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J. Glister
A. J. Sarty
E. McCullough
A. Kelleher
William & Mary

M. Meziane
William & Mary

See next page for additional authors

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Authors

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Polarization observables in deuteron photodisintegration below 360 MeV


a Saint Mary’s University, Halifax, Nova Scotia B3H 3C3, Canada
b Dalhousie University, Halifax, Nova Scotia B3H 3J5, Canada
c Tel Aviv University, Tel Aviv 69978, Israel
d Seoul National University, Seoul 151-747, Republic of Korea
e Thomas Jefferson National Accelerator Facility, Newport News, VA 23606, USA
f Rutgers, The State University of New Jersey, Piscataway, NJ 08855, USA
g University of South Carolina, Columbia, SC 29208, USA
h University of Kentucky, Lexington, KY 40506, USA
i Temple University, Philadelphia, PA 19122, USA
j Argonne National Laboratory, Argonne, IL 60439, USA
k Institut für Kernphysik, Johannes Gutenberg-Universität, D-55099 Mainz, Germany
l NRCN, P.O. Box 9001, Beer-Sheva 84190, Israel
m University of Maryland, Baltimore, MD, USA
n George Washington University, Washington, DC 20052, USA
o Florida International University, Miami, FL 33199, USA
p Christopher Newport University, Newport News, VA 23606, USA
q University of New Hampshire, Durham, NH 03824, USA
r University of Virginia, Charlottesville, VA 22904, USA
s INFN, Sezione Sanità and Istituto Superiore di Sanità, Laboratorio di Fisica, I-00161 Rome, Italy
t Longwood University, Farmville, VA 23909, USA
u Old Dominion University, Norfolk, VA 23508, USA
v Université Blaise Pascal / CNRS-IN2P3, F-63177 Aubière, France
w Cairo University, Giza 12613, Egypt
x College of William and Mary, Williamsburg, VA 23187, USA
y Kent State University, Kent, OH 44242, USA
z Saint Norbert College, Greenbay, WI 54115, USA
aa Jozef Stefan Institute, 1000 Ljubljana, Slovenia
ab NSC Kharkov Institute of Physics and Technology, Kharkov 61108, Ukraine
ac Massachusetts Institute of Technology, Cambridge, MA 02139, USA
ad Norfolk State University, Norfolk, VA 23504, USA
ae Duke University, Durham, NC 27708, USA
af Ohio University, Athens, OH 45701, USA
ag Yerevan Physics Institute, Yerevan 375036, Armenia

* Corresponding author.
E-mail address: jglister@jlab.org (J. Glister).

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The conventional nuclear model uses baryon and meson degrees of freedom to describe nuclear structure and reactions. While this approach has been broadly successful for low-energy phenomena, it is widely believed that it will break down at high energies. Meson–baryon model (MBM) calculations require high precision NN potentials which are used to describe the finite spatial extent of hadrons [1] and contain free parameters fit to experimental NN scattering data. MBM calculations have been quite successful below excitation energies of a few hundred MeV in describing cross-section and polarization observables for electromagnetic reactions involving small nuclear systems [2–5].

In the few GeV energy region, cross-section measurements of the deuteron photodisintegration reaction [6] were found to approach approximately scale according to the constituent counting rules [7–9], predictions based on quark degrees of freedom. Also, quark models such as the quark–gluon string (QGS) [10,11] and hard rescattering (HR) [12] have been moderately successful in describing $d(\vec{γ}, \vec{p})n$ polarization observables above $\sim 1$ GeV [13,14].

Small nuclear systems, such as the deuteron and $^3$He, provide a useful testing ground for MBM calculations as they allow for reliable theoretical calculations. Electromagnetic probes of these small systems are useful since the weak coupling constant allows for perturbative methods to be used. Furthermore, polarization measurements in electron– and photon–deuteron reactions allow for a detailed study as they are sensitive to small amplitudes and effects. Since the beginning of polarization measurements, over 70 publications have presented over 1200 polarization data points for photodisintegration and the time-reversed radiative capture reaction. These data have been very useful in constraining and testing low energy MBM calculations. In order to test the upper limit in energy of the meson–baryon model, experiments and calculations have been extended to higher and higher energies. As the energy and momentum transfer increase, the distance scale probed decreases and one would expect that at some point the sub-nucleonic degrees of freedom would have to be considered.

