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The objectives, basic research programs, recent results, and continuing activities of the UCLA Particle Physics Research Group are presented herein. The objectives of the research are to discover, to formulate, and to elucidate the physics laws that govern the elementary constituents of matter and to determine basic properties of particles. The research carried out by the Group last year may be divided into three separate programs. A synopsis of each is given below. The main body of this report is the account of the techniques used in our investigations, the results obtained, and the plans for continuing and new research. An update of the group bibliography is given at the end.

INTRODUCTION

The least understood and most challenging section of particle and nuclear physics is the field of strong interactions. There exists a generally accepted theory of electromagnetic interactions, QED, and of weak interactions, the V-A current-current theory. There is even a unified model, the Weinberg-Salam electroweak model. Until recently there was no general theoretical framework for the strong interactions and the theory consisted of many phenomenological models. The quark hypothesis may be changing this.

The basic tenet of the quark model is that all hadronic matter is made up of elementary constituents, the quarks that interact via gluon exchange. Quarks have spin $1/2$, a non-integral electric charge and obey parastatistics. No free quarks have been observed which suggests a permanent confinement condition. The multitude of different hadrons require the "existence" of at least six different types of quarks: up, down, strange etc., called the quark flavors. Parastatistics imply that quarks have a new quantum number, color, which has three values.

The quark hypothesis lacks a spectacular Ω^- - type prediction that propelled SU(3) to prominence. Though several properties of the quarks may be bordering on preposterous, the quark model has been immensely successful in providing a qualitative account of a very large variety of hadron properties and interactions. The ultimate test of the quark model is to come up with a quantitative account of the complete hadron spectroscopy.

For the above reasons, the UCLA Particle Physics Research Group has chosen to direct a substantial part of its effort towards improved baryon spectroscopy in the energy region accessible at LAMPF.

Program I of our group is entitled "Baryon Spectroscopy". Its objectives are to determine the properties of the πN resonances, their mass, width, decay

modes and quantum numbers, and furthermore to measure the radiative decay amplitudes. As it turns out these amplitudes provide one of the most important and sensitive tests of the quark model. Finally, at some time in the future, we plan to make an improved measurement of the magnetic dipole moment of the Δ -resonance which gives a very basic test of the quark model, QCD and lattice techniques.

Program II is "Investigations of Charge Symmetry and Isospin Invariance". Both features appear in the quark model as accidental properties that do not apply at the level of the basic Lagrangian. Detailed experimental tests that involve large momentum transfer processes are almost non existent and need to be made.

Program III is "Tests of Time Reversal Invariance". The V-A current-current theory of the weak interactions has one major flaw, namely that CP violation is not accounted for. There is an ad hoc theory, the superweak model, designed to patch up this flaw, but it lacks universality. As CP violation implies T violation, which has major consequences in other areas of physics, we are engaged in testing T-invariance in selected reactions.

Each of the above three programs has several parts involving different experiments, they are listed below. The major part of this report consists of detailed accounts of each experiment, many preliminary and some final results obtained, and plans for new research.

Program I: Baryon Spectroscopy

I-a: "Measurement of Spin Rotation Parameters A and R in $\pi^+p \rightarrow \pi^+p$ and $\pi^-p \rightarrow \pi^-p$ ". LAMPF proposal #806. Approved. Preparations are under way.

I-b: "Measurement of Asymmetry Parameter in $\pi^-p \rightarrow \gamma n$ Using a Transverse Polarized Target". This is our ongoing, large experiment. LAMPF proposal #804.

I-c: "Measurement of the Analyzing Power, A_N , for $\pi^\pm p$ Elastic Scattering from 471-687 MeV/c". The data analysis is progressing well. LAMPF Exp. #120*.

I-d: "Measurement of the Analyzing Power, A_N , $\pi^-p \rightarrow \pi^0 n$ between 471-687 MeV/c". The data analysis is in progress. LAMPF Exp. #120**.

I-e: "Measurement of $\pi^-p \rightarrow \pi^0 n$ Differential Cross Section from 247 MeV/c to 687 MeV/c". The data taking was done the previous year. Preliminary results have been obtained. LAMPF Exp. #120.

I-f: "Elastic $\pi^\pm p$ Scattering from 378 to 687 MeV/c". The main part of the data is published and final results are being evaluated. LAMPF Exp. #363.

I-g: "Neutron Counter Calibration Using Tagged Neutrons from the Reaction $\pi^-d \rightarrow nn$. LAMPF Exp. #689. This work provides the input needed for new research, see II-a.

I-h: "Measurement of Analyzing Power, A_N , and Spin Correlation Parameter, A_{NN} , for $pp \rightarrow d\pi^+$ and $pp \rightarrow pp$ from 500 to 800 MeV". Research performed in collaboration with LANL and TAM. Preliminary results have been published. LAMPF Exp. #517.

I-i: "Phenomenology of πN Interactions. Theoretical analysis in support of the above program.

I-j: "Absolute Calibration of Proton Polarimeter". LAMPF proposal #807, Approved. New research in support of program I-a.

Program II: Investigations of Charge Symmetry and Isospin Invariance

II-a: "Test of Charge Symmetry by a Comparison of $\pi^-d \rightarrow nn$ with $\pi^+d \rightarrow pp$.
New proposal submitted to TRIUMF.

II-b: "Measurement of $d\sigma(\pi^{\pm}{}^3\text{H} \rightarrow \pi^{\pm}{}^3\text{H})$ and $d\sigma(\pi^{\mp}{}^3\text{He} \rightarrow \pi^{\mp}{}^3\text{He})$ to Test Charge Symmetry". The experiment has been performed using a 30,000 Curie gaseous tritium target at the EPICS facility. The results show a substantial violation of nuclear charge symmetry. The results have been presented at meetings and seminars, and a paper has just been finished. LAMPF Exp. #546.

II-c: " $\pi^{\pm}$ Elastic Scattering on ${}^3\text{He}/{}^3\text{H}$ at Large Angles". Experiment was performed in previous years. Preliminary results have been published. Final analysis is in progress. LAMPF Exp. #90.

II-d: "Comparison of $p+d \rightarrow {}^3\text{He}+\pi^0$ and $p+d \rightarrow t+\pi^+$ ". A spin off of Program
III-b. Saturne Exps. #37 and 68. Analysis is completed, the paper is in progress.

II-e: " $\pi^{\pm}$ Elastic Scattering on Isotopes and Isobars of the Light Nuclei".
This is theoretical analysis in support of Program II.

Program III: Investigation of Time Reversal Invariance

III-a: "Two Body Photodisintegration of ${}^3\text{He}$ between 150 and 350 MeV".
Experiment has been performed at Bates by UCLA-CU-MIT-WPI collaboration, Bates Exp. #8013. The final results are to appear in press soon. This part of the program is complete.

III-b: "Measurements of $p+d \rightarrow {}^3\text{He}+\gamma$ Differential Cross Section to Test Detailed Balance". Research performed at Saturne II in collaboration with the Saclay Medium Energy Nuclear Physics Group. Two separate experiments have been performed. The analysis is nearly complete. Saturne Exps. #37 and 68, part I.

III-c: "Measurement of $d+d \rightarrow {}^4\text{He}+\gamma$ To Test Detailed Balance". Research

performed at Saturne II by the same collaboration as Program III-b. The final data will appear in press shortly. Program is completed. Saturne Exp. #66.

III-d: "Comparison of (p,π) and (p,γ) Reactions". Theoretical work in support of Programs II and III.

PROGRAM I-a

Measurement of Spin Rotation Parameters A and R in $\pi^+p \rightarrow \pi^+p$ and $\pi^-p \rightarrow \pi^-p$

The π^+p elastic scattering matrix, M, may be decomposed into a simple sum of two independent amplitudes, the spin-nonflip, f, and the spin-flip amplitude, g,

$$M = f + i g \hat{n} \cdot \vec{\sigma} \quad (I-1)$$

The general proof that this simple expression is sufficient to provide a complete description of $\pi p \rightarrow \pi p$ is given by Csonka and Moravcsik¹ and others. The proof depends only on rotational and reflection (= parity) symmetry. It does not depend on time reversal invariance. To determine the two amplitudes there are three independent experiments required measuring $d\sigma/d\Omega$, A_N and β , where:

$d\sigma/d\Omega$ is the pion elastic scattering differential cross section for an unpolarized target.

A_N is the left-right asymmetry measured using a transverse polarized target. Note that $A_N = P$ where P is the transverse polarization of the recoil proton in π scattering from an unpolarized target.²

β is the Wolfenstein spin rotation angle measured using a longitudinal polarized target. β may be expanded in terms of the two traditional spin rotation parameters A (named D_{LS} in Ann Arbor convention) and R (or D_{SS}), also introduced by Wolfenstein.³

The measureable quantities can be expressed as follows:

$$d\sigma/d\Omega \sim |f|^2 + |g|^2 \quad I-2$$

$$P = A_N = \frac{2 \operatorname{Im}(fg^*)}{|f|^2 + |g|^2} \quad I-3$$

$$\beta = \arg \frac{f - ig \sin \theta}{f + ig \sin \theta} \quad I-4$$

$$A = D_{LS} = \frac{(|f|^2 - |g|^2) \sin \theta + 2 \operatorname{Re}(fg^*) \cos \theta}{|f|^2 + |g|^2} \quad I-5$$

$$R = D_{ss} = \frac{(|f|^2 - |g|^2)\cos\theta - 2 \operatorname{Re}(fg^*) \sin\theta}{|f|^2 + |g|^2} ,$$

There is a little redundancy in the above spin-equations which can be expressed as follows

$$P^2 + A^2 + R^2 = 1 \quad \text{I-7}$$

The validity of this equation depends only on rotation and reflection invariance as it follows directly from Eqs. 3, 5, and 6.

It has been pointed out by Keaton et al.⁴ that the quadratic relation of Eq. 7 provides a unique case for accurately calibrating polarization values. Even a crude measurement of A and R will strongly constrain the possible value for P. For example, if R and A each are ≤ 0.05 then it follows from Eq. 7 that $P \geq 0.997$. Table 1 gives a further illustration of the powerful restrictions placed upon A, R, and P by the quadratic relation of Eq. 7.

Another case of the special polarization calibration opportunities is provided at 0° and 180° . Since $P = A = 0$ we have that $R = +1$ and -1 , at 0° and 180° respectively. Shown in Figs. 1 and 2 are examples of the angular variation of P, A, and R for $\pi^\pm p + \pi^\pm p$ at 547 MeV/c based on the Karlsruhe-Helsinki partial wave analyses predictions.⁵ The experimental points are our preliminary results of A_N obtained recently in Exp. 120*. It is interesting that large values for the spin parameters P, A, and R in the energy region of the proposed experiment are the rule and not the exception for both π^+ and π^- scattering. We have no intuitive explanation for this as it does not seem to be connected directly to the established πN resonances.

Table 1:	A = R	P
	$5 \pm 5\%$	$99.7 \pm 0.4\%$
	$10 \pm 5\%$	$99.0 \pm 0.7\%$
	$30 \pm 5\%$	$90.6 \pm 2.3\%$
	$50 \pm 5\%$	$70.7 \pm 5.0\%$
	$60 \pm 5\%$	$52.9 \pm 8.0\%$

I-2 Partial Wave Analyses

A partial wave analyses, PWA, is a (unique) fit of all available πN experimental data to a limited number of partial waves $A_{\ell\pm}$ or phase shifts δ_{ℓ} . The mass, width spin, parity and isospin of resonances comes from PWA, which continues being the indispensable tool of hadron spectroscopy. The PWA enterprise may lack flashiness and the possibility of a truly spectacular discovery is remote, but without a PWA there is no detailed input for testing the quark model or any other theory of strong interactions.

PWA fall into two categories:

- (a) Full scale, complete analysis. There are three ongoing such analyses by groups at 1) Carnegie-Mellon University, Lawrence Berkeley Laboratory, CMU-LBL;⁶ 2) Karlsruhe-Helsinki, K-H;⁵ and 3) Virginia Polytechnique Institute, VPI.⁷ There also was a group active at Saclay until recently, its current plans are not known. These analyses supersede the monumental effort by Lovelace at CERN some years ago.
- (b) Limited scope analyses. They consist of improvements of an older, complete analysis by incorporating more recent experimental results. A typical example is the SIN '82 work which is an update of Carter's results near $T_{\pi} = 300$ MeV. These analyses are not concerned with uniqueness and analytic constraints and shall not be further discussed here.

1. The CMU-LBL PWA covers the region p_{π} is 0.42 to 2.0 GeV/c. The distinct features of this analysis are:

- a The experimental data has been amalgamated⁸ by shifting the data in a given momentum-angle bin to a central point where they are statistically combined. "Inconsistent" data have their errors stretched and/or momenta adjusted.
- b Energy-independent PWA are made that incorporate iteratively constructed dispersion relation constraints. Use is made of analyticity at fixed s in the variable $\cos\theta$.

c The energy dependence of the partial wave amplitudes is fit using a multi-channel coupled-resonance schema. The general features of $d\sigma/d\Omega$ for $\pi^\pm p \rightarrow \pi^\pm p$ are confirmed by our Exp. 363 results but there are significant differences in the details.

2. The K-H PWA covers the range from threshold to 2 GeV. The basic idea of this program is to exploit as far as possible all general theoretical constraints: Lorentz invariance, unitarity, crossing symmetry, analyticity and isospin invariance, performing tests of the latter two properties where this is possible. Specifically, K-H rely heavily on fixed- t and fixed-angle analyticity. The K-H PWA provides the best available description of our Exp 363 data but it is far from perfect, see Fig. 3.

3 The original VPI analysis⁷ was limited to 350 MeV. It is now being extended to 2 GeV. The data base is currently scrutinized carefully and "cleansed" of bad data points.

The properties of the low mass πN resonances is given in Table II as determined by various PWA.

Particle	LJ	Rating	Mass MeV	Width MeV	Elast	PWA	Ref.
N(1440)	P ₁₁	****	1440±30	340±70	0.58±0.04	CMU-LBL	1
			1410±12	135±10	0.51±0.05	K-H	2
			1411	334		Glasg.	3
			1472	113		Baker	4
N(1520)	D ₁₃	****	1525±10	120±15	0.58±0.03	CMU-LBL	1
			1519± 4	114± 7	0.54±0.03	K-H	2
N(1535)	S ₁₁	****	1550±40	240± 80	0.50±0.10	CMU-LBL	1
			1526± 7	120±20	0.38±0.04	K-H	2
N(1540)	P ₁₃	*	1540	200		Long.	5
Δ(1232)	P ₃₃ ⁺⁺	****	1230.9±0.3	111.0±1.0	1.0	K-H	2
			1230.6±0.2	113.2±0.3	1.0	VPI	6
			1231.1±0.2	111.3±0.5	1.0	SIN	7
Δ(1550)	P ₃₁	**	1506	137		Glasg.	3
			1525	40		Bar.	8
			1550	110		Long.	5
Δ(1600)	P ₃₃	***	1600±50	300±100	0.18±0.04	CMU-LBL	1
			1520±13	220± 40	0.21± .06	K-H	2
			1690	250		Bar.	8
			1560	180		Long.	5

Table II Properties of low mass πN resonancesReferences

1. R. Cutkosky et al. Baryon Conf, Toronto 1980, page 19.
2. R. Koch et al., *ibid* v. 3.
3. R.L. Crawford, based on PWA of pion photoproduction, *ibid* p. 107.
4. Baker et al. Nucl. Phys. B156, 93 (1979).
5. Longacre et al. Nucl. Phys. B122, 493 (197).
6. V.S. Zideell et al. Phys. Rev. D21, 1255 (1980).
7. E. Pedroni et al. Nucl. Phys. A300, 321 (1978), based on total cross sections.
8. Barnham et al. Nucl. Phys. B168, 243 (1980), based on $\pi N + \pi\pi N$.

I-3 Ambiguities in πN Phase Shifts

In the absence of experimental information on spin rotation in the πN system, there is a continuous ambiguity in the phase of the two eigenstates of M_N as $d\sigma/d\Omega$ and A_N are invariant under the transformation

$$f \pm ig \rightarrow (f \pm ig) \exp. \left(\pm \frac{1}{2} i\phi \right).$$

The only non-trivial limitation on ϕ is that ϕ (at $\theta = 0$) = 0 in order to ensure that the spin-flip amplitude vanishes in the forward direction.

For the special case $\phi = -\theta$ we obtain, after some algebra,⁹ that

$$f_{\lambda\pm}^M = -f_{\lambda\pm 1, \mp}^*$$

which is the well known Minami transformation, implying a most unpleasant ambiguity that invalidates the unique spin-parity assignment of resonance, e.g.

$S_1 \rightarrow P_1$ and $P_3 \rightarrow D_3$ and $P_1 \rightarrow S_1$.

Below inelastic threshold, $T_\pi < 300$ MeV, the infinity of ambiguities can be restricted to the Minami one by the use of unitarity which implies that

$$\text{Im } f_{\lambda\pm} = |f_{\lambda\pm}|^2.$$

Further help may come from dispersion relations,

$$\text{Re } f(s) = \text{pole terms} + \frac{1}{\pi} \frac{\text{Im } f(s') ds'}{s' - s}.$$

The full use of this expression, which is by no means trivial, may yield a unique phase shift solution below 300 MeV. The resonances in the upper energy region of our experiment are all very inelastic, see Table II, and the phase shifts are not unique.

Thus far we have not worried about the fact that there is a π^+ as well as a π^- meson. Inclusion of isospin considerations in the πN formalism doubles the number of amplitudes to be determined, namely $f(I=1/2)$, $f(I=3/2)$, $g(I=1/2)$ and $g(I=3/2)$, all the while assuming that isospin is a good quantum number. Instead of 3 independent experiments for a complete description there are now seven, since 4 moduli need to be determined and 3 phases. We have already

measured $3 \times d\sigma/d\Omega$, namely for $\pi^+p \rightarrow \pi^+p$, $\pi^-p \rightarrow \pi^-p$, and $\pi^-p \rightarrow \pi^0n$, Exps. 363 and 120 respectively as well as $3xA_N$ for the same reactions, Exps. 120* and 120**. As a result of the similar structure of π^+ and π^- elastic scattering formalism one must measure the spin rotation parameters for $\pi^+p \rightarrow \pi^+p$ as well as $\pi^-p \rightarrow \pi^-p$ to solve all possible ambiguities in the PWA. Fortunately, it is not necessary to measure A/R for CEX.

I-4 Quark Model

The quark hypothesis of Gell Mann and Zweig is a major breakthrough in the study of the strong interactions. Quarks are considered to be the elementary constituents of all hadronic matter, interacting via gluon exchange. Quarks have spin 1/2, a non-integral electric charge and obey "parastatistics". The quark approach to strong interactions has mushroomed in the last decade. To account for the fact that free quarks have not been observed, the quark interactions are restricted by a confinement property. The problem of parastatistics is "solved" with the color assignment. The quark hypothesis lacks a spectacular Ω^- type prediction that propelled SU(3) to prominence. The remarkable properties of the quarks are accepted as they provide the basis for a quantitative account of experimental baryon spectroscopy.

One of the very successful specific quark models is that of Isgur and Karl.¹⁰ It is an improved version of the classical non relativistic quark model of Dalitz and others that incorporate the QCD improvements proposed by de Rujula, Georgi, and Glashow.¹¹ An important feature of this model is color magnetism, a spin-spin interaction which is the key to the good results¹² of the phenomenological spectroscopic calculations. The success of the I-K model has been detailed in the literature.¹³ An example of the hadronic spectroscopy results is shown in Fig. 2. The discovery of new low mass πN resonances or a splitting of the $P_{11}(1440)$ would have serious implications for the quark model.

Ref.

1. P.L. Csonka and M.J. Moravcsik, Phys. Rev. 152, 1310 (1966).
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3. L. Wolfenstein, Ann Rev. Nucl. Sci. 6, 43 (1956).
4. P.W. Keaton, et al., Phys. Rev. Lett. 29, 880 (1972) also C. Daum and P.W. Keaton, Nucl. Inst. Meth 129, 85 (1975).
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11. A de Rujula, H. Georgi and S.L. Glashow, Phys. Rev. D12, 147 (1975).
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Fig. 1. (a) Transverse polarization parameter P in π^-p elastic scattering at $p_\pi = 547$ MeV. The incident momentum corresponds to the total energy $\sqrt{s} = 1400$ MeV. The dashed line is the result obtained in the Karlsruhe-Helsinki partial wave analysis.¹ The data points are some very, very preliminary results for A_N obtained by UCLA in an experiment currently under way at LAMPF. (b) Spin rotation parameters A and R for the same reaction as (a).

Fig. 2. Same as Fig. 1 for $\pi^+p + \pi^+p$ at $p_\pi = 547$ MeV/c.

II-1 Experimental Set Up

The detection strategy and the experimental lay out of the proposed measurement of the spin rotation parameters follows closely the successful technique employed in Exp. #120* for measuring A_N in $\pi^\pm p \rightarrow \pi^\pm p$. At many angles in that experiment the background was less than 5%, this is substantially better than obtained in competing πN experiments. This feat is accomplished by the overdetermination of the measured quantities. We measure both pion and proton which allow a 3 C fit to be made to every event. A floor layout for the experiment is shown in Fig. II-1.

II-2 Longitudinal Polarized Target

We propose to use HERA, the French built, CERN operated, SERPUKOV used, LAMPF bargain-bought polarized target. It includes a superconducting air core magnet with a very high current density. The magnet is made of two Helmholtz coils to insure adequate magnetic field homogeneity. The superconducting material used is a niobium-zirconium alloy. The inner bore of the coils has a useful diameter of 40 cm and the unobstructed cones around the horizontal axis of the coils have opening angles of 90° . A cross section of the coils is shown in Fig. II-2. The current for the solenoids is 260A yielding 25 kG. The coils are maintained at 4.5° K by liquid ^4He . The continuous flow cryostat is of the "standard" CERN type. The target material is 1.2 propanediol, used in Exps 120* and 120**. It yields routinely polarizations of 80-82%. A standard NMR is used to monitor the average polarization with an absolute accuracy of better than 3%.

II-3 Pion Beams

We plan to use the P^3 East beam line. A special set of dipole magnets, one vertical the other horizontal, located some 6 m upstream of the target are used for steering. We have encountered no unexpected problems in Exp. 120* in obtaining good quality $\pi^\pm$ beams of spot size $< 2 \times 2 \text{ cm}^2$. Beam monitoring is done with the aid of two small angle counter telescopes located above and below the beam to detect decay muons leaving the beam pipe through 2 small windows. Additional checks are made using the counting rates in various detectors. The exact position of the beam is measured with the beam profile wire chambers placed upstream at about 1 and 3 meters. These BPM's have 2 mm wire spacing and are used in current readout mode. They have proven to be very useful for rapid beam tuning.

II-4 Detectors

The scattered pions are detected using the Large Aperture Spectrometer, LAS,¹⁾ and the recoil protons using a carbon plate polarimeter. The bend plane of LAS is vertical thus particle momentum and scattering angle are determined independently. The magnet configuration of LAS is two quadrupole and one dipole magnet. The detectors consist of 3 sets of scintillation counters and 4 sets of wire chambers, one pair before and one after the dipole.

The polarization of the recoil proton is measured using a "standard" polarimeter based on scattering by a 2-8 cm thick carbon plate. The protons are detected in four wire chambers and two counter hodoscopes. The calibration of this polarimeter, using a tagged beam of nearly 100% polarized protons obtained in the reaction $\pi^- p \rightarrow \pi^- p$, is discussed in a separate proposal. This calibration uses much of the same equipment except for the HERA target. It can take place in the P^3 East beam prior to the experiment.

II-5 Rates

A practical approximation to the calculation of the expected accuracy for different number of events is given by

$$\Delta R \leq \frac{1}{P} \frac{1}{\epsilon} \sqrt{\frac{2}{N}}$$

where

ΔR = rms error in R (or A)

N = total number of events (sum of both spin directions)

P = target polarization; the HERA target has $P \geq 0.80$

ϵ = effectiveness of polarimeter; ϵ varies from 0.03 to 0.08.

In Exp #120* we measured some 60 data points with typical accuracy of 0.02 to 0.04 depending on value of A_N and $d\sigma/d\Omega$. Thus with a similar set up as for Exp #120*, we can comfortably measure some 30 data points with a typical accuracy of 0.05.

The choice of angles for the measurements of the spin rotation parameters is determined on the basis of a new partial wave analysis recently begun at VPI and that includes the results of Exps 363, 120, 120*, and 120**.

Reference

1. E. Colton, Nucl. Inst. Meth. 178, 95 (1980).

P_{π} MeV/c	$d\sigma/d\Omega$		A_N		A	R
	$\pi^{\pm}p$	CEX	$\pi^{\pm}p$	CEX	$\pi^{\pm}p$	$\pi^{\pm}p$
247		t				
267		t				
301		t				
331		t				
351		t				
378	f	t			?	✓
408	f					
427	f	t				
471	f	t	t	t	✓	✓
509	f	t				
547	f	t	t	t	✓	✓
586	f	t				
625	f	t	t	t	?	✓
657	f	t				
687	f	t	t	t		

Table I

Status of πN program of the UCLA Particle Physics Research Group

f = finished (absolute accuracy is 2%)

t = data taken, but not completely analyzed (preliminary results available)

✓ = planned

Fig. II-1

Layout for A/R experiment

Fig. II-1 HERA Target

PROGRAM I-b

Measurement of the Asymmetry Parameter, A_N , in $\pi^- p \rightarrow \gamma n$
 Using a Transverse Polarized Target

Exp. #804 is our large LAMPF experiment now being installed in the P³ East Cave. It is scheduled to start taking beam on December 28. The total running time is 1100 hours of which 400 hours are scheduled for cycle 40 in December and January and the remaining 700 hours to be used when LAMPF resumes running after the winter-spring break, tentatively in mid-June.

The experiment is a natural continuation of our πN investigations, LAMPF expts. #363, 120, 120*, and 120**. The physics motivation can be given as follows: Nearly two decades ago a quark hypothesis was proposed by Gell-Mann¹ and independently by Zweig who, however, could not get his papers published. The quarks have some unusual properties namely fractional electric charge, they obey parastatistics and they are very likely unobservable in the laboratory. Despite these strange characteristics and in spite of the lack of a spectacular experimental prediction--such as the Ω^- hyperon was for SU(3)--the quark hypothesis has gained a wide, if not a universal, acceptance because it provides a rational basis for the entire collection of hadron resonances. One of the very impressive accomplishments of the early or naive quark models was the calculation of the correct order of magnitude and sign of the helicity amplitudes of the radiative decay of many πN resonances. The experimental determination of the various helicity amplitudes is done using an amplitude analysis of pion photoproduction data. Because the electromagnetic interactions obey only a very loose isospin rule, the so called $|\Delta I| < 1$ rule, one must consider three separate isospin amplitudes. Consequently, there is no

direct relation between the radiative decays of neutral and charged resonances. This situation may be compared to πN elastic scattering where isospin invariance limits one to two independent isospin amplitudes and it is sufficient to study π^+p scattering without the need for π^+n measurements and there is no need for a neutron target. The radiative decays of the singly charged πN resonances have been studied extensively using π^+ and π^0 photoproduction results obtained with a hydrogen target. The radiative decay of the neutral πN resonances have been investigated mainly in $\gamma d \rightarrow \pi^- p$ experiments which carry the curse of the deuteron corrections leading to large uncertainties. One can do fundamentally better by measuring instead inverse pion photoproduction, $\pi^- p \rightarrow \gamma n$, in which case one avoids the deuteron complications.

The impressive success of the original naive quark models was spoiled somewhat by a glaring discrepancy of the helicity amplitude of the neutral Roper resonance which disagreed in sign as well as order of magnitude. In 1975, a seminal paper by de Rujula, Georgi, and Glashow appeared in which they suggested that the long distance quark - quark interaction is dominated by the one-gluon-exchange, OGE, contribution for which they suggested a simple expression. The modern quark models based on OGE have been phenomenally successful in particular the one fathered by Isgur and Karl. In these modern calculations the Roper resonance is not such a glaring exception anymore in that at least the sign of the helicity amplitude is in agreement with the experiment. To explain the remaining discrepancy in the magnitude of the helicity amplitude, several possibilities must be considered:

- 1) large experimental uncertainties as a result of the deuteron complications that beset the γd experiments;
- 2) a break down of the Karl-Isgur model as a consequence of the limitations of the OGE contribution;

- 3) the resonance that is now believed to be the Roper is actually a split resonance and one of the two P_{11} 's could actually be a hermaphrodite baryon.

An important objective of Exp. #804 is to provide necessary data to determine the radiative decay of the neutral Roper resonance which is a sensitive test of modern quark models.

