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First measurement of the near-threshold $^{2}\mathrm{H}(\vec{\gamma},n)p$ analyzing power using a free-electron laser based γ-ray source

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The first measurement of the $^{2}\mathrm{H}(\vec{\gamma},n)p$ analyzing power near threshold has been performed using the High-Intensity Gamma-ray Source (HIGS) at the Duke Free-Electron Laser Laboratory. A 3.58 MeV γ-ray beam having an energy resolution of 2.5% and 100% linear polarization was incident on an active C_6D_{12} target. Outgoing neutrons were detected parallel and perpendicular to the plane of γ-ray polarization at a lab angle of 150°. The experimentally determined analyzing power provides a sensitive measurement of the relative $E1$ and $M1$ contributions to the total cross section.

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The deuteron is a well-studied system in nuclear physics. Deuteron photodisintegration, $d(\gamma,n)p$, and its reverse reaction, $p(n,\gamma)d$, have often served as a testing ground for theories of the nucleon-nucleon interaction. Due to the comparative availability of neutron beams over photon beams, the majority of these studies have focused on n-p capture reactions. A thorough review of previous experiments over a wide range of energies is found in [1]. One energy regime that has not received a great deal of experimental attention is the region just above the threshold for photodisintegration ($E_{\gamma}\sim 2.23$ MeV) where the $E1$ and $M1$ amplitudes are expected to dominate. An accurate determination of the $p(n,\gamma)d$ cross section in this energy region, corresponding to neutrons of a few hundred keV, is of great interest in nuclear astrophysics, specifically with regard to big bang nucleosynthesis [2,3]. Uncertainties in the $p(n,\gamma)d$ cross section are the dominant uncertainties in the determination of the relative abundances of heavier elements in the early universe. This energy region is experimentally difficult for n-p capture studies because of the tendency of neutrons at this energy to thermalize and produce large backgrounds. While recent measurements of the $p(n,\gamma)d$ total cross section [4] improve on previous experiments, they are subject to the same limitations. Previous photodisintegration experiments have focused on measuring the angular distribution as a method of extracting the relative $E1$ and $M1$ contributions to the cross section [5]. These distributions, however, are most sensitive to the $M1$ contribution near 0° and 180°, where measurements are difficult to make. Previous $d(\vec{\gamma},p)$ experiments [6] have been performed using polarized beams from a bremsstrahlung source at γ-ray energies between 5 and 10 MeV, putting the measurements into a region dominated by $E1$ radiation.

In the present work, we have measured the analyzing power $\Sigma(\theta)=(N_{\parallel}-N_{\perp})/(N_{\parallel}+N_{\perp})$ at $E_{\gamma}=3.58$ MeV and $\theta=150°$ using a 100% linearly polarized γ-ray beam [7]. $N_{\parallel}$ and $N_{\perp}$ are the number of outgoing neutrons detected in and out of the horizontal γ-ray polarization plane, respectively. Since the value of $\Sigma(\theta)$ would be 1.0 at all angles for the case of pure $E1$ absorption, deviations from this value should allow us to determine the relative strength of the $M1$ radiation present at this energy. The γ-ray beam was generated using the High-Intensity Gamma-ray Source (HIGS) at the Duke Free-Electron Laser (FEL) Laboratory. In this facility, electrons from a linear accelerator are injected into a storage ring, and pass through an electromagnetic undulator on each trip around the ring. The undulator causes the electron bunch to emit a pulse of 100% linearly polarized light into an optical cavity, where subsequent interactions of the light with the electrons in the undulator produces an intense FEL pulse of photons. The injection of a second electron bunch into the storage ring is timed such that the new electron bunch and the photon pulse meet in a field-free region of the undulator region traveling in opposite directions. The resulting Compton scattered FEL photons are then projected in the direction of electron propagation as high-energy γ-rays, with the highest energy γ rays being projected directly down the beam axis and lower energy γ rays at small angles. This correlation between photon energy and scattering angle in Compton scattering allows γ-ray energy distributions of better than $\Delta E/E=1\%$ to be obtained by collimating the beam. A detailed description of the operation and capabilities of the facility is given in [7,8].

