$p(\vec{\gamma},\pi^0)$ Reaction and the $E2$ Excitation of the Δ

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Results from three independent measurements of the $p(\vec{\gamma},\pi^0)$ reaction are presented for incident photon energies between 243 and 314 MeV, and for c.m. angles of 105°, 122°, and 150°. The ratio of cross sections measured with orthogonal states of linear polarization is sensitive to the $E2$ excitation of the Δ resonance. Comparisons are made to the predictions of various models, all of which fail to reproduce these data.

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Essentially all constituent quark models invoke a tensor interaction between the quarks in a proton which comes about through one-gluon exchange. This tensor force between quarks mixes a D state into what would otherwise be a purely S-wave proton. The D-wave component breaks spherical symmetry, resulting in a nonvanishing $\langle r^2 Y_2 \rangle$ matrix element for the nucleon and a static quadrupole moment and deformation for its first excited state, the delta (Δ) resonance, at $\sim$320 MeV. The magnitude and sign of this D-state component are quite sensitive to the internal structure of the proton and have been of great interest in recent years [1].

The experimental signature of a D-wave component lies in the excitation of the nucleon to the Δ. The Δ is excited mainly by $M1$ photons which induce quark-spin-flip transitions. If the wave function of the Δ contains a D-wave component then this transition can also be excited by $E2$ photons. The challenge is to evaluate the relative magnitude of this $E2$ excitation in the presence of the dominant $M1$ transition. Models predict this mixing ratio to be quite small, anywhere from -0.9% to -6% [2], so that a high degree of precision is demanded of experiment.

The isospin (I) $\frac{3}{2}$ Δ decays with a 99.4% branch to a pion-nucleon final state. An $E2$ photon will produce a p-wave pion, so that the ratio of interest is usually written in terms of photo-pion multipoles as E_{1+}/M_{1+}. To extract the part of the $E_{1+}(I=\frac{3}{2})$ multipole associated with the Δ requires a further decomposition of this amplitude into resonant and background components. This decomposition is not unique, and various models have quoted values ranging from $+4\%$ to -8% for the mixing ratio between the resonant parts of the $E_{1+}(I=\frac{3}{2})$ and M_{1+} amplitudes [3–5].

The pion photo-production observable that is most sensitive to the E_{1+} multipole is associated with the $p(\vec{\gamma},\pi^0)$ reaction. Calculated cross sections for different orientations of linear polarization are shown in Fig. 1 [5]. Those shown as thick (thin) lines assume that the incoming photon's electric field vector is parallel (perpendicular) to the reaction plane. Calculations are shown with (solid lines) and without (dashed lines) the inclusion of the $E2$

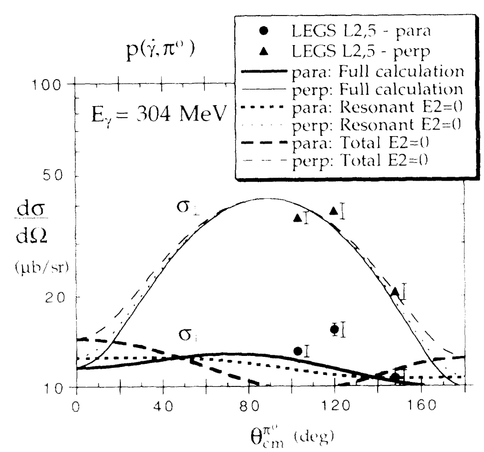

FIG. 1. Measured (solid circles and triangles) and calculated (Ref. [5]) cross sections for different orientations of linear polarization, either parallel (para) or perpendicular (perp) to the $p(\vec{\gamma},\pi^0)$ reaction plane. Bars next to the data points reflect the systematic errors.

amplitude. The dotted curves give the predictions for the case when only the resonant part of the E_{1+} is set to zero. The data points, triangles for $\sigma_\perp$ and circles for $\sigma_\parallel$, are from the experiments described below. Statistical errors are generally smaller than the symbols. The bars next to the symbols reflect the systematic uncertainties, which make it difficult to distinguish predictions with different $E2$ components.

