Double Polarization Measurements of Deuteron Photodisintegration between $E_\gamma = 4\, MeV$ and $20\, MeV$

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1. **Experiment Summary:**

Understanding the deuteron is a defining problem for nuclear physics. Its importance was recognized very early when J. Chadwick and M. Goldhaber wrote [1]

“Heavy hydrogen was chosen as the first to be examined, because the diplon has a small mass defect and also because it is the simplest of all nuclear systems and its properties are as important in nuclear theory as the hydrogen atom is in atomic theory.”

We are proposing to perform a detailed study of single and double polarization observables in deuteron photodisintegration using the HI\(\gamma\)S polarized photon beam, the polarized deuterium target under development at UVA and Duke University, and the *Blowfish* detector constructed by UVA and the University of Saskatchewan. The energy region to be spanned is from \(E_\gamma = 4\,\text{MeV}\) to \(E_\gamma = 20\,\text{MeV}\). This energy region was chosen for a combination of compelling scientific and technical reasons:

1) in this energy region the process is \(E1\) dominated, having evolved from being \(S=0\) resonance dominated at energies near threshold;

2) in this energy region the contribution to the Gerasimov-Drell-Hearn Sum Rule integrand is large and changes from negative to positive, resulting in strong cancellations;

3) in this energy region there are few precise data on neutron angular distributions and the most extensive and most widely cited data set has been found to contain a serious error;

4) in this energy region there are few measurements of beam asymmetries and emitted nucleon asymmetries, no measurements involving target asymmetries, and no measurements of double asymmetry observables;

5) in this energy region there is evidence from several measurements at several labs of anomalous behavior in the \(n-p\) final state; and

6) in this energy region one does not require an active target, a target from which a signal from a recoiling proton can be extracted.

The program of measurements will involve four combinations of beam and target polarization directions. The principal scientific foci of the proposed program are:

1) the Gerasimov-Drell-Hearn Sum Rule for the deuteron;

2) stringent testing of deuteron models using polarization observables; and

3) examining and clarifying anomalies in the \(n-p\) final state.

Our previously proposed approved measurements of the GDH integrand over a restricted energy range (HIGS-E-20-09) can be regarded as a subset of this proposal.
2. **Introduction:**

The Gerasimov-Drell-Hearn (GDH) sum rule was the original motivation for this program of study and it remains a high priority. It was the focus for the proposal (HIGS-E-20-09) that was submitted in 2009. That proposal was narrowly focused on three energies most critical to our understanding of the GDH integrand in this energy region. Subsequent analyses of our data as well as data and calculations in the literature have highlighted several discrepancies between theory and experiment in the two-nucleon system. Accordingly, we have decided to expand the scope of our planned measurements to address a broader set of issues.

The argument for submitting a very limited proposal in 2009 was to use the measurements as a “break in” experiment for the polarized target. However, we have concluded that the large amount of effort required to develop, instrument, install, and calibrate the polarized target and associated apparatus makes it more efficient to schedule longer running periods from the outset. Accordingly, we are proposing an expanded program of measurements, of which those proposed in 2009 will constitute one part.

**Spin Asymmetry and the GDH Sum Rule for Nucleons and the Deuteron:**

Spin-dependent Compton scattering of a photon with energy $\omega$ from nucleons can be expressed in the forward scattering limit as

$$A(\omega) \rightarrow f(\omega^2) \vec{e} \cdot \vec{\omega} + i \omega \vec{\sigma} \cdot (\vec{e} \times \vec{\omega})$$

where

$$f(\omega^2) = f(0) + f'(0) \omega^2 + O(\omega^4)$$

$$f(0) = -\frac{\alpha}{M}$$

$$f'(0) = \alpha + \beta \equiv \text{electric and magnetic polarizabilities}$$

$$g(\omega^2) = g(0) + g'(0) \omega^2 + O(\omega^4)$$

$$g(0) = -\frac{\alpha \beta}{2M}$$

$$g'(0) = \gamma_0 = \frac{\alpha_1 + \beta_1}{M} \equiv \text{forward spin polarizability}$$

while in the backward scattering limit

$$A(\omega) \rightarrow A_0^{\text{Born}} + (\alpha - \beta) \vec{e} \cdot \vec{\omega} + \left[ -\frac{2}{M} (\alpha - \beta) \vec{e} \cdot \vec{\omega} + i \gamma_x \vec{\sigma} \cdot (\vec{e} \times \vec{\omega}) \right] (\omega^3)$$

where

$$\gamma_x = \frac{1}{M} (\alpha_2 - \beta_2) \equiv \text{backward spin polarizability}$$

