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Exclusive $^{16}O(\gamma,\pi^- p)$ reaction in the Δ resonance region

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We report the first exclusive $(\gamma,\pi^- p)$ measurements on a complex nucleus. The $^{16}O(\gamma,\pi^- p)$ reaction was measured at pion laboratory angles of 64° and 120°. Coincident protons were detected over the quasifree angular correlation range using a vertical array of seven plastic scintillator detectors spanning ±33° about the scattering plane. The cross sections are compared to factorized distorted-wave impulse approximation calculations; these provide a good description of the backward angle data, but are in serious disagreement with the forward angle data.

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I. INTRODUCTION

The physics associated with the excitation of the $\Delta(1232)$ resonance in nuclei has been a major research interest for more than two decades. In particular, various inclusive and exclusive pion-induced reactions, such as (π,π') and $(\pi,\pi'N)$, have been studied in this energy region [1–4]. These pion-induced reactions appear to be predominantly quasifree, although the elementary πN interaction turns out to be substantially modified in the nuclear medium. For example, it has been found that the forward-backward ratio of quasifree $(\pi,\pi'N)$ cross sections can be significantly modified by the interaction of a Δ propagating through the nuclear medium [2,3]. These experimental results, together with theoretical studies [5], have significantly advanced our understanding of medium-energy pion-induced reactions.

In a similar effort, photon-induced reactions such as (γ,π) have been investigated in the Δ resonance region, thus providing complementary information about the Δ-nucleus interaction in the nuclear medium [6–8]. The weaker interaction of the photon, compared to that of the pion, and the different character of the coupling can be advantageous in trying to identify the different effects on quasifree reactions. However, nonresonant processes can contribute significantly in photopion reactions [9]. Also, because of experimental limitations, few photopion experiments have actually been carried out in the Δ resonance region.

Several theoretical approaches, such as distorted-wave impulse approximation (DWIA) calculations [10], Δ-hole model calculations [5,9,11], and a combined DWIA and Δ-hole model approach [12], have been used to interpret the experimental data in the Δ resonance region. In spite of successes (see, for instance, Ref. [5]), serious discrepancies remain between some experimental data and these calculations. In particular, exclusive (γ,π) cross sections appear to be dominated by nuclear structure effects which have so far prevented a good understanding of the underlying reaction mechanism [13].

Exclusive $(\gamma,\pi^- p)$ data should provide stringent constraints on theoretical models, as only one or a few final states are involved and use is made of a well-understood probe. However, the few published $(\gamma,\pi^- p)$ data in the Δ resonance region are actually obtained from *inclusive* $(\gamma,\pi^- p)$ experiments in which the yield has been integrated over the bremsstrahlung spectrum (see, e.g., Ref. [14]).

In this paper we present the first *exclusive* $(\gamma,\pi^- p)$ measurements made on a complex nucleus. Several aspects of the experiment are discussed in greater detail in Ref. [15].

II. EXPERIMENTAL SETUP

The experiment was carried out at the Bates Linear Accelerator Center. We measured $(\gamma,\pi^- p)$ cross sections on ^{16}O using the low flux bremsstrahlung photon facility. As a target we chose ^{16}O (water) because of the relatively large amount of $(\pi,\pi'N)$ data available for this nucleus and because of the simple shell structure of the dominant low-lying states of the residual ^{15}O nucleus. The free protons in the water do not, of course, yield any $(\gamma,\pi^- p)$ events. Figure 1 shows the layout of our experimental apparatus.

