Polarized Compton Scattering from the Proton

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New precision measurements of cross sections and polarization asymmetries in the $p(\vec{\gamma}, \gamma p)$ reaction at 90° c.m. are presented for incident energies between 213 and 333 MeV. A long-standing problem with earlier experiments that appeared to violate unitarity at the peak of the Δ is resolved. Data are compared to theories based on baryon resonance structure and to dispersion relations. Recent calculations using the proton polarizabilities are closest to the data, although inconsistencies are observed near the Δ resonance.

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Elastic (Compton) scattering of intermediate energy photons from the proton is a potentially rich source of structure information. It is sensitive to the proton's electric ($\overline{\alpha}$) and magnetic ($\overline{\beta}$) polarizabilities [1], to the deformation of the nucleon through the electric $\gamma N \Delta$ coupling [2], and even to the sign of the π^0 decay constant, F_π [3,4]. There are many published calculations for Compton scattering. These can be grouped into two general categories, those based on the baryon resonance spectrum or its underlying quark structure [5–7], and those relying upon unitarity and dispersion relations to phenomenologically describe elastic scattering in terms of photopion production [3,4,8–10]. These calculations give significantly different predictions, particularly in the region of the Δ resonance.

A number of measurements of proton Compton scattering have been reported [1,11–16], and several authors of dispersion calculations have pointed out a significant inconsistency between many of these experiments and π photoproduction data near the peak of the Δ [3,8–10]. Compton scattering can be described by six independent amplitudes. Their imaginary parts can be calculated from (γ, π) multipoles using *s*- and *u*-channel unitarity, and dispersion integrals can be written for their real parts. Four of these integrals converge rapidly with energy. However, the remaining two, those involving a photon helicity flip, do not converge rapidly, making subtractions essential. One of these is dominated by *t*-channel π^0 exchange, the *Low* amplitude [17], and can be readily evaluated in terms of the π^0 lifetime. However, the other contains contributions from multiple meson exchange in the *t* channel that are quite poorly determined. In principle, the beam-polarization asymmetry constrains this other amplitude [4]. But prior to our new measurements, only a single datum with large errors had been published for this observable [18]. Alternatively, sum rules can be used to write the subtraction function for this spin-flip amplitude in terms of the difference of the proton polarizabilities, $\overline{\alpha} - \overline{\beta}$, which can then be fixed by fitting a perturbative expansion of the cross section to data below the π threshold [3,4]. Although this provides a good description of scattering below the Δ [1,19], the peak cross sections appear to be overestimated [3,4].

A lower *unitarity* bound on the Compton cross sections, which avoids the uncertainties of the dispersion calculations, can be constructed by using π production to evaluate the imaginary parts of the amplitudes while setting their real parts to zero [3,8,10]. Beyond this, minimal real parts can be formed from the *s*- and *u*-channel Born and *t*-channel π^0-pole graphs [9]. These exercises lead to a common conclusion. Previously published data near the peak of the Δ resonance, and particularly at 90° center of mass (c.m.), appear to completely exhaust these bounds, if not violate them, and leave no room for the *t*-channel dispersive contributions.

We report here new measurements of the $p(\vec{\gamma}, \gamma p)$ reaction using the Laser Electron Gamma Source (LEGS) facility located at the National Synchrotron Light Source of Brookhaven National Laboratory. Linearly polarized γ rays between 213 and 333 MeV were produced by backscattering polarized ultraviolet laser light from 2.58 GeV electrons. The γ-ray energies were determined to $\sim$5 MeV by detecting the scattered electrons in a tagging spectrometer [20]. During the measurements, the polarization was flipped between directions parallel ($\parallel$) and perpendicular ($\perp$) to the scattering plane at random intervals between 150 and 450 s. The net γ-ray polarization was greater than 80% at all tagged energies. Both the polarization and the γ-ray flux normalization were monitored frequently and are known with accuracies of $\sim$1%.

The chief experimental background to Compton scattering comes from the $\gamma p \rightarrow \pi^0 p$ channel, where one high energy photon from π^0 decay is detected. The cross section for this process is $\sim$200 times that expected from Compton scattering. In this measurement, photons were detected in a large (48 cm diam $\times$ 48 cm long) high resolution ($\Delta E_\gamma / E_\gamma < 2\%$) NaI(Tl) spectrometer, positioned 0.3 m from a *6 cm diam* $\times$ 13 cm long target of liquid H_2 (LH_2). The trajectories of recoil protons were tracked through wire chambers and their energies were measured, both by energy deposition and by time of flight (TOF), in an array of plastic scintillator bars 4 m from the target. This arrangement is shown schematically in Fig. 1. A 2.5 cm thick plastic scintillator in front of the large NaI *rejected charged particles,* and in front of this a 5 cm thick lead collimator with a conical aperture (not shown in the figure) restricted the γ-ray acceptance to the full diameter of the NaI at its back face. High resolution drift chambers *were used to reconstruct the proton recoil angle to ~0.4°, limited by multiple scattering in the target.* A thin-walled helium bag after the wire chambers minimized *further* multiple scattering. The protons stopped in an array of 16 plastic scintillators, each 10 cm $\times$ 10 cm $\times$ 160 cm. The relative timing of light signals from opposite ends of these bars provided a horizontal position (to $\sim$7 cm) while the segmentation of the array determined the vertical position.