In 1954 M. Gell-Mann, M. Goldberger, and W. Thirring [2] showed that

$$g'(0) \equiv \gamma_0 = \frac{1}{4\pi^2} \int_{\omega_0}^{\infty} \frac{\sigma_{1/2} - \sigma_{1/2}}{\omega^3} d\omega$$
where $\sigma_{1/2} (\sigma_{3/2})$ is the total inelastic cross section when the target nucleon spin and the incident photon helicity are anti-parallel (parallel). Similarly, S. B. Gerasimov [3] in 1965 and, independently, S. D. Drell and A. C. Hearn [4] in 1966 showed that, under the very reasonable assumption that $g(\infty) = 0$, 

$$g(0) = -\frac{\alpha \kappa^2}{2M^2} = \frac{1}{4\pi^2} \int_{\omega_t}^{\infty} \frac{\sigma_{1/2} - \sigma_{3/2}}{\omega} d\omega,$$

the Gerasimov-Drell-Hearn Sum (GDH) Rule. Thus, the coefficients of the scattering amplitudes are related to integrals over the difference of total photoabsorption cross sections for target and photon spins parallel and antiparallel. Due to the $1/\omega$ weighting the integral for nucleons is dominated by pion production; in particular, it is dominated by the $\Delta_{33}$ resonance.

Recent measurements from Mainz and Bonn [5] on the proton at photon energies from 0.2 to 2.9 GeV yielded a value of $254 \pm 5 \pm 12 \mu b$ for the integral, exceeding the total expected value of $204 \mu b$. A negative contribution of $-28 \mu b$ is expected [6,7] from the near pion-threshold region below 0.2 GeV, leaving $-22 \mu b$ to come from higher energies if the sum rule is to be satisfied. Such contributions are possible, as indicated by some Regge models [8,9]. Last year the LEGS collaboration reported [10] measurements of $\bar{p}(\not\!{\gamma}, \pi^+)$ and $\bar{p}(\not\!{\gamma}, \pi^0)$ which indicated that no high energy contribution was required to achieve agreement. Parallel measurements of $\not\!{d}(\not\!{\gamma}, \pi^0)X$ gave lower cross sections than similar, albeit less precise, measurements made at Mainz [11]. The LEGS measurements indicated a discrepancy with calculations [12] and suggested that the GDH sum rule may not be satisfied for the neutron.

It was pointed out by Hosada and Yamamoto [13] and Gerasimov [3] that these arguments could be applied equally well to the deuteron. That is, the deuteron could be treated as the object of the sum rule rather than simply as a source of neutrons. The resultant "GDH" sum rule is given by

$$\int_{\omega_t}^{\infty} \frac{\sigma^d - \sigma^n}{\omega} d\omega = 4\pi^2 \alpha \left( \frac{\kappa_d}{m_d} \right)^2$$

where $\omega_t$ is the threshold not for pion production ($\approx 145$ MeV) but for photodisintegration ($\approx 2.2$ MeV), and $m_d (\kappa_d)$ is the mass (anomalous magnetic moment) of the deuteron. The sum rule values for the proton, neutron, and deuteron are
<table>
<thead>
<tr>
<th>Target</th>
<th>$\kappa$</th>
<th>$\int GDH$</th>
</tr>
</thead>
<tbody>
<tr>
<td>p</td>
<td>1.79</td>
<td>204.0 $\mu b$</td>
</tr>
<tr>
<td>n</td>
<td>-1.91</td>
<td>232.0 $\mu b$</td>
</tr>
<tr>
<td>d</td>
<td>-0.14</td>
<td>0.6 $\mu b$</td>
</tr>
</tbody>
</table>

The GDH integral for the deuteron can be separated into three pieces

$$
\int_{\omega_2}^{\omega_1} \frac{\sigma_p^d - \sigma_A^d}{\omega} d\omega = \int_{\omega_2}^{\omega_3} \frac{\sigma_p^d - \sigma_A^d}{\omega} d\omega + \int_{\omega_3}^{\omega_{\text{max}}} \frac{\sigma_p^d - \sigma_A^d}{\omega} d\omega + \int_{\omega_{\text{max}}}^{\infty} \frac{\sigma_p^d - \sigma_A^d}{\omega} d\omega = 0.6 \mu b
$$