In the experiment, a 0.5% duty factor electron beam of

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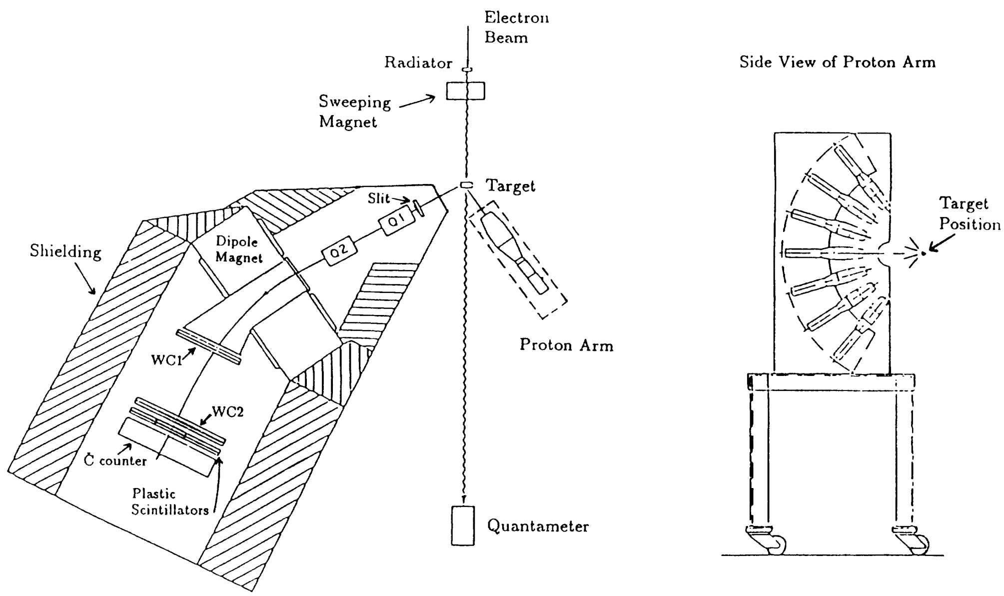

FIG. 1. Layout of the $^{16}O(\gamma,\pi^- p)$ experiment at the Bates Linear Accelerator Center.

about 360 MeV passed through a 1.5-mm Al radiator and a 0.13-mm Be viewing screen located upstream of the experimental target, thus providing a bremsstrahlung photon beam with an end-point energy of about 360 MeV. The electron beam was deflected into a beam dump while the photon beam continued through about 3 m of air and was subsequently collimated by a Pb slit with an opening of 7.6 mm$\times$1.3 mm. The distance from the Pb slit to the target position was about 15 m. At the target position, the photon beam spot was 4 cm (vertical) $\times$ 1 cm (horizontal).

The target was a water-filled rectangular box of 9.9$\pm$0.4 mm thickness (for the forward pion angle) and consisted of a metal frame with 50-μm Mylar windows. For the backward pion angle, the target thickness was 11.1$\pm$0.5 mm. These thicknesses were determined with a γ-ray attenuation measurement. After passing through the target, the photon flux was measured to a precision of 3% with a Wilson-type quantameter [16].

The pions were detected with the Bigbite magnetic spectrometer [17]. The energy-dependent acceptance of Bigbite was calibrated by measuring the known $^{12}C(e,e)$ elastic-scattering cross section. The momentum resolution was determined to be 1.2% (full width at half maximum) including the contribution from the beam spot size. The solid angle of Bigbite was 5.1 msr ($\pm$1%).

It was expected that, at each pion angle, the distribution of the associated protons would be peaked at the angle corresponding to the kinematics of the free $\gamma n \rightarrow \pi^- p$ process; the width of the distribution was expected to be determined primarily by the Fermi momentum of the target neutron. By using a vertical array of seven plastic scintillator counter telescopes, it was possible to cover a large part of this distribution. The detectors were separated from each other by 11° and mounted symmetrically about the γ-π^- scattering plane. Each proton detector telescope consisted of a ΔE-E pair of plastic scintillators with thicknesses 3 and 152 mm, respectively. Such a configuration allows particle detection and identification over a range of proton energies of about 30–110 MeV.

The proton detectors were constructed at the University of Illinois and then calibrated at the Indiana University Cyclotron Facility (IUCF) using a monoenergetic proton beam. The FWHM energy resolution of the detectors was found to be 3.7%. The energy calibration and linearity of the system were continuously monitored during all phases of data taking by using a laser system. All E counters were connected by optical fibers to one N_2 laser, which was also linked to a separate E counter exposed to a ^{60}Co source. This system allowed monitoring of the relative and absolute calibrations of the gain of each detector.

We investigated the $^{16}O(\gamma,\pi^- p)$ reaction in two sets of kinematics: the first run was centered at a pion laboratory angle of $\theta_\pi^{lab}=64°$ and a corresponding proton laboratory angle θ_p^{lab} of 40°, while the second run was centered at $\theta_\pi^{lab}=120°$ and $\theta_p^{lab}=20°$. In both cases the singles rates in the proton detectors (primarily from low-energy photons) were reduced by mounting a 1.6-mm Al plate in front of the counters. At the more forward proton angle we also had to put a permanent magnet (75 mT) between the target and the proton counters to remove electrons produced in the target. In the end, significantly more integrated luminosity was obtained for the forward pion-angle setup than for the backward pion-angle setup.

