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LEGS Facility Operations:

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The LEGS facility[†] produces monochromatic, polarized gamma ray beams, now extending up to 360 MeV, by backscattering laser light from relativistic electrons circulating in the X-Ray storage ring of the National Synchrotron Light Source (NSLS) at Brookhaven National Laboratory [1]. The average gamma-ray beam rate is 6×10^6 per second, integrated over all energies up to the edge of the Compton spectrum. The latter is determined by the choice of laser wavelength. Those available with the present Ar-Ion laser yield the spectra shown as the thick curves in fig. 1. A new laser system now under development will soon add the capability of producing the spectra shown as the thin curves [2]. The beam spot at the target is roughly gaussian with a FWHM of 8 mm vertical and 18 mm horizontal, and the location of the beam center is stable to ± 0.5 mm. The linear polarization of the beam is greater than 96% at the high-energy Compton edge. This drops with decreasing energy, but with appropriate choices of laser lines the polarization can be

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maintained at levels greater than 85% throughout the tagging range. The gamma-ray energy is determined by tagging to a resolution of 5 MeV FWHM for energies above 185 MeV (see inset to fig. 1), and to 15 MeV for energies from 90 to 110 MeV. The beam is also very "clean": typical "true" to "random" coincidence ratios for any of the experiments conducted at LEGS have been at least 30 to 1.

fig. 1

LEGS can produce gamma-rays whenever the X-ray storage ring is operating, which amounts to about 2/3 of the calendar year. Of this fraction, high quality γ-ray beams can be available about another 2/3 of the time. During the last 2 years, approximately 30% of the available running time was used for beam and detector development. The balance was devoted to the experiments described below.

† Supported by the U.S. Department of Energy under Contract No. DE-AC02-76-CH00016.

- [1] A. M. Sandorfi et al., IEEE NS-30, 3083 (1983);
C. E. Thorn et al., Nucl. Inst. Meth. A285, 447 (1989).
- [2] A frequency-quadrupled Nd-YLF, now under construction in collaboration with G. Giordano and G. Matone, INFN-Laboratori Nazionali di Frascati, Italy.

Exp. L1: Polarization in $D(\vec{\gamma}, p)n$ and the N-N Tensor Force, $E_\gamma \leq 225$ MeV

The LEGS collaboration

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Reactions with polarized photons inevitably reflect interference terms that, for the most part, remain hidden in spin-averaged unpolarized measurements. This provides a tool for probing interactions that depend upon spin. In particular, linear polarization is a quite effective probe of tensor interactions. The nuclear tensor force comes about largely from one pion exchange, and is attractive. The tensor interaction mixes intrinsic spin and orbital angular momentum. In particular it brings in a D wave into what would otherwise be a purely S wave deuteron. In the absence of the tensor interaction, the deuteron could have no quadrupole moment. The quadrupole moment of the deuteron fixes the long range part of the tensor force, but its short range behavior can only be extracted from spin observables.

Fig. 1 shows calculations from Arenhoevel and Schmitt [1] for the photo-disintegration of the deuteron using three different choices for the short range behavior of the N-N tensor interaction. These are indistinguishable in the unpolarized cross section, but well separated in the linear-photon beam-polarization asymmetry.

In Exp. L1, a new set of photo-disintegration measurements on the deuteron covered the energy range from 185 MeV to 226 MeV [2]. These measurements involved two independent sets of detectors surrounding a liquid deuterium target. One set consisted of 24 phoswich detectors, arranged in sets of three at eight different angles. These units are sandwiches of two types of scintillator, giving both energy loss and total energy information that allowed the identification of protons. The other detector was comprised of a set of microstrip detectors that were able to

fig. 1

fig. 2

accurately reconstruct the reaction angle of the proton. This array was backed by a high resolution sodium iodide crystal that measured total energy. The data from the phoswich detectors were analyzed only tagged, requiring an electron in the tagging spectrometer to define the energy of the photon that initiated the reaction. The microstrip detectors were analyzed untagged, that is using just the angle information and energy to reconstruct what the gamma-ray energy must have been to produce the reaction. Here, the tag information was used only to determine when to stop this reconstruction process so as to avoid backgrounds from three-body decays involving a pion in the final state. The data at all angles and at all energies were collected simultaneously.

