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New measurements of $^{2}H(\vec{\gamma},p)n$ and spin problems in coupled $N\Delta/NN$ interactions

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New precision measurements of the $^{2}H(\vec{\gamma},p)n$ reaction taken with tagged polarized photons, and covering a wide angular range, are presented for incident energies between 113 and 315 MeV. In the region of the Δ resonance, the photodisintegration observables can potentially be used to probe the $N\Delta$ interaction. Coupled-channel calculations are in agreement with cross sections measured with linear polarization parallel to the reaction plane but fail to account for data taken with perpendicular kinematics.

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Although the Δ isobar dominates nuclear reactions from pion threshold to about 1 GeV, its interaction with the nucleon is still poorly known. Microscopic reaction models necessarily require a consistent treatment of the $N\Delta$ and NN interactions. While the parameters of the NN force can be directly determined from nucleon scattering data, the $N\Delta$ interaction must be inferred from processes such as $\pi D\rightarrow\pi NN$ and $\pi D\rightarrow NN$ for which the Δ plays a prominent role in the intermediate state. Because of the strong coupling of the Δ to πN, realistic models must satisfy three-body unitarity, connecting reactions starting from NN, πD, or γD entrance channels, and leading to NN, πD, or πNN final states. Several such calculations have been developed in recent years [1–4]. In these works, the $\pi D\rightarrow\pi D$ and $\pi D\rightarrow\pi NN$ cross sections are reasonably well described, primarily because quasifree scattering dominates there. However, pion and photon absorption channels have proven to be more challenging.

The predicted effects of the $N\Delta$ interaction are of course largest near the energy of the Δ resonance, and polarization observables are expected to be rather sensitive to the $N\Delta$ potential [3]. The $^{2}H(\vec{\gamma},p)n$ reaction can provide an interesting test for $N\Delta/NN$ coupled-channel models since, as first noted by Leidemann and Arenhövel [5], both the cross section and the beam-polarization asymmetry are sensitive to the $N\Delta$ force. Unfortunately, comparisons with existing data have tended to be somewhat inconclusive due to a rather large spread in published results. Correlating the comparisons with cross sections and asymmetries, which might help remove some of the ambiguities, has been problematic because the two have never been measured in the same experiment.

We present here highlights of recent measurements of the $^{2}H(\vec{\gamma},p)n$ reaction (Experiments L1 and L3), which were conducted at the Laser Electron Gamma Source (LEGS) facility, located at the National Synchrotron Light Source of Brookhaven National Laboratory. Absolute cross sections were measured for two orthogonal states of linear polarization, parallel ($\sigma_{\parallel}$) and perpendicular ($\sigma_{\perp}$) to the reaction plane. The data from both experiments have been combined to yield results spanning γ-ray beam energies from 113 to 315 MeV. (The lower energies are sensitive to details of the NN force, rather than the $N\Delta$ interaction, and some of these results have been discussed in Ref. [6].) The full data set is available electronically [7], and will be detailed in a forthcoming publication.

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Linearly polarized γ rays were produced by backscattering the polarized light from an Ar-ion laser against 2.53 GeV electrons. Visible laser light (488 nm) was used to produce γ rays up to 222 MeV (Experiment L1) and ultraviolet wavelengths (364–333 nm) were used to provide γ energies ranging up to 315 MeV (Experiment L3). The γ-ray energies were determined, to typically 5 MeV, by detecting the scattered electrons in a tagging spectrometer [8]. Since the γ-ray production process involves only Klein-Nishina scattering from free electrons, the final γ polarization can be easily calculated from the laser polarization. The latter was measured frequently, both before and after the laser light passed through the electron beam interaction region. An additional cross-check of the polarization is provided by the data near 210 MeV. Although the calculated γ-ray polarizations from Experiments L1 and L3 were quite different, 98% and 80% at this energy, respectively, the deduced asymmetries are in excellent agreement. (The difference between the two asymmetry measurements at each angle can be compared with the expected value of zero. Summing over angles gives a χ^2/N_f of 0.84.) During the measurements, the polarization was randomly flipped between directions parallel and perpendicular to the reaction plane at intervals ranging from 90 to 300 s. An unpolarized contribution from bremsstrahlung in the residual gas of the electron-beam vacuum chamber ($<1\%$) was also monitored with the same frequency. The net γ-ray polarization was greater than 80% for all energies. The γ flux was monitored by counting e^+e^- pairs in scintillators interspersed with thin, high-Z converters. The efficiency of these monitors ($\sim 5\%$) was determined by decreasing the flux and comparing with rates measured in a large NaI(Tl) crystal placed directly in the beam. Such efficiency measurements were made frequently throughout the course of the experiments.