The second term on the RHS was measured at LEGS, Jlab, and Bonn; the first term will be measured at H1\gamma S. For the high photon energies relevant to the third (unmeasured) piece we note that to the order of 0.1% the deuteron can be treated as the sum of a neutron plus a proton plus small corrections. Thus, if the sum rule is valid then the sum of the unmeasured pieces of the GDH integral for the neutron and proton must equal the unmeasured piece of the deuteron. Adding these to the measured pieces of the deuteron GDH integral should yield a value in agreement with the sum rule prediction. If such agreement is observed, then we can conclude that the sum rule is valid and calculating the "unmeasured" pieces of the neutron and proton integrals will be a test of nucleon models. If no agreement is observed, then something is wrong with the sum rule. Perhaps the assumption of unsubtracted dispersion relations?

We propose to measure the DHG integrand for the deuteron from 4 MeV to 20 MeV in 1 MeV steps. Indirect measurements of the GDH integrand below 4 MeV have shown reasonable agreement with theory [14]. The projected statistical precision is indicated in figure 2; the associated systematic uncertainties are expected to be approximately twice the statistical. It must be noted that if this were the only focus of the program of measurements, then the statistics (i.e., running time) would be excessive. However, the running times have been determined by the requirements of the second focus of the measurements. The high statistical quality of the GDH measurements are an added benefit. The curve represents the calculation of H. Arenhoevel [15].

**Tests of Deuteron Models via Single and Double Polarization Observables:**

Several measurements of angular distributions ($d\sigma/d\Omega$) for $d(\gamma,n)p$ or, equivalently, $d(\gamma,p)n$ have been reported for photon energies between 4 MeV and 20 MeV. As well, an even more limited number of measurements of angular dependence of the photon asymmetry ($\Sigma$) and the emitted

![GDH Sum Rule for Deuteron](image-url)
neutron polarization \( P_y \) have been reported. We will not attempt to provide a compendium of these. Rather, we will address selected data sets to illustrate the current state of affairs and to highlight specific issues. It should be noted that the only sets of simultaneous measurements of \( d\sigma/d\Omega \) and \( \Sigma \) are from HI\( S \) at 4, 6, 10, [16] 14, and 16 MeV [17].

First, differential cross sections alone can provide inconsistent indications of the constituent components of the photodisintegration process. This is illustrated by comparing multiple data sets taken at various laboratories at various times with a beam energy of 20 MeV. The differential cross section for the case of a linearly polarized photon beam and unpolarized target can be expanded in an orthonormal Legendre basis as

\[
\frac{d\sigma}{d\Omega} = \frac{\sigma_{\text{tot}}}{4\pi} \left[ 1 + \sum_{n=1} a_n P_n^\gamma (\cos \theta) + P_\gamma^2 \sum_{n=2} e_n P_n^2 (\cos \theta) \cos 2\phi \right]
\]

where \( P_\gamma^\gamma \) is the degree of photon (linear) polarization.

Figure 3 shows the recent results of Kucuker et al., [18] the 1974 results of Skopik et al., [19] the results of an analysis of earlier data by De Pascale et al., [20] and the calculation of Arenhoevel. [15] The \( a_n \) coefficients fit to each are shown in table 1. Note that the \( d_4 \) in the De Pascale analysis was taken from theory, not fit to data. Note also that no uncertainty could be attached to the De Pascale result as no error matrix was available.

It is to be noted that the data of Kucuker et al. are closer to the calculation of Arenhoevel than the other two, but the dominant expansion coefficient differs more from Arenhoevel's value than either of the other two. That the curve fit to the Kucuker et al. data still agrees best with that of Arenhoevel implies that the orthonormality of the expansion basis is broken by the discreteness of the data. This example illustrates clearly the need to further constrain the description of the data by the use of at least one polarization observable. A truly reliable extraction of parameters requires multiple polarization observables.
Table 1. Expansion coefficients for differential cross section at $E_\gamma = 20\,MeV$.