The most advanced MBM calculation for $d(\vec{γ}, \vec{p})n$ in the few hundred MeV region comes from Schwamb and Arenhövel [15–17, 2]. They have included meson-exchange currents, final-state interactions, relativistic corrections and a modern baryon–baryon potential in a non-relativistic field theory with nucleon, meson and $\Delta$ degrees of freedom. Free parameters are constrained by fits to NN scattering, $\pi N$ scattering and pion photoproduction data [15]. Up to excitation energies of roughly 500 MeV, there is generally good agreement between their calculations and data for the differential cross-section, the cross-section asymmetry for linearly polarized photons ($\Sigma$) and the polarized target asymmetry ($\Upsilon$). However, a striking disagreement emerges between 300 and 500 MeV, where the induced recoil proton polarization ($P_x$) at $\theta_{CM} = 90^\circ$ is predicted to approach zero with increasing energy, yet the data grow in magnitude to nearly $-1$ at 500 MeV. Kang et al. [18] developed a model for $d(\vec{γ}, \vec{p})n$ using a diagrammatic method which predicted a large magnitude of $P_x$ above 300 MeV. They considered $\pi$, $\rho$, $\eta$ and $\omega$ meson exchanges and 17 well-established nucleon and $\Delta$ resonances with a mass less than 2 GeV and $J \leq 5/2$, with all resonance parameters taken from the Particle Data Group [19]. However, the work cannot be validated as it was not published; it did not include channel coupling or consider final-state interactions completely (by solving the Schrödinger equation with an NN potential) and failed to describe the large induced polarization seen at $\sim 500$ MeV [13].

The pre-existing data between 300 and 500 MeV consist mainly of induced polarization measurements taken at different labs (with good angular distributions at only a few energies), $\Sigma$ cross-section asymmetry measurements [20–23], along with a recent set of tensor analyzing powers [24] spanning 25–600 MeV. Also, no data of polarization transfer for circularly polarized photons had been taken below 500 MeV. We obtained a systematic set of the induced recoil polarization observables between 277 and 357 MeV in order to identify where in energy the measurements and the existing calculations begin to diverge. Benchmark measurements of transferred recoil polarization were also taken in this energy region to further constrain the theory. The polarization observables are written as $(P^x, P^y, P^z)$, where $c'$ denotes transferred polarization due to a circularly polarized photon beam, $\hat{z}$ is along recoil proton momentum in the center-of-mass frame, $\hat{y}$ is perpendicular to the reaction plane in the center-of-mass frame and $\hat{x} = \hat{y} \times \hat{z}$.

The experiment was carried out in Hall A of Jefferson Lab [25]. A continuous electron beam with longitudinal polarization ranging from 80–85% was produced using a strained gallium–arsenide (GaAs) source [26,27]. The longitudinal polarization in Hall A was limited to 38–41% due to multi-hall running. The beam helicity was flipped pseudo-randomly at 30 Hz, with negligible difference in total beam charge between the two helicity states. The electron beam, with energy 362 MeV, was incident on a copper radiator with thicknesses of 3, 4 or 5% of a radiation length. The outgoing (untagged) circularly polarized Bremsstrahlung photons were incident on a 15 cm long deuterium target. The ratio of photon to electron polarization varied from 80 to near 100% and was calculated on an event-by-event basis using the formula found in [28].

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- Deuteron photodisintegration
- Polarization
- Meson-baryon model
The protons were detected in the left High Resolution Spectrometer (HRS) [29], made up of one dipole and three quadrupole magnets. The vertical drift chambers, or VDCs, were used to track the protons after the magnetic field of the dipole. The HRS optics matrix was used to reconstruct the scattering angles, momentum and positions at the target. Triggering and time-of-flight information was provided by two planes of plastic scintillators, S1 and S2.

The Focal Plane Polarimeter (FPP), downstream of the VDCs and trigger panels, is used to determine the recoil polarization of the protons by measuring a secondary scattering of the protons and triggering panels, is used to determine the recoil polarization of the protons after the magnetic field of the dipole. The HRS optics matrix was used to reconstruct the scattering angles, momentum and positions at the target. Triggering and time-of-flight information was provided by two planes of plastic scintillators, S1 and S2.

