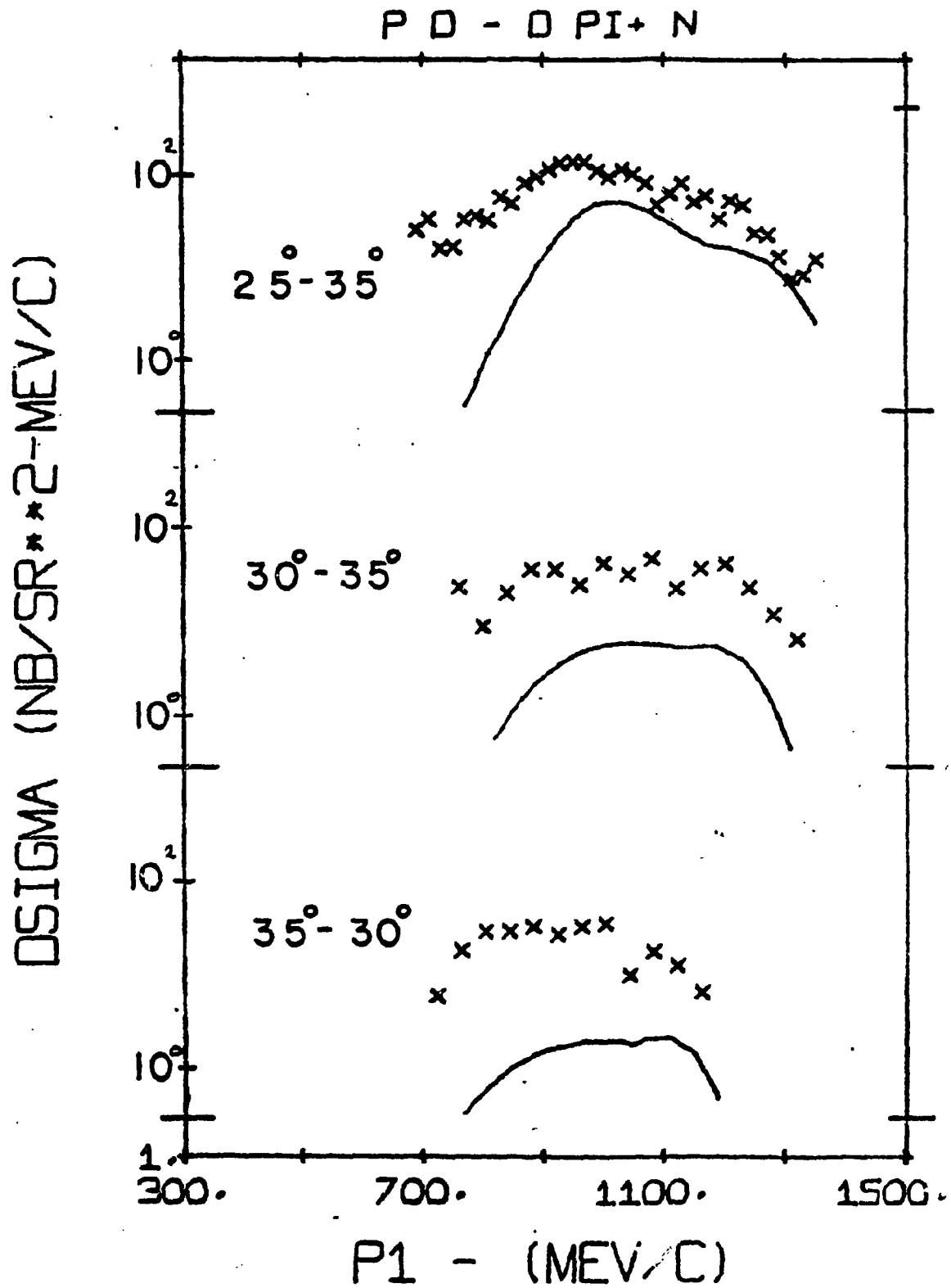


Fig.1b

Preliminary results from the analysis of E-341. The x represents the data points. The solid lines are calculated using the One Nucleon Exchange Model. The angle pairs for each curve are shown.

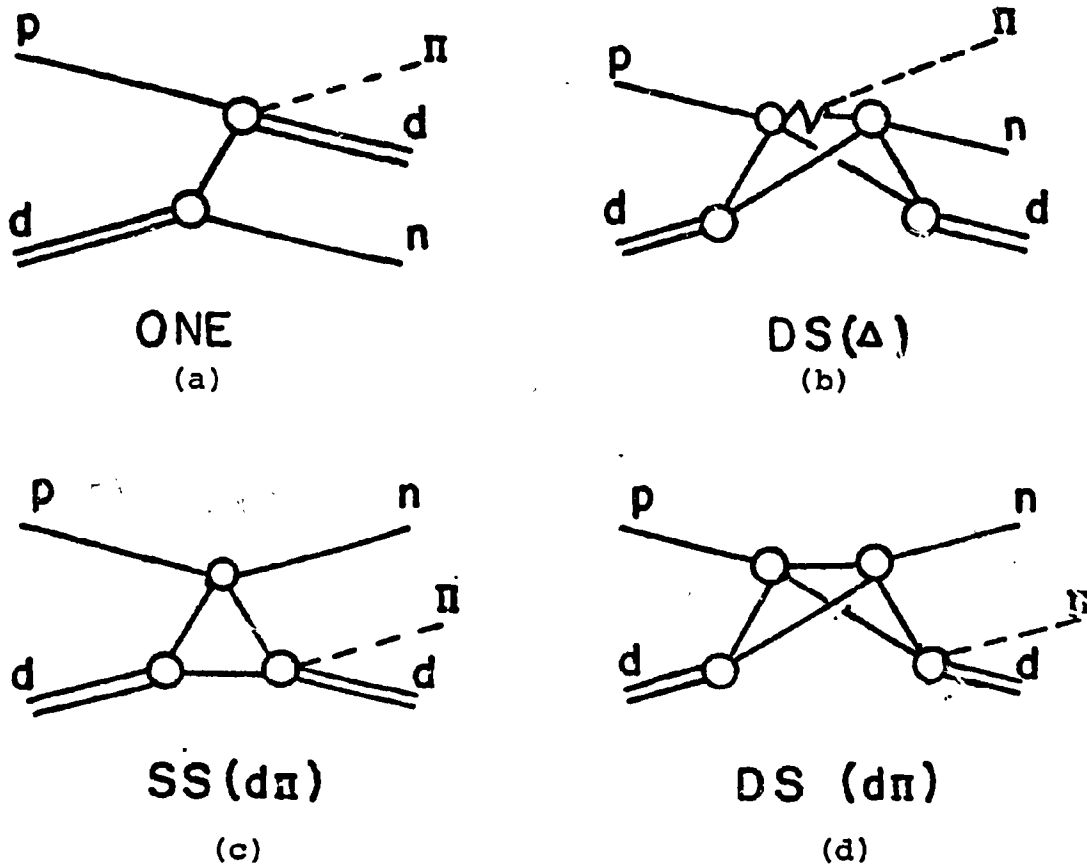
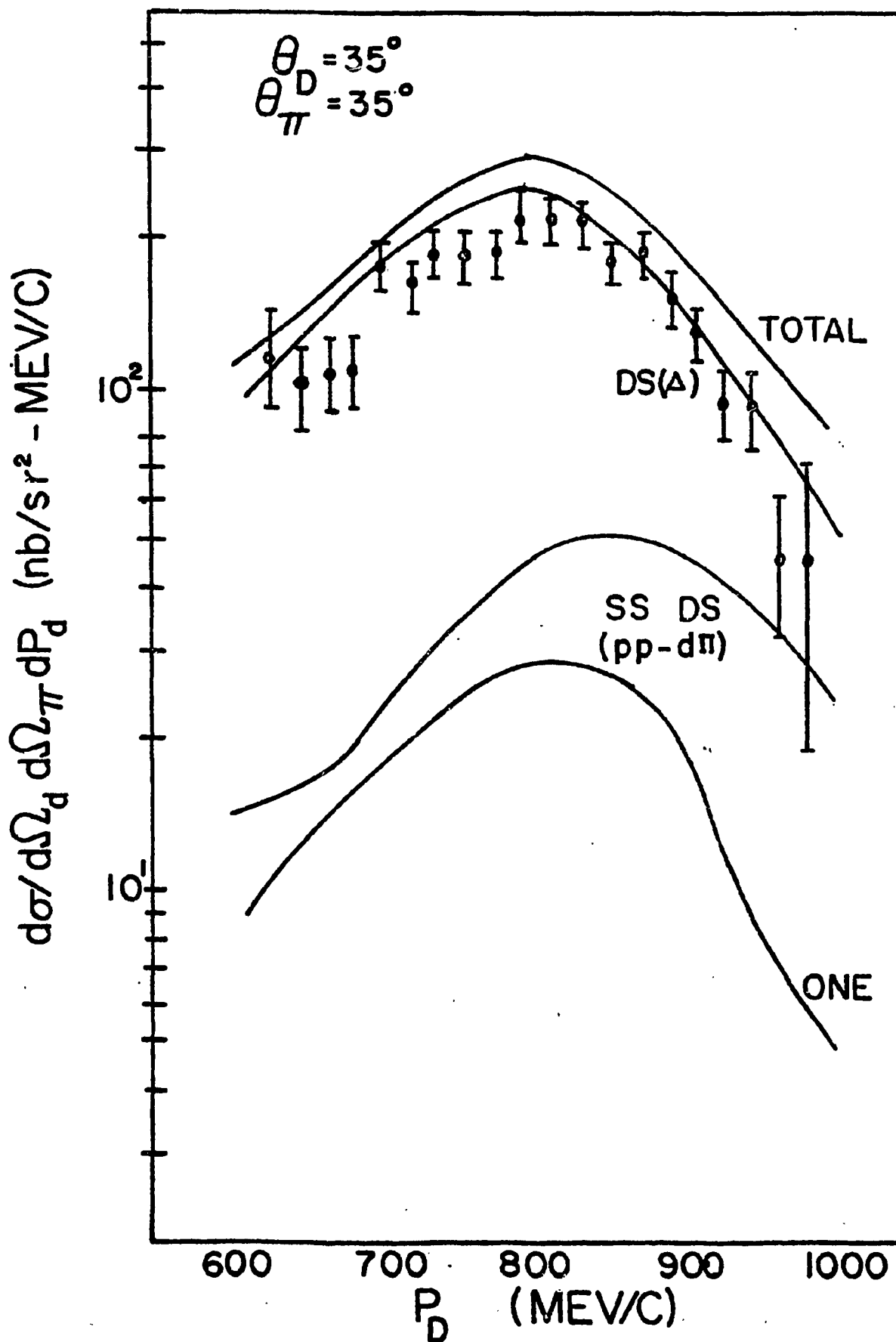


Fig.2: (a) One Nucleon Exchange Model (ONE)  
 (b) Double Scattering with a  $\Delta$  produced in an intermediate state  $DS(\Delta)$   
 (c) Single Scattering with a final state interaction between the deuteron and pion  $SS(d\pi^+)$ .  
 (d) Double Scattering with a final state interaction between the deuteron and pion  $DS(d\pi^+)$

Fig.3: Fit to large momentum transfer data previously obtained with 585 MeV incident proton energy for the reaction  $pd \rightarrow d\pi^+N$ .



momentum transfers.<sup>(1)</sup> The discrepancy between the model and the data at  $15^\circ$ - $41.7^\circ$  is due to the rapid variation of the theory over the large deuteron acceptance angle. Suitable averaging in the final calculations will resolve this discrepancy.<sup>(1)</sup> The model fails at larger momentum transfers and second order diagrams are needed to explain the data.<sup>(2,3)</sup> Possible diagrams are shown in Fig.2a-d. Fig.3 shows the fit to the large momentum transfer data previously obtained at 585 MeV using these diagrams.<sup>(2)</sup> The line labelled SS-DS( $d\pi^+$ ) represents a coherent sum of the terms shown in 2c and 2d. The line labelled total represents an incoherent sum of the SS-DS( $d\pi^+$ ) term and the DS( $\Delta$ ) term, Fig.2b. Further refinements of the theory are detailed elsewhere in this report (Section D.7).

These results have been presented at the November 1978 APS Meeting in Asilomar, California, APS Bull. 23, p. 941, and will constitute the Ph.D. thesis of D. M. Judd.

#### References:

- (1) J. Lo, see Section B.4 of this report.
- (2) K. R. Hogstrom *et al.*, Phys.Rev. C17(1978) 259.
- (3) Ian Duck *et al.*, Phys.Rev. C18(1978) 887.

## 2. "The Reaction $pd \rightarrow {}^3\text{He}\pi^0$ "

LAMPF E-197, E. V. Hungerford

The  $(p, \pi)$  reaction on nuclei has been a subject of continuous interest. One of the motives behind studying this reaction is that high momentum components of nuclear wave functions can be investigated. In particular the  $pd \rightarrow {}^3\text{He}\pi^0$  reaction is of interest because it involves nuclei whose wave functions are well determined.

