Reaction $\pi^- p \rightarrow \gamma n$ below the Δ resonance

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The reaction $\pi^- p \rightarrow \gamma n$ has been studied at $T_\pi = 45.6$, 62.2, 76.4, 91.7, 106.8, and 121.9 MeV for nine laboratory angles between 30° and 140°. The differential cross section measurements have angle to angle errors of about 4% with an additional 3% normalization error. The results are typically a factor of 2 more accurate than previous radiative capture data and are more reliable than cross sections obtained from the reverse reaction $\gamma d \rightarrow \pi^- p p_s$. The data are compared with recent multipole analyses, various calculations, as well as previous data, and the best agreement is with the Tokyo multipole analysis.

I. INTRODUCTION

There is still a lot of uncertainty regarding photomeson production below the Δ resonance. Although the overall scheme of things is now well established, there are many points of detail which have not been settled. This experiment described here was undertaken to obtain reliable and precise information on a key reaction which has a mottled history.

There are four basic photomeson reactions on the nucleon and they can be described by three isospin amplitudes, a scalar S_1 and two vectors V_1 ($\Delta I = 0$) and V_3 ($\Delta I = 1$), where the isospin states refer to the hadronic system. The relations are

$$A(\gamma p \rightarrow \pi^0 p) = (V_1 + 2V_3 + 3S_1)/3 ,$$

$$A(\gamma p \rightarrow \pi^+ n) = \sqrt{2}(V_1 - V_3 + 3S_1)/3 ,$$

$$A(\gamma n \rightarrow \pi^0 n) = (V_1 + 2V_3 - 3S_1)/3 ,$$

$$A(\gamma n \rightarrow \pi^- p) = -\sqrt{2}(V_1 - V_3 - 3S_1)/3 .$$

Thus, to obtain complete experimental information, one needs to study at least three of these reactions.

The first two reactions have been thoroughly investigated up to about 1 GeV, though some minor inconsistencies remain. The problem has always been to obtain reliable information on the other reactions. The most obvious one to tackle is $\gamma n \rightarrow \pi^- p$, but this means that a deuteron target has to be used, and at low energies it is necessary to make large corrections ($\sim 20\%$) to take account of the presence of the spectator proton. It was realized 20 years ago that a way out of this problem was to investigate the time-reversed reaction ($\pi^- p \rightarrow \gamma n$), but the techniques then available meant that one had to detect both the gamma ray and the neutron in coincidence to distinguish the reaction from the more prolific charge exchange ($\pi^- p \rightarrow \pi^0 n$). Because of the difficulties of detecting two neutral particles with uncertain efficiencies, the final errors were typically 10%, or more.

With the advent of the meson factories, it became clear that an adequate pion flux was thus available to improve the precision if a superior technique could be found. It was clear that a large NaI crystal would have sufficient energy resolution to distinguish the radiative capture from the charge-exchange reaction without any need to detect the recoiling neutron. As early as 1967, Carroll[1] reported such a measurement at 54 MeV at Berkeley using a large plastic detector. This simple technique results in a greater control over systematic errors and avoids a lot of the pitfalls of previous experiments. Thus, with this experiment in mind, a large NaI crystal was ordered by TRIUMF, and it was nicknamed TINA for TRIUMF iodide of natrium. The detector was used initially to study the Panofsky ratio at rest in hydrogen[2] and also in deuterium, ^{3}He, and other elements. However, it was then diverted to study some particle decays such as $\mu^+ \rightarrow e^+ \gamma$ and $\pi^+ \rightarrow e^+ \nu$, but finally, we were able to take data on the present investigation, viz., TRIUMF experiment No. 9. The first measurements were made at the very low energies of 26.4 and 39.3 MeV on channel $M13$, and the results have already been published.[3] A second round of data acquisition was taken on $M11$ to reach higher energies, and we are presenting those results here; preliminary reports have already appeared in various conference proceedings.[4,5] Complete details of the experiment are available in the Ph.D. thesis of one of us.[6]

The standard technique to analyze photomeson production data is via multipole analyses, and thereby to obtain information on the N and Δ families of baryons. The subject has a long history which has recently been reviewed.[7] There are two ongoing efforts to update the energy dependent multipole analyses, one at Glasgow[8] and one at Tokyo,[9] although this is now centered at Tsukuba since Arai moved there recently. As there are few polarization data, there is not sufficient experimental information to do an *ab initio* analysis, and so these calculations obtain the imaginary part of the multipoles from existing pion-nucleon phase-shifts via the Fermi-Watson theorem. An attempt by Smith and Zagury[10] to use only photoproduction data had a limited success because of the lack of polarization data near threshold.

At slightly higher energies there are more data, so Grushin *et al.*[11] were able to make multipole analyses at six different energies between $E_\gamma = 300$ and 420 MeV. It should be noted that, in general, seven measurements are required (with two more needed to remove discrete ambiguities),[12] but at the present time one is fortunate if there exists a minimal set of $d\sigma/d\Omega$, Σ, P, and T; however, assuming only s and p-wave pion production, these are sufficient. Grushin *et al.*, analyzed only two channels, viz., $(\gamma p \to \pi^+ n)$ and $(\gamma p \to \pi^0 p)$, so they could not obtain the isoscalar amplitude separately but only in the combination $V_1 + 3S_1$. Because of inconsistencies in the data bank, the same family of solutions did not always have the minimum χ^2, so some judicious choice of continuity was needed. They were able to obtain the imaginary parts of the multipoles and, thus, this approach offers an important check on the more conventional analyses and gives a better feeling for the actual errors on the multipole amplitudes.

There has been a lot of discussion recently about the possibility of the Δ and the nucleon having deformed bags.[13–20] This introduces a d state into the quark wave function and thus creates the possibility of an $E2$ amplitude for the Δ decay in addition to the well established $M1$ amplitude. Our measurements cover the flank of the resonance, where there is some sensitivity to the $E2$ component, so our results will be useful because of their large angular coverage and high precision. A thorough review of the $M_{1+}^{(3/2)}$ and $E_{1+}^{(3/2)}$ multipoles has recently been given by Jurewicz[21] who emphasizes that the $E2$ amplitude is mainly nonresonant, so that when the experimental multipole has been determined, the resonance contribution is still hard to extract. It is clear that a large $E2$ component is excluded, the present indication[14,20] is that the amplitude ratio $E2/M1 \approx -(1.0 \pm 0.5)\%$, so to improve on this estimate will require very precise measurements, as well as a more reliable estimation of the nonresonant contribution to the $E_{1+}^{(3/2)}$ multipole.

