Low Energy Deuteron Photodisintegration

F. Butaru,[1] R. Gilman (spokesperson),[2,3] C. Glashausser,[2] D. Higinbotham,[3]
X. Jiang,[2] E. Kuchina,[2] G. Kumbartzki,[2] J. Lister,[4] Z.-E. Meziani,[1] S. Nanda,[3]
R. Ransome,[2] B. Reitz,[3] A. Saha,[3] A. Sarty (spokesperson),[4] B. Sawatzky,[1]
P. Solvignon,[1] E. Schulte,[2] S. Strauch (spokesperson),[5] and H. Yao[1]

[1]*Temple University, Philadelphia, Pennsylvania 19122, USA*
[2]*Rutgers, The State University of New Jersey, Piscataway, New Jersey 08854, USA*
[3]*Thomas Jefferson National Accelerator Facility, Newport News, Virginia 23606, USA*
[4]*St. Mary's University, Halifax, Nova Scotia, CANADA B3H 3C3*
[5]*George Washington University, Washington, DC, USA*

(Dated: June 28, 2005)

We propose to study deuteron photodisintegration recoil polarization observables in the region $E_\gamma \approx 400$ MeV. This is an energy range in which the available hadronic calculations are starting to disagree with the available data, in particular for the induced polarization p_y. This disagreement is the most prominant precursor for the breakdown of these calculations in the GeV region. But the existing polarization data are arguably lousy. Our goal is to provide a high quality, systematic data set that might allow theoretical studies to identify what elements are missing from the calculations. This request is being made contingent on, first, a special low energy run period during which G0 takes low energy one pass beam to measure backward angle data, and, second, the ability to run a low current, low energy - also one pass beam - experiment in Hall A at the same time as the G0 experiment. The time request is for 14 days of running with typically 10 μA of polarized beam.
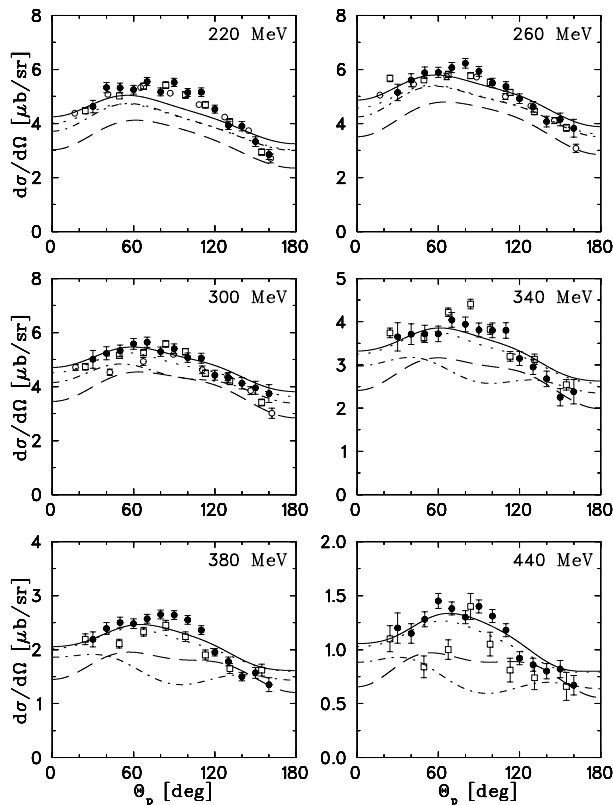
FIG. 1: Comparison of data and calculations for the differential cross section at several beam energies, taken from [4]. The data should be compared to the solid curve. The generally good agreement of theory and data, and the unsatisfactory quality of some of the measurements, is evident.

MOTIVATION

Deuteron photodisintegration has been studied experimentally for over 70 years; polarization observables have been studied for over 40 years. In recent years, the dominant interest has been in the GeV region. The systematics of the high energy cross sections and polarizations combined with theoretical studies make it clear that, first, it is difficult to construct a satisfactory hadronic model for the reaction at high energies, and second, quark-based model calculations are in qualitatively good agreement with the available data. A review of deuteron photodisintegration, focusing on the high energy data and theories, can be found in [1].

