BNL-64650

CONF-970564--

The E2/M1 Ratio in Δ Photoproduction

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Abstract. New high-precision measurements of $p(\vec{\gamma},\pi)$ and $p(\vec{\gamma},\gamma)$ cross sections and beam asymmetries have been combined with other polarization ratios in a simultaneous analysis of both reactions. The E2/M1 mixing ratio for the $N \rightarrow \Delta$ transition extracted from this analysis is EMR = -3.0% ± 0.3 (stat+sys) ± 0.2 (model).

The well-isolated $N \rightarrow \Delta$ resonance serves as a sensitive test for models of nucleon structure [1–4]. To lowest order, $N \rightarrow \Delta$ is a simple M1 quark spin-flip transition. Small L=2 components in the N and Δ wavefunctions allow this excitation to proceed via an electric quadrupole transition. The most sensitive observable to E2 strength is the beam asymmetry in $p(\vec{\gamma},\pi^{\circ})$ [5]. In a recent Mainz measurement of $p(\vec{\gamma},\pi)$ an EMR of -2.5% was extracted using the π° channel alone [6]. As will be shown, this value is artificially inflated by a factor of 2 due to multipole ambiguities. We report an improved value for the EMR that is constrained by new measurements and two new observables.

At any energy, a minimum of 8 independent observables are required to specify the photo-pion amplitude [7]. Such complete information has never been available and previous analyses have relied on at most four observables, usually measured separately with independent systematic errors. Although the $\tau = 3/2$ M1 and E2 components can extracted from a multipole fit, many observables are needed to avoid multipole ambiguities [8]. In the present work, $p(\vec{\gamma},\pi^{o})$, $p(\vec{\gamma},\pi^{+})$ and $p(\vec{\gamma},\gamma)$ cross sections and beam asymmetries were all measured simultaneously to provide new constraints on the photo-pion multipoles.

At LEGS, polarized tagged γ-ray beams between 209 and 333 MeV were produced by backscattering laser light from 2.6 GeV electrons at the National Synchrotron Light Source. Beams, with linear polarizations greater than 80% and known to $\pm 1\%$, were flipped between orthogonal states at random intervals between 150 and 450 seconds.

One goal of this experiment was the first complete separation of Compton scattering and π^{o}-production. The two reactions were distinguished by comparing their γ-ray and proton-recoil energies. High energy γ-rays were detected in a large NaI(Tl) crystal, while recoil protons were tracked through wire chambers and stopped in an array of plastic scintillators. A schematic of this arrangement and a spectrum showing the separation of the two channels is given in [9]. All detector efficiencies were determined directly from the data itself, an important advantage. Charged pions were detected in 6 NaI detectors, including the large crystal used for the Compton and π^{o} channels. The high resolution of the NaI detectors was essential in determining π^{+} efficiencies, which were simulated with GEANT [10] using GCALOR to model hadronic interactions [11]. Systematic effects were combined in quadrature with statistical errors ($\sim 1\%$) for a net measurement error.

In the vicinity of the Δ peak, the spin-averaged π^{o}, π^{+}, and Compton cross sections determined in this experiment are all consistently higher than earlier measurements from Bonn [12–15] while for energies lower than $\sim$270 MeV substantial agreement is observed. Of the previous π^{+} cross section measurements, those from Tokyo [16] are in closest agreement to the present work. The present work is also in very good agreement with two recent Compton measurements from Mainz at 90° and 75° [17,18]. All LEGS cross sections are locked together with a common systematic scale uncertainty, due to possible flux and target thickness variations, of 2%.

To obtain a consistent description of these results we have performed an energy-dependent analysis, expanding the π-production amplitude into electric and magnetic partial waves, $E^{\tau}_{\ell\pm}$ and $M^{\tau}_{\ell\pm}$, with relative πN angular momentum ℓ, and intermediate-state spin $j = \ell \pm \frac{1}{2}$ and isospin $\tau = \frac{1}{2}$ or $\frac{3}{2}$. In order to reproduce our angular distributions in the region of the Δ, we must vary the D wave contributions. To reduce ambiguities [8], we truncate our fit at F waves, while keeping the Born terms up to order $\ell = 19$.

