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The Photodisintegration of the Deuteron
with Polarized Photons from LEGS

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Abstract

An experiment is described which will measure the $d(\gamma, p)$ reaction with polarized photon beams from LEGS ranging in energy from 50 MeV to 530 MeV. The data will yield a new high-resolution high-statistics determination of the total unpolarized cross section, will isolate for the first time the polarization dependent part of the reaction, and will measure the photon-beam asymmetry with much higher resolution and accuracy than available from existing data. These will provide one of the most stringent tests for models of the nuclear force. In addition, high-resolution data will be taken with both linear and circularly-polarized γ rays to search for the effects of bibaryons.

1. Scientific Motivation

Being the simplest nucleus, the deuteron has been extensively used to study the strong interaction that binds nucleons together. It is also the simplest object containing more than three quarks and has been the target of many searches for multiquark resonances. For both of these goals, photodisintegration has been the preferred reaction since the properties of the electromagnetic entrance channel can be calculated exactly, thus providing a stringent test of nuclear and quark models.

a. Energies below Pion Threshold

There have been a number of recent calculations of the photodisintegration of the deuteron below pion threshold¹⁻⁶. Several of these have included non-nucleonic degrees of freedom such as pion exchange and virtual delta excitation. Most of these calculations agree on the total cross sections, both among each other and with experimental data. However, the asymmetry in the predicted cross sections from interactions with polarized photons has turned out to be very sensitive to the way in which these non-nucleonic terms are included. The recent asymmetry measurements by the LADON group at Frascati, using linearly polarized photons produced by back-scattering laser light from electrons circulating in the ADONE storage ring, have demonstrated the importance of π -meson Exchange Currents (MEC) and of the virtual excitation of deltas giving rise to Isobar Currents (IC) in photodisintegration even well below pion threshold⁷⁻⁸. The cross section for this reaction can be written as

$$d\sigma/d\Omega(\theta) = I_0(\theta) + P I_1(\theta) \cos 2\phi, \quad (1)$$

where I_0 is the usual component measured with an unpolarized beam, P is the degree of linear polarization, and ϕ is the angle between the electric vector of the incident γ ray and the reaction plane. The asymmetry is just the ratio between the polarization-sensitive and -insensitive parts of the cross section

$$\Sigma(\theta) = \frac{I_1(\theta)}{I_0(\theta)} = \frac{d\sigma_{||} - d\sigma_{\perp}}{d\sigma_{||} + d\sigma_{\perp}}, \quad (2)$$

where the parallel and perpendicular components are measured with $\phi = 0^\circ$ and 90° , respectively. The recent asymmetry data taken by the LADON group at 90° is shown in Fig. 1 (solid and open circles) together with some other data taken at higher energies⁷⁻¹⁰. The dashed curve is the prediction excluding non-nucleonic effects¹¹, and the solid line is from a recent calculation by Arenhövel which includes both MEC and IC contributions³. These calculations are limited to energies below pion threshold since they do not include real excitation of deltas. Nonetheless, the difference is quite appreciable and demonstrates the importance of the non-nucleonic degrees of freedom even at low energies. Moreover, the trend suggests that these effects become very large at higher energies.

Sensitivity to the way in which MEC and IC are included, and to the nuclear potentials used, comes chiefly through $I_1(\theta)$. Angular distribution data from the LADON group for $I_0(\theta)$ and $I_1(\theta)$ are shown in Fig. 2⁷. Here the dashed lines have been obtained by Arenhövel using a Reid soft-core (RSC) nucleon-nucleon potential²⁻³, and are identical with the calculations of Gambi et al.⁴. There is no appreciable difference in the predictions if

the Hamada-Johnston or the Paris potentials are used⁴. On the other hand, the solid lines have been calculated using version B of the DeTourreil-Sprung (DTS-B) potential⁶. Arenhövel's calculation was quite adequate to explain the asymmetry data of Fig. 1. However, as the energy increases, the differences between the predicted I_1 angular distributions become more noticeable, and the highest energy data at 60.8 MeV favors the older DTS-B potential. This sensitivity of $I_1(0)$ to nuclear models must become even more dramatic at higher energies, and illustrates the power of polarization data in the understanding of nuclear forces.