Photomeson production on nuclei has been studied quite extensively in recent years, but for certain nuclei there has been considerable difficulty in fitting the data. Although this is probably related to nuclear structure effects, or to medium effects, it is essential to use elementary amplitudes that fit the nucleon data. We shall show that the versions offered by Blomqvist and Laget,[22] although quite adequate, do depart from our data by up to 15%, and that the more recent amplitudes of Wittman and Mukhopadhyay[23] are not that much better.

Some 15 years ago, there was much speculation[24] on the violation of time reversal invariance in the reactions $\gamma n \to \pi^- p$ and $\pi^- p \to n\gamma$. We shall confirm the present belief that no time reversal violation has been observed by showing that there is as much discrepancy among experiments investigating the same reaction as between the reactions $\gamma n \to p\pi^-$ and $\pi^- p \to n\gamma$. Another short-lived suggestion was that the electromagnetic current had an isotensor component. The so-called dip test was invented, and this indicated that the isotensor amplitude was less than 2% of the amplitude.[25] An alternative method to test this possibility is to have excellent data on all low photomeson production reactions, and our results contribute to that goal.

Finally, it should be noted that the photomeson production reactions have been used as a testing ground for the chiral bag model.[26]

II. THE EXPERIMENT

The experiment was carried out on the $M11$ beam line at TRIUMF and the layout was very similar to our earlier runs on $M13$. The $M11$ channel reaches much higher energies but, because it is longer, the μ-e contamination is worse at the lower energies; nevertheless, we took useful confirmatory data at $T_\pi = 45.6$ MeV to verify consistency.

The incoming beam was defined and counted by a three-scintillation-detector telescope $S1$-$S2$-$S3$ (Fig. 1). An intensity of approximately 10^5 pions/s was used with beam energies of from 50 to 125 MeV. The γ rays from the $\pi^- p \to \gamma n$ and $\pi^- p \to \pi^0 n$ ($\pi^0 \to 2\gamma$) reactions were detected in a 46 cm diameter and 51 cm long NaI (Tl) crystal (TINA) at laboratory angles from 30° to 145°. In order to avoid interference from the walls of the target vessel, separate liquid hydrogen target cells were used for measurements in the forward and backward directions.

A scintillation counter $S4$ in front of the γ detector was used to identify charged particles. Events defined as a coincidence of ($S1$ $S2$ $S3$ TINA) were recorded on tape

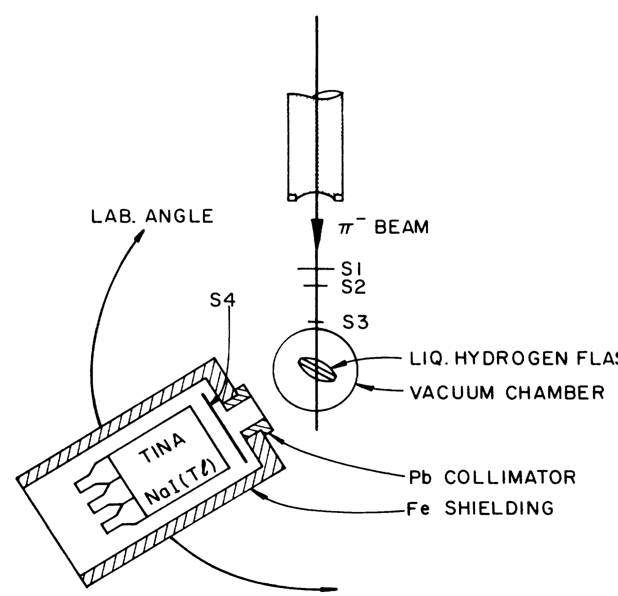

FIG. 1. Experimental setup. $S1$, $S2$, $S3$, and $S4$ are scintillation counters. TINA is a NaI(Tl) γ-ray detector, movable around the target from 0° to 145°, and is surrounded by an iron shield 25 cm thick at the front and 10 cm thick on the sides.

during the course of the experiment with the aid of a computer (PDP 11/34). For each event the amplitudes of the signals in $S3$ and TINA were recorded, together with timing signals from the primary proton beam, the $S3$ counter, and TINA. These timing signals were used to identify pions in the beam and γ rays in TINA. The logic signal of counter $S4$ was also recorded, and used during the data analysis to reject charged particles striking TINA.

The beam size and position at the target was determined using a multiwire proportional chamber. The beam spot was a horizontal ellipse, 1.5 cm wide and 1.3 cm high, which increased to 2.8 cm by 2.4 cm when the beam telescope was in place. The beam-defining counter $S3$, 6.4 cm diameter and 0.16 cm thick, was placed against the target vacuum chamber, 20.5 cm upstream of the target center. The beam composition was determined from the time-of-flight between the time that the primary proton beam strikes the production target and the arrival time of the secondary beam at $S3$. Note that this was monitored continuously during the actual experiment. A typical time spectrum is shown in Fig. 2 for a pion beam energy of 66 MeV. The total cross section for $\pi^- p \rightarrow n\gamma$ changes up to 1% per MeV around $T_\pi = 100$ MeV, so some care must be taken to carefully define the mean energy of the beam, although it is not as critical as in $\pi^+ p$ elastic scattering measurements. The beam momentum was determined from a previous calibration with an α source, using the magnetic fields of the bending dipoles which were continuously monitored with an NMR device. Other checks were made in a related elastic scattering measurement.[27] From the beam momentum one can quickly derive the energy at the center of the target. The important characteristics of the beam are listed in Table I.

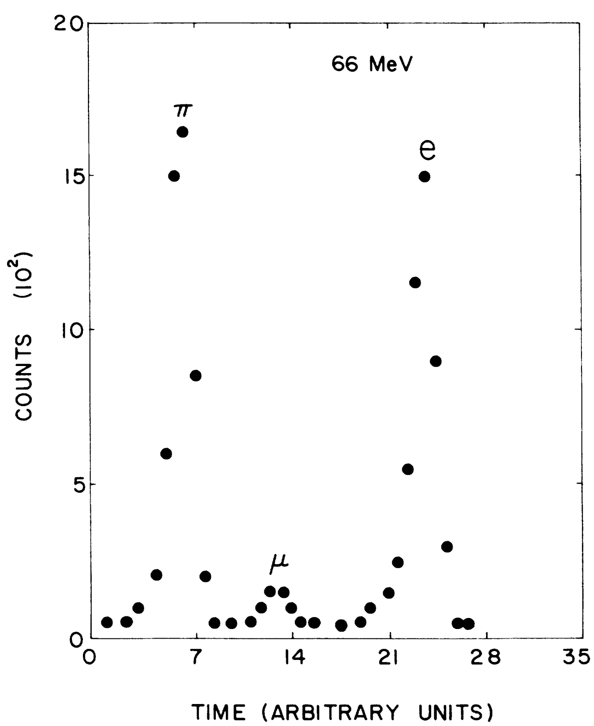

FIG. 2. The time distribution of the beam particles ($S1$, $S2$, and $S3$) with respect to the rf buckets of the primary proton beam ($T_\pi = 66$ MeV). The beam composition at $S3$ is obtained from this histogram.