Another objective, perhaps equally important, is to investigate the possible electric quadrupole excitation of the Δ^0 resonance. The OGE term proposed by de Rujula et al., implies that there is a small d-wave component in the 3-quark wave function of the nucleon and the Δ -resonance which can be numerically evaluated, Isgur et al., obtain $E_{1+} / M_{1-} = 0.007$. The relevant part of this calculation is based on the color hyperfine interaction as expressed in the OGE model. This interaction is called color magnetism because it is formally the color analog of the magnetic dipole - magnetic dipole interaction of electromagnetism.

Further theoretical aspects of our experiment are discussed in some detail in the proposal to Exp. #804.

Some activities in connection with the preparation for the running of the experiment are:

- a) the polarized target borrowed from P-division is set up by our group with good support from MP7; some improvements in the gas cart system are apparent from the lay out given in Fig. 1;
- b) the neutron counters have been tested with charged particles in the LAMPF test channel;
- c) shielding studies have been conducted for the neutron counters using the test channel facilities as detailed in Appendix A.
- d) the gamma detectors originally proposed (the UCLA chamber + counters

and lead converters used in Exps 120 and 120**) have been replaced by two sets of lead glass Cherenkov counters borrowed from Temple University. The Cherenkov counters have about 30% resolution for 240 MeV electrons and therefore enable us to use pulse height discrimination for reducing the background from pion interaction in the carbon. Also, the detection efficiency of the lead glass counters is higher than for our converter system and the maintenance during running is less for counters than for our chambers.

The new gamma detector consists of two arrays of 3 x 5 lead glass counters. Each counter is 15.6 cm x 15.6 cm x 25.6 cm deep and made of type F-2 lead glass. Each counter is viewed by a 5" photomultiplier.

One of the arrays has been studied using a tagged electron beam in the test channel. The best energy resolution obtained for 240 MeV electrons is $\pm 14\%$. An exchange of the energy resolution obtained by adding the pulse height in adjacent counters is shown in Fig. 2. A layout of our set up is shown in Fig. 3.

Appendix

We have investigated various possible shielding arrangements for the neutron counters which will be used in LAMPF experiment #804. The tests were conducted in the LAMPF "Test Channel" using a 360 MeV/c π^- beam which had a 2% muon and electron contamination and had an emittance of approximately 10^6 particle/sec. The neutron counter consisted of a cylindrical piece of scintillator 3" in diameter and 18" long, which was coupled by a light pipe to an RCA 8575 photomultiplier tube. The pulse height discrimination level on the counter was set using the Compton edges from a ^{60}Co source and corresponded to a minimum neutron energy of approximately 4 MeV. The neutron

detector was centered inside an anticounter array of triangular cross section which consisted of three 1/4" thick pieces of scintillator 5 1/4" wide by 28" long. The entire array was placed on the floor roughly in the center of the test channel cave. The beam passed 4 1/2 ft. above the neutron counter whose axis was oriented perpendicular to that of the beam. An additional anticounter was used to cover the open end of the anticounter array that was pointed toward the main proton beam line. The discrimination level on the anticounters was set to 1/2 the pulse height produced by minimum ionizing particles. The beam was monitored by a counter in the beam halo. The following quantities were scaled:

- 1) N: neutron counter singles
- 2) ΣA : an OR of all 4 anticounters
- 3) $N \cdot \overline{\Sigma A}$: an AND of N and the anti of ΣA .
- 4) : beam monitor counter
- 5) : beam gates.

The scalars were all gated by the beam gate. The macro structure of the LAMPF beam was 120 pulses/second with an 8.76% duty factor. Runs of approximately 10 seconds long were taken and normalized by beam monitor counts.

Three beam conditions were taken for each shielding arrangement:

- 1) Beam Plug in and Beam Jaws closed. (Normalized to 2600 beam monitor counts).
- 2) Beam Plug out and Beam Jaws wide open. The beam was directed at the concrete shielding blocks at the back of the cave, located approximately 11 ft. behind the neutron detector array. (Normalized to 20,000 beam monitor counts).
- 3) The same arrangement as 2) but a 1" thick piece of Lead Sheet was placed in the beam path approximately 13 ft. upstream of the detector array. (Normalized to 65,000 beam monitor counts).

The results are presented in Table 1, where the various shielding arrangements were:

- A) No shielding.
- B) a 2" thick CH₂ house surrounded the detector array.
- C) a 1/8" thick lead house was placed inside the CH₂ house used in B).
- D) a 1/8" thick lead house was placed outside the CH₂ house used in B).
- E) a 1/4" thick lead house was placed inside the CH₂ house used in B).
- F) same as E) but an additional 1/8" thick lead house was placed outside the CH₂ house.
- G) same as E) but an additional 2" thick CH₂ house was put outside the original CH₂ house.
- H) same as G) but an additional 1/8" lead house was put between the two CH₂ houses.

Notes: the inner CH₂ house was a rectangular box 14 1/4" high x 21" wide x 72" long. No shielding was placed under the detector array, and all shielding was placed outside the anticounters.

TABLE 1

I-b-7

R U N	N Neutron Counter Singles	ΣA OR of the anticounters	N- ΣA AND of the Neutron Counter and the anti of the ANTI OR	Beam Gates (120/second)	Ratio of $\frac{N(\quad)}{N(A)}$	Ratio of $\frac{\Sigma A(\quad)}{\Sigma A(A)}$	Ratio of $\frac{N-\Sigma A(\quad)}{N-\Sigma A(A)}$
A1	63506	65392	55045	1140	1	1	1
B1	54394	54810	46783	1173	.857	.838	.850
C1	49601	52503	42330	1178	.781	.803	.769
D1	51398	51922	44126	1174	.809	.794	.802
E1	48591	52190	42571	1236	.765	.792	.773
F1	46796	49679	40034	1230	.736	.760	.726
G1	44449	48080	37430	1254	.700	.735	.680
H1	42122	45238	35681	1263	.663	.692	.648
A2	79612	85800	67958	1262	1	1	1
B2	67601	69135	57615	1252	.849	.806	.848
C2	59203	64450	50010	1231	.744	.751	.736
D2	61888	64461	52800	1264	.777	.751	.777
E2	57663	62089	48750	1304	.724	.724	.717
F2	55349	59042	46876	1296	.695	.688	.690
G2	49729	53670	40877	1266	.625	.624	.602
H2	46412	51629	38892	1258	.583	.602	.573
A3	98906	117552	79303	1193	1	1	1
B3	84180	96122	68029	1202	.851	.818	.858
C3	76475	96122	68029	1186	.773	.766	.776
D3	77436	87354	63398	1208	.783	.743	.799
E3	73996	83638	60654	1237	.748	.711	.765
F3	69218	81032	56237	1227	.700	.689	.709
G3	62933	76399	49909	1219	.636	.650	.629
H3	59001	70992	47011	1221	.596	.604	.593
B	751	711	733	1226	proton beam off for 30 minutes		

Conclusions

1) Most of the background to be expected is due to the accelerator, and not the beam in the cave. (With the beam plug in and jaws closed the radiation in the cave was 3.5 mR/hour neutrons and 2.3 mR/hour betas and gammas.)

2) The shielding is equally effective removing neutral and charged particles.

3) The lead is a few percent more efficient when placed inside the CH2 as opposed to outside it.

4) The 1st 1/8" of lead is several times more effective than the 2nd 1/8" of lead (comparing cases C) and E)).

5) The lead is more effective in reducing counts in the neutron counter than in the anticounter.

In addition to the shielding studies undertaken in the test channel, the following was also looked at in the test channel:

1) The 24 neutron counters were calibrated and their timing and pulse height characteristics were studied as a function of where a beam was allowed to pass through them. Multiple pulsing problems caused by heavily ionizing particles in these counters were also studied and solved.

2) Gains were set on all the hodoscope elements which will be used to define the incident beam.

3) Performance of the hodoscope as a function of the beam rate was studied.

4) The performance of the lead glass γ counters was studied using an electron beam. Leakage of energy out of the sides of the counters was measured as a function of the position of the incident electron on the γ counter.

Fig. 1

Fig. 2

Typical pulse height spectrum for 320 MeV electron incident at an inclination of about 30° obtained by summing two adjacent counters.

Status of Experiment

The proposal for Exp. #806 has been approved at LAMPF with the following comment of the P³ subcommittee: "The subcommittee recognizes the fundamental importance of these measurements. They will be the first such data below 1 GeV, and will have a clear and direct influence upon a determination of the basic πN amplitudes throughout the LAMPF range of energies".

The preparatory phase in 1984 includes making Monte Carlo simulations of the experiment, arranging, assembling, and testing the frozen spin target, testing the polarimeter and detectors, preparing the floor lay out, etc. The data taking phase of this very large experiment is planned for 1985.

Fig. 3

PROGRAM I-c

"Measurement of the Analyzing Power, A_N , for π^+p Elastic Scattering at 471, 547, 625, and 687 MeV/c"

1. Pion-Nucleon Elastic Scattering Formalism

The π -N interaction is spin dependent. To include explicitly the spin wave function of the nucleon and to allow for the possibility that the nucleon spin may flip as a result of the interaction, the asymptotic form of the wave function in the center of mass system must be written as

$$\psi_{\mu} = e^{ikz} \chi_{\mu} + M_{\nu\mu} \chi_{\nu} \frac{e^{ikr}}{r},$$

where $M_{\nu\mu}$ is the scattering amplitude for scattering from $(\vec{k}_i, \mu)$ state to $(\vec{k}_f, \nu)$ state, and $\vec{k}_i$ (along the z-axis) and $\vec{k}_f$ are the initial and final momenta. χ_{μ}, χ_{ν} ($\mu, \nu = \pm 1/2$) are the initial and final spin states. The most general form of the 2×2 matrix M invariant under spatial rotations and parity is

$$M = f(\theta) + g(\theta) \vec{\sigma} \cdot \hat{n},$$

where

$$\hat{n} = \frac{\vec{k}_i \times \vec{k}_f}{|\vec{k}_i \times \vec{k}_f|},$$

is the unit axial vector normal to the scattering plane. The partial cross section for scattering from spin state χ_{μ} to spin state χ_{ν} is given by

$$\frac{d\sigma}{d\Omega} (\mu \rightarrow \nu) = |\langle \chi_{\nu} | M | \chi_{\mu} \rangle|^2,$$

and since we do not measure the spin orientation of the nucleon in the final state, we sum over ν and get

$$I(\theta, \phi) \equiv \frac{d\sigma}{d\Omega} = |f|^2 + |g|^2 + 2\text{Re}(fg^*) \hat{n} \cdot \vec{P}_i,$$

where $\vec{P}_i = \langle \chi_{\mu} | \vec{\sigma} | \chi_{\mu} \rangle$ is the initial polarization of the nucleon. The differential cross section for an unpolarized initial state is

$$I_0(\theta) \equiv |f|^2 + |g|^2,$$

thus

$$I(\theta, \phi) = I_0(\theta) (1 + A_N(\theta) \hat{n} \cdot \vec{P}_i),$$

where

$$A_N(\theta) = \frac{2\operatorname{Re}(fg^*)}{|f|^2 + |g|^2},$$

is the analyzing power of the reaction. For a transversely polarized target the differential cross section shows a left-right asymmetry. For scattering to the left

$$L = I_0(1 + A_N P_1),$$

while for scattering to the right

$$R = I_0(1 - A_N P_1).$$

Thus

$$\epsilon \equiv \frac{L-R}{L+R} = A_N P_1,$$

ϵ is called the left-right asymmetry. Therefore by measuring the left-right asymmetry and the initial polarization one can obtain the analyzing power:

$$A_N(\theta) = \frac{\epsilon}{P_1}.$$

2. Target

A polarized proton target was used with the axis of polarization perpendicular to the scattering plane. The polarized target material consisted of 1,2 propanediol ($C_3H_8O_2$) beads and was contained in a cylindrical cell 2 cm in diameter and 4 cm long. The target beads were embedded in a He^3 -bath at .5 °K temperature. The polarization was measured using NMR techniques. The NMR system was calibrated by measuring the natural polarization at thermal equilibrium. In thermal equilibrium at temperature T, the polarization is given by

$$P = \tanh \frac{\hbar\omega}{2k_B T}$$

At equilibrium (i.e. when the NMR signal has stopped growing or decaying) the polarization is known if the temperature is known.

The area of the absorption signal A is proportional to the nuclear polarization P . By comparing the area A of the signal from dynamically polarized nuclei to the area A_0 of the thermal equilibrium signal of known polarization P_0 , the polarization P is given by

$$\frac{P}{P_0} = \frac{A}{A_0}.$$

This method has some limitations, the most serious one is poor signal-to-noise ratio and the measurement of A_0 is imprecise. The target polarization was about 80%. It was measured with a relative accuracy of typically $(\frac{\Delta P}{P} \approx) 5\%$.

3. Beam

The experiment was done in the P^3 area at LAMPF. Pion beams with average intensities from .5 to 5×10^6 pions/sec were focused on the target cell. Steering magnets at the end of the P^3 channel were used to compensate for the bending of the beam in the field of the polarized target magnet and to correct for mis-steering of the beam. The beam spot position was monitored using two beam profile monitors upstream of the target and a hole counter at the target position. The beam spot size at the target is approximately 2 cm in diameter. The relative beam intensity was measured by means of two scintillator telescopes which detected muons from the decay of pions in the beam. The systematic uncertainties in beam monitoring was estimated to be of order of 3-4%.

4. Detectors

The experimental layout is shown in fig. 1. In almost all measurements the scattered pion and the recoil proton were detected in coincidence using the Large Acceptance Spectrometer, LAS, and a recoil detector. The LAS is a QGD spectrometer with a vertical bend, so that scattering angle and particle momentum are determined in orthogonal planes. A steering magnet was placed at the spectrometer entrance to increase the acceptance for low-momentum particles. The particle's momentum is determined from four wire chambers. First one is in front of quadrupoles, the second one after the quadrupoles, the third and

fourth chambers are placed at the exit of the bending magnet (see fig. 2). A scintillator counter in front of chamber 1 and an array of five scintillators behind chamber 4 provided time-of-flight and pulse height data. The recoil detector consisted of a 100 cm by 65 cm wire chamber sandwiched between two arrays of eight scintillator counters each. Pulse height, time of flight and wire numbers were recorded for each particle detected in the recoil array. These, together with the determination of scattering angle, momentum, and particle type in LAS provided an over constrained signal for coincidence events, as a result the signal to background ratio is high, despite the low ratio of free to bound protons in the target material.

5. Background Subtraction

The background was mainly due to quasi-elastic scattering on carbon nuclei contained in the propanediol, He^3 coolant, and cryostat walls. The background was measured in separate runs with propanediol replaced by carbon with approximately the same number of carbon nuclei. This background is treated as being independent of target polarization and has been subtracted from all yields.

6. Results

Our results for A_N are shown in Figs 3 and 4 together with the results of published partial wave analyses¹⁻³ which were generated before our data were available. The error bars represent only statistical uncertainties. The data show strong variations with scattering angle reflecting the strong interference among contributing partial wave amplitudes. New partial wave analyses based on our data are in progress. They are particularly important for establishing the properties of the $P_{11}(1440)$ resonance.

References

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Fig. 1

A) TOP VIEW B) SIDE VIEW

Figure 2

FIGURE 3
Measured A_N values (•) for $\pi^-p \rightarrow \pi^+p$ and the results of the partial wave analyses of Karlsruhe-Helsinki¹ (—), CMU-LBL² (---), and VPI³ (-.-).

FIGURE 4

Measured A_N values (•) for $\pi^+ p \rightarrow \pi^+ p$ and the results of the partial wave analyses of Karlsruhe-Helsinki¹ (—), CMU-LBL² (---), and VPI³ (-.-).

PROGRAM I-d

Measurement of the Analyzing Power, A_N , in $\pi^-p \rightarrow \pi^0 n$ Between 471 and 687 MeV/c.

This experiment, LAMPF Exp. 120**, represents the fourth part of a five part program undertaken by this group to measure a complete set of πN scattering observables in the energy region of the first two resonances. The aim is to provide a precise determination of the πN phase shifts in this region free of ambiguities. Detailed discussions of the physics objectives of these measurements appear in previous annual reports.

The interest in this program has been fueled by some recent results challenging our understanding of the πN system in this energy regime. For example, a Russian group¹ has studied some existing data in terms of the isospin relationships between the πN amplitudes. They have found a substantial (better than two standard deviations in three consecutive data points) disagreement with predictions based on isospin invariance. Their analysis employed data from several different sources including some which have drawn severe criticism from the most recent partial wave analyses^{2,3}. Specifically, this is the charge-exchange data of refs. 4 and 5. Is this effect real or an indictment of the existing data? This question can only be answered by studying complete, precise data sets.

Experiment

The experiment was performed in the High Energy Pion Channel (P^3) at the Los Alamos Meson Physics Facility (LAMPF) during Fall 1982 using approximately

800 hours of beam time. Six different beam momenta were selected for study, namely: 471, 547, 586, 625, 657, and 687 MeV/c. Angular distributions, each containing 9 or 10 points, were obtained in the range: $-0.9 < \cos\theta_{\text{cm}}^{\pi} < +0.9$. A floor plan for the experiment appears in fig. 1.

For a detailed description of the experimental apparatus see the previous annual report. Briefly, the target used was the transverse polarized proton target (PPT) developed by the Los Alamos National Laboratory P-Division. The target material was composed of 1,2-propanediol doped with EHBA (2-ethyl-2-hydroxybutyric acid) and was manufactured as 1 mm diameter beads. The target polarization was monitored every 5-10 minutes during a run and was found to be approximately 82% throughout the course of the experiment. In addition, four separate sets of calibration runs were taken during the experiment, and preliminary analysis of these has shown consistency at the 1-2% level.

The recoil neutrons were detected in 9 or 10 pairs of scintillation counters (N) arrayed on beam left. These counters were 3 inch diameter cylinders 45.7 cm long for counters 10 and 1-5 while ones 19.1 cm long were used for counters 6-9. Five large, thin scintillation counters were mounted in front of them and were used to veto charged particles (NV). The bending of charged particles in the magnetic field of the PPT necessitated this arrangement yielding few if any gaps in the coverage of the neutron counters.

At least one of the two decay photons from the neutral pion were detected in the gamma arrays on beam right. The gamma detectors consisted of two identical arrays, each mounted on a moveable cart. Mounted at the front of the cart were eight thin charged particle veto counters (GV) arranged in

"picket fence" fashion. Following these counters was a lead converter 1.7 radiation lengths thick. The photon-induced shower was detected in an MWPC immediately following the converter and in an eight counter hodoscope mounted behind the MWPC. The counters of this hodoscope had photomultiplier tubes on both ends to supply timing information and were used to signal the requisite gamma component (G) of the event trigger. A Monte Carlo simulation of the experiment demonstrated the need for two cart positions to optimize the event rate in all ten neutron counter pairs. This motivated the construction of moveable carts mounted on a circular track centered on the PPT.

Beam monitoring was accomplished through the use of two counter telescopes, two beam profile monitors (BPMs), and a Fast Beam Hodoscope. Each counter telescope consisted of a one-inch wide scintillator followed by a two-inch wide counter. The two telescopes were mounted just above and below the beam line and sampled the beam muon halo. The BPMs, one at 1 meter and the other at 3 meters upstream of the target, were MWPCs placed directly in the beam. The Hodoscope (B) was constructed from ten scintillators with five mounted in each of two orthogonal planes. It was placed directly in the beam preceding BPM #1 and was used to ensure that the event originated from a beam particle.

The event trigger was $N \cdot NV \cdot G \cdot GV \cdot B$. For each event, pulse height information was recorded for all counters. In addition, gamma time of flight (TOF) with respect to B and the neutron TOF with respect to G were also recorded. Finally, information from the cart mounted MWPCs was recorded.

Data was taken at the six momenta for scattering from the polarized

protons. Immediately following this, the target material was removed and replaced by carbon beads to study the background. Carbon was used because it is by far the major "contaminant" in the polarized target material. The time spent obtaining the background data at each momentum and each cart position was roughly half as long as that for the polarized protons; thus, the times for spin up, spin down, and background were approximately equal.

Results

A preliminary pass through the data at 625, 657, and 687 MeV/c has been completed and has shown reasonable consistency among the different runs. The prominent feature from this analysis is the extreme sensitivity to background subtraction at angles where the magnitude of the asymmetry is close to 1.0. We present our very preliminary results at the three momenta in figs. 2-4. Included in these figures are the results from two recent PWAs (refs. 2 and 3) along with the only published data on these measurements (ref. 4). The results shown for 687 MeV/c represent less than one-half of the data taken at this momentum. This data was taken early in the experiment before the discriminators for the counters of the Fast Beam Hodoscope were exchanged for faster ones. The replacement occurred in the middle of the 687 runs, and it is hoped that the analysis of the other momenta will shed some light on how best to incorporate this data.

Since a large amount of data was recorded for each event, we are presented with a variety of cuts that can be applied. The analysis is now proceeding in a painstaking, methodical study of the effect of the many possible cuts on the data at 657 MeV/c. This momentum was selected for this study because it was

the last momentum used before background measurements commenced. Thus, we were able to avoid possible sources of systematic uncertainties such as having to make shielding changes or re-tune the channel. The search continues for the optimal analysis which we define as yielding physically realizable asymmetries (magnitude not greater than 1.0) with as small an absolute error as possible.

The aim of the analysis is to provide a high precision set of asymmetries which will enable us to study the possible violation of isospin symmetry in the πN system. Very powerful, model-independent tests of isospin invariance are the triangle inequalities between the differential cross sections

$$\frac{1}{2}(\sqrt{\sigma^+} - \sqrt{\sigma^-})^2 < \sigma^0 < \frac{1}{2}(\sqrt{\sigma^+} + \sqrt{\sigma^-})^2$$

where $\sigma^\pm$ are the differential cross sections for $\pi^\pm p$ elastic scattering and σ^0 is the differential cross section for charge-exchange. Additional, more sensitive triangle inequalities are based on the so-called transversity cross sections, $\Sigma^\pm(\pm) = \sigma^\pm(1 \pm A_N^\pm)$ for example, and are found by substituting Σ for the appropriate σ in the triangle inequality above.

Prompted by the Russian results at 690 MeV/c, we have analyzed our data (LAMPF Exps. 363, 120, 120*, and 120**) to test these inequalities, see figs. 5 and 6. The curves representing the upper and lower isospin limits arise from a Legendre fit to the differential cross sections as well as fits to A_N after multiplying by σ and dividing by $\sin\theta$. The triangles occur at the angles where $A_N^\pm$ was measured. The open circles coincide with the angles where A_N^0 was measured while the differential cross sections were once again taken from a Legendre fit. On the basis of figs. 5 and 6, we conclude that isospin symmetry is not violated in the πN system.

Additional collaborators in the measurements described above were M. E. Sadler and students from Abilene Christian University.

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Fig. 1 Floor Plan for Charge-Exchange Asymmetry Measurements

Fig. 2

Fig. 3

Fig. 4

Charge-Exchange Asymmetries

Dotted curve from Ref. 2

X-ed curve from Ref. 3

◆ UCLA Preliminary (Not for Publication)

◆ Data from Ref 4 at 617 MeV/c for Fig. 2, 675 MeV/c for Fig. 3, and 698 MeV/c for Fig. 4.

PROGRAM I-e

Measurement of the $\pi^+p \rightarrow \pi^0n$ Differential Cross Section From 247 to 687 MeV/c.

This experiment, LAMPF Exp. 120, is the second stage of a five part program to measure a complete set of πN scattering observables in the energy region of the first two resonances. The objective of this program is to provide the input for a new partial wave analysis (PWA) determination of the πN amplitudes free of ambiguities. An important aspect of this project is to measure all of these observables at the same momenta. A complete discussion of the physics objectives of this program appears in previous annual reports.

The experimental set-up was similar to that of Experiment 120**, as described elsewhere in this report. A detailed description of the apparatus and data acquisition appears in previous annual reports. The analysis of the data is almost complete with only a more precise neutron counter calibration remaining. Therefore, we have decided to use it to address the validity of isospin symmetry in the πN system.

Very powerful, model-independent tests of isospin symmetry are the following triangle inequalities

$$\frac{1}{2} (\sqrt{\sigma^+} - \sqrt{\sigma^0})^2 < \sigma^\pm < \frac{1}{2} (\sqrt{\sigma^+} + \sqrt{\sigma^0})^2$$

where $\sigma^\pm$ are the differential cross sections for $\pi^\pm p$ elastic scattering and σ^0 is the differential cross section for charge-exchange. In addition, similar tests can be made using the so-called transversity cross sections, $\Sigma^\pm(\pm) = \sigma^\pm(1 \pm A_N^\pm)$ for example, and this is one of the aims of Experiments 120* and 120**, discussed elsewhere in this report. Above is the analyzing power in

π^+p elastic scattering, and the $\pm$ refer to polarization up and down, respectively.

Recently, a Russian group¹ has published results employing the preceding triangle inequalities on some data from a number of different sources and find a substantial (better than 2 standard deviations) violation of isospin symmetry at 690 MeV/c at three backward angles. Some of this data, in particular the charge-exchange differential cross section² and asymmetry³ measurements, cannot be reconciled by two recent PWAs^{4,5}. A major problem inherent in using several sources for the data is how to handle the systematic uncertainties, not to mention the fact that these measurements were not made at the same momenta.

We have been very careful to avoid this problem by employing identical momenta for measurement of all scattering observables. In addition, by using only our own data, we have minimized the problem of systematic uncertainties. Their only effect should be an overall scale factor thus leaving the relative orientation of the data intact.

Since the Russian group found what could be a violation of isospin symmetry at 690 MeV/c, we have used our data at 687 MeV/c in the triangle inequality for the differential cross sections, see fig. 1, as well as the inequalities based on the transversity cross sections, see elsewhere in this report. In addition, we present the results of our analysis at 625 MeV/c in fig. 2. In these figures the curves representing the upper and lower limits result from Legendre fits to the differential cross sections while the triangles occur at the angles where $\sigma^\pm$ were measured. The open circles

indicate the points where σ^0 was measured. On the basis of these tests, we do not find any evidence for isospin violation in the πN system.

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Fig. 1.

Fig. 2.

Test of Isospin Symmetry using the Triangle Inequality for the Differential Cross Sections.

Statistical uncertainties are $\leq 1\%$ except for measurements taken in the minimum at higher momenta. The overall normalization of the cross section was obtained by evaluating the incident pion flux, the effective target length and density, the background signal from the target walls, pion absorption in the target and counters, and the pion decay between the target and the beam monitors. Overall normalization uncertainties are 2% except for the 657 and 687 MeV/c π^+ measurements, in which cases the proton contamination was large and time-of-flight measurements of this contamination could not be obtained. The normalization uncertainty for these cases is 15%.

Angle-dependent corrections have been made for pion decay between the target and the pion hodoscopes and for multiple scattering in the target. These corrections are each less than 1.5%. Corrections for nuclear interactions of the pion and recoil proton vary from 0.1 to 4.8%. Yet to be evaluated are Coulomb, radiative and finite solid angle corrections. These are expected to affect the present results by less than 2%. The central momentum of the incident pion beam is known to be better than 0.3% based on TOF measurements performed by a LAMPF group [5]; we have verified these measurements within an uncertainty of $\pm 1\%$ using the range technique [6]. The spread in the incident beam momentum is less than $\pm 0.5\%$.

Examples of the angular distributions *1 obtained for $\pi^+p \rightarrow \pi^+p$ are shown in figs. 2-4 together with previous data and the results obtained by recent partial wave analyses. In general, at all momenta for which the results of these analyses mutually agree, they also agree with our data. The agreement is better for π^+p .

Our results for π^-p at 408 MeV/c are plotted in fig. 2a along with those of Bussey et al. [7] and Gordaev et al. [8]. The data of ref. [7] agree very well with our results, and the data of ref. [8] agree reasonably well within the 5% systematic uncertainty quoted in that work. As can be seen in fig. 2b, our results for π^+p at 427 MeV/c agree with the data of Ogden et al. [9] and Gordaev et al., but less well with those of Rogers et al. [10]. Improved determination of the background based on analysis of off-coplanarity events

Fig. 2. Differential cross sections for π - p elastic scattering compared to other experiments and to phase shift analyses. (a) π^-p at 408 MeV/c: $\bullet$ This experiment, $\circ$ Bussey, $\circ$ Gordaev, $---$ Karlsruhe-Helsinki, $---$ VPL. (b) π^+p at 427 MeV/c: $\bullet$ This experiment, $\circ$ Rogers, $\triangle$ Ogden, $\circ$ Gordaev, $---$ K-H and VPL.

may explain the deeper minima obtained in the present experiment.

In fig. 3, our results for π^-p at 427 MeV/c are compared with those of Rugge and Vik [11] which are the only available data at this momentum. The data sets

Fig. 3. π^-p at 427 MeV/c: $\bullet$ This experiment, $\circ$ Rugge and Vik.