b. Energies above Pion Threshold

The situation at energies above pion threshold is much more complicated, both experimentally and theoretically. The photodisintegration of deuterium has been studied for years, but still the data is in a terribly confused state. The total cross section is shown in Fig. 3. The various data sets are taken from Refs. 12-19. At energies sufficiently above the delta, the data sets seem to converge, but from 180 to 350 MeV there are variations of as much as 60% among them. Most of these data were taken by measuring the angle and energy of the emitted proton, which determines the kinematics completely without having to know the incident photon energy. Each measurement had its own background problems which supposedly were dealt with adequately. The last two data sets, solid squares (from Ref. 18) and solid circles (calculated from the data in Ref. 19), were taken with quasi-monochromatic photons, thus overdetermining the kinematics. Unfortunately, these two data sets do not cover the same energy range and can only be compared at one point, 220 MeV. Here they still differ by 12%, although they also report 8% and 10% systematic errors, respectively, which are not

indicated in this plot. There are various calculations for this region. Two are shown in Fig. 3. The use of different potentials, with or without a coupled-channels treatment to take into account various final state interactions²⁰, can easily move the predicted cross section among the data sets of Fig. 3. A careful remeasurement of this photodisintegration cross section in the region of the delta, with low backgrounds and monochromatic photons to overdetermine the kinematics, is sorely needed before any progress can be made in understanding the underlying physics.

As was the case at lower energies, polarization data is much more sensitive to the details of nuclear model calculations, and if one focuses on the asymmetry (Eq. 2) the systematic errors that plague the total cross section data have the chance of cancelling out. The available data on the photodisintegration cross section asymmetry, taken with linearly polarized γ rays at proton c.m. angles of 45° , 90° , and 135° , are shown in Figs. 4, 5, and 6, respectively. The short-dashed, long-dashed and dot-dashed curves are calculations by Laget^{1,21} in which the reaction amplitude is expanded into leading elementary diagrams, each of which is explicitly calculated. The short-dashed curves result from using phenomenological wave functions assuming only s waves in the final state, and keeping only the fewest terms in the expansion. Curiously, this gives the best fit to the 45° data, albeit limited. Nonetheless, this approximation fails dramatically at larger angles. The long-dashed curves are calculated to the same order in the expansion, but now include P waves in the final n-p system and gauge invariance of the full photodisintegration amplitude. These are much closer to the data at 90° and 135° for energies below 350 MeV, but rise considerably above the few data points that are available at higher energies. The dot-dashed curves result from taking a larger number of terms in the

expansion with a Levinger-type form factor²⁵. This combination reproduces the Reid wave function at the deuteron bound state²⁶ and should be the most realistic. Nonetheless, these curves deviate significantly from the data above 100 MeV. The solid orange curve for $\theta = 90^\circ$ is the same as the solid line in Fig. 1 for energies below 150 MeV. This is from a calculation by Arenhovel in which the explicit degrees of freedom inherent to the diagrams of Laget are replaced by a perturbative expansion including one-pion-exchange potential and current operators, and two-body meson exchange currents (MEC) and virtual isobar currents (IC)³. Above pion threshold this approach becomes considerably more complicated since the pion decaying from a delta can either be reabsorbed or emitted as a real particle. Leidemann and Arenhovel have extended this approach using a coupled-channel calculation to explicitly account for such final state interactions^{20,24}. Their result is shown as a solid orange line above 200 MeV in Fig. 5. Within the accuracy of the available data, this is as good as Laget's long-dashed curve below 350 MeV, but also rises above existing data at higher energies.

The data and calculations from pion threshold up to about 350 MeV are now in a state similar to the condition of the low-energy region prior to the LADON experiments. Measurements with much higher statistics, better energy resolution, and many more angles are needed before the details of the various models can be compared in a critical way. As was the case at low energies, the most sensitive test of these nuclear models would come through comparisons with I_1 , the polarization dependent part of Eq. 1. There are as yet no measurements of this term, and the confused state of the unpolarized data (Fig. 3) precludes any attempt to extract I_1 from Σ and I_0 .

