The N → Δ Transition from Simultaneous Measurements of $p(\vec{\gamma}, \pi)$ and $p(\vec{\gamma}, \gamma)$

The LEGS Collaboration - Beamline X5

The Laser Electron Gamma Source facility (LEGS) provides intense, polarized, monochromatic γ-ray beams by Compton backscattering laser light from relativistic electrons circulating in the X-Ray Ring of the National Synchrotron Light Source at Brookhaven National Laboratory. Such a beam has a high degree of polarization (typically ~90%) with very low background and the energies of the photons are well determined by measuring the loss of energy of the struck electrons(±1%). Photon energies up to 333 MeV can be obtained with the present laser shining on 2.58 GeV electrons. With a new frequency-quadrupled laser that is now being installed and 2.8 GeV stored electrons, photon energies up to 470 MeV will be obtained.

LEGS has its high degree of polarization because the interaction of the laser photons with relativistic electrons preserves the polarization of the photons. By orienting the linear or circular polarization of the laser to give the desired polarization for the γ-rays, measurements can isolate specific contributions to nuclear reaction amplitudes. If the linear polarization (direction of the electric field vector) is in the plane of the reaction, the cross section is sensitive to electric multipole moments. This cross section is denoted as $\sigma_{\parallel}$. If the linear polarization is perpendicular to the reaction plane, the cross section is sensitive to magnetic multipole moments. This cross section is symbolized by $\sigma_{\perp}$. The data is usually presented in terms of $\sigma_{\parallel}/\sigma_{\perp}$ or $\sigma_{\parallel} - \sigma_{\perp}$, or as the asymmetry $\Sigma = (\sigma_{\parallel} - \sigma_{\perp})/(\sigma_{\parallel} + \sigma_{\perp})$. Comparing these cross sections allows for the separation of effects due to static charge distributions from those due to spin and current distributions. Thus, this polarization degree of freedom is extremely important in the understanding of nucleon and nuclear structure.

Since 1990, experiments have concentrated on single polarization observables (polarized beams on unpolarized targets) in nuclear reactions involving the Δ resonance. The Δ resonance is the first excited state of the nucleon with an energy of 294 MeV above the mass of the proton and a width of 120 MeV. It decays with a 99.4% branch to pion-nucleon (πN) final states and a 0.6% branch to γN. By studying photon induced nuclear reactions in the energy region of this excitation, it is possible to measure fundamental quantities such as the deformation of the Δ, to test models describing the internal structure of the nucleon and the Δ and the transition between them, and to study the effects of Δ's produced inside of nuclei. Highlights of this year's results are given below. An updated status of LEGS, including recent publications, is available on the World Wide Web at http://WWW.LEGS.BNL.GOV/~LEGS/ .

The properties of the transition from the nucleon to its first excited state, the Δ(1232) resonance, serve as a bench mark for models of nucleon structure. An important ingredient in most quark models is a tensor interaction that mixes quark spins with their relative motion. This results in D-wave components which break spherical symmetry, leading to a static deformation for the Δ, and to a small electric quadrupole transition strength, E2, that competes with the dominant magnetic dipole, M1, quark spin-flip transition in N→Δ photo-excitation. This resonance transition is described by two helicity amplitudes, $A_{3/2}$ and $A_{1/2}$, which depend on the E2/M1 mixing ratio (EMR). In simple spherical models of the nucleon their ratio is simply $\sqrt{3}$, while the presence of a D-wave component results in the correction

$A_{3/2}/A_{1/2} \cong \sqrt{3}\,(1 - 4\ \mathrm{EMR})$.

The first precision measurements of this ratio were made at the Laser Electron Gamma Source (LEGS)[1], and a fit of these data to the model parameters of Davidson, Mukhopadhyay and Wittman (DMW)[2] gave an EMR of –2.7 %[3]. This EMR was significantly larger than the conventional Particle Data Group (PDG) value of –1.5%[4], and implies a ~10% correction to $A_{3/2}/A_{1/2}$.

At a given energy, a minimum of 7 (and up to 9) independent observables are necessary to specify the photo-pion amplitude[5]. Such complete information is not available and previous analyses have relied almost exclusively on only four, the cross section and the three single polarization asymmetries, Σ (linearly polarized beam), *T* (target) and *P* (recoil nucleon). The π^o and π^+ channels are usually measured separately, introducing the complication of independent systematic errors. In our current work, $p(\vec{\gamma},\pi^o)$, $p(\vec{\gamma},\pi^+)$ and $p(\vec{\gamma},\gamma)$ cross sections and beam asymmetries have all been measured in a single experiment and a dispersion calculation of Compton scattering has been used to provide two new constraints on the photo-pion multipoles.