*1 The complete data sets are available on request from B.M.K. Nefkens and M.E. Sadler.

Fig. 5

Fig. 6

Test of Isospin Symmetry using Triangle Inequalities for the Transversity Cross Sections.

Fig. 4. • This experiment, ○ Gordsev, — K-H, --- CMU-LBL.

disagree by as much as 20% at forward angles. The serious disagreement in the shape of the angular distributions affects the phase shifts obtained in partial wave analyses. The most important difference in the two measurements is that in the older experiment only the scattered pions were detected. Because the charge exchange background in the yield could not be measured, Rugge and Vik calculated this contribution. Older partial wave analyses, such as those of Carter et al. [12], depend strongly on the data of refs. [10,11] and may be in error in the energy region above 380 MeV/c. In figs. 2a and 3 our data for 408 and 427 MeV/c are compared with the phase shift solutions of the VPI [1] and the Karlsruhe-Helsinki [3,4] groups. In the latter isospin invariance is required in all partial waves and analytic constraints based on dispersion relations are applied; in the former isospin splitting is allowed in the S_{31} and P_{33} partial waves and almost no use is made of analytic constraints. The analyses also differ slightly in the data sets used.

For π^+p at our higher momenta the results of the CMU-LBL [2] and Karlsruhe-Helsinki partial wave analyses disagree somewhat with each other and with

our data. For example, as shown in fig. 4 for 586 MeV/c, our angular distributions exhibit deeper minima than either of the phase shift results. Our data somewhat favor the Karlsruhe-Helsinki results. In fig. 4 our data are compared to recently published results for π^+p at 588 MeV/c [8]. Good agreement is seen for $\cos \theta_{cm} > -0.6$. At more backward angles the Gordsev results have a much steeper slope than that of our data. Similar disagreements are seen at other momenta above 500 MeV/c. The disagreement is particularly significant in light of the claim that inclusion of the data of ref. [8] in a partial wave analysis produces strong evidence for a split P_{11} resonance.

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PROGRAM I-h

Measurement of the Analyzing Power, A_N , and Spin Correlation Parameter, A_{NN} ,
for $pp \rightarrow d\pi^+$ and $pp \rightarrow pp$ from 500 to 800 MeV

The status of this work is well reflected in the following two contributions to the Few Body X Conference at Karlsruhe.

MEASUREMENT OF THE ANALYZING POWER FOR THE $pp \rightarrow d\pi^+$ REACTION IN THE REGION 500-800 MeV

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Data on the analyzing power for $pp \rightarrow d\pi^+$ at medium energies coming from TRIUMF¹ for energies 305-450 MeV and from SIN² for energies 515-578 MeV recently have been supplemented by data from Saclay³ for energies 725-1000 MeV and precise data from LAMPF⁴ for energies 547, 598, 648, 698 and 793 MeV. New data for energies 500, 600, 650, 700, 733 and 800 MeV obtained in conjunction with an A_{NN} experiment, also done at LAMPF⁵, are presented in Fig. 1 (next page). The polarized beam-polarized target data were analyzed to yield $A_{ND}(\theta)$ values by weighted summing of data for up and down target polarizations, and to yield $A_{DN}(\theta)$ values by weighted summing of data for up and down beam polarizations. The $A_{DN}(\theta)$ values obtained have been converted to $A_{ND}(\theta)$ values before plotting through use of the relationship $A_{ND}(\theta) = -A_{DN}(\pi - \theta)$. The results presented here are in reasonable agreement with the results obtained by others^{3,4}, where available at approximately the same energies.

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FIGURE 1
Measured values of analyzing power $A_{no}(\theta)$, including directly measured values (•) and values obtained from $A_{on}(\theta)$ measurements (○).

MEASUREMENT OF THE SPIN CORRELATION PARAMETER $A_{NN}(a)$ FOR THE $pp + d\pi^+$ REACTION IN THE REGION 500-800 MeV

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The two-body final-state reaction $NN + d\pi$ is an important inelastic component of the NN interaction. Just as for the case of elastic scattering, a variety of experiments involving different initial-state polarizations and/or final state polarization measurements are required for a complete determination of the reaction matrix. The information available on the reaction $pp + d\pi^+$ includes an abundance of cross section data and reasonably comprehensive analyzing power measurements spanning the region 305-1000 MeV but only one set of spin-correlation experiments¹ at energies 440-578 MeV. In this and two accompanying papers^{2,3}, new spin-correlation and analyzing power data for the region 500-800 MeV are presented.

In this experiment, the LAMPF proton beam, vertically polarized (~80%), bombarded a vertically polarized (~80%) hydrogen target at energies of 500, 600, 650, 700, 733 and 800 MeV. Deuterons produced in the reaction $pp + d\pi^+$ were detected in a magnetic spectrometer equipped with four x-y multiwire proportional chambers (MWPC's) and two scintillator planes for determination of the deuteron trajectory and time-of-flight, which yielded a momentum and mass determination. The flight time and angle of the conjugate pion from the reaction were measured in a recoil arm containing two MWPC's and a scintillator plane. The pion angle determination was important for discrimination against quasifree $pp + d\pi^+$ reactions occurring in non-hydrogenic target components. The beam polarization was reversed every three minutes and was measured by the quench ratio method and also by scattering asymmetry measurements in a polarimeter. The target polarization was measured continuously by the NMR technique and was reversed in an up-down-down-up cycle of ~8 hr duration.

The experimental results are presented in Fig. 1. The statistical uncertainties are approximately the size of the plotted points. The normalization uncertainty due to beam and target polarization errors is ~5%. Also shown in Fig. 1 are the phase-shift predictions of Hiroshige *et al.*⁴ and isobar model calculations by Hiskanen⁵ and by Silber⁶. More realistic

FIGURE 1

Comparison of measured A_{nn} values (•) with phase shift predictions of Hiroshige et al.⁴ and isobar model calculations of Miskanen⁵ and Silbar⁶. The curves labeled D and S are different types of solution obtained in Ref. 4.

calculations by Rinat⁷ (too recently received for inclusion in Fig. 1) are in relatively good agreement with the data.

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PROGRAM I-i

"Phenomenology of πN Interactions"A The πN Data Base Star System

There are over 120 baryon resonance candidates listed in the 1982 edition of the Review of Particle Properties.¹ Many users of this helpful compilation do not realize that all basic information on the πN resonances, m , Γ , n , J , P , is extracted from the output of the two major partial wave analyses,^{2,3} and never comes directly from the experiments. New theoretical developments in the field of strong interactions have generated a renewed interest in hadron spectroscopy. Some current topics include investigations of the possible existence of glue balls, hemaphrodite matter, and dibaryons; a renewed search for isospin breaking; the determination of the πN sigma term; etc.

A partial wave analysis, PWA, such as for πN scattering, may be described as the best possible fit to the available πN data base in terms of unitary partial wave amplitudes with the correct analyticity properties. The data base is a compilation of all existing, relevant experimental results. It consists mainly of cross section and asymmetry data at different energies and angles. Usually there are several different possible fits to the experimental data and in order to obtain a unique set of phases a certain amount of theoretical input consisting of the unitary bounds and dispersion relations must be invoked.^{2,3}

The objectives of this πN scattering workshop are twofold:

1) To obtain the most reliable πN resonance parameters using the presently available experimental data. Since a PWA is no better than its data base, the first order of business must be to look at the accuracy and quality of the entries into the existing data base. We propose today to establish some reasonable standards for all the entries and to use 3, 2, 1, or no stars to categorize the quality of the data.

2) To provide a forum for suggestions for new experiments and better theoretical input that will substantially improve future PWAs and thereby our knowledge of the πN resonance parameters.

The size of the πN data base necessitates its handling via computer, e.g., the unexpurgated πN base from 0 to 1000 MeV currently has some 8500 data points from 645 different experiments! The three major data bases now in use - the ones from Karlsruhe,² CMU-LBL,³ and VPI⁴ - will be checked for

completeness by R. Arndt⁵ from VPI, and copies of data base tapes will be made available. We propose to have four categories of μN data base entries:

- a. Category A is reserved for three star data and is the most selective group. To qualify, the data must come from an impeccable experiment performed in recent times and published in a good, refereed journal. The publication should include a discussion of systematic and random errors, beam normalization, and detector calibrations.
- b. Category B consists of the two star experiments. These are still good data sets but with one of the strict criteria listed under a) not fulfilled.
- c. Category C has one star data. It contains some acceptable data, but there is a risk that data points are wrong, that the beam normalization or target thickness are incorrect, etc.
- d. Category D includes the no star data. This group contains all other available data; the only published data that are deleted are preliminary results that have been superseded by final values.

What are the criteria for obtaining the stars?

The first star is given when the experiment is published in a full-fledged, refereed journal, e.g., Physical Review, Nuclear Physics, etc. This requirement specifically excludes theses, conference contributions, laboratory year reports and the like. Also excluded, for reasons detailed below c), are the letter journals such as Phys. Rev. Lett., Phys. Lett., and Lettre al N.C. The article should indicate that the quoted numbers are the final result of the full analysis and are not a preliminary edition. The insistence on publication in a refereed journal with a good reputation is our main assurance that the data have been reviewed critically by someone who is not connected with the experiment.

The second star indicates that the data are of recent vintage. Most experiments performed in the fifties and sixties are outdated, and results published before about 1972 should be considered obsolete for the purpose of PWA except for a few special or unique data sets. The justification for this cut off date comes from the significant improvements in experimental techniques that have occurred in the last dozen years or so. Consider, for instance, the polarized targets. Instead of LNM targets with 3% free hydrogen and 50% polarization used in the early sixties, the modern experiments make use of propanediol or a similar type target material that has 6% free hydrogen with proton polarizations routinely above 80%. Another little advertised but significant technical improvement that has occurred is in the reproducibility of the NMR signals used for the monitoring of the target polarization, thus reducing the absolute polarization uncertainty from 10% to better than 3%.

Cross section measurements have improved as a result of using large computer power for the experiment and the data analysis. This helps in four ways: 1) better calculation of pion beam phase space; 2) better monitoring with the use of CAMAC; 3) more elaborate off line data analysis, e.g., in a recent πp elastic scattering experiment⁶ all pulse height, time of flight and coplanarity cuts were made off-line using 30 pion and 40 proton kinematic regions; 4) larger Monte Carlo simulations of the data gathering for more accurate evaluation of the effects of multiple scattering and inelastic reactions.

The third star is awarded when adequate coverage is given of systematic and random errors, the determination of the beam composition, spread, and momentum and the efficiencies of the detectors.

The final rating is the sum of the above three possible stars minus the antistars given because of the flaws which can be

- I. Experimental shortcomings such as
 1. no identification of scattered pion,
 2. no removal of reversed elastic events,
 3. poor detector calibration. This is particularly important for the neutron counters used in charge exchange measurements.
- II. Inconsistency with reasonable theoretical considerations such as
 1. $\int (d\sigma/d\Omega) d\Omega (\text{elastic}) > \sigma_t$,
 2. $d\sigma/d\Omega$ at $0^\circ < \text{optical point}$,
 3. large fluctuations in zero trajectories,
 4. $d\sigma/d\Omega$ is not smooth, varying more rapidly with angle than consistent with $\lambda(\text{max})$.

π^- charge exchange experiments are notoriously difficult to perform accurately as they have only neutral final state particles and the instant decay $\pi^0 \rightarrow 2\gamma$ complicates the geometry in $d\sigma/d\Omega$ measurements. Some groups have therefore chosen to simplify $d\sigma/d\Omega$ measurements by measuring only one photon in a zero constraint experiment reporting their results only in the form of Legendre polynomial coefficients. Such experiments must discuss the unfolding of the complicated photon spectra in detail paying sufficient attention to the propagation of errors. Unless this is done satisfactorily these experiments do not get more than one star in the final rating.

As a first step to the star assignment the new listing of the Karlsruhe Data Base will feature several new columns for preliminary evaluations. Detailed comments and rebuttals, if they exist, will be published separately in an informal set of reports called " πN Newsletter".

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B Review of Pion-Nucleon Elastic Scattering*

1. INTRODUCTION

According to a hypothesis of Gell-Mann¹ and Zweig² all baryon resonances consist of three quarks, thus qualifying for a review at a Few Body Conference. The lightest πN resonance, the Δ^{++} (1232), is made up of three u-quarks, $|\Delta^{++}\rangle = |uuu\rangle$. If this hypothesis is correct the u-quark must have two remarkable properties, namely a fractional electric charge, $Q(u) = +\frac{2}{3}e$ and parastatistics of order three, known as the "color degree of freedom".³

The general acceptance of the quark hypothesis comes partly from the fact that quarks provide a simple, qualitative basis for understanding the over 200 known hadron resonances. All baryon resonances can be arranged in a few series, the N, Λ , Σ , etc. series, each characterized by quantum numbers I, S, C, as illustrated in Fig. 1. This picture is based on the Table of Resonances from the Review of Particle Properties,⁴ RPP, our only regularly updated and generally accepted data compilation. A property of a long-lived particle listed in RPP, for example the mass of the π^+ meson, is the weighted average of different experimental measurements; in contrast, the mass, width, and quantum numbers of the πN resonances are not measured directly, their values are determined from the partial wave analyses, PWA. This may come as a surprise to many faithful users of the RPP Resonance Tables. It needs to be

emphasized that the Resonance Tables are still rather incomplete listings, furthermore, the quality of one or two star resonances is not equivalent to the standing of a one or two star restaurant; to the contrary, one and two star resonances are not well established, and several may disappear when better experimental data become available while new resonances may very well show up.

Fig. 1. Baryon resonances arranged in groups with the same I, S, C. The ordinate shows the mass. Data from Review of Particle Properties,⁴ 3 and 4 star resonances only.

Because of the important role that the πN resonances play in any quantitative quark theory it was deemed useful to have a workshop on πN scattering to discuss the many nagging uncertainties and the problems currently facing the πN PWAs. The workshop was held here in Karlsruhe on the Saturday preceeding this conference. Since a PWA is not better than its data base much of the discussion was centered around establishing criteria for evaluating the quality of the entries to the data base. A proposal was made for grading the experimental data assigning three, two, one, or zero stars to indicate the quality as outlined in Table 1.

A report on the workshop appears elsewhere in the proceedings and more information is available from G. Höhler and myself.

As an example of the confusing status of several resonance parameters consider the $P_{11}(1420)$ πN resonance. It is narrow in Germany and Finland as the Karlsruhe-Helsinki⁵ PWA gives a width of 135 MeV, it is broad in the United States where CMU-LBL⁶ gives $\Gamma = 340$ MeV, and the Roper resonance is split in two in France⁷ and Russia.⁸ This divergence of opinions is a direct consequence of the poor quality of the πN scattering data in the region of the Roper resonance as discussed in the πN workshop. Until the needed three star data become available, the $P_{11}(1420)$ parameters remain ill-defined and should not be used in support of theoretical work.

PROGRAM I-g

Neutron Counter Calibration Using Tagged Neutrons from the Reaction $\pi^-d \rightarrow nn$

The preliminary results of LAMPF Exp. #689 show that a high quality tagged neutron beam can be made using the reaction $\pi^-d \rightarrow nn$. Details of the experiment are given in last year's progress report. This investigation is the basis of a proposal for new research discussed under II-a.

TABLE 1
Outline of πN Data Base Star System

Data category	Data quality	Standards
A: ***	Impeccable	5/5
B: **	Good	4/5
C: *	Iffy	3/5
D: no star	Questionable	< 2/5

Standards:

1. Sufficient detail on calibrations, errors, ...
2. Full length article in good, refereed journal.
3. Modern measurement, published after about 1972.
4. No measurement shortcomings, e.g., lack of counter calibrations.
5. No inconsistencies with reasonable theoretical considerations, e.g., very rapid variations of $d\sigma/d\Omega$.

II. πN ELASTIC SCATTERING AMPLITUDES

A complete representation of π^+p elastic scattering free of ambiguities requires two independent amplitudes, e.g., the spin-nonflip, F , and the spinflip amplitude, G . The proof of this statement is based on rotation and reflection invariance⁹ and does not require time reversal invariance unlike nucleon-nucleon scattering.

The three reactions, $\pi^+p \rightarrow \pi^+p$, $\pi^-p \rightarrow \pi^-p$, and $\pi^-p \rightarrow \pi^0n$ are related by isospin invariance. The scattering amplitude may be divided further into two independent isospin parts as discussed below.

To determine the two complex amplitudes, F and G , without ambiguity, leaving aside the isospin decomposition, one needs three independent measurements namely the cross section, $d\sigma/d\Omega$, the left-right asymmetry, A_N , measured using a transverse polarized target, and the spin rotation angle, β , measured using a longitudinal polarized target. The connections with the amplitudes are:

$$d\sigma/d\Omega = |F|^2 + |G|^2, \quad (1)$$

$$A_N = 2 \operatorname{Im} (F^*G) / (|F|^2 + |G|^2), \quad (2)$$

$$\beta = \arg \left((F - iG \sin\theta) / (F + iG \sin\theta) \right). \quad (3)$$

There is a wealth of experimental data on $d\sigma/d\Omega$ and A_N but most is not of three star quality. There is no data on β below 6 GeV/c; consequently, the determination of F and G from Eqs. 1 and 2 above is racked with ambiguities. For example, both $d\sigma/d\Omega$ and A_N are invariant under the transformation:

$$F \pm iG \rightarrow (F \pm iG) \exp \left(\pm \frac{1}{2} i\phi \right), \quad (4)$$

with ϕ ($\theta=0$) = 0. An especially disturbing case known as the generalized Minami ambiguity occurs when $\phi = -\theta$ changing all scattering waves by one unit

of angular momentum, e.g., $S_1 \leftrightarrow P_1$ and $P_3 \leftrightarrow D_3$.

To compensate for the lack of data on the spin rotation angle all PWAs introduce some theoretical constraints to eliminate the many ambiguities and to select a solution in cases where there are several acceptable fits to the experimental data. The theoretical constraints used are: a) unitarity via the unitarity bounds on the scattering amplitudes; b) analyticity expressed in the form of forward, fixed- t or hyperbolic dispersion relations; c) isospin invariance. There is no need to worry about the validity of the unitarity bounds. The application of dispersion relations, which requires evaluating the dispersion integral including a contribution of the unknown distant part of the left hand cut, has been questioned since the forward scattering amplitude measured in $\pi^-p + \pi^-p$ around 20 GeV/c by Foley et al.¹⁰ does not agree with the predictions of forward dispersion relations. Recently new measurements have been reported by Fajardo et al.¹¹ and Burq et al.¹² up to 300 GeV/c incident π^- momentum which are in good agreement with the most recent dispersion relation evaluation by Höhler and Kaiser,¹³ see Fig. 2. This justifies our relying on the use of dispersion relations until spin rotation angle measurements become available.

Fig. 2. Test of forward dispersion relations. The solid line is the calculation by Höhler et al.^{13, 23} for $\pi^-p + \pi^-p$. The experimental points are: ∇ Fajardo et al.,¹¹ $\circ$ and $\times$ Burq et al.,¹² and $\triangle$ Foley et al.¹⁰

Isospin invariance is expected to be valid down to the level of the Coulomb corrections and the effects of the u- and d-quark mass difference. There are only two isospin amplitudes in πN scattering, $A_{1/2}$ and $A_{3/2}$, see Table 2.

Table 2
Isospin Decomposition

$$\begin{aligned}
 A(\pi^+p + \pi^+p) &\equiv A^+ = A_{3/2} \quad \text{and} \quad \sigma^+ \equiv |A^+|^2 = d\sigma/d\Omega(\pi^+p + \pi^+p) \\
 A(\pi^-p + \pi^-p) &\equiv A^- = \frac{2}{3} A_{1/2} + \frac{1}{3} A_{3/2} \quad \text{and} \quad \sigma^- \equiv |A^-|^2 = d\sigma/d\Omega(\pi^-p + \pi^-p) \\
 A(\pi^-p + \pi^0n) &\equiv A^0 = -\frac{1}{3}\sqrt{2} (A_{1/2} - A_{3/2}) \quad \text{and} \quad \sigma^0 \equiv |A^0|^2 = d\sigma/d\Omega(\pi^-p + \pi^0n)
 \end{aligned}$$

Isospin invariance in πN elastic scattering implies the relation:

$$A^+ - A^- = \sqrt{2} A^0. \quad (5)$$

This amplitude equality which holds at every energy and every scattering angle can be converted directly into triangle inequalities for the differential cross sections:

$$(\sqrt{\sigma^+} - \sqrt{\sigma^-})^2 < 2\sigma^0 < (\sqrt{\sigma^+} + \sqrt{\sigma^-})^2. \quad (6)$$

These relations provide a model independent test of isospin invariance. They hold for spin-averaged cross sections measured with an unpolarized proton target and also apply to the cross sections obtained using a transverse polarized target, separately for spin up and spin down, the so called transversity cross sections, $\Sigma_{\pm} = \sigma(1 \pm A_N)$.

Fig. 3. Violation of isospin invariance reported by the Gatchina group. The data points are $A_N (\pi^- p \rightarrow \pi^0 p)$ at $T_{\pi} = 550$ MeV from Ref. 16. The shaded region is forbidden by isospin conservation, it is calculated using the triangle inequality relations and the data from Ref. 14.-16.

Fig. 4. Test of isospin invariance using the triangle inequalities, Eq. 6, at 625 MeV/c. The squares are $d\sigma/d\Omega (\pi^- p \rightarrow \pi^0 n)$. The shaded area is obtained using $\pi^{\pm} p \rightarrow \pi^{\pm} p$ measurements and is forbidden by isospin conservation. Input data are from the UCLA group at LAMPF.¹⁷

It was somewhat of a surprise when the Leningrad group^{14,15} hinted that the bounds of Eq. 6 tested using transversity cross section measurements,

were violated in the region of the Roper resonance at backward angles, see Fig. 3, implying isospin violation. The data used for this surprise announcement were a mixture of recent Gatchina^{14,15} and some questionable Rutherford data.¹⁶ The UCLA group at LAMPF is in the process of measuring the three relevant cross sections and the three left-right asymmetries. Their preliminary results contributed at this conference,¹⁷ see Fig. 4, do not show a violation of the triangle inequalities in support of the approximate validity of isospin invariance in the region of the Roper resonance.

To alleviate the dependence of PWAs on theory and to check that the existing PWAs are on the right track, it is absolutely necessary that measurements of the spin rotation angle β be made. This is now realized at Gatchina¹⁸ and at LAMPF¹⁹ where measurements are being prepared.

III. COMPARISON OF πN PARTIAL WAVE ANALYSES

There are three major, modern partial wave analyses. The largest project, covering the momentum region from threshold to 10 GeV/c, is by the Karlsruhe group which is updating and expanding the original Karlsruhe-Helsinki PWA.⁵ Fixed- t and fixed- θ dispersion relations are used to compensate for the lack of spin rotation data and sometimes for imprecise experimental results. The second effort is spearheaded by R. Cutkoski who is continuing the original Carnegie-Mellon University-Lawrence Berkeley Laboratory PWA, CMU-LBL 79 and 80.⁶ This work covers the momentum region from 0.4 to 2.5 GeV/c and uses continuity along certain hyperbolas in the Mandelstam plane as theoretical input. The third and relatively new group is from VPI.²⁰ Aside from a report²¹ covering the low momenta region up to 0.4 GeV/c, no detailed information is available as yet. There are also several outdated PWAs and some special, fixed energy analyses.^{8,22} An encyclopedic treatise of all aspects of πN scattering by Höhler²³ in which these PWAs are included has just become available. We restrict ourselves here to a comparison of the results obtained by the K-H and CMU-LBL analyses.

There is good agreement between the resonance parameters obtained by both PWAs. Of the 26 3 or 4 star N and Δ resonances 23 agree in the mass value within the quoted error, 19 agree in the width and 24 in the elasticity, and for the others the differences are minor. The situation for the 1 and 2 star "resonances" is almost opposite: mass and width differ typically by 100 MeV and there is no agreement on the existence of 5 one star resonance candidates.

Finally, we compare both PWAs with experiments performed recently and not included in the data base. Shown in Fig. 5 is $d\sigma/d\Omega$ ($\pi^+p \rightarrow \pi^+p$) at $p_{\pi} = 586$ MeV/c measured at LAMPF by the UCLA group.²⁴ The systematic uncertainties in the data are about 2%. The agreement of both PWAs with the data is reasonable

except in the dip near $\cos\theta = -0.4$. The K-H result is slightly better than CMU-LBL. The left-right asymmetry, A_N , measured by the same group,²⁵ is shown in Fig. 6 for π^-p elastic scattering, again the agreement is reasonable except near $\cos\theta = -0.5$ where the old data used in the PWAs has large errors. This goes to illustrate that a PWA is not better than its data base.

Fig. 5. Comparison of recent $d\sigma/d\Omega$ ($\pi^-p \rightarrow \pi^-p$) data²¹ with predictions based on K-H⁵ (dashed) and CMU-LBL (dashed-dotted) PWA.

Fig. 6. Comparison of recent $\pi^-p \rightarrow \pi^-p$ asymmetry²⁵ data with predictions based on PWA, solid line is K-H,⁵ dotted is CMU-LBL,⁶ and dashed is VPI.²⁰

It is noted that K-H lists 24 N and Δ 1 and 2 star resonance candidates. In general, the existing experimental data are insufficient and/or inaccurate to assert the true nature of these 24 resonance candidates. More and better data are required before we can become confident about knowing the baryon resonances with natural flavor.

IV. CLUSTERS OF RESONANCE POLES

In his new πN handbook,²³ Höhler has made an interesting observation. It appears that many πN resonances have, within the quoted error, the same pole positions. This clustering of resonances has potentially interesting

consequences for the quark model and other theories of the strong interaction.

When there are several overlapping resonances with large inelastic channels, a unique and theoretically palpable definition of a resonance is non-trivial. The energy dependence of the elastic partial wave amplitude, in the ideal case, is given by a pure Breit-Wigner type formula:

$$A(W) = R_1 / (M - W - \frac{1}{2}i\Gamma) . \quad (7)$$

This equation implies that the resonance amplitude in an Argand diagram follows a counter-clockwise rotation, that the resonance phase shift increases rapidly near $\delta = \pi/2$ and that the speed of the resonance amplitude $|dA/dW|$ has a clear maximum. However, resonances are not purely elastic and besides the resonance part, A_R , there is a background component, A_B :

$$A = A_R (1 + 2i A_B) + A_B . \quad (8)$$

The modified Breit-Wigner resonance formula is:

$$A_R(s) = R(q) / [M^2 - s - iM \Gamma(q)] . \quad (9)$$

Most compilations characterize a resonance by the parameters M , Γ , and η where the resonance mass, M , is the c.m. energy at which the real part of the denominator of Eq. 9 vanishes; the resonance width, Γ , is taken at $W = M$ and so is the elasticity, $\eta = \Gamma_e / \Gamma_t$. A resonance can also be specified by the location of the complex pole of A which occurs in Eq. 7 when $W = M - \frac{1}{2}i\Gamma$ and by the value of the complex residue R_1 of Eq. 7. The difficulty with this definition is that one has to perform an analytic continuation of the scattering amplitude into the second sheet over an appreciable distance. Such an analytic continuation has been carried out by Cutkosky.⁶ The values for the real parts of the pole position are shifted in comparison with the values of the mass parameters, M , by different amounts in the range 0 to 100 MeV. When Höhler arranged the πN resonances according to their pole positions, he noticed several distinct clusters of resonances, as summarized in Table 3. It is important that selected new πN experiments be done to reduce the spread in uncertainty of the pole positions so the extent of the resonance pole clustering can be probed. It would, of course, be very interesting to determine the pole positions of the various Λ and Σ resonances to see if there is a similar clustering.

If further experimentation would strengthen the case for clustering rather than proving that Table 3 is a mere accident, it would have interesting consequences for the Isgur-Karl and other quark models.

TABLE 3
Clusters of πN Resonance Poles in the Complex Plane

N	Pole Position		Isospin	Name
	Re (MeV)	Im (MeV)		
6	1665±25	-55±15	1/2	S ₁₁ , P ₁₁ , P ₁₃ , D ₁₃ , D ₁₅ , F ₁₅
6	1880±30	-120±30	3/2	S ₃₁ , P ₃₁ , P ₃₃ , D ₃₅ , F ₃₅ , F ₃₇
5	2110±50	-180±50	1/2	D ₁₃ , D ₁₅ , G ₁₇ , G ₁₉ , H ₁₉

N = number of 3 and 4 star resonances

V. THE u- AND d- QUARK MASS DIFFERENCE

There are strong theoretical prejudices for the case of the u- and d- quarks having different bare masses. Weinberg²⁶ estimates $\Delta m = m(d) - m(u) = 3$ MeV and $m(d)/m(u) = 1.8$; a recent calculation by Gasser and Leutwyler gives $m(d)/m(u) = 1.76 \pm 0.13$ and Δm , which is more difficult to evaluate, about the same as Weinberg's value. Different u- and d- quark masses imply isospin violation; this holds also in QCD. Consider the usual QCD Lagrangian

$$L = L_0 - m(u) \bar{u} u - m(d) \bar{d} d - \dots \quad (10)$$

L_0 contains the quark and gluon kinetic energy and the interaction terms and is invariant under chiral $SU_N \times SU_N$ transformations. If $m(d) \neq m(u)$ this Lagrangian is manifestly isospin noninvariant. As Δm is only a few MeV the expected isospin breaking is of the same order of magnitude as the one induced by the isospin violating Coulomb interactions. It would be interesting to see some experimental manifestations of this intrinsic isospin violation, originating from the quark mass difference.