For the $^{2}\mathrm{H}(\vec{\gamma},n)$ measurement, the HIGS facility generated γ rays with a peak energy of 3.58 MeV by scattering 383 nm (3.24 eV) FEL light from 270 MeV electrons. Because these beam parameters are at the low end of the operating range of the storage ring, the total γ-ray flux was limited to approximately 10^{4} γ/sec. To enhance the number of γ rays on target, a large 1.5 cm diameter aperture steel collimator was used, giving an energy resolution of $\Delta E/E=2.5\%$. An energy profile of the γ-ray beam measured with a high-purity germanium (HPGe) detector placed downstream of the target area is shown in Fig. 1. This γ-ray beam

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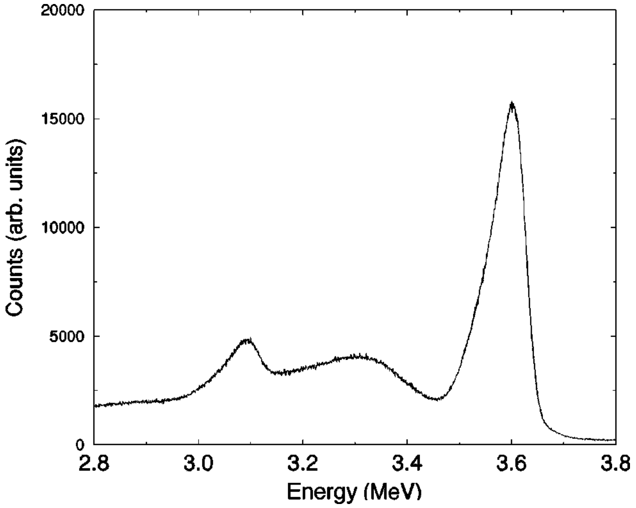

FIG. 1. Energy distribution of the γ-ray beams measured by a high-purity germanium detector. The FWHM of the distribution is 80 keV. The structure below the full-energy peak is due to detector response.

was then incident on a liquid scintillating C_6D_{12} target 3.7 cm in diameter and 4.18 cm long. Neutrons emitted from the target were detected by four 5-cm diameter BC501A neutron detectors at a lab angle of 150° in the up, down, left, and right positions with respect to the beam direction. The detectors were mounted on a rotating frame so that each detector could be positioned in and out of the plane of γ-ray polarization. The 150° lab angle was chosen to maximize the sensitivity to the $M1$ strength while minimizing the number of scattered photons incident on the detectors. Because of the low available γ-ray flux, the front face of the detectors were placed very close (5.08 cm) to the deuterium target to maximize the counting rate in the neutron detectors. The HPGe detector was placed downstream of the deuterium target as a beam monitor. A schematic of the experimental apparatus is shown in Fig. 2.

An accurate measurement of the analyzing power requires a careful separation of photon and neutron events in the detectors. Using an active target allowed the time of flight (TOF) between the target and detector to be measured and used as one method of separating photon events from neutron events in the detectors. Because photons and neutrons leave differently shaped signals in BC501A, pulse-shape discrimination (PSD) techniques could also be used to identify neutron events. Because of limitations in both detector and electronics response, however, very high-energy γ rays can produce a saturated signal that appears as a neutron signal in a one-dimensional PSD spectrum. Pulse height information from the neutron detectors was therefore stored and combined with the standard PSD spectra to produce two-dimensional PSD spectra that displayed well-separated neutron and photon events. Gates set in these two-dimensional spectra could then be used to select events in the TOF spectra, providing two well-separated peaks, as shown in Fig. 3. Finally, storing the pulse height of the signal from the deuterium target allowed an additional selection between photon and neutron events to be made. Because an electron from a Compton scattering event generally deposits more energy than a recoiling proton from a photodisintegration event, a gate set around the probable region of photodisintegration events can further isolate the neutron events of interest. These techniques of separating photon and neutron events were tested by replacing the C_6D_{12} target with a C_6H_{12} target. Because the γ-ray energy is below the photoneutron threshold of all materials present in the experimental apparatus, no neutrons should be produced when operating with this target. Using the techniques listed above, the photon contamination of the neutron region of the TOF spectra was found to be less than 1%.

