Threshold deuteron photodisintegration ($d(\vec{\gamma},n)p$) at HI$\vec{\gamma}$S

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Abstract

Potential models (Arenhövel et al. 1998), effective field theory calculations (Burles et al. 1999; Chen and Savage 1999; Nollett and Burles 2000), and phenomenological R-Matrix calculations all predict a rapid fall off of the M1 cross section for the reaction $d(\vec{\gamma},n)p$ as the energy increases from threshold to 10 MeV. A detailed knowledge of the M1 component of this cross section is important as it determines the cross section at the energies relevant to Big-Bang nucleosynthesis as well as the dominant threshold contribution to the GDH sum-rule for the deuteron. A precision asymmetry measurement was recently made at the High Intensity Gamma Source (HI$\vec{\gamma}$S) at the Duke Free Electron Laser Laboratory using 100% linearly polarized γ's at energies of 2.6, 3.5, 4.0, and 6.0 MeV incident upon a deuterated target. The newly constructed BLOWFISH array was used to detect neutrons scattered from the target. Analysis of the experimental data is underway and a sample of the results at 6 MeV will be presented. Ultimately, the connection of the experimental data to theory is dependent upon a Monte Carlo simulation to correct for finite detector size and multiple scattering effects. This simulation is being developed by a member of the collaboration from the University of Saskatchewan. It is now (Feb. 2002) functionally complete but must be thoroughly shaken down before the final corrections can be made.

Introduction

Big-bang nucleosynthesis (BBN) provides a direct probe of the physics in the very early universe ($t \sim 0.01$–200 s). Comparison of the observed abundances of the light elements D, ^{3}He, ^{4}He, and ^{7}Li with their calculated abundances provides a very strong test of big-bang cosmology. BBN is also provides the best determination of the cosmic baryon density and is fundamentally tied to the exploring the existence and extent of nonbaryonic dark matter. The foundation of these early nuclear processes lies in the strength of the reaction producing deuterium, the lightest nuclear bound state. Unfortunately experimental data in the energy range appropriate to BBN ($25 < 300$ keV in the center of mass system) are sorely lacking. Present phenomenological models (Nollett and Burles 2000; Burles et al. 1999) rely on theoretical extrapolations constrained by np scattering phase shifts measured in the 1970's, some questionable photodisintegration data, and a minor update to match some thermal neutron capture ($E_n < 0.1$ eV) data taken in the 1980's. An alternative to directly measuring the np capture cross section is to measure the *inverse* reaction $d(\gamma,n)p$ instead. The ability of new laboratories such as HI$\vec{\gamma}$S to provide high intensity, high quality γ-ray beams has rekindled interest in this approach. Recently, a number of accurate effective field theory (Chen and Savage 1999) and potential model (Arenhövel et al. 1998) calculations have been completed for the $d(\vec{\gamma},n)p$ reaction from threshold up to 10 MeV.

In our experiment we took advantage of the 100% linear polarized γ beam available at HI$\vec{\gamma}$S to make a precision measurement of the $d(\vec{\gamma},n)p$reaction. An important characteristic of the capture cross section at energies relevant to BBN is that it goes from being dominated by an E1 contribution at higher energies to being almost completely M1 at lower energies. The M1 component manifests itself in an anisotropic distribution of the ejected neutrons in azimuthal angle (ϕ). Referred to as the *analyzing power*, or simply the neutron *asymmetry*, this will allow us to provide a strong constraint on the cross section extrapolation by precisely pinning down the E1/M1 ratio over this energy range. Moreover, this asymmetry may be easily computed using the various theoretical models and will provide an excellent test of those calculations near threshold.

Finally, the same data will be used to extract absolute cross sections for $d(\vec{\gamma},n)p$ (and conversely, for $p(n,\gamma)d$). However, until a more sophisticated γ flux monitoring device comes online at HI$\vec{\gamma}$S in 2003, these results are unlikely to have sufficiently low systematic uncertainties to be decisive.

The HI$\vec{\gamma}$S Facility

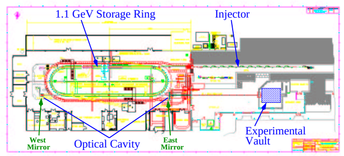

Figure 1. Overview of the HI$\vec{\gamma}$S facility.