In the quark model $|\Delta^{++} (1232) \rangle = |uuu\rangle$ and $|\Delta^- \rangle = |ddd\rangle$. Naively we have $m(\Delta^-) - m(\Delta^{++}) = 3\Delta m$ or about 9 MeV. More refined estimates^{29,31} yield about 2/3 of this value, see Table 4.^{32,33} There are as yet no reliable measurements of this mass splitting. Fortunately, one can check a related, less sensitive mass difference namely $m(\Delta^0) - m(\Delta^{++}) = 2\Delta m$ which is experimentally accessible using $\pi^{\pm}p$ scattering; the status is shown in Table 4. The best determination is by Koch and Pietarinen³³ based on an update of the K-K PWA. The evaluation by Zidell et al.²¹ is not listed in Table 4 as the nearby left hand cut singularities were not included in the original πN partial wave parametrization, and the PWA is being updated.²⁰ Table 4 shows that the experiment favors $m(d) > m(u)$ with Δm having the expected magnitude, though there is room for a better determination.

TABLE 4

Mass and Width Differences between Members of the $\Delta(1232)$ Quartet

Theory		Ref.	Experiment		Ref.
mass $\Delta^- - \Delta^{++}$	mass $\Delta^0 - \Delta^{++}$		mass $\Delta^0 - \Delta^{++}$	width $\Gamma^0 - \Gamma^{++}$	
MeV	MeV		MeV	MeV	
4.5	1.6	28	2.7 ± 0.3	6.6 ± 1.0	32
6.9	3.0	29	2.7 ± 0.6	2.0 ± 1.8	33
4.5	1.3	30			
4.5	1.3	31			

Related to the preceding discussion is the direct measurement of an isospin violation in π^+p elastic scattering above the peak of the $\Delta(1232)$ which is experimentally easier. A group at SIN²² has carefully measured the asymmetry parameter, A_N , in π^+p elastic and π^-p charge exchange scattering and used their new data as input in a new simplified PWA. They have found a small, but clear difference in the P_{33} phases measured in π^+p and π^-p scattering:

$$\text{at } T_\pi = 238 \text{ MeV} \quad \delta_{33}(\pi^+p) - \delta_{33}(\pi^-p) = 1.61^\circ \pm 0.55^\circ \text{ and}$$

$$\text{at } T_\pi = 292 \text{ MeV} \quad \delta_{33}(\pi^+p) - \delta_{33}(\pi^-p) = 1.95^\circ \pm 0.44^\circ.$$

This is currently our best available evidence for an intrinsic -- not of Coulombic origin -- violation of isospin invariance.

VI. THE QUARK MODEL OF ISGUR AND KARL

At the "Baryon 1980" Conference, the Isgur-Karl, I-K, quark model³⁴ was hailed as the most successful quark model calculation of the baryon resonances made thus far. The model is an extended version of the early non-relativistic three-quark models of baryons based on an ad hoc flavor-independent confinement perturbed by hyperfine interactions that originate from one gluon exchange.³⁰

A review of both pre- and post- QCD quark models has just appeared³⁵ together with a discussion of existing experimental data and data analysis.

It is of interest to determine the level of agreement between the published πN resonance parameters, which are the best known set of resonance parameters and the I-K model calculations. The interest is enhanced by Hhler's observation²³ about resonance pole clustering. A global comparison between the Koniuk-Isgur³⁶ I-K model calculations and the Δ and N parameters listed in RPP⁴ is given in Table 5. Below about 1800 MeV all predicted resonances are observed, though often with a mass or πN decay amplitude just outside the quoted uncertainties. This is certainly a very nice accomplishment. The weak

aspect of the I-K model calculations occur at higher energies where there are three resonances predicted with a strong πN channel as well as seven weak ones that have not been seen, see Table 6. New πN scattering experiments are needed to clarify this matter.

TABLE 5
Comparison of Isgur-Karl Quark Model Predictions from Ref. 36
with Experimental Data from RPP, Ref. 4

Family	Mass		πN Amplitude		nN Amplitude	
	Correct	Incorrect	Correct	Incorrect	Correct	Incorr
N	6	5	8	3	7	4
Δ	5	3	4	4		

TABLE 6
Resonances Predicted by Isgur-Karl Quark Model, Ref. 36,
not seen by RPP, Ref. 4

Family	Strong	Weak	Name
N	2		$P_{13}(1870)$, $P_{11}(1890)$
N		5	$P_{13}(1955)$, $F_{15}(1955)$, $P_{13}(1980)$, $P_{11}(2055)$, $P_{13}(2060)$
Δ	1		$P_{31}(1875)$
Δ		2	$P_{33}(1975)$, $F_{35}(1975)$

TABLE 7
Comparison of the Experimental Radiative Decay Amplitude of some light
 πN Resonances with the Predictions³⁶ of the Isgur-Karl, I-K, Model

Resonance	Isospin	A_p		A_n	
		"Exp"	I-K	"Exp"	I-K
$P_{33}(1232)$	1/2	-141 ± 6	-103		
$P_{33}(1232)$	3/2	-258 ± 8	-179		
$P_{11}(1420)$	1/2	-70 ± 9	-24	$+42 \pm 19$	+16
$D_{13}(1520)$	1/2	-17 ± 11	-23	-69 ± 14	-45
$D_{13}(1520)$	3/2	$+166 \pm 7$	+128	-136 ± 14	-122
$S_{11}(1535)$	1/2	$+67 \pm 15$	+147	-78 ± 29	-119
$S_{11}(1650)$	1/2	$+45 \pm 17$	+88	-23 ± 33	-35
$D_{15}(1675)$	1/2	$+13 \pm 8$	+12	-37 ± 24	-37
$D_{15}(1675)$	3/2	$+22 \pm 12$	+16	-54 ± 24	-53

Amplitudes are given in the unit of $10^{-3} \times [\text{GeV}]^{-1/2}$

The radiative decay of the πN resonances is of particular interest as the magnitude as well as the sign can be determined using pion photoproduction. In the case of the neutral resonances it is preferred to use the inverse reaction, $\pi^- p + N^* \rightarrow n \gamma$ to avoid the deuteron corrections that trouble $\gamma n + \pi N$ experiments. Table 7 gives a detailed comparison between the I-K model and experiment for the 6 lightest resonances. The agreement for the sign of the decay amplitude is very good but the magnitude is usually well outside the quoted error, particularly disturbing are the discrepancies seen in the lowest two resonances, the $\Delta(1232)$ and the Roper, showing little improvement over the work of the pre-one-gluon-exchange era.

VII. HERMAPHRODITE BARYONS

In the early years of the quark age the pivotal role in understanding hadron spectroscopy was played by the quarks. All baryons were identified by the type and configuration of the three constituent quarks; the gluons were used only for binding and otherwise had a passive role. The introduction of the "color degree of freedom"³ has brought the emancipation of glue: 2 or 3 colored gluons can form a colorless and, therefore, observable object called a glueball, G. The experimental search for glueballs is just getting into full gear; the expected mixing with conventional (q^3) systems and possible occurrence of radially excited ($q\bar{q}$) or even ($q\bar{q}q\bar{q}$) states may make it hard to discover these glueballs.

TABLE 8

Comparison of the Mass of Positive Parity πN Resonances
Predicted for Hermaphrodites ($q^3 G$) and I-K Three Quark (q^3)
States with Experimental Data from RPP, Ref. 4

Mass in MeV				
# stars	Name	Exp	($q^3 G$)	(q^3)
4	P11	1440 $\pm$ 40	1430 $\pm$ 20	1405
4	F15	1680 $\pm$ 10	1980 $\pm$ 30	1715
3	P33	1700 $\pm$ 200	1600 $\pm$ 30	1780
4	P11	1710 $\pm$ 30	1680 $\pm$ 30	1705
4	P13	1745 $\pm$ 55	1770 $\pm$ 20	1710
4	P31	1900 $\pm$ 50	1800 $\pm$ 30	1875
3	P33	2010 $\pm$ 15	1960 $\pm$ 20	1925

If glueballs exist then there must also be hybrids of quarks and glueballs, (q^3G), called hermaphrodite³⁷ or meikton³⁸ matter. Since the πN system is the best known resonance system, it is a natural system to give us evidence for or against this proposed new hadronic matter. Golowich et al.³⁹ have calculated the expected (q^3G) spectrum of positive parity states using harmonic oscillator and a bag model. The result is shown in Table 8 and compared to the previously discussed Isgur-Karl three quark calculation.³⁶ On the basis of this table there is no need to invoke the existence of hermaphrodite baryons.

Barnes and Close⁴⁰ have considered the photoproduction of hermaphrodite baryons finding that the photoexcitation of the lightest candidates from a proton target is strongly suppressed but allowed from neutrons, not unlike the Moorhouse selection rule in the old quark model. They suggest that this eliminates the Roper resonance as a hermaphrodite baryon candidate as the radiative decay $P_{11}(1420) \rightarrow \pi\gamma$ is not suppressed, see Table 6. Instead, they propose the $P_{11}(1710)$ as a new candidate. We consider the case of the Roper candidacy not yet closed: suppose the new pion scattering experiments would find that the Roper actually has a double peak as originally suggested by Aved.⁷ Finding a single peak, charged radiative Roper and a double peak, neutral radiative one would be indicative of a (q^3G) state. New experiments on the radiative decay from the $P_{11}(1420)$ and $P_{11}(1710)$ from both the neutral and charged states will be very helpful in probing the proposed existence of the hermaphrodite baryons.

VIII. THE πN SIGMA TERM

Important among the low-energy results stemming from theories with broken chiral symmetry is the so-called πN sigma term, i.e., the nucleon expectation value of the equal-time (sigma) commutator of the axial-vector current with its divergence. The importance of the σ -term stems from the fact that it is directly proportional to the strength of chiral symmetry breaking. In the framework of QCD this can be calculated directly from the quark bare mass term:

$$\sigma = \frac{1}{2} (m_u + m_d) \langle N(p) | \bar{u}u + \bar{d}d | N(p) \rangle + \text{small isospin breaking term} . \quad (11)$$

Gasser and Leutwyler²⁷ recently have reviewed and updated the available calculations; they find $\sigma(QCD) = 35 \pm 5$ MeV, where older calculations give values from 20 to 40 MeV.⁴¹

The "experimental" value of the σ -term can be obtained from on-shell πN scattering amplitudes extrapolated to an unphysical point in energy⁴² using dispersion relations. Extrapolations published since 1973 have yielded values for the σ -term from 56 to 86 MeV.⁴¹ Recently R. Koch⁴³ has obtained $\sigma(\text{exp}) = 68$

± 8 MeV; in this new evaluation he makes use of hyperbolic dispersion relations and the $K\text{-}H^6$ PWA phases.

The σ -term is one of the few cases where a numerical prediction based on QCD together with a few reasonable dynamical assumptions can be tested experimentally at low energy. Thus, the discrepancy between "experiment" and theory looks interesting. Upon close inspection it turns out that the low energy PWA is not at all certain as it is based on no-star data. There is urgent need for new, accurate low energy πN data. A Karlsruhe group⁺⁺ at SIN is planning a careful measurement of the difference between π^+p and π^-p scattering in the Coulomb region with the aim of obtaining a reliable value for the σ -term.

IX. CONCLUDING COMMENTS

The salient features of this πN review have been summarized in the abstract. We want to stress here the need for new $d\sigma/d\Omega$, A_N , and δ data at intermediate energies: a) to resolve the fate of the 24 tiny peaks in various partial waves found by the partial wave analyses and euphemistically called one or two star resonances by RPP; b) to strengthen or dismiss the potentially very interesting case of resonance pole clusters; c) to provide a strong test of the Isgur-Karl quark model by settling the case of the 3 strong and 7 weak resonances predicted but not seen; d) to probe the possible existence of hermaphrodite baryons; e) to provide a new value for the πN sigma term.

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PROGRAM I-j

"Absolute Calibration of Proton Polarimeter"

A I Introduction

The essential element in our proposed "A" and "R" measurement for $\pi^\pm p$ elastic scattering is a large solid angle proton polarimeter. The device under consideration uses a carbon plate, up to 10 cm thick, to scatter the recoil protons. In the range of proton energies from 100 to 500 MeV similar polarimeters have been used very successfully to analyze the spin alignment of protons.¹ Besides the usual method of calibration using the polarized proton beam of area A and measuring the average rescattering angle for a particular polarization we propose to use $\pi^\pm - p$ elastic scattering as an excellent source of protons of known polarization. In a previous experiment, Program I-c, $A_N (=P)$ was measured at several momenta between 425 and 687 MeV/c. By selecting momenta and scattering angles at which P is large (Section C), we can calibrate our apparatus independent of other measurements of proton spin orientations.

B Equipment

The rescattering polarimeter consists of a carbon plate up to 10 cm thick, placed between four MWPC's: $X_1, Y_1 - 30 \times 30 \text{ cm}^2$, $X_2, Y_2 - 40 \times 40 \text{ cm}^2$; and four MWPC's $X_3, Y_3 - 50 \times 50 \text{ cm}^2$, $X_4, Y_4 - 100 \times 100 \text{ cm}^2$. Two scintillator hodoscopes of eight counters each will be used in coincidence as a trigger. These counters are sandwiched between the carbon plate and MWPC pairs 2 and 3, and are included as part of the rescattering material.

The entrance of the polarimeter will be 2 meters from the LH_2 target and defines a 23 msr solid angle.

C Measurements are considered at the following conditions:

P_π MeV/c	polarity	$\cos\theta_{cm}$	$P=A_y$	θ_p deg	P_p MeV/c	T_p MeV	θ_π deg	P_π MeV/c
586	-	0.45	-0.90	55	425	92	45	491
427	-	-0.60	+0.45	26	560	154	107	260
471	-	-0.55	+0.8	26	608	179	100	278
509	-	-0.55	+0.9	26	649	202	102	294
586	-	-0.45	+0.98	29	695	230	93	348

Pions will be scattered from a 2" LH_2 target supplied by the laboratory. The use of a negative pion beam greatly reduces the proton background inherent in a positive beam. During our running of Exp 120* we found that detecting pions in LAS and protons in our recoil arm greatly enhanced our ability to separate clearly signal from background. We shall follow this procedure in our calibration runs and since HERA will not be in place at the time of the calibration no modification in LAS will be necessary. The 30 x 30 cm front chamber of the polarimeter will approximately match the LAS acceptance.

We expect an analyzing efficiency of ~3% at these energies.¹ By comparison to our Experiment 120* measurement we should expect to take 100 hours of data per point (average). However, the use of PCOS III readout for the chambers in the polarimeter allows us to handle data at a much higher rate (a factor of 8-10). In experiment 120* the curved trajectory of the charged particles accounted for a 40% loss of events. This is not the case here. Thus we expect that an average run will take 9 hours. We add 3 hours overhead per point (beam time and detection system adjustment) to yield 12 hours per point average. We will take the five points listed above and three points with two different carbon plate thicknesses for a total of 8 points $\times \frac{12 \text{ hours}}{\text{point}} = 96 \text{ hours}$. We expect setup to take a full working week (24 hours x 5 days) of 120 hours for a total of 216 hours.

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PROGRAM II-a

TEST OF CHARGE SYMMETRY BY A COMPARISON OF $\pi^-d \rightarrow nn$ WITH $\pi^+d \rightarrow pp$

I Introduction

Charge symmetry in nuclear physics is the equality of the n-n and p-p interactions. For many years it was believed that pure hadronic interactions obey charge symmetry, C.S., and that the observed small violations are of electromagnetic origin. With the discovery of ρ - ω mixing came the possibility of a genuine (small) charge dependence of nuclear forces.¹ Recently it has become common to use QCD in discussing strong interactions. The basic QCD Lagrangian

$$L = L_0 - \bar{u}u m_u - \bar{d}d m_d \text{ ----}$$

with $m_u \neq m_d$, clearly violates isospin invariance.² Calculations³ show that the C.S. breaking effects are of the same magnitude as the Coulomb effects making experimental verification difficult. The best known test so far is a comparison⁴ of $\sigma_t(\pi^+d)$ with $\sigma_t(\pi^-d)$ in which a difference of -1% to +3% was seen for different incident pion momenta in the region of the Δ -resonance. This result is difficult to interpret due to the complications in calculating the Coulomb corrections⁵ in a total cross section measurement of a very inelastic reaction.

If C.S. breaking is due mainly to the difference in the u- and d- quark, there should be a mass splitting among the members of the Δ quartet of non-e.m. origin. Recall that $|\Delta^{++}\rangle = |u+u+u+\rangle$ and $|\Delta^-\rangle = |d+d+d+\rangle$, thus, $m(\Delta^-) - m(\Delta^{++}) = 3\Delta m$ where $\Delta m = m(d) - m(u)$. Current estimates are that $\Delta m = 3$ MeV or $m(\Delta^-) - m(\Delta^{++}) = 9$ MeV. Detailed calculations suggest a slightly smaller value.^{6,7}

We propose to investigate C.S. by comparing $d\sigma(\pi^-d \rightarrow nn)$ to $d\sigma(\pi^+d \rightarrow pp)$. The reaction $\pi^-d \rightarrow nn$ is the only feasible way to make a pure nn final state. All other measurements involve three body reactions. In the first stage we will measure $\pi d \rightarrow NN$ using counters relying on good time of flight measurements for background suppression. In a later stage we also want to compare the asymmetries in $\pi^-d \rightarrow nn$ to $\pi^+d \rightarrow pp$ using a polarized deuterium target. We plan to vary the

energy of the di-nucleon system by using different incident pion energies going from about $T_\pi = 140$ to 290 MeV. If C.S. is broken and the origin is the u- and d- quark mass difference, we expect the ratio $R = d\sigma(\pi^+d + nn)/d\sigma(\pi^+d + pp)$ to deviate from one, with $R > 1$ at $T_\pi \approx 140$ MeV and $R < 1$ at $T_\pi = 250$ MeV. If C.S. breaking is due to different meson exchange effects we expect R to deviate from 1.0 in a monotonic way.

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II Experiment

The equipment for this experiment is grouped into three categories:

1. beam related components,
2. target,
3. proton/neutron detectors.

1. The pion beam elements are:

- a) A beam hodoscope with fast timing capabilities that is located upstream. It is used to eliminate events with two pions in one beam bucket and to reduce the phase space of the pion beam.
- b) A vacuum pipe between the hodoscope and target with windows for μ -decay monitors and a helium bag between target and beam dump. These items reduce the scattering of the beam and the beam blow up and minimize the generation of unwanted background from pion interactions in air.
- c) Beam monitors. The relative π^+ and π^- beam intensities should be determined to an accuracy of 1%. We plan to use TOF method for this. Equipment include two μ -decay monitors, beam profile monitors and an in-beam counter.
- d) A good beam stop. To minimize the room background originating from the stopping pions in the beam dumps we like a cave-type or window frame type beam stop.

2. The target needed in this experiment is a standard cylindrical liquid deuterium target, 2" diameter and 4" high that is stable over the course of a run period of about two days. For background measurements we need a liquid hydrogen target of the same dimensions as the deuterium target.
3. The principal parts of the proton/neutron detector, the so-called nucleon detector, are two blocks of scintillators placed side by side; each block is 4" wide, 5" deep, and 9" high and viewed top and bottom by a photomultiplier. Having two photomultipliers on each block improves the vertical resolution to 3" and it does result in a position independent timing signal. Between the target and the thick counter is a 1/8" counter which is used as anticounter when neutrons are being detected and as coincidence counter for the protons. The proton/neutron detectors are located on trolleys at 1.5 to 3 meter from the target. They are well shielded using lots of cement bricks, polyethelene, and boronated paraffin. There are 8 identical counters, 4 are located on the left side of the target and the other 4 on the right side at the conjugate angles of the left side counters. Conjugate angle here means the angles governed by the geometry of the reaction $\pi d \rightarrow NN$.

DETAILED STATEMENT OF PROPOSED RESEARCH

Sheet of

Good $\pi^- d \rightarrow nn$ events are identified by the unique time of flight between the pion trigger from the beam hodoscope, H, and the neutron trigger from the nucleon detector, N, and the signal in the anticounter, A. Thus, the signature of a good event trigger is $H\bar{D}A$. A similar procedure holds for $\pi^+ d \rightarrow pp$ events, the difference is that we now require a trigger in counter A signaling a charged particle.

Half the time we use the four nucleon counters placed on the left side of the beam, the N_L -counters, for our cross section measurements while at the same time calibrating N_R , the four nucleon detectors placed on the right side of the pion beam at the conjugate angles to N_L for $\pi d \rightarrow NN$. The other half of the time the procedure is reversed and the N_R counters are used for the cross section measurements while calibrating N_L .

The efficiency measurement of the N-counters is clearly essential to the success of the experiment. The idea of the simultaneous calibration is quite simple. The process $\pi^- d \rightarrow N_L N_R$ in which N_L is detected provides the ideal tagged neutron beam for the N_R counters. Such a tagged beam has all the desired properties for a good calibration: the right neutron energy, detection geometry, etc. We plan to vary the distance from the N-counters to the target during the calibration runs.

Finally, the background runs are taken with a hydrogen target of the same properties as the deuterium target.

III Rates

The average counting rate per nucleon counter for $\pi^+d \rightarrow pp$ is 2 events per sec based on a beam of $10^6 \pi^+/\text{sec}$ and a solid angle of the N-counter of 10 msr. The counting rate for $\pi^-d \rightarrow nn$ is a factor of 10 less as the efficiency of the N-counter for neutrons is 10%. Thus, the data taking alone can be accomplished in about 1 day per incident energy yielding a statistical accuracy of 2%. The success of the experiment is determined by the careful, absolute calibration of the neutron detectors to a level of 2-4% and the relative π^+ and π^- beam calibration to a level of 1-2%. We estimate that this can be accomplished using 300 hours of dedicated beam time and 140 hours for data gathering. The 10 shifts of 8 hours each of parasite time are needed for beam tuning and shielding studies.

We expect to obtain an accuracy of 3-5% in testing charge symmetry in this experiment.

IV Test of Isospin Invariance

A precision measurement of the shape of the angular distribution of

$$n + p \rightarrow d + \pi^0$$

at $T_n = 795$ MeV has been reported recently.¹ The result is shown in Fig. 1.

The neutron energy corresponds to a pion energy in the inverse reaction of $T_\pi = 254$ MeV. When isospin invariance holds the shape of the angular distributions of the reactions $np \rightarrow d\pi^0$ and $\pi^+d \rightarrow pp$ are the same except for the effects of the electromagnetic interactions and the $(\pi^- - \pi^0)$ and $(n-p)$ mass differences which we discuss later, they cause no difficulties.

The requirements of isospin invariance, I.I., is more restrictive than charge symmetry, C.S. It is likely therefore that I.I. is violated more than C.S. Possible origins of I.I. violation are similar as for C.S. violations namely,

1) difference in coupling constant, g ,

$$g(p\pi^+) \neq g(p\pi^0) \text{ etc.}$$

2) intermediate state boson mixing such as

$$\rho \leftrightarrow \omega \text{ and } \pi^0 \leftrightarrow \eta$$

3) difference in u - and d - quark masses with the resulting mass splitting of the Δ -quartet,

$$m(\Delta^0) \neq m(\Delta^-) \text{ etc.}$$

The comparison of the existing measurement of the angular distributions of $np \rightarrow d\pi^0$ ¹ with $pp \rightarrow d\pi^+$ at $T_p = 800$ MeV² shows a small, tantalizing difference, but the size of the errors precludes drawing a firm conclusion as regards a possible isospin violation, see Table 1. Our proposed measurement at $T_\pi = 254$ MeV will give the needed improvement in the $pp \rightarrow d\pi^+$ data.

The existing evidence for a direct violation of I.I. is meager, we quote the recent measurement³ of a small difference of $\sim 1.5^\circ$ in the P_{33} phase measured in π^+p and π^-p elastic scattering and the well advertized difference in scattering

length between np and pp or nn.

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Table 1

Angular distribution coefficients of $np \rightarrow d\pi^0$, Ref. 1, at $T_n = 795$ MeV, and $pp \rightarrow d\pi^+$, Ref. 2, at $T_p = 800$ MeV.

<u>Reaction</u>	<u>A_2/A_0</u>	<u>A_4/A_0</u>	<u>A_6/A_0</u>
$np \rightarrow d\pi^0$	0.827 ± 0.012	-0.247 ± 0.013	-0.071 ± 0.017
$pp \rightarrow d\pi^+$	0.795 ± 0.016	-0.213 ± 0.016	-0.047 ± 0.020

Fig. 1 The angular distribution for the $np \rightarrow d\pi^0$ reaction measured in the present experiment, plotted versus $\cos^2(\Theta_{cm})$ with Θ_{cm} that of the deuteron. The symbol $\nabla(\Delta)$ is for center of mass angles less than (greater than) 90 degrees. The solid line represents the 6th order Legendre polynomial fit which best describes the data.

From Hallas et al

V Corrections for Electromagnetic Interactions

1. Bremsstrahlung.

The emission of soft photons, up to ~ 50 MeV, can be evaluated using the external emission dominance¹ approximation. The effect on $R \equiv d\sigma(\pi^+d + pp)/d\sigma(\pi^-d + nn)$ is less than one percent.

2. Coulomb energy shift, E_C .

There is as yet no unanimity on the calculation of this effect. Masterson et al.² quote $E_C = \pm 0.75$ MeV for πd elastic scattering at $T_\pi = 143$ MeV. Ingram et al.³ mentions $E_C = \pm 4$ MeV for pion elastic scattering on ^{16}O and $E_C = \pm 7$ MeV on ^{40}Ca at $T_\pi = 163$ MeV; on the basis of this they predict a 3° shift in the position of the first minimum for $\pi^{40}C$ while the experimentally observed shift is only $1\frac{1}{2}\%$. The effect on R in our experiment is $< 1\%$ at $T_\pi = 142-254$ MeV and $< 2\%$ at $T_\pi = 292$ MeV.

3. Coulomb distortion of the nuclear potential.

Again, there is some controversy about the best way for calculating this.

A. Reitan⁴ finds the effect on the cross section to be less than 1% .

4. Coulomb barrier difference.

W. Gibbs⁵ has pointed out that as a result of different Coulomb effects in the large inelastic channels-- $d\sigma(\pi^+d + \pi^0pp)$ is slightly different from $d\sigma(\pi^-d + \pi^0nn)$ -- the imaginary part of the π^+d scattering potential is not the same for π^-d . The effect in our case is very small, $< 1\%$.

There are several investigations^{2,3,7,8,9} of $\pi^\pm$ elastic scattering on d , 4He , ^{12}C , and ^{16}O at $T_\pi = 140$ to 260 MeV. They indicate that the electromagnetic interactions do not give rise to hidden surprises and effect the cross section only in a minor way except, of course, in the forward direction or in the region of the diffraction dips.^{9,10}

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VI Corrections for the (nn-pp) Mass Difference of the Final States

To evaluate the effect of the small (nn-pp) mass difference of the final states we express the cross section as a function of the variables s (= total energy) and t (= four momentum transfer) as follows:¹

$$d\sigma \sim \rho_N |M(s,t)|^2,$$

where ρ_N is the phase space factor which depends indirectly on the mass of the final state. The ratio of the density of states is $\rho(\pi^-d + nn)/\rho(\pi^+d + pp) = \tilde{\rho}_n/\tilde{\rho}_p$ which is about 0.996 for the five incident pion energies of our experiment.

The matrix element $M(s,t)$ depends on s and t . Except for the Coulomb energy shift the π^+d and π^-d interactions are compared at the same s in this experiment. The t -dependence of M is of course well known experimentally. So we can evaluate precisely the effects of the (nn-pp) mass difference in our experiment.

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VII The Mass Splitting of the $\Delta(1232)$

SU(3), SU(6), and various quark models¹⁻⁹ all enable one to obtain a reasonable idea about isospin breaking in the form of estimates of the masses and widths of isospin multiplet members. Of particular interest here are predictions about the Δ quartet. Table 1 gives a sample of some recent predictions.