The (γ,π) multipoles were parameterized with a K-matrix-like unitariza-

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tion,

$$A^{\tau}_{\ell\pm} = \left(A^{\tau}_{B}(E_\gamma) + \alpha_1\epsilon_\pi + \alpha_2\epsilon_\pi^2 + \alpha_3\Theta_{2\pi}(E_\gamma - E_\gamma^{2\pi})^2\right) \times \left(1 + iT^{\ell}_{\pi N}\right) + \beta\cdot T^{\ell}_{\pi N}. \quad (1)$$

Here, E_γ and ϵ_π are the beam and corresponding π^+ kinetic energies, and A^{τ}_{B} is the full pseudo-vector Born multipole, including ρ and ω t-channel exchange [19]. The VPI[SM95] values are used for the πN scattering T-matrix elements [20]. Below 2π threshold, $E_\gamma^{2\pi} = 309$ MeV, $T^{\ell}_{\pi N}$ reduces to $\sin(\delta_\ell)e^{i\delta_\ell}$, $\delta_\ell(E_\gamma)$ being the elastic πN phase shift. Thus, eqn. 1 explicitly satisfies Watson's theorem [21] below $E_\gamma^{2\pi}$ and provides a consistent, albeit model-dependent, procedure for maintaining unitarity at higher energies. The β term was fixed at zero for all multipoles except $M^{3/2}_{1+}$, $E^{3/2}_{1+}$, and $M^{1/2}_{1-}$, the first two describing M1 and E2 N $\rightarrow$ P_{33} excitation and the latter allowing for a possible tail from the P_{11} resonance. The other terms describe the non-resonant background, with the α_i included to account for non-Born contributions. Each fitted multipole contains a term in α_1, while the additional α_2 term is used only in $E^{1/2}_{0+}$, $M^{3/2}_{1+}$ and $E^{3/2}_{1+}$. The α_3 term containing the unit Heavyside step function $\Theta_{2\pi}$ (=1 for $E_\gamma > 309$ MeV) is used only in the E_{0+} amplitudes to accommodate possible effects from S-wave 2π production.

Once the (γ,π) multipoles are specified, the imaginary parts of the six Compton helicity amplitudes are completely determined by unitarity, and dispersion integrals can be used to calculate their real parts, where we have implemented the computation of L'vov and co-workers [22]. This requires the evaluation of the dispersion integrals at energies outside the range of the present work. For this we have used the VPI-SM95 solution up to 1.5 GeV [20], and estimates from Regge theory for higher energies. The polarizabilities can also be extracted from this analysis, but they have only small effects on the N $\rightarrow$ Δ amplitudes.

We report here a summary of the results of a fit to the parameters of the (γ,π) multipoles, minimizing χ^2 for both predicted (γ,π) and (γ,γ) observables. In this fit we have used $p(\vec{\gamma},\pi^\circ)$, $p(\vec{\gamma},\pi^+)$ and $p(\vec{\gamma},\gamma)$ cross sections only from the present experiment, since these are locked together with a small common scale uncertainty, and augmented our beam asymmetry data with other published polarization *ratios* (in which systematic errors tend to cancel). These include our earlier $\Sigma(\pi^\circ)$ data [5],$\{T(\pi^\circ), T(\pi^+)\}$ data from Bonn [23], $\{T(\pi^\circ), P(\pi^\circ), T(\pi^+), P(\pi^+)\}$ data from Khar'kov [24,25], and the few beam-target asymmetry points $\{G(\pi^+), H(\pi^+)\}$ from Khar'kov [26]. Systematic scale corrections were fitted following the procedure of ref. [27]. To minimize the effect of 2π-production we have limited the fitting interval from 200 MeV to 350 MeV. The reduced χ^2 for this analysis is $\chi^2_{df} = 997/(644-34) = 1.63$.

