Meson-Exchange Currents and the Reaction $^2H(\gamma, n_{pol})H$

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The neutron polarization for the reaction $^2H(\gamma, n_{pol})H$ was measured with high accuracy at an angle of 90° and in the photon energy range 6 to 13 MeV. The results were found to be in disagreement with present theoretical predictions which include meson-exchange currents.

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It has long been expected[1,2] that a measurement of the polarization of the emitted nucleons from the photodisintegration of the deuteron would provide a significant constraint on the meson-exchange current (MEC) in the n-p system. For example, the neutron polarization from the reaction $^2H(\gamma, n_{pol})H$ at an angle of 90° and at low energy is predicted[3] to be dominated by $E1$-$M1$ interference terms. Furthermore, the MEC is believed[4] to have a substantial effect on the $M1$ amplitude. The most compelling evidence for this effect arises from two types of measurements: the thermal n-p capture cross section[5] and the electrodisintegration cross section[6] at large reaction angles and low excitation energies. Although there are three previous measurements[7-9] of the photonucleon polarization in this energy range below 30 MeV, there are discrepancies among the data sets. The most notable disagreement exists between the early data of Nath, Firk, and Schultz[8] and the more recent results of Drooks.[9] The data of Drooks agree with present theoretical calculations[1,10] while those of Nath, Firk, and Schultz do not. In order to resolve this issue, we have measured with high accuracy the photoneutron polarization from the reaction $^2H(\gamma, n_{pol})H$ at an angle of 90° and in the photon energy range 6 to 13 MeV. The results were found to be in agreement with Nath, Firk, and Schultz, and thus, in disagreement with the theoretical predictions. The discrepancy between the present data and the impulse calculation is increased by including the MEC.

The photoneutron polarization method has been discussed[11] previously, but will be outlined here. Energy-analyzed 19.0-MeV electrons in bursts of 4-ns width, 15-A peak current, and 800-Hz rate were focused onto an air-cooled graphite block. This graphite block served to provide bremsstrählung photons, stop the electron beam, and provide a current pulse for the neutron time-of-flight spectrometer. The photons irradiated a sample of deuterated polyethylene of dimensions 2.5 cm high × 5.0 cm along the photon axis × 0.4 cm thick along the neutron axis. Photoneutrons in the energy range of interest are not expected from the C contaminant in CD_2 since the (γ, n) threshold of ^{12}C is 18.7 MeV. Although the ^{13}C threshold is only 4.95 MeV, the abundance and photoneutron cross section of this isotope are not sufficient to alter the present results. The photoneutrons then traveled through a well-shielded 9.0-m flight path, which included a 2-m-long spin-precession solenoid, before scattering from a natural C analyzing target in the form of graphite of dimensions 10.0 cm wide × 5.0 cm high × 1.0 cm thick. The neutrons which scattered from the C target up (+50°) and down (−50°) with respect to the (γ, n) reaction plane were detected in plastic scintillators of dimensions 20.0 cm × 10.0 cm × 5.0 cm thick which were located 35.0 cm from the C target. The data were collected during three separate, four-day-long periods. During the first period the solenoid was set to precess the spin of a 2.43-MeV neutron through an angle of $\pi/2$ radians; while the solenoid was set to precess a 3.26-MeV neutron through $\pi/2$ for the latter running periods. The integrated field strength of the solenoid was determined to an overall accuracy of 0.5%. The field direction in the solenoid was reversed automatically approximately every 30 min in order to minimize any long-term systematic drifts. The results from all three experiments were found to be in excellent agreement with one another. No multiple-scattering corrections were applied to the data since two previous estimates[8,9] for *much thicker* targets have shown that these effects are small for the polarization. In fact, an estimate for the number of neutron multiple-scattering events in the sample was made from a Monte Carlo analysis. It was found that the yield from this process was approximately 5% of the primary (γ, n) yield at $E_\gamma = 7.0$ MeV and 2% of the yield at 13.0 MeV.