The High Intensity Gamma Source (HI$\vec{\gamma}$S) is located at the Duke Free-Electron Laser Laboratory. An overview of the facility layout is shown in Figure 1. The operating principle of HI$\vec{\gamma}$S is the Compton backscattering of the free-electron laser (FEL) photons in the storage ring. In FEL mode a single electron bunch is injected into the storage ring. As the electron bunch orbits counterclockwise it passes through a region of rapidly alternating magnetic field called a undulator located in the south straight section. The electrons oscillate as the move though this field and radiate photons which are captured in an optical encompassing that portion of the beamline. The length of the cavity is tuned such that the time it takes a radiated photon to travel from the east mirror to the west mirror and back to the center is the same as orbital period for the electron bunch. When the photon(s) pass through the undulator at the same time as the electron bunch there is a stimulated emission of photons with the same phase and frequency (*ie.* a LASER). These FEL photons are typically in the optical region of the spectrum. When γ-rays are needed, a second electron bunch is injected into the ring 180° out of phase with the original bunch. When *this* bunch enters the straight section it encounters the FEL photons (generated by the initial bunch) head on. Some fraction of the FEL photons will Compton scatter 180°, reversing their direction in the optical cavity and being boosted in energy a million-fold by the transfer of kinetic energy from the electron in the interaction. Those photons (now γ-rays) are no longer reflected by the mirror at the east end of the optical cavity and are collimated for use in the experimental vault. The energy of the γ-ray beam may be selected by appropriately adjusting the energy of the electrons in the ring and the field strength in the undulator. The energy spread of the resulting γ-ray beam is primarily a function of the collimator size (with a limiting resolution of about 0.5% due to properties of the originating electron beam). The γ-ray beam also maintains the 100% linear polarization of the FEL photons. Prior to an extended shutdown for upgrades beginning in November 2001 (extending through mid-2002), beams having a maximum energy of 50 MeV and an energy spread of 1% had been produced with intensities on the order of 5×10^7 γ/s.

Experimental Setup

The BLOWFISH detector array (Fig. 2) is currently the flagship detector available at HI$\vec{\gamma}$S. The component cells were extracted from a decommissioned detector originally built at the Saskatchewan Accelerator Laboratory several years ago. In order to satisfy the experimental requirements at HI$\vec{\gamma}$S a new support frame was designed and built at the University of Virginia. Completed in early 2001, the final configuration consists of 88 BC-505 liquid scintillator cells located on the surface of a 16" diameter sphere centered on the target in 8 uniformly spaced arms of equal azimuthal angle ϕ. The 11 cells in each arm are uniformly distributed between polar scattering angles θ of 22.5° and 157.5°. The excellent pulse-shape discrimination (PSD) properties of BC-505 provide a strong handle on neutral particle (neutron/γ) identification down to about 200 keV$_{electron-equivalent}$ (keV$_{ee}$). This particle ID capability is enhanced and extended by taking advantage of the pulsed nature of the HI$\vec{\gamma}$S γ-beam to provide time of flight (ToF) information. The broad coverage (25% of 4π sr) of the detector and its ability to be rotated about the beam axis permit high statistical precision as well as an accurate determination of systematic effects.

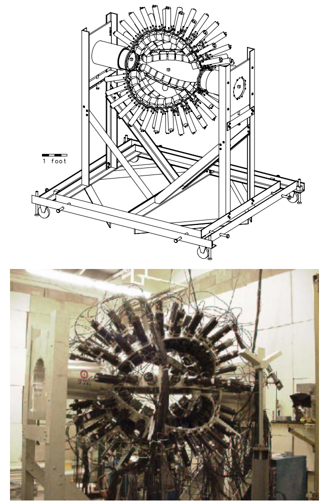

Figure 2. The 88 cell BLOWFISH detector array (two of the array's eight arms have been cut-away in the top figure).

The first experiment using this detector was a precision measurement of the reaction $d(\vec{\gamma},n)p$ completed at HI$\vec{\gamma}$S in July 2001. In that measurement 100% linearly polarized γ's with energies of 2.6, 3.5, 4.0, and 6.0 MeV were incident upon a deuterated target. Neutrons scattered from the target were detected in the newly commissioned BLOWFISH array. Figure 3 provides a cartoon layout of the experimental apparatus used for this experiment.

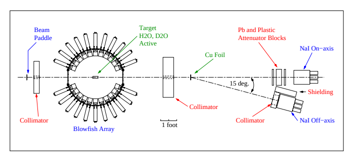

Figure 3. Diagram of the experimental apparatus used for the $d(\vec{\gamma},n)p$ measurement.

The beam paddle (a 1/8" thick plastic scintillator detector) upstream of the BLOWFISH was used to provide a nominal measure of the incident γ flux. The downstream NaI detectors provide a monitor of the γ beam energy and may provide a more accurate measure of the γ flux. Clearly this is hardly an optimal approach as the flux seen by the downstream NaI's has already been reduced by the beam's interaction in the target. The γ beam was collimated to a diameter of 1" providing an energy resolution (ΔE/E) of $\sim 3\%$. The typical on-target intensity of the beam was on the order of 5×10^5 γ/s. The resulting 44 data points (11 bites in θ at each energy) will be used to test the predictions of potential and effective field models that apply to the np system.