The Δ^{++} and Δ^0 resonances have been studied in detail using π^+-p and π^-p elastic scattering and charge exchange. The experimental data are those of A. Carter et al.¹⁰ and Pedroni et al.³ and recent phase shift analyses of interest have been carried out by J. Carter et al.¹¹, Zidell et al.¹², and Koch et al.¹³ There is still a controversy about the details of the Coulomb corrections necessary to extract the masses and widths from the experimental data but everyone seems to agree that $m(\Delta^{++}) < m(\Delta^0)$ (see Tables 2 and 3). The Δ^+ resonance is known chiefly from photoproduction studies, particularly $\gamma p \rightarrow \Delta^+ \rightarrow p\pi^0$, but the data are not sufficiently accurate to extract meaningful values for the mass and width of the Δ^+ . The Δ^- resonance has not been studied in a direct production process due to the nonexistence of a neutron target.

VIII Estimate of Charge Symmetry Breaking Effect

The $\pi^+d \rightarrow pp$ total cross section as a function of the pion momentum in the c.m. is shown in Fig. 1. The dots represent measurements of $\pi^+d \rightarrow pp$ and the crosses measurements of $pp \rightarrow d\pi^+$, multiplied by the detailed balance factor. Examples of the angular distributions are given in Fig. 2. Since the two final state particles are identical, the angular distribution is symmetric about 90° in the center of mass.

The reaction process for $T_\pi \sim 150$ MeV is dominated by pion scattering on one nucleon, leading to the formation of a Δ intermediate state, followed by absorption of the scattered pion by the second nucleon¹⁸⁻²². Rescattering of the hadrons and Δ -N scattering take place as well but are not important for the present discussion.

The Feynman diagrams for the reaction $\pi^- d \rightarrow nn$ based on pion scattering are illustrated in Fig. 3a. The intermediate state resonances are Δ^- and Δ^0 . The process $\pi^+ d \rightarrow pp$ is shown in Fig. 3b: the intermediate states here are Δ^{++} and Δ^+ . The reaction $\pi^0 d \rightarrow np$ is illustrated in Fig. 3c and the intermediate states are Δ^+ and Δ^0 .

The following nomenclature is useful to refer to $I = 3/2$ amplitudes for πN scattering in various charge states:

$$\begin{aligned} f_{3/2}^- &: \pi^- n \rightarrow \pi^- n, \\ f_{3/2}^0 &: \pi^0 n \rightarrow \pi^0 n, \\ f_{3/2}^+ &: \pi^+ n \rightarrow \pi^0 p, \text{ and} \\ f_{3/2}^{++} &: \pi^+ p \rightarrow \pi^+ p. \end{aligned}$$

The $I = 1/2$ N scattering amplitudes $f_{1/2}$ are expressed similarly. In the spirit of Fig. 3 we can write:

$$R = \frac{d\sigma(\pi^- d \rightarrow nn)}{d\sigma(\pi^+ d \rightarrow pp)} = \frac{|3f_{3/2}^- + f_{3/2}^0 - f_{1/2}^0|^2}{|3f_{3/2}^{++} + f_{3/2}^+ - f_{1/2}^+|^2}.$$

In the vicinity of $T_\pi \sim 150$ MeV:

$$R \approx \frac{|3f_{3/2}^- + f_{3/2}^0|^2}{|3f_{3/2}^{++} + f_{3/2}^+|^2}.$$

The scattering amplitude, f , is related to the width, Γ , and mass, M , of a resonance and the center of mass momentum, p , as follows:

$$f = \frac{M\Gamma/p}{M^2 - S - iM\Gamma},$$

where $S = p^2 + m^2$. For a numerical example, one can use the values Γ and M from Ref. 6 and find that R is approximately 0.93 at $T_\pi = 150$ MeV, 1.0 at $T_\pi = 200$ MeV, and 1.08 at $T_\pi = 250$ MeV.

The amplitude analysis of the relation: $R_0 = d\sigma(\pi^- d \rightarrow nn)/d\sigma(\pi^0 d \rightarrow np)$, which is a test of isospin invariance, is similar to the one above. Note that the Δ^+ and Δ^0 intermediate states appear in identical fashion in the process $np \rightarrow d\pi^0$ [see Fig. 3(c)]. Therefore, no first order asymmetry around 90° is expected, even if isospin invariance is violated, i.e., $d\sigma(\pi^- d \rightarrow nn) \neq 2d\sigma(\pi^0 d \rightarrow np)$. A calculation of the asymmetry around 90° in $np \rightarrow d\pi^0$ based on $\pi^0 - n$ mixing has been given by Cheung et al.²⁵ The expected asymmetry everywhere is less than 1%.

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Table 1
Theoretical Predictions of Mass Differences
of the Δ Quartet

$\Delta^{++} - \Delta^+$ (MeV)	$\Delta^+ - \Delta^0$ (MeV)	$\Delta^0 - \Delta^-$ (MeV)	Ref.
0.8	-2.2	-3.4	6
0.4	-1.2	-2.7	7
0.4	-1.2	-2.7	8
-0.7	-2.3	-3.9	9

Table 2
Theoretical Predictions of M, p, Γ and Γ_T of Members
of the Δ Quartet, by Myhrer and Pilkuhn (Ref. 6)

Member	M (MeV)	Decay Mode	p (MeV/c)	Γ (MeV)	Γ_T (MeV)
Δ^{++}	1231.1	$p\pi^+$	226.4	111.5	111.5
Δ^+	1230.3	$\begin{bmatrix} p\pi^0 \\ n\pi^+ \end{bmatrix}$	$\begin{bmatrix} 227.8 \\ 224.5 \end{bmatrix}$	$\begin{bmatrix} 76.1 \\ 36.8 \end{bmatrix}$	113.5
Δ^0	1232.5	$\begin{bmatrix} p\pi^- \\ n\pi^0 \end{bmatrix}$	$\begin{bmatrix} 227.6 \\ 228.7 \end{bmatrix}$	$\begin{bmatrix} 38.3 \\ 76.7 \end{bmatrix}$	115.7
Δ^-	1235.9	$n\pi^-$	229.6	116.0	116.0

Table 3
Experimental Determination of the Mass and Hadronic Decay Width
of Δ^{++} and Δ^0 from π_T (πN) Measurements after Coulomb Corrections

Resonance	M (MeV)	Γ_T (MeV)	Ref.
Δ^{++}	1231.1 ± 0.2	111.3 ± 0.5	3
Δ^{++}	1230.9 ± 0.3	111.0 ± 1.0	13
Δ^{++}	1230.6 ± 0.2	113.2 ± 0.3	12
Δ^0	1233.8 ± 0.2	117.9 ± 0.9	3
Δ^0	1233.6 ± 0.5	113.0 ± 1.5	13
Δ^0	1232.5 ± 0.3	121.3 ± 0.4	12
$\Delta^{++} - \Delta^0$	-2.7 ± 0.3	-6.6 ± 1.0	3
$\Delta^{++} - \Delta^0$	-2.7 ± 0.6	-2.0 ± 1.8	13
$\Delta^{++} - \Delta^0$	-1.9 ± 0.4	-8.1 ± 0.5	12

DETAILED STATEMENT OF PROPOSED RESEARCH

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Fig. 1

DETAILED STATEMENT OF PROPOSED RESEARCH

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From R. Serre's data
Ref. 14 Fig. 2

$$\sqrt{2} \, f_{3/2}''$$

$$\frac{1}{3}\sqrt{2}(f_{3/2}^0 - f_{1/2}^0)$$

Fig. 3(a)

$$\sqrt{2} f_{3/2}^{++}$$

$$\frac{1}{3}\sqrt{2}(f_{3/2}^+ - f_{1/2}^+)$$

Fig. 3(b)

$$\pi^0 p \rightarrow n \pi^+$$

$$\frac{2}{3}(f_{3/2}^+ - f_{1/2}^+)$$

$$\pi^0 n \rightarrow n \pi^0$$

$$\frac{1}{3}(2 f_{3/2}^0 + f_{1/2}^0)$$

$$\pi^0 n \rightarrow p \pi^-$$

$$\frac{2}{3}(F_{3/2}^0 - F_{1/2}^0)$$

$$\pi^0 p \rightarrow p \pi^0$$

$$\frac{1}{3}(2 F_{3/2}^+ + F_{1/2}^+)$$

$$f(\theta) = F(180^\circ - \theta)$$

Fig. 3(c)

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Appendix

Comparison with $pp \rightarrow d\pi^+$ Data

There exists a fair amount of data on the reaction

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

most of it is not of the highest quality. However, the results by Hoftiezer et al.,¹ at $T_p = 575$ MeV corresponding to $T_\pi = 143$ MeV are stated to have an overall absolute precision of better than 2%, while Nann et al.,² quote $\pm 6\%$ at $T_p = 800$ MeV which corresponds to $T_\pi = 256$ MeV. They warrant a limited test of detailed balance. We are not concerned about a novel, large violation of time reversal invariance in the strong interactions that is waiting to be discovered. The comparison between $pp \rightarrow d\pi^+$ and $\pi^+d \rightarrow pp$ at present serves the purpose of intercalibrating different experimental techniques, pion beams, proton beams, etc. It seems to us a useful byproduct of the proposed experiment.

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PROGRAM II-b

"Measurement of $d\sigma(\pi^{\pm 3}\text{H} \rightarrow \pi^{\pm 3}\text{H})$ and $d\sigma(\pi^{\pm 3}\text{He} \rightarrow \pi^{\pm 3}\text{He})$ To Test Charge Symmetry"

We present here the results of a novel test of the validity of charge symmetry, C.S., at intermediate energy based on measurements of the superratio, R , which is the ratio of ratios of two pairs of conjugate charge symmetric reactions,

$$R \equiv \left(\frac{d\sigma(\pi^+{}^3\text{H} \rightarrow \pi^+{}^3\text{H})}{d\sigma(\pi^-{}^3\text{He} \rightarrow \pi^-{}^3\text{He})} \right) : \left(\frac{d\sigma(\pi^+{}^3\text{He} \rightarrow \pi^+{}^3\text{He})}{d\sigma(\pi^-{}^3\text{H} \rightarrow \pi^-{}^3\text{H})} \right) . \quad (1a)$$

If C.S. is valid R must be one at each angle at all energies. In this experiment, the superratio is measured as the product of two ratios such that the absolute normalization of the incident π^+ and π^- cancels,

$$R = \frac{d\sigma(\pi^+{}^3\text{H} \rightarrow \pi^+{}^3\text{H})}{d\sigma(\pi^+{}^3\text{He} \rightarrow \pi^+{}^3\text{He})} \cdot \frac{d\sigma(\pi^-{}^3\text{H} \rightarrow \pi^-{}^3\text{H})}{d\sigma(\pi^-{}^3\text{He} \rightarrow \pi^-{}^3\text{He})} . \quad (1b)$$

The great advantage of a measurement of R is thus that it does not depend on a careful measurement of the incident beam flux or the acceptance of the spectrometer used in our experiment. Another advantage of using R as a test of C.S. is that several corrections due to the Coulomb interactions cancel in first order.

The experiment was performed at the Clinton P. Anderson Meson Physics Facility using the EPICS spectrometer. We employed five identical target cells with different gases. Each cell was a 12 cm diameter stainless steel sphere of 0.06 cm wall thickness, equipped with a special fill tube that was welded shut after the sphere was filled to obtain a hermitical seal; it is a solid guarantee that the number of target nuclei remained unchanged throughout the experiment. The spheres were copper clad and covered with a gold flash to insure that the diffusion of tritium out of the target was well below the ambient tritium level in the EPICS cave resulting from interactions of the

beam in the windows and walls. The first sphere was filled with a mixture of tritium, amounting to 30,000 Curies, and deuterium with partial pressures of 1.0 MPa (10 atm) and 0.3 MPa, respectively. The second sphere contained a mixture of ^3He at 1.0 MPa and deuterium at 0.3 MPa. The admixture of the deuterium in both targets enabled us to simultaneously measure π -d scattering along with the π - ^3He and π - ^3H scattering. At $\theta_\pi = 40^\circ, 50^\circ, \text{ and } 60^\circ$ the π -d measurements were sufficiently accurate to provide a completely separate and very convincing check on the proper functioning of the beam monitor and the stability of the detection system. The three remaining spheres were used for calibration purposes: the first contained hydrogen at 1.3 MPa, the second was filled with deuterium at 1.3 MPa, and the third was an empty sphere for background studies.

The EPICS spectrometer was used to measure the elastic scattering of pions from $\theta_\pi(\text{lab}) = 40^\circ$ to 90° in steps of 10° at $T_\pi = 180$ MeV. At each angle we measured successively the π^+ yield from the tritium, ^3He , and hydrogen targets with the spectrometer tuned for the kinematics of pion-tritium elastic scattering. The ratio, $\rho_1 \equiv d\sigma(\pi^+{}^3\text{H})/d\sigma(\pi^+{}^3\text{H})$, is obtained directly from the yields,

$$\rho_1 = (\text{yield } ^3\text{H} - \text{yield bgd tgt})/(\text{yield } ^3\text{He} - \text{yield bgd tgt}) ,$$

where we used the hydrogen target for the background measurements. The measurement of ρ_1 was followed immediately by data collection on the hydrogen and empty targets with the spectrometer tuned for π -p kinematics to obtain a measure of the pion flux and spectrometer acceptance for use in the measurements of the "simple" ratios, r_1 and r_2 , that are discussed below. After the π^+ data at various angles had been gathered the data collection

sequence was repeated for incident π^- to measure the ratio $\rho_2 \equiv d\sigma(\pi^-^3\text{H})/d\sigma(\pi^-^3\text{He})$.

The superratio is obtained as $R = \rho_1 / \rho_2$; it is obviously independent of the absolute calibration of the π^+ and π^- beams and the spectrometer acceptance. The results for R are shown in Fig. 1, the error bars indicate only statistical uncertainties. The sole important systematic error is the one in the ratio of the pressures of the tritium and ^3He gases in the targets. The partial pressure of each target component was measured at the time of filling. At the end of the experiment the pressure in each cell was measured using a special device to open the sealed containers without loss of gas, followed by a mass spectroscopic analysis. A generous error of +3% and -1.5% is assigned to the ratio of the $^3\text{H}/^3\text{He}$ gas pressure, giving a +6% and -3% uncertainty in R . The shaded area of Fig. 1 indicates this systematic error. The superratio measured deviates substantially from 1.0 which is the predicted value when C.S. is strictly valid. The largest effect occurs at $\theta_\pi = 60^\circ$ where $R = 1.3 \pm 0.1$.

There are two other ratios measured in our experiment, the "simple" ratios, r_1 and r_2 , defined as:

$$r_1 \equiv d\sigma(\pi^+^3\text{H}) / d\sigma(\pi^+^3\text{He}) , \quad (2a)$$

$$r_2 \equiv d\sigma(\pi^-^3\text{H}) / d\sigma(\pi^-^3\text{He}) . \quad (2b)$$

If C.S. is valid, r_1 and r_2 are expected to be one also.

To eliminate the errors inherent in measuring accurately the pion flux of the EPICS beam and the acceptance of the EPICS spectrometer, we determined the ratios r_1 and r_2 from the pion scattering yields from tritium, ^3He , and hydrogen as follows:

$$r_1 = \frac{(\pi^+{}^3\text{H-bgd})}{(\pi^+{}^3\text{He-bgd})} \cdot \frac{(\pi^+{}^1\text{H-bgd})}{(\pi^+{}^1\text{H-bgd})} \cdot \left[\frac{d\sigma(\pi^+p + \pi^+p)}{d\sigma(\pi^+p + \pi^-p)} \right] \cdot \text{PWA} \quad \text{and}$$

$$r_2 = \frac{(\pi^-{}^3\text{H-bgd})}{(\pi^-{}^3\text{He-bgd})} \cdot \frac{(\pi^-{}^1\text{H-bgd})}{(\pi^-{}^1\text{H-bgd})} \cdot \left[\frac{d\sigma(\pi^-p + \pi^-p)}{d\sigma(\pi^-p + \pi^+p)} \right] \cdot \text{PWA}.$$

We have taken the "known" value for $[d\sigma(\pi^+p)/d\sigma(\pi^-p)]$ PWA from on the Karlsruhe-Helsinki¹ partial wave analysis. Fortunately, at $T_\pi = 180^\circ$ various partial wave analyses such as Karlsruhe-Helsinki¹ and VPI² are in agreement to within $\pm 3\%$. The results for the ratios r_1 and r_2 are shown in Fig. 2. The shaded area around $r = 1.0$ reflects $\pm 5\%$ uncertainty in the π^+/π^- normalization ratio stemming from 3% in $[d\sigma(\pi^+p)/d\sigma(\pi^-p)]$ PWA and 4% in the yields $(\pi^+{}^1\text{H-bgd})/(\pi^-{}^1\text{H-bgd})$, to which we have added the $(+3, -1)^{1/2}\%$ uncertainty in the ratio of the tritium to ${}^3\text{He}$ gas pressures. Note that a change in the π^+/π^- normalization would effect r_1 and r_2 in opposite ways.

External radiation of soft photons has been evaluated using the external emission dominance approximation³ and found to have less than one percent effect on the above ratios. The evaluation of the isospin violating Coulomb interactions is more complicated. The effect of the pure Coulomb interaction, $d\sigma = |A_C|^2$ with $A_C = 2\eta k F_\pi F_A/t$ and where the symbols have been defined in the literature^{4,6} is always less than 1% at our scattering angles. The Coulomb-nuclear interference term is $2 A_C A_N \cos\phi$ where A_N is the nuclear scattering amplitude and ϕ is the relative phase between A_C and A_N . At $T_\pi = 180$ MeV ϕ is near 90° making the interference term small⁷ but even in the highly implausible case that ϕ is not close to 90° , the maximum effect is still less than 5% in r_1 and r_2 and cancels in first order in R . The effect of the Coulomb energy shift, ΔE_C , also cancels in first order in R but not in r_1 and r_2 . There is some uncertainty about the magnitude of ΔE_C ; Masterson et

al.,⁸ use 0.75 MeV, for πd scattering at $T_\pi = 143$ MeV, Ingram et al.⁹ quote 4 MeV for O^{16} and 7 MeV for ^{40}Ca . The last value gives a shift in the position of the first minimum at $T_\pi = 163$ MeV of 3° , while only $\approx 1.5^\circ$ is observed. We estimate that the Coulomb energy shift could, at most, increase r_1 by 4% and decrease r_2 by a similar amount. The Coulomb distortion of the nuclear potential is expected to be small; an estimate by W. Gibbs⁹ indicates that the correction for this effect has the wrong sign to explain our measured ratios. We summarize the above in the statement that the Coulomb effects are too small to account for the observed derivations of the ratios R , r_1 and r_2 from one. The smallness of the Coulomb corrections in this experiment is due in part to our careful choice of incident energy at the peak of the Δ -resonance and to the large scattering angles. In a recent $\pi^\pm$ ^{12}C scattering experiment¹⁰ at $T_\pi = 180^\circ$, the π^+/π^- ratio was measured to be close to one except in very forward directions and in the diffraction dip, this corroborates our evaluation of the smallness of the Coulomb corrections which are much larger in ^{12}C due to its greater Z .

The magnitude of the observed derivations from the expectations based on C.S. can be studied in another way as follows: shown in Table 1 are the differences between C.S. related reactions measured in this experiment, $d\sigma(\pi^+{}^3\text{H}) - d\sigma(\pi^-{}^3\text{H})$ and $d\sigma(\pi^-{}^3\text{H}) - d\sigma(\pi^+{}^3\text{He})$ and measurements by others on deuterium⁸ at $T_\pi = 143$ MeV, $d\sigma(\pi^+d) - d\sigma(\pi^-d)$ and on ^4He ¹⁸ at T_π , $d\sigma(\pi^-{}^4\text{He}) - d\sigma(\pi^-{}^4\text{He})$. Besides the statistical errors given in Table 1, we have also listed the systematic ones. For the deuterium experiment we used $\pm 3\%$ based on the variation between the πp cross sections based on the various πp partial wave analysis^{1,2} and for the ^4He experiment we use $\pm 10\%$ as quoted by the authors.¹¹ At each angle the difference $d\sigma(\pi^-{}^3\text{H}) - d\sigma(\pi^+{}^3\text{He})$ far exceeds the differences measured with a deuterium or ^4He target which are consistent with

zero within error. The fact that $d\sigma(\pi^-3\text{H}) - d\sigma(\pi^+3\text{He})$ is larger than $d\sigma(\pi^+d) - d\sigma(\pi^-d)$ or $d\sigma(\pi^+4\text{He}) - d\sigma(\pi^-4\text{He})$ implies that the large deviation of R from 1.0 is not due mainly to a possible $d\sigma(\pi^+p) \neq d\sigma(\pi^-n)$ which would be a direct violation of C.S. Rather, it indicates that the origin of $R \neq 1.0$ stems from a difference in the hadronic properties of 3H and 3He . This is not the first time that the trinucleon system reveals C.S. breaking properties: the binding energy difference between 3H and 3He is 764 keV of which 87 ± 23 keV cannot be accounted for by electromagnetic interactions¹² and are therefore attributed to C.S. breaking interactions.

Detailed calculations show that the pure Coulomb repulsion between the two protons in 3He does not generate a large C.S. violation.¹³ Based on the approximate validity of the factorization¹⁴

$$d\sigma(\pi^3\text{H}) \sim d\sigma(\pi p) |F(3\text{H})|^2$$

where $F(3\text{H})$ is the tritium form factor one may speculate that there is a small difference in the 3H and 3He form factors. From $R = 1.3$ one obtains $F(3\text{H}) \approx 1.07 F(3\text{He})$ which is not inconsistent with measurement^{15,16} of the ratio $d\sigma(pd \rightarrow 3\text{He}\pi^+)/d\sigma(pd \rightarrow 3\text{He}\pi^0) \approx 2.2$. However, the full numerical analysis requires introducing spin flip and no flip πp scattering amplitudes as well as mass and spin form factors.

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Table 1

Differences in Differential Cross Sections Related by Charge Symmetry

units are mb/sr

θ_L	$\pi^+{}^3\text{H}-\pi^-{}^3\text{He}$	$\pi^-{}^3\text{H}-\pi^+{}^3\text{He}$	$\pi^+d-\pi^-d$	$\pi^+{}^4\text{He}-\pi^-{}^4\text{He}$
40°	$-0.1 \pm 0.4 \pm 0.6$	$+2.3 \pm .4 \mp 1.0$	$-0.2 \pm 3 \pm .2$	$+0.2 \pm 0.5 \pm 1.9$
50°	$+0.26 \pm 0.18 \pm 0.24$	$+0.6 \pm 0.2 \mp 0.3$	$-0.1 \pm .2 \pm .14$	$+0.2 \pm 0.1 \pm 0.5$
60°	$+0.12 \pm 0.10 \pm 0.08$	$+ .26 \pm 0.07 \mp 0.08$	$-0.1 \pm 0.1 \pm 0.07$	$+0.07 \pm 0.04 \pm 0.09$
70°	$+0.04 \pm 0.03 \pm 0.03$	$+0.05 \pm 0.02 \mp 0.02$	$-0.03 \pm 0.05 \pm 0.05$	$-0.013 \pm 0.004 \pm 0.015$
80°	$-0.01 \pm 0.01 \pm 0.01$	$+0.05 \pm 0.03 \mp 0.02$	$-0.07 \pm 0.04 \pm 0.04$	$-0.01 \pm 0.01 \pm 0.02$
90°	$-0.02 \pm 0.01 \pm 0.02$	$+0.05 \pm 0.02 \mp 0.01$	$-0.06 \pm 0.04 \pm 0.03$	
T_π	180 MeV	180 MeV	143 MeV	200 MeV

Super Ratio

11-b-9
 $T_{\pi} = 180 \text{ MeV}$
 $\pi_{\text{pressure}} = 0.533 \pm 0.02$

Fig. 1

46 0782

16-55 11 X 10 TO THE INCHES 7 X 10 INCHES
 EQUIP. CO. 11-10-55

$\frac{\pi^+T}{\pi^+3He}$ Ratio

$T_\pi = 180 \text{ MeV}$

$\pi^+p_{\text{initial}} = 0.533^{+0.006}_{-0.005}$

46 0782

π^+

10 X 10 TO THE (ICM) 2 X 10 INCHES
REINFORCED & LAMINATED CO. AND NOT

1.3
1.2
1.1
1
0.9
0.8

40° 50° 60° 70° 80° 90° θ_{lab}^π

Fig 2a

PROGRAM II-c

 $\pi^\pm$ Elastic Scattering on $^3\text{He}/^3\text{H}$ at Large Angles

The preliminary results of this LAMPF experiment #90 have been checked. The test of charge symmetry C.S. via the "simple" ratios is shown in Table 1. There is no evidence for a large violation of C.S. Typical cross sections are displayed in Fig. 1 and compared with theory.

$\bar{\theta}_\pi$	R_c		
	$P_\pi = 232 \text{ MeV/c}^a$	$P_\pi = 250 \text{ MeV/c}^a$	$P_\pi = 250 \text{ MeV/c}^b$
97.0		1.42 ± 0.41	
101.5	0.95 ± 0.38	1.12 ± 0.22	0.79 ± 0.12
106.6	0.96 ± 0.21	1.14 ± 0.21	0.96 ± 0.19
111.7	0.93 ± 0.14	0.99 ± 0.21	0.84 ± 0.14
116.7	1.22 ± 0.14	0.61 ± 0.20	0.76 ± 0.18
121.4	1.35 ± 0.17	0.99 ± 0.30	
126.4	1.06 ± 0.17	1.20 ± 0.71	
131.4	1.37 ± 0.21	0.76 ± 0.37	
135.4	1.00 ± 0.20	1.06 ± 0.54	
Av	1.11 ± 0.17	1.00 ± 0.23	0.83 ± 0.07
a) $R = \frac{d}{d}(\pi^-T \rightarrow \pi^-T) / \frac{d}{d}(\pi^+He^3 \rightarrow \pi^+He^3)$			
b) $R_c = \frac{d\sigma}{d\Omega}(\pi^-He^3 \rightarrow \pi^-He^3) / \frac{d\sigma}{d\Omega}(\pi^+T \rightarrow \pi^+T)$			

Table 1 Test of Charge Symmetry.

Fig. 1

Fig. 2

Fig. 3

PROGRAM II-d

Comparison of $p+d + {}^3\text{He}+\pi^0$ and $p+d + {}^3\text{H}+\pi^+$

Isospin invariance implies that the relation between the invariant matrix elements, M , evaluated at identical s and t ,

$$M(p+d+{}^3\text{He}^0) = \sqrt{2} M(p+d+{}^3\text{H}\pi^+) , \quad (1)$$

must hold after suitable corrections for Coulomb effects and mass difference have been made. To test validity of Eq. 1 using our measured cross sections we have considered the following four effects:

1. Our measurements were made at identical (or nearly identical) laboratory angles for the ${}^3\text{He}$ and ${}^3\text{H}$, leading to slightly different angles and momentum transfers in the center-of-mass.
2. The mass differences between π^0 and π^+ and between ${}^3\text{H}$ and ${}^3\text{He}$ result in a small difference in phase space between the two reactions.
3. The coulomb repulsion between the outgoing π^0 and ${}^3\text{H}$ is not present between π^+ and ${}^3\text{He}$.
4. The wave functions and form factors of the ${}^3\text{He}$ and ${}^3\text{H}$ differ because of the coulomb repulsion of the two protons in ${}^3\text{He}$ and because of the slight mass difference between protons and neutrons.

The difference between the Jacobians of the two reactions has already been considered in converting our differential cross sections to the center-of-mass system.

We have interpolated between our results to obtain differential cross sections for the two reactions at equal values of t (for t - momentum transfer squared in the center-of-mass). The correction is substantial up to 20% in the forward direction, near $t=0.4$ (GeV/c)², because of the rapid variation of $d\sigma$ with angle there. Near $t=0.1$ (GeV/c)², however, $d\sigma$ is nearly constant and the correction is negligible.

The difference in phase space between the two reactions is easily calculated from the reaction kinematics and the formula:

$$P = (p_c E_c E_d) / (E_c + E_d)$$

for the relativistic phase space for a two body reaction $a+b \rightarrow c+d$ (all quantities are in the center-of-mass). The phase space for $pd \rightarrow {}^3\text{He}\pi^+$ is 1.0% larger than that for $pd \rightarrow {}^3\text{He}\pi^0$ at 500 MeV.

It is difficult to account quantitatively for the coulomb interaction between the outgoing π^+ and ${}^3\text{He}$. An estimate by Kohler indicates that the effect at 500 MeV is to increase $d\sigma(pd \rightarrow {}^3\text{He}\pi^+)$ by about 1% relative to $d\sigma(pd \rightarrow {}^3\text{He}\pi^0)$. The effect is thus opposite in sign and roughly equal in magnitude to the correction for the phase space difference. We assume that the two effects almost cancel and so have not included the corrections explicitly.