Two different liquid-deuterium targets were used to collect a total of five different data sets with three different proton detector systems. One detector system consisted of 23 phoswich assemblies, each a composite of 1–2 mm of CaF_2 followed by 30–50 cm of plastic scintillator, and arranged at eight angles. For these detectors, empty target runs were used to subtract the contributions from the mylar walls of the target cell. The background to peak ratio was typically 20% or less. A second proton detector consisted of four planes of silicon microstrips followed by a thin scintillator and a large NaI(Tl) crystal. The track reconstruction provided by the silicon microstrips allowed imaging of the source to remove the contributions of the mylar target walls, thus eliminating the need for subtracting empty target data. The phoswich and silicon-microstrip detector systems are discussed further in Ref. [6]. Both were used in Experiments L1 ($E \leqslant 222$ MeV) and L3 ($E \leqslant 315$ MeV) with a 3.8 cm diameter cylindrical target, oriented with its symmetry axis perpendicular to the beam. Only tagged-photon data were collected with the phoswich array. This overdetermined the kinematics and the proton energy spectrum in each detector was dominated by the two-body ${}^2\mathrm{H}(\gamma,p)n$ peak. The microstrip detector system was not tagged and the γ-ray energy was reconstructed from the measured proton energy and momentum vector. Comparisons with tagged data were used to avoid the kinematic regions contaminated by the $pp\pi^-$ and $pn\pi^0$ final states. Finally, during a second phase of Experiment L3 ($E \leqslant 315$ MeV), a different liquid deuterium target, a 13 cm long cylinder oriented along the beam direction, was used with a third proton detector system. This consisted of a stack of four multiwire drift chambers backed by a thin plastic scintillator and a large NaI(Tl) crystal positioned at $\approx 90°$ center of mass (c.m.). Here, tagged data were collected and track reconstruction was used to avoid contributions from the mylar target walls. For each of the three detector systems, corrections for multiple scattering and reaction losses, ranging between 10 and 30%, have been calculated with the Monte Carlo code GEANT [9]. The accuracy of these corrections, 1–3 %, was verified by reproducing measured response functions for monoenergetic protons in plastic scintillator and NaI [6].

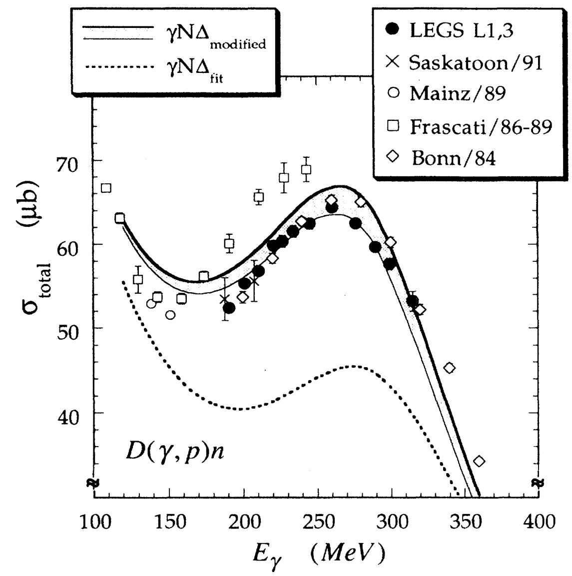

FIG. 1. The total cross sections for ${}^2\mathrm{H}(\gamma,p)n$ (solid circles) from LEGS Experiments L1,3 compared to previously published data (open symbols and crosses) from Refs. [10–14]. Errors on the LEGS data points reflect the combined statistical and polarization-dependent systematic uncertainty, and are generally smaller than the symbols. (Additional normalization uncertainties from polarization-independent systematic effects are estimated at 5%, 4.5%, and 4% for the LEGS, Frascati, and Bonn data sets, respectively.) Also shown are coupled-channel calculations using different $\gamma N\Delta$ coupling constants [19], one from a fit to the elementary $M_{1+}^{(3/2)}$ multipole of $N(\gamma,\pi)$ assuming a Born+Breit-Wigner amplitude decomposition (dotted curve), and the other from a modified fit in which the Born terms were dropped (solid curves—the shaded band reflects an uncertainty in the π-MEC contribution). Note the suppressed zero on the vertical scale.