The complicated angular acceptance of the two-arm setup (especially when the permanent magnet was used) was evaluated by means of a Monte Carlo simulation. The nonzero size of the beam spot was also accounted for in these calculations. Typical values of the effective solid angle of each proton detector were 12.5 (first run) and 10.0 msr (second run). The uncertainty of these effective solid angles is about 3%.

III. DATA ANALYSIS

Reconstructed photon energy spectra at both pion angles are shown in Fig. 2 for events in which the coincident proton was detected in the central proton detector. Also shown are spectra obtained by summing over all proton detectors. The reconstructed photon energy E_γ is defined as follows:

$$E_\gamma = E_\pi + E_p - \Delta M + T(^{15}O) . \quad (1)$$

E_π and E_p are the measured total energies of the coincident pion and proton, ΔM is the difference between the masses of ^{16}O and ^{15}O, and $T(^{15}O)$ is the (very small) recoil energy of the residual nucleus. Near the end point of the bremsstrahlung spectrum, E_γ thus corresponds to the energy of a photon which produced a pion and a proton, leaving ^{15}O in its ground state. Events with E_γ significantly lower than the end-point energy may correspond as well to a $(\gamma,\pi^- p)$ reaction with the residual nucleus left in an excited state. A threshold of 30 MeV was applied for the proton kinetic energy in the analysis of the forward pion-angle data; a threshold of 35 MeV was applied in the analysis of the backward angle data.

Cross sections were extracted from the spectra shown in Fig. 2 by fitting a theoretical bremsstrahlung spectrum [18], smeared with a Gaussian representing the nonzero energy resolution, to the end-point region. Particular care was exercised in the fitting because of the low statistics of the data (cf., Ref. [19]). We first fitted the theoretical bremsstrahlung shape to the spectra summed over all proton detectors. The theoretical shape included both the transition to the $\frac{1}{2}^-$ ground state and the one to the $\frac{3}{2}^-$ state at 6.2 MeV in ^{15}O. Since, in a quasifree reaction, the transition to the $\frac{3}{2}^-$ state is expected to be twice as strong as that to the ground state, the relative strength of the two added bremsstrahlung shapes was taken to be a factor of 2. We then determined the best end-point energy E_γ (see Fig. 2). We found $E_\gamma = 361$ and 363 MeV for the forward and backward pion angles, respectively. These values are within the uncertainty of our knowledge