This research problem was a study of the  $d(p, \pi)^3$  reaction at 800 MeV. The recoil  ${}^3\text{He}$  were detected at angles between  $5^\circ$  and  $21^\circ$  in  $2^\circ$  steps with a single spectrometer arm. This corresponded to the CM pion angles of  $10^\circ$  and  $140^\circ$ . The upper and lower angle limits were restricted by the momentum acceptance of the analyzing magnet and the physical dimension of the experimental set up. A  $d(p, \pi)^3\text{He}$  signature was identified by its

unique pulse height, TOF, and momentum. The CM differential cross section  $d\sigma/d\Omega_{\pi}(pd \rightarrow {}^3\text{He}\pi^0)$  calculated from the data is plotted in Fig.1. Along with it are three points of the  $pd \rightarrow {}^3\text{H}\pi^+$  differential cross section measured in the same experiment. The data for angles greater than  $80^\circ$  are not shown. The solid line is a distorted wave impulse calculation of the reaction  $pd \rightarrow {}^3\text{H}\pi^+$  made by Fearing<sup>(1)</sup> normalized for the  $pd \rightarrow {}^3\text{He}\pi^0$  reaction.

Work is still needed to refine the data analysis. However, from this preliminary result one can see the  $\sigma_{{}^3\text{He}}/\sigma_{{}^3\text{H}}$  ratio is roughly 1/2 and the slope agrees with the  $pd \rightarrow {}^3\text{H}\pi^+$  data.

Reference: (1) H. Fearing, Phys. Rev. C11 (1975) 1210 and 1495.

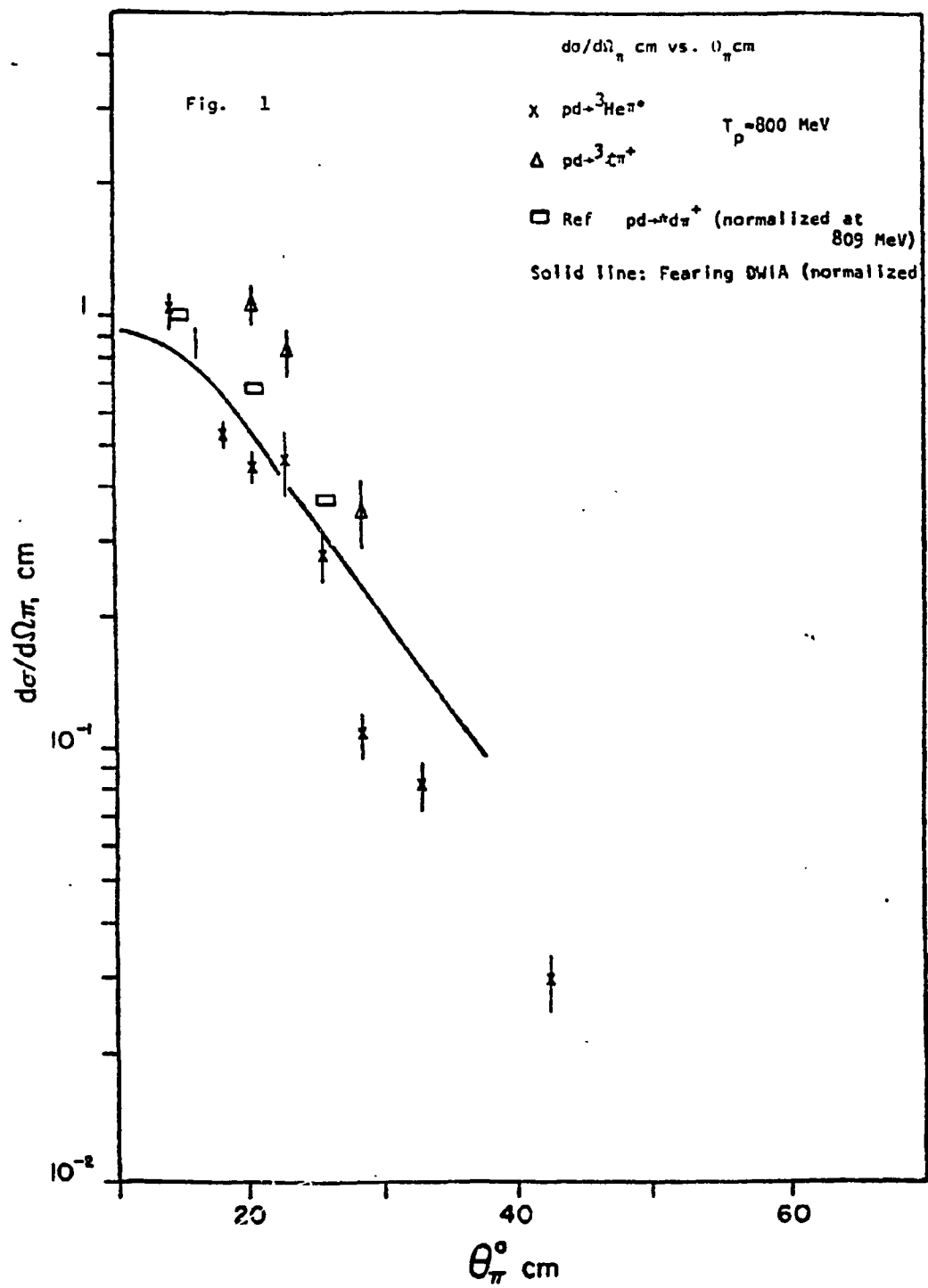
### 3. "Pion Production by 800 MeV Protons from Deuterium with a Spectator Neutron"

LAMPF E-81, J. Lo, University of Houston

Pion production from deuterium is interesting because it involves only a few nucleons and the inclusive  $\pi$  production at 730 MeV<sup>(1)</sup> was found to be less than the sum of the inclusive  $\pi$  production from protons on protons and protons on neutrons. To further understand the  $\pi$  production mechanism from deuterium, it is important to study the  $\pi$  production in specific reaction channels.

The reaction  $d(p, d\pi^+)n$  at 800 MeV was investigated under conditions where the neutron in the deuteron target remains a spectator to the reaction in a kinematically-complete experiment. The product deuteron and pion were detected in coincidence by a magnet arm and a TOF arm respectively (see Fig.1). The positions of the arms are selected such that the product neutron carried the minimum momentum.

It was found that the cross section for this process is large (of order  $\sim 10^2 \mu\text{b}/\text{sr}^2 \text{Mev}/c$ ) and accounts for a large fraction of total pion production in this kinematic region. A calculation using the simple spectator model accounts for about 90% of the measured cross section for neutron recoil momentum  $p_n=0$



and about 60% of the cross section for  $p_n=100$  MeV/c.

The results of the analysis of the  $pd \rightarrow d\pi^+n$  reaction in the kinematic region where the neutron recoil momentum,  $p_n$ , can vanish are given in Fig.2. The error bars on the data points are statistical uncertainties, and the solid line histograms are the differential cross sections calculated using the spectator model. No adjustment of normalization has been made to improve the fit. The 5th order differential cross sections shown here have been averaged over the entire solid angle of both the TOF arm and the MAG arm so that they may be expressed as functions of  $p_d$ . Strong peaks centered near  $p_n=0$  are still observed. The results of the analysis in the region where  $p_n$  cannot be zero are given in Fig.3. Again, the angular average of the  $d\sigma^5/dp_d d\Omega_d d\Omega_\pi$  spectrum dominates at a  $p_d$  for which the corresponding  $p_n$  is a minimum.

From this experiment, one notes that the quasi-free process is a valid approximation at least in the region investigated. This still leaves open the question presented by the data of Cochran *et al.*<sup>(1)</sup> Simple Glauber shadowing is ruled out because it would effect all quasi-free exit channels equally.

Inclusive pion production data from hydrogen and deuterium targets is now under analysis to check the results of reference (1) (see Section B.4). This problem is not well publicized but the solution may be extremely important in understanding the spin dependent pion production amplitudes.

This work was presented at Asilomar at the APS-DNP November Meeting, APS Bull. 23(September 1978), p. 951.

Reference: (1) D. Cochran *et al.*, Phys.Rev. D6(1972) 3085.

4. "Inclusive Production of  $\pi^+$  and  $\pi^-$  from Hydrogen, Deuterium and  ${}^6\text{Li}$  at 800 MeV"

LAMPF E-81, T. M. Williams

Inclusive, or single-counter experiments do not provide detailed information on the reaction mechanism, but rather give a complete description of the reaction in terms of the momentum and angle of

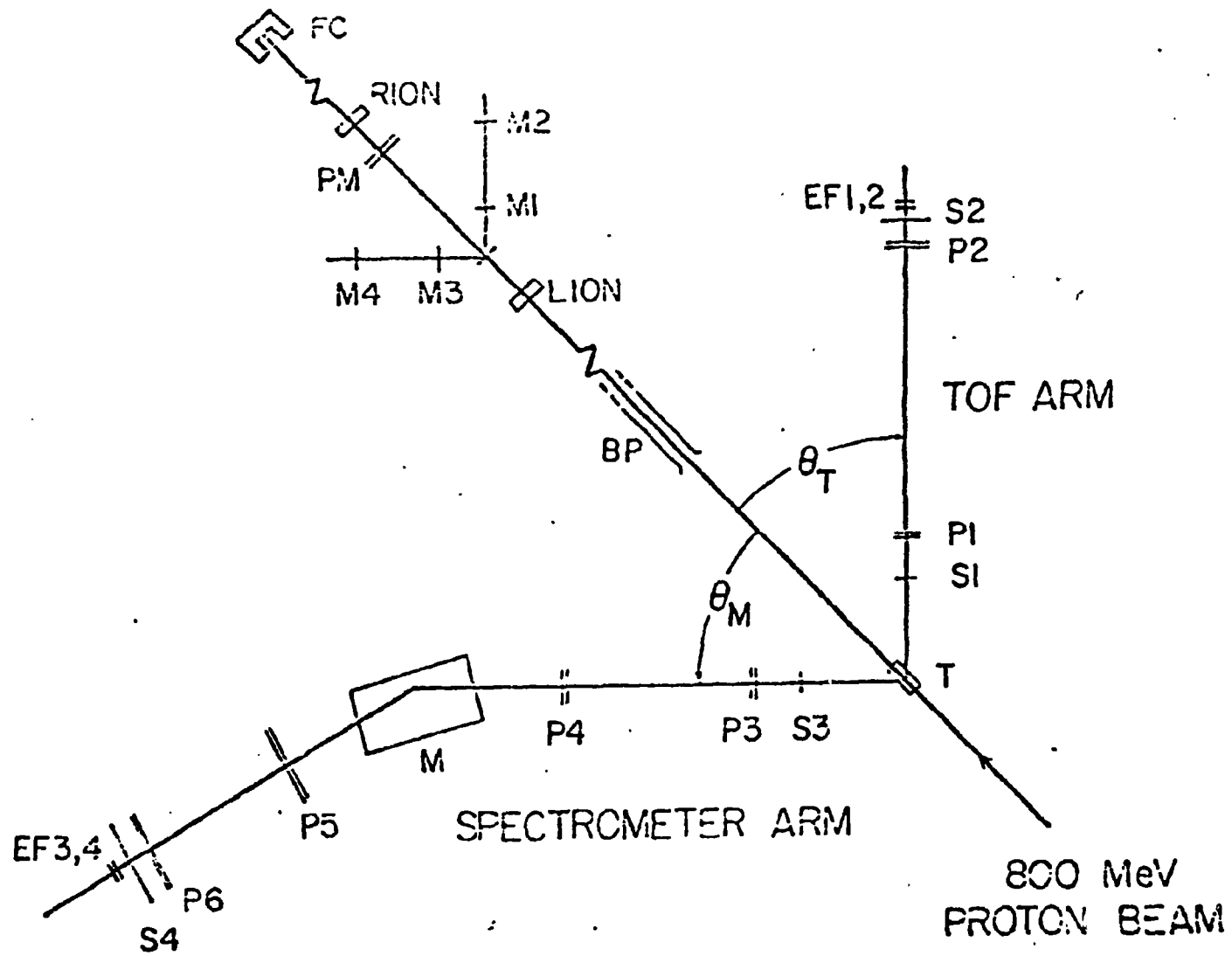
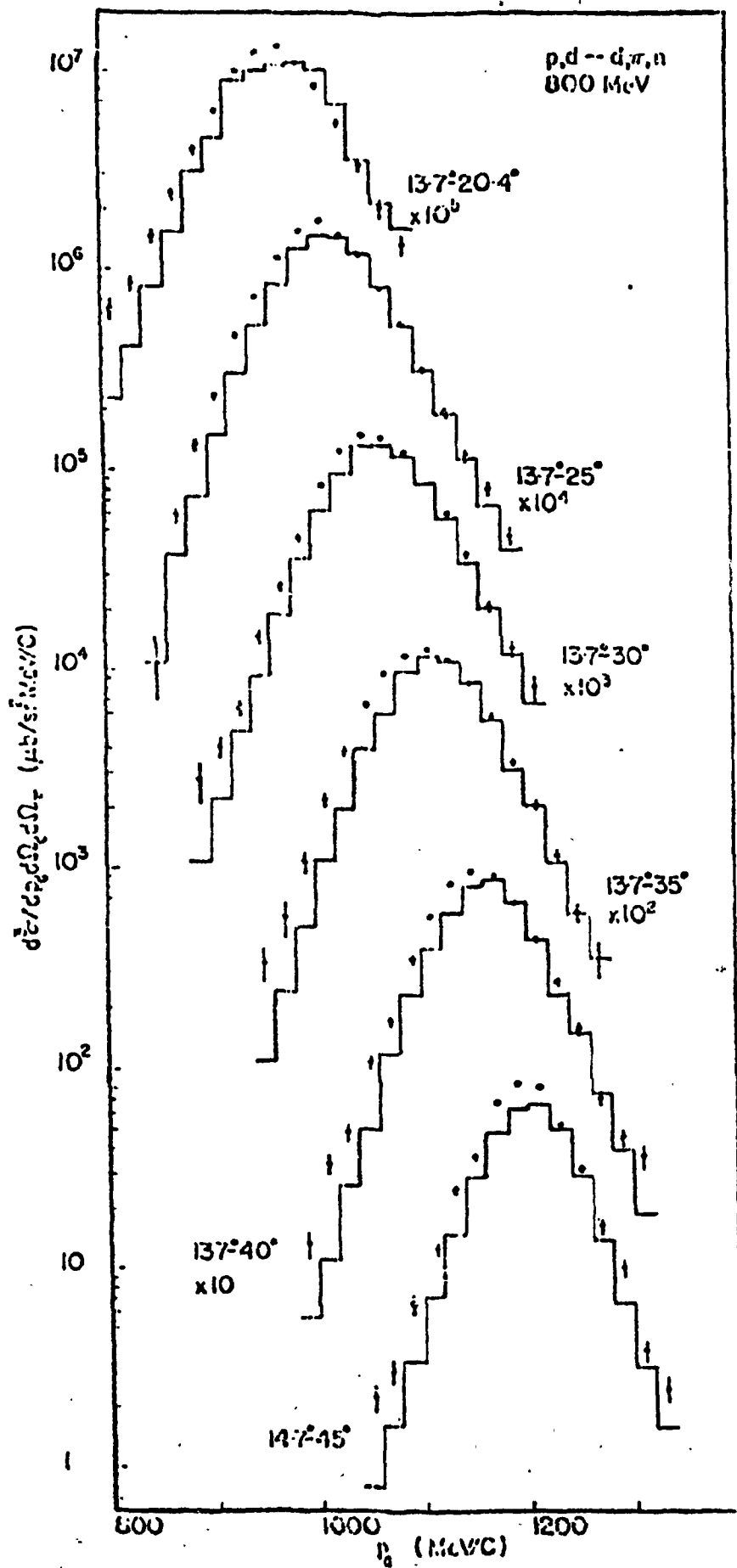