For all but extreme forward and backward angles, reactions with the perpendicular orientation of the beam polarization vector are completely insensitive to the $E2$ mixing in the Δ. Essentially all the sensitivity comes from reactions with the parallel polarization geometry. (The perpendicular cross section is much larger than the parallel and dominates unpolarized measurements, rendering the unpolarized cross section insensitive.) This is actually a convenient situation, since the ratio of parallel to perpendicular cross sections ($d\sigma_\parallel/d\sigma_\perp$) can now be formed. All of the sensitivity to the E_{1+} multipole will be preserved through the numerator of this ratio, and at the same time most systematic experimental errors will cancel out.

The cross section for $\gamma p \to \pi^0 p$ can be measured by detecting either the recoil proton or the two photons from the decay of the π^0. The efficiency of the latter changes with both angle and incident γ energy, which is not desirable when studying small effects. Detecting the recoil protons avoids this problem, although at forward angles the proton energy becomes quite low.

We report here measurements of the $p(\vec{\gamma},p)\pi^0$ reaction, performed at the Laser Electron Gamma Source (LEGS) located at the National Synchrotron Light Source of Brookhaven National Laboratory [6]. Linearly polarized γ rays up to 314 MeV were produced by backscattering ultraviolet laser light from 2.5-GeV electrons. The γ-ray energy was determined, typically to 5 MeV, by detecting the scattered electrons in a tagging spectrometer [7]. Many of the details of these measurements are similar to those described in Ref. [8]. Here, recoil protons were detected at three laboratory angles, corresponding to π^0 center-of-mass (c.m.) angles of 105°, 122°, and 150°.

To test the sensitivity to systematic uncertainties that may survive the $d\sigma_\parallel/d\sigma_\perp$ cross-section ratio, three independent experiments have been conducted at 105° (c.m.) with different detectors, different methods of determining the γ-ray energy and monitoring the γ-ray flux, different polarizations, and using two targets of liquid hydrogen having different cell configurations. The main characteristics of these three experiments (designated as L2s, L2p, and L5) are summarized in Table I. The μ-strip array of Expt. L2s consisted of four planes of silicon microstrips, providing track reconstruction for each proton, followed by a 1-cm-thick plastic scintillator and a 25-cm-deep NaI(Tl) crystal. An array of phoswich detectors, composites of 1–2 mm of CaF_2 followed by 30–50 cm of plastic scintillator, were used in Expt. L2p. During the latter experiment, data were also collected at 122° and 150° (c.m.). The operation of these detectors is described in greater detail in Ref. [8]. For Expt. L5, a 1-cm-thick plastic scintillator followed by a 25-cm-deep NaI(Tl) crystal were used. In each detector system, protons were selected by imposing cuts in energy loss and total energy deposition. During analysis of data from the μ-strip array, the photon tag was ignored and the γ-ray energy was reconstructed from the measured proton energy and momentum vector. Only tagged-photon data were collected during the other two measurements. For the μ-strip data, the γ-ray flux in each energy interval was calculated in a Monte Carlo simulation of the laser backscattering process, normalized to the total tagged flux. For the other two experiments, the tagged flux was monitored as a function of energy by counting the Compton-scattered electrons in coincidence with e^+e^- pairs produced in thin, high-Z converters that remained in the γ-ray beam throughout the measurements. During all of the experiments, the polarization was randomly flipped between directions parallel and perpendicular to the reaction plane at a frequency averaging once every 180 sec. The contribution from unpolarized bremsstrahlung in the residual gas of the electron-beam vacuum chamber ($< 1\%$) was also monitored every 180 sec. During Expts. L2s and L2p the laser light was partially depolarized, while during Expt. L5 its polarization was nearly unity. The resulting polarizations of the high-energy γ rays are given in the table. The targets were liquid-hydrogen-filled cylinders, 3.8 cm in diameter transverse to the γ-ray beam during Expts. L2s and L2p and 10.0 cm along the beam during Expt. L5. Background contributions from reactions within the walls of the target chambers and of the vacuum-chamber windows were subtracted in measurements with the targets filled with ^{4}He gas, normalized to the same integrated γ-ray flux. All of the data in various energy intervals from 243 to 314 MeV were col-

TABLE I. Characteristics of the experiments at 105° (c.m.).