The polarimeter, which consisted of the solenoid, C target, and the two scintillators, was calibrated *in situ* by a neutron double-scattering method.[12] The graphite electron-stopping block was replaced with a sample of water-cooled, depleted uranium. The neutrons from this source then scattered from a second C target which was identical to that in the polarimeter and also at a scattering angle of 50°. The analyzing power of C was found in this way to be in reasonable agreement with previous studies. The error in the measured analyzing power of the polarimeter was found to be 3%, 12%, and 23% at $E_n = 2.4$, 4.42, and 5.4 MeV, respectively. Note that an error in scale of approximately 13% at $E_n = 2.4$ MeV and 50% at 4.4 MeV would be necessary to bring the present results into agreement with the predicted[1] polarization for the reaction $^2H(\gamma, n_{pol})H$.

The background rate was determined by three separate tests. First, the C sample was removed from the polarimeter. This reduced the overall counting rate by a factor of approximately 15. This proved to be the main source of background, i.e., neutrons produced in the CD_2 sample and scattered into the detector from air or collimator edges. Other tests performed were (i) to replace the CD_2 sample with CH_2 and with the C target in and out of the neutron beam, and (ii) to move the CD_2 target upstream of the photon beam so that it was out of the direct line of sight with the neutron flight path. These latter two tests yielded background levels which were approximately 20% of the main component of background. The final signal-to-background ratio varied from approximately 25 at $E_n = 2$ Mev to 10 at 6 MeV. Beam monitoring is necessary only to ensure that the background events can be subtracted accurately. The beam was monitored in two ways. First, the charge collected in the graphite stopping block was recorded, and secondly, neutrons from the (γ, n) target were detected in a counter that was located downstream from the polarimeter. These two monitors agreed to within 0.5% for each run taken with the CD_2 in place. As a test of the sensitivity of the final results to the monitor and background subtraction, the background monitor was shifted arbitrarily by 5% and the data were reanalyzed. The largest change in the data was to shift the polarization by only 10% of the error.

The final results are shown as the points in Fig. 1. The error limits shown in the figure reflect the uncertainty in the analyzing power of the polarimeter as well as the statistical error. Clearly, the data are systematically less negative than the calculation which includes the MEC.

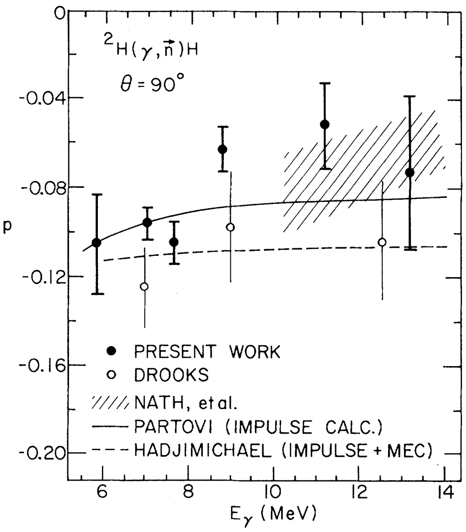

FIG. 1. Comparison of the present work with previous results and theoretical calculations. The solid points represent the present work. The hatched region indicates the work of Ref. 8, while the open circles represent the work of Ref. 9. The solid curve is the result of an impulse calculation of Ref. 10. The dotted curve represents the calculation of Ref. 1 which includes the MEC.

In fact, the present results are in better agreement with the impulse calculation of Partovi than that which includes the MEC. The trend of the present work is consistent with a previous measurement of Nath, Firk, and Schultz[8] at higher energies, but it is less negative than the results of Drooks.[9] Nath, Firk, and Schultz found the photoneutron polarization at 90° to be consistently less negative than the impulse calculation above $E_\gamma = 10$ MeV. These results are shown as the hatched region in Fig. 1. Note that Nath, Firk, and Schultz employed a liquid ^{4}He polarimeter in their work. The discrepancy in this low-energy region $6 < E_\gamma < 13$ MeV is particularly striking since corrections such as including (i) nucleon form factors, (ii) relativistic effects, (iii) higher multipole and N-N partial waves, and (iv) short-range components of the deuteron wave function have much less importance than at higher energy.