Fig.1:  $pd \rightarrow d\pi^+ n$



Cross Section vs. pd  
Fig.2: Solid Curves are  
Calculated Using  
Spectator Model

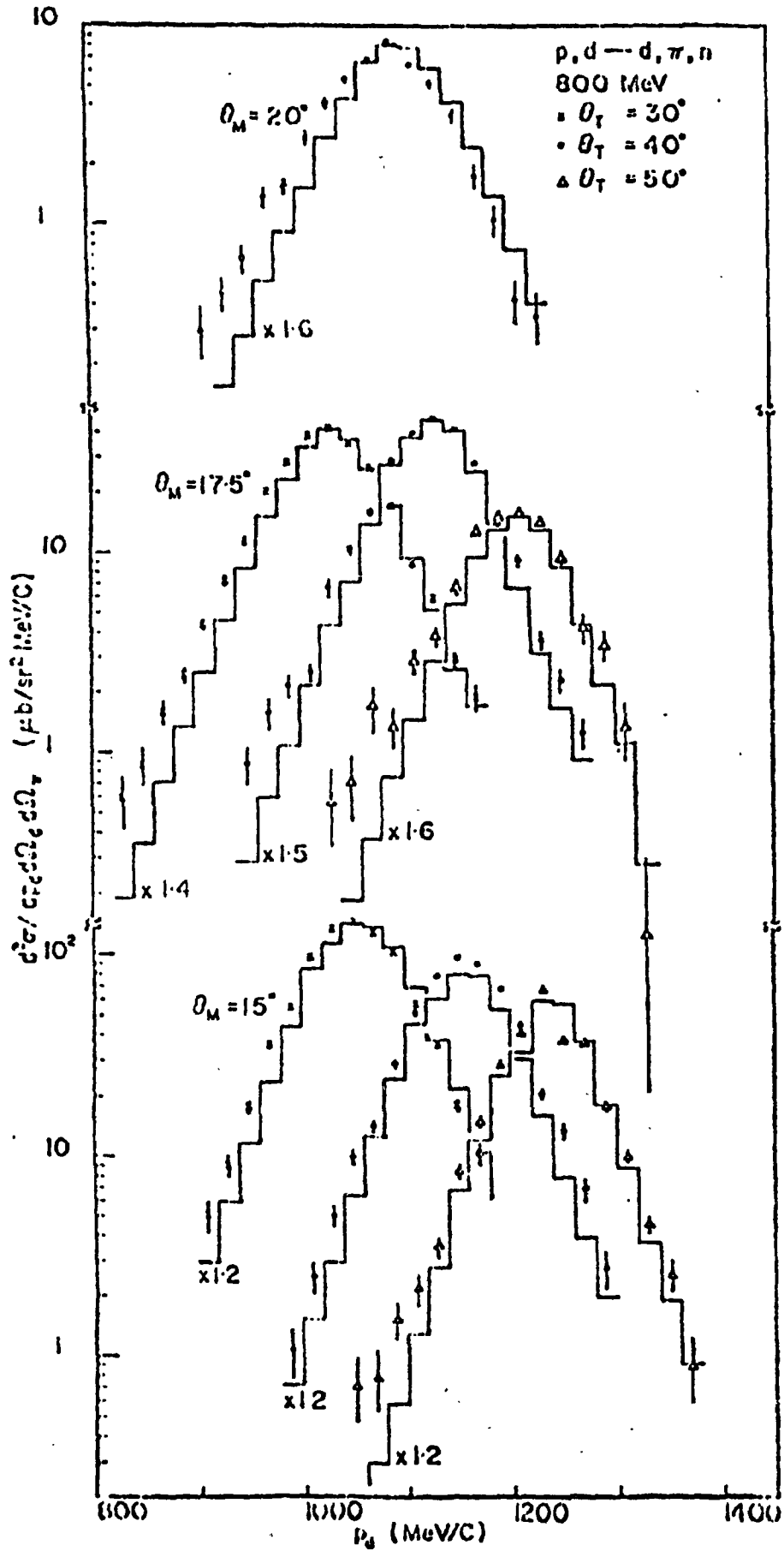


Fig.3: Cross Section vs. pd  
Solid Curves are  
Calculated Using Spectator  
Model

the detected particle. The knowledge of the cross section for inclusive production of both charged pions ( $\pi^+$ ,  $\pi^-$ ) gives additional information for testing theoretical models, and is also important as an input for the design of pion beams. <sup>(1)</sup>

In the present experiment, the differential cross section  $d^3\sigma/dpd\Omega$  has been measured over an angular range from  $15^\circ$  to  $50^\circ$  in the lab, for both  $\pi^+$  and  $\pi^-$  produced by 800 Mev protons interacting with hydrogen, deuterium and  ${}^6\text{Li}$ . The targets were cryogenic liquid targets for the first two elements while the  ${}^6\text{Li}$  target consisted of a solid isotopically enriched slab of  ${}^6\text{Li}$  in an inert gas atmosphere. The charged pions were detected and their momentum determined by a magnetic spectrometer. The trajectory of each individual particle was traced using multi-wire proportional counters triggered by a fast two-fold coincidence of scintillator counters. The wireplane coordinates together with time-of-flight signals were read in and transferred to a PDP 11/45 computer by way of CAMAC interface. The momentum resolution was 1.5%, while the angular resolution was 4 mr with an angular opening  $\pm 3^\circ$ .

The preliminary results of the data analysis for  $pp \rightarrow \pi^+ X$ ,  $pd \rightarrow \pi^+ X$ , and  $p{}^6\text{Li} \rightarrow \pi^+ X$  are shown in Fig. 1-5. The  $pp \rightarrow \pi^+ X$  data, Fig. 1, show a broad peak corresponding to the  $\Delta^{++}$  and  $\Delta^+$  resonances which dominate the  $pp$  interaction at 800 MeV, while the narrow peak at the maximum pion momentum is produced by the reactions  $pp \rightarrow \pi^+ d$  and  $pp \rightarrow \pi^+ d^*$ , where  $d^*$  represents the neutron-proton final state interaction at low n-p inelastic momenta. Except for this peak, the  $\pi^+$  cross section measured for the  $\text{LH}_2$  and  $\text{LD}_2$  targets are very similar. The  ${}^6\text{Li}$  data is larger than either the  $\text{H}_2$  or  $\text{D}_2$  data by about a factor of 3, as might be expected since it has three protons. The peak in the Lithium data is of a slightly smaller momenta. This indicates that the proton interacts with the nucleons (quasi-free production), not the nucleus as a whole. The  $\pi^-$  data is lower than the corresponding  $\pi^+$  data by about a factor of 9. This is in reasonable