One of the reasons for the focus on high-energy photo-disintegration is the generally good agreement of modern calculations with the existing lower-energy data set, up to several hundred MeV. Schwamb and Arenhövel in particular have developed a detailed modern theory of photodisintegration, detailed in a series of articles [2–4] which agrees well with existing data, mainly as a result of improvements in the treatment of relativistic effects and the use of modern high-precision NN potentials.
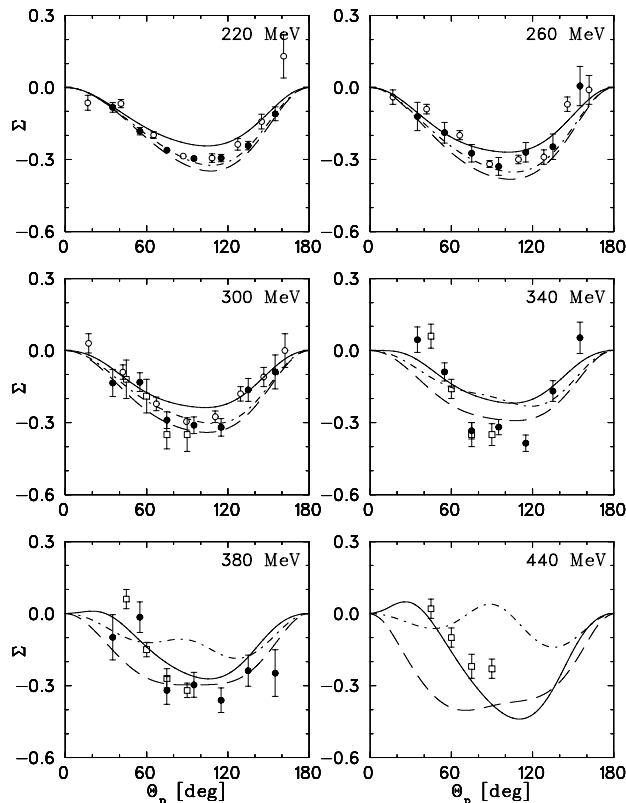
FIG. 2: Comparison of data and calculations for the Σ asymmetry at several beam energies, taken from [4]. The data should be compared to the solid curve. The generally good agreement of theory and data, and the unsatisfactory quality of some of the measurements, is evident.

Numerous examples can be found of this agreement. Figure 1 shows the angular distributions for cross sections in the few hundred MeV region. There is generally good agreement between calculation and data. Figure 2 shows angular distributions for the Σ asymmetry, the cross section asymmetry for linearly polarized photons, in the few hundred MeV region. There tends to be good agreement between the theory and the measurements, although in some cases the measurements are not of the quality one would like.

Figure 3 shows angular distributions for six observables, the differential cross section, Σ, the polarized target asymmetry T, and the induced polarization p_y, at an energy of 300 MeV. An older theoretical calculation, from [5], is also included. Again there is generally good agreement between data and theory, with perhaps a hint of problems in the induced polarization. The data appears to be flatter in shape than the calculation, and there is no clear minimum near $\theta_{cm} = 90°$.

A similar view at 450 MeV is shown in Fig. 4. Here again there is qualitative agreement for three of the observables. The hint of trouble in the induced polarization has now turned into a full disagreement, as Schwamb and Arenhövel predict the polarization is small near $\theta_{cm} = 90°$, rather than maximum. Apparently the shape of the p_y angular distribution changes, going from either flat or having a slight minimum near $\theta_{cm} = 90°$ at 300 MeV, to have a pronounced peak in the polarization near $\theta_{cm} = 90°$ at 450 MeV.