Recoil protons were uniquely separated in a two-dimensional plot of their TOF vs their energy deposition in the scintillator bars. The requirements of a γ ray with energy greater than 100 MeV in the NaI, no signal above 4 MeV in its veto plastic, a straight wire chamber track reconstructed from the target and pointing to the scintillator bar array, and a proton with the correct TOF and energy in the bars, removed all background processes. Empty target data were collected, but the number of events that survived these analysis requirements was completely negligible.

Compton scattering and π^0 production were distinguished by comparing their γ-ray and proton-recoil energies. The Compton and π^0 separation is shown in Fig. 2 where the γ-ray energy measured in the large NaI is plotted against the proton energy, the latter determined from a combination of TOF and energy in the plastic bars. For both axes, the energies expected for Compton scattering, as calculated from the tagged beam energy and the proton recoil angles measured by the wire chambers, have been subtracted. Compton scattering is clearly resolved.

Both the $p(\gamma, \gamma p)$ and the $p(\gamma, \pi^0 p)$ reactions are completely specified by two kinematic observables. In this experiment, six quantities were measured, the beam energy, the scattered γ-ray energy, the polar and azimuthal angles of the recoil proton, and the proton's TOF and energy. This large degree of kinematic overdetermination has two important consequences. First, it guarantees an accurate separation of the two competing channels, even at high beam energies. Secondly, it enables all detector efficiencies to be evaluated directly from the data itself, without resorting to simulations and thus avoiding their associated uncertainties. The geometric solid angle was modeled by Monte Carlo simulations, and different angular acceptances, determined by the wire chambers, produced consistent results.

In this Letter we focus on Compton scattering for 90° c.m., this being the angle that has led to the most

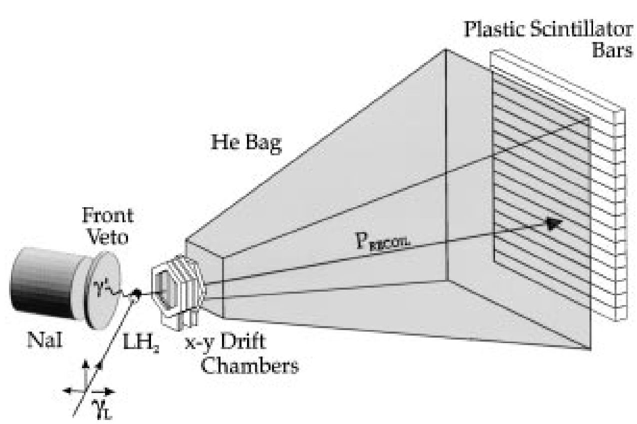

FIG. 1. Schematic arrangement used to identify γ-proton coincidences, with photons measured in a NaI(Tl) crystal and protons in an array of scintillator bars.

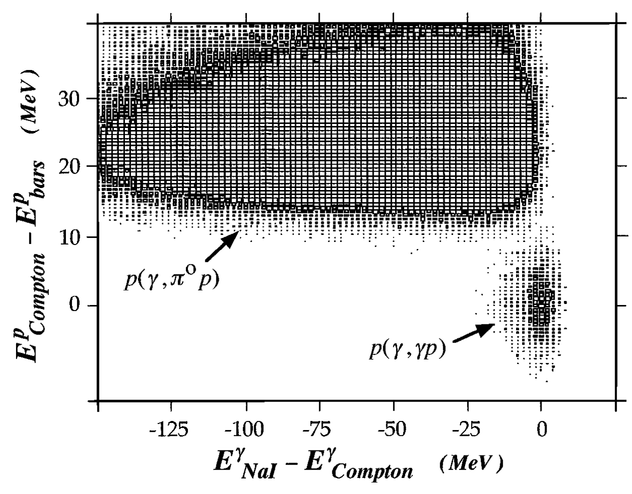

FIG. 2. A typical scatter plot of γ-ray energies in the large NaI and proton-recoil energies in the scintillator bars (see Fig. 1). For both, the energies expected for Compton scattering, as calculated from the beam energy and the recoil angles measured by the wire chambers, have been subtracted.

challenging unitarity problems and the largest number of calculations. Preliminary asymmetry values have been reported in Ref. [2].