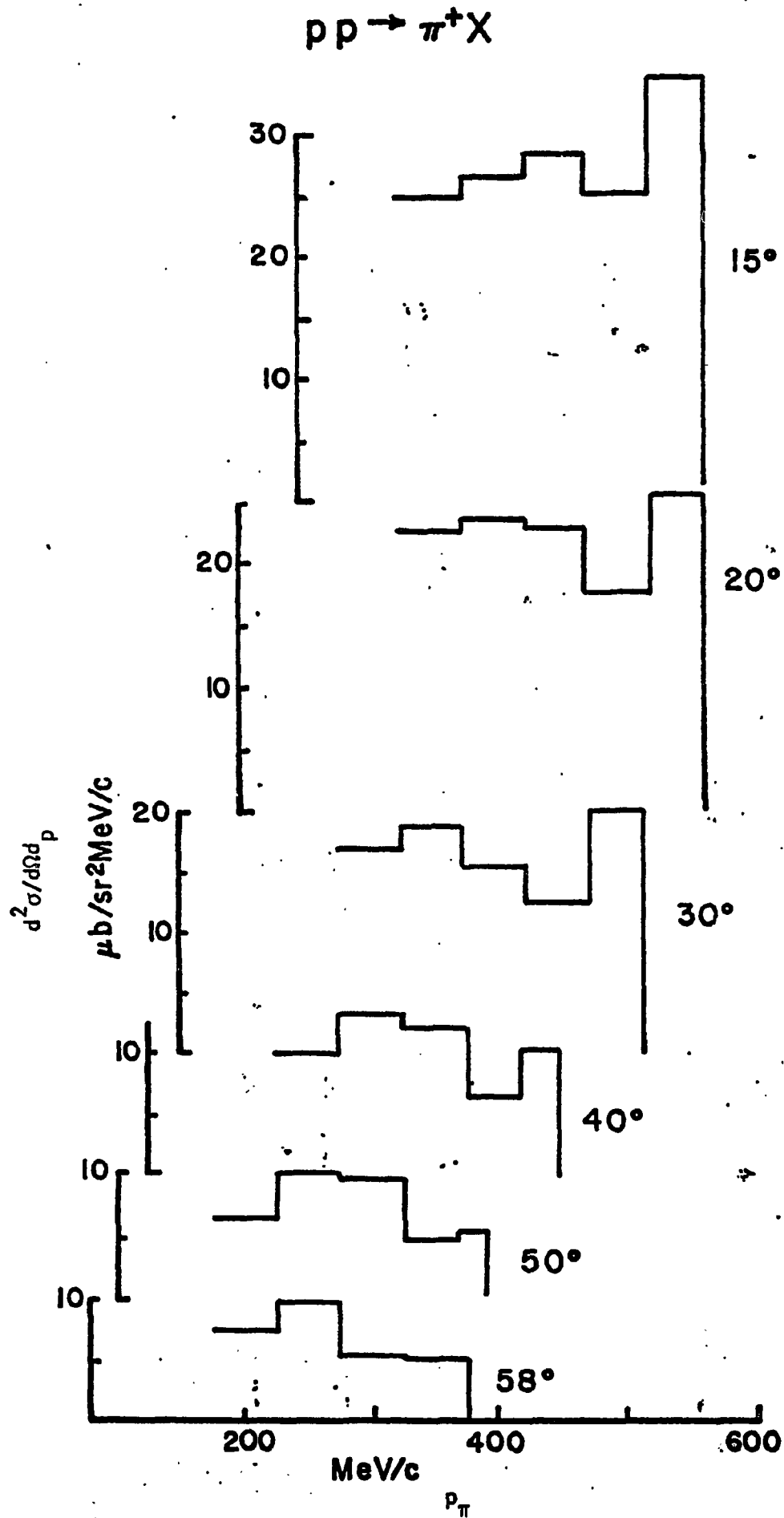
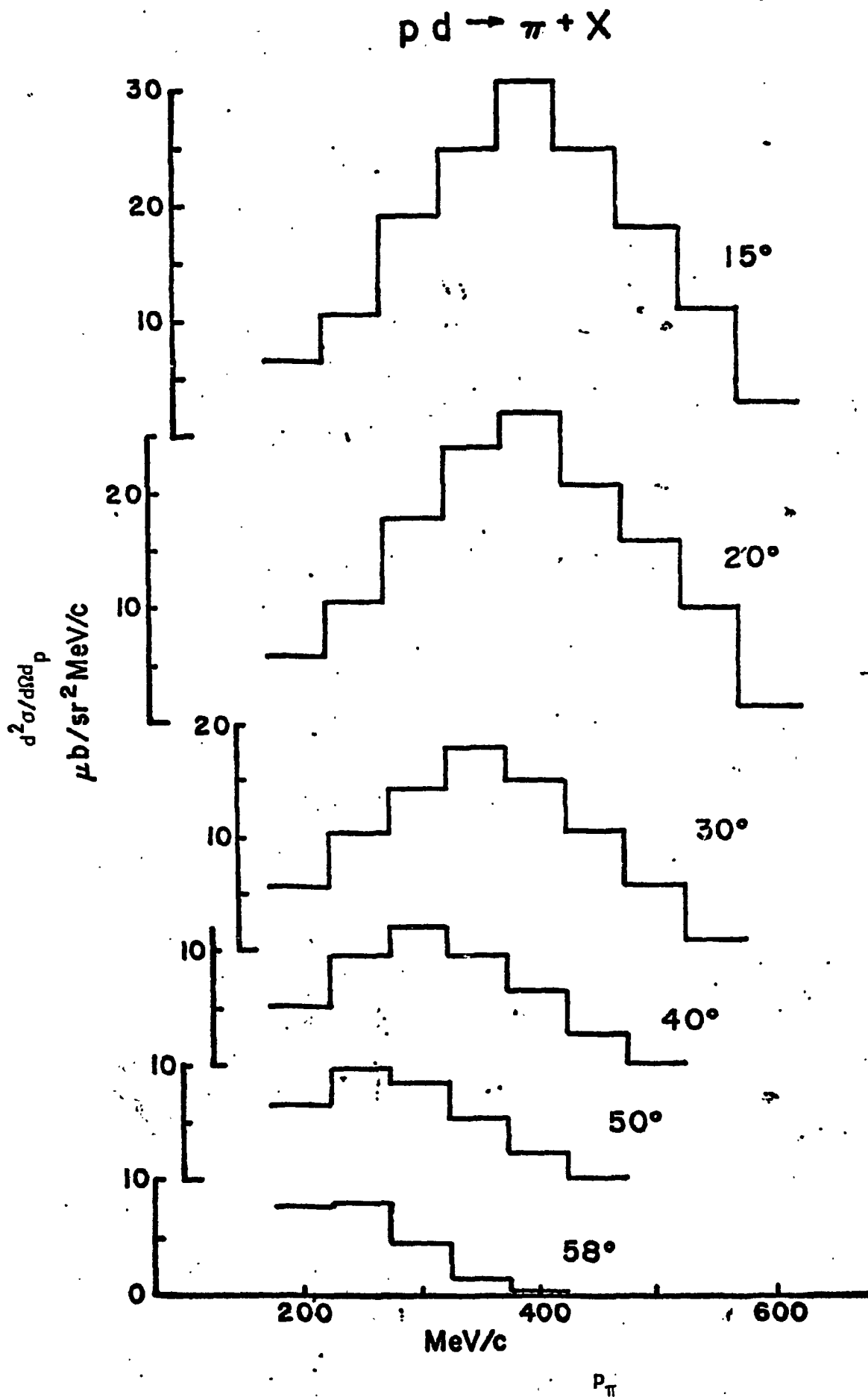
Fig.1: Cross section vs.  
pion momentum

Fig.2: Cross section vs.  
pion momentum

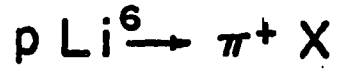


Fig.3: Cross section vs. pion momentum

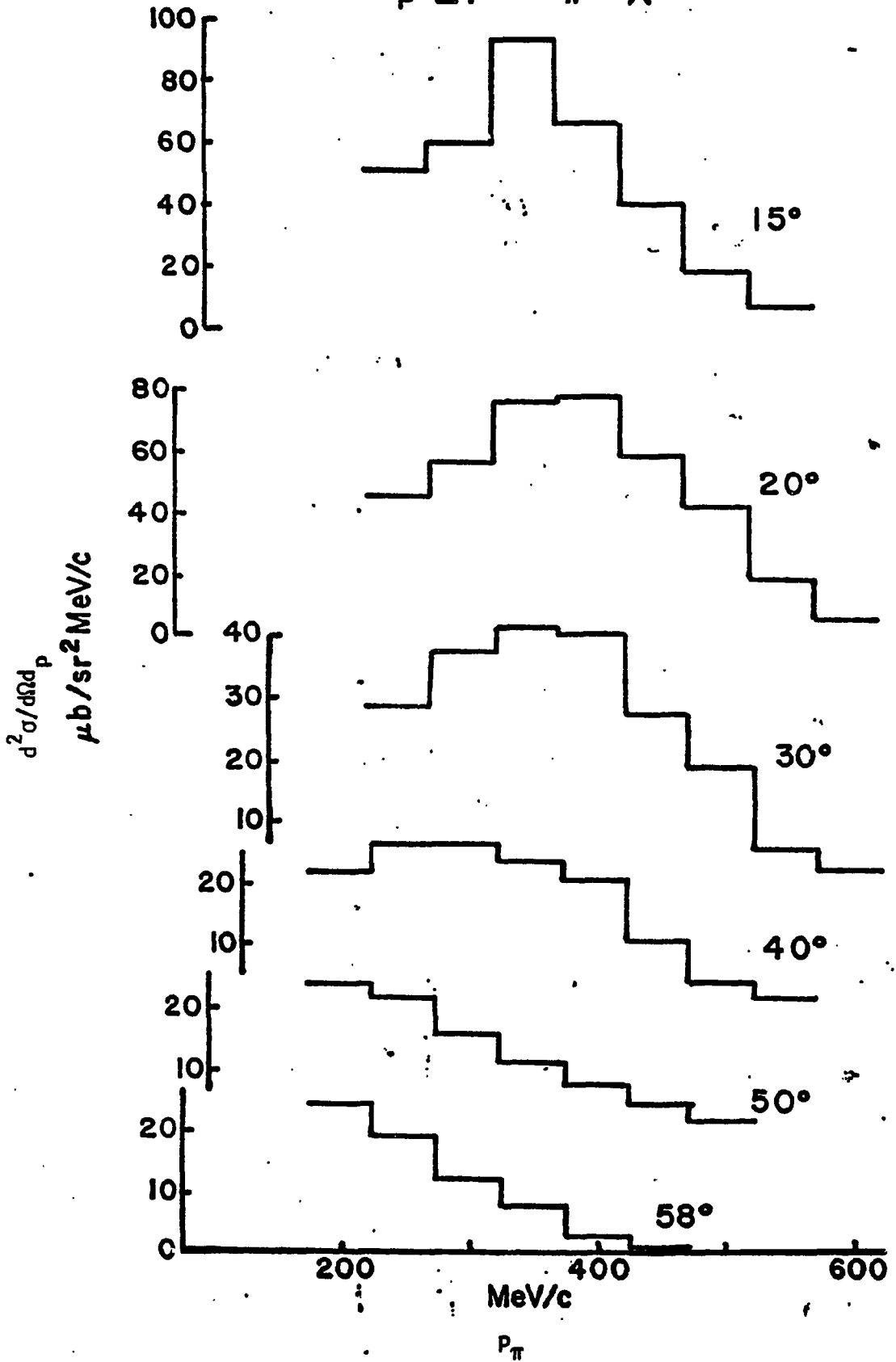


Fig.4: Cross section vs. pion momentum

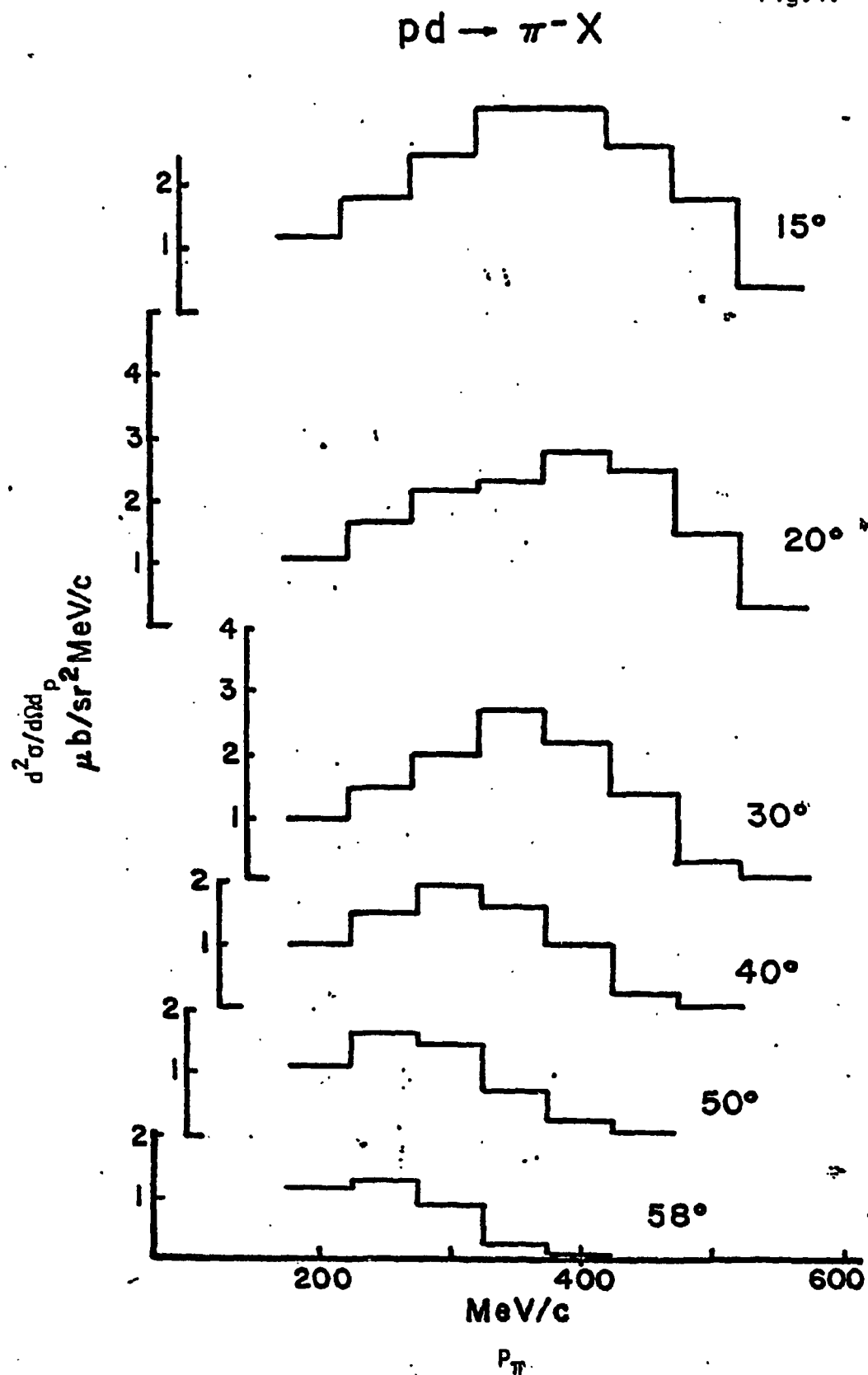
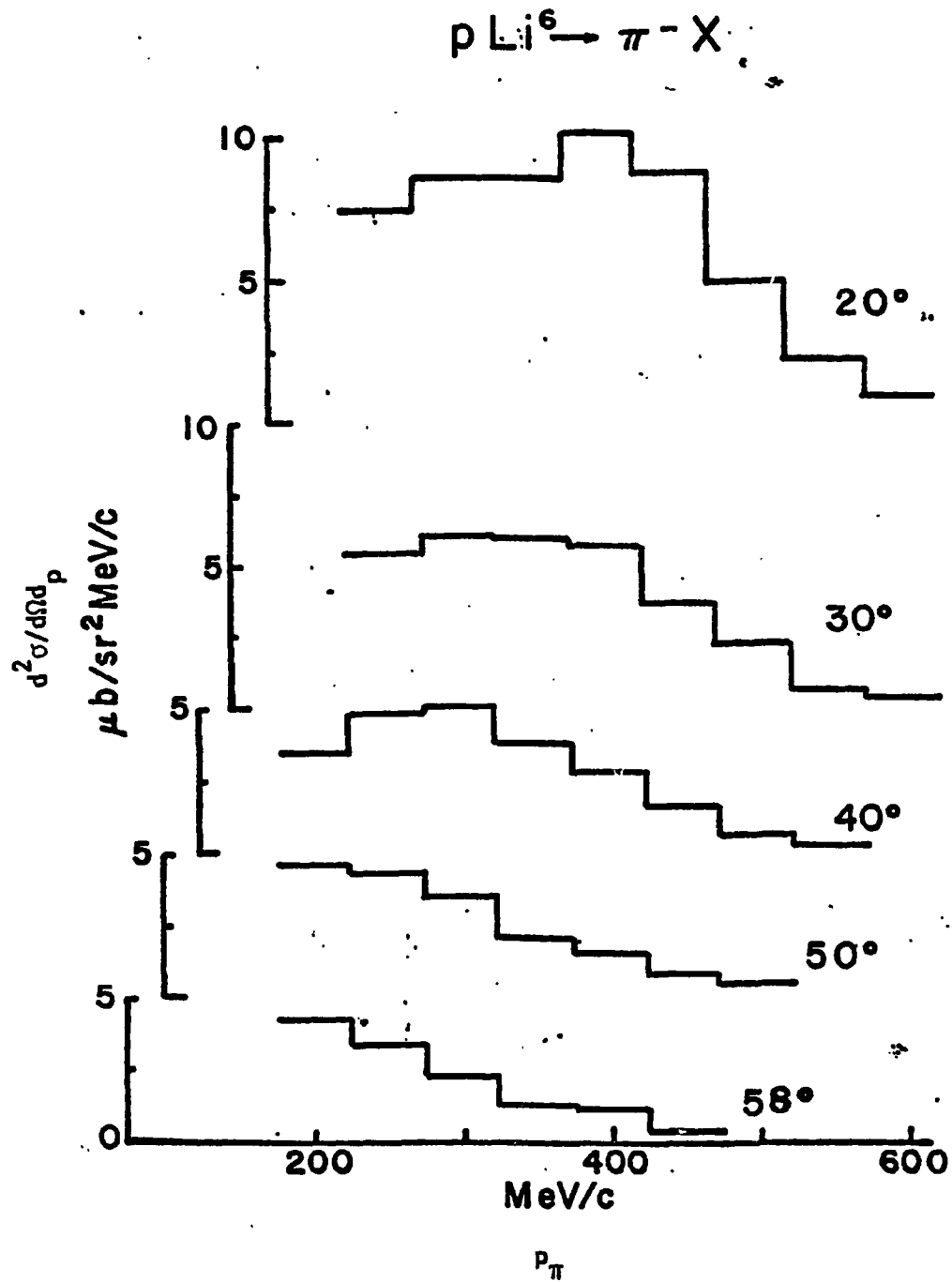