The last of the four effects mentioned, that due to the difference between the ${}^3\text{H}$ and ${}^3\text{He}$ wave functions, has been considered in a very simple model by Kohler. His estimate is that it increases R by 6-8%.

We can consider the opposite approach and use our experiment to make a comparison between ${}^3\text{H}$ and ${}^3\text{He}$ at a large momentum transfer. To a first approximation we expect that after the first three corrections mentioned above have been made:

$\frac{\pi-T}{\pi+{}^3\text{He}}$ Ratio

II-b-11
 $T_{\pi} = 180 \text{ MeV}$

$\eta_{\text{Pressure}} = 0.533 \pm 0.040$

46 0782

PT

10 X 10 TO THE INCHES
REUTERS & ESKER CO. NEW YORK

1.4
1.3
1.2
1.1
1
0.9
0.8

Fig 2b

$$R \approx |F_{3H} / F_{3He}|^2$$

where the F 's are the transition matter form factors. There is no convenient way to relate these matter form factors to the electromagnetic form factors. The effect of the p-p Coulomb repulsion in ${}^3\text{He}$ is to make the ${}^3\text{He}$ radius larger than the ${}^3\text{H}$ radius, resulting in $F_{3H} > F_{3He}$, and thus $R > 1$. Our experimental results for R at 500 MeV, after effects 1-3 above have been accounted for, are shown in Table I. We find $R = 1.10 - 1.29$, depending on angle. It is difficult to say whether or not these values are consistent with isospin invariance without a detailed analysis of the effects of the Coulomb interaction and the mass difference between ${}^3\text{H}$ and ${}^3\text{He}$ and π^+ and π^0 .

$$\text{Ratio } \frac{d\sigma(pd + t\pi^+)}{2 \cdot d\sigma(pd + {}^3\text{He}\pi^0)}$$

corrected to same momentum transfer t in units $(\text{GeV}/c)^2$

$$T_p = 500 \text{ MeV}$$

<u>t</u>	<u>R</u>
0.116	1.10±0.03
0.428	1.26±0.04
0.398	1.29±0.08

PROGRAM II-e

 $\pi^\pm$ Elastic Scattering on Isotopes and Isobars of the Light Nuclei

To provide some perspective of the consequences of our results at $T_\pi = 180$ MeV of $\pi^\pm$ elastic scattering on ^3H and ^3He , Program II-b, we are comparing the π^+/π^- ratios, ρ , on various light nuclei reported in the literature. It is at once clear that our values for the superratio R cannot be explained by Coulomb effects. The ratios ρ deviate most from one at small angles, due to Coulomb nuclear interference, and at the diffraction minima.

Data:

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PROGRAM III-a

The Two-Body Photodisintegration of ^3He between 150 and 350 MeV

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ABSTRACT

Differential cross sections for ${}^3\text{He}(\gamma, d)p$ for incident energies between 150 and 350 MeV at center-of-mass proton angles near 60° and 90° have been measured with an absolute uncertainty of less than 6 %. The experiment used a single-arm spectrometer, a gas target and an uncollimated bremsstrahlung beam. The results are in good agreement with new measurements of the time-reversed reaction, $d(p, {}^3\text{He})\gamma$, giving no evidence for a violation of time-reversal invariance. The differential cross sections decrease smoothly with energy and show only a small contribution from the $\Delta(1232)$ resonance.

NUCLEAR REACTIONS ${}^3\text{He}(\gamma, d)p$, $E_0 = 150 - 350$ MeV; measured $d\sigma/d\Omega$ at $\theta_p(\text{c.m.}) \approx 60^\circ, 90^\circ$; tested detailed balance and time-reversal invariance.

I. Introduction

The two-body photodisintegration of ${}^3\text{He}$

and its inverse reaction

at energies near the $\Delta(1232)$ resonance provide an excellent system for testing time-reversal invariance (TRI) and for studying the dynamics of the three-body system. Cross sections for reactions (1) and (2) were measured around 1970 at Caltech and Berkeley by Heusch *et al.*,^{1,2} and the agreement of the cross sections with the detailed balance relationship was cited as evidence for TRI. However, other measurements of the cross section for reaction (1)³⁻⁶ disagree with the Caltech results by as much as a factor of two in either direction, and recent measurements of reaction (2)^{7,8} disagree, though less dramatically, with the earlier measurement. Such large discrepancies in the experimental data base have precluded meaningful tests of TRI and few-body calculations.

Time-reversal invariance implies that a reaction and its inverse (both averaged over polarizations) are related by detailed balance. For electromagnetic interactions of hadrons, however, current conservation prohibits the violation of detailed balance at the γ -N-N vertex, in which a real or virtual photon couples to a nucleon which remains on its mass shell.⁹ Thus, at low energy, observation of detailed balance in electromagnetic interactions is a test of current conservation and not of TRI. At vertices such as γ -N- Δ and γ -N-N*, however, TRI is needed to ensure that detailed

balance be satisfied. Meaningful tests of TRI by detailed balance in the electromagnetic interactions are therefore best performed in the resonance region, where these vertices play a significant role. Such tests have been performed using the reaction pairs $\gamma + d \leftrightarrow n + p$,^{10-12,13-14} $\gamma + n \leftrightarrow \pi^- + p$,^{15-18,19-21} and, as mentioned above, $\gamma + {}^3\text{He} \leftrightarrow p + d$.¹⁻⁸

The detailed balance relationship between differential cross sections involving unpolarized particles at the same center-of-mass energy and angle is

$$\frac{d\sigma(a+b \rightarrow c+d)}{d\sigma(c+d \rightarrow a+b)} = \frac{(2S_c+1)(2S_d+1)p_c^{*2}}{(2S_a+1)(2S_b+1)p_a^{*2}}. \quad (3)$$

The factors $(2S+1)$ are the spin multiplicities, and p_a^* and p_c^* are the center-of-mass momenta in the initial and final 2-body systems, respectively. (For the photon, $2S+1$ is replaced by 2.) For the reactions listed above, the interpretation of the detailed balance tests has been made especially difficult by the lack of agreement among measurements of the same process. Of the three reaction pairs, $\gamma + {}^3\text{He} \leftrightarrow p + d$ appears to be experimentally the most tractable as it involves neither a neutron beam nor the extraction of free-neutron cross sections from a deuterium target.

To resolve the large discrepancies among the four published data sets for ${}^3\text{He}$ photodisintegration at intermediate energies, we have performed a new measurement of this reaction using the MIT-Bates Linear Accelerator. The experimental approach was substantially different from those of the earlier measurements, and was chosen to minimize systematic errors. Preliminary results of this experiment have already been published.²² The

final results and a more detailed account of the experiment are presented here.

The present experiment differs from the previous measurements of ${}^3\text{He}(\gamma, p)\text{d}$ in several significant ways.

(i) Only the deuteron was detected. The deuteron production angle and momentum were measured in a high-resolution magnetic spectrometer. The single-arm technique eliminates the potential difficulties of acceptance matching inherent in a coincidence experiment, although special care is required to minimize and investigate backgrounds.

(ii) A gas target was used, eliminating the uncertainties involved in controlling and measuring the density of a liquid ${}^3\text{He}$ target. The target thickness was a small fraction of that of the liquid targets used in each of the previous experiments, greatly reducing the effects of energy loss and multiple scattering of the outgoing deuteron.

(iii) The incident photon beam was the full, uncollimated bremsstrahlung beam produced by a well-calibrated electron beam in a thin radiator of known composition and thickness. This allowed the absolute flux to be determined independently of quantameter calibrations and eliminated the possibility of introducing a net polarization of the photons as a result of collimation. Production of secondary particles in the beam by photon interactions in collimators was avoided, and the beam-target interaction volume was well-defined and small. Because the electron beam passed through the target, measurement and subtraction of electron-induced events was necessary.

(iv) The momentum calibration of the spectrometer was checked repeatedly during the experiment. This allowed the incident photon energy of each event to be determined accurately, a matter of considerable importance in measuring a cross section which varies rapidly with energy.

(v) With minor changes the spectrometer could be used to select electrons, protons, deuterons, tritons or ^3He 's. This feature allowed us to test the normalization factors used in calculating the cross section, and to measure the purity and density of the target gas by elastic electron scattering.

(vi) Cross sections were measured at a number of electron beam energies with overlapping photon-energy ranges.

In Section II we discuss the experimental technique in more detail. The analysis of the data is described in Section III, and the results are presented in Section IV along with comparisons to theory and to other experiments.

II. Experimental Method

A. Photon Beams

Cross sections were measured at two deuteron laboratory angles, 72.0° and 103.0° , corresponding to proton center-of-mass angles of approximately 90° and 60° , respectively. For each angle, measurements were made using electron beams of four energies: 275, 300, 325 and 360 MeV at 72° , and 210, 260, 310 and 360 MeV at 103° . Bremsstrahlung photons were produced in a thin radiator foil located inside the scattering chamber (Fig. 1), 15 cm from the center of the ^3He target. Tantalum was chosen as the radiator material after some early test runs were made using both tantalum and aluminum radiators. For the same thickness in radiation lengths, an Al

radiator of greater areal density is required, producing a significantly higher empty-target background.

The cross section measurements were made using a tantalum radiator foil 235 mg/cm² (0.0354 radiation length) thick. For comparison, additional measurements were made with tantalum radiators of thickness 93 and 441 mg/cm² (0.0137 and 0.0656 radiation lengths) or with a 284 mg/cm² copper radiator (0.0221 radiation lengths). The thickness of each foil was determined by weighing. A sample of the standard Ta radiator foil was determined by mass-spectroscopic analysis to consist of more than 99.9 % Ta. A thin (35 mg/cm² or 0.0009 radiation length) BeO screen attached to the downstream face of the standard 0.035-radiation-length tantalum radiator was viewed by a television camera in order to monitor the size and position of the electron beam on the radiator. The thickness of the BeO screen was included in the total radiator thickness used to calculate the photon spectrum.

Average beam currents in the range from 30 to 50 microamperes were used in the experiment. Two independent measurements were made of the flux of incident electrons on the radiator by integrating the current from two separate toroid beam monitors located between the beam switchyard and the target chamber. The toroids and integrators have been calibrated to the 0.1 % level,²³ and under the conditions of this experiment are believed reliable to ± 0.5 %.

At each electron energy, measurements were made for a range of photon energies from at least 10 MeV above, to approximately 80 MeV below, the bremsstrahlung endpoint energy. Because of the short distance between the radiator and the gas target, all the photons produced in the radiator were incident on the target. Thus, only a calculation of the full angle-integrated bremsstrahlung spectrum was necessary, a much more accurate and

reliable procedure than calculating the spectrum of a collimated photon beam, which depends on the angular acceptance.

The photon spectrum was calculated using computer codes based on three different parameterizations of thick-target bremsstrahlung.²⁴⁻²⁶ The three spectra obtained agreed to within 0.7 % over the entire photon spectrum to 10 MeV below the endpoint. (None of our reported results include data from the 10 MeV interval below the endpoint.) Because the thick-target corrections are small (<8 %), the calculated spectra is as reliable as the thin-target Bethe-Heitler formula^{25,27} with intermediate screening, to an accuracy of a few percent.

B. ³He Gas Target

The ³He gas was contained in a cylindrical aluminum cell of 10 cm diameter with its axis vertical. The target cell was a copy of the target used by Dunn et al.²⁸ in a measurement of elastic electron scattering from ³He. It was constructed by machining a 0.40-mm-thick, 38-mm-high window in a thick-walled aluminum cylinder which was welded to a solid aluminum plate on the bottom and to a liquid nitrogen reservoir above. Gas was transferred between the target cell and a storage cylinder through a thin transfer line by means of a diaphragm pump. The filling procedure consisted of evacuating the target and fill lines, filling with room temperature gas, recording the target pressure, cooling with liquid nitrogen and recording the final pressure. In both cases, pressures were recorded after thermal equilibrium was reached.

During the experiment the target was emptied and filled several times; the gas pressure in the target was slightly different after each filling and was typically 1.03 MPa (149 PSIA), measured to ± 0.3 %. The temperature of the target gas was calculated to be 80.6 ± 1.8 K based on the equilibrium

pressure measurements made during the filling sequence. The target density was calculated from the temperature and pressure of the gas; the typical density was about 4.6 mg/cm^3 . The target cell was valved off from the storage tank, so that the quantity of gas in the target remained constant during runs, although the temperature and pressure increased slightly as a result of beam heating. A small correction (less than 5 %) was made for the variation in local density due to beam heating. This correction was based on our measurements of electron scattering at various beam rates, and agrees with previous results obtained with this target system.²⁸

The purity of the gas was reported by the supplier²⁹ as greater than 99.9 %. The recoil-energy resolution of our electron scattering measurements was adequate to provide an on-line mass analysis of target composition for light nuclides. The target impurities observed in the spectra were a poorly-resolved multiple peak in the carbon-nitrogen-oxygen region, corresponding to less than 0.05 % by mass, and a ^4He component which increased from 0.6 to 1.0 % by mass in the course of the experiment. A mass-spectroscopic analysis of a gas sample after the experiment corroborated the latter ^4He value. The increase in ^4He content is thought to be due to small amounts of ^4He not purged from the system prior to the various ^3He fillings, and to diffusion through the rubber diaphragm during pumping.

C. Spectrometer and Detector System

Deuterons were detected in the Bates 900-MeV/c high-resolution spectrometer.³⁰ The trigger required a two- or three-fold coincidence in a set of 5 plastic scintillation counters,³¹ of thicknesses 1.6, 3.2, 12.7, 12.7 and 12.7 mm (Fig. 2). The deuteron momentum was measured by a set of multiwire chambers in the focal plane region.³² Because high resolution was

not necessary for our measurements, only the coarse momentum channels (each corresponding to one of the 100 wires of the vertical drift chamber without software interpolation) were used. This results in a channel width of 0.06% in deuteron momentum. The photon energy was calculated from the deuteron kinematics: the bin width in photon energy was less than 0.5 MeV. The photon energy resolution was dominated by the angular acceptance of the spectrometer and the finite target size, and varied from 1.2 MeV to 4.5 MeV FWHM.

The usable momentum acceptance of the spectrometer was $\pm 2.8\%$. In order to cover the desired photon energy ranges, the spectrometer magnetic field was varied in overlapping steps. The magnetic field was measured by an NMR probe in each of the two dipole magnets which compose the spectrometer. The calibration of the spectrometer field was verified by means of measurements of elastic electron scattering and by an evaluation of the bremsstrahlung endpoint energy in $^3\text{He}(\gamma, d)p$ spectra.

The angular acceptance of the spectrometer was determined by two pairs of remotely-driven jaws which define the horizontal and vertical apertures. The spectrometer jaws were set to define a solid angle of 2.00 msr (± 7.9 mr horizontal by ± 63.4 mr vertical) at the center of the target cell. A steel-and-tungsten slit with a 2.54 cm horizontal aperture was used inside the scattering chamber to prevent the spectrometer from viewing the target cell windows (Fig. 1). These apertures defined a product of target length times solid angle which was equal to 5.61 cm-msr when the spectrometer angle was 72° and 5.48 cm-msr at 103° , each known to a precision of $\pm 2\%$. The edges of the target-defining slit consisted of cylindrical tungsten rods 0.95 cm in diameter. Each rod was embedded in, and protruded 0.76 mm from, a steel block 2.54 cm thick whose inner faces sloped outward toward the spectrometer to eliminate slit face scattering. The use of dense material to form the

slits minimizes particle penetration of the slit edges; penetration by deuterons with momenta in the spectrometer acceptance range was calculated to contribute a background of no more than 0.7 % under the conditions of the experiment.

For each event, spatial information from the focal plane chambers and pulse heights from the five scintillation counters were recorded. Discriminator thresholds were set well below the pulse height for deuterons at each spectrometer field setting. The event trigger accepted all deuterons, as well as many protons which were easily rejected in subsequent analysis.

D. Run Procedures

The measurements at two spectrometer angles and four endpoint energies at each angle result in eight data sets which compose the main part of the experiment. Four or five overlapping magnetic field settings were used at each endpoint energy in order to measure the desired range of photon energies. For each data set and field setting, four different types of runs were required:

- (1) radiator in, target full (IF)
- (2) radiator out, target full (OF)
- (3) radiator in, target empty (IE)
- (4) radiator out, target empty (OE)

The IF runs include the true ${}^3\text{He}(\gamma, d)p$ events. The OF runs measure the yield due to electron interactions in the target, which are also present in the IF runs and must be subtracted by a procedure described in Section III. The IE and OE runs measure a small background which is subtracted from the full-target data.

In addition to the main data set described above, several auxiliary data sets were taken for the purpose of calibration and testing. These measurements include:

- (i) runs in which only a single parameter was changed, such as radiator thickness and material, gas pressure, or spectrometer acceptance,
- (ii) elastic electron scattering from ^3He ,
- (iii) deuteron photodisintegration: $d(\gamma, p)n$,
- (iv) $^4\text{He}(\gamma, ^3\text{H})p$, and
- (v) $^4\text{He}(\gamma, d)$.

The experimental changes required for these supplementary measurements were small, consisting only of changing the target gas, adjusting the gain on the scintillator output pulses, or, for the electron scattering measurements, reversing the spectrometer field.

III. Analysis and Tests

A. Event Reconstruction and Selection

The measurement of the angle and energy of the deuteron is sufficient to determine the kinematics of a $^3\text{He}(\gamma, d)p$ event. (Deuterons produced in multi-particle final states, such as $d-N-\pi$, are kinematically excluded for photon energies within 120 MeV of the end point.) The crux of the experiment is the ability to ascertain that the detected particle is in fact a deuteron. The deuteron energy was always greater than 38 MeV, enough to pass through at least two of the five trigger counters. For particles of equal momentum, as selected by the spectrometer, the ionization energy loss of a deuteron was about twice that of a proton and 2/3 that of a triton, so

that the pulse height data in several counters provided the basis for a clean separation of deuterons from background particles.

Figure 3(a) shows the distribution of raw events according to pulse height and momentum in counter 1. Distinct groups corresponding to protons, deuterons and tritons are clearly seen. As the discriminator threshold for each of the trigger counters was set safely below the deuteron distribution, many protons were accepted. The observed tritons cannot be produced by any one-step reaction on ^3He , and originate in the target walls. Even if they were not rejected on the basis of pulse height, most tritons would be eliminated by the empty-target subtraction. The slope and curvature of the particle distributions are due primarily to the attenuation of light in the long scintillation counters. The pulse height was corrected to a position-independent value by means of empirical correction functions fitted to the data. After correction, the deuteron events form a distinct peak in each counter. When pulse heights in 2 counters are correlated (Fig. 3(b)), the deuterons are even more easily identified. The final selection of deuteron events was made on the basis of cuts on corrected pulse height correlated in two or more counters. A small number of events, normally fewer than 1 %, did not fall neatly into a particle classification, having deuteron-like pulse heights in the upstream counters but anomalously high pulse heights in the downstream counters. These were interpreted as due to deuterons interacting in the upstream counters and were accepted.

The selection cuts were determined separately for each radiator-in, full-target run (category IF defined in section II-D.) For the background runs (OF, IE and OE), which had far fewer events, cuts were made using the values determined for the associated IF run.

The events which passed these cuts were then normalized to the total charge of the incident electron beam as measured by the beam toroid

integrators and corrected for losses due to dead time and detector inefficiencies. During a typical beam pulse of 15 μ s width and 6 to 10 mA peak current, there were typically several background events in the wire chambers uncorrelated with a valid trigger signal. If one of these events occurred within ~ 300 ns of a good event, it had a high probability of confusing the delay-line electronics and causing the event to be rejected in the subsequent analysis. Wire chamber inefficiencies result in a similar rejection. A simple algorithm, whose applicability was checked by examining the raw data from the drift chamber delay lines, was used to correct for these rejected events. Another type of dead time arises because the electronics could not digitize more than one set of scintillator signals per beam burst. By counting the number of such unanalyzed events (usually less than 3 %) one can correct in a straightforward manner for these losses. The total correction for both categories was normally between 3 and 5 %, ranging up to 12 % in a few runs at the highest counting rate.

B. Event Subtraction

The radiator-in, full-target runs (IF runs) contain two types of deuteron background: (i) deuterons produced in multi-step reactions, or rescattered after production, and (ii) events induced by the electron beam passing through the ^3He target, either via additional real photons produced in the target walls and gas, or through the electrodisintegration reaction $^3\text{He}(e,e'd)p$. The latter process is the dominant background; a simple calculation using the Dalitz-Yennie virtual photon model³³ predicts the $(e,e'd)$ contribution to be approximately 30 % of the total event rate with the standard tantalum radiator. When the radiator is removed (as in the OF runs), electrodisintegration is the dominant process.

In the limit of an infinitely thin radiator, the rate of good ${}^3\text{He}(\gamma, d)p$ events is given by the simple subtraction

$$R_{\text{In}} - R_{\text{Out}} = (R_{\text{IF}} - R_{\text{IE}}) - (R_{\text{OF}} - R_{\text{OE}}) . \quad (4)$$

The last four subscripts refer to the categories defined in section II-D, and the rates are normalized as described in section III-A. The relative magnitudes of the four rates are shown in Fig. 4(a). The spectra have been converted from the form $R(P)$, where P is the deuteron momentum, into the form $R(k)$, where k is the effective photon energy, i.e., the energy of a photon required to produce a deuteron of the given momentum P at the specified angle via the reaction ${}^3\text{He}(\gamma, d)p$. For both photodisintegration and electrodisintegration events, k must be less than the electron beam energy. The endpoint is clearly discernible in the full-target rates (IF and OF) of Fig. 4(a).

The finite thickness of the radiator complicates this subtraction, as the electrons which pass through the ${}^3\text{He}$ target in the IF and IE runs have been degraded in energy by the radiator, and thus produce a slightly different spectrum of deuterons than do the undegraded electrons in the OF and OE runs. The electron-induced counting rate in a spectrum bin is a function of both the effective photon energy k and the electron energy E . For a bin of effective photon energy k , the desired subtraction is

$$R_{\gamma}(k, E) = R_{\text{In}}(k, E_0) - \int_k^{E_0} R_{\text{Out}}(k, E) (dN/dE) dE , \quad (5)$$

where E_0 is the incident electron energy and dN/dE is the differential energy spectrum of electrons emerging from the radiator. The quantity dN/dE can be calculated by the simple formula³⁴

$$dN/dE = [E_0 \Gamma(t')]^{-1} [\ln(E_0/E)]^{t'-1} \quad (6)$$

where Γ is the gamma function, and t' is the radiator thickness in radiation lengths divided by $\ln 2$. This formula is not significantly different from more elaborate formulas quoted by Tsai;²⁵ its adequacy was verified by means of a Monte Carlo shower calculation using the Stanford EGS code.³⁵ The integral in Eq. (5) was evaluated numerically using 5-MeV bins. The integrand for the highest-E bin (which includes more than 80 % of the electrons) was evaluated using $R_{out}(k, E_0)$. For the lower-E bins, $R_{out}(k, E)$ was approximated by fitting empirical curves to the data taken at the four values of E_0 ; the variation with E over the necessary range is small enough that one can be confident of the extrapolation. The degraded-energy subtraction of Eq. (5) typically results in a 5 % higher cross section than the simple subtraction given by Eq. (4). An example of the result of this subtraction is shown in Fig. 4(b).

As shown in Fig. 4, the region of effective photon energy above the endpoint has very few counts in the individual rates. Although most of this background is removed automatically by the subtractions discussed above, a small, apparently flat, residual background is observed above the endpoint in some runs. A constant background, equal to the average rate observed above the endpoint, was subtracted from the radiator-in and radiator-out data separately. This adjustment resulted in a reduction of 1 to 6 % in the event rate for the highest energy bin of each subtracted spectrum, and had a much smaller effect on the lower energy bins. (The absence of more significant backgrounds is demonstrated in Section F below.)

C. Energy Calibration

As can be seen from the raw and subtracted spectra of Fig. 4, the counting rates for this reaction are strongly dependent on photon energy. For this reason, it is essential that the photon energy of each event be well known. In our experiment, the photon energy was determined by reconstruction of the 2-body kinematics of the event using the deuteron momentum and angle. In order to test the photon energy reconstruction, we performed least-squares fits to the event spectrum in the endpoint region, with the endpoint energy as one of the varied parameters, using the theoretical bremsstrahlung spectrum shape near the endpoint,²⁶ corrected for resolution, and a simple parameterization of the cross section. Despite the limited statistics, the endpoint energy can be fit with a statistical uncertainty of less than ± 1 MeV (Fig. 5). In all cases the result is within 2 MeV of the beam energy as determined from the beam switchyard magnet calibrations. The beam energy was also confirmed by the electron scattering measurements which were made during our experiment. Combining the results of all runs, we obtain an uncertainty of ± 1.2 MeV in our reconstructed photon energy, far better than in previous measurements of this reaction.

D. Cross Section Calculation

The differential cross section for the bin of photon energy $k \pm \Delta k/2$ is:

$$d\sigma/d\Omega = \epsilon \frac{Y(k)J(k, \theta)}{N_Y(k)\rho(L\Delta\Omega)}, \quad (7)$$

where $Y(k)$ is the net number of good events in each bin (corrected for dead

time and chamber inefficiency), ρ is the target gas density, $L\Delta\Omega$ is the product of target length viewed by the spectrometer and the spectrometer solid angle (Section II-C), and $J(k,\theta) = d\Omega(\text{lab})/d\Omega(\text{c.m.})$ is the kinematic conversion factor from laboratory to center-of-mass cross sections. $N_\gamma(k)$ is the number of incident photons in the energy interval Δk (10 MeV in our analysis.) It is proportional to the integrated electron charge, the radiator thickness, and the bremsstrahlung spectrum calculated as described in Section II-A. The factor ϵ contains the following small corrections to the cross section:

- (i) deuteron losses through interactions in the target wall, spectrometer end window, chambers and upper counter (1.5 %);
- (ii) reduction of the local gas density in the target because of beam heating (3.8 to 5.5 %);
- (iii) contributions of 1.5 to 3.7 % from the ^4He and heavier impurities in the target gas based on the measured contaminations and on measurements of the yield of deuterons from a ^4He -filled target.

The normalization factors and uncertainties are summarized in Table I.

E. Tests of Normalization

Because of the wide variations among the previously reported measurements of this reaction, we felt it was imperative to calibrate our measurement in as many ways as possible within the allotted running time. Our comparisons were of two different types: "internal" (measurement of the same $^3\text{He}(\gamma,d)p$ cross section with different experimental parameters), and "external" (measurement of other reactions with only small changes in our experimental configuration). These tests are discussed below and summarized in Table II.

1. External Tests

a) Elastic Electron Scattering

Measurements of elastic electron scattering from ^3He were made for incident energies of 180 MeV at 72° and 210 MeV at 103° . The elastically scattered electrons formed a background-free peak in the focal plane. The summed counts in the peak, corrected for radiative energy loss, yielded values of the ^3He elastic form factor (Fig. 6(a)) which agreed within 2 % with the results of previous experiments.^{28,36,37} The normalization of these experiments is not substantially in doubt because of the strong theoretical requirement that the distortion-corrected form factor extrapolate to 1 at zero momentum transfer. Thus our measurements constituted a powerful check on several important factors in the $^3\text{He}(\gamma, d)p$ cross section: electron beam intensity, target density, effective target length and solid angle. Including the quoted uncertainties of the previous measurements of $^3\text{He}(e, e)$ and the effects of the uncertainty in incident energy (< 0.5 MeV), the sensitivity of this normalization test is better than 4 %.

The (e, e) measurement afforded several additional checks on systematic effects.

(i) Target impurities were accurately determined by measuring the elastic scattering peaks due to the contaminants and comparing them to known elastic scattering cross sections for ^4He ³⁶ and ^{14}N .³⁸⁻³⁹

(ii) The position of the elastic peak in the focal plane checked the momentum calibration of the spectrometer and the energy calibration of the electron beam.

(iii) By varying the spectrometer field to step the elastic peak along the focal plane, we confirmed the uniformity of the efficiency of the chambers and scintillators.

(iv) by varying the electron beam current by a factor of 3, we checked the effects of beam heating on the target gas density.

b) Deuteron Photodisintegration

Differential cross sections for $d(\gamma, p)n$ were measured for photon energies between 250 and 320 MeV at 72° (approximately 90° in the CMS). In this region, the most recent published measurements^{10-12,40} of this process agree to within $\pm 8\%$. Our measurement is fully consistent with these (Fig. 6(b)). In this case, the factors tested also include the radiator thickness and the calculated bremsstrahlung spectrum. Our excellent agreement with the most recent measurement at Bonn,⁴⁰ using tagged photons, is especially significant, as the tagged-photon measurement is free of uncertainty in the photon flux, one of the limiting errors in any bremsstrahlung measurement.

c) Two-body Photodisintegration of ^4He

A measurement of $^4\text{He}(\gamma, t)p$ was made with photon energies near 250 and 290 MeV, detecting the triton in the spectrometer at 103° . The resulting cross sections (Fig. 6(c)) agree well with published results from Saclay¹⁵ and Bonn.⁴¹ This provides an additional independent test of the overall normalization.