TABLE I. Characteristics of the $M11$ pion beam line.

Nominal beam energy (MeV)	Energy at target center (MeV) (±1%)	Beam energy spread (MeV)	Pion percentage (±1%)
50	45.6	0.9	31
66	62.2	1.2	49
80	76.4	1.5	63
95	91.7	1.8	76
110	106.8	2.1	83
125	121.9	2.4	88

The liquid hydrogen was contained in a flask 14 cm diameter and 4.4 cm thick with flat Mylar walls surrounded by hydrogen gas in pressure equilibrium with the liquid. A guard ring was installed to divert bubbles which might transverse the beam path. The target assembly was contained in a vacuum chamber with a 0.025 cm thick Mylar window. The total thickness in the beam path was 0.079 cm or 0.111 g/cm^2 of Mylar. The target thickness was measured to be 4.47 cm and 4.40 cm for the forward and backward targets, respectively. The angles of these targets with respect to the beam were 31° and −29.5° as measured with a laser beam across fiducial marks on the targets. During the runs, the targets were kept cool by a refrigerator controlled by the pressure in the flask, allowing a maximum variation of temperature between 20.5 and 20.7 K. Therefore, the density of the liquid hydrogen (0.0703 g/cm^3) changed less than 1%. The total uncertainty of the target proton number was 1.5%.

The acceptance of γ rays into the NaI (*Tl*) detector was defined by a lead collimator 25.4 cm thick. For the lower energies, an aperture of 25.4 cm was used. which provided good solid angle acceptance with reasonable energy resolution (5–6%). This resolution was judged inadequate for the higher energy runs and a smaller aperture of 15.2 cm was used which gave a slightly better resolution (4–5 %) but at the cost of nearly a factor of 3 in count rate. At $T_\pi = 90$ MeV, both collimators were used to check consistency between the data sets. The collimator was placed such that the rear edge was 95.6 cm from the target, and this was considered the defining aperture (apart from a minor edge correction which was applied). The highest energy used in this experiment (125 MeV) was limited by the inadequate energy resolution of TINA, because the γn peak was quickly merging into the $\pi^0 n$ continuum of γ rays.

The electronics was relatively standard and will not be discussed here. Further details are available in Ref. 6.

III. DATA ANALYSIS

The selection of acceptable events for final analysis was done by restricting events to correspond to the arrival of pions in the beam time-of-flight spectrum. A cut in the TINA target time-of-flight spectrum (Fig. 3) was used to

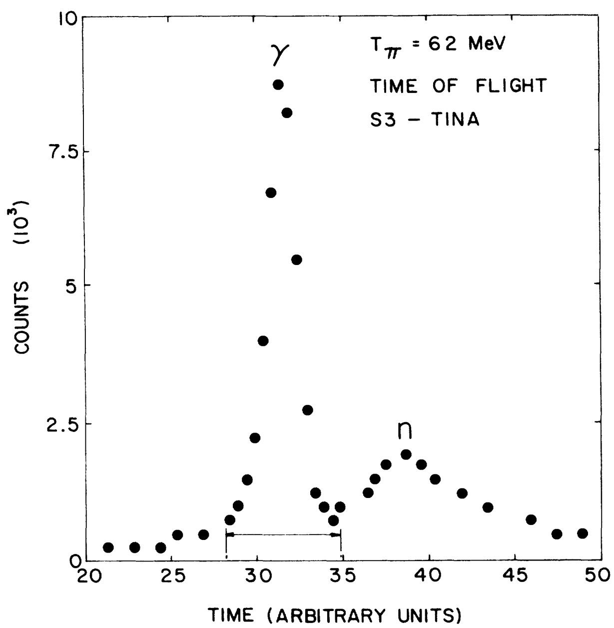

FIG. 3. The time distribution of neutral events in the NaI(*Tl*) crystal, obtained by a "start" signal from a $S1$, $S2$, and $S3$ coincidence, and a stop signal from the crystal. The γ-ray cut is indicated.

select γ rays and reject neutrons. The efficiency of the above cuts was determined by selecting high-energy signals in TINA which could be assigned unambiguously to the $\pi^- p \rightarrow \gamma n$ reaction and determining the loss of events by applying the selected cut to the data. In this way the cut efficiencies for pions in the beam and gammas in TINA were found to be 99% and 98%, respectively. Charged particle events were rejected using the signals in $S4$ which were identified by a logic signal.

At each angle of the γ-ray detector, several runs were recorded with the target full and empty. In the data analysis, normalized empty target runs were subtracted from target full runs after cuts were made to produce TINA pulse-height histograms. Typical complete spectra are illustrated in Fig. 4 to indicate the clean separation in energy between the radiative capture γ ray and the π^0 continuum.

It was decided to analyze the radiative capture data independently from the π^0 continuum. The latter will be discussed in a companion paper. The shape of the response function for the NaI (*Tl*) detector has been shown by earlier work to be well described by the following expression:

$$P(E_\gamma, A,B,C,D) = Ae^{(E_\gamma - B)/C}\{1-\mathrm{erf}[(E_\gamma - B)/D]\} , \tag{1}$$