The spin-averaged Compton cross sections from the present work (LEGS Expt. L8), corrected for finite detector acceptances, are plotted as the solid circles in Fig. 3 together with previous results. There have been two other recent measurements of the Compton cross sections. *At the Saskatchewan Accelerator Laboratory (SAL) [1], simulations were used to extract the $p(\gamma,\gamma)$ component from scattered bremsstrahlung (open circles), while in measurements with tagged photons at Mainz [21] (cross in Fig. 3), highly collimated detectors were used to isolate $p(\gamma,\gamma p)$ coincidences. Both are consistent with our results.* Data from the earlier Cornell 61 [12], Tokyo 64 [13], Illinois 67 [15], and Bonn 76 [16] experiments at energies higher or lower than the Δ peak are either consistent or slightly lower than the new group of measurements from LEGS, Mainz, and SAL. Why these earlier results are so dramatically lower near the resonance energy is not known.

The solid curve in Fig. 3 is a prediction using the model of L'vov [4], in which recent (γ,π) multipoles have been used to calculate the imaginary parts of the scattering amplitudes [22] while low energy measurements of the proton polarizabilities have been used to fix the dispersion integrals [19]. This gives a reasonable description of the new data, except for an overprediction near the Δ peak. The dotted curve restricts the real parts to their Born and π^0-pole values, and the dashed curve gives the unitarity bound obtained by setting the real parts to zero. Although slightly lower bounds have been obtained with other pion multipoles [10], all are significantly higher near the Δ peak than the four points from Cornell 61, Tokyo 64, Illinois 67, and Bonn 76. Although these four measurements appear to be in quite good agreement, we assert that they are, nonetheless, quite wrong.

The beam-polarization asymmetry data from the present experiment are shown in the lower panel of Fig. 4 (solid circles), together with the only published datum (cross-hatched square [18]). There are many published calculations for Compton scattering, and a selection illustrating different approaches is shown in Fig. 4. Several predict cross sections that lie relatively close to the data but the asymmetry provides a discriminating test where differences are often magnified. *Isobar* models assume the baryon resonance spectrum dominates scattering in order to extract the associated photon couplings. *The early work of Berkelman [5] and the later calculation by Ishii*

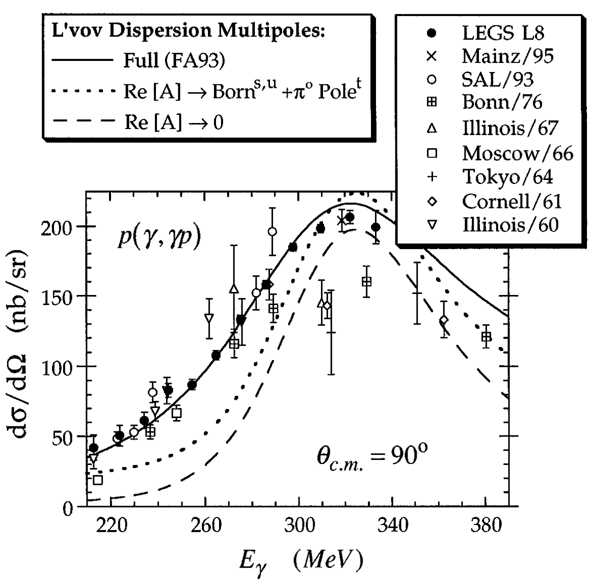

FIG. 3. Cross sections for proton and Compton scattering at 90° c.m. from the present experiment (solid circles) compared with *results from other laboratories* [1,11–16,21]—see legend. The calculations were carried out using the model of Ref. [4] with different assumptions for the real parts of the scattering amplitude.