Fig.5: Cross section vs. pion momentum



agreement with the isobar model prediction of a factor of 11.

Reference: (1) D. Cochran *et al.*, Phys.Rev. D6(1972) 3085.

### C. Nuclei

#### 1. "Pion-Nucleus Forward Scattering Amplitudes at $\Delta(1236)$ Energies"

LAMPF E-80, W. H. Dragoset

Using the LAMPF  $P^3$  channel, small angle elastic cross sections in the nuclear-Coulomb interference region,  $\sigma_{EL}(\theta)$ , and total cross sections,  $\sigma_T$ , were measured for  $\pi^\pm$ - $^{12}\text{C}$ ,  $^{40}\text{Ca}$ , and  $^{48}\text{Ca}$ . The incident pion kinetic energies, 120-220 MeV in 20 MeV increments, were chosen to span the energy region where the  $\pi N$  reaction is dominated by the  $\Delta(1236)$  resonance. The analysis of this data has been completed and some of the results were described in previous progress reports. Additional results are discussed below.

The elastic data were fit by a modified version of the West-Yennie theory; for example, Fig.1 shows fits to the  $\pi^+$ ,  $\pi^-$  difference for  $^{40}\text{Ca}$  at two energies. From the fits the real part of the forward nuclear scattering amplitudes were extracted. Fig.2 displays  $\text{Re } f_N(0^\circ)$  for  $^{40}\text{Ca}$  and  $^{48}\text{Ca}$ . The  $^{40}\text{Ca}$  results agree favorably with some theoretical calculations as well as with forward amplitudes of lighter nuclei. The  $^{48}\text{Ca}$  results are not yet completely understood; however, recent developments in the theoretical description may, when applied to  $^{48}\text{Ca}$ , significantly alter the results.

The total cross section results are given in Table I. In Fig.3. the  $^{48}\text{Ca}$ ,  $^{40}\text{Ca}$  difference for  $\sigma_T(\pi^-)$  is plotted versus kinetic energy. Comparison to a Kisslinger Optical Model calculation shows that the RMS radius of the neutron distribution in  $^{48}\text{Ca}$  exceeds the proton radius by about 0.1 fermi. This is not

a definitive result because small changes in the mathematical form of the densities entered into the calculation may yield significantly different answers. Nevertheless, the  $\sigma_T$  data, when combined with elastic data over the full angular range, should yield a much clearer picture of the neutron-proton distributions in calcium.

Theoretical progress in the application of the West-Yennie theory to non-isoscalar nuclei was described at the Fall Meeting of the Division of Nuclear, Asilomar (November 1978), paper FE-11 APS Bull 23(September 1978), p. 964. A paper describing these results is nearing completion.

## 2. "The $\sigma_{\text{total inelastic}}$ for $^{12}\text{C}$ "

SREL IC-540, E. V. Hungerford

The analysis of this data continues. A report on the total absorption pion range telescope was presented at the Asilomar APS-DNP Meeting, APS Bull. 23(September 1978), p. 937. A totally absorbing range telescope was used to observe 120 MeV negative pions scattered from  $^{12}\text{C}$ . This detector has an energy resolution of about 20 MeV and is useful for pion energies less than 100 MeV where other methods for detecting negative pions are difficult. It consists of fourteen plastic scintillators varying in size from .32cm at the front to 6.35cm at the back. The scintillator thickness corresponds to the range straggling at that scintillator position. Calibration was done by placing varying amounts of polyethylene absorber in front of the detector with the apparatus placed in a beam of known energy. The end of range for each event is determined by energy enhancement due to pion absorption at the end of range. The properties of this detector including efficiency and resolution were discussed at the APS meeting.

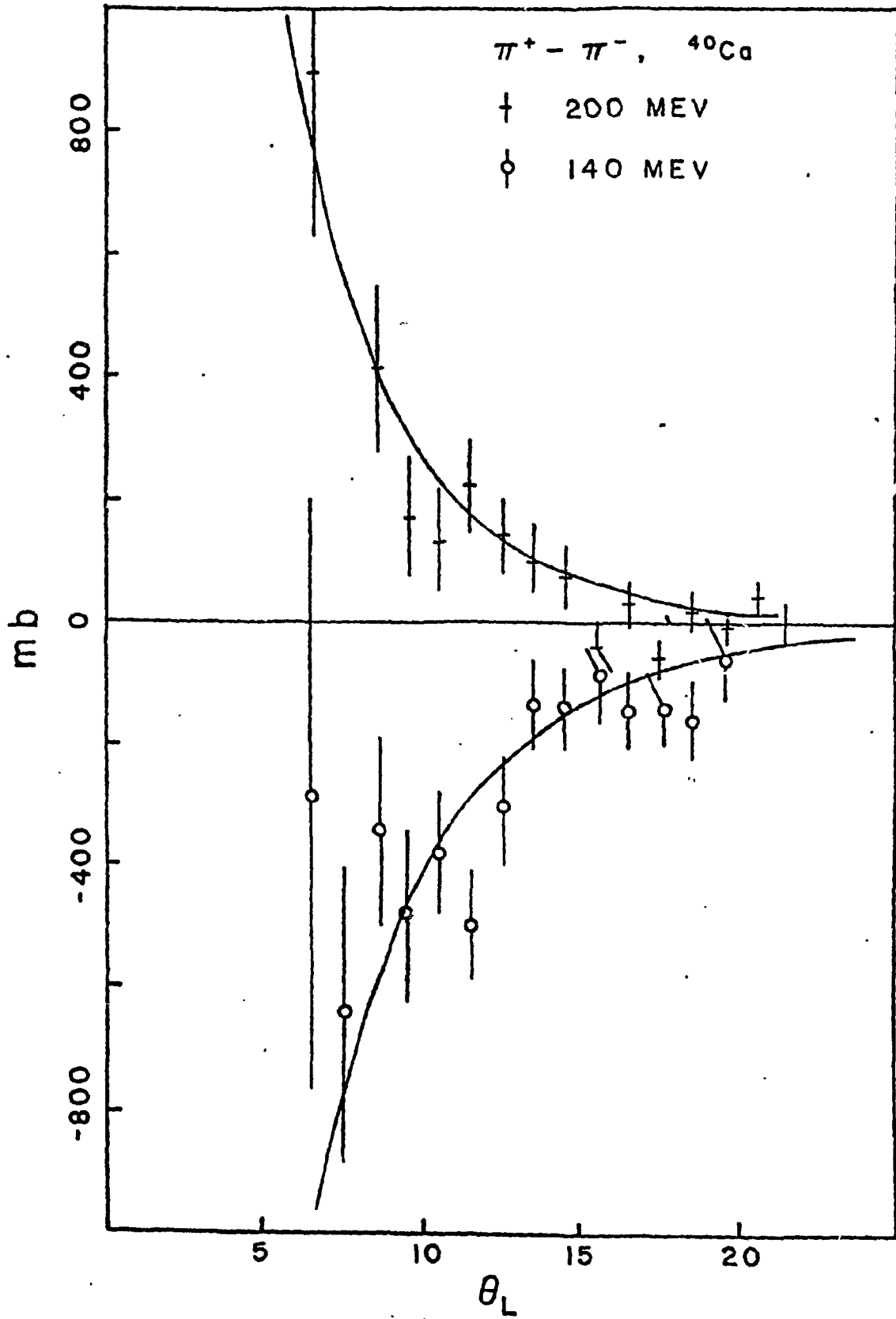


Figure 1:  $^{40}\text{Ca}$  Difference Fits

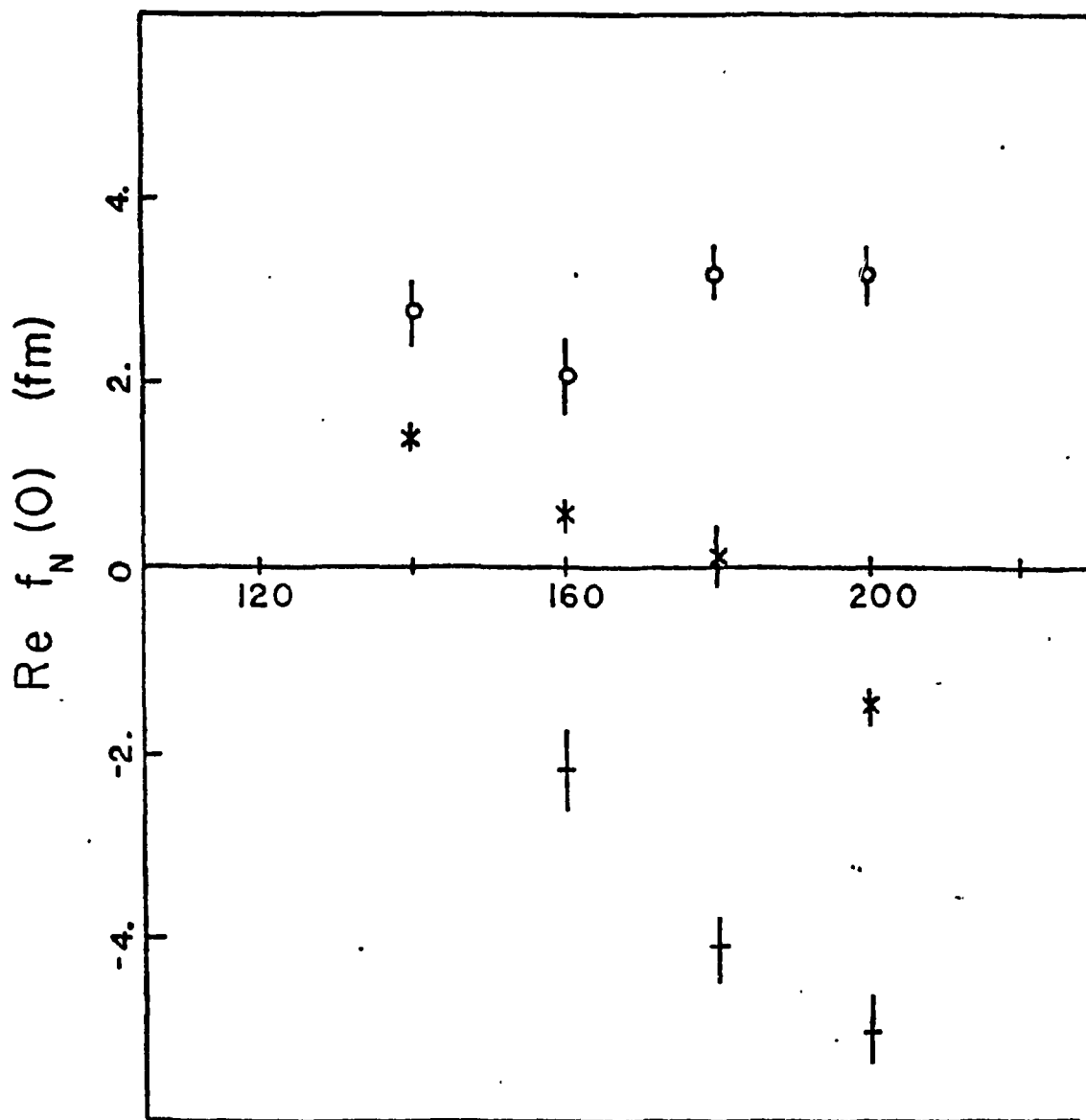


Figure 2:  $\text{Re } f_N(0)$  for  $^{40,48}\text{Ca}$

The open circles are from positive pions on  $^{48}\text{Ca}$ .