Conclusions

Figure 4 provides a sample of the data taken at 6 MeV. The data shown represents roughly 10% of the data taken at that energy setting and comprises perhaps 2% of the total data set. Error bars (statistical only) are already at the few percent level. The good agreement at forward and backward angles is an indication of the quality of our neutron-γ particle discrimination as photon backgrounds were 10–100$\times$ larger at the forward angles.

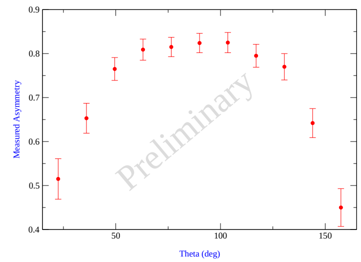

Figure 4. A sample of the $d(\vec{\gamma},n)p$ data taken at 6 MeV.

Future Plans

First and foremost we are focusing on the shakedown of the Monte Carlo simulation of the BLOWFISH array. Once we are confident of its performance the final corrections can be applied to the data and the connection to theory can be made.

The data at $E_\gamma = 2.6$ MeV (not shown) were a pleasant surprise. At that γ energy the resulting neutron can deposit a *maximum* of about 60 keV$_{ee}$ in a cell (the majority of neutrons will only deposit a third of that amount). With our present equipment we were able to push the detection threshold down to < 10 keV$_{ee}$. The reaction signature is quite small relative to the higher energy data but it will be possible to extract a good asymmetry measurement from it nevertheless. One option to further improve the array's performance is to replace the PMTs and bases (which are showing their age) with new, quieter versions. The improved gain and reduced tube noise will provide even lower thresholds and improve PSD performance at these low energies.

Optimizing the array to perform well in this very low energy region will allow our results to overlap with analogous measurements done using the inverse capture reaction $n(p,d)\gamma$ at Duke University's TUNL facility. The combined effect of these two approaches will provide an exceptional handle on the physics that dominate that energy region.

In order to perform an absolute cross section measurement one must know the neutron detection efficiency of the detector. The cell efficiencies already been well established over the neutron energy range of 2–15 MeV through work done at the University of Saskatchewan (Sawatzky 1999). An overlapping efficiency measurement at low neutron energies (100 keV–8 MeV) was completed in February 2002. Once analyzed, this efficiency data can then be used to extract absolute cross sections from the neutron yields in addition to the precision asymmetry results.

Gerasimov-Drell-Hearn Sum Rule

The ultimate goal for the BLOWFISH array and a priority measurement at the HI$\vec{\gamma}$S facility is the measurement of the Gerasimov-Drell-Hearn (GDH) sum rule for the deuteron. First derived in 1966 (Drell and Hearn 1966; Gerasimov 1966) the sum rule connects the anomalous magnetic moment (κ) of a particle with the energy weighted integral (I^{GDH}) from threshold up to infinity over the difference of total photoabsorption cross sections for circularly polarized photons on a target with spin parallel and anti-parallel to the spin of the photon ($\sigma^{P/A}$ respectively). For a particle with mass M, and spin S, the relationship can be written

$$I^{\mathrm{GDH}} = 4\pi^2\kappa^2\frac{e^2}{M^2}S = \int_0^\infty \frac{dk}{k}\left(\sigma^P(k) - \sigma^A(k)\right).$$

This result is quite remarkable as it connects a macroscopic ground state property of a particle (κ) to a cumulative effect of its entire excitation spectrum. A future upgrade of the current undulator at HI$\vec{\gamma}$S is planned for 2003. This next-generation model will be capable of providing the necessary circular polarized photons (while maintaining the ability to produce linear polarized light). In conjunction with an upgrade to the electron ring scheduled for the same shutdown cycle, this will allow a precision measurement of the GDH integrand to be made from near-threshold up to 50 MeV.

REFERENCES

Arenhövel, H., Kress, G., Schidt, R., & Wilhelm, P. 1998, Nucl. Phys. A, 631, 612.

Burles, S., Nollett, K. M., Truran, J. W., & Turner, M. S. 1999, Phys. Rev. Lett., 82, 4176.

Chen, J. W., & Savage, M. J. 1999, Phys. Rev. C, 60, 065205.

Drell, S. D., & Hearn, A. C. 1966, Phys. Rev. Lett., *16*(20), 908.

Gerasimov, S. B. 1966, Sov. J. Nucl. Phys., 2, 430.

Nollett, K. M., & Burles, S. 2000, Phys. Rev. D, 61, 123505.

Sawatzky, B. D. 1999. *Calibration of a BC-505 Segmented Neutron Detector over the energy range of 2–15 MeV*. M.Sc. Thesis, University of Saskatchewan.

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