FIG. 3: Comparison of data and calculations for six observables at an energy of 300 MeV. The solid calculation is from Schwamb and Arenhövel; the dashed line is from Kang, Erb, Pfeil, and Rollnik. The generally good agreement of theory and measurements is evident, except for hints in the poor p_y data of disagreements.
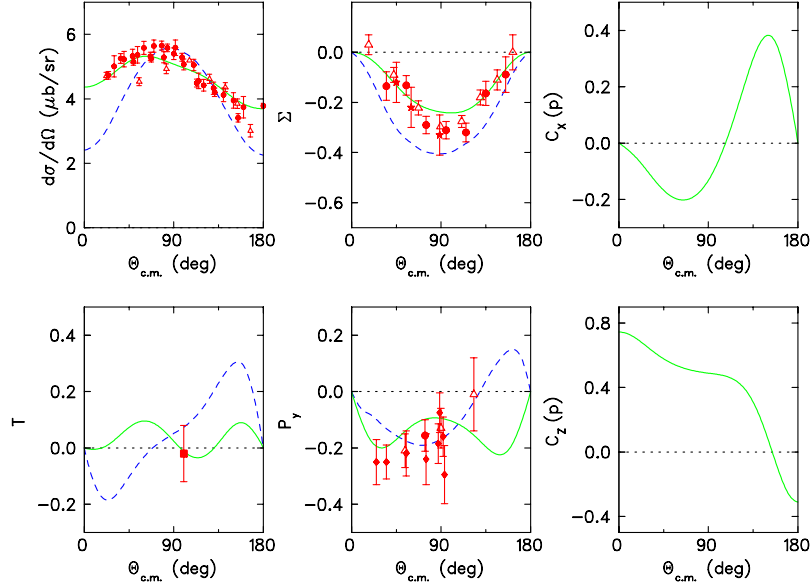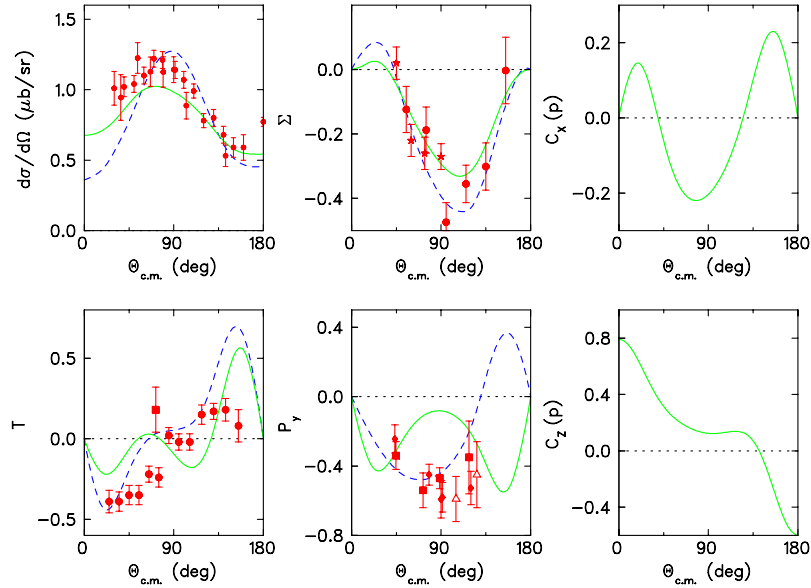

FIG. 4: Comparison of data and calculations for six observables at an energy of 450 MeV. The solid calculation is from Schwamb and Arenhövel; the dashed line is from Kang, Erb, Pfeil, and Rollnik. The cross section and polarized target asymmetry data are qualitatively reproduced. The Σ asymmetry data are well reproduced despite some outlier points. The disagreement in p_y, which increases with energy, is now clear.
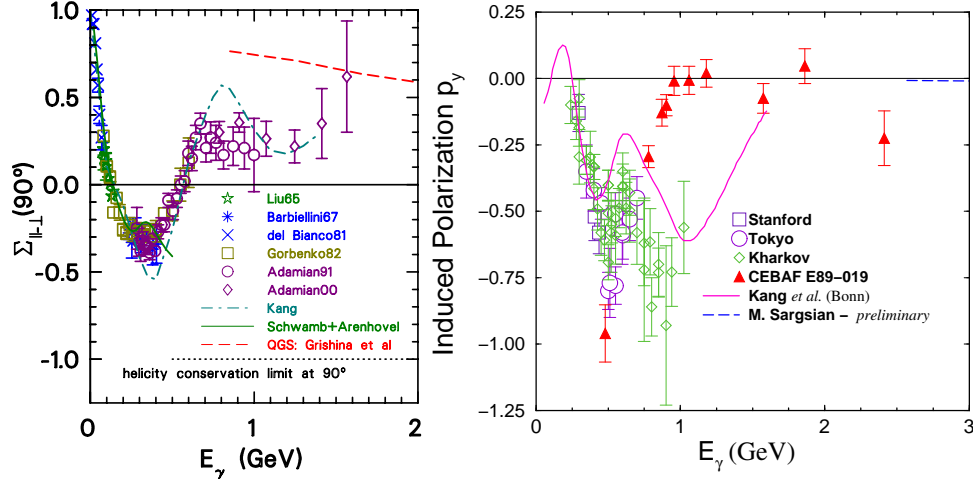
FIG. 5: Excitation functions at $\theta_{c.m.} = 90°$ for the Σ asymmetry (top) and induced polarization p_y (bottom). The Σ asymmetry data are well reproduced by Shwamb and Arenhövel up to about 450 MeV, and are qualitatively reproduced by Kang *et al.* The induced polarization starts to diverge from calculations at about 300 MeV. The high energy Kharkov points suffered from large backgrounds, and the generally poor quality of the data are apparent.