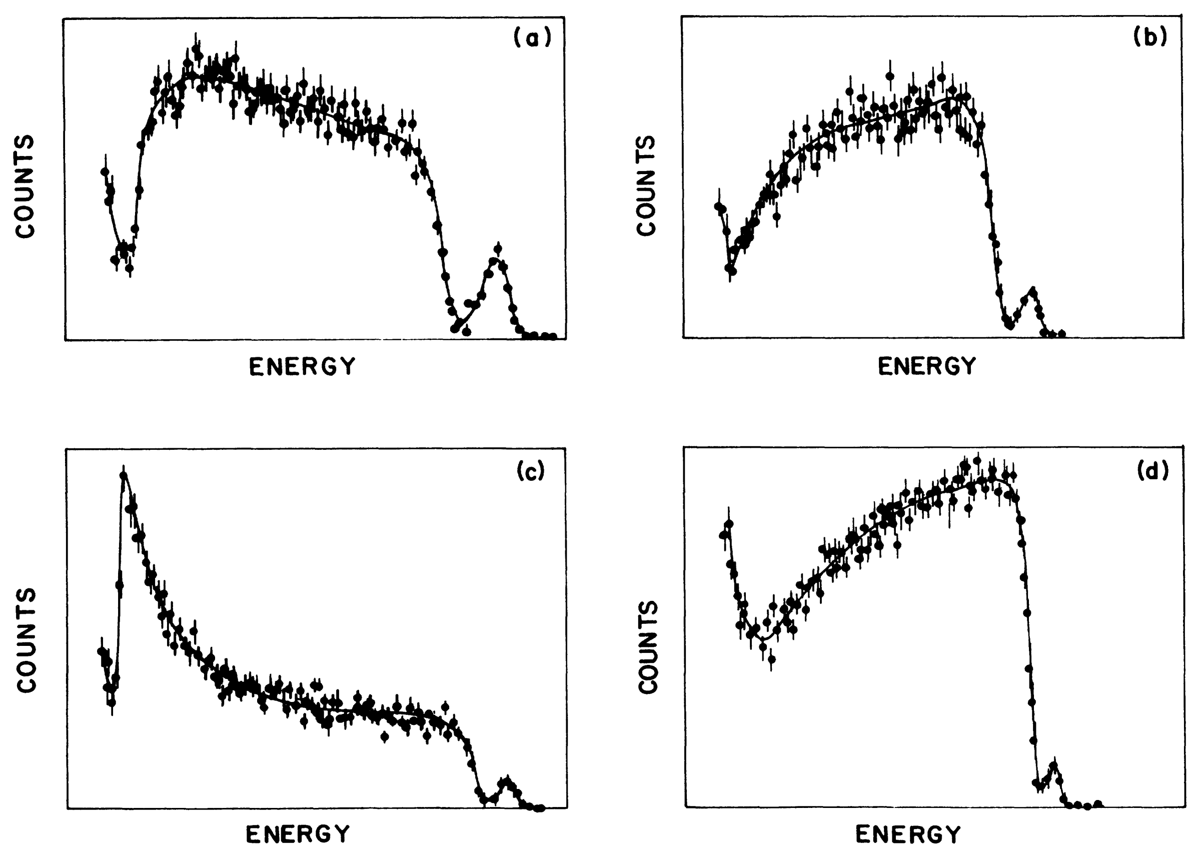

FIG. 4. Typical γ-ray energy spectra in TINA with all cuts applied. The line is a fit which is used to obtain the cross section. Notice the deterioration in the separation of the radiative capture peak at higher energies. The data were taken at (a) 62.2 MeV and 90°; (b) 76.4 MeV and 120°; (c) 106.8 MeV and 45°; (d) 121.9 MeV and 141°.

where A is the amplitude, B is approximately the peak position, C describes the high-energy edge, and D describes the low-energy tail.

For this part of the analysis, the π^0 γ rays are considered a background and the upper edge was described by the function

$$BG = X\{1-\text{erf}[(E_\gamma - Y)/Z]\} . \quad (2)$$

Thus, the fitting was initially carried out using seven parameters. However, it soon became clear that the statistical accuracy (a few hundred counts in the peak) was insufficient to permit full freedom, and it was noticed that C and D fluctuated quite wildly. Because a large value of D increases the tail considerably, and thereby the number of counts attributed to the peak, the apparent cross sections were fluctuating outside the overall statistical accuracy. From previous experience it was known that the response function was fairly stable and, in particular, the ratio D/C varied very slowly with energy. It was therefore decided to fix the ratio to be 1.0, but all data were analyzed with an alternative value (typically 0.9 and/or 1.1) to monitor the sensitivity of the cross section to this decision, and we ascribe a systematic error of 1% to this restriction. Typical fits are illustrated in Fig. 5.

The angle to angle error was dominated by the statistical accuracy, because several hours of data taking were required at each angle. The aim was to obtain about 1,000 counts in the peak, depending on the acquisition rate. Thus, typical cross sections have a relative error of about 5% when fitting fluctuations are added. The overall normalization included uncertainties in beam composition, pion decay corrections, target thickness, detector solid angle, and resolution function, giving a total normalization error of $\pm 3\%$.

In the first run on $M11$, we took complete data at $T_\pi = 50$ and 66 MeV but the normalization appeared to be somewhat low. We modified the liquid hydrogen target by adding a guard ring to divert bubbles to the sides of the flask. A second run was plagued by a faulty TDC which caused neighbors in the Camac rate to malfunc-