The EMR for N $\rightarrow$ Δ is just the ratio of fitted β coefficients in eqn. 1 for the $E^{3/2}_{1+}$ and $M^{3/2}_{1+}$ multipoles, -0.0296 $\pm$ 0.0021. The fitting errors reflect

TABLE 1. Dependence of the EMR on p(γ,π) cross sections. Rows 1 and 3 summarize our multipole fit to p(γ,π) and p(γ,γ) using unpolarized p(γ,π) results from this work in row 1, and substituting only the Bonn cross sections from [12,13] in row 3.

Source	$\frac{d\sigma}{d\Omega}(\gamma,\pi)$	EMR(%)	χ^2_{df}
$(\gamma,\pi)+(\gamma,\gamma)$ fit	LEGS	-3.0 ± 0.3	1.63
fit to DMW	LEGS	$-3.0+0.2/-0.3$	
$(\gamma,\pi)+(\gamma,\gamma)$ fit	Bonn	-1.3 ± 0.2	1.89
Sato-Lee [3]	Bonn	-1.8 ± 0.9	

all statistical and systematic uncertainties. The full *unbiased estimate* of the uncertainty is $\sqrt{\chi^2}$ larger [28]. We have studied the variations that result from truncating the multipoles at D waves, using a different πN phase shift solution [29], allowing for differences in energy calibration between photoproduction and πN scattering, and varying the assumptions used to compute the Compton dispersion integrals [22]. The EMR is most sensitive to the multipole order and to the energy scale. Combining these *model* uncertainties in quadrature leads to our final result:

$$\text{EMR} = \text{-3.0\%} \pm 0.3\ \text{(stat+sys)} \pm 0.2\ \text{(model)}\ .$$

To investigate the effect of the difference in the p(γ,π) cross sections between our results and the Bonn data, we have repeated this analysis substituting the values from [12,24] for our own. This reduces the EMR substantially (Table 1, row 3).

In ref. [6], a fit to the recent Mainz π° cross section and $\Sigma(\pi^\circ)$ data, neglecting non-Born contributions beyond S and P waves, was used to extract an EMR of -2.5% ± 0.2 (stat) ± 0.2 (sys). The Mainz data agrees with Bonn cross sections [12] and LEGS $\Sigma(\pi^\circ)$ data, and thus should correspond to row 3 of table I, and the factor of 2 difference between this value and their reported results reflect the ambiguities in the multipoles constrained by only 2 observables.

Various theoretical techniques have been used to separate the N $\rightarrow$ Δ component. Our result can be directly compared with models, such as DMW [30] and Sato & Lee [3], that report ratios of γNΔ couplings deduced with a K-matrix type unitarization equivalent to eqn. 1. We have refit the DMW parameters to our multipoles, with the result EMR $= -3.0\% + 0.2/-0.3$. This, and the result of Sato & Lee who fitted their parameters to the Bonn cross sections and our $\{\Sigma(\pi^\circ), \Sigma(\pi^+)\}$ data, are listed in table I and are consistent with the set of (γ,π) cross sections that were used to fix their parameters.

To summarize recent data and analyses, there are two new sets of measurements of p(γ,π) and p(γ,γ), the Mainz experiments reported in [6,17,18] and the LEGS experiment reported here and in [9]. While Compton cross sections measured in the two labs agree, $p(\gamma,\pi)$ cross sections do not. A consistent analysis applied to both groups of data yields EMR values different by more than a factor of 2. The source of this difference is the $p(\gamma,\pi)$ cross section scale, and the advantage of the LEGS data lies in the fact that both $p(\gamma,\pi)$ and $p(\gamma,\gamma)$ channels are locked together with a small common systematic scale uncertainty.

LEGS is supported by the U.S. Dept. of Energy under Contract No. DE-AC02-76-CH00016, by the Istituto Nazionale di Fisica Nucleare, Italy, and by the U.S. Nat. Science Foundation.

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