Another view of the data is provided by excitation functions at $\theta_{cm} = 90°$, shown in Fig. 5. The Schwamb and Arenhövel calculation accounts well for the Σ asymmetry data almost over its entire energy range, up to 500 MeV. The older Kang *et al.* calculation also generally agrees with the data, over a much wider energy range. The induced polarization data in contrast are clearly of much poorer quality than the Σ asymmetry data, as they exhibit large uncertainties and poor overlap in the few hundred MeV region. The Kang *et al.*calculation starts diverging from the data near 300 MeV. The Schwamb and Arenhövel calculation (not shown here) is worse, as it predicts the induced polarization at $\theta_{cm} = 90°$ stays nearly constant, near -0.1. The large energy Kharkov data suffered from large backgrounds, as opposed to our later CEBAF E89-019 data [6]; the agreement of the Kang *et al.* calculation with the Kharkov data should be held against it.

The inability of theory to reproduce the large induced polarizations measured at $\theta_{cm} = 90°$ at energies above 300 MeV has in fact been a problem for nearly 30 years. In the late 1970s and early 1980s, this lack of agreement led to, in retrospect, a large and sad diversion of resources into the search for dibaryon resonances in deuteron photodisintegration. A number of experiments were motivated, along with a number of theoretical calculations that combined what we would now consider to be rather poor conventional calculations with arbitrary Breit-Wigner amplitudes, which were interpreted as dibaryon resonances. The better agreement of the Kang *et al.* calculation was highlighted as one of the successes of this model, but one can conclude looking at the better CEBAF data that the model's success is perhaps intermittent and fortuitous. While the dibaryon interpretation efforts eventually ended, we are still left with a large amount of generally poor induced polarization data, for which we have no good explanation.
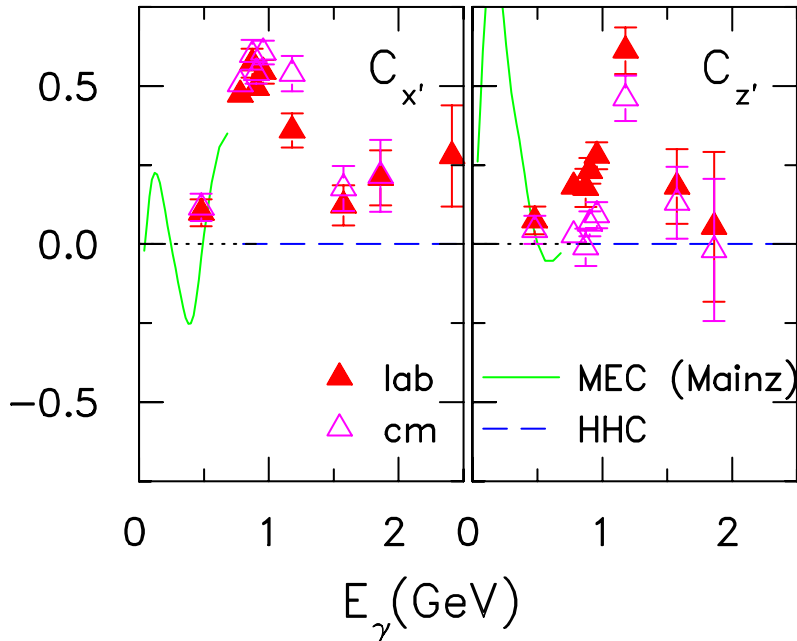
FIG. 6: The polarization transfer data from [6] compared to the calculation of Schwamb and Arenhövel, as a function of energy. All data are at $\theta_{cm} = 90°$. The c.m. data should be compared to the calculation.