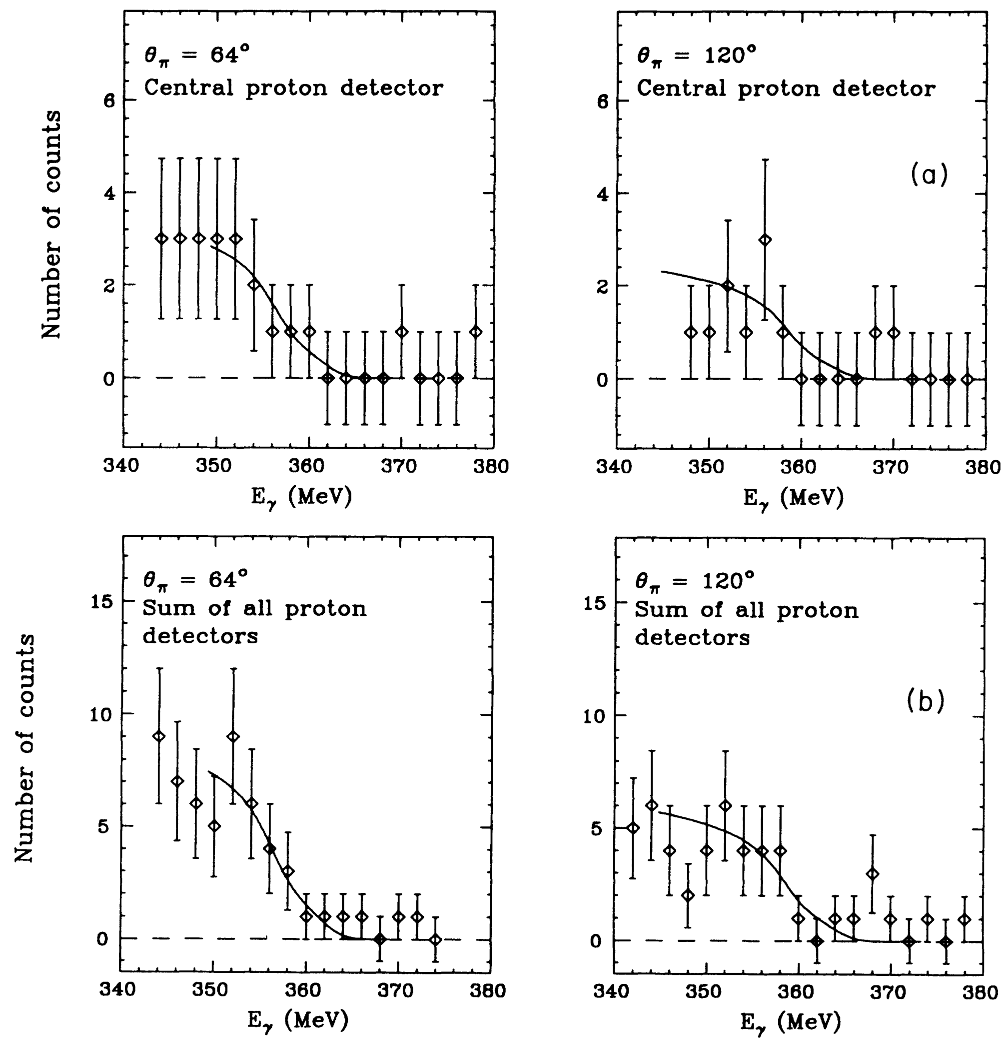

FIG. 2. End-point energy distributions for (a) the central proton detector and (b) the sum of all proton detectors. The parameter E_γ is defined in the text. The fits to the data include the transitions to the ^{15}O ground state and to the first $\frac{3}{2}^-$ excited state, as described in the text.