Throughout the angular range, the differential cross sections from the two recent LEGS measurements [2] agree very well, both with each other as well as with tagged bremsstrahlung experiments from Bonn [3] and from Mainz [4]. Similar agreement is seen in the total angle-integrated cross section, as shown in fig. 2. Here some recent tagged bremsstrahlung data from Saskatoon have also been included [5], and these are also in quite good agreement. Another data set, for which there was some direct information on the photon energy, has come from Frascati [6], and is shown as the crossed-boxes in fig. 2. In these measurements, the photon beam was

produced by positron annihilation in flight. This process produces a peak in the gamma-ray spectrum but is accompanied by a rather large tail which greatly complicates the analysis. Above 140 MeV these data rise significantly above all of the tagged measurements.

As can be seen in the equation below, the cross section for this reaction can quite generally be written as the average of the parallel and perpendicular cross sections, plus P , the degree of linear polarization, times the average difference cross section, multiplied by $\cos(2\phi)$. Here, ϕ is the azimuthal angle between the electric vector of the linearly polarized photon and the reaction plane.

$$\begin{aligned}\frac{d\sigma}{d\Omega}(\theta, \phi) &= \frac{1}{2} \left[\frac{d\sigma_{||}}{d\Omega}(\theta) + \frac{d\sigma_{\perp}}{d\Omega}(\theta) \right] + P \cdot \frac{1}{2} \left[\frac{d\sigma_{||}}{d\Omega}(\theta) - \frac{d\sigma_{\perp}}{d\Omega}(\theta) \right] \cdot \cos(2\phi) \\ &= \frac{d\sigma}{d\Omega}(\theta) + P \cdot \Delta(\theta) \cdot \cos(2\phi) \\ \Sigma(\theta) &= \Delta(\theta) / \frac{d\sigma}{d\Omega}(\theta)\end{aligned}$$

The average of the parallel and perpendicular cross sections is just what would be measured with an unpolarized photon beam. We will call the average difference, $\Delta(\theta)$. It is Δ and the unpolarized cross section that are the linearly independent observables here. The beam asymmetry, Σ , is simply their ratio.

Angular distributions for the unpolarized cross section and for the polarization difference, $\Delta(\theta)$, are shown for 4 beam energies in fig.3. (These are the first measurements of $\Delta(\theta)$. Although this quantity is just the product of the unpolarized cross section and the beam asymmetry, the latter two have never been measured in the same laboratory, and systematic uncertainties associated with different experiments have prevented their being combined to produce a meaningful estimate for Δ .) Also plotted here are calculations from Arenhoevel and collaborators [1] using the PARIS N-N potential. The vertical bar at 80 degrees in each panel of the figure indicates the extent of the systematic uncertainty in the LEGS data set. Allowing for this uncertainty, the predictions using the Paris potential provide a reasonable representation of the unpolarized cross sections. For $\Delta(\theta)$, these calculations are in quite good agreement with the data at energies near 190 MeV. But as the energy increases the Polarization difference data become systematically more negative than the calculations. There are two possible sources for this. One is simply that the tensor force in the Paris potential was empirically adjusted to fit values of N-N phase shift parameters (most notably ϵ_{11}), but it is

fig. 3

likely that the errors that were assumed for these quantities were unrealistically small [7]. The other possible problem may lie in the fact that these calculations treat the N- Δ and Δ - Δ interactions in exactly the same way as the N-N force. As we approach the peak of the Delta, about 265 MeV in deuterium, this has to have some effect. The better approach would be to treat these interactions in a couple channel calculations framework. This is now under development [1]. Clearly, it will be quite interesting to see if the trends evident in fig. 3 continue to higher energies.

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- [5] K. Garrow, Queens Univ. thesis, private comm.
- [6] E. DeSanctis et al., Phys. Rev. C34, 413 (1986);
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- [7] G.S. Chulick, et al., Phys. Rev. C37, 1549 (1988).