In contrast to the poor quality of reproduction of the induced polarization, we show in Fig. 6 the recoil polarization transfer data compared to the calculations of Schwamb and Arenhövel, and to helicity conservation, which predicts that both observables vanish. The only data here are our data, from Hall A experiment E89-019 [6]. The Schwamb and Arenhövel calculation agrees well with the lowest energy data points, the only ones for which it is valid, and appears to head in the direction of the higher energy data.

Perhaps all of these observations make some sense together if we consider how the observables are constructed from the amplitudes [1]. The cross section and polarization transfer $C_{z'}$ result from sums (and differences) of the ampltiudes squared. These are generally well reproduced. The Σ asymmetry and polarization transfer $C_{x'}$ result from the real part of the intereference of ampltiudes. These are generally well reproduced. The target asymmetry T and induced polarization p_y result from the *imaginary* part of the intereference of ampltiudes. These are more poorly reproduced. Thus, the difficulty in the calculation seems to reside mostly in the imaginary part of the amplitudes, which one associates phenomena such as resonances and inelastic processes.

To summarize, we propose the interpretation that low energy deuteron photodisintegration is at least qualitatively understood, with quantitative agreement for much of the data. It is probably not too surprising that a generally good theory can now be formulated, given the many years of effort that have gone into the many aspects of this task. There are many detailed problems with this viewpoint[1], but the main problem in our view is that, starting

---

[1] We note several examples. Much of the data are of poor quality. There are regions in which the agreement is poorer than desired, such as the differential cross section near 200 MeV for c.m. angles near 90°. Theory seems to agree with $d\sigma/d\Omega_\parallel$ better than $d\sigma/d\Omega_\perp$ [7]. The induced neutron polarization at a few tens of

at energies of 300 - 400 MeV, one can see particularly in the induced polarization that the theory is rapidly diverging from the data, even though the data are of poor quality. The theory is starting to "break down".

It is not clear why in hadronic terms this would be so. Although it is an inferior calculation in essentially every other way, the work of [5] includes pole diagrams corresponding to the excitation of 17 resonances. Perhaps the many resonances allow [5] to better, though still poorly, explain the induced polarization, which is an imaginary part of the interference of amplitudes. However other calculations see little effect in this region from resonances other than the Δ.

The point of this proposal is to make a high precision systematic measurement of recoil proton polarizations in deuteron photodisintegration. The deuteron photodisintegration calculations have already been compared to a large quantity of photodisintegration data. As pointed out in [1], about 40 experiments have reported nearly 1200 data points in 70 articles. These data are predominantly in the region from threshold to a few hundred MeV. The only reasonable strategy for an experiment to provide hints as to how to improve the theory is to provide a large quantity of high precision data points, over a range of kinematics. With the FPP in HRS, we can make precise measurements of the recoil proton polarizations, the induced polarization p_y, and the polarization transfers $C_{x'}$ and $C_{z'}$.

The uncertainties in the existing induced polarization data shown are typically in the range of 0.1 – 0.15. We had an opportunity to take data for three hours at 528 MeV during the running of E89-019 [6] in the fall of 1999. The data of these three hours allowed us to determine the induced polarization to ±0.11, and the polarization transfer coefficients to ±0.04 – spin transport rotated the induced polarization to be 10° from longitudinal in the focal plane, increasing the uncertainties on the induced polarization. The 100 % duty factor of the CEBAF beam, with a few microampere current into Hall A, and the Hall A focal plane polarimeter make a systematic, high-precision determination of the recoil proton polarization in few hundred MeV deuteron photodisintegration a trivial matter. In earlier accelerators, the small duty factors and necessitated large instantaneous currents, generating lots of background; luminosities were also limited by small cryotargets with low beam power capability. The only significant issue for this experiment at Jefferson Lab is that of being able to schedule an experiment that requires a few hundred MeV beam – it is essentially impossible to do, unless the experiment has a full A priority, due to the large amount of high energy, high priority physics at the laboratory.