2. Internal Tests

a) Variation of Endpoint Energy

For most measured photon energies, cross sections were obtained from data taken at two or more endpoint energies. If correctly measured, the photodisintegration cross section at a given photon energy must be independent of the endpoint energy of the bremsstrahlung beam, but in an experiment two types of endpoint-dependent effects might be anticipated: those due to incorrect calculation of the bremsstrahlung spectrum, and those due to background events initiated by photons of higher or lower energy. In our

data (Fig. 7), no significant endpoint dependence is seen: the data points measured at two or more endpoint energies are consistent, yielding a χ^2 of 9.7 for 11 degrees of freedom at 72° and 7.6 for 9 degrees of freedom at 103° . When compared with the statistical errors on the data points, this sets an upper limit of approximately 2 % on background effects which have an endpoint dependence different from that of the good events.

b) Variation of Radiator

The cross section data were taken with a 0.0354-radiation-length tantalum radiator foil, but some runs were repeated with thinner and thicker tantalum radiators, or with a copper radiator, as described in Section II. After subtraction, the number of events per incident electron was found to be exactly proportional to the photon flux calculated for each radiator, within the statistical uncertainties of 4 to 8 % (Table II). This test is especially important, as it sets severe upper limits on possible background processes, as discussed in detail below.

c) Variation of Spectrometer Aperture and Target Gas Pressure

To search for other potential systematic effects, the horizontal and vertical spectrometer apertures and the target gas density were each reduced by a factor of approximately two for some test runs. The subtracted event rates in each case changed as expected (Table II), indicating no significant contributions from target vessel or slit rescattering.

F. Discussion of Backgrounds

In a single-arm measurement of a low-cross-section reaction, it is necessary to take special care in investigating possible contamination of the good-event signal by background processes. In the present experiment, four classes of deuteron background events are possible, initiated by: (1) photons incident on ^3He , (2) photons incident on the target cell walls, (3)

hadrons produced by real photons within the radiator foil, and (4) hadrons produced by virtual photons within the radiator. In each case, a subsequent interaction in the gas, target walls, or slits is necessary, as the spectrometer does not view the radiator or the target entry and exit windows directly. (Note that electron-induced events corresponding to classes (1) and (2) are eliminated by the radiator-out subtraction.) Background events of category (1) are due mainly to the slit-scattering of deuterons (known to be small by our aperture-varying tests) and the production of deuterons by outgoing protons in the gas or target wall. The known cross sections for deuteron production by protons⁴² precludes a contamination of more than 0.1 % from this effect.

Process (2) can be stringently related to process (3) by the fact that the hadron production cross sections per nucleon are approximately the same in aluminum and tantalum, while the radiator is much thicker than the target wall. Thus an upper limit on class (3) leads to a much smaller upper limit for class (2).

Because the virtual photon spectrum³³ is known to be roughly equivalent to bremsstrahlung from a real radiator of thickness 0.02 radiation lengths, the number of events of classes (3) and (4) must be roughly equal. Thus an upper limit on either of these two background categories places firm limits on the total background present in the data. Backgrounds of type (3) have a unique experimental signal: they are proportional to the square of the radiator thickness t . Fitting a polynomial in t to the data taken at several radiator thicknesses (Fig. 8), we find an upper limit of 1.7 % for the t^2 contribution at the normal radiator thickness. The small empty-target background shows a significant t^2 contribution which, however, has negligible effect on the final results.

The absence of measurable background of this type is not surprising when specific examples are considered. We calculated the expected rate due to π^- photoproduction in the radiator followed by ${}^3\text{He}(\pi^-, d)n$ in the target gas, one of the few 2-step processes that can produce deuterons of sufficiently high energy. Using cross section estimates based on experimental data,⁴³ we found a predicted contribution of no more than 0.1 % of our good-event rate at any angle or energy.

From the agreement of the cross section measured at different endpoint energies, as well as the considerations discussed in this section, we are confident that the background contamination in our cross section is everywhere less than 3 %, and contributes only modestly to the total systematic uncertainty.

IV. Results

A. Comparison with Other Measurements and Detailed Balance

The cross sections obtained in this experiment, binned in 10-MeV intervals centered on the indicated photon energy, are plotted in Fig. 9 and tabulated in Table III. Measurements at different endpoint energies have been combined. The uncertainties quoted are statistical only; a systematic uncertainty of ± 6 % is not shown. The values plotted in Fig. 9 have been adjusted slightly so as to correspond to center-of-mass proton angles of exactly 60° and 90° . The angular adjustment factors are derived from the angular distributions of Ref. 4 and 6, and do not exceed 9 %.

The results of previous measurements of ${}^3\text{He}(\gamma, p)d$ are also shown in Fig. 9. The present results are significantly higher than those of Saclay⁵ and Bonn,⁶ and lower than those of Caltech¹ and Frascati.³ In Fig. 10 we compare our cross sections with the results of several measurements of the

time-reversed reaction $d(p,\gamma)^3\text{He}$. The latter are multiplied by the detailed-balance factor of Eq. (3), $3/2 (p^*/k^*)^2$, where p^* and k^* are the center-of-mass momenta of the proton and photon respectively. While the agreement with the published data of Refs. 2 and 7 is poor, our data are in excellent agreement with recent data from TRIUMF.⁸ We also note that new data from the UCLA-Saclay collaboration,⁴⁴ which differ from the published results of the earlier measurement by this same group,⁷ are also in good agreement with our experiment.

With few exceptions, the measurements of $^3\text{He}(\gamma,p)d$ and $d(p,\gamma)^3\text{He}$ agree at least qualitatively as to the shape of the energy and angular distributions in this region, differing primarily in normalization. The disagreement between our results and those of the previous $^3\text{He}(\gamma,p)d$ experiments is considerably greater than their estimates of systematic uncertainty (which are included in the plotted error bars.) It is probable that some or all of these experiments have underestimated their systematic uncertainties. The most likely sources of error appear to be the determination of liquid target density and the calibration of the photon energy. Other factors common to previous experiments include the use of: (a) collimated photon beams, requiring more complicated and possibly less reliable calculations of the photon flux and quantameter calibrations, (b) thick targets in which the effects of multiple scattering and energy loss can be large, especially at low energies, and (c) range telescopes for detection of either the proton or deuteron, leading to substantial corrections for interactions in the range material. The present experiment is far less susceptible to such errors than its predecessors.

To illustrate the differences among the various measurements in this energy region, we have performed a quantitative comparison of the absolute

value and energy dependence of each cross section. First, an empirical formula of the form

$$\frac{d\sigma}{d\Omega} = A \left[\frac{1}{E_\gamma} + \frac{B}{E_\gamma^2} + \frac{C}{(E_\gamma - D)^2 + F^2} \right] \quad (8)$$

was fitted to the data points of this experiment at each of the two angles. The third term in brackets contributed negligibly, and the fit yielded a χ^2 of better than 1.2 per degree of freedom in each case. This function was then used as a reference shape, and was fitted to the data (with statistical uncertainties only) of the other $^3\text{He}(\gamma, p)d$ and $d(p, \gamma)^3\text{He}$ experiments which fell in the energy range covered by our measurement, with only the overall factor A varied in the fit. The χ^2 of this fit thus describes the agreement of the relative energy dependence of the two experiments, while the ratio of the multiplicative factors

$$R = A(\text{other experiment})/A(\text{this experiment})$$

indicates the consistency of the absolute cross sections averaged over this energy region. For the radiative capture experiments, a ratio of 1 indicates agreement with the detailed balance relationship of Eq. (3). The results of these fits are shown in Table IV. The uncertainty in the ratio R includes the statistical uncertainty in the fits (multiplied by the square root of the χ^2 per degree of freedom when the latter exceeded 1) as well as the quoted systematic uncertainties of the experiments. When the present experiment is compared with the most recent $d(p, \gamma)^3\text{He}$ results of TRIUMF⁸ and UCLA-Saclay,⁴⁴ no evidence is seen for a violation of detailed balance; the ratio is unity to an accuracy of better than 15 %.

B. Comparison with Theory

There are few theoretical calculations of ${}^3\text{He}(\gamma, p)d$ in the energy range of this experiment. Finjord⁴⁵ calculated the cross section between 165 and 330 MeV, using the CGLN photoproduction amplitude⁴⁶ and a pseudoscalar πNN interaction to compute the two-nucleon pion-exchange contribution. The results are in approximate agreement with the Saclay data,⁵ but are very sensitive to the choice of wave functions and to the assumptions about nucleon off-shell effects.

Craver, Kim and Tubis⁴⁷ have performed a calculation using Faddeev 3-body wave functions based on the Reid soft core nucleon-nucleon interaction.⁴⁸ Above 100 MeV, their cross sections are much lower than experiment, and the angular distribution has an incorrect shape.

Prats⁴⁹ found that agreement with experiment near 150 MeV could be obtained by adding a "quasi-deuteron" diagram to the direct photon-nucleon interaction employed in previous calculations. His calculation has recently been extended⁵⁰ to the energy region of the present experiment by the addition of an explicit $\Delta(1232)$ contribution to the photon-deuteron interaction, with a single parameter chosen to give agreement with experimental measurements of deuteron photodisintegration near 250 MeV. The results of this calculation, with and without the $\Delta(1232)$ term, are shown with the data in Fig. 11. The agreement with the results of this experiment is excellent at 60° , but at 90° the calculation appears to overestimate the size of the $\Delta(1232)$ resonant contribution.

In a similar spirit, Fearing has performed a phenomenological calculation using deuteron photodisintegration data as input; his results are plotted in Ref. 8 and are in reasonable agreement with the TRIUMF data.

C. Influence of the $\Delta(1232)$ Resonance

Neither the data nor the calculations discussed above exhibit a sharp enhancement at the $\Delta(1232)$ peak energy, in contrast with the cross section for $d(\gamma, p)n$ in this energy region. The calculation of Prats,⁴⁹⁻⁵⁰ which is plotted in Fig. 11, predicts a larger contribution of the Δ at 90° than at 60° , but the experimental results at 90° show no evidence for this. The relative insignificance of the $\Delta(1232)$ for this reaction is also exhibited by a plot⁵¹ of the square of the invariant matrix element, defined by

$$|M|^2 = \frac{(8\pi/\hbar c)^2}{(2S_p+1)(2S_d+1)} \cdot s \cdot \frac{k^*}{p^*} \cdot \frac{d\sigma}{d\Omega}, \quad (9)$$

versus the squared four-momentum transfer $-t$. (s , k^* and p^* are respectively the total center-of-mass energy squared and the photon and proton 3-momenta in the center-of-mass system.) Results for our measurements at both angles are shown in Fig. 12. The arrows indicate the t -values at which $\sqrt{s} - m_d = 1232$ MeV for 60° and 90° . In reactions such as pion photoproduction and deuteron photodisintegration, in which the $\Delta(1232)$ is known to be important, a similar kinematic prescription predicts where the maximum contribution of the $\Delta(1232)$ resonance is to be found,⁵² and at such values of t the magnitude of $|M|^2$ is strongly dependent on s . For this experiment, the 60° and 90° data fall on a single curve, indicating that in this energy region the cross section is a function only of t and phase space factors.

D. Conclusions

Our new measurement of ${}^3\text{He}(\gamma, d)p$ is in satisfactory agreement with the two most recent measurements of the inverse reaction $d(p, \gamma){}^3\text{He}$. There is therefore no evidence for a violation of detailed balance, although the precision of the test is limited to about 15 %, mainly by the systematic uncertainties of the data sets. This is a more precise test of detailed balance than has been obtained in any other electromagnetic process at intermediate energy without bound-nucleon corrections or an arbitrary overall normalization.

Because of uncertainties in the precise role of the $\Delta(1232)$ resonance in this reaction, it is not possible at this time to convert this result to a quantitative test of time-reversal invariance, and we have not attempted to calculate an upper limit on a possible time-reversal-violating phase or other model-dependent parameter. Future theoretical work should make such a calculation possible.

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Table I. Normalization constants, corrections, and uncertainties.

<u>Factor</u>	<u>Units</u>	<u>$\theta_d = 72^\circ$</u>	<u>$\theta_d = 103^\circ$</u>
Target density	mg/cm ³	4.59±0.10 to 4.64±0.10	4.48±0.10 to 4.58±0.10
Target length x solid angle	cm-msr	5.61±0.11	5.48±0.11
<u>Correction</u>	<u>Units</u>		
Target impurity	%	-3.1±0.7 to -3.7±0.7	-1.5±0.3 to -1.8±0.3
Deuteron interaction	%	+1.5±0.5	+1.5±0.5
Deadtime and chamber efficiency	%	+2.9±1.0 to +10.4±2.0	+2.8±1.0 to +7.9±2.0
<u>Other uncertainties</u>			
Electron flux		±1.5 %	±1.5 %
Tantalum radiator thickness		±0.5 %	±0.5 %
Bremsstrahlung spectrum		±2.0 %	±2.0 %
Particle identification		±1.0 %	±1.0 %
Counting rate corrections		±1.5 %	±1.5 %
Detector efficiency		±1.0 %	±1.0 %
Slit penetration		±0.3 %	±0.3 %
Energy scale (± 1.2 MeV)		±1.6 %	±1.0 %
Background subtraction		±3.0 %	±3.0 %
<u>Total systematic uncertainty</u>		±5.8 %	±5.7 %

Table II. Tests of normalization.I. External tests

Ratio of cross section measured in this work to other published results.
(Includes systematic errors in published results.)

	<u>θ_{lab}</u>	<u>E_0</u>	<u>Relative to Results of Ref.</u>	<u>Ratio</u>
$^3\text{He}(e,e)$	72°	180 MeV	28	1.02 ± 0.02
$^3\text{He}(e,e)$	103°	210 MeV	28	0.98 ± 0.04
$^2\text{H}(\gamma,p)n$	72°	250-320 MeV	10	1.10 ± 0.08
			11	0.94 ± 0.06
			12	0.94 ± 0.06
			40	0.99 ± 0.05
$^4\text{He}(\gamma,\tau)p$	103°	240-300 MeV	5	1.00 ± 0.13
			41	0.99 ± 0.09

II. Internal tests

	<u>Expected Ratio</u>	<u>Measured Ratio</u>
Thicker Ta radiator	1.765	1.748 ± 0.088
Thinner Ta radiator	0.400	0.412 ± 0.034
$d\sigma/d\Omega$ with Cu radiator	1.00	1.03 ± 0.05
compared to Ta radiator		
Halve vertical acceptance	0.501	0.479 ± 0.035
Halve horizontal acceptance	0.500	0.497 ± 0.035
Reduce gas pressure	0.542	0.550 ± 0.035

Table III. Differential cross sections in the center-of-mass system for ${}^3\text{He}(\gamma, d)p$ at laboratory deuteron angles of 72° and 103° , determined for 10-MeV-wide bins of photon energy centered on the specified values of E_γ . The errors quoted are due to statistics only. There is an additional systematic uncertainty of $\pm 6\%$.

E_γ (MeV)	<u>$\theta_d(\text{lab}) = 72.01 \pm 0.02^\circ$</u>		<u>$\theta_d(\text{lab}) = 103.05 \pm 0.02^\circ$</u>	
	<u>$\theta_p(\text{c.m.})$</u> (deg)	<u>$d\sigma/d\Omega$</u> (nb/sr)	<u>$\theta_p(\text{c.m.})$</u> (deg)	<u>$d\sigma/d\Omega$</u> (nb/sr)
155	64.0	1277 ± 39		
165	63.6	1152 ± 40		
175	63.2	1010 ± 38		
185	62.9	885 ± 25		
195	62.5	835 ± 21		
205	62.2	767 ± 32		
215	61.9	713 ± 24		
225	61.6	599 ± 28	92.9	325.4 ± 16.9
235	61.3	570 ± 23	92.6	280.4 ± 10.9
245	61.0	563 ± 18	92.3	229.0 ± 10.5
255	60.7	507 ± 22	92.0	193.7 ± 8.5
265	60.4	510 ± 18	91.7	167.8 ± 9.1
275	60.1	459 ± 21	91.4	149.4 ± 8.4
285	59.8	396 ± 17	91.1	121.1 ± 7.8
295	59.6	360 ± 20	90.9	127.8 ± 8.6
305	59.3	318 ± 31	90.6	112.1 ± 9.0
315	59.0	283 ± 21	90.3	93.7 ± 9.2
325	58.8	285 ± 23	90.1	101.6 ± 11.4
335	58.5	278 ± 22	89.8	81.8 ± 9.6
345	58.3	242 ± 22	89.6	60.5 ± 10.6

Table IV. Comparison of ${}^3\text{He}(\gamma, p)d$ and $d(p, \gamma){}^3\text{He}$ cross sections at $\theta_p(\text{c.m.}) = 60^\circ$ and 90° , using fits to the cross sections measured in this experiment.

Data Set	χ^2 (a) DF	No. of Data Points	Uncertainty in Fit	Systematic Uncertainty	R (c)	
<u>${}^3\text{He}(\gamma, p)d$ at 60°</u> ($E_\gamma = 150\text{--}350$ MeV)						
This Exp.	1.14	20	1.0%	6%	-	-
Bonn ⁶	2.29	9	3.5%	10-15%	0.65	± 0.10
ALS ⁵	4.73	11	3.6%	10%	0.66	± 0.09
Caltech ¹	21.1	5	7.7%	6%	1.16	± 0.42
<u>$d(p, \gamma){}^3\text{He}$ at 60°(d)</u> ($E_\gamma = 150\text{--}350$ MeV)						
TRIUMF ⁸	3.48	5	3.9%	12%	0.98	± 0.15
Saclay ^{4,4}	2.30	8	4.5%	16%	0.95	± 0.18
Caltech ²	-	1	10 %	1%	1.32	± 0.13

<u>${}^3\text{He}(\gamma, p)d$ at 90°</u> ($E_\gamma = 220\text{--}350$ MeV)						
This Exp.	0.85	13	2.4%	6%	-	-
Bonn ⁶	6.09	5	5.9%	10-15%	0.72	± 0.15
ALS ⁵	2.60	10	1.1%	10%	0.75	± 0.09
Caltech ¹	9.04	3	5.9%	6%	1.45	± 0.20
Frascati ³	19.2	5	11 %	>5%	1.64	± 0.78
<u>$d(p, \gamma){}^3\text{He}$ at 90°(d)</u> ($E_\gamma = 220\text{--}350$ MeV)						
TRIUMF ⁸	3.83	5	6.5%	12%	1.01	± 0.19
Saclay ^{4,4}	1.00	8	2.2%	16%	1.24	± 0.22
Caltech ²	2.08	2	15 %	1%	1.60	± 0.36

a) Number of degrees of freedom (DF) is 1 less than the number of data points.

b) As stated in cited publication.

c) Ratio to present experiment. Uncertainty includes the uncertainty in fitting the factor A of Eq. 8 (multiplied by $\sqrt{\chi^2/\text{DF}}$ when the latter is > 1) and the systematic uncertainties of the experiments.

d) Multiplied by detailed balance factor.

Figure Captions

- Fig. 1 Geometry of scattering chamber, including bremsstrahlung radiator, target cell, target defining slits and shielding.
- Fig. 2 Detectors in the focal-plane region of the Bates 900 MeV/c spectrometer. VDC and TA are the multiwire chambers which provide spatial information, and S_1 - S_5 are plastic scintillation counters.
- Fig. 3 (a) Distribution of events vs. momentum and pulse height in scintillation counter 1. Higher channel number corresponds to lower momentum.
 (b) Distribution of events vs. pulse heights in scintillation counters 1 and 2. The pulse heights have been corrected for light attenuation as a function of position in the focal plane.
- Fig. 4 (a) Spectra of the 4 raw data categories described in the text: IF (radiator in, target full), IE (radiator in, target empty), OF (radiator in, target full), OE (radiator in, target empty).
 (b) Spectrum after the subtraction described by equation (5).
- Fig. 5 Spectrum of events (radiator in) near the bremsstrahlung endpoint. The solid curve is the result of a least-squares fit which was used to determine the endpoint energy (212.1 ± 0.2 MeV).
- Fig. 6 Tests of normalization using measurements of other reactions taken during this experiment.
 (a) Form factor for elastic electron scattering from ^3He at 72° and 180 MeV, compared with charge form factor from Ref. 28 and 37. Our result has been reduced by 2.8 % to correct for magnetic scattering, and its error bar includes the effects of energy uncertainty.
 (b) Cross section (with statistical errors) for deuteron photodisintegration at $\theta_p(\text{lab}) = 72^\circ$ ($\theta_p(\text{c.m.}) = 86.4 - 88.1^\circ$), compared with results (including systematic errors) of Refs. 10 (squares), 11 (triangles), 12 (open circles), and 40 (crosses),

shifted to the same lab angle by means of their published angular distribution fits.

(c) Cross section (with statistical errors) for ${}^4\text{He}(\gamma, t)p$ at $\theta_L(\text{lab}) = 103^\circ$ adjusted to $\theta_p(\text{c.m.}) = 60^\circ$, compared with results (including systematic errors) of Refs. 5 (squares) and 41 (triangles).

Fig. 7 Cross sections (in laboratory system) measured using different bremsstrahlung endpoint energies. Error bars show statistical errors only.

Fig. 8 Dependence of counting rates on radiator thickness. t_{eff} is the thickness in radiation lengths, corrected slightly so that the calculated number of photons per radiation length in the accepted photon energy interval is the same as for the 0.0354-radiation-length radiator.

Fig. 9 Center-of-mass cross sections for $\gamma+{}^3\text{He}+p+d$ measured in this experiment, adjusted to $\theta_p(\text{c.m.}) = 60^\circ$ and 90° (solid circles), compared with other measurements of this reaction: Refs. 1 (squares), 3 ($\times$), 4 (+), 5 (inverted triangles) and 6 (triangles). The error bars for this experiment indicate statistical errors only, those for the other measurements indicate total error (statistical and systematic errors combined in quadrature).

Fig. 10 Cross sections for $\gamma+{}^3\text{He}+p+d$ measured in this experiment (solid circles) compared with measurements of the inverse reaction $p+d+{}^3\text{He}+\gamma$ multiplied by the detailed balance factor: Refs. 2 (squares), 7 (open circles), 8 (triangles), and 44 (diamonds). The error bars for the other measurements include systematic errors.

Fig. 11 Cross sections for $\gamma+{}^3\text{He}+p+d$ measured in this experiment, compared with the theoretical calculation of Prats.⁴⁹⁻⁵⁰ The solid curves include an explicit $\Delta(1232)$ contribution; the dashed curves show the same calculation with the $\Delta(1232)$ term omitted.

Fig. 12 Invariant matrix element (Eq. 9) extracted from the cross sections of this experiment, plotted versus invariant momentum transfer squared. The arrows indicate where the maximum contribution of the $\Delta(1232)$ is expected at each angle.

PROGRAM III-b

Measurements of $p+d \rightarrow {}^3\text{He}+\gamma$ Differential Cross Sections to Test Detailed Balance

This program is the complementary half of the preceding one, III-a. A detailed discussion of the theoretical and practical aspects is already given in the preceding section. Our preliminary results are given in Table I and the comparison with the inverse reaction as measured by us at Bates is shown in Fig. 1. The agreement is good, we see no evidence for a possible violation of time reversal invariance.

TABLE I

$pd \rightarrow {}^3\text{He} \gamma$	Run	T (MeV)	Results for $pd \rightarrow {}^3\text{He} \gamma$ and $dp \rightarrow {}^3\text{He} \gamma$		Target Used	Distance to Gamma Counter
			$\sigma_{\gamma-p}$ (cm) (deg)	$d\sigma/d\Omega$ (nb/sr)		
$pd \rightarrow {}^3\text{He} \gamma$	523	300	92.7	45.7 $\pm$ 5.4	Thin CD2	121.5 cm
	536	350	94.6	30.4 $\pm$ 3.7	Thin CD2	118.4
	504	400	90.6	25.9 $\pm$ 2.9	Thick CD2	134.0
	506	400	55.2	61.1 $\pm$ 3.6	Thick CD2	139.5
	552	425	57.7	55.1 $\pm$ 12.6	Thick CD2	131.5
	543	425	93.2	19.2 $\pm$ 3.6	Thick CD2	123.1
	499	450	60.3	50.5 $\pm$ 11.3	Thin CD2	129.5
	496	450	60.3	40.8 $\pm$ 5.7	Thick CD2	129.5
	500	450	60.3	46.0 $\pm$ 3.2	Thick CD2	149.5
	503	450	90.3	20.6 $\pm$ 1.9	Thin CD2	134.0
	371	450	60.2	43.8 $\pm$ 4.1	Thin LD2	149.5
	366	450	90.3	18.7 $\pm$ 2.2	Thin LD2	149.5
	400	470	89.1	14.7 $\pm$ 1.7	Thin LD2	129.5
	396	470	53.9	45.4 $\pm$ 4.8	Thin LD2	149.5
	418	500	56.5	29.0 $\pm$ 2.5	Thin LD2	129.5
	424	500	91.6	12.9 $\pm$ 1.7	Thin LD2	149.5
$dp \rightarrow {}^3\text{He} \gamma$	332	376	83.6	110.8 $\pm$ 8.9	Thin LD2	129.5
	333	376	83.6	128.0 $\pm$ 11.6	Thin LD2	149.5
	334	376	83.6	106.9 $\pm$ 15.0	Thin LD2	159.5
	337	376	98.3	96.8 $\pm$ 8.0	Thin LD2	144.0
	338	376	98.3	85.7 $\pm$ 7.7	Thin LD2	125.0
	342	376	113.4	61.1 $\pm$ 7.2	Thin LD2	153.0
	343	376	113.4	58.1 $\pm$ 5.1	Thin LD2	138.0
	351	600	105.0	20.4 $\pm$ 3.7	Thin LD2	129.5
	350	600	105.0	25.0 $\pm$ 2.5	Thin LD2	103.0
	354	600	95.6	34.0 $\pm$ 7.0	Thin LD2	129.5
	355	600	95.6	42.9 $\pm$ 9.7	Thin LD2	144.3 cm

Figure 1. Comparison of $\text{pd} + {}^3\text{He}$ data with ${}^3\text{He} + \text{pd}$ data from Bates. The circles are the ${}^3\text{He} + \text{pd}$ measurements of ref. 10; the solid squares are for this experiment, after multiplication by the detailed balance factor. Both data sets have been adjusted to 60° and 90° in the center-of-mass.

PROGRAM III-c

Measurement of $d+d \rightarrow {}^4\text{He}+\gamma$ to Test Detailed Balance

A measurement of the differential cross section for the reaction $dd+{}^4\text{He}\gamma$ at intermediate energy is of interest for several reasons.

(1) There is a large discrepancy between the published results for the $dd+{}^4\text{He}\gamma$ ^{1,2} and $\gamma{}^4\text{He}+dd$ ^{3,4} reactions at intermediate energy.

Since these reactions are related by detailed balance, this discrepancy, if taken at face value, implies a large and surprising violation of time-reversal invariance in the electromagnetic interaction of hadrons.⁵

(2) The shape of the angular distribution sheds light on the reaction mechanism, which at lower energies is completely dominated by an electric quadrupole transition.

(3) The measurement of the $dd+{}^4\text{He}\gamma$ cross section may be a useful guide in evaluating the limits on the validity of charge symmetry⁶ derived from searches for the related reaction $dd+{}^4\text{He}\pi^0$.

In the intermediate energy region ($T_d=200-600$ MeV) two measurements of $dd+{}^4\text{He}\gamma$ have been reported; both were obtained in conjunction with searches for the reaction $dd+{}^4\text{He}\pi^0$. Akimov et al.¹ at the Joint Institute for Nuclear Research quote $d\sigma/d\Omega=1.6\pm0.6$ nb/sr for $\theta_\gamma(\text{cm})=42^\circ$ at $T_d=404$ MeV, while Poirier and Pripstein² at LBL report an upper limit of 0.22 ± 0.06 nb/sr for $\theta_\gamma(\text{cm})=90^\circ$ at 460 MeV. There are two measurements of the inverse reaction, $\gamma{}^4\text{He}+dd$. Two cross section values have been obtained at Purdue by Asbury and Loeffler³, based on eight events observed at $E_\gamma=221$ MeV and two events observed at $E_\gamma=265$ MeV. Twelve data points were measured for $E_\gamma=213, 258$ and 330 MeV at Bonn by Arends et al.⁴ The experimental data for

$dd-\gamma^4\text{He}$ at intermediate energies prior to our measurements are shown in Fig. 1. The $\gamma^4\text{He}+dd$ data of Arends et al. are in disagreement by a factor of 200 with the measurement of the inverse reaction reported by Akimov et al. [Fig. 1(a)] in apparent violation of detailed balance. The data of Arends et al. also lie considerably below the upper limit of Poirier and Pripstein [Fig. 1(b)]. Even the less precise data of Asbury and Loeffler for $\gamma^4\text{He}+dd$, while more than an order of magnitude larger than those of Arends et al., fail to agree with the cross sections measured for $dd+^4\text{He}\gamma$. Because the time-reversal operator is anti-unitary, the sensitivity of a given type of reaction to possible violations of time-reversal invariance cannot be estimated theoretically without the use of a detailed model; consequently, time-reversal invariance must be investigated in many different reactions. It is therefore important that large discrepancies in cross section between reactions which are related by detailed balance be resolved experimentally.