Exp. L3: Constraints on the Nuclear Tensor Force from $D(\vec{\gamma},p)n$, $E_{\gamma} \leq 315$ MeV

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As demonstrated in Exp. L1 [1], the beam-polarization observables in deuteron photodisintegration, particularly the difference of cross sections measured in orthogonal states of linear polarization, are quite sensitive to the short range part of the N-N tensor interaction. For energy-independent potentials, data at a single energy are sufficient to constrain the parameters of the interaction. However, for the more general energy-dependent potentials, data are needed over a wide range of beam energies so that true tensor force effects can be separated from non-local components of the interaction. Exp. L1 covered the limited γ -ray energy range

between 189 to 225 MeV. In Exp. L3, these measurements were extended from 200 MeV up to 315 MeV, using a different laser line for the production of higher γ energies.

In Exp. L3, the same array of phoswich and μ -strip detectors were used, surrounding the same 3.8 cm diameter target as in Exp. L1. The analysis of these data is underway. Preliminary data on the photon-beam asymmetry at 221 MeV and 299 MeV is shown in fig. 1 (solid diamonds), along with the 222 MeV results from Exp. L1 (solid circles) and previously published data from Khar'kov [2].

fig. 1

The comparison between Exps. L1 and L3 at 221 MeV provides a cross check on the determination of the γ -ray beam polarization. During Exp. L1 this energy was

close to the maximum of the laser photon- e^- beam Compton scattering edge. Here the γ -ray is produced with 100% of the laser polarization. However, the polarization drops as the γ -ray energy decreases. In Exp. L3, a triplet of Compton edges, corresponding to three closely spaced UV-laser lines, was centered at 304 MeV, and 221 MeV γ -rays were produced with only 83% of the laser polarization. As seen in fig. 1, the results of the two experiments are in excellent agreement.

The solid curves in fig. 1 are recent calculations [3] by Arenhoevel and collaborators using the PARIS N-N potential. These calculations treat the N- Δ and Δ - Δ interactions in exactly the same way as the N-N force. A further refinement would be to solve the three associated Schroedinger equations in a coupled-channel framework. Although the present calculations agree very well with the asymmetry data, the ultimate test of whether or not this level of sophistication is necessary lies in comparisons with the polarization difference, $\Delta(\theta)$. These will soon be available.

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W.K. Mize, Ph.D. thesis, Univ. South Carolina (1992).
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Exps. L2,5: The $p(\gamma,\pi^0)$ Reaction and the E2 Excitation of the Δ

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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 in a D state into what would otherwise be a purely S wave proton. The D wave component breaks spherical symmetry, resulting in a non-vanishing $\langle r^2 Y_2 \rangle$ matrix element for the nucleon and a static quadrupole moment and deformation for its first excited state, the delta (Δ) resonance, at about 320 MeV. The magnitude and sign of this D state component are quite sensitive to how the internal structure of the proton is treated in quark models and have been of great interest in recent years [1].

The experimental signature of such 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 there is a D wave component in the Δ 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. A variety of 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) 3/2 Δ decays with a 99.4% branch to a pion-nucleon (πN) final state. An E2 photon will produce a p-wave pion so that, in the Chew-Goldberger-Low-Nambu notation [3], the mixing ratio of interest is written in terms of photo-pion multipoles as E_{1+}/M_{1+} . The observable that is most sensitive to the E_{1+} multipole is associated with the $p(\vec{\gamma}, \pi^0)$ reaction. Calculated cross sections for

fig. 1

different orientations of linear polarization are shown in fig.1 [4]. The thick and thin lines assume that the incoming photon's Electric field vector is parallel and perpendicular to the reaction plane, respectively. Calculations are shown with (solid lines), and without (dashed lines), the inclusion of the E2 amplitude. The dotted curves give the predictions for the case when only the resonant part of the E_{1+} is set to zero.

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 bigger than the parallel and dominates unpolarized measurements, thus rendering the unpolarized cross section largely insensitive.) This is actually a rather convenient situation, since the ratio of parallel/perpendicular cross sections ($d\sigma_{||}/d\sigma_{\perp}$) 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 of the systematic experimental uncertainties will cancel out.