In contrast to the easiness of running this experiment in Hall A, it is difficult or impossible elsewhere. For example, LEGS does not have the luminosity to obtain the high statistics needed for a several hundred MeV beam energy recoil polarization measurement. Further, it lacks a recoil proton polarimeter, and a magnetic spectrometer that would allow all three recoil polarization components to be measured. At Mainz A1, there is no radiator, and one needs to rebuild the cryotarget and the beam line and dump downstream of the cryotarget to accomodate the expanded beam dimensions after a radiator, and to be able to switch between hydrogen and deuterium targets in a few minutes, instead of in several hours. With the present setup, the experiment can not be run in a reasonable manner.

There is now a potential target of opportunity to do this measurement in Jefferson Lab Hall A, such that it requires almost no lab resources and does not compete with other experiments for beam time. Under discussion now is a potential low energy G0 run using
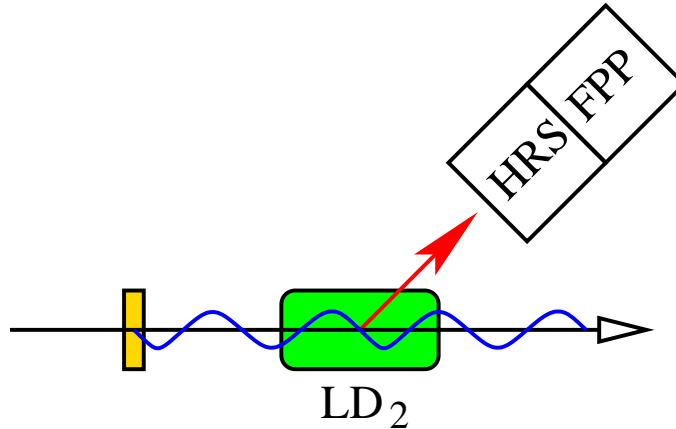
MeV is not understood [8].

FIG. 7: The planned experimental configuration. See text for details.

one pass beam, accelerated by only a single linac, into Hall C. The intent is to minimize power consumption by the lab, and costs to the lab, and take data during what would otherwise be the summer 2006 shutdown. The energy that G0 would use is not clear at this point, and might range from about 360 to 500 MeV. A scheme has been devised that would allow Hall A to simultaeously take one-pass beam, by putting the low energy beam into the fifth pass arc and using the standard RF separator.

Assuming this scheme is accepted by the laboratory, it then becomes trivial to do this measurement in Hall A during a time in which it is likely nothing else would be run. There is only one short existing experiment in the Hall A queue that is able to run at this beam energy. Thus, approval of this experiment, under the condition that the laboratory only run during the special low energy G0 run, would prevent it from any scheduling conflicts with other Hall A experiments.

Summary

We have shown above that most of the deuteron photodisintegration data are well reproduced by modern theories up to energies of about 500 MeV or even higher. The clear exception is the induced polarization data, with theory and data starting to diverge at an energy of perhaps 300 MeV. Understanding these large induced polarizations has been an outstanding problem for some 30 years.

There is now an opportunity, that requires minimal lab resources, to try to help resolve this problem, by obtaining a comprehensive, high-precision set of recoil polarization data. It requires running in Hall A during the low-energy, back-angle, Hall C G0 experiment. There are no other foreseeable opportunities to resolve this issue. If the experiment is not approved by PAC 28, there will be no opportunity to approve it in time to schedule it for the summer 2006 run.

EXPERIMENT

Overview of Technique

Our experimental plan for running this deuteron photodisintegration experiment is identical to our procedure during E89-019, which ran in the fall of 1999 [6]. In particular, during the last days of that experiment we had a special 3 hour opportunity as a result of accelerator testing to take data with ≈528 MeV beam. An overview of the experimental setup is shown in Fig. 7.

We mostly ran a 10 μA polarized electron beam into the 4 % copper radiator to generate the bremstrahlung photon beam. The HRS spectrometer was set to 726 MeV/c central momentum at an angle of $\theta_{lab} = 70°$, corresponding to $\theta_{cm} = 90°$. The FPP was set to use only the 1.5 inch carbon analyzer, for these low momentum protons. The data acquisition rate was around 1 kHz. The average photon energy for our data sample was 480 MeV, and the HRS acceptance corresponeded to a ≈100 MeV range of photon energies. The measured polarizations were p_y = -0.96 ± 0.11, $C_{x'}$ = 0.08 ± 0.04, and $C_{x'}$ = 0.10 ± 0.04. The larger uncertainty for p_y results from the spin precession, which for this point rotates the y spin component to be nearly in the momentum direction, and the z component to be nearly transverse.