	Expt. L2s	Expt. L2p	Expt. L5
Detector	μ-strip	Phoswich	NaI
E_γ definition	Reconstruction	E_e tagging	E_e tagging
γ flux	Monte Carlo	Tagged e^+e^-	Tagged e^+e^-
γ polarization (%)	83.0 ± 1.5	83.0 ± 1.5	95.0 ± 1.0
Target (cm)	3.8	3.8	10.0

lected simultaneously, but angle measurements were made sequentially.

The $d\sigma_\parallel/d\sigma_\perp$ cross-section ratios measured at 105° in the three experiments of Table I are plotted in Fig. 2. The error bars reflect the combined statistical and polarization-dependent systematic uncertainties, which are smallest for Expt. L5. Compared to the weighted mean of these results, the reduced χ^2 of the three measurements is 1.8 over the overlapping energy range of the three data sets. This weighted mean is plotted as the solid circles in Fig. 3 (bottom). Data at 122° and 150°, taken during Expt. L2p, are also shown, in the middle and top panels, respectively. The results of Fig. 3 have been corrected for the contamination from $p(\vec{\gamma},p)\gamma$ events, using the Compton-partial-wave amplitudes of Ref. [9]. Also shown in Fig. 3 are previously published data (open symbols) where available [10,11].

Plotted with the data of Fig. 3 are the results of two recent model calculations. The curves lying generally above the data (labeled as NBL) are the work of Nozawa, Blankleider, and Lee [4], and result from explicit evaluation of the various diagrams for photo-pion production, including final-state interactions (FSI). The curves lying generally below the data (labeled as DMW) are the work of Davidson, Mukhopadhyay, and Wittman [5], in which photoproduction is evaluated in terms of effective Lagrangians, with FSI implicitly included through a unitarization procedure. Both models calculate observables in terms of a few free parameters, most notably the electric (G_E) and magnetic (G_M) coupling constants of the $\gamma N\Delta$ vertex. These arise in the decomposition of the amplitudes into resonant and background components. In the calculations of Fig. 3, the parameters of both models have been determined by fitting the amplitudes to the Berends and Donnachie (BD) photo-pion multipole [12]. From this procedure, NBL deduced a resonant $E_{1+(3/2)}/M_{1+(3/2)}$ mixing ratio for Δ excitation of -3.1%, while DMW obtain about half that, -1.4%. However, it should be noted that the NBL value of

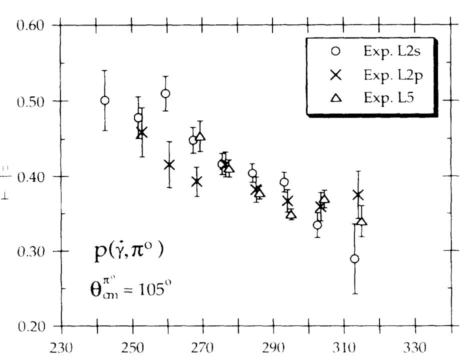

FIG. 2. Data from the three new experiments at 105° (c.m.) (Table I). Errors reflect the combined statistical and polarization-dependent systematic uncertainties.

-3.1% reflects the "bare" $\gamma N\Delta$ coupling, without any dressing from FSI, while that of the DMW calculation includes FSI at some level. The predictions of these models for the $d\sigma_\parallel/d\sigma_\perp$ ratio are shown in Fig. 3 as the long-dashed–short-dashed (NBL) and the solid (DMW) curves, respectively. The dash-dotted and dashed curves are obtained by setting the resonant part of the $E_{1+(3/2)}$ multipole to zero ($G_E=0$).