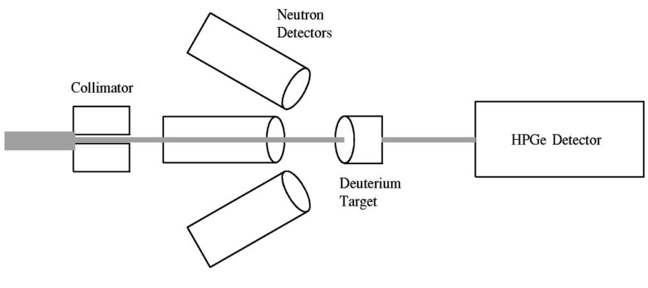

FIG. 2. Schematic of experimental setup. The neutron detectors are placed at a lab angle of 150° with respect to the beam direction, and are placed in the up, down, left, and right positions, being perpendicular and parallel to the direction of the γ-ray polarization.

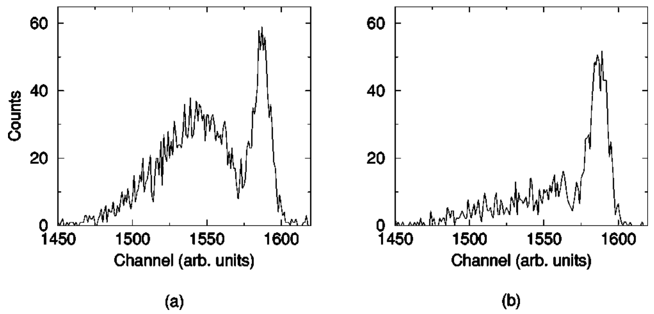

FIG. 3. Particle time-of-flight spectra from a single detector located (a) in the plane of photon polarization and (b) in a plane perpendicular to the photon polarization. Time increases from right to left, indicating that the left peaks contain neutron events, while the right peaks contain photon events. All counts in these spectra have passed the two-dimensional PSD cut. The photon peak can be eliminated from the spectrum by making a cut on the pulse-height spectrum from the C_6D_{12} target spectrum.

A neutron asymmetry of 0.629 ± 0.021 was measured using the above techniques and apparatus. This measured asymmetry is not a direct measurement of the $^2\mathrm{H}(\vec{\gamma},n)$ analyzing power at 150°, however. The finite size of the deuterated target and the detectors allow neutrons from a considerable angular acceptance around 150° to be detected. In addition, a neutron from a photodisintegration event can elastically or inelastically scatter off other nuclei in the apparatus, changing its trajectory and energy and causing it to interact with a detector it would have otherwise missed. To extract the ''true'' asymmetry from the measured value, these finite geometry and multiple scattering effects were simulated in a Monte Carlo code. The code assumes an initial angular distribution for the neutrons of the form

$$\sigma(\theta,\phi)\propto a+b\sin^2\theta[1+\cos(2\phi)], \tag{1}$$

where θ is the angle with respect to the γ-ray beam axis, ϕ is the angle with respect to the direction of γ-ray polarization, a is a constant representing the $M1$ (s wave) strength, and b is a constant representing the $E1$ (p wave) strength in the distribution. This form is expected on the basis of $M1$ (s wave) and $E1$ (p wave) absorption [1] and the assumption of spin-independent interactions. Because an analyzing power measurement is a relative measurement, only the shape of the distribution is required. The user can vary the ratio between the $M1$ and $E1$ strengths by varying a single parameter corresponding to the ratio of a/b. The outgoing neutron, with characteristics chosen from the above distribution, is then propagated through the experimental apparatus and allowed to interact with the carbon and deuterium nuclei in the target. Elastic, inelastic, and differential cross sections obtained from [9,10] determine the probability of interaction. If an interaction occurs, a new neutron trajectory and energy is assigned, and the process is repeated until the neutron escapes the target. Once the neutron leaves the C_6D_{12} target, the Monte Carlo code checks to see if its trajectory intersects with any of the detectors. If an intersection occurs, the probability of detecting the neutron is calculated according to the path length through the detector, the elastic scattering cross section with the detector materials, and an estimated detector response function. The entire process is repeated for additional neutrons until sufficient statistics are gathered to determine what asymmetry should be measured based on the original user-defined angular distribution for $^2\mathrm{H}(\vec{\gamma},n)$. The processes was repeated until the a/b ratio corresponding to the measured analyzing power is found. The ‘‘true’’ analyzing power can now be deduced from Eq. (1) using

$$\Sigma(\theta)=\frac{\sigma(\theta,\phi=0°)-\sigma(\theta,\phi=90°)}{\sigma(\theta,\phi=0°)+\sigma(\theta,\phi=90°)}, \tag{2}$$

and is found to be $\Sigma(150°)=0.78\pm0.035$. The program was tested by using it to successfully reanalyze data from the higher energy deuterium photodisintegration experiment documented in [7].