In Exps. L2 and L5, the π^0 -production cross sections were measured with linearly polarized photons up to 314 MeV [5]. Recoil protons were detected at three lab angles, corresponding to π^0 -center of mass angles of 105° , 122° , and 150° . To test the sensitivity to systematic uncertainties that may survive the $d\sigma_{||}/d\sigma_{\perp}$ cross section ratio, three independent measurements have been conducted at 105° -CM with different detectors, different methods of defining the γ -ray energy and monitoring the γ -flux, different polarizations, and using two targets of liquid hydrogen having different cell configurations. All of the data in various energy intervals from 243 MeV to 314 MeV were collected simultaneously. Two of the measurements utilized the same μ -Strip and Phoswich detector arrays that were used in Exps. L1 and L3, along with the same 3.8 cm diameter liquid target oriented transverse to the beam. The detector of the third measurement was a 1-cm-thick plastic scintillator followed by a 25-cm-deep NaI(Tl) crystal, which viewed a 10 cm long liquid target oriented along the beam. As in Exps. L1,3, the photon tag was ignored during analysis of data from the μ -Strip array, and the γ -ray energy was reconstructed from the measured proton energy and momentum vector. Only tagged-photon data were collected from the Phoswich and NaI detectors during the other two 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 Exp. L2, in which μ -Strip

and Phoswich data were collected, the laser light was partially depolarized, while for the NaI data of Exp. L5 the polarization was nearly 100%. The results of these three measurements are in excellent agreement and their weighted mean is plotted in fig.2 (solid circles), along with other published results (open symbols), where available [6]. The reduced χ^2 of the measurements relative to the weighted-mean is 1.4 over the overlapping energy range of the three data sets. These results have been corrected for proton-Compton scattering, which was not separated in the recoil-proton spectra.

Plotted with the data of figs. 2 are the results of two recent model calculations. The curves lying generally above the data (labeled as NOZ) are the work of Nozawa, Blankleider and Lee [7], 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 DAV) are the work of Davidson, Mukhopadhyay and Wittman [4], in which photo-production 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 (a process that is not unique). In the calculations of fig. 2, the parameters of both models have been determined by fitting the amplitudes to the Berends and Donnachie (BD) photo-pion multipoles [8]. From this procedure, Nozawa et al. deduced an $E_{1+(3/2)}/M_{1+(3/2)}$ mixing ratio of -3.1%, while Davidson et al. obtain about half that, -1.4%. However, it should be noted that the NOZ value of -3.1% represents the "bare" $\gamma N\Delta$ coupling, without any dressing from FSI, while that of the DAV calculation includes FSI at some level.

At 105° where the sensitivity to a resonant E2 component is nearly maximal, both the NOZ and DAV calculations approach the data near the peak of the Δ (about 320 MeV). However, the energy dependence of the $d\sigma_{||}/d\sigma_{\perp}$ ratio provides the crucial test of the resonance-background decomposition, and both models clearly exhibit the wrong energy dependence. At larger angles the comparison with Nozawa et al. becomes dramatically worse, while those of Davidson et al. become much more reasonable.

It is interesting to compare the NOZ and DAV curves with direct predictions of the BD multipoles. These are shown as the dashed curves, labeled (BDLE) in fig. 2 [9]. The full calculations of either the NOZ or DAV models should reproduce the BDLE curves which were used to fix the model parameters. Neither do, and there are two possible reasons for the large discrepancies evident here: (1) The description of the physical process in both of the models is incomplete; or (2) although one of

fig. 2

the models may provide a sufficiently complete description of the (γ, π) reaction, the multipole set used to fix model parameters is flawed. In fact, fig.2 provides the motivation to question the validity of existing multipole decompositions, at least for small amplitudes such as the $E_{1+}(I=3/2)$. Although the predictions of the BDLE solution are in excellent agreement with the data at 105° , this appears fortuitous since the agreement at the larger angles is quite poor.

The differences between the measured $d\sigma_{||}/d\sigma_{\perp}$ 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.