The plus signs are from negative pions on  $^{48}\text{Ca}$ .

The crosses are from the combined  $^{40}\text{Ca}$  data.

TABLE I

Total Cross Section Results (mb)

Energy (MeV)	$^{12}\text{C}$		$^{40}\text{Ca}$		$^{48}\text{Ca}$	
	$\pi^+$	$\pi^-$	$\pi^+$	$\pi^-$	$\pi^+$	$\pi^-$
224	584.±11.	598.±13.	1479.±28.	1495.±32.	1481.±28.	1525.±31.
204	590.±9.	624.±14.	1506.±23.	-	1589.±24.	-
184	631.±10.	-	1498.±24.	1560.±35.	1590.±26.	1735.±36.
164	692.±12.	705.±15.	1544.±27.	1565.±33.	1652.±29.	1756.±35.
144	686.±12.	704.±15.	1552.±27.	1572.±33.	1606.±28.	1683.±34.
124	648.±10.	678.±18.	1538.±24.	1550.±41.	1534.±24.	1703.±45.

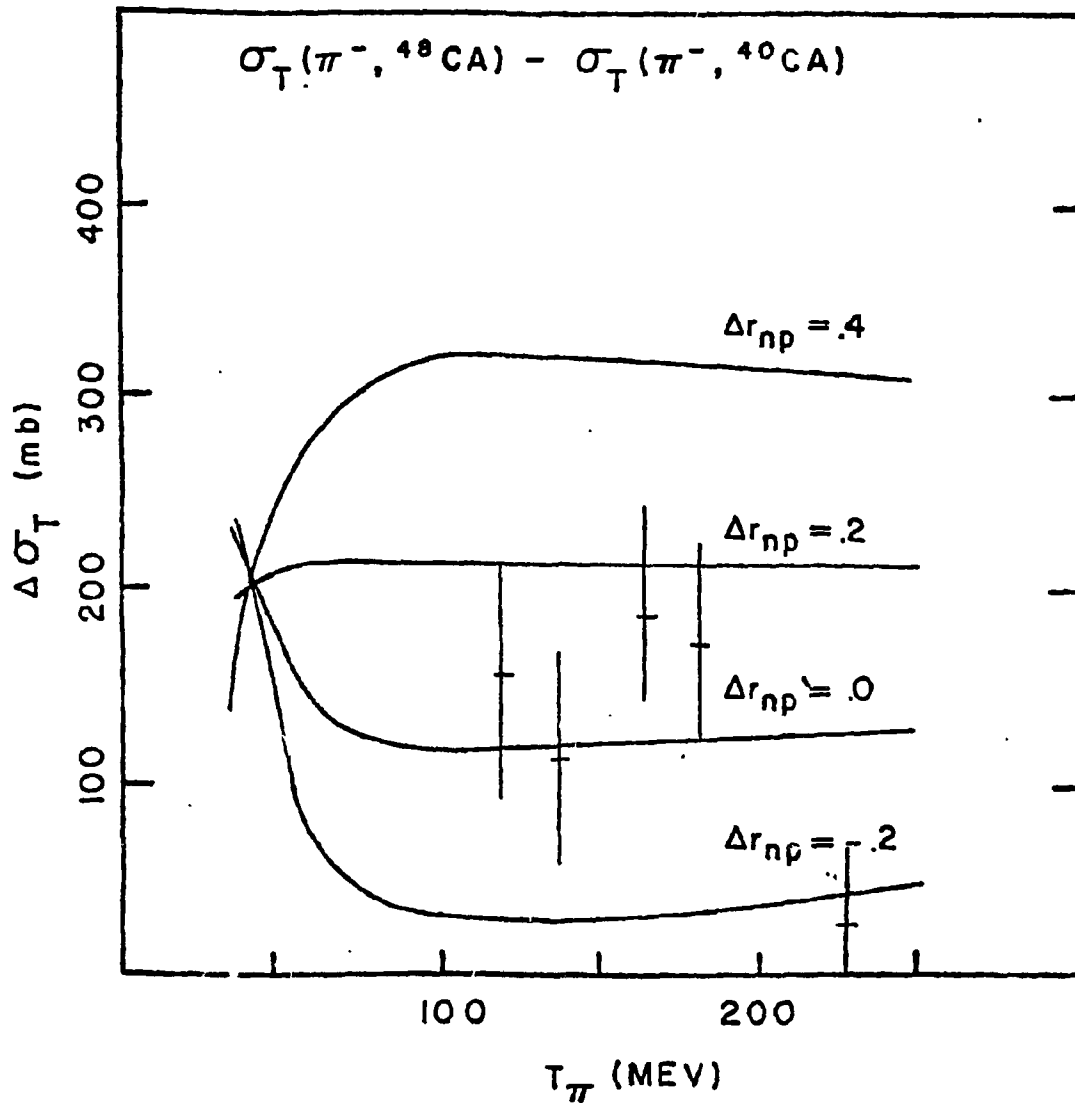


Figure 3: Kisslinger Optical Model Calculation for  ${}^{40,48}\text{Ca} (\pi^-)$  Cross Section Difference

See reference (Co2).

3. "The  ${}^6\text{Li}(p,2p){}^5\text{He}$  and  ${}^6\text{Li}(p,\pi^+d){}^5\text{He}$  Reactions  
LAMPF E-81, J. Hudomalj-Gabitzsch

A paper is being prepared; the data analysis is complete.

D. Theory

1. " $pd \rightarrow nd\pi^+$  Reaction Mechanisms"

I. M. Duck, K. R. Hogstrom, and G. S. Mutchler

Reaction mechanisms for  $pd \rightarrow nd\pi^+$  were examined at energies in the  $\Delta$  resonance region. A model based on single and double scattering amplitudes with  $\pi$  production at any one of the vertices provides a reasonable fit to the data. This work is published (see Publication No. 2).

2. "Analysis of Dominant Features of  $pp \rightarrow p\pi N$  at 800 MeV"

Miroslav Furić *et al.*

A model including  $\pi$  and  $\rho$  exchanges with various baryonic intermediate states is in agreement with the properties of kinematically-complete  $pp \rightarrow p\pi N$  data. Simultaneous fits to the spectra accumulated in different geometries determine the value for the  $\pi$  and  $\rho$  form factor range parameters. The absolute normalization depends mainly on the  $t_{\Delta}$  variable while the shapes of individual spectra are determined by the parameters of the intermediate states. The relative importance of various contributions ( $\Delta$ ,  $N^*$ , etc.) to the total amplitude is illustrated with  $pp \rightarrow N\Delta$  being dominant. Additional tests of the model's adequacy are proposed. This work was presented as a paper at the APS-DNP Asilomar Meeting and appears in the APS Bull. 23 (September 1978), p. 963.

3. "Asymptotic Spin Dependence in N-N Scattering"

Ian Duck

Spin dependent NN total cross sections have been evaluated in a hard gluon/quark constituent exchange model. Glauber theory,

asymptotic freedom for the massless quarks, confinement for the gluons and a closure approximation are used to sum over virtual six quark states. The optical theorem provides NN total cross sections for longitudinally and transversely polarized nucleons. The model does not yet contain the intermediate structure observed by Yokosawa<sup>(1)</sup>. The spin dependence of large angle NN scattering is also calculated in a hard gluon/quark constituent exchange and is sensitive to the spin flip structure of the qq amplitude.

This work was presented as a paper at the Asilomar APS Meeting and appears in the APS Bull. 23(September 1978), p.963.

Reference: (1) I. P. Auer *et al.*, Phys.Rev.Lett.41 (1978) 354.

4. "Quarks, Gluons, and the  $\pi$ -Nucleus Coupling Constant"  
Ian Duck.

A variant of the MIT bag model of confined quarks is used to express the pion-nucleon coupling constant  $f_\pi$  in terms of the  $\Delta(1232)$ - $N(938)$  mass difference  $\Delta M$ . Both  $\Delta M$  and  $f_\pi$  are supposed to occur via the exchange of a single magnetic gluon. The result, which scales with the 5/2 power of the proton charge radius  $R_p$ , produces about one half the experimental value for quark wave functions fitted to nucleon parameters.

This work is published (see Publication No. 1).

5. " $pp \rightarrow p\pi^+n$ "

LAMPF E-81, Miroslav Furić and Ian Duck

A theoretical model and the corresponding computer program were constructed<sup>(1)</sup> for the process  $pp \rightarrow p\pi^+n$  with the inclusion of several perturbation theory graphs (see Fig.1). The contributions of  $\pi$  and  $\rho$  exchanges to the formation of  $\Delta^{++}$  and  $\Delta^+$  intermediate states were calculated. The non-resonant parts coming from  $\pi$  exchanges with  $N$  and  $N^*$  (Roper resonance) intermediate states were also included. Neutron-proton Final State

Interaction modification of the above production amplitude was made in the part of the phase space exhibiting this effect experimentally. Despite the large number of graphs, the dynamics turned out to be dominated by  $\Delta^{++}$  production. The angular dependence of the kinematically-complete spectra is mainly determined by the  $\pi$ -N off-shell form-factor behavior. Good agreement with the data was obtained in the resonant part with the range parameters values:  $\Lambda_{\pi}=780$  MeV/c and  $\Lambda_{\rho}=1800$  MeV/c (see Fig.2). The requirement of a simultaneous fit to four experimental spectra proved to be a rather stringent constraint which determined the values of the range parameters that are needed for calculations on more complex nuclei. In the future we intend to study a modification of  $\pi$ -N- $\Delta$  form factors that was recently suggested.<sup>(2)</sup> The non-resonant part also deserves further study. We intend to add a few more meson exchanges in the calculation. Additional data is needed, especially at lower incident energies where resonant dynamics are less important, so that the non-resonant parts can be investigated in more detail.

#### References:

- (1) J. Hudomalj-Gabitzsch *et al.*, to be published in Phys.Rev.C.
- (2) L. S. Kisslinger, Carnegie-Mellon University; private communication.