Symmetry considerations play an important role in determining possible reaction mechanisms for $dd+^4\text{He}\gamma$. The two-deuteron initial state requires the cross section to be symmetric about 90° and the state function to obey Bose-Einstein statistics. This severely restricts the number of allowed spin-parity states and thus the possible electromagnetic transitions to the ^4He final state. To the extent that the assumptions of charge symmetry and a central nuclear force are valid, the $E1$, $M1$ and $M2$ transitions are forbidden.⁷ The first allowed multipole transition is the $^1D_2 \rightarrow ^1S_0$ electric quadrupole. It is thus expected that the angular distribution will have a $\sin^2 2\theta$ shape. At low energies ($T_d < 32$ MeV) this is indeed the case.^{8,9} However, the $\gamma^4\text{He}+dd$ angular distributions of Arends et al. at energies corresponding to $T_d=350$ to 600 MeV show a marked deviation from this shape.

Rather than a zero cross section at 90° a maximum is observed and the data are consistent with a $\sin^2\theta$ angular distribution. It is difficult to reconcile this with a simple reaction mechanism involving only low-order multipoles. An alternative description is a two-step process involving meson and/or nucleon exchange; this is discussed in Section III.

II. EXPERIMENT

We have measured the differential cross section for $dd+{}^4\text{He}\gamma$ at $\theta_\gamma(\text{cm}) = 73^\circ$ and 91° for $T_d = 376$ MeV; this energy matches the total center-of-mass (cm) energy of the $\gamma{}^4\text{He}+dd$ measurement of Arends et al. at $E_\gamma = 213$ MeV. The experiment was performed at the Laboratoire National Saturne at Saclay. The Saturne II synchrotron provided a deuteron beam of about 2×10^{11} d/sec. The beam was incident on a liquid deuterium target 15.6 mm (254 mg/cm^2) thick, with 0.025 mm titanium windows. The beam intensity was monitored by a secondary emission chamber, which was normalized using measurements of the induced radioactivity from the reaction $\text{natC}(d,X){}^{11}\text{C}$.¹⁰

The laboratory cross sections expected for $dd+{}^4\text{He}\gamma$ based on the results of Ref. 4 are of the order of 20 pb/sr. It is therefore important to have an overconstrained event signal, which is accomplished by detecting the ${}^4\text{He}$ and γ in coincidence. The detection system (Fig. 2) was similar to that used in an earlier measurement of $pd+{}^3\text{He}\gamma$;¹¹ experimental details may be found in Ref. 12. The ${}^4\text{He}$'s were momentum analyzed and detected in the SPES I spectrometer¹³ which consisted of a bending magnet (A_2 in Fig. 2) followed by four scintillator hodoscopes (H, A, B and C in Fig. 2). These hodoscopes furnished time-of-flight (TOF) measurements over a flight path of 5.23 m, as well as energy loss measurements, to provide unique particle

identification of the ${}^4\text{He}$. Gammas were detected in two lead glass Cherenkov counters,¹⁴ each $10 \times 10 \times 15 \text{ cm}^3$, located 103 cm from the target and heavily shielded. For each ${}^4\text{He}$ - γ coincidence event, we recorded the spectrometer data, the pulse height of the photon signal and the TOF between the ${}^4\text{He}$ and the γ . The solid angle of the system was determined by the photon counters. For each γ angle, the spectrometer angle and momentum acceptance were set for the associated ${}^4\text{He}$ particle from $dd+{}^4\text{He}\gamma$. We verified these settings using the reaction $dp+{}^3\text{He}\gamma$, which has a cross section approximately 3000 times that of $dd+{}^4\text{He}\gamma$.

The signal for the $dd+{}^4\text{He}\gamma$ reaction was derived from the ${}^4\text{He}$ - γ TOF spectrum, which was gated by a cut on the pulse height in the photon counter. The background in the TOF spectrum, primarily due to ${}^4\text{He}$ production in the target walls in coincidence with accidental signals in the photon counters, is substantially reduced by means of this cut. The TOF spectrum at $\theta_\gamma(\text{cm}) = 73^\circ$ is shown in Fig. 3; the peak indicated by the arrow is at the position expected in the TOF spectrum for the $dd+{}^4\text{He}\gamma$ reaction. The remaining background under the peak was determined using a linear fit to the spectrum outside the region of the peak. The resulting net area of the peak in Fig. 3 is 36 ± 9 counts. The probability that this peak is due to statistical fluctuations is less than 10^{-6} ; for the peak observed at 91° this probability is approximately 10^{-3} . It should be noted that the unlikely possibility of contamination of the $dd+{}^4\text{He}\gamma$ signal by the isospin-forbidden reaction $dd+{}^4\text{He}\pi^0$ is prevented by the kinematic separation of the two reactions.

The number of events in the TOF peak was corrected to account for the good events discarded by the cut on photon counter pulse height. This correction factor, determined by analysis of photon counter pulse height

data obtained for $dp+^3\text{He}\gamma$, is tabulated for several thresholds in Table I. Consistent results for the corrected numbers of events were obtained for a wide range of photon-counter pulse-height cuts, as can be seen in Table I; the degree of variation is reflected by the range of values, 1.5 to 6.9, obtained for the correction factor. Small ($\sim 10\%$) corrections were made for losses due to insufficient momentum acceptance in the spectrometer, and for interaction of γ 's before reaching the detectors. These corrections were based on Monte Carlo calculations incorporating the Stanford Electron-Gamma Shower (EGS) code¹⁵ for the γ shower development. The gamma counter efficiency (0.78 or 0.80 depending on angle) was calculated using the EGS program along with measurements of the detection efficiency for incident electrons. The results agree well with those of a "self-terminating" Monte Carlo calculation discussed in a previous calibration report.¹⁴

III. RESULTS AND DISCUSSION

Our measured cross sections for $d+^4\text{He}\gamma$ at 376 MeV are given in Table II and are shown in Fig. 4. The error bars indicate the uncertainties due to counting statistics and to the correction procedure described above; not included is an overall systematic uncertainty of 28%, due to the uncertainties listed in Table II. The angular acceptance for γ 's was approximately $\pm 3^\circ$.

Our results at $T_d = 376$ MeV are a factor of 60 lower than the measurement of Akimov et al. at $T_d = 404$ MeV. If one assumes the $\sin^2\theta$ angular dependence suggested in Ref. 4, the disagreement becomes a factor of 130. The possibility that this disagreement is due to a strong dependence of the cross section on energy is not supported by the measurements of the

inverse reaction by Arends et al.. The primary difference in technique between the present measurement and that of Akimov et al. is that the latter was a single-arm experiment in which only the ${}^4\text{He}$ was detected. The ratios of our results to those measured by Arends al.⁴ for the inverse reaction, $\gamma{}^4\text{He}+dd$, are 2.0 ± 0.9 at 91° and 1.7 ± 0.9 at 73° . (The uncertainties reflect the combined statistical and systematic uncertainties in the two measurements). The large uncertainties limit us to the conclusion that detailed balance is satisfied to within a factor of two in this system.

As can be seen in Fig. 4, our data are consistent with the cross section maximum observed by Bonn near $\theta_\gamma(\text{cm}) = 90^\circ$, in disagreement with the $\sin^2 2\theta$ angular distribution which is observed at lower energies.^{8,9} The deviation from the $\sin^2 2\theta$ shape indicates a different reaction mechanism than the ${}^1\text{D}_2 \rightarrow {}^1\text{S}_0$ electric quadrupole transition which governs the data at lower energies. Effects of the non-central part of the nuclear force, specifically of the d-wave part of the deuteron wave function, are not expected to be large and are not needed to explain the low energy data. It is not altogether surprising that the lowest allowed multipole transitions fail to describe the reaction at the energies considered here; the approximation represented by the use of only the low-order terms of a multipole expansion is valid only in cases in which the photon wavelength is large compared to the dimensions of the radiating system. In our case ($E_\gamma = 202$ MeV) the photon wavelength is approximately 1 fm, which is comparable to the size of the ${}^4\text{He}$ nucleus (rms charge radius ≈ 1.6 fm). At intermediate energies, we expect the reaction mechanism to include a strong contribution from nucleon and/or meson exchange which in similar cases dominates the simple radiative term. For example, in the $np \rightarrow d\gamma$ reaction it is known¹⁶ that production of the $\Delta(1232)$ resonance in the intermediate state

contributes greatly to the cross section at intermediate energies. For the reaction $pt+{}^4\text{He}\gamma$, which has the same final state as $dd+{}^4\text{He}\gamma$, it is straightforward to construct Feynman diagrams which include the production of a Δ [Figs. 5(a) and 5(b)]. However, for $dd+{}^4\text{He}\gamma$ the possibilities are limited by symmetry requirements. For this reaction to occur with a Δ in the intermediate state requires dissociation of the deuterons and an unlikely vertex between four nucleons and the ${}^4\text{He}$ [Fig. 5(c)]. Exchange of a nucleon leads to an allowed two-step process [Fig. 5(d)], but one that does not include the Δ . In light of our results, some such exchange process appears necessary to explain the deviation from the $\sin^2 2\theta$ shape which fits the data at lower energies.

In conclusion, our data, when compared with those of Arends et al. for the inverse reaction, show no evidence for a large violation of detailed balance in the $dd+{}^4\text{He}\gamma$ system. Our data are consistent with a large, unexplained deviation from the expected E2 reaction mechanism, as previously reported in Ref. 4.

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TABLE I

Event yields for $dd+{}^4\text{He}$ vs. photon counter pulse height cut.

Cm Angle (Degrees)	Channel of PH Cut	Total Yield	Net Yield	Correction Factor	Corrected Number of Events
73	83	867	63 ± 41	1.85 ± 0.19	117 ± 77
73	90	403	68 ± 27	2.08 ± 0.21	142 ± 58
73	95	188	48 ± 18	2.30 ± 0.23	110 ± 43
73	100	110	50 ± 13	2.60 ± 0.26	130 ± 36
73	105	58	36 ± 9	2.97 ± 0.30	107 ± 29
73	110	40	28 ± 7	3.48 ± 0.35	98 ± 26
73	116	24	21 ± 5	4.65 ± 0.47	98 ± 25
73	122	17	14 ± 5	6.33 ± 0.63	89 ± 33
91	160	718	46 ± 37	1.50 ± 0.11	69 ± 56
91	180	281	53 ± 23	1.82 ± 0.15	96 ± 42
91	200	114	22 ± 15	2.33 ± 0.19	51 ± 35
91	220	61	20 ± 10	3.22 ± 0.32	64 ± 33
91	240	32	17 ± 7	4.85 ± 0.58	82 ± 35
91	260	16	10 ± 5	6.87 ± 0.89	69 ± 36

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Table II

Measured cross sections for $dd+{}^4\text{He}\gamma$ at 376 MeV. Also shown are the results of Arends et al.⁴ for the inverse reaction $\gamma+{}^4\text{He}+dd$ at 213 MeV after division by the detailed balance factor, and the ratio between the two experiments. A systematic uncertainty of 28% (see Table III) is included in the uncertainty quoted for the ratio. Other uncertainties are statistical only.

<u>This Experiment</u>		<u>Arends et al.</u>		<u>Ratio</u>
$\theta_\gamma(\text{cm})$ deg	$\frac{d\sigma}{d\Omega}(dd+{}^4\text{He}\gamma)$ pb/sr	$\theta_\gamma(\text{cm})$ deg	$\frac{d\sigma}{d\Omega}(\gamma+{}^4\text{He}+dd)$ pb/sr	$\frac{\text{This Experiment}}{\text{Arends et al.}}$
73°	21 ± 5	73°	10.5 ± 2.3	2.0 ± 0.9
91°	23 ± 10	87°	13.9 ± 2.6	1.7 ± 0.9

Table III

Systematic uncertainties for this experiment.

Beam monitor:	4%	cross section of monitor reaction
	3%	consistency of measurements
Target thickness:	9%	
Solid angle:	1%	
${}^4\text{He}$ detection efficiency:	7%	
Photon detection efficiency	7%	
Correction for:		
spectrometer acceptance	10%	
photon interaction	10%	
photon pulse height cuts	20%	
TOTAL	28%	

Figure Captions

Fig. 1. (a) World data for $dd+{}^4\text{He}\gamma$ and the inverse reaction near 376 MeV.

The $dd+{}^4\text{He}\gamma$ measurements are those of Akimov et al. (Ref. 1, diamond). The $\gamma^4\text{He}+dd$ data of Arends et al. (Ref. 4, circles) and of Asbury and Loeffler (Ref. 3, triangle) have been divided by the appropriate detailed balance factors (38.9 for Ref. 4). No correction for energy dependence has been made for the data of Akimov et al. ($T_d=404$ MeV) or of Asbury and Loeffler (equivalent $T_d=391$ MeV). (b) Same as (a) for deuteron energies near 465 MeV. The $dd+{}^4\text{He}\gamma$ measurement is that of Poirier and Pripstein (Ref. 2, inverted triangle) at 460 MeV. The equivalent deuteron energy of the Asbury and Loeffler measurement is 479 MeV.

Fig. 2. The detection system used in this experiment. Gammas were detected in the lead glass Cherenkov counters G_1 and G_2 . VAPORETTO is a quadrupole magnet used for focussing in the vertical plane; PECHE is a sextupole magnet not used in this experiment. The H and V slits determine the horizontal and vertical acceptance of the spectrometer. A_{23} is the main dipole magnet of the SPES I spectrometer. Alphas were detected by the scintillator hodoscopes H, A, and B, with the hodoscope C used in anticoincidence to veto lighter particles.

Fig. 3. ${}^4\text{He}-\gamma$ TOF spectrum at $\theta_\gamma(\text{cm}) = 73^\circ$ after a cut has been placed on the γ pulse height. The peak indicated by the arrow is due to $dd+{}^4\text{He}\gamma$.

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Fig. 4. Results for $dd+{}^4\text{He}\gamma$ at 376 MeV from this experiment (solid squares). Also shown are the previously-reported results for $dd+{}^4\text{He}\gamma$ and the inverse reaction near 376 MeV. The $dd+{}^4\text{He}\gamma$ measurement is that of Akimov et al. (Ref. 1, diamond). The $\gamma+{}^4\text{He}+dd$ data of Arends et al. (Ref. 4, circles) and of Asbury and Loeffler (Ref. 3, triangle) have been divided by the appropriate detailed balance factors. No correction for energy dependence has been made for the measurement of Akimov et al. ($T_d=404$ MeV) or of Asbury and Loeffler (equivalent $T_d=391$ MeV). Systematic uncertainties (28% for the present experiment) are not shown.

Fig. 5. (a) and (b) Possible Feynman diagrams for $pt+{}^4\text{He}\gamma$ that include exchange of a pion and production of the Δ -resonance. (c) Diagram for $dd+{}^4\text{He}\gamma$ including pion exchange. The Δ -resonance can be formed but dissociation of the deuterons is required to conserve isospin. (d) Diagram for $dd+{}^4\text{He}\gamma$ including nucleon exchange. The Δ -resonance cannot be formed if isospin is to be conserved.

Fig. 1

Fig. 2

Fig. 3

Fig. 5

Fig. 4

PROGRAM III-d

Comparison of (p,π) and (p,γ) Reactions

The role of the Δ (1232) resonance in the photodisintegration of ^3He ,

$$\gamma + {}^3\text{He} \rightarrow p + d \quad (1)$$

is not well known at present, not even in a qualitative way. Recently, new $d\sigma/d\Omega$ data at $\theta_p = 60^\circ$ and 90° for $E_\gamma = 150\text{--}350$ MeV have been obtained at Bates by the UCLA-CU-MIT-WP collaboration.¹ The measured cross sections are displayed in Fig. 1; they are sufficiently accurate to prompt a new search for possible manifestations of the Δ . The cross sections decrease almost exponentially with increasing incident energy, the slope of the 90° data is 1.8 times larger than the 60° data, and the cross section values at 90° are 2-4 times smaller than at 60° at identical incident energies.

(γ,p) processes like the one of Eq. (1) or the inverse reactions are very non-elastic. The phase space factor for (γ,p) reactions, and even more for (p,π) , changes rapidly with incident energy. The observed variation of the cross section with incident energy gives a distorted view of the real energy dependence of the matrix elements. To aid in interpreting the results displayed in Fig. 1, we have converted the cross section data of Ref. 1 into invariant matrix elements,

$$|M|^2 = C \cdot s \cdot (\tilde{p}_\gamma / \tilde{p}_p) \cdot d\sigma/d\Omega, \quad (2)$$

where

$$C = 64\pi^2 / (2S_p + 1)(2S_d + 1) \times 0.3894 \text{ mb}^{-1} \text{ GeV}^{-2},$$

$$s = (P_\gamma + P_{\text{He}})^2,$$

$$t = (P_\gamma - P_p)^2,$$

$$\tilde{p} = \text{center of mass momentum}.$$

The matrix element for two body interactions of unpolarized particles depends on two kinematic variables. We prefer using the variables s and t defined above instead of the noncovariant q (three momentum transfer) and E_γ which are popular in the literature. A clear signature for a significant role of the Δ in the ^3He photodisintegration reaction would be a "bump" in $|M|^2$ as function of s in the kinematic region of the Δ . Before determining the s -dependence of $|M|^2$, we must investigate an expected strong t -dependence of $|M|^2$ associated with the ^3He form factor.

The data of Ref. 1 expressed as $|M|^2$ are shown in Fig. 2 as function of the four momentum transfer squared between the incident photon and outgoing proton. The calculated peak position of the Δ is indicated by the vertical, dashed arrow. The data of Fig. 2 reveal two surprising features:

1) The slope of the excitation curves at 60° (dots) and 90° (triangles) is the same; 2) in the overlapping t -region the $|M|^2$ values obtained at $\theta_p = 60^\circ$ and 90° are the same. Thus, the $\gamma^3\text{He} \rightarrow \text{pd}$ excitation functions at 60° and 90° for $E_\gamma = 150\text{--}350$ MeV can be summarized as follows:

$$|M(\gamma^3\text{He} \rightarrow \text{pd})|^2 = A e^{\alpha t} \quad (3)$$

with $\alpha = 5.6 \pm 0.5 (\text{GeV}/c)^{-2}$.

The matrix element of Eq. (3), with its simple exponential dependence on the four momentum transfer t and with no dependence on the total energy s , represents the excitation functions at 60° and 90° accurately; it also describes quite well the new $p+d \rightarrow \gamma+^3\text{He}$ angular distribution data obtained recently by the Alberta group² at TRIUMF for $T_p = 350$ and 500 MeV (see Fig. 3). The straight line in this picture is Eq. (3). The applicability of Eq. (3) is restricted to intermediate energies. When $E_\gamma \lesssim 140$ MeV, some modifications are required. The low energy data taken at Illinois³ can be fit to an expression similar to Eq. (3) except that the factor A is angle dependent and α is $12 \pm 2 (\text{GeV}/c)^{-2}$.

It is helpful when evaluating the importance of Eq. (3) to have available a comparison with a process known for the substantial role of the Δ . Such is the case for pion photoproduction on hydrogen $\gamma+p \rightarrow n+\pi^+$. Shown in Fig. 4 are $d\sigma/d\Omega$ ($\gamma p \rightarrow n\pi^+$) data⁴ converted to $|M|^2$ at $\theta_n = 60^\circ$ (dots) and 90° (triangles) for $E_\gamma = 250\text{--}590$ MeV. Both excitation curves reveal structure in the form of a nice bump, the maximum of which occurs at a total energy just below 1232 MeV; the vertical, dashed arrow in our figures marks the energy where $\sqrt{s} = 1232$ MeV. The curves of the 60° and 90° data do not overlap, implying that the matrix element for $\gamma p \rightarrow n\pi^+$ depends strongly on s and t , and that Eq. (3) is not applicable.

Another case where the Δ is expected to play a significant role is the photodisintegration of the deuteron. Shown in Fig. 5 are $d\sigma/d\Omega$ ($\gamma d \rightarrow pn$) excitation functions⁵ at $\theta_p = 66^\circ$ and 101° for $E_\gamma = 160\text{--}590$ MeV converted to $|M|^2$. The general shape of the excitation curves in Fig. 5 are remarkably similar to the ones of $\gamma p \rightarrow n\pi^+$ shown in Fig. 4. These figures dispel any lingering doubt there might be about the importance of the Δ in $\gamma d \rightarrow pn$. The

difference in the $|M|^2$ dependence shown in Figs. 2 and 5 is substantial. We conclude from this that the deuteron and ^3He photodisintegration reaction mechanisms are quite different. The $\gamma d \rightarrow pn$ reaction resembles the process $\gamma p \rightarrow \pi^+ n$ in which the Δ plays a prominent role. We do not find a clearly identifiable effect of the Δ in the 60° and 90° excitation curves of $\gamma^3\text{He} \rightarrow pd$. The matrix element for this reaction for $E_\gamma \gtrsim 150$ MeV depends only on the momentum transfer, t , and not on the incident energy and not on the scattering angle; this provides a challenge to all entrepreneurs in the Δ -hole business.

The role of the Δ in ^4He photodisintegration is not clear; the situation is not made easier by the fact that the two most recent experiments are not in good agreement with one another. The $d\sigma/dQ$ ($\gamma^4\text{He} \rightarrow p^3\text{H}$) data at $\theta_p = 60^\circ$ and 90° for E_γ is 200-420 MeV from Ref. 7, converted to invariant matrix elements are shown in Fig. 6. The $|M|^2$ excitation curve at 60° does not coincide with the one at 90° , and we conclude that the reaction mechanism for $\gamma^4\text{He} \rightarrow p^3\text{H}$ is somewhat different than for $\gamma^3\text{He} \rightarrow pd$. This may be related to the fact that the sequence $\gamma^4\text{He} \rightarrow \Delta^3\text{H} \rightarrow p^3\text{H}$ is allowed while the analogous sequence $\gamma^3\text{He} \rightarrow \Delta d \rightarrow pd$ is forbidden by isospin conservation.

As our last (γ, p) reaction we consider the two body photodisintegration of ^{16}O . The $d\sigma/dQ$ ($\gamma^{16}\text{O} \rightarrow p^{15}\text{N}$) data^{8,9} measured at $\theta_p = 45^\circ$ and 90° for $E_\gamma = 40$ -380 MeV converted to invariant matrix elements are shown in Figs. 8 and 9. Though the differential cross section curves at 45° and 90° seem quite unrelated, for instance, there is a break in the $d\sigma/dQ$ excitation curve near $E_\gamma = 120$ MeV at $\theta_p = 90^\circ$ and near $E_\gamma = 220$ MeV at $\theta = 45^\circ$, the $|M|^2$ excitation curves are similar. For $0.8 < t < 0.6$ (GeV/c)², the 45° and 90° data are governed by very similar expressions, $|M|^2 = B \exp \beta t$ with $\beta = 43 \pm 6$ (GeV/c)⁻². The $t < 0.6$ (GeV/c)² region displayed in Fig. 8 shows an interesting bump not seen in the light nuclei. The position of the Δ -peak at 1232 MeV is indicated by a vertical, dashed arrow. Since the peak of the bump occurs at $E_\gamma = 352$ MeV and there is no peak in the 90° data at 1232 MeV, we are investigating the possibility that the structure in the 45° data is associated with a dip in the $^{16}\text{O}/^{15}\text{N}$ transition form factor.

We note that the slope of the $|M|^2$ in all cases considered, Figs. 2-8, is very similar. The significance of this is currently under investigation.

It has been argued¹⁰ that the reaction mechanism for a (γ, p) process is similar to the related (π, p) one. We want to probe briefly the reaction $pd \rightarrow$

$\pi^+{}^3\text{H}$ which is related to $\gamma^3\text{He} \rightarrow \text{pd}$. First we show the $|M|^2$ excitation curve¹¹ for $\pi^+p \rightarrow \pi^+p$ at $\theta_p = 90^\circ$ for $p_\pi = 200\text{--}700$ MeV/c (Fig. 9). The peak in the $|M|^2$ distribution occurs at $\sqrt{s}$ just below 1232 MeV. Shown in Fig. 10 are $|M|^2$ angular distributions for the reaction $\text{pd} \rightarrow \pi^+{}^3\text{H}$ measured¹²⁻¹⁴ at many angles at four incident energies, $T_p = 400, 500, 605,$ and 800 MeV. For $t \geq 0.3$ (GeV/c)² we see that $|M|^2 = F \exp \eta t$, and it appears that F is dependent on the incident energy. Better data are needed in particular at lower incident energies and at $t < 0.3$ (GeV/c)².

Our final conclusions are the following. In (γ, p) reactions on ${}^3\text{He}$, ${}^4\text{He}$, and ${}^{16}\text{O}$, nature has conspired successfully in hiding a direct, strong manifestation of the Δ . This stands in contrast to the reactions $\gamma p \rightarrow \pi^+n$ and $\gamma d \rightarrow pn$ where the Δ causes a peak in $|M|^2$. It does not bode well for models of (γ, p) reactions based on a $\gamma d \rightarrow pn$ intermediate reaction. The strong t -dependence of (γ, p) reactions makes the popular excitation functions at fixed angles unattractive for the Δ search.

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Fig. 1. Differential cross sections for $\gamma + {}^3\text{He} \rightarrow p + d$ at $\theta_p = 60^\circ$ and 90° measured at Bates, Ref. 1.

Fig. 2. Square of the invariant matrix elements, $|M|^2$, in arbitrary units of the $\gamma + {}^3\text{He} \rightarrow p + d$ excitation function of Fig. 1 versus the square of the invariant four-momentum transfer, $t = (P_\gamma - P_p)^2$. A vertical, dashed arrow indicates the energy of the Δ resonance calculated as $\sqrt{s} - m(d) = 1232$ MeV. The dots are the measurements made at 60° for $E_\gamma = 150$ -350 MeV and the triangles are the 90° data for $E_\gamma = 210$ -350 MeV.

Fig. 3. $|M|^2$ in arbitrary units for $p+d \rightarrow \gamma + {}^3\text{He}$ angular distributions measured at $T_p = 350$ MeV (corresponding to $E_\gamma = 239$ MeV of the inverse reaction), and at $T_p = 500$ MeV (corresponding to $E_\gamma = 339$ MeV), measured at $\theta_\gamma = 46^\circ$ - 150° at TRIUMF, Ref. 2. The straight line represents the straight line fit through the data of Fig. 2 using Eq. (3).

Fig. 4. $|M|^2$ excitation functions in arbitrary units for the reaction $\gamma + p \rightarrow n + \pi^+$ measured at $\theta_n = 60^\circ$ and 90° for $E_\gamma = 250$ - 590 MeV, Ref. 4.

Fig. 5. $|M|^2$ excitation functions in arbitrary units for the reaction $\gamma + d \rightarrow p + n$ measured at $\theta_p = 66^\circ$ and 101° for $E_\gamma = 160-590$ MeV. The triangles and circles are data taken at Lund, Ref. 5; the open squares at Tokyo, Ref. 6.

Fig. 6. $|M|^2$ excitation functions in arbitrary units for the reaction $\gamma + {}^4\text{He} \rightarrow p + {}^3\text{H}$ measured at $\theta_p = 60^\circ$ and 90° for $E_\gamma = 210-420$ MeV, Ref. 7.

Fig. 7. $|M|^2$ excitation functions in arbitrary units for the reaction $\gamma + {}^{16}\text{O} \rightarrow p_0 + {}^{15}\text{N}$ measured at $\theta_p = 45^\circ$ and 90° for $E_\gamma = 40\text{--}380$ MeV, Refs. 8 and 9.

Fig. 9. $|M|^2$ excitation functions in arbitrary units for $\pi^+ + p \rightarrow p + \pi^+$ at $\theta = 90^\circ$ for $p_\pi = 200\text{--}700$ MeV/c, Ref. 11.

Fig. 8. Same as Fig. 7.

Fig. 10. $|M|^2$ angular distributions in arbitrary units for $p + d \rightarrow \pi^+ + {}^3\text{He}$ at various angles for incident proton energies $T_p = 410, 605,$ and 809 MeV from Ref. 12, $T_p = 500$ MeV from Ref. 13, and at $T_p = 800$ MeV from Ref. 14.

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