<table>
<thead>
<tr>
<th>Coefficient</th>
<th>De Pascale et al.</th>
<th>Skopik et al.</th>
<th>Kucuker et al.</th>
<th>Arenhoevel</th>
</tr>
</thead>
<tbody>
<tr>
<td>$a_1$</td>
<td>$-0.196 \pm 0.022$</td>
<td>$-0.269 \pm 0.009$</td>
<td>$-0.154 \pm 0.002$</td>
<td>$-0.165$</td>
</tr>
<tr>
<td>$a_2$</td>
<td>$-0.879 \pm 0.029$</td>
<td>$-0.902 \pm 0.016$</td>
<td>$-0.811 \pm 0.003$</td>
<td>$-0.872$</td>
</tr>
<tr>
<td>$a_3$</td>
<td>$0.190 \pm 0.017$</td>
<td>$0.257 \pm 0.020$</td>
<td>$0.170 \pm 0.003$</td>
<td>$0.150$</td>
</tr>
<tr>
<td>$a_4$</td>
<td>$-0.19$</td>
<td>$-0.024 \pm 0.024$</td>
<td>$-0.035 \pm 0.004$</td>
<td>$-0.180$</td>
</tr>
</tbody>
</table>

Second, the most extensive and most widely cited set of angular distributions in the $E_\gamma = 4\,MeV$ to $20\,MeV$ region is that of Stevenson, Holt, McKeown, and Specht. [21] Unfortunately, these data have a serious problem as do their measurements of $d\,(\gamma,\bar{n})\,p$. In both of these measurements an untagged bremsstrahlung beam was incident on a $3.8\,cm$ long, $2.5\,cm$ high, and $0.2\,cm$ wide $CD_2$ target. The geometry was chosen to maximize the target thickness seen by the photon beam while minimizing the thickness traversed by emitted neutrons. However, as a result the photons striking the target were all emitted in a thin vertical line which meant that they were polarized in the horizontal direction to an energy-dependent degree. Figure 4 shows the average polarization of the photons striking the target. This polarization of the beam affected not only the measurements themselves but the detector calibrations in ways that were not possible to reconstruct more than 20 years after the measurements. [22] One way to evaluate the impact is to extract from the data the $a_1$, $a_2$, and $a_4$ Legendre coefficients. The $a_1$ and $a_3$ coefficients are, for angular momentum reasons, very closely coupled, with $a_1$ being very close to $-a_3$. [23] This relationship has been confirmed in a wide range of measurements including all those made at HI$\gamma$S. In extracting Figure 4. Photon polarization in ANL experiment

Figure 5. Legendre coefficients from ANL data.
$a_1$, $a_2$, and $a_4$ the relationship was imposed. The results are shown in figure 5. The energy dependences of the coefficients bear no resemblance to the calculations of Arenhoevel, despite the fact that the measured cross sections are actually not that far from the calculated values. It should also be noted that the values of $a_2$ and $a_4$ take on truly unphysical values.

The conclusion to be drawn from these analyses is that the existing data do not place constraints on model calculations adequate to test them at more than the most basic level. In order to test these models at a truly meaningful level additional, complementary data are required.

The full expression for the differential cross section is [24]

$$
\frac{d\sigma}{d\Omega} = \frac{\sigma_{\text{tot}}}{4\pi} \left[ 1 + P^d_1 \Sigma^l (\theta) \cos 2\phi + \sum_{I=1,2} P^l_1 \sum_{M=0}^I \left( T^l_{IM} (\theta) \cos \left( M (\phi_d - \phi) - \delta_{11} \pi / 2 \right) 
+ P^r_{c,T} (\theta) \sin \left( M (\phi_d - \phi) - \delta_{11} \pi / 2 \right) \right) d^l_{M,0} (\theta_d) 
+ P^r_{c,T} \sum_{M=-1}^I \left( T^l_{IM} (\theta) \cos \left( \psi_M - \delta_{11} \pi / 2 \right) d^l_{M,0} (\theta_d) \right) \right]\right]
$$

where $P^r_1 (P^c_1)$ is the degree of linear (circular) polarization in the beam, $P^d_1$ is the degree of deuteron polarization, $\Sigma^l (\theta)$ is the photon asymmetry for linearly polarized photons, $T^l_{IM} (\theta)$ is the target [photon-target] asymmetry, $\psi_M = M (\phi_d - \phi) + 2\phi$, $d^l_{M,0} (\theta_d)$ is the reduced rotation matrix element, $(\theta, \phi)$ is the neutron emission direction with respect to the photon direction, and $(\theta_d, \phi_d)$ is the target polarization direction with respect to the photon direction. While it is theoretically possible to orient the vector-polarized target in arbitrary directions and extract all terms through $I=1$, the constraints of the target geometry limit us to $\theta_d = 0$ and $\pi / 2$; the large coverage of the Blowfish renders the choice of $\phi_d$ essentially irrelevant. Using both linearly and circularly polarized photons we plan to make four sets of measurements:

$$
\frac{d\sigma}{d\Omega} = \frac{\sigma_{\text{tot}}}{4\pi} \left[ 1 \pm P^d_1 P^c_1 T^l_{1,0} (\theta) \right]
$$

$$
\frac{d\sigma}{d\Omega} = \frac{\sigma_{\text{tot}}}{4\pi} \left[ 1 + P^d_1 \left( T^l_{1,1} (\theta) \sin (\phi - \phi_d) \pm P^c_1 T^l_{1,1} (\theta) \cos (\phi - \phi) \right) \right]
$$

$$
\frac{d\sigma}{d\Omega} = \frac{\sigma_{\text{tot}}}{4\pi} \left[ 1 + P^r_1 \Sigma^l (\theta) \cos 2\phi \pm P^d_1 P^c_1 T^l_{1,0} (\theta) \sin (2\phi) \right]
$$

$$
\frac{d\sigma}{d\Omega} = \frac{\sigma_{\text{tot}}}{4\pi} \left[ 1 + P^r_1 \Sigma^l (\theta) \cos 2\phi + P^d_1 \left( T^l_{1,1} (\theta) \sin \cos (\phi - \phi_d) \pm P^c_1 T^l_{1,1} (\theta) \sin \cos (3\phi - \phi_d - T^l_{1,1} (\theta) \sin \cos (\phi + \phi_d) \right) \right]
$$

where the subscripts on the cross section represent beam (circular, linear) and target (longitudinal, transverse) polarization, respectively. We will therefore measure seven linearly independent polarization observables:
\(\Sigma^l, T_{1,1}, T_{1,0}, T_{1,1}^c, T_{1,-1}^c, T_{1,0}^l, T_{1,1}^l,\) and \(T_{1,1}^l.\)

plus the unpolarized differential cross section. Each of these is a function of \(\theta,\) so the precision with which we will measure each term for a given \(\theta\) will vary greatly. The differential cross sections will be determined to a statistical precision of better than 1%. By making this statistical uncertainty so small, we will have an excellent opportunity to analyze systematic irregularities and uncertainties. The functions \(\Sigma^l\) and \(T_{1,1}\) each appear in multiple beam-target combinations, the results of which can be summed. Accordingly, they will be determined to a statistical precision approaching 1%. Each term \(T_{1,1}^l\) (with the exception of \(T_{1,1}^l\) which is expected to be essentially zero) has, for most incident photon energies, angles at which its contribution is several percent. For these angles we will be able to determine them with a statistical precision of 3-5%. This set of eight (seven if \(T_{1,1}^l\) is as small as expected) observables will permit testing of deuteron models to a degree never before possible.

We based our projections for time required to run the experiment on beam polarizations of almost 100\%, target polarizations of 50\%, and obtaining an average of 1\% statistics per detector per polarization combination. Based on our experience with measurements using H\(\gamma S\) and the Blowfish, we believe that this will enable us to evaluate and, where possible, compensate for systematic irregularities and extract a (semi-) complete data set adequate to stringently test the most sophisticated models of this most basic nuclear system.

**Anomalies in the n-p Final State:**

Many discrepancies, beyond those mentioned here, exist between measurements and calculations of deuteron photodisintegration. For the purpose of illustration we address one in particular; that is, the anomalous behavior in the \(N-N\) system near a relative energy of \(E_{rel} = 10\text{ MeV}.\)

In 2000 L.V. Fil'kov et al. [25] reported the existence of sharp peaks in the missing mass spectra in the reaction \(d(p,p')X\) at the Moscow Meson Factory (MMF). They identified these peaks as evidence of narrow, bound, \(T=1\) states of two neutrons with energies of 1904 MeV and 1925 MeV: dibaryons. Such states had been predicted by Martem'yanov and Shchepkin [26] as well as Wagner et al. [27], with the narrow widths being attributable to the facts 1) that the states did not have enough energy to decay through pion emission and 2) that they were Pauli blocked from decaying into two neutrons. They could only decay electromagnetically with the emission of an accompanying \(\gamma.\)