The experiment covered an angular range of $\theta_{cm} = 20^\circ$–$120^\circ$, generally in $10^\circ$ steps, although some intermediate angles were skipped due to time constraints. Five 20 MeV bins in photon energy spanning 277–357 MeV (bin center) were covered at each center-of-mass angle using two spectrometer momentum settings, except at the three largest angles and one of the intermediate ones. In all measurements the proton had sufficient momentum to exclude the existence of a pion in the final state. Background due to electrodisintegration reactions and interactions with the target walls was subtracted using a method similar to previous photodisintegration experiments [13].

The FPP was calibrated with ep elastic scattering [34], which determines the false asymmetry and the analyzing power [35], the strength of the spin-dependent p–C interaction. False asymmetries, caused by chamber misalignments and inhomogeneities in detector efficiency, cancel to first order for polarization transfer but remain for the induced polarization. The FPP chambers were aligned both internally and to the VDCs using straight-through trajectories, with the analyzer block removed. The remaining false asymmetries were parameterized as a Fourier series and subtracted out.

The angular dependence of the present transferred ($P^c_x$ and $P^c_z$) and induced ($P_y$) polarization data are shown as filled circles in Fig. 1 for photon energies of 277 MeV (left-hand side) and 357 MeV (right-hand side). Previous induced polarization measurements [37–46] are also shown, where uncertainty bars are statistical only, except for the Tokyo measurements (open circles) [39] which have bars representing both statistical and systematic uncertainties. The uncertainty bars for the present measurements are statistical only; systematic uncertainties are shown as black bands. The systematic uncertainties include uncertainties in beam energy, polarization and position, false asymmetry and analyzing power parameterizations, spin transport, momentum, and FPP angular resolution. The spin transport systematic analysis was similar to that of a previous work [32]. Absolute statistical (systematic) uncertainties for $P^c_x$, $P_y$, and $P^c_z$ ranged from 0.01–0.15 (0.01–0.04), 0.01–0.50 (0.01–0.33) and 0.01–0.15 (0.02–0.10), respectively. The largest contribution to the systematic uncertainty for both $P^c_x$ and $P^c_z$ was the analyzing power parameterization while the largest contribution for $P_y$ was the false asymmetry parameterization.

Our $P_y$ data at $70^\circ$ and $90^\circ$ for $E_\gamma = 357$ MeV are larger in magnitude than previous results. We are in a region where there is the start of a strong energy dependence and small cross-sections. Measurements covered different energy ranges. As a result of this, older measurements suffered from large backgrounds and poor consistency. This was seen previously [13]. The trend of $P_y$ in our data at $90^\circ$ is consistent with higher energy measurements, and our $P_y$ results cannot be changed independently of the polarization transfer data.

The solid line is the Schwamb and Arenhövel calculation [15–17,2]. The dashed line is a recent refinement from [36], which includes several additional advances such as a non-perturbative treatment of the $\pi NN$ dynamics (as opposed to an approximate treatment). The new calculation fulfills unitarity to leading order,

\begin{align*}
\frac{d\sigma}{d\Omega}(\gamma p \rightarrow np) &= \frac{d\sigma}{d\Omega}(\gamma p \rightarrow np)_{\text{Born}} + \frac{d\sigma}{d\Omega}(\gamma p \rightarrow np)_{\text{NN}} + \frac{d\sigma}{d\Omega}(\gamma p \rightarrow np)_{\text{NN\pi}} + \frac{d\sigma}{d\Omega}(\gamma p \rightarrow np)_{\text{NN\pi\pi}} + \cdots \\text{(Born terms)} \\
&+ A \int d\Delta E \frac{d\sigma}{d\Omega}(\gamma p \rightarrow np)_{\text{NN}}(\Delta E) + B \int d\Delta E \frac{d\sigma}{d\Omega}(\gamma p \rightarrow np)_{\text{NN\pi}}(\Delta E) + C \int d\Delta E \frac{d\sigma}{d\Omega}(\gamma p \rightarrow np)_{\text{NN\pi\pi}}(\Delta E) + \cdots \\text{(Born terms with corrections)} \\
&+ \text{higher order terms}.
\end{align*}
The real part appears to be better predicted above the threshold, indicating a need for improved QCD-inspired potentials at the lowest energy. It may be possible to remedy the situation by improving the fits of NN scattering partial waves above pion threshold, including higher mass resonances in a coupled channel approach or extending the calculation beyond the one-meson approximation. These present measurements should provide input for important tests to the state-of-the-art meson–baryon model calculations above pion threshold and it will be interesting to see whether the issue can be resolved or if other models (based on chiral perturbation theory, for instance) should be considered.

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