The regime above 350 MeV, where the solid, long-dashed, and short-dashed curves all rise above the available data, is the region in which a

number of possible dibaryon resonances have been reported. Among the best candidates are the features with $T(J^\pi) = 1(3^- \text{ or } 2^-)$ at 423 MeV and $T(J^\pi) = 0(3^+ \text{ or } 1^+)$ at 572 MeV extracted by the TOKYO group from proton polarization data²⁷. Their description in terms of dibaryons has since been shown to be at least incomplete by some rather difficult photodisintegration measurements extending to very forward angles²⁸. This latter data is shown in Fig. 7, together with the calculations of Ogawa²⁷. The three diagrams included in these calculations are shown at the bottom of the figure. (a) corresponds to one-pion reabsorption (OPR) and yields the solid curves. The non-resonant (NR) terms, (a) and the Born term (b) are summed to produce the dashed curve, and the dashed-dot curve shows the effect of including (c) as a pair of dibaryons with $J^\pi = 3^-$ and 3^+ . At the most forward angle the data fall significantly below this dibaryon prediction. This persists at all of the energies that were measured and indicates the inadequacy of this model. On the other hand, one could have come to this same conclusion by simply comparing the predictions from this model for the photon asymmetry. These are shown for the same choice of $J^\pi = 3^-$ and 3^+ as the dotted curves in Figs. 4, 5, and 6, and clearly bear no resemblance to the data. In retrospect, it is not surprising that polarization data is much more sensitive to the presence of high-spin dibaryons than are measurements such as those of Fig. 7. This is particularly the case when resonances of opposite parity are allowed to interfere. Other choices for the TOKYO resonances such as $T(J^\pi) = 1(3^-)$ and $0(1^+)$ can be rejected with equal ease on the basis of the predicted asymmetry.

This leaves a puzzle as to the nature of the phenomena seen in proton polarization, and this puzzle is emphasized by the higher-energy asymmetry data. The calculations by Ogawa that are reported in Ref. 27 for the non-

resonant contribution, (a) + (b) in Fig. 7, include the same diagrams as those calculated by Laget²¹, and in fact Ogawa's NR calculation has the same general behavior, although somewhat smaller in magnitude, as the long-dashed lines of Figs. 4-5 in the region between 350-500 MeV where the two can be compared. In the expansion of the OPR graph, Laget has included no baryon resonances higher than the delta, and one might argue that the P_{11} (1470) and D_{13} (1520) resonances contribute significantly even down to 350 MeV owing to their long tails. However, in Ogawa's calculation the $\gamma N \rightarrow \pi N$ part of the OPR graph has been replaced by the experimentally determined one pion photoproduction amplitudes. This effectively takes into account all possible intermediate excitations of Δ or N^* resonances. Without resorting to very high-order processes, the only graph not included in either Ogawa's or Laget's calculations is the deuteron pole. This corresponds to promoting the deuteron to a highly excited compound state which then disintegrates, but its contribution is expected to be very small at high energies where the intermediate deuteron is highly off-shell. The calculated NR photon asymmetries are quite far from the data, even in sign, and there simply isn't much left to include other than a dibaryon of some sort. In short, the photon asymmetry data shows that the spin and energy assignments made by the TOKYO group are incorrect, but that the suggestion that one or more dibaryons are involved may not be.

Photodisintegration with polarized photons may in fact be a quite sensitive way of searching for dibaryons. The asymmetry function (Σ) is a sensitive test of hypothesized dibaryons, but this is not the most straightforward way to search for such phenomena since Σ is the ratio of two cross sections. Most dibaryons are predicted to be of high spin. Their presence should thus show up most dramatically in I_1 (Eq. 1), the polarization

dependent part of the cross section. But, once again, there are as yet no measurements of this term.