We have data from LEGS [28] on the photodisintegration of deuterium using polarized photons. These data were analyzed for evidence of the production of such states via the reaction:

\[
d(p,\pi^+\pi^-)n\equiv n(p,\pi^+\pi^-)\gamma.
\]

where the \(n\) and \(\gamma\) in the square brackets were detected but their energies were not determined to a
usable precision. Consequently, they were not used in the subsequent analysis. It was surmised that
the reaction we observed proceeded via:
\[ \tilde{\gamma} + d \rightarrow D^* + \pi^+ \]
\[ \rightarrow n + n + \gamma' \]

We observed that when the \( \pi^+ \) was emitted parallel to the polarization of the incident \( \tilde{\gamma} \), two peaks were observed in the missing mass spectrum at the same energies that Fil'kov et al. saw peaks (Fig. 6) and a third within 3 MeV of the energy at which Fil'kov saw a peak. A possible fourth peak near 1.887 GeV fell just below the missing mass range covered by Fil'kov et al. No discernible peaks were observed when the \( \pi^+ \) came out perpendicular to the \( \tilde{\gamma} \) polarization.

It should be noted that the peak at 1.947 GeV fell just at the edge of our acceptance. In addition, it is underlaid by a background with an assumed shape that is varying quite sharply. As a result its position and amplitude must have an extra uncertainty attached to them. Consequently, the 3 MeV difference between the location of the peak in our spectrum and that of the peak in Fil'kov's spectrum should probably not be considered significant. A similar degree of uncertainty should be attached to the structure at 1.887 GeV.

It is interesting to note the sequence of energies at which peaks were observed in the missing mass spectrum (Table 2). This is, of course, just the spectrum of states one would expect from a linear quantum harmonic oscillator \( [E_n = (n + 1/2)\hbar \omega] \) with \( \hbar \omega = 20 \text{ MeV} \). In view of the single axis defined in the two-body problem such a spectrum might not be unexpected.

Given the checkered history of the “dibaryon” we were disinclined to make a definitive statement about the significance of these peaks. However, try as we did (changing a variety of cuts, selecting different ranges of \( \pi^+ \) emission angles, changing thresholds, varying the way the photon tagging data were treated, etc.), we could not make the peaks disappear.

In 1972 Nath et al. [29] made measurements of the differential polarization of neutrons emitted in the reaction \( d (\gamma, \tilde{n}) p \).

They found that for neutrons emerging at 45° there is a clear, sudden change in the polarization at around \( E_\gamma = 12−13 \text{ MeV} \) (see Fig. 7), corresponding to a relative n-p energy of about 9-10 MeV. This sharp break is not reproduced by any calculation. It should be noted that the calculations use the Fermi-Watson Theorem to constrain the phases of the matrix elements to be the same as those observed in n-p scattering, based on the assumption that the only

Table 2. Energies of n-p structures.

<table>
<thead>
<tr>
<th>State</th>
<th>Energy</th>
<th>Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Two neutrons</td>
<td>1.878 GeV</td>
<td></td>
</tr>
<tr>
<td>Peak # 1</td>
<td>1.887 GeV</td>
<td>9 MeV</td>
</tr>
<tr>
<td>Peak # 2</td>
<td>1.906 GeV</td>
<td>19 MeV</td>
</tr>
<tr>
<td>Peak # 3</td>
<td>1.926 GeV</td>
<td>20 MeV</td>
</tr>
<tr>
<td>Peak # 4</td>
<td>1.947 GeV</td>
<td>21 MeV</td>
</tr>
</tbody>
</table>

Figure 7. Anomalous behavior in \( d (\gamma, \tilde{n}) p \).
exit channel available is simply \( n + p \). Given the small degree of mixing between final states of
different angular momentum, this leads to a smooth variation of the polarization asymmetry throughout
this region of photon energy.

The shape of the observed break is exactly that of a Wigner or unitary cusp which can occur
when a new reaction channel becomes available. Such cusps have been observed in neutral pion
photoproduction from the proton \([30]\) when the incident photon energy corresponds to the \( \pi^+ \)
photoproduction threshold.

Returning now to the data of Stevenson et al. in figure 5, one sees a sharp discontinuity in the
energy dependence of each of the three coefficients: \( a_1 \), \( a_2 \), and \( a_4 \). In all three cases it occurs at
exactly the same photon energy, 12 MeV. The unaccounted for effects of the beam polarization vary
smoothly across the energy range so they cannot be the source of such structure. That the \( a_2 \) and \( a_4 \)
coefficients should show similarities is not surprising as the corresponding Legendre polynomials are of
the same parity so the coefficients are strongly coupled in such a sparse data set, especially one in which
the beam polarization effects negate the argument that the angular distribution should be describable in
terms of the first few Legendre functions. That the \( a_1 \) coefficient shows an identical behavior at an
identical energy suggests an underlying origin, perhaps the onset of a process hitherto not included.