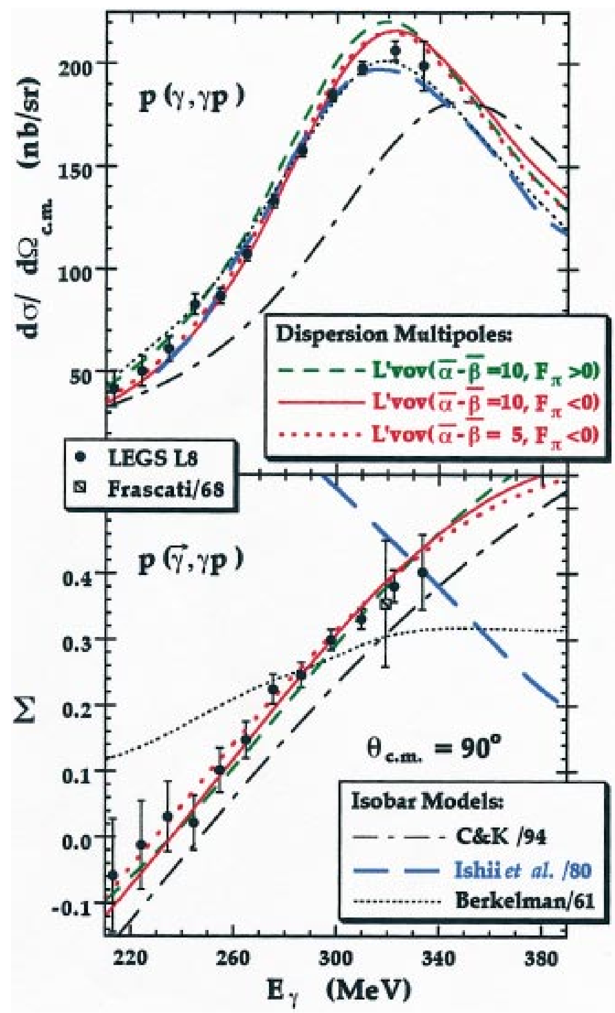

FIG. 4 (color). Polarization asymmetries ($\Sigma = \{\sigma_\parallel - \sigma_\perp\}/\{\sigma_\parallel + \sigma_\perp\}$, bottom panel) and cross sections (top panel) for $p(\vec{\gamma},\gamma p)$ at 90° c.m. from the present work (solid circles), together with the only published asymmetry datum [18]. These are compared to predictions of isobar models [5–7] and dispersion theory calculations [4]—see legend.

et al. [6] *are both quite close to the measured cross sections,* but their asymmetry predictions are dramatically different from the data. Capstick and Keister (CK) calculated Compton scattering using nonrelativistic quark model wave functions to predict the resonance photon amplitudes [7]. Their calculations have been *revised* by replacing the transverse helicity amplitudes for the Δ with those from Ref. [23]. Although their cross sections peak at a higher energy due to limitations in the basis states, the predicted asymmetry is similar to the data.

Comparing both cross sections and asymmetries, the dispersion calculations of L'vov (red curves in Fig. 4) are closest to the new data. There have been two recent determinations of the key free parameter of this model, the polarizability difference: in units of 10^{-4} fm^3, $\overline{\alpha} - \overline{\beta} = 5.5 \pm 0.7\text{(stat)} \pm 2.1\text{(syst)} \pm$ *1.6 (model)* was extracted from the SAL experiment of Ref. [1] using data between 149 and 286 MeV, and $\overline{\alpha} - \overline{\beta} = 10.8 \pm 1.1 \pm 1.4 \pm$ *1.0* has been obtained from a second experiment at SAL using energies between 70 and 149 MeV [19]. The calculations shown in red have been updated from the work of Ref. [4] by the use of recent $p(\gamma, \pi)$ multipoles [22], and by the inclusion of isospin splitting in the π^0/π^+ masses. The use of earlier multipole solutions has only a small effect, but if the isospin differences are ignored the predicted peak cross sections decrease while the asymmetry increases, both by about 3%. This would give a better representation of the cross section data but would deteriorate the agreement with the asymmetries. The deviations of either the dotted-red ($\overline{\alpha} - \overline{\beta} = 5$) or solid-red ($\overline{\alpha} - \overline{\beta} = 10$) curves from the data near the Δ resonance are substantially larger than the variations between them. Until calculations and data can be reconciled, we caution against using high-energy Compton data in the extraction of polarizabilities.

The Compton cross sections and asymmetries are also sensitive to the electric coupling at the $\gamma N \Delta$ vertex [2,24]. The $E2$ component has a destructive effect, lowering the peak cross section at 90° by $\sim$3% while increasing the asymmetry by $\sim$8%. A larger $E2$ strength in the dispersion calculations would improve the comparison with the cross section data, but not without destroying the agreement with the asymmetries. A proper determination of the $E2$ contribution requires data over a wide angular range, and these are presently under analysis.

Finally, the dashed-green curves in Fig. 4 were calculated assuming a positive sign for the π^0 decay constant, $F_\pi > 0$. The resulting cross sections are consistently above the data, *giving a* χ^2 *per point of 10 compared with 2 for the* $F_\pi < 0$ *solid-red curve.* This *supports* the arguments of Ref. [4] that the *Low* amplitude, used with the correct sign for F_π, *decreases* the Compton cross sections at energies below the Δ, and contradicts several other calculations ([3], and references in [4]).

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