In addition to the TOKYO results, there are a number of other possible candidates for dibaryons. So far, the only one gaining wide acceptance is the 3F_3 at 2.26 GeV. This shows up in pp scattering and, although it appears at the same energy as the lower TOKYO candidate, it probably does not contribute to deuteron photodisintegration because of the different combination of quarks involved. However, there are other candidates that have been reported in $\gamma+d$ reactions such as the 40 MeV wide peak reported by the Saclay group in the $d(\gamma,p)X$ cross section at 2.23 GeV ($E_\gamma = 390$ MeV)²⁹, and the recent observation from Bonn of a very narrow (<5 MeV) peak in the pp invariant mass distribution from $d(\gamma,pp)\pi^-$ at 2.01 GeV³⁰. (If the latter were formed as an intermediate state in photodisintegration it would appear at a photon energy of 143 MeV.) However, the available asymmetry data of Figs. 4-6 is far too sparse and of too poor resolution to see effects due to either of these narrow features.

For high-spin dibaryons, probably the most striking reaction would be forward angle deuteron disintegration with circularly polarized γ rays. For example, the magnetic substates of a $J \geq 1$ dibaryon that contribute to such a reaction are shown in Fig. 8. The specific helicity of the incoming photon highly polarizes the dibaryon intermediate state, so that for positive helicity only $M=0$ or 1 substates contribute in the forward direction. As J increases the relative polarization of the dibaryon becomes quite large. (In fact, for $J=3$ this is almost as good as the ultimate extreme of polarizing the target as well as the beam.) With these conditions, the excitation function and the forward part of the proton angular distribution could be drastically different from those of background processes. There is of

course no data available on such reactions. At present, the only foreseeable source of circularly polarized γ rays in this energy region is the LEGS facility at Brookhaven. Measurements of circularly polarized photodisintegration at LEGS could open an exciting new chapter in the search for dibaryons.

2. Scope of the Experiment at LEGS

The LEGS (Laser Electron Gamma Source) facility at Brookhaven will provide intense low-background beams of monochromatic and polarized high-energy photons³¹. These γ rays will be produced by Compton backscattering laser light from the electrons circulating in the 2.5-3.0 GeV 'X-ray' storage ring of the National Synchrotron Light Source. A continuous range of energies will be available, with the photon energy determined by tagging the corresponding scattered electrons. The ring is presently operating at 2.52 GeV, and the LEGS Ar-Ion laser will provide up to 304 MeV γ rays. With only a slight reduction in intensity, the frequency-quadrupled Nd(YAG) will extend this range up to 386 MeV. By the time this experiment is underway, the X-ray ring will begin the shift to operation at 3.0 GeV. The LEGS γ -ray energy will then extend up to 420 MeV with the Ar-Ion laser, and up to 530 MeV with the Nd(YAG).

The photodisintegration of deuterium will be measured from the maximum LEGS energies down to about 50 MeV, to tie onto the high-quality LADON data. The proton will be detected at lab angles between about 10° and 160° . Cross sections and angular distributions will be measured in energy steps corresponding to the energy resolution of the tagging spectrometer (5 MeV). A complete set of high-statistics measurements will be performed with

linearly polarized photons so that I_0 and I_1 (Eq. 1) can be independently determined, along with their ratio, the asymmetry function E , throughout the entire energy range. The I_0 data will give a new measurement of the total cross section, while I_1 and E will provide one of the most stringent tests for models of the nuclear force. In addition, the high energy resolution I_1 excitation function will be used to search for the effects of dibaryons. Finally, to augment this dibaryon search, forward angle excitation functions will be taken with circularly polarized γ rays.

3. Experimental Apparatus

The $d(\gamma, p)$ reaction has a simple two body final state so that a measurement of either the γ -ray energy and proton angle, or the proton energy and proton angle determines the kinematics completely. This experiment will utilize two different detection systems. To avoid the background problems that plagued the measurements of Fig. 3, both systems are designed to overdetermine the kinematics as much as possible.

The γ -ray energy is related to the proton's kinetic energy T_p and angle θ_p by

$$E_\gamma = \frac{2 T_p}{1 + T_p/M_p C^2 (\cos \theta_p \sqrt{1 + 2 M_p C^2/T_p} - 1)} \quad (3)$$

(This neglects the mass difference between the neutron and proton, and the binding energy of the deuteron.) This relation is plotted in Fig. 9 for various values of T_p in the kinematic regime of this experiment. As is

evident here, for a fixed γ -ray energy the proton energy decreases with angle.