Both Compton scattering and π^o-production have a proton and at least one photon in their final states. We have made the first complete separation of these two processes. 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. By measuring more kinematic parameters than are required to specify the reaction, all detector efficiencies are determined directly from the data itself.

Near the Δ peak (≈ 320 MeV photon energy), the spin-averaged π^o, π^+, and Compton cross sections found here are consistently higher than earlier measurements from Bonn[6-8], while for energies lower than ~270 MeV substantial agreement is obtained. We present here results at 323 MeV and 265 MeV as examples. Angular distributions for $p(\vec{\gamma},\pi^o)$, $p(\vec{\gamma},\pi^+)$ and $p(\vec{\gamma},\gamma)$ are shown with their measurement uncertainties as solid circles in the figure. All cross sections are locked together with a common systematic scale uncertainty, due to possible flux and target thickness variations, of 2%.

In the center panel of Figure N-1, π^+ cross sections from Tokyo[9] are shown as cross-hatched squares. These are in good agreement with the present work. In the right panel, two recent Compton measurements from Mainz at 90° and 75° are shown as open circles[11,12]. These data sets are in quite good agreement with the present work over our full energy range. As discussed in Ref. [14}, earlier 90° Compton cross sections from Bonn[15] are about 28% too low in the vicinity of the Δ peak. Whatever the error in that early experiment, it is likely to be common to all angles measured with the same detector. The Bonn results are shown here, rescaled by 1.28 (open squares).

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. 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.