Further evidence for anomalous behavior in the \( n-p \) system is found in our measurements of
\( d(\vec{\gamma}, n) p \) at HIGS with \( E_\gamma = 6, 10, 14, \) and \( 16 \) MeV. At each energy the expansion coefficients \( a_1 \), \( a_2 \),
\( a_3 \), \( a_4 \), \( e_2 \), \( e_3 \), and \( e_4 \) were extracted from the data and found to be in reasonable but not precise
agreement with the calculations of Arenhoevel. Each coefficient can be expressed in terms of complex
transition matrix elements (TMEs), with the phase determined by \( n-p \) scattering and the Fermi-Watson
Theorem. \([31, 32]\) In principle, an infinite number of TMEs contribute, but one can incorporate most of
the physics using seven: \( ^1S_0, ^3P_0, ^3P_1, ^3P_2, ^3D_1, ^3D_2, ^3D_3 \). These now constitute “effective” TMEs.
The included \( P \) amplitudes are by far the largest odd \( - \ell \) contributors but the included \( S \) and \( D \)
amplitudes are less dominant among the even \( - \ell \) components. When the coefficients from
Arenhoevel’s calculation were fit to the seven amplitudes there were four mathematically equivalent
families of solutions. Significantly, all families had the same maximum value for \( ^1S_0 \), but different sets
of values for the \( P \) and \( D \) amplitudes, with all \( P \) amplitudes being positive and each family having a
different set of signs for the \( D \) amplitudes. This was not unexpected for the \( D \) amplitudes as the
amplitudes enter the expressions for the coefficients with various signs so cancellations among
amplitudes, including neglected amplitudes, could result in a negative “effective” amplitude. We then
applied the same fitting to the data. The combined results are summarized in Table 3.

Two points are striking. First, the four families of solutions for both the data and Arenhoevel’s
calculation at each energy yield \( ^3P_0 \) (as well as \( ^3P_1 \) and \( ^3P_2 \) not shown) amplitudes that are in almost
perfect agreement. Second, at \( 10 \) MeV the signs of the \( D \) amplitudes agree perfectly whereas at \( 14 \) MeV
they disagree in every case. Although not shown, this pattern is consistent in the cases of \( E_\gamma = 6 \) MeV
and \( E_\gamma = 16 \) MeV. That is, below \( E_\gamma = 12 \) MeV the TME phases imposed by the Fermi-Watson
Theorem are reproduced by the data. Above \( E_\gamma = 12 \) MeV the even \( - \ell \) TMEs, including possibly some
omitted from the expansion, have changed sufficiently to alter the phase of the effective TME by \( \pi \).
While admittedly not conclusive, these data suggest that something is happening at or near $E_γ = 12 \text{ MeV}$ that is not accounted for by theory.

<table>
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<tr>
<th></th>
<th>$E_γ = 10 \text{ MeV}$</th>
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<th>$E_γ = 14 \text{ MeV}$</th>
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<td>$^3D_{1,2,3}$</td>
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<td>0.59</td>
<td>(+,−,+)(+,−,+)</td>
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<td>0.43</td>
<td>0.41</td>
<td>(+,−,+)(+,−,+)</td>
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Table 3. Effective Transition Matrix Elements

Lending support to the observation that something anomalous is happening in the $N-N$ system at rather low energies are observations by Huisman et al. [33] of $p-p$ bremsstrahlung at an incident proton energy of 190 MeV. They observed that the best available theories could not reproduce the angular distributions, with the discrepancy being dependent on the energy of the final $p-p$ state. Figure 8 shows this discrepancy. Note that there is a sharp increase in the discrepancy at about 12 MeV. This energy is for the $p-p$ system; to obtain the corresponding energy at which such a discrepancy would appear in the $n-p$ system one must subtract the Coulomb energy, on the order of 1-2 MeV. This yields an energy, $E_{rel}$, of about 10 MeV, close to the energy of the discontinuity in the $d(\gamma,\bar{n})p$ data discussed above. A theoretical analysis of the $pp \to pp\gamma$ results and discrepancies by Cozma, Tjon, et al. [34] yielded the conclusion that “at least an important part of the problem resides in the description of the low energy $NN$ interaction.” If there is a significant problem with our understanding of the $N-N$ interaction at such a low energy, the implications could be dramatic. Perhaps it is the source of the longstanding $A_γ$ problem in light nuclei? [35] A detailed study of the photo-disintegration of the deuteron promises to shed much light on this issue.