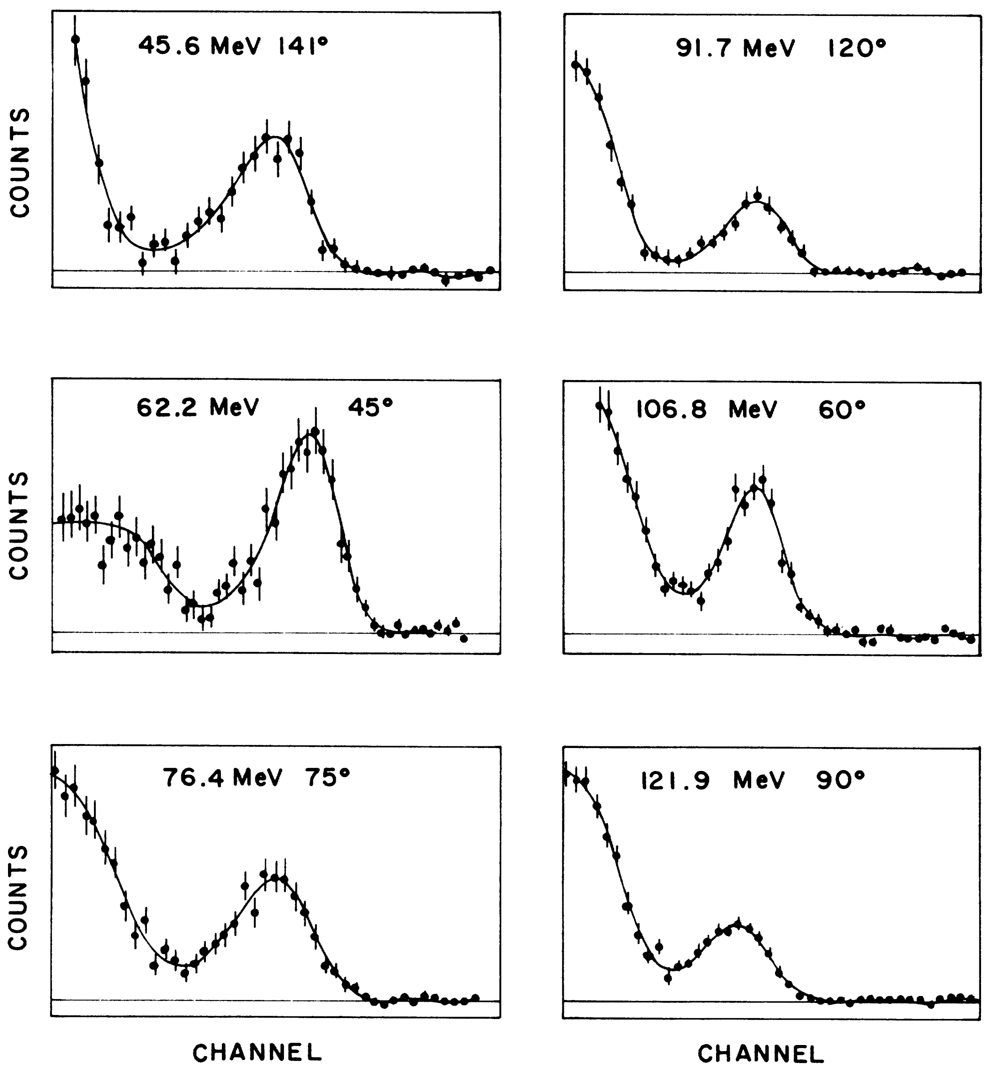

FIG. 5. The γ-ray spectra and the fit for the $(\pi^- p \rightarrow \gamma n)$ reaction at several different energies and angles. The background from the π° decay $(\pi^\circ \rightarrow 2\gamma)$ is also shown.

tion, but we obtained some data in the last few days. Almost all our final data was obtained in a third run a month long. However, there was only sufficient time to obtain four angles (two forward, two backward) at 50 and 66 MeV. A detailed analysis showed that a single normalizing factor of $(22.5\pm2.0)\%$ was necessary to compare with the first run. This could be monitored via the π^0 γ rays for which a total cross section is obtained at *every* separate angle. We have therefore combined the results by using the differential cross sections for those angles available in the final run and supplemented them with renormalized data from the first run. All other data have been taken from the final run only.

IV. RESULTS AND DISCUSSION

The final results are presented in Figs. 6–12 and Tables II–IV. As is conventional in this field, all cross sections have been transformed, using detailed balance, to values for the reaction $\gamma n \to \pi^- p$.

It would be impossible to compare our results with every previous experiment and every previous multipole analysis. Some of the older experiments were as much as a factor of 2 away from the presently accepted values. To illustrate this confusion, we have included on Fig. 7 a variety of old experiments which all studied the reaction $\gamma d \to \pi^- pp$. Beneventano *et al.*[28] made a small empirical correction for the bound neutron, but clearly there is another problem of normalization too. Rossi *et al.*[29] made no correction while at low energies Benz *et al.*[30] overcorrected. For the other figures we have therefore limited ourselves to the most recent experiments and calculations. In these references, and the compilation of Menze *et al.*,[31] can be found further details on the complex history of this subject.

For the radiative capture experiments, there were two major groups, one at CERN (Refs. 32–34), the most

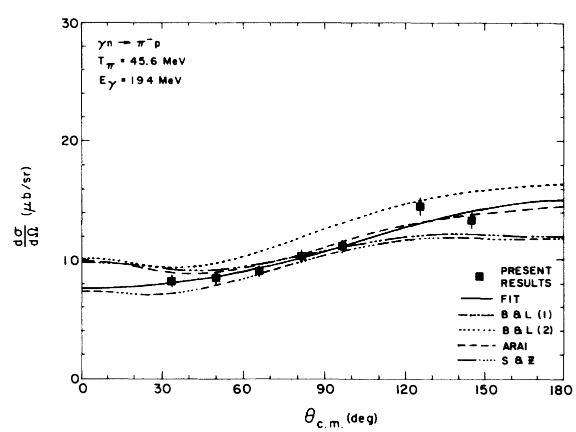

FIG. 6. The differential cross section for the $(\pi^- p \to \gamma n)$ reaction at $T_\pi^{\rm lab} = 45.6$ MeV shown as the time reversed reaction $(\gamma n \to \pi^- p)$ at $E_\gamma^{\rm lab} = 194$ MeV. Also shown are the multipole analyses of Arai and Fujii (Ref. 9), Smith and Zagury (*S&Z*) (Ref. 10) and the calculations by Blomqvist and Laget (Ref. 22). *B&L*(1) is the result of a multipole analysis while *B&L*(2) shows the result of a pseudoscalar-relativistic calculation.

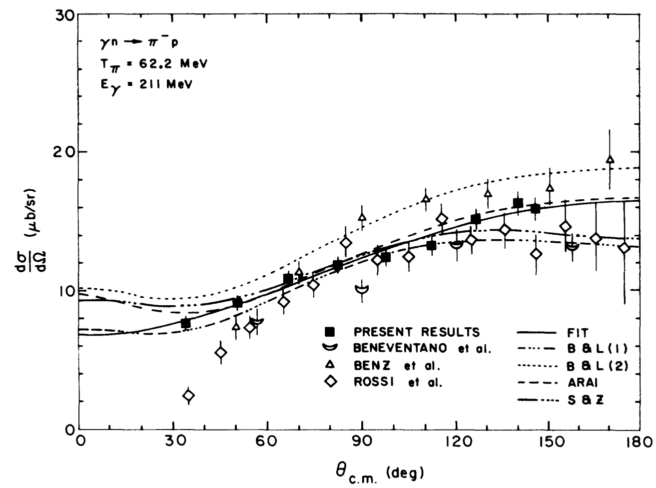

FIG. 7. Differential cross section for the $(\pi^- p \to \gamma n)$ reaction at $T_\pi^{\rm lab} = 62.2$ MeV shown as the time reversed reaction $(\gamma n \to \pi^- p)$ at $E_\gamma^{\rm lab} = 211$ MeV. See Fig. 6 for explanation of the curves. Some old photoproduction data (Refs. 28–30) are included to illustrate the confusing situation which existed in the early 1970's.

complete description being given by Tran *et al.*[34] and the other at Berkeley which has been reported by Berardo *et al.*[35] and by Comiso *et al.*[36] Isolated data points are also available from CERN[37] and SIN.[38] Slight corrections are needed for the published results of Martoff *et al.* from SIN.[38] For all the other previous experiments we have renormalized them in the figures if the energy was not the same as ours, using an average variation of the total cross section. This is a relatively small effect however.