To extract the percentage $M1$ contribution to the cross section from this corrected measurement, we express the cross section and analyzing power in terms of Legendre functions and transition matrix elements (TMEs). Using the formalism for $(\vec{\gamma},X)$ reactions described in [11] and making the simplifying assumptions described below, the cross section can be written as

$$\sigma(\theta,\phi)=\frac{\bar{\lambda}^2}{24}\left[|S|^2+\frac{27}{2}|P|^2\sin^2\theta(1+\cos2\phi)\right], \tag{3}$$

where $\bar{\lambda}$ is the wavelength of the incident γ ray divided by 2π, $|S|^2$ is the $M1$ (s wave) intensity, and $|P|^2$ is the $E1$ (p wave) strength. Note that this expression has the same form as Eq. (1) used in the Monte Carlo code. This expression for the cross section makes the following assumptions:

(a) Due to the low energies involved, only $l=0$ and $l=1$ partial waves are considered in the outgoing channel. This allows two $M1$ states and four $E1$ states.

(b) The spin zero $(l=1,\ s=0)E1$ term does not contribute because of the spin independence of the $E1$ operator, since the ground state is predominantly $l=0{,}2,\ s=1$.

(c) The spin one $(l=0,\ s=1)M1$ term does not contribute because it has the same quantum numbers as the deuteron ground state and is therefore suppressed. (Note that our results are independent of this assumption.)

(d) The $l=1,\ s=1\ E1$ terms $(j=0{,}1{,}2)$ are combined to form a single p-wave amplitude.

Using Eq. (3), the analyzing power can then be expressed as

$$\Sigma(\theta)=\frac{\frac{27}{2}|P|^2\sin^2\theta}{|S|^2+\frac{27}{2}|P|^2\sin^2\theta}. \tag{4}$$

The $M1$ contribution to the total cross section can be determined by integrating Eq. (3) and inserting the ratio into the result. The integrated cross section is given by

$$\sigma_{tot}=\pi\bar{\lambda}^2\left[\frac{1}{6}|S|^2+\frac{3}{2}|P|^2\right], \tag{5}$$

which defines the percentage s-wave contribution to the cross section as

$$S=\frac{\frac{1}{6}n}{\frac{1}{6}n+\frac{3}{2}}, \tag{6}$$

where $n=27a/2b$ represents the relative $M1$ and $E1$ strengths. Based on this expression and the previously determined value of a/b, the total $M1$ contribution to the cross section for $E_\gamma=3.58$ MeV is $9.2\pm1.8\%$, where the error is statistical only. This $M1$ contribution corresponds to a ‘‘true’’ analyzing power at 150° of 0.787 ± 0.035. These results are in good agreement with the theoretical calculations of Arenhövel [1,12], which predict an $M1$ contribution of 7.3% and a corresponding analyzing power at 150° of 0.81.

The $p(n,\gamma)^2$H cross sections most relevant to big bang nucleosynthesis (BBN) calculations involve a neutron center of mass energy between 25 and 200 keV [2]. In the reverse reaction, this corresponds to photodisintegration with $E_\gamma=2.28$–2.63 MeV. The measurement reported here is therefore not directly applicable to current BBN calculations. However, the agreement with theory obtained at $E_\gamma=3.58$ MeV lends substantial credibility to the theoretical extrapolation down to these energies, eventually connecting to the previously well-determined ($M1$) cross sections at thermal energies [13].

In conclusion, the first nuclear physics measurement at the HIGS facility has been successfully completed. The $M1$ contribution to the $p(n,\gamma)^2$H cross section has been measured near the energy region relevant to big bang nucleosynthesis calculations, and is in agreement with theory. The method used for this measurement can easily be reapplied with lower γ-ray energies. Improvements to the HIGS facility planned for early 2000 will allow increased intensities in the desired energy range with sufficient γ-ray flux to significantly improve the statistical uncertainties and contribute to a better understanding of the n-p system in this energy regime.

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