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with the VPI-code SAID;

Exp. L4: Quasi-two- and three-body absorption in $^3\text{He}(\vec{\gamma}, \text{NN})$

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Photoabsorption measurements on ^3He have been completed using a large solid angle scintillator array surrounding a 10 cm long liquid target. Data on the reaction channels $^3\text{He}(\vec{\gamma},p)X$, $^3\text{He}(\vec{\gamma},d)p$, $^3\text{He}(\vec{\gamma},pp)$ and $^3\text{He}(\vec{\gamma},pn)$ were collected simultaneously. Protons and deuterons were detected at lab angles $20^\circ \leq \theta_1 \leq 160^\circ$ in the array of 24 phoswich detectors used during Exps. L1,3. Coincident protons and neutrons were measured at lab angles of $20^\circ \leq \theta_2 \leq 140^\circ$ in a time-of-flight array consisting of 32 scintillator bars having an azimuthal acceptance of approximately $\pm 40^\circ$. These data are now being analyzed.

The $^3\text{He}(\vec{\gamma},pp)n$ channel provides a particularly interesting test of theory. Dipole absorption on the two-proton pair is forbidden since the protons are identical particles. Meson exchange contributes almost nothing since charged mesons cannot be exchanged between the protons and a photon cannot couple to a neutral pion. Finally, parity conservation strongly suppresses the excitation of the Δ on a p-p pair in the relative s-state. In selected regions of phase space, this reaction is predicted to

fig. 1

be dominated by γ absorption on three nucleons. Calculations for the beam-polarization asymmetry are shown in fig. 1 for the quasi-free kinematics where the spectator neutron has very low momentum [1]. The contributions of one- and two-body currents, shown by the solid line, are expected to produce very large asymmetries. These are reduced by the inclusion of three-body contributions, an example of which is shown as the dashed curve.

fig. 2

Preliminary target-empty subtracted proton momentum spectra from $^3\text{He}(\vec{\gamma}, pp)$ are shown in fig. 2 for CM angles of one proton near 90° . Here, the momentum spectra of the second coincident proton have been integrated. Data for two beam energy intervals are shown, 217 ± 17 (left panels) and 287 ± 17 MeV (right panels), and for the two polarization states, perpendicular to the p-p plane (top panels) and parallel to it (bottom panels). These spectra have been normalized to the incident γ flux. The two-body quasi-free peak stands out in the perpendicular cross sections at about 500 and 570 MeV/c in the $E_\gamma = 217$ and 287 MeV spectra, respectively. Although it is less pronounced in the parallel spectra, the

asymmetries are clearly not as large as predicted by the solid curve of fig. 1. However, conclusions about three-body currents must await further analyses in which restrictions are placed on the missing neutron momenta.

[1] J.M. Laget, priv. comm.

Exp. L6: The Δ -N interaction in $D(\vec{\gamma}, p\pi^-)p$ and $D(\vec{\gamma}, pn)\pi^0$

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An important aspect of the Nucleon-Nucleon interaction is the distinction between the N-N and N- Δ forces. Coupled channel calculations that allow for such differences rely on a refitting of nucleon scattering data with shifted coupling constants for the N-N, N- Δ and Δ - Δ interactions. This process greatly increases the number of free parameters since there are very few constraints on the N- Δ force.

Since the Delta decays by emitting a pion, the simplest channels for a study of the N- Δ force are deuteron breakup into NN π final states. In Exp. L6 data on the $D(\vec{\gamma}, p\pi^-)p$ and $D(\vec{\gamma}, pn)\pi^0$ reactions have been taken, using a liquid deuterium target and the same arrangement of detectors as in Exp. L4. Charged pion production off of the Nucleon has large non-delta-resonance components. However, these can be suppressed in kinematic regimes of quasi-free $p\pi^-$ production having high recoil proton momenta. Deviations from the quasi-free amplitude can be studied by detecting the spectator neutron from the $D(\vec{\gamma}, pn)\pi^0$ reaction in regimes far from quasi-free kinematics. Here the theoretical interpretation is simplified by the fact that the elementary amplitudes for π^0 production are almost purely resonant.

The analysis of the data from these measurements is in its early stages.

END

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