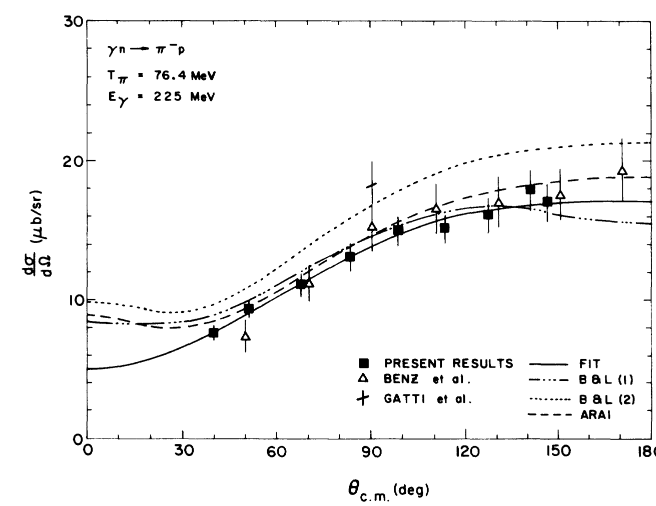

FIG. 8. Differential cross section for the $(\pi^- p \to \gamma n)$ reaction at $T_\pi^{\rm lab} = 76.4$ MeV shown as the time reversed reaction $(\gamma n \to \pi^- p)$ at $E_\gamma^{\rm lab} = 225$ MeV. See Fig. 6 for explanation of the curves. Also included is the Deutsches Elektronen-Synchrotron (DESY) data of Benz *et al.* (Ref. 30) for the reaction $\gamma n \to \pi^- p$, and the datum of Gatti *et al.* (Ref. 37) for $\pi^- p \to \gamma n$ at $T_\pi = 72$ MeV.

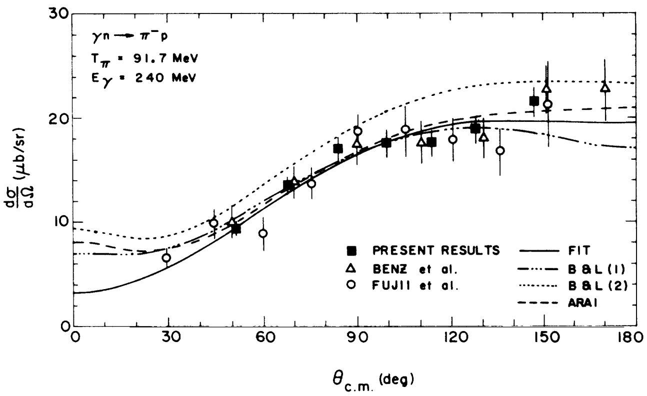

FIG. 9. Differential cross section for the $(\pi^- p \rightarrow \gamma n)$ reaction at $T_\pi^{\mathrm{lab}} = 91.7$ MeV shown as the time reversed reaction $(\gamma n \rightarrow \pi^- p)$ at $E_\gamma^{\mathrm{lab}} = 240$ MeV. See Fig. 6 for explanation of the curves. Also included are results for $\gamma n \rightarrow \pi^- p$ of Fujii *et al.* (Ref. 39) and Benz *et al.* (Ref. 30).

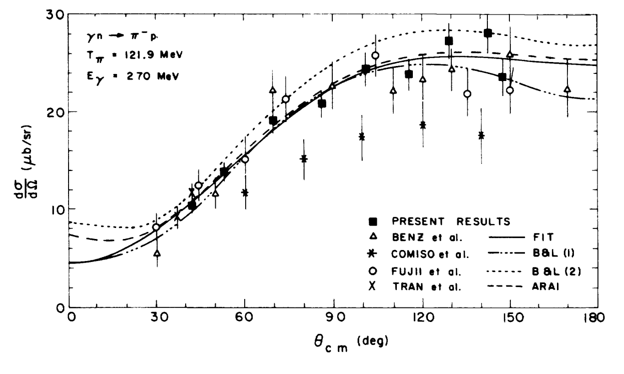

FIG. 11. Differential cross section for the $(\pi^- p \rightarrow \gamma n)$ reaction at $T_\pi^{\mathrm{lab}} = 121.9$ MeV shown as the time reversed reaction $(\gamma n \rightarrow \pi^- p)$ at $E_\gamma^{\mathrm{lab}} = 270$ MeV. See Fig. 6 for explanation of the curves. Also included are results for $\gamma n \rightarrow \pi^- p$ of Fujii *et al.* (Ref. 39) and Benz *et al.* (Ref. 30), as well as the radiative capture data of Tran *et al.* (Ref. 34), and Comiso *et al.* (Ref. 36).

For the experiments on photomeson production on the deuteron, we have selected only the recent results for which considerable care was taken to estimate the effects of the spectator proton. The most extensive have been the work of Fujii *et al.* from Tokyo[39] using a magnetic spectrometer, and the bubble chamber results of Benz *et al.* from DESY.[30] In addition to these, Argan *et al.*[40] at Saclay made a careful measurement of the 90° cross section.

For the calculations, we have selected the Tokyo multipole analysis,[9] the analysis by Smith and Zagury,[10] the calculations by Blomqvist and Laget,[22] and those by Wittman and Mukhopadhyay.[23] In addition, we have made a simple Legendre polynomial fit to the data (and used it to calculate the total cross section). This total cross section is presented in Fig. 12 and we have added some lower-energy results, viz., the photomeson results of Adamovich,[41] and the radiative capture measurement from Saclay of Balestri *et al.*[42]

The results show overall agreement, although the present results are more precise. The only obvious discrepancy is with the Berkeley result of Comiso *et al.*[36] at their lowest energy. This had been discussed as a possible violation of time reversal invariance, but it is clearly a normalization problem in that experiment because three other radiative capture experiments agree, viz., our own, that of Tran *et al.* at CERN[34] and that of Martoff *et al.* at SIN,[38] and these are all compatible with the photomeson results of Fujii *et al.*,[39] Benz *et al.*,[30] and Ar-

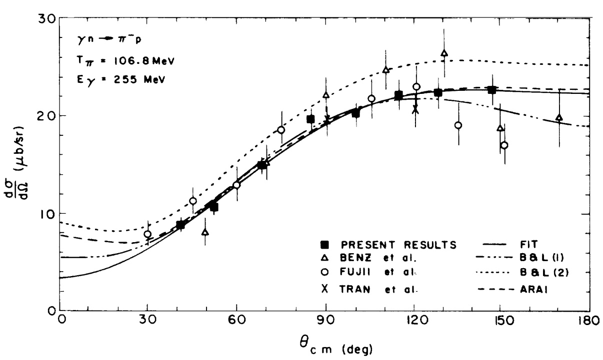

FIG. 10. Differential cross section for the $(\pi^- p \rightarrow \gamma n)$ reaction at $T_\pi^{\mathrm{lab}} = 106.8$ MeV shown as the time reversed reaction $(\gamma n \rightarrow \pi^- p)$ at $E_\gamma^{\mathrm{lab}} = 255$ MeV. See Fig. 6 for explanation of the curves. Also included are results for $\gamma n \rightarrow \pi^- p$ of Fujii *et al.* (Ref. 39) and Benz *et al.* (Ref. 30), as well as the radiative capture data of Tran *et al.* (Ref. 34).