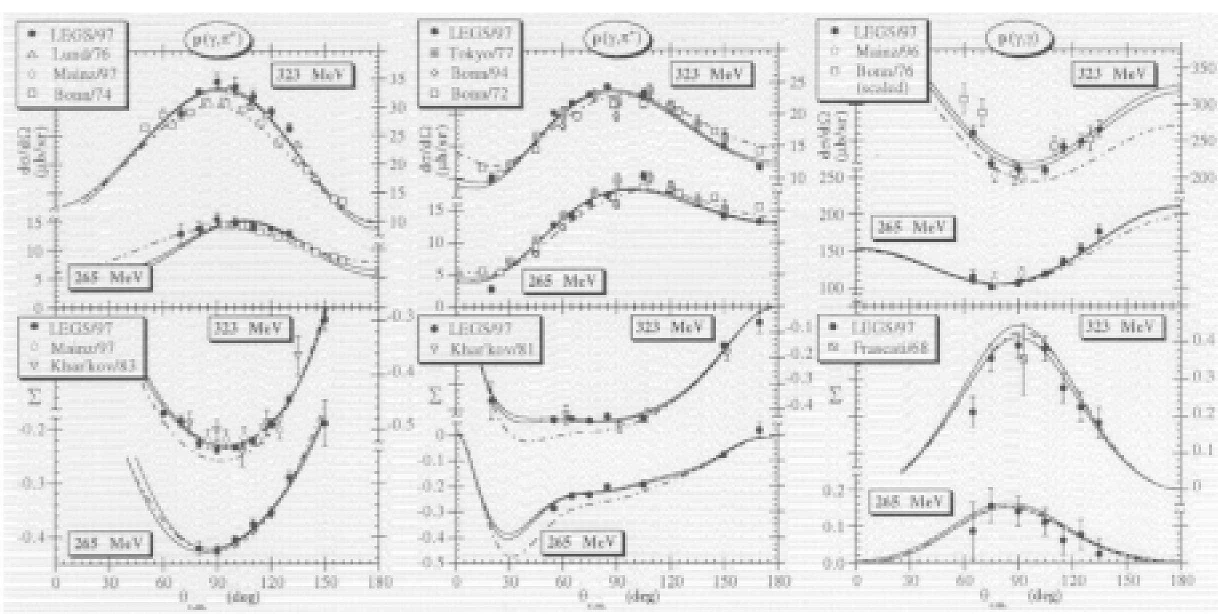

Figure N-1: Cross sections (top row), and polarization asymmetries $\Sigma=(\sigma_{\parallel}-\sigma_{\perp})/(\sigma_{\parallel}+\sigma_{\perp})$ (bottom row), from the present work (•) for $p(\vec{\gamma},\pi^o)$ – left panel, $p(\vec{\gamma},\pi^+)$ – center, and $p(\vec{\gamma},\gamma)$– right panel, together with published data – (γ,π^o): [16-18], (γ,π^+): [9,10,19,20], (γ,γ): [15 (see text),9-11]. Results are shown for 265 MeV (323 MeV) beam energy with scales on the left (right) of each plot. Predictions from our multipole fit are shown with uncertainties as bands bounded by solid curves. Predictions from the VPI[SP97k] multipoles [21] are given by dash-dot curves. The dotted curves in the right panel show the Compton predictions using the prescription in refs. [12, 22].

Quantity	This Experiment	Particle Data Group[4]
$A_{1/2}$	–137.4 ($\times 10^{-3}$ GeV$^{-1/2}$) ±1.8 (*stat+sys*) ±1.8 (*model*)	–141±5
$A_{3/2}$	–268.9 ($\times 10^{-3}$ GeV$^{-1/2}$) ±2.8 (*stat+sys*) ±4.9 (*model*)	–257±8
EMR	–3.0 (%) ±0.3 (*stat+sys*) ±0.2 (*model*)	–1.5 (%)±0.4

Figure N-2: Table.

Fitting the parameters of the (γ,π) multipoles by minimizing χ^2 for both predicted (γ,π) and (γ,γ) observables allows the extraction of the EMR. In this fit we have used $p(\vec{\gamma},\pi^o)$, $p(\vec{\gamma},\pi^+)$ 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.

The predictions from the (γ,π) multipoles determined in this fit are shown in the figure as pairs of solid curves to indicate the corresponding uncertainty bands. The reduced χ^2 for this analysis is
χ^2_{df} = 997/(644–34) = 1.63 .

The EMR for N→ Δ is –0.0296 ±0.0021. The fitting errors reflects all statistical and systematic uncertainties. Combining *model* uncertainties in quadrature leads to our final results given in Figure N-2 along with the values accepted by the Particle Data group for comparison.

Other information on the structure of the nucleon can be extracted from these data and this work is in progress. In particular, when placed in a strong static electric or magnetic field, a proton or neutron will experience an internal rearrangement of the quarks and gluons. An electric field will induce a dynamic electric dipole moment by separating the positive and negative quarks and a magnetic field will produce a dynamic magnetic dipole moment by separating the currents and/ or spins of the quarks. The measure of the ease with which these internal rearrangements can be done is called the electric, magnetic, or spin polarizability.

Determination of the polarizabilities of the neutron require a neutron target. Since the free neutron is not a stable particle, deuterium the lightest isotope of hydrogen is commonly used to provide a quasi-free neutron. Here the single proton and neutron are bound by only 2.2 MeV, minimizing the corrections necessary to go from the bound neutron to the free neutron.

Since the initial photon and neutron have no charge, a detector is required that has a good efficiency for neutral particle in the final state (π^0 which decays to 2γ's, γ-rays, and neutrons) as will as charged particles. to provide the neutral particle efficiency and the angular coverage for charged and uncharged particles, a new detector has been commissioned. SASY, the Spin-ASYmmetry detector array provides complete determination of angle, energy, and particle identity for all reactions induced by photons on hydrogen and deuterium over the entire energy range planned for LEGS. SASY will consist of several "layers" designed to fulfill these requirements.

The construction of SASY is being done in two phases. For the first set of experiments to measure the electric and magnetic polarizability of the neutron, only the major calorimetry subsystems will be instrumented: the XTAL BOX (an array of 432 NaI(Tl) crystals) covering all azimuthal angles for scattering angles between about 40° and 130°, the forward neutron wall of plastic scintillator consisting of three layers of 10 cm × 10 cm × 1.6 m bars, and the wall of 176 Pb-glass Cerenkov counters. The second phase will add the capability to track charged particles through a large volume magnetic field thereby permitting the identification of the sign of the charge. This is crucial for the the next phase of LEGS in which double-polarization data will be obtained from the polarized hydrogen and deuterium using the a novel, polarized HD target. This is now in the development stage and initial experiments (without tracking) will begin in the summer of 1998.

Measurement of Compton scattering from the neutron occupied most of calendar 1997. These data are presently being analyzed. ■

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