#### 6. "Calculation of Various Spin Observables in Proton-Proton Collisions from Phase Shifts"

Miroslav Furić and S. E. Turpin

A program to calculate variables such as  $P$ ,  $C_{nn}$ ,  $C_{ll}$ ,  $C_{ss}$ ,  $\Delta\sigma_L$ ,  $\Delta\sigma_T$  etc. in proton-proton collisions from a complete set of phase shifts has been written. Recent findings of energy dependent structures in  $\Delta\sigma_L^{(1)}$  and  $\Delta\sigma_T^{(2)}$  for proton-proton collisions have generated a lot of interest in these quantities. The existence of resonances has been suggested as an explanation. As the group should have a significant body of  $C_{nn}(\theta, P_{inc})$  data<sup>(3)</sup> analyzed soon (ZGS E-434), it is natural to see what behavior

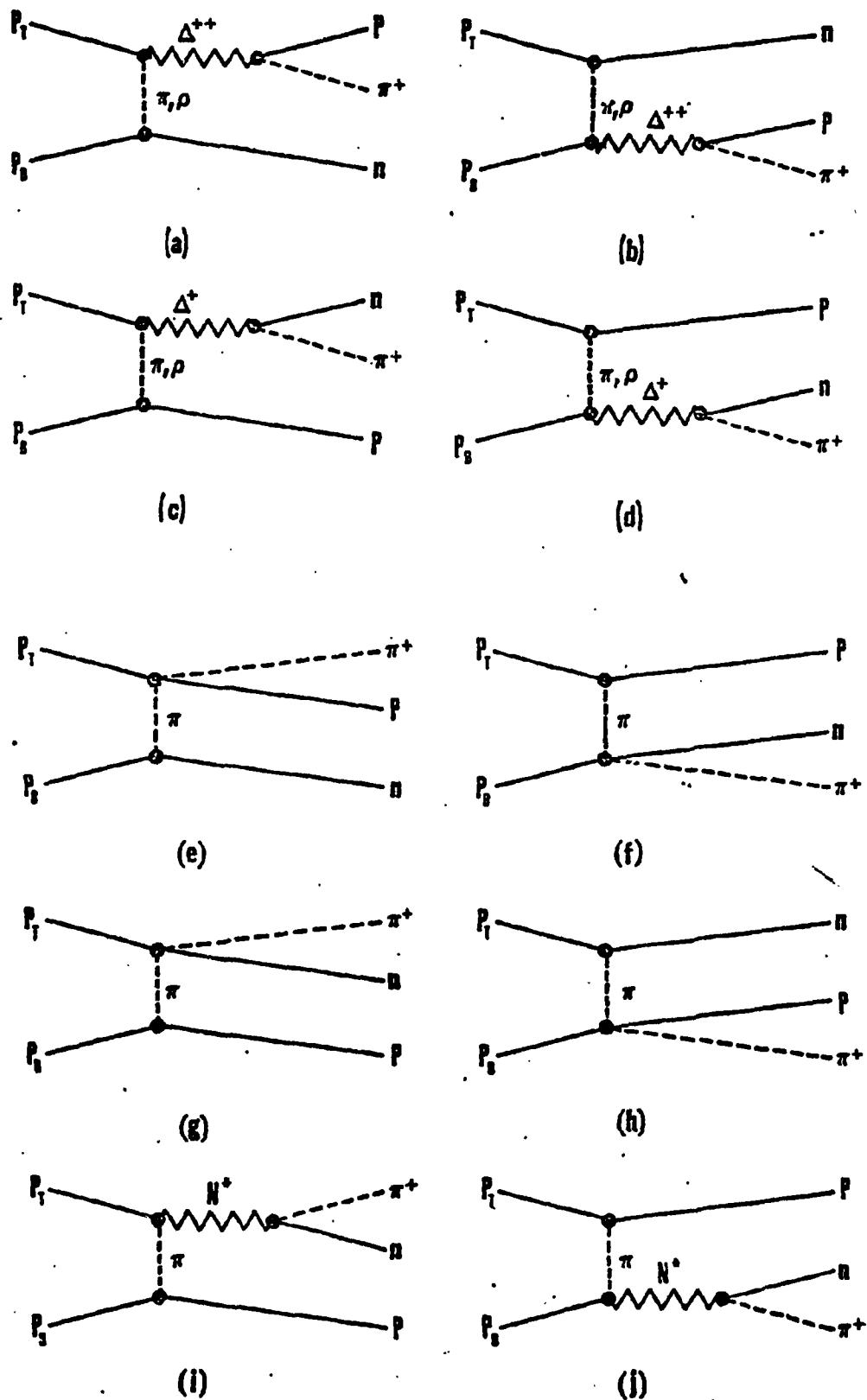


Figure 1: Feynman Diagrams for OPE and VME Model (see p. 42)

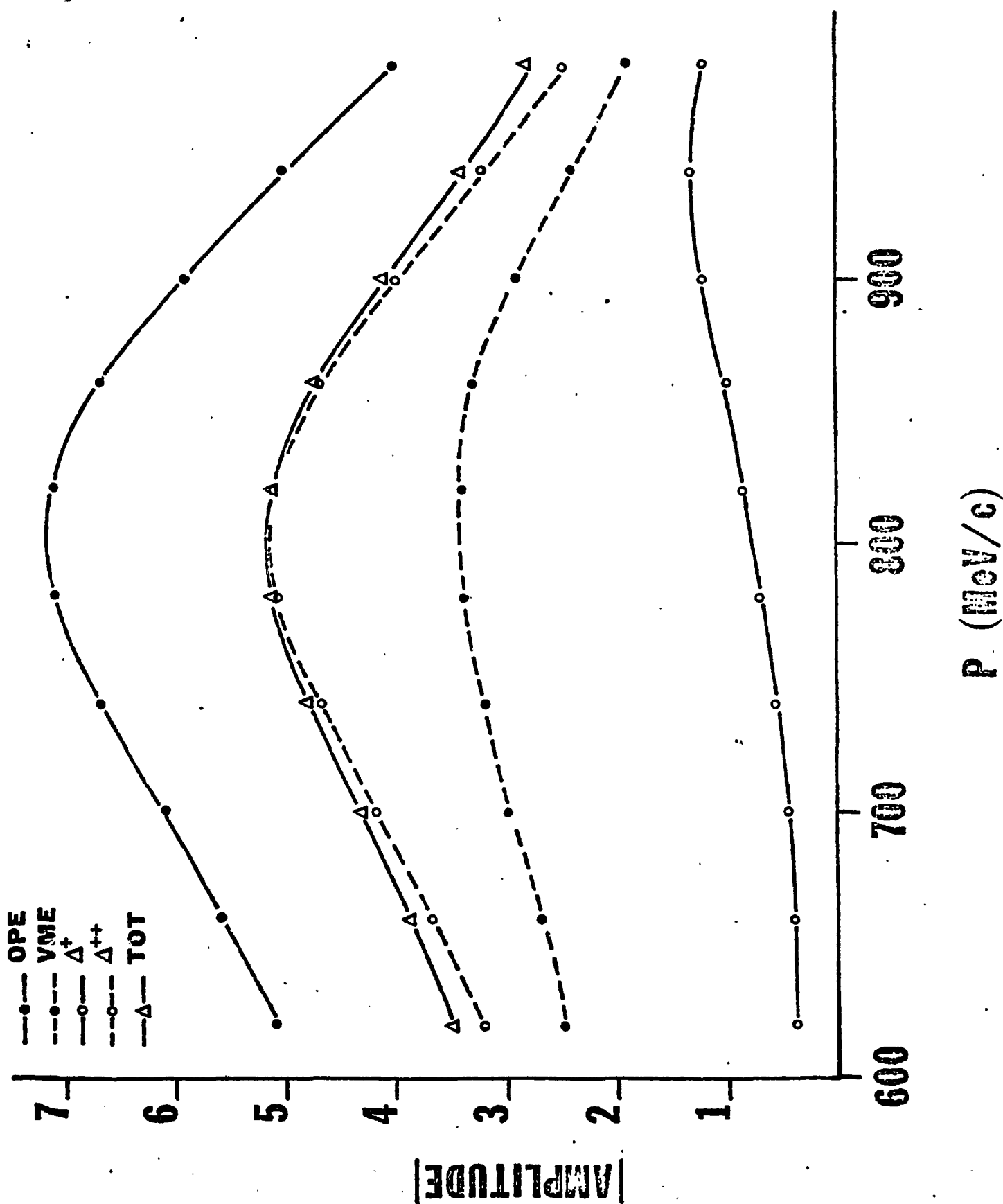


Figure 2 : Relative Amplitudes for  $pp \rightarrow p\pi^+n$  at  $\theta_p=15^\circ$  and  $\theta_\pi=20.8^\circ$  (see p. 42)

Figure 1: Feymann Diagrams for OPE and VME model.

- (a) - (d): OPE and VME leading to the  $\Delta^{++}$  and  $\Delta^+$  resonance
- (e) - (h): non-resonant S and P wave OPE
- (i) and (j): OPE leading to the  $N^*(1470)$  resonance.

Figure 2: Relative amplitudes for  $pp \rightarrow p\pi^+n$  at  $\theta_p = 15^\circ$  and  $\theta_\pi = 20.8^\circ$ .

- (a) OPE, contribution from diagrams (a)-(d) in Fig.1. for pion exchange
- (b) VME, contribution from diagrams (a)-(d) in Fig.1, for rho exchange
- (c)  $\Delta^{++}$  contribution from diagrams (a) and (b) in Fig.1, for pion and rho exchange combined
- (d)  $\Delta^+$  contribution of diagrams (c) and (d) in Fig.1. for OPE and VME
- (e) TOT, total amplitude (coherent sum of all diagrams shown in Fig.1).

is expected for that variable. Values of  $C_{nn}(\theta, P_{inc})$  were generated for incident momenta between 1.2 and 1.7 GeV/c through the interpolation of the modified Livermore and Kyoto phase shifts.<sup>(4)</sup> Main features of the angular distribution are a strong increase of  $C_{nn}$  between  $10^\circ$  and  $40^\circ$  reaching a level of 0.50 to 0.60. Very little variation follows at higher energies. Even with the resonant parameterization suggested,<sup>(5)</sup> no bumps are expected either in the  $C_{nn}$  angular distribution or in the  $C_{nn}$  excitation curves arising from these resonances.  $C_{nn}(\theta, P_{inc})$  data provide, however, stringent constraints on the phase shifts. Therefore, significant body of  $C_{nn}(\theta, P_{inc})$  points should be helpful in determining a reliable set of phase shifts.

#### References:

- (1) I. P. Auer *et al.*, Phys.Rev.Lett.41 (1978) 354.
- (2) E. K. Biegert *et al.*, Phys.Lett. 73B(1978) 235.
- (3) T. A. Mulera, contribution to the III Symposium on High Energy Physics with Polarized Beams and Targets, Argonne 1978.
- (4) M. Arik and P. G. Williams, Nucl.Phys.B376 (1978) 425.
- (5) N. Moshizaki, Kyoto University Preprint NEAP-18 and 19, 1978.

#### 7. "pd $\rightarrow$ d $\pi^+$ n at 800 MeV"

LAMPF E-341, Miroslav Furić, Ian Duck, and S. E. Turpin

A comprehensive computer program is being built to calculate systematically a number of Glauber type single scattering and double scattering graphs.<sup>(1)</sup> The One Nucleon Exchange Mechanism will also be included. As the neutron ("spectator") momenta span a wide range (0-600 MeV/c), simultaneous insight is expected into both quasifree processes and double scattering amplitudes which are important at low and high spectator momenta respectively.

Reference: (1) Ian Duck, K.R. Hogstrom, and G. S. Mutchler  
Phys.Rev. C18(1978) 887.

8.  $pp \rightarrow pp\pi^0$ 

Miroslav Furić and Ian Duck

The pion production channels  $pp \rightarrow p\pi^+n$  and  $pp \rightarrow pp\pi^0$  differ in our measurements (see Section A.2) not only in isospins of the final particles, but also in the regions of phase space covered. Regardless of dynamical symmetries, our experimental, kinematically-complete spectra in the  $pp\pi^0$  channel do not correspond directly to any configuration reached in our  $p\pi^+n$  data. Thus, the  $pp\pi^0$  data provide additional tests of the pion production model (see Sections D.1, D.2, and D.5).

The theoretical model and the corresponding program for the  $p\pi^+n$  channel have been modified to take into account both of these differences. Our predications are in reasonable agreement with some preliminary data (see Section A.2).

E. Instrumentation

## 1. Fast MWPC Electronics

James Buchanan

An additional 50 amplifier cards and six driver modules were constructed. This allows use of as many as six X-Y planes with 1200 total wires instrumented in fast electronics.

## 2. Bonner Lab Computer System

James Buchanan

Configuration and installation of a DEC 11/34 data analysis computer system in Bonner Labs was accomplished. This improved facility was jointly funded in 1978, and is jointly used by Rice's Intermediate and High Energy contracts. Most of the computer system was delivered in June, with the last components arriving in August. The system became operational under RSX 11-M in September, and has been used continuously since in analysis of E-81, E-82 and E-341 data.

### 3. NMR System

James Buchanan

An NMR system was developed to measure polarization of a polarized proton target. Initial use has been at the Argonne ZGS, but it is expected that it will be used later at LAMPF.

A DEC LSI-11 microcomputer, with analog-to-digital and digital-to-analog sub-systems (see Fig.1), steps a Rockland 5600 frequency synthesizer through the proton nuclear magnetic resonance. The change in impedance of a coil surrounding the target volume is measured and averaged over a large number of sweeps, has a background level subtracted, and is then displayed on a CRT as the change in RF level versus frequency plot (see Fig.2.). Polarization is calculated from the area under this curve and the Thermal Equilibrium value.

The NMR system operates autonomously, but presents data to the main computer system, through a CAMAC interface, on demand.

### 4. High-rate Phototube Bases

James Buchanan

A photomultiplier tube base was designed to minimize voltage changes at the phototube dynodes under high rate conditions. Stiff voltage sources for the dynodes are provided by using high beta, high voltage, video transistors as emitter followers. Eight of these bases were built.

### 5. High Speed Data Bus

James Buchanan

Design has been started on a high speed (10 megawords per second) data bus with microprocessor controlled pre-processing and interfacing systems for future high data rate experiments.