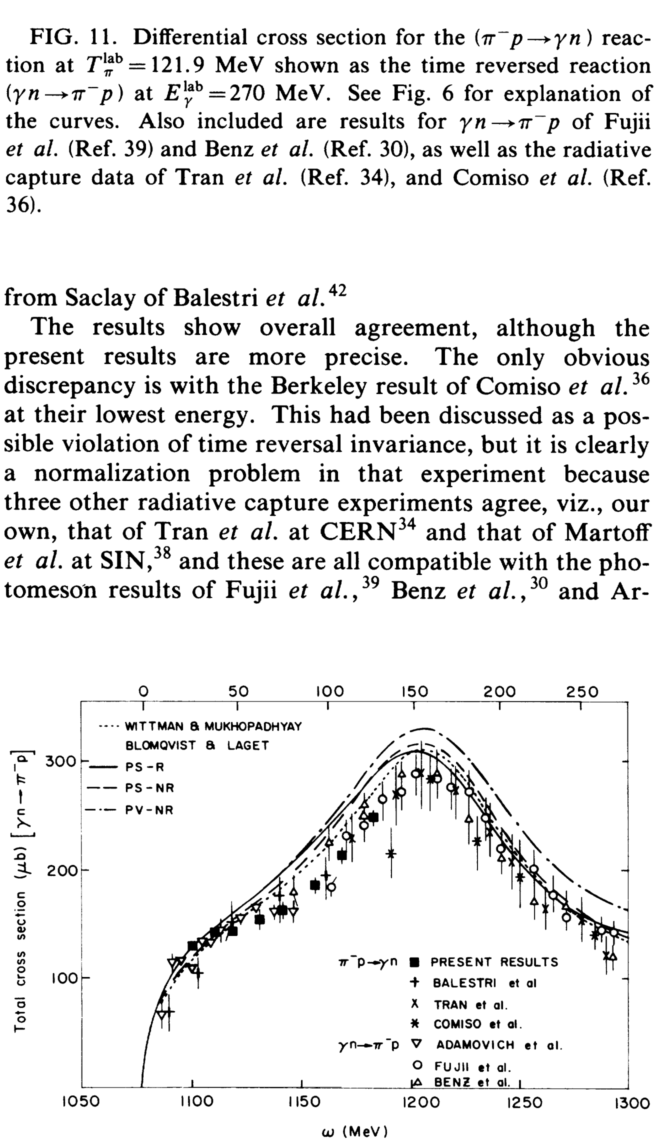

FIG. 12. The total cross section of the $(\gamma n \rightarrow \pi^- p)$ reaction as a function of energy including previous experimental results of Balestri *et al.* (Ref. 42), Tran *et al.* (Ref. 34), and Comiso *et al.* (Ref. 36) from the reaction $(\pi^- p \rightarrow \gamma n)$, and Adamovich *et al.* (Ref. 41), Fujii *et al.* (Ref. 39) and Benz *et al.* (Ref. 30) from the reaction $(\gamma n \rightarrow \pi^- p)$. Also included are the theoretical results of Blomqvist and Laget (Ref. 22), and Wittman and Mukhopadhyay (Ref. 23). (The axis marked at the top is the pion laboratory energy for the reaction $\pi^- p \rightarrow n\gamma$).

TABLE II. Experimental results for the reaction ($\pi^- p \to \gamma n$) [quoted as c.m. cross sections for the inverse ($\gamma n \to \pi^- p$) reaction]. Normalization error of 3% is included in the total error.

	T_π=45.6 MeV ω=1116.8 MeV				T=62.2 MeV ω=1130.7 MeV			
Lab angle	c.m. angle	$\frac{d\sigma}{d\Omega}$ (μb/sr)	Angle dependent error (μb/sr)	Total error (μb/sr)	c.m. angle	$\frac{d\sigma}{d\Omega}$ (μb/sr)	Angle dependent error (μb/sr)	Total error (μb/sr)
30°	33°	8.3	0.3	0.4	34°	7.6	0.3	0.4
45°	50°	8.5	0.3	0.4	50°	9.2	0.4	0.5
60°	66°	9.0	0.4	0.5	66°	10.9	0.5	0.6
75°	81°	10.3	0.4	0.5	82°	11.9	0.5	0.6
90°	96°	11.1	0.5	0.6	97°	12.5	0.5	0.6
105°					112°	13.3	0.6	0.7
120°	125°	14.5	0.5	0.7	126°	15.2	0.7	0.8
135°					140°	16.4	0.6	0.8
141°	145°	13.3	0.6	0.7	145°	16.0	0.6	0.8
σ_{total}(μb)		138.0	5.6	7.0		153.0	5.3	7.0

TABLE III. Experimental results for the reaction ($\pi^- p \to \gamma n$) [quoted as c.m. cross sections for the inverse ($\gamma n \to \pi^- p$) reaction]. Normalization error of 3% is included in the total error.

	T_π=76.4 MeV ω=1142.5 MeV				T_π=91.7 MeV ω=1154.9 MeV			
Lab angle	c.m. angle	$\frac{d\sigma}{d\sigma}$ (μb/sr)	Angle dependent error (μb/sr)	Total error (μb/sr)	c.m. angle	$\frac{d\sigma}{d\Omega}$ (μb/sr)	Angle dependent error (μb/sr)	Total error (μb/sr)
35°	40°	7.5	0.4	0.5	41°			
45°	51°	9.3	0.5	0.6	52°	9.2	0.5	0.6
60°	67°	11.0	0.7	0.8	68°	13.4	0.8	0.9
75°	83°	13.0	0.8	0.9	84°	16.9	0.9	1.0
90°	98°	14.9	0.9	1.0	99°	17.3	0.8	1.0
105°	113°	15.1	1.1	1.2	114°	17.4	1.0	1.1
120°	127°	16.0	1.1	1.2	128°	18.7	1.1	0.9
135°	141°	17.9	1.3	1.4	141°			
141°	146°	17.0	1.3	1.4	146°	21.4	1.2	1.4
σ_{total}(μb)		163.0	3.5	6.0		186.0	4.0	7.0

TABLE IV. Experimental results for the reaction ($\pi^- p \to \gamma n$) [quoted as c.m. cross sections for the inverse ($\gamma n \to \pi^- p$) reaction]. Normalization error of 3% is included in the total error.