There are significant regions of overlap among these five different data sets. The measurements are in agreement and have been combined into a set of average results by dividing the energy spanned into roughly 10 MeV bins, arranged so that no one set contributes more than one datum to a single energy bin [7]. For each bin, the mean of the measurements from the different sets has been constructed, weighted by the combined statistical and polarization-dependent-systematic errors. The reduced χ^2 of all the data from the five sets compared to these average results is $\chi^2/N_f = 277.8/92 = 3.0$,

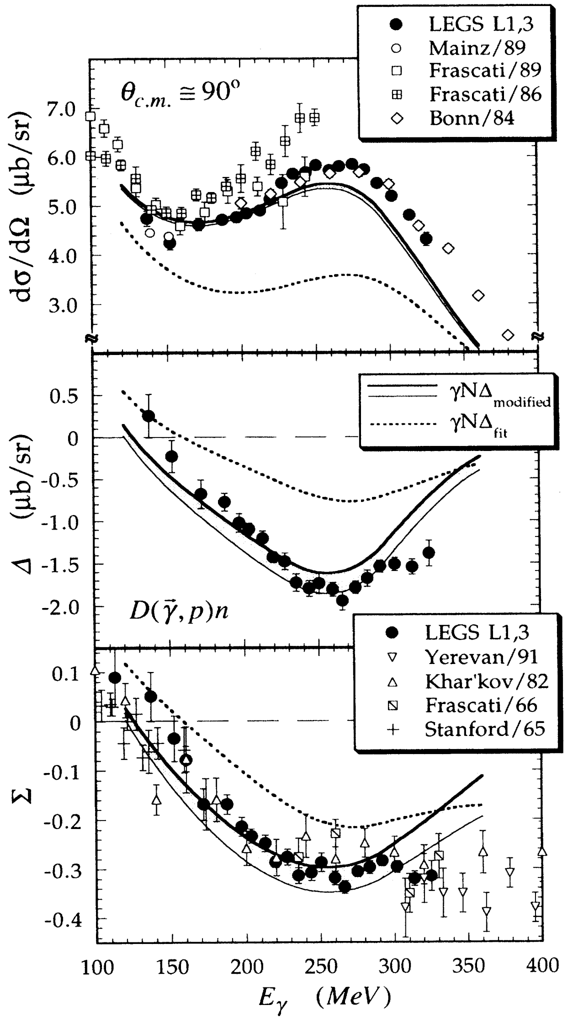

FIG. 2. The $\theta_{c.m.} \cong 90°$ cross section $\sigma(\theta)=\frac{1}{2}(d\sigma_\parallel/d\Omega + d\sigma_\perp/d\Omega)$, the polarization difference $\Delta(\theta)=\frac{1}{2}(d\sigma_\parallel/d\Omega - d\sigma_\perp/d\Omega)$, and their ratio, the asymmetry $\Sigma=\Delta(\theta)/\sigma(\theta)$, for ^{2}H($\vec{\gamma}$,$p$)$n$ from the LEGS experiments (solid circles), compared with previous data (open symbols) from Refs. [10–13] (top panel) and [15–18] (bottom panel—data points with errors $>\pm 0.07$ have not been plotted). The indicated errors bars on the asymmetry reflect the combined statistical and systematic uncertainties. Possible normalization errors in the cross section measurements are as in Fig. 1. Also plotted are the coupled-channel calculations of Fig. 1. Note the suppressed zero on the vertical scale of the top panel.

omitting asymmetries. For the asymmetries, to which systematic errors should not contribute, $\chi^2/N_f=82.1/94=0.9$. The polarization-independent systematic uncertainties represent possible scale errors in absolute cross sections that are common to those data points which were measured simultaneously. Estimates for these ranged between 4% and 5% for the different data sets. Since no offsets between the different sets of measurements were observed, we conservatively ascribe a uniform 5% possible scale uncertainty to the combined net results for absolute cross sections.

The total angle-integrated ^{2}H(γ,p)n cross sections are shown as the solid circles in Fig. 1, and the 90° c.m. excitation function is shown in the top panel of Fig. 2. The photodisintegration of deuterium has a long history with large variations among reported measurements (almost a factor of 2), particularly in the region of the Δ resonance. Over the last decade, this uncertainty has been significantly reduced by experiments at Frascati [11,12] and Bonn [10] with (quasi)monochromatic photon beams which provided an overdetermination of kinematics. However, as is evident in Fig. 1, there remained a 10% to 15% discrepancy between these two sets. The Bonn measurements (open diamonds in the figures) used tagged bremsstrahlung and are in excellent agreement with the net LEGS results. A few tagged bremsstrahlung points recently measured at Saskatoon (crosses) [14] and at Mainz (open circles) [13] are also in good agreement. Two measurements have been reported by the Frascati-LEALE group, the first covering a broad angular range (crossed squares in Fig. 2, [11]) and the other focusing on 0°, 90°, and 180° (open squares in Fig. 2, [12]). There is some variation between the two, but in the later work [12], both results were combined to give the integrated cross sections shown as the open squares in Fig. 1. The Frascati experiments used positron annihilation in flight to create a quasimonochromatic peak. Such a peak is accompanied by a significant low-energy bremsstrahlung tail, and events from this tail were included in their analysis. Although tests were made to insure that this did not lead to the inclusion of $pN\pi$ channels [11], the published tests were all restricted to an angle ($\theta_{c.m.}=105°$) where phase space limits protons from these channels to rather low energies that are generally below detection thresholds. In the tagged spectra from Experiments L1 [6] and L3 where the pn and $pN\pi$ final states are completely separated, the $pN\pi$ component is appreciable only at more forward angles for the range of energies covered at Frascati. This may have contributed to the rise evident in the combined Frascati results above the tagged measurements at energies over π threshold (Fig. 1).