### 6. Gas Recovery System

W. P. Madigan and J. Windish

A device for recovering neopentane from the argon/neopentane gas

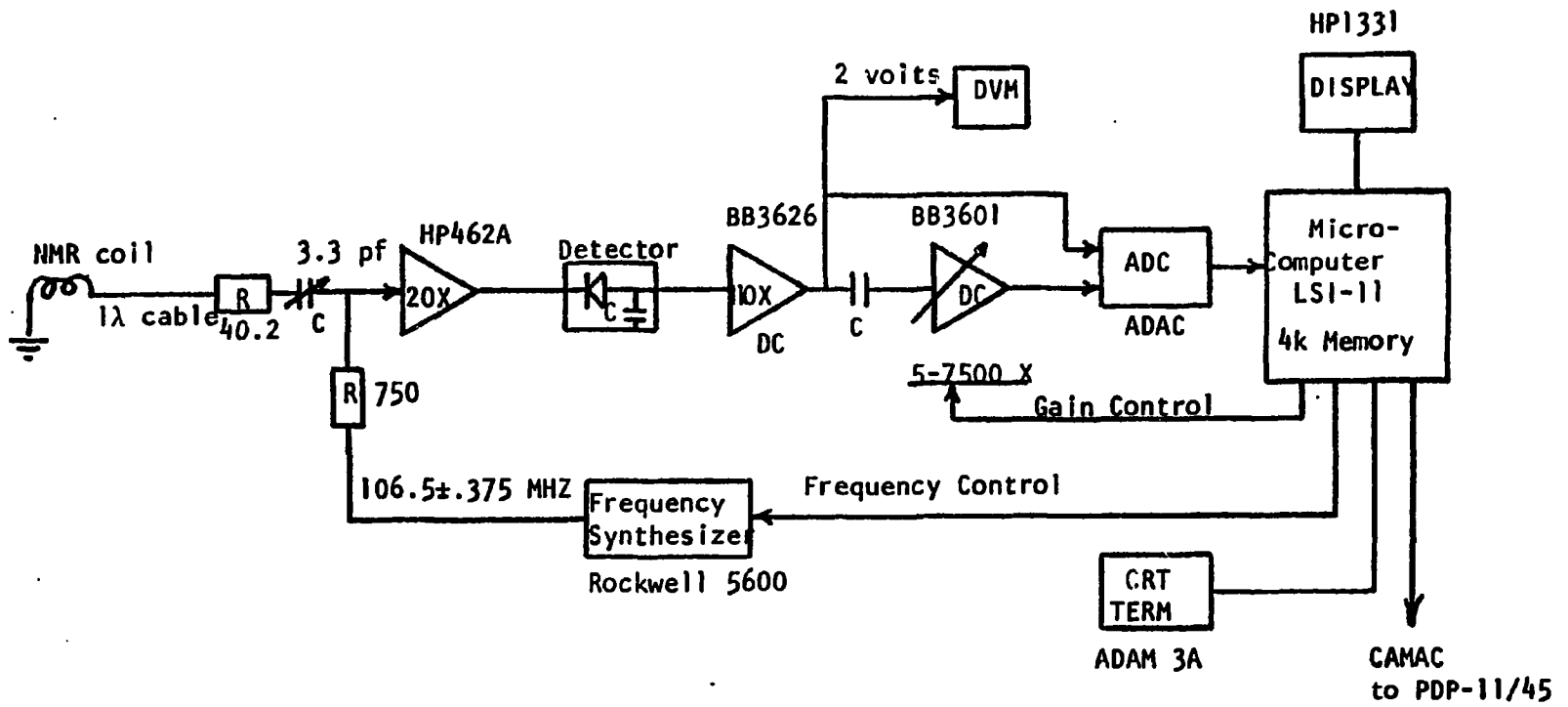


Fig.1: NMR Circuit

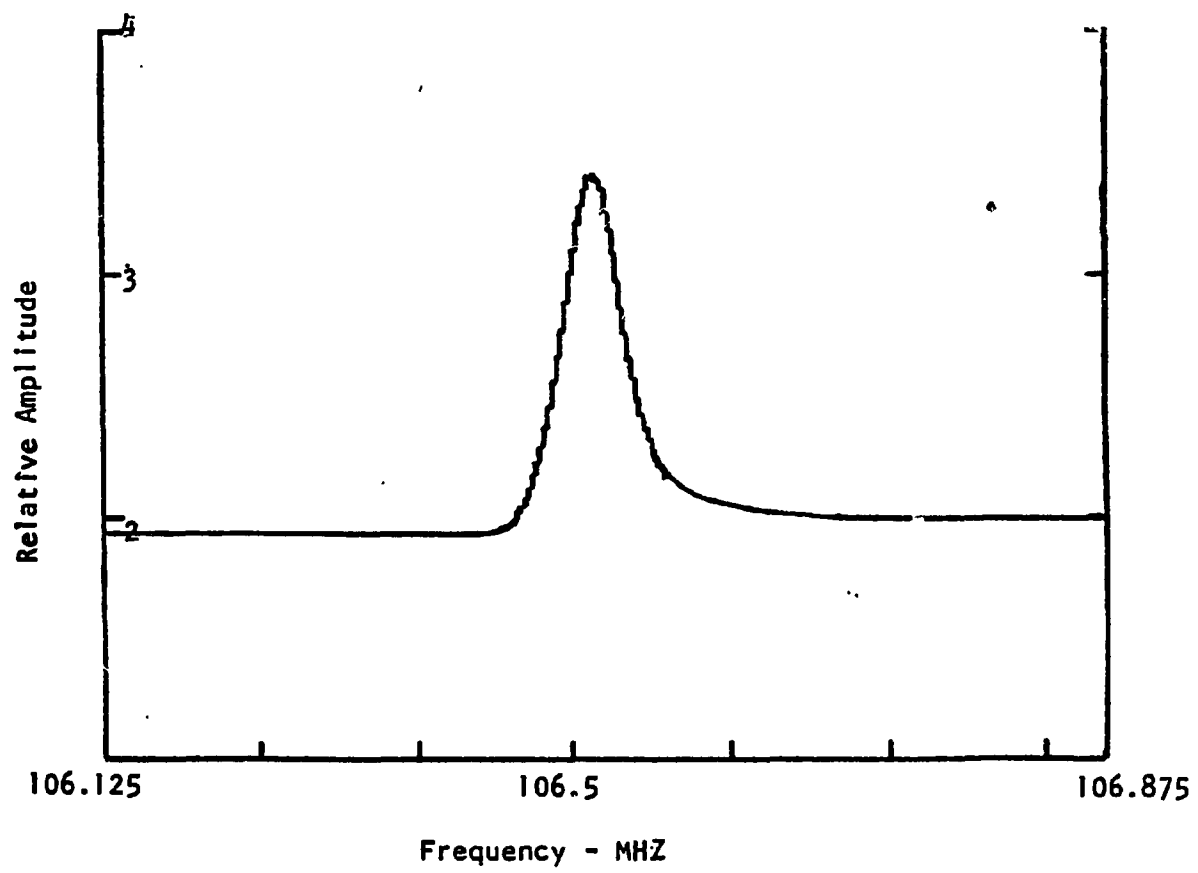


Fig.2: NMR Signal

mixture used in the multiwire proportional chambers was perfected and is now in use. The device recovers more than 85% of the neopentane present in the argon/neopentane mixture.

7. 12"x18" Multiwire Proportional Chambers

W. P. Madigan and J. Windish

Two new 12"x18" multiwire proportional chambers were designed and built. They are now being used in Experiment E-434 at the Argonne ZGS.

8. Cryogenic Target Chamber

W. P. Madigan

A target chamber was designed to accommodate a 5" diameter x 12" long liquid hydrogen target. The chamber allows an unobstructed view of the entire target through an angular range of  $210^\circ$ . The fabrication was done at the University of Texas-Austin. The chamber is now being used in a collaboration with Peter Riley (UT-Austin). The Rice Group will join the collaboration in 1979 for Experiment E-366 at LAMPF.

9. C-Frame MWPC

W. P. Madigan and J. Windish

A multiwire proportional chamber with an active area of 1.5"x5" was designed and built. The unique feature of this chamber is that one end is practically free of mass, allowing the active area of the chamber to be placed close to the primary beam without the beam striking the framework of the chamber.

10. Scintillator Polarimeter

W. P. Madigan and J. Windish

A beam polarization monitor was designed and built. The polarimeter consists of a fixture with two 24" arms which can be rotated about a common axis. Each arm accommodates three phototubes and can be positioned anywhere between  $10^\circ$  and  $90^\circ$  with respect to the beam direction. The polarimeter is now used in Experiment 434 at the Argonne ZGS.

### 11. Central Cooling Fans for MWPC Electronics

W. P. Madigan and J. Windish

Two fan units with flexible ducts connecting to the shielding boxes containing the electronics on the multiwire proportional chambers were designed and built. Each fan unit provides forced-air cooling for two chambers.

### 12. Power Supply Carts

W. P. Madigan and J. Windish

Three mobile carts were designed, built to locate the multi-wire proportional chamber low-voltage power supplies near the chambers. The system load is now carried by the three strategically-located racks of power supplies, rather than by one central rack of high-current power supplies.

### 13. Computer Development: Hardware

John M. Clement

This year our data analysis ability has been doubled by the addition of an PDP 11/34 processor with dual tape drives, card reader, and two terminals. Now data analysis can proceed independently from data acquisition by the portable PDP 11/45 on-line system. The new system duplicates nearly all of the features of the 11/45 system, with the exception of fast printed output, and general graphics capabilities. In particular, considerable effort has been made to ensure compatibility at the level of the Fortran programmer.

### 14. Computer Development: Software

John M. Clement

Considerable effort has been expended in converting from the old DOS operating system to the RSX-11M system. The 11/34 analysis system was completely under RSX, but the 11/45 acquisition system still mainly uses DOS. The conversion for the 11/45, which should probably be completed six months from now, will increase the speed of analysis fourfold.

The Monte Carlo programs can now write their results event by event to tape. This allows replay of simulated data to assess the contributions of various geometrics, reactions, and so on to the accuracy of final results. This facility can be used before an experiment is set up to test the actual experimental geometry and optimize it.

#### F. Applied Physics

##### 1. "Linear Energy Transfer Spectra of 100 Mev Pions in a Tissue-Equivalent Phantom"

SREL IC-533, Roger C. Newman

A 1.27cm spherical, tissue-equivalent, proportional counter was used to accumulate the energy loss spectra of pions at depths of 12.5cm, 25cm, and 27.5cm in a tissue-equivalent phantom. The experiment was performed at SREL using the 100 Mev pion beam, which had a range of 25cm in the phantom. This beam was approximately 48% pions, 21.2% muons, and 30.8% electrons. Particles were identified using their time-of-flight in a three meter flight path. Energy losses above the maximum for muons were assumed to be due to pions. The distributions of track length versus LET[T(L)] and of dose versus LET[D(L)] were derived from the smoothed energy loss spectra obtained. These spectra were compared to existing LET calculations

This data comprised the M.A. thesis of Roger C. Newman, and was reported in APS Bull. 22(1977), p. 625; a paper based on the work has been submitted to Radiation Research.

##### 2. "Pion Radiotherapy: Studies with Nuclear Emulsions"

John C. Allred

Nuclear emulsions were used to provide information on the pion star distribution for a therapy beam, star production as a function of pion energy, and residual range in nuclear emulsion, the distribution of nuclear fragment ranges in emulsion, and the neutron energy spectrum and fluence produced by negative

pion capture in tissue, during treatment of a patient. This last item is important for determining the whole-body dose delivered to a patient undergoing pion radiotherapy.

This work was published in *Physics for Medicine and Biology* (see Publication No. 3).

#### Changes in Personnel

One student received his Ph.D. degree from Rice University in May 1978, W. H. Dragoset, who also received the H. A. Wilson Prize for the best Ph.D. Thesis of the year in the School of Natural Sciences. Dr. Dragoset had joined the group as a post-doctoral Research Associate after completing his thesis work in 1977.

S. E. Turpin joined the group as a graduate student. Malcolm Day joined the group as an undergraduate student assistant.

W. P. Madigan completed his B. S. degree program in Physics at the University of Houston in December 1978.

#### Other Financial Assistance

No external funds to Rice University and D.O.E. were received for the work reported here.

#### PUBLICATIONS:

1. Ian Duck, "Quarks, Gluons, and the Pion-Nucleon Coupling Constant," *Physics Letters* 77B (July 1978), 223-226.
2. Ian Duck, K. R. Hogstrom, G. S. Mutchler, " $pd+nd\pi^+$  Reaction Mechanisms," *Physical Review* C18 (August 1978), 887-897.
3. John C. Allred, J. N. Bradbury, Louis Rosen, E. V. Hungerford, H. R. Kidder, W. Z. Osborne, and G. C. Phillips, "Pion Radiotherapy: Studies with Nuclear Emulsions," *Phys.Med.Biol.* 23(1978), 603-609.

4. J. Hudomalj-Gabitzsch, I. M. Duck, M. Furić, G. S. Mutchler, J. M. Clement, R. D. Felder, W. H. Dragoset, G. C. Phillips, J. C. Allred, E. V. Hungerford, B. W. Mayes, L. S. Pinsky, and T. M. Williams, "Production of the  $\Delta^{++}$  in the Reaction  $pp \rightarrow p\pi^+n$  at 800 MeV," accepted for publication, Physical Review C.

INCIDENT REPORT:

No incidents such as those outlined in attachment "A" have occurred during the contract year.

*G. C. Phillips*

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G. C. Phillips  
Principal Investigator

December 20, 1978

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