The first detector system is comprised of an array of 24 plastic scintillator modules each subtending 4° in θ and $\pm 12^\circ$ in ϕ . A portion of this array is shown around the liquid deuterium target in Fig. 10. Each module is a PHOSWITCH, consisting of a 2 mm layer of CaF followed by about 30 cm of plastic. (The lengths vary with angle to match the proton kinematics.) The CaF is completely insensitive to neutrons, and the comparison between its ΔE signal and the E signal in the plastic rejects other backgrounds as well as events in which a proton suffered a nuclear reaction in the detector. The latter effect becomes appreciable at high energies. The proton energy resolution of each module will be between 2% and 3% at energies above 150 MeV, but increases appreciably for lower proton energies (to about 7% at 50 MeV).

The second detection system is optimized for proton energies below 150 MeV, and consists of four silicon micro-strip detectors to accurately measure the proton angle, a 2.5 cm thick plastic ΔE detector and an 18 cm thick NaI E detector. The energy resolution of this system will be about 3% for 50 MeV protons. There is a low-energy threshold in the electron-tagging spectrometer of 170 MeV, and the second detection system will be particularly important in extending the forward-angle measurements below this threshold. Part of our goal is to go down to 50 MeV in photon energy to tie onto the high quality LADON data. In this low-energy region the kinematics will only be determined by the proton angle and energy measurements.

The propagation of errors in these measurements can be calculated by differentiating Eq. (3). The error in the reconstruction of the γ -ray energy is given by

$$(\Delta E_{\gamma})^2 = \left(\partial E_{\gamma} / \partial T_p \Delta T_p \right)^2 + \left(\partial E_{\gamma} / \partial \theta_p \Delta \theta_p \right)^2. \quad (4)$$

Typical values for the terms in this equation are listed in Table 1, assuming a proton energy resolution of 3%. The fifth column gives the angular resolution which would produce the same error in the γ -ray energy as the proton energy measurement. In other words,

$$\partial E_{\gamma} / \partial \theta_p \Delta \theta_p^* = (0.03) T_p \partial E_{\gamma} / \partial T_p. \quad (5)$$

The fractional error on the reconstruction of the γ -ray energy is almost a constant (4-5% with the indicated choices of $\Delta \theta_p^*$). At low energies, below the threshold of the tagging spectrometer, this ranges from about 1 to 3 times the resolution of the tagged beam (5 MeV, independent of energy). At high energies, where the γ ray is defined by its tagged electron, this would represent a very stringent overdetermination of the kinematics.

The micro-strip array of the second detection system has been designed to keep the error on the angle measurement significantly below the contribution to the error from the proton energy measurement, so that the values in Table 1 represent a worse case. The geometry of this system is detailed in Fig. 11, and an exploded view of its components is shown in Fig. 12. The array will be positioned very close to the target, with the first detector (red micro-strip #1 in Figs. 11 and 12) at about 6 cm. The pitch of the silicon strips is designed to provide 2° accuracy in θ_p and 8° in ϕ_p . The characteristics of the strips are summarized in Table 2. As shown in

Figs. 11 and 12, the printed circuit boards containing the strips are notched to allow this system of detectors to rotate to very forward angles.

The liquid deuterium in the target is cooled by a recirculating He refrigerator. The target cell is constructed out of 0.008 cm mylar and contains 3.8 cm of liquid, which represents 0.5% of a radiation length to the beam. The cell is wrapped with a total of 0.013 cm of aluminized-mylar superinsulation. The mylar window of the vacuum chamber, through which the protons must pass, is another 0.008 cm thick, so that the total thickness of mylar between the liquid deuterium and the detectors is 0.029 cm. The target cell and cryostat is designed to reduce bubbles in the liquid deuterium so that the effective thickness in the target can be maintained to 1%. The energy loss of the protons in the material of the target, the insulation and the vacuum chamber window is given in Table 3. By comparing the third and fifth columns, the greatest contribution clearly comes from the deuterium itself. In minimizing this energy loss our design makes use of the fact that the photon beam, imaging the electron beam from which it scattered, is a ribbon in the horizontal plane, 41 mm wide by 9 mm high at the position of the target cell. It is for this reason that the reaction plane is taken vertically, as shown in Fig. 10.