At a reaction angle of 90° only $E1$-$M1$ or $E1$-$E2$ interference terms give rise to photoneutron polarization. The polarization is expected,[3] however, to be insensitive to the $E2$ amplitude at these low photon energies. In fact, this point was checked by eliminating the $E2$ amplitudes from Partovi's calculation. In the photon energy range 5 to 20 MeV, the contribution of $E1$-$E2$

interference terms to the polarization at 90° was found in this way to be $\lesssim 0.3\%$. If only $E1$ and $M1$ amplitudes need be considered then the differential photoneutron polarization [the differential cross section $\sigma(\theta)$ × the polarization $p(\theta)$] can be written as

$$\sigma(\theta)p(\theta) = A_{EM}\sin\theta + B_{EE,MM}\sin\theta\cos\theta,$$

where A_{EM} depends on $E1$-$M1$ interference and $B_{EE,MM}$ depends on the products of $E1$ and $M1$ amplitudes that lead to different final states of the np system. Of course, only A_{EM} contributes to the polarization at 90°. The primary effect of the MEC is to increase[4] the $M1$ transition amplitudes, namely the $({}^3S_1 + {}^3D_1) \to {}^1S_0$ transition. Thus, the magnitude of the photoneutron polarization $p(90°)$ must become larger. In order to explain the present data, one must reduce the $M1$ transition amplitude in such a manner that the thermal n-p capture cross section is not changed, or increase the $E1$ transition amplitude in a way that does not alter the total photoabsorption cross section.[13]

Clearly, a high-accuracy angular distribution of photoneutron polarization and cross section is necessary in order to unravel the multipole components of the reaction ^{2}H(γ, n)H at low energy. In addition, further theoretical work will be necessary in order to explain this simplest nuclear reaction.

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[1]E. Hadjimichael, Phys. Lett. 46B, 147 (1973).

[2]H. Arenhovel, W. Fabian, and H. G. Miller, Phys. Lett. 52B, 303 (1974).

[3]M. L. Rustgi, W. Zernik, G. Breit, and D. J. Andrews, Phys. Rev. 120, 1881 (1960).

[4]D. O. Riska and G. E. Brown, Phys. Lett. 38B, 193 (1972).

[5]A. E. Cox, S. A. R. Wynchank, and C. H. Collie, Nucl. Phys. 74, 497 (1965).

[6]M. Bernheim, E. Jans, J. Mougey, D. Royer, D. Tanowski, S. Turck-Chieze, I. Sick, G. P. Capitani, E. De Sanctis, and S. Frullani, Phys. Rev. Lett. 46, 402 (1981).

[7]W. Bertozzi, P. T. Demos, S. Kowalski, C. P. Sargent, W. Turchinetz, R. Fullwood, and J. Russell, Phys. Rev. Lett. 10, 106 (1963).

[8]R. Nath, F. W. K. Firk, and H. L. Schultz, Nucl. Phys. A194, 49 (1972).

[9]L. J. Drooks, Ph.D. thesis, Yale University, 1976 (unpublished).

[10]F. Partovi, Ann. Phys. (N.Y.) 27, 79 (1964).

[11]R. J. Holt, J. R. Specht, H. E. Jackson, and R. M. Laszewski, Nucl. Instrum. Methods 141, 125 (1977).

[12]R. J. Holt, F. W. K. Firk, R. Nath, and H. L. Schultz, Nucl. Phys. A213, 147 (1973).

[13]E. Hadjimichael and D. P. Saylor, Phys. Rev. Lett. 45, 1776 (1980).

High Rydberg States of an Atom in a Strong Magnetic Field

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Classical trajectories and semiclassical eigenvalues are calculated for an atomic Rydberg state in a magnetic field. Perturbation theory describes a classical trajectory as a Kepler ellipse which rocks, tilts, and flips in space as orbital parameters evolve slowly in time. Exact numerical calculations verify the accuracy of perturbation theory for $n \simeq 30$, $B \leqslant 6$ T. Action variables are calculated from perturbation theory and from exact trajectories, and semiclassical eigenvalues obtained by quantization of the action. Good agreement is found with observations.

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The behavior of a highly excited atom in a strong magnetic field is a topic of much current interest.[1] The present studies were motivated by the desire to understand and interpret experimental measurements[2] made at Masschusetts Institute of Technology on one-electron atoms in