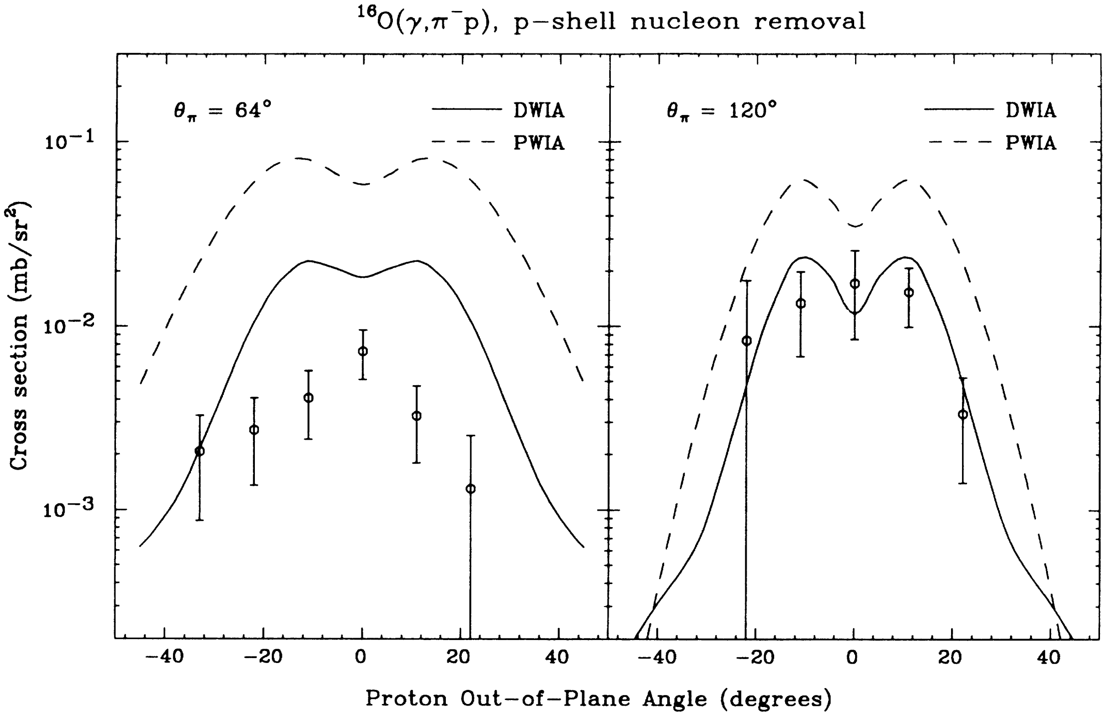

FIG. 3. Out-of-plane angular correlations for the $^{16}O(\gamma,\pi^- p)$ reaction at $E_\gamma = 360$ MeV. The experimental cross sections include the ground-state transition and the transition to the first $\frac{3}{2}^-$ state, as described in the text. Indicated uncertainties are statistical only. Additional systematic uncertainties are estimated to be 30%. The DWIA and PWIA calculations are described in the text.

of the electron beam energy. The E_γ values thus obtained were used in the fitting of the end-point spectra of each individual proton detector.

Due to the low statistics, we could not obtain independent results for the ground-state transition and the transition to the excited state at 6.2 MeV. We instead used the method described above to derive a cross section corresponding to both transitions. For the two outermost proton detectors we simply counted the number of coincidence events in the top 10-MeV end-point region, as an end-point fit was not feasible in this case.

Figure 3 shows the extracted laboratory cross sections as a function of the proton out-of-plane angle for both the forward and backward pion-angle measurements. The error bars are statistical only. The systematic uncertainty in the cross section is due mainly to the bremsstrahlung fitting and is estimated to be 30%. Note that the cross section at the forward pion angle is about a factor of 3 lower than that at the backward pion angle.

IV. MODEL CALCULATIONS

As mentioned before, several models have been developed to interpret charged pion photoproduction; however, none of these calculations was dedicated to the $(\gamma,\pi^- p)$ reaction in the Δ resonance region. In order to have a means of interpreting our data, we have performed a simple factorized DWIA calculation corresponding to the kinematics of our experiment.

The factorized DWIA formalism was developed by Laget [20] to study quasifree pion photoproduction on nuclei. His calculation gives a reasonable account of inclusive $^4He(\gamma,\pi^- p)$ data taken at Saclay [14]. In this model the $(\gamma,\pi^- p)$ cross section is expressed as the product of two terms: one term describes the pion photoproduction process on a free nucleon, and the other term describes the nuclear structure and final-state interactions relevant to the reaction. There are potential difficulties with this approach; for example, it has been pointed out that such a relationship between the elementary pion photoproduction process and the measured photopion yield on nuclei does not exist for inclusive quasifree (γ,π) reactions [20], for which one has to integrate over all processes leading to the emission of a pion.

In the factorized DWIA approach, the $(\gamma,\pi^- p)$ cross section is given by

$$\frac{d^3\sigma}{dT_\pi d\Omega_\pi d\Omega_p} = k\sigma^{\text{c.m.}}_{\gamma n\to\pi p}|\Phi_l^D|^2 , \quad (2)$$

where k is a constant including kinematical factors and a recoil term. The elementary photon-neutron pion production cross section in the center-of-mass system, $\sigma^{\text{c.m.}}_{\gamma n\to\pi p}$, is calculated using the Blomqvist-Laget operator [21]. The distorted momentum distribution Φ_l^D is given by

$$\Phi_l^D = S_{1p}^{1/2}\int \chi_{\pi^-}^{-(*)}\chi_p^{-(*)}e^{i\mathbf{k}_\gamma\cdot\mathbf{r}}\phi_l(\mathbf{r})d\mathbf{r} . \quad (3)$$

In this expression $\chi^{-(*)}$ represents an outgoing distorted wave function, ϕ_l is a bound-state wave function, and S_{1p} is the spectroscopic factor that takes into account the number of $1p$ nucleons taking part in the reaction. The distorted pion wave is generated from an optical potential using the Cottingame-Holtkamp [22] parametrization. The distorted proton wave is calculated using one of the conventional parametrizations of the proton-nucleus optical potential [23]. Using different parametrizations of either the proton or the pion optical potential has only a modest effect (about 20%) on the calculated cross sections.