The photodisintegration measurement is a singles measurement. The highest momentum end of the proton spectrum is clean $\gamma d \to pn$ events. No other reaction generates such high momentum protons from deuterium. Furthermore, at forward angles the protons are higher in momentum than pions from $\gamma d \to \pi^+ nn$, and our past experience is that the singles π^+ background is not significant at any angle.

Observables

We plan to measure three observables.

$\mathbf{C_{x'}}$: the transferred polarization component in the reaction plane, perpendicular to the outgoing c.m. momentum,

$\mathbf{p_y}$: the induced polarization component, perpendicular to the reaction plane, and

$\mathbf{C_{z'}}$: the transferred polarization component in the reaction plane, parallel to the outgoing c.m. momentum.

The only previous measurements of the polarizaton transfers in deuteron photodisintegration were done by us.

FPP

The experiment measures the polarization of low energy protons, with momenta typically around 500 - 700 MeV/c. We plan to use the thinner carbon analyzers of the Hall A FPP – it is likely we will simply use the 1.5 inch analyzer for all of the experiment. The analyzing power in these kinematics is large, in the region of 0.3 - 0.5, and is a strong but well known function of energy. Several such polarimeters have been used in the past, all giving consistent

results. As a check of the polarimeter, and to provide a calibration of the alignment, we will likely take a limited amount of low Q^2 ep elastic scattering data.

Backgrounds

Our previous experience in Hall A is that deuteron photodisintegration near the bremsstrahlung end point is nearly background free. At forward angles the photodisintegration protons have higher momentum than any other particles from the deuterium target. While higher momentum pions are kinematically allowed at backward angles, past experience indicates that π/p separation is trivial at these momenta, and that for photodisintegration the π rates are generally negligible. If there are pions, there can be removed by techniques such as β cuts – 0.7 GeV/c protons (pions) have $\beta = 0.6$ (0.98), so they are well separated compared to out resolution ($\approx$0.08).

Cosmic rays are a significant background rate for our high energy experiments due to the $\approx$ Hz signal rate. Here the signal rate is closer to 1 kHz, so the $\approx$20 Hz cosmic rate is small, and the cosmics are removed through β cuts.

Background events from the target end caps are usually removed by reconstructed target position cuts, but for lab angles above about 45°, the target end caps are outside the spectrometer acceptence. Due to the low beam energies of this proposal, there is not much of a boost in the c.m. to lab transformation, so for much of the experiment the target end caps are not in view.

Kinematics and Time request

Our plan is to run the experiment at whatever energy G0 chooses for its backward angle data. The energy choice seems to be in the region of 360 - 500 MeV, and we do not at this point know what the energy will be. We plan to bin the data in 20 – 30 MeV bins, due to the strong variation of the observables with energy.

The angles that we need to measure are based on the angular distribution predictions shown in Figs. 3 and 4. One can see that it is desirable to cover a broad range in c.m. angle. At these energies, a c.m. angle of 20° corresponds to a lab angle of about 15°, and can be easily measured. This small angle is desired because it allows us to determine if the forward angle structures in the polarization are as predicted, and evolve with energy as predicted. Because of smaller back angle cross section, the c.m. to lab Jacobian, and decreasing proton momentum, which lowers the FPP figure of merit, and hurts the spin transport for the induced polarization, a c.m. angle of 110° represents the practical limit at which 1 day suffices for high precision measurements. To map out the structures, we request to measure the angular distribution in steps of 10° in the c.m. Thus, we plan to measure at 10 angles.

We plan to use a 10 μA beam incident on a 4% radiator to generate our polarized photon beam. We will use a standard 15 cm (1.05 g/cm^2) liquid hydrogen target. These were the conditions of our 1999 run. We make time estimates using these conditions, the calculated cross sections from Schwamb and Arenhövel, and parameterizations of the FPP performance. These estimates are consistent with the uncertainties we obtained from the 1999 data.

At forward angles, the clean region of the bremsstrahlung spectrum is about 100 MeV – the clean region limits depend mostly on the angle, rather than the energy. It requires

2 spectrometer settings to cover this region, getting good statistics in each of the 20-MeV energy bins. For larger c.m. angles, from 70° – 120°, it requires three spectrometer settings to cover the expanded clean kinematic region. At $\theta_{c.m.} = 90°$, for example, the clean region has expanded to 140 MeV. Thus, the experiment requires 25 spectrometer settings.