Backgrounds from atomic showering in the target have been estimated. The liquid deuterium volume, and the total amount of mylar around the target, represent 0.5% and 0.1% of a radiation length, respectively. The filled-target to empty-target ratio is thus expected to be 5:1 for atomic events. These are concentrated mostly within 5° of the beam, but even the rare large-angle events can be removed by a cut on the ΔE -E information.

4. Expected Counting Rates

Each of the 24 PHOSWITCH modules of the first detector array subtends a solid angle of about 29 msr. The solid angle of the second detector system is determined by the third micro-strip, and is about 160 msr. The 3.8 cm of liquid deuterium is equivalent to 0.62 g/cm^2 . The average differential cross section for the $d(\gamma, p)$ reaction will be about $5 \text{ } \mu\text{b/sr}$. The γ -ray beam intensity is expected to be about $2 \times 10^7 \text{ s}^{-1}$. At 2.5 GeV ring energy, the Nd(YAG) will produce a spectrum spread more or less uniformly from 180 MeV to 380 MeV. Since the energy resolution of the tagging spectrometer is 5 MeV, this represents $5 \times 10^5 \text{ s}^{-1}$ per 5 MeV resolution bin. These conditions imply an event rate of

$$R_1 = 96 \text{ (hr)}^{-1} (5 \text{ MeV})^{-1}, \quad (6a)$$

in each of the PHOSWITCH modules of the first detection system, and

$$R_2 = 532 \text{ (hr)}^{-1} (5 \text{ MeV})^{-1}, \quad (6b)$$

in the second detector system. As an example of what these rates imply, consider a measurement of the beam asymmetry

$$\Sigma = (N_{11} - N_{\perp}) / (N_{11} + N_{\perp}), \quad (7a)$$

where N_{11} and $N_{\perp}$ are the number of events measured with beam polarizations parallel and perpendicular to the reaction plane, respectively. It is straightforward to show that the uncertainty in this quantity is just

$$\Delta E/E = 1/\sqrt{N_{11}+N_{\perp}} \sqrt{1-E^2/E^2} . \quad (b)$$

From Figs. 4-6 the average value of E in the energy range of interest is about ± 0.3 . A 2% measurement of E then implies that $(N_{11}+N_{\perp}) = 2.5 \times 10^4$ events are needed. This would take 260 hours for each angle of the PHOSWITCH array, although in this case the $\Delta\theta=4^\circ$ bins of this detection system are probably a bit too fine and data from adjacent detectors could easily be added together, cutting this time estimate by a factor of 2 or 3. Similarly, the time required for a 2% measurement of E with the second detection system is about 48 hours per angle setting. In all cases, data at all tagged energies is collected simultaneously.

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Table 1: Contributing error terms in the reconstruction of the γ -ray energy from $d(\gamma, p)$.

θ_p (deg)	T_p (MeV)	$\partial E_\gamma / \partial T_p \times (0.03) T_p$ (MeV)	$\partial E_\gamma / \partial \theta_p$ (MeV/deg)	$\Delta \theta_p^*$ (deg)	$\Delta E_\gamma / E_\gamma$ (MeV/MeV) (%)
60	50	2.6	0.4	6.5	3.7/89.9 = 4.1%
	100	5.3	1.1	4.8	7.5/176.9 = 4.2%
	150	7.9	2.1	3.8	11.2/264.6 = 4.2%
	200	10.9	3.2	3.4	15.4/353.9 = 4.4%
	250	14.0	4.7	3.0	19.8/445.6 = 4.4%
	300	17.3	6.3	2.7	24.5/540.1 = 4.5%
90	50	3.3	0.6	5.5	4.7/105.6 = 4.4%
	100	7.4	2.0	3.7	10.5/223.9 = 4.7%
	150	12.5	4.1	3.0	17.7/357.1 = 5.0%
	200	19.4	7.7	2.5	27.4/508.4 = 5.4%

Table 2: Characteristics of silicon micro-strips.