Due to the Fermi motion of the nucleons inside the nucleus, the $(\gamma,\pi^- p)$ cross section is strongly dependent on the proton out-of-plane angle, which is directly related to the initial momentum of the struck neutron. Hence, a good description of the basic dependence of the cross section on this angle requires a proper choice of the wave function of the bound neutron. The bound-state wave function ϕ_l is generated from a mean-field potential represented by a (real) Woods-Saxon shape. Parameters which yield a good description of the existing $^{16}O(e,e'p)$ data [24] have been chosen. These data are known to be sensitive to the shape of this bound-state wave function. The value $S_{1p}=3.6$ also agrees with the $(e,e'p)$ data [24], including the transitions to both the ground state and the $\frac{3}{2}^-$ excited state.

In order to compare the theoretical cross sections with the data, the threefold differential cross section was integrated over the momentum acceptance of Bigbite. The integration was limited to pion momenta with a corresponding proton momentum above the cutoff used in the analysis (see Sec. III). The pion and proton distortions were kept the same in all calculations. Furthermore, only the free $\gamma n \rightarrow \pi p$ amplitudes were used, i.e., no dynamical medium effects were included.

In Fig. 3, the results of a plane-wave impulse approximation (PWIA) calculation as well as of the factorized DWIA calculation are shown together with the experimental data. The PWIA calculations are similar to the DWIA calculations except that the π^- and p distorted waves are replaced by plane waves. From this comparison we conclude that the backward angle data are fairly well described by the DWIA calculation, whereas the forward angle data are overestimated by a factor of about 4. We stress that no adjustment of parameters in the DWIA calculations was performed in order to fit the data. The difference between the PWIA and DWIA curves indicates that the final-state interaction has considerable influence on this reaction; the PWIA and DWIA calculations differ by a factor of 3.

In an effort to study possible Δ-hole effects in the final state, we replaced the Cottingame-Holtkamp distorted pion wave by one evaluated in a Δ-hole framework [25]. The resulting curves (not shown) are about 15% above the ones displayed in Fig. 3, and hence do not affect our conclusions.

In Ref. [15] it is shown that in the elementary Blomqvist-Laget operator the contribution from the Δ term dominates at forward pion angles, while the contribution from the nonresonant terms is more important at backward pion angles. This may indicate that the discrepancy at the forward angle could be related to a Δ medium effect. However, these considerations apply only to the elementary photoproduction cross section; more sophisticated dynamical Δ-hole calculations of the type [5] that have been used to explain the exclusive $(\pi,\pi' p)$ cross section ratios [2] may be necessary in order to assess realistically the observed discrepancy.

V. DISCUSSION AND CONCLUSIONS

Comparing the measured exclusive $^{16}O(\gamma,\pi^- p)$ data to the DWIA calculations, we found that, although the factorized DWIA calculations give a fairly good account of the backward pion-angle cross sections, they overestimate the cross sections at the forward pion angle. However, the width of the calculated angular correlation is consistent with the data, indicating that the quasifree picture of the reaction has validity.

The disagreement between the forward angle data and the calculations may not be surprising since, in the factorized DWIA approach, the Δ production and the final-state interactions are decoupled and no Δ propagation effects are taken into account. These effects have been found to be important in $(\pi,\pi' p)$ reactions [5]. Moreover, as was mentioned above, the nonresonant terms in the $(\gamma,\pi^- p)$ cross section are important and might, in some cases, even dominate the cross section. In our factorized DWIA calculation these nonresonant terms are included in the free $\gamma n \rightarrow \pi p$ cross section. Any consistent models must include these nonresonant terms.

In this paper we have presented the first exclusive $(\gamma,\pi^- p)$ data on a complex nucleus. In spite of limitations due to statistics, we have been able to observe a significant disagreement between our forward angle data and quasifree DWIA calculations. In order to assess these data in a more quantitative way, in concert with other existing π-induced data in the Δ region, more sophisticated calculations are called for.

The precision of our data is limited by low statistics. This limitation is essentially due to the low duty factor of the electron beam used to generate the bremsstrahlung photon beam. Presently, major programs are underway to rectify this situation by building new photonuclear facilities that will provide duty factors close to 100%. At these facilities new high-resolution $(\gamma,\pi^- p)$ experiments (possibly making use of tagged photon beams) can be performed that should provide valuable information on Δ production and Δ propagation mechanisms in nuclei.

If the large discrepancy observed at the forward pion angle turns out to be due to a Δ medium effect, the sheer size of the effect and the availability of new high-duty-factor beams will make the $(\gamma,\pi^- p)$ reaction an extremely useful probe of such effects.

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