	T_π=106.8 MeV ω=1167.1 MeV				T_π=121.9 MeV ω=1179.2 MeV			
Lab angle	c.m. angle	$\frac{d\sigma}{d\Omega}$ (μb/sr)	Angle dependent error (μb/sr)	Total error (μb/sr)	c.m. angle	$\frac{d\sigma}{d\Omega}$ (μb/sr)	Angle dependent error (μb/sr)	Total error (μb/sr)
35°	41°	9.0	0.4	0.5	42°	10.3	0.7	0.8
45°	52°	10.6	0.5	0.6	53°	13.8	0.7	0.8
60°	69°	14.9	0.8	0.9	70°	19.0	0.9	1.1
75°	85°	19.6	1.0	1.2	86°	20.7	1.0	1.2
90°	100°	20.1	1.0	1.2	101°	24.3	1.5	1.7
105°	114°	22.2	1.1	1.3	115°	23.8	1.3	1.5
120°	128°	22.4	1.3	1.5	129°	27.1	1.7	1.9
135°	142°	17.9	1.3	1.4	142°	27.9	1.6	1.8
141°	147°	22.8	1.4	1.6	147°	23.5	1.7	1.9
σ_{total}(μb)		216.0	4.7	8.0		250.0	6.6	10.0

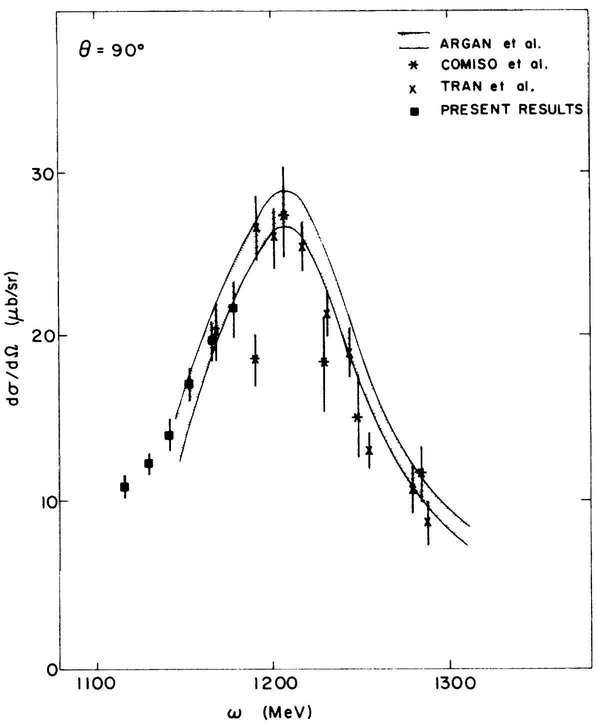

FIG. 13. A comparison between the Saclay data of Argan *et al.* (Ref. 40) (shaded area) for the reaction $\gamma n \to \pi^- p$ at 90° c.m., and the cross section, deduced by detailed balance, from the ($\pi^- p \to \gamma n$) results of CERN [Guex *et al.* (Ref. 33)], Berkeley [Berardo *et al.* (Ref. 35) and Comiso *et al.* (Ref. 36)] and TRIUMF (present experiment). [Adapted from Argan *et al.* (Ref. 40)].

gan *et al.*[40] This is illustrated dramatically in Fig. 13 which is adapted from Argan *et al.* and compares their 90° cross section with radiative capture results.

The comparison with the various calculations shows that the best fit is the Tokyo multipole analysis of Arai and Fujii.[9] The only slight difference is that their analysis tends to be always slightly above the data at the smallest angle point of 30° (it should be noted that this point is the most difficult one to measure experimentally because the NaI detector is approaching the muon halo and great care had to be taken to protect the crystal from this rain of particles. We would have liked to go to smaller angles, but it was totally impossible). The agreement with Smith and Zagury is better than the lower energies of our earlier experiment, which indicates that their extrapolation to zero energy is in doubt. This improvement at higher energies is necessary, anyway, because Fig. 7 of their second paper shows that, at $E_\gamma = 250$ MeV, they fit the previous data quite well. The amplitudes obtained by Blomqvist and Laget[22] give an adequate fit to the data, but there are deviations of up to 15%. The most obvious problem is that none of the various options adequately follows the knee in the data at about $\omega = 1150$ MeV. The improvements developed by Wittman and Mukhopadhyay[23] do not provide a significantly better fit in this low-energy region, probably because their calculations are based on relatively old multipole analyses which relied on inadequate data for the π^- reaction. This group is continuing to work on this problem, so improved fits should soon be available.

V. CONCLUSIONS

Our results have added considerable information on the cross section for the reaction $\pi^- p \leftrightarrow \gamma n$. Recent results have also been reported at slightly higher energies on the asymmetry in the same reaction $\pi^- p \to n\gamma$ (Refs. 43 and 44). With this renewed interest in this reaction, it is time to reopen the multipole analyses and to assess the effect. There are clearly problems at low energies. A recent experiment on $\gamma p \to p\pi^0$ near threshold by Mazzucato *et al.*[45] has obtained a cross section which is much lower than found before; and they have shown that a full understanding of that reaction is sadly lacking. All of these new results should be digested simultaneously in order to produce a new set of improved multipole amplitudes.

The present measurements show that the amplitudes of Blomqvist and Laget do not fit the reaction $\gamma n \to \pi^- p$ to better than 15%; since their fits to the total cross section have a wrong energy dependence, it indicates that the relative importance of some important multipoles are in error. People who use these valuable amplitudes to calculate nuclear cross sections should therefore be careful, but normally there are other problems which mask this relatively minor discrepancy.

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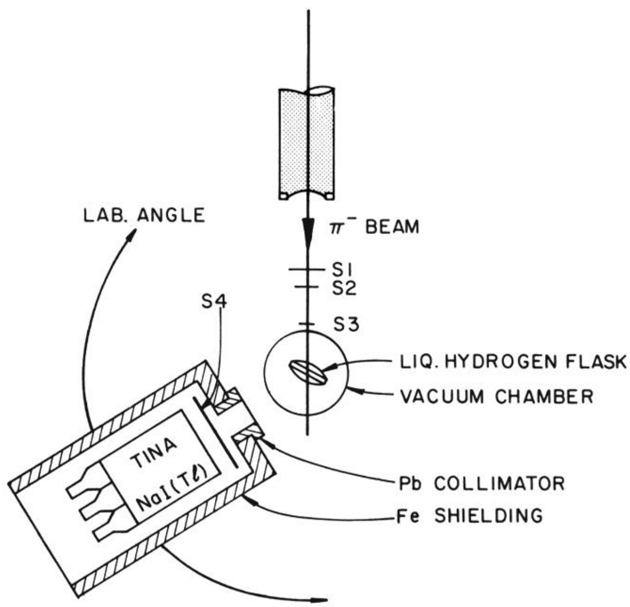

FIG. 1. Experimental setup. $S1$, $S2$, $S3$, and $S4$ are scintillation counters. TINA is a NaI(Tl) γ-ray detector, movable around the target from 0° to 145°, and is surrounded by an iron shield 25 cm thick at the front and 10 cm thick on the sides.