Strip #	Active Area (mm x mm)	Thickness (mm)	No. of Strips	Strip Spacing (mm)	Distance from Target (mm)
1	40 x 40	0.300	200	0.2	60
2	42 x 50	0.500	24	2.0	70
3	40 x 40	0.300	200	0.2	100
4	42 x 50	0.500	24	2.0	110

Table 3: Proton energy loss.

T_p (MeV)	dE/dX in LD_2 (MeV/cm)	ΔE in LD_2 (MeV)	dE/dX in Mylar (MeV/cm)	ΔE in Mylar (MeV)
50	2.0	7.4	15.1	0.4
100	1.1	4.1	8.5	0.2
150	0.8	3.1	6.4	0.2
200	0.7	2.5	5.0	0.1
250	0.6	2.1	4.2	0.1
300	0.5	1.9	4.0	0.1

Figure Captions

- Fig. 1: The 90° asymmetry in $d(\gamma, p)$ at low energies (from ref. 7).
- Fig. 2: The angular dependence of the polarization sensitive (I_1) and insensitive (I_0) parts of the disintegration cross section (ref. 7).
- Fig. 3: Total cross sections for $d(\gamma, p)$ above pion threshold. Open squares are from ref. 12; inverted triangles are from ref. 13; open circles are from ref. 14; X's are from ref. 15; diamonds are from ref. 16; triangles are from ref. 17; solid squares are from ref. 18; and solid circles have been calculated from data in ref. 19. The dashed curve has been calculated by Laget (ref. 1), and the dot-dashed line by Arenhovel (ref. 3).
- Fig. 4: $d(\gamma, p)$ cross section asymmetry taken with linearly-polarized photons, and $\theta_p^{\text{cm}} = 45^\circ$. Data are taken from ref. 7 (dark-blue circles), and ref. 10 (red squares). Calculations are taken from ref. 1 (short-dashed curve), ref. 21 (long-dashed and dot-dashed curves), and ref. 22 (dotted curve).
- Fig. 5: As in Fig. 4 for $\theta_p^{\text{cm}} = 90^\circ$. Additional data taken from ref. 8 (light-blue circles), ref. 23 (purple crosses), and ref. 9 (green triangles). The solid orange curve below 150 MeV is from ref. 3, and above 200 MeV from ref. 20.
- Fig. 6: As in Fig. 5 for $\theta_p^{\text{cm}} = 135^\circ$.
- Fig. 7: Angular distributions for $\gamma d \rightarrow np$ taken with unpolarized photons (ref. 28). The solid curves are the calculated contributions from one-pion reabsorption (OPP), corresponding to the diagram labelled (a) at the bottom. The dotted curves are the predicted non-resonant (NR) contributions corresponding to diagrams (a) and (b). The dashed-dot lines show the effect of including a pair of dibaryon resonances ($J^\pi = 3^-$ and 3^+), corresponding to diagram (c).
- Fig. 8: Magnetic substates populated in $\gamma + d \rightarrow \text{DB}^{J \geq 1} \rightarrow np(0^\circ)$.
- Fig. 9: The relation between E_γ and the angle of the detected proton from $d(\gamma, p)$ for the indicated proton energies T_p .

Fig. 10: Side and front views of the liquid deuterium target and refrigerator cryostat. Also shown are the micro-strip-NaI detection system and 5 modules of the 24 segment PHOSWITCH array.

Fig. 11: Geometry and components of second detection system.

Fig. 12: Exploded view of silicon micro-strip array.

Fig. 1

Fig. 2

Fig. 3

Gamma Ray Energy (MeV)

Fig. 4

Gamma Ray Energy (MeV)

Fig. 6

Fig. 7

Fig. 8

PROTON LAB ANGLE (deg)

Fig. 10

Fig. 11

NaI(Tl) DETECTOR

15.24cm DIA. X 17.78cm LONG

PLASTIC SCINTILLATOR

2.5 cm THICK

MICRO-STRIP #4

42mmX50mm 24 STRIPS

MICRO-STRIP #3

40mmX40mm 200 STRIPS

MICRO-STRIP #2

42mmX50mm 24 STRIPS

MICRO-STRIP #1

40mmX40mm 200 STRIPS

Fig. 12