The dependence of the cross section upon the polar reaction angle (θ) and the azimuthal polarization angle (ϕ) is given by

$$\frac{d\sigma}{d\Omega}(\theta,\phi)=\frac{d\sigma}{d\Omega}(\theta)+P\Delta(\theta)\cos(2\phi),$$

where P is the degree of linear polarization. The polarization-difference cross sections, $\Delta(\theta)=\frac{1}{2}(d\sigma_\parallel/d\Omega - d\sigma_\perp/d\Omega)$, and their ratio to the polarization-independent cross sections, the beam asymmetry $\Sigma=\Delta(\theta)/\sigma(\theta)$, are shown in the middle and bottom panels of Fig. 2, respectively. There are several published measurements of the beam asymmetry in this energy region, all using coherent bremsstrahlung in diamond. Most of these have large uncertainties [15–18] and, for clarity, only those with errors less than ± 0.07 have been retained in the figures. LEGS Experiments L1,3 are the first to directly measure $\sigma_\parallel$ and $\sigma_\perp$ and determine $\Delta(\theta)$.

In the $\gamma+N$ system, delta excitation is almost purely $M1$, although when transformed to the deuteron c.m. many magnetic as well as electric multipoles contribute. The dotted curves in the figures have been calculated by decomposing the elementary M_{1+} (isospin-3/2) multipole of $\gamma+N$ into a sum of Born and resonant terms [19]. The resonance part was parametrized with a Breit-Wigner shape and the $\gamma N\Delta$ coupling was extracted from the fit to the $M_{1+}(3/2)$ amplitude, as determined from $N(\gamma,\pi)$ data. In the $\gamma+D$ c.m. frame, all multipoles with $L\leqslant 4$ were included. In this fitting procedure, the $\gamma N\Delta$ coupling was allowed to be both complex and energy dependent, thereby absorbing the effects of pion rescattering, while preserving unitarity. The result reproduces the general features of the cross sections and polarization observables, particularly the shift of the resonance position from the free $N\Delta$ value (317 MeV) which is due mainly to pion rescattering [1,4], and the negative asymmetry in the region of the resonance which reflects the spin dependence of the elementary $\gamma+N$ amplitudes. Nonetheless, the dotted curves significantly underestimate the data in the region of the delta resonance.

The models of Tanabe and Ohta (TO) [1] and Lee [2] used similar procedures to fix elementary amplitudes in terms of Born and resonant components. There, the fitted $\gamma N\Delta$ coupling was real and leading-order rescattering diagrams were explicitly included. Their results are very similar to the dotted curves shown here.

The discrepancy between these predictions and the data of Figs. 1 and 2 increases with energy, suggesting that the method of decomposing the amplitudes into background and resonant components is incomplete. Greater flexibility in the models can be obtained by dropping the Born terms in the $\gamma+N$ amplitudes and refitting a modified $\gamma N\Delta$ coupling of the elementary M_{1+} (3/2) multipole, now purely resonant, to $N(\gamma,\pi)$ data. This results in the heavy-solid curves. Such a procedure has the potential for double-counting pion-exchange current (π-MEC) contributions. This effect has been estimated and the associated uncertainty is shown as the light-shaded band. Since the amplitudes certainly must contain nonresonant terms, the improvement obtained with this effective coupling suggests that the use of static π-MEC is inadequate and nonlocal effects are important [4].