It is interesting to note that the discrepancies at an $E_{rel}$ of about 10 MeV appear to manifest themselves as peaks in processes in which a pion is created but as discontinuities when only photons are involved. Accordingly, it is important to investigate them with both reactions involving only photons as proposed here as well as with reactions involving pions. A proposal to study the reaction

![Figure 8. Discrepancy in $pp \to pp\gamma$](image)
In summation, we have six independent data sets all indicating that some hitherto unexplained interaction is occurring at or about an energy of $E_{\text{rel}} = 9 - 10 \text{MeV}$ in the $n$-$p$ (slightly higher in the $pp$) final state. Given the fundamental importance of the two-nucleon system to nuclear physics it is worth pursuing. The broad set of polarization observables we propose to measure should greatly clarify this situation.

**Summary:**

The principal scientific foci of the proposed program are 1) measuring the spin asymmetry of the GDH Sum Rule for the deuteron, 2) stringent testing of deuteron models using polarization observables, and 3) examining and clarifying anomalies in the $n$-$p$ final state. The set of unpolarized, single, and double polarization observables to be obtained will enable us to make strong contributions to all three.
3. **Experiment Description:**

We will utilize the polarized deuteron target currently being assembled at the University of Virginia by Don Crabb *et al*. Transverse target polarizations will be possible with the addition of the magnet coils designed and built by Pil-Neyo Seo, formerly of Duke University and the University of Massachusetts and now at the University of Virginia. We will use the *Blowfish* detector to measure the emitted neutrons. We will use the University of Saskatchewan’s 5-paddle photon monitor, [36] calibrated against a NaI detector, to measure the incident photon flux. We will use the University of Saskatchewan LUCID-ROOT system for data acquisition.

Given the broad range of beam (and therefore neutron) energies, emission angles, and polarization combinations only average estimates of expected uncertainties can be given. First, the beam time was determined so as to provide no worse than 3% statistical precision in any *Blowfish* cell for any given beam-target polarization combination. The average statistical precision will be about 1% per cell. The fiber-optic gain monitoring system maintains the detector efficiencies to the level of 3%. In the fall of this year we will be investigating the use of newly developed flash ADC’s to process the *Blowfish* signals. If, as anticipated, they result in improved real-time characterization of the detector response we will instrument the entire *Blowfish* with FADCs. The large body of available data on the total photodisintegration cross section [37] has an associated uncertainty of less than 2%. We therefore have the option of normalizing our results to these data. The symmetry of the *Blowfish* detector and our ability to rotate it will limit uncertainties due to mechanical variations. Moreover, we have demonstrated that with the large coverage of the *Blowfish* we can measure and correct precisely for even small irregularities such as the 1.4 mm displacement of the photon beam centroid during the measurements of ref. [16].

The 5-paddle photon monitor has been shown able to measure incident beam fluxes to a precision of 2%. We will also have the option of normalizing the overall luminosity using the Compton scattered photons detected in the (mostly) forward detectors.

The polarization of the target will be determined to a precision of about 3% and that of the incident beam to about 1-2%.
4. **Run Plan:**

The schedule for the experiment is driven by that of the polarized target. It is currently estimated that the target will be ready for installation at HIγS during the first quarter of 2011. Upon installation, we would propose an “engineering” run using circularly polarized photons at a convenient energy followed by a several month period to analyze the data and address any problems that may have been revealed. Production running would begin thereafter. The comparatively high overhead associated with installing the target suggests that subsequent running periods should involve about 200 hours per run.

The beam time estimate was based on an effective target length of 2 cm of deuterated butanol and an average deuteron polarization of 50%. An additional 10% is requested for target repolarization, detector rotations, and flux monitor calibrations.

<table>
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<th>( E_r ) [MeV]</th>
<th>( \sigma_{_{\text{tot}}} ) [mb]</th>
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</table>

- Production beam time: 824
- Calibrations & polarizations: 82
- Total beam time request: 906
References:

[18] S. Kucuker, PhD dissertation, Department, University of Virginia (expected 2005).


[28] A. Cichocki, PhD Dissertation, Department of Physics, University of Virginia, (2003).