At 105°, where the sensitivity to a resonant $E2$ component is nearly maximal, both the NBL and DMW calculations approach the data near the peak of the Δ (about 320 MeV). However, the energy dependence of the $d\sigma_\parallel/d\sigma_\perp$ ratio provides the crucial test of the resonance-background decomposition, and here both models fail rather badly. At larger angles the comparisons with Nozawa *et al.* become dramatically worse, while those with Davidson *et al.* become more reasonable. The method of separating the multipoles into background and resonant components is not unique. In the calculations shown here

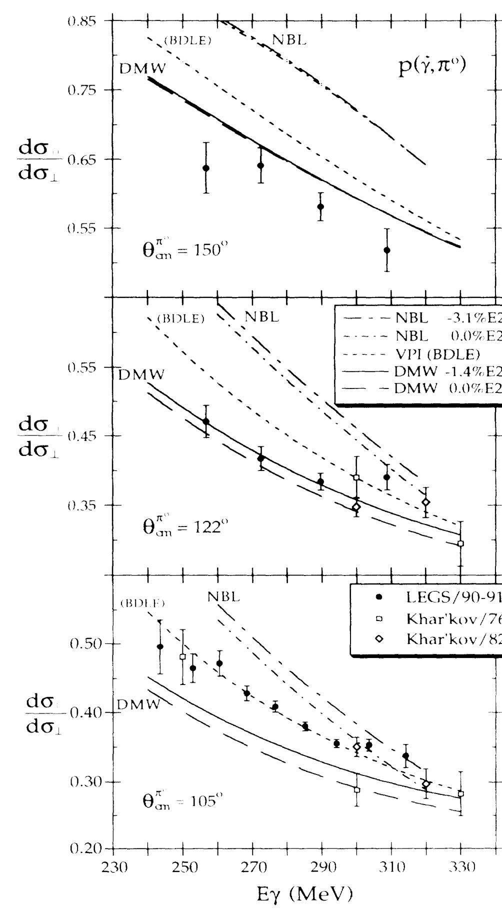

FIG. 3. Shown as the solid circles are $p(\vec{\gamma},p)\pi^0$ data for 150° (c.m.) (top) and 122° (c.m.) (middle), together with the weighted mean of the data from Fig. 2 at 105° (c.m.) (bottom). Previous results are from [10] (open squares) and from [11] (open diamonds). The NBL calculations are from Ref. [4], BDLE are from Ref. [13], and DMW are from Ref. [5].

the background and resonant parts have been made separately unitary, referred to as the "Olsson method" in [5]. Other prescriptions have been investigated in Ref. [5], but these result in predictions that are even farther from the data of Fig. 3.

It is interesting to compare the NBL and DMW curves with direct predictions of the BD multipoles. The latter are published as fixed-energy solutions. Since energy-dependent fluctuations in these are averaged out in the process of fitting the model parameters, the appropriate comparison should be to predictions made with a smoothed-energy-dependent form of these multipoles. These are shown as the dashed curves, labeled (BDLE) in Fig. 3 [13]. The full calculations of both the NBL and the DMW models should reproduce the BDLE curves which were used to fix their model parameters. Neither does, and there are two possible reasons for the large discrepancies evident here: (1) The description of the physical processes in both of the models is incomplete; or (2) although one of the models may provide a sufficiently complete description of the $p(\gamma,\pi)$ reaction, the multipole set used to fix model parameters is flawed. In fact, the data of Fig. 3 question the validity of existing multipole decompositions, at least for small amplitudes. Although the BDLE predictions are in fairly good agreement with the 105° results, this appears fortuitous since the agreement at larger angles is quite poor.

A number of π-production experiments have been completed since the BD analysis, most notably the measurements of spin observables made at Khar'kov [10,11]. However, the inclusion of these data into a multipole analysis does not lead to a superior representation of the E_{1+}-sensitive $d\sigma_{\parallel}/d\sigma_{\perp}$ ratio [14]. This is at least partly due to the larger errors in previously published polarization data, and partly to ambiguities in the analysis resulting from the systematic uncertainties associated with the various unpolarized measurements.

The accuracy of the present data set would be sufficient to distinguish differences equivalent to $\sim \frac{1}{3}$ of the separation between the full and 0%-$E2$ calculations of Fig. 3. However, the large discrepancies between the measured $d\sigma_{\parallel}/d\sigma_{\perp}$ ratios and the various calculations described above must be resolved before attempting to confront QCD hadron models with a resonant $E2$ component of Δ excitation. Although new experiments are needed, particularly large sets of simultaneously measured observables with few systematic uncertainties, it is doubtful that this could bring *both* the NBL and DMW model predictions into agreement.

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