In the region of the Δ resonance, the band of curves corresponding to the modified $\gamma N\Delta$ coupling are centered slightly above the total cross section data, while their predictions at 90° are consistently low [19]. This is due to a depression in the calculated angular distributions near 90°, which grows with energy. A similar "90° dip" is a common feature of most $\gamma D\rightarrow pn$ calculations near 300 MeV, even appearing in earlier works that did not include coupled-channel treatments [20,21]. The dip predicted by TO [1] was considerably more dramatic than that of the band in Fig. 2, but was accentuated by an improper treatment of the $L\leqslant 1$ NN phase shifts. This was subsequently rectified in the work of Lee [2], where this "90° dip" was reduced but still not eliminated. (The calculations of Peña *et al.* [3], which are similar to the earlier work of Ref. [5], are not so noticeably depressed at 90°. However, the neglect of the relativistic spin-orbit current in both of these works is known to distort the angular dependence [22].)

Angular distributions at 300 MeV for the two orthogonal spin states are shown in Fig. 3. The behavior of the cross section measured with parallel kinematics is quite well reproduced by the calculation with the modified $\gamma N\Delta$ coupling, and even the fitted-$\gamma N\Delta$ curve has the correct shape. The apparent "90° dip" arises entirely from the predictions

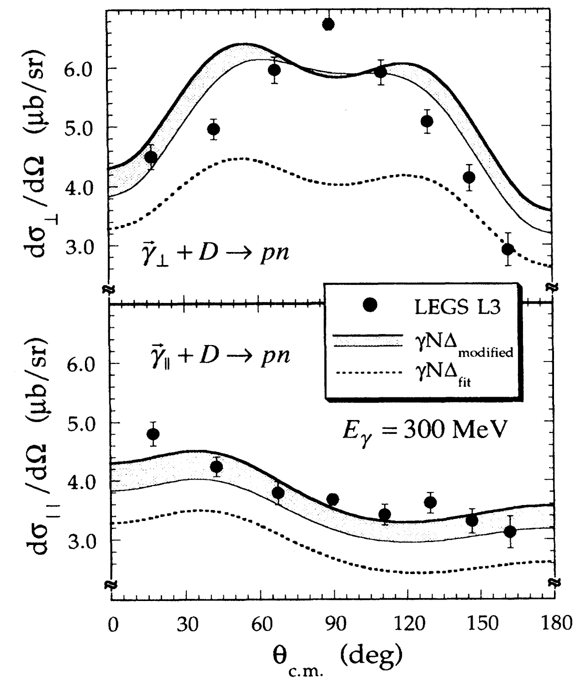

FIG. 3. Angular distributions of the $^2H(\vec{\gamma},p)n$ cross sections at $E_\gamma = 300\pm 5$ MeV taken with linear polarization parallel (bottom) and perpendicular (top) to the reaction plane. Plotted errors are as in Fig. 1. Note the suppressed zero. The calculations are the same as those of Figs. 1 and 2.

for the perpendicular spin orientation. Although interference with the Born amplitudes, which contain high angular momentum components, can potentially affect angular distributions, this is evidently not the origin of the 90° depression since the fitted-$\gamma N\Delta$ calculation, which explicitly includes the Born terms, has a similar shape. In addition, the modified-$\gamma N\Delta$ predictions for $\sigma_\perp$ are consistently higher than the data at forward and backward angles, although both the calculations and the data for $\sigma_\perp$ converge to the $\sigma_\parallel$ values at 0° and 180° where the azimuthal polarization angle becomes undefined.

At present, there is no clear explanation for the success of the coupled-channel calculations in one polarization kinematics and their failure for the orthogonal state. Spin observables provide a considerably more sensitive test of the angular momentum modeling than cross sections. Although the model parameters of the calculations discussed here were fitted to NN phase shifts, all assumed static NN potentials, with retardation effects included only in the $N\Delta$ and NN-$N\Delta$ transition potentials. The additional use of retarded potentials in the NN interaction could significantly alter the angular momentum decomposition.

Finally, it is interesting to note that the polarization difference cross section (middle panel of Fig. 2) appears to change slope near 290 MeV beam energy (2146 MeV c.m.), whereas no such change is seen in the unpolarized cross section. This causes the asymmetry to fall below the modified-$\gamma N\Delta$ band, and the general behavior of the Yerevan and Khar'kov data indicates that this trend persists to higher energies. The onset of this change in slope appears to coincide with the $np\pi\pi$ threshold. Two-π channels have not been included in any of the calculations of Refs. [1–5] and it remains to be seen whether or not an explicit treatment of this degree of freedom would improve the agreement with experiment.

In summary, precise values for the cross section and beam polarization observables in deuteron photodisintegration are now available throughout the energy region sensitive to the $N\Delta$ force. Static-NN coupled-channel calculations are in good agreement with the new data taken in parallel kinematics but fail to reproduce the perpendicular polarization state. The inclusion of retardation, particularly in the π-MEC, and possibly an explicit treatment of 2π channels, may be some of the more hopeful avenues to reconciling theory and experiment.

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