For 400 - 500 MeV beam energy, we find that about 12 hours will cover each spectrometer setting, giving uncertainties on the polarization transfer observables of 0.02 – 0.03 for each 20 MeV bin, if the beam polarization is the usual ≈80 %. The uncertainty is smaller at forward angles, due to the improved FPP figure of merit at thie higher momenta. The uncertainty on the induced polarization tends to be 2 – 3 times as large, due to the less favorable spin transport. The spin transport also tends to make the uncertainties smaller for the higher momentum, forward angle induced polarization points.

The lower beam energy actually requires about the same time as the higher beam energy. As the photon energy drops from 500 MeV to 300 MeV, the proton momentum drops (at $\theta_{c.m.} = 90°$) from 700 MeV/c to 600 MeV/c, and the polarimeter figure of merit drops by about a factor of 3. Figure 1 shows that the cross sections decrease from about 5 μb/sr at 300 MeV to about 1 μb/sr at 440 MeV, so the factor of 3 decrease in the figure of merit is compensated by a factor of 5 increase in the cross sections. The practical lower momentum limit for a carbon analyzer FPP is usually taken to be around 400 MeV/c.

Additional time is needed for the following purposes:

- 9 angle changes require 1 hour each.

- 15 spectrometer momentum changes require 20 minutes each.

- 1 straight through run is used to calibrate the FPP alignment. This requires about 1 hour.

- 4 low Q^2 ep measurements will check the FPP performance. These are done in about 6 hours each, using proton singles.

With 12.5 days of data runs, plus ≈1.5 days of calibrations and overhead, our total time request is for 14 days.

One potential issue for the experiment is how to determine the beam polarization. The beam energy is too low to use the standard Hall A Moller configuration. Our plan is to use ep elastic scattering into the FPP to determine the product hA_C, and to then use standard carbon analyzer parameterizations to extract the beam helicity h. Since the measurement of the polarization transfer coefficients depends on the product hA_C, there is no increase in uncertainty. However this does add some systematic uncertainty to the knowledge of A_C alone. Knowledge of the beam polarization for G0, the Wien angle, and measurements by the Mott polarimeter should keep the uncertainty small. It is also possible to reconfigure the Hall A Moller polarimeter, replacing the first quad by a sweeper magnet [9]; at present we do not believe that this reconfiguration is needed.

COLLABORATION, CONFLICTING EXPERIMENTS, AND SCHEDULING

The core of the current collaboration consists of individuals who have been deeply involved in previous Hall A photon experiments and the construction and operation of the Hall A FPP. There are no conflicting experiments since these measurements are difficult to impossible elsewhere.

All equipment needed for the experiment exists. It might be necessary to reinstall the photon radiator, or reconfigure the cryotarget, which requires between a few days and a week with no beam in the Hall.

We are requesting the experiment be approved to run during the low energy G0 backward angle run.

[1] R. Gilman and Franz Gross, J. Phys. G **28**, R37 – R116 (February 27, 2002), preprint nucl-th/0111015.
[2] M. Schwamb and H. Arenhvövel, Mod. Phys. Lett. A **18**, 190 (2003); preprint nucl-th/0209083.
[3] M. Schwamb and H. Arenhvövel, Nucl. Phys. A **696**, 556 (2001); preprint nucl-th/0105033.
[4] M. Schwamb and H. Arenhvövel, Nucl. Phys. A **690**, 682 (2001); preprint nucl-th/0008034.
[5] Y. Kang, P. Erbs, W. Pfeil, and H. Rollnik *Abstracts of the Particle and Nuclear Intersections Conference*, (MIT, Cambridge, MA) (1990), and Y. Kang, Ph.D. thesis, Bonn (1993).
[6] K. Wijesooriya *et al.* Phys. Rev. Lett. **86**, 2975-2979 (April 2, 2001).
[7] Blanpied G *et al.*(The LEGS Collaboraton) Phys. Rev. C **52**, R455 (1995)
[8] R. Schiavilla, preprint nucl-th/0505066.
[9] E. Chudakov, private communication.