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

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How well do we understand the Deuteron?

The **deuteron** is the simplest nuclear system. There are just two participants, one neutron and one proton, loosely bound by the strong nuclear force. This simplicity has made it a wonderful system for physicists to explore and use as testing ground for our theories of the nucleon-nucleon (NN) interaction.

The purpose of our experiment was to perform a measurement on this system in order gain insight in the physics at these energies and to test the low energy performance of our best models. (The *threshold* in the poster title refers to the minimum energy needed to break the bond between the nuclei.) Relevant theories in this energy domain include

- **Effective Field Theories** (EFT) in which certain symmetries of Quark Chromodynamics (QCD) are used to simplify the fundamental, yet prohibitively complicated, quark-gluon interactions into something that can be computed (Chen and Savage 1999; Burles et al. 1999; Nollett and Burles 2000).
- **Potential models** (Arenhövel et al. 1998) do not contain any reference to QCD (quarks, gluons, etc.) but instead model the interactions as exchanges of composite particles (in the QCD sense) like pions and other heavier mesons.

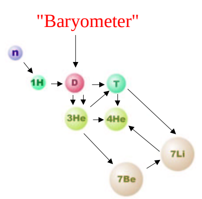

Figure 1. Deuterium production lies at the foundation of the Big-bang nucleosynthesis reaction chain.

The creation and destruction of deuterium also plays a fundamental role in astrophysics. **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 (deuterium), ^{3}He, ^{4}He, and ^{7}Liwith 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 non-baryonic dark matter. The foundation of these early nuclear processes lies in the strength of the reaction producing deuterium, the lightest nuclear bound state (Fig. 1).

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

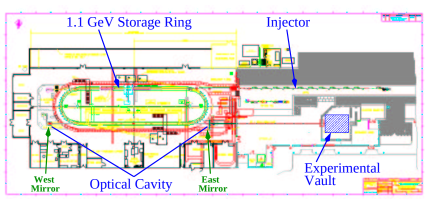

Figure 2. Overview of the HI$\vec{\gamma}$S facility.

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 2. The operating principle at 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 fields located along the south (bottom) straight section (called the OK-4). The electrons oscillate as they move though this field and radiate photons which are captured in an optical cavity 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 (right-hand) mirror to the west (left-hand) mirror and back to the center is the same as orbital period for the electron bunch. When the photons pass through the OK-4 at the same time as the electron bunch they stimulate the radiation of photons with the same phase and frequency – just as in a conventional laser. The magnetic field of the photons are aligned along the OK-4's magnetic field plane, hence the resulting beam is also linearly polarized.

The FEL photons are fairly low in energy, typically in the optical region of the spectrum. When γ-rays are needed, a second electron bunch is injected into the ring exactly halfway around the orbit relative to the original bunch. When the second bunch enters the straight section it encounters the FEL photons (generated by the first 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 through the collision. The resulting 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 (Fig. 3). This unique facility provides us with a very clean, virtually monoenergetic, 100% polarized γ-ray beam.

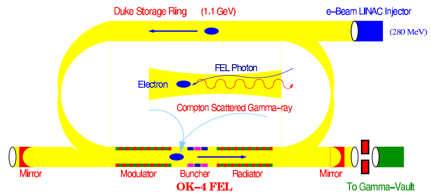

Figure 3. Low energy photons in the optical cavity are converted to γ-rays by scattering off an electron bunch.

Experimental Setup

Designed and built here at UVA in 2001, the **BLOWFISH array** (Fig. 4) is one of the of the key detector packages available at HI$\vec{\gamma}$S. The detector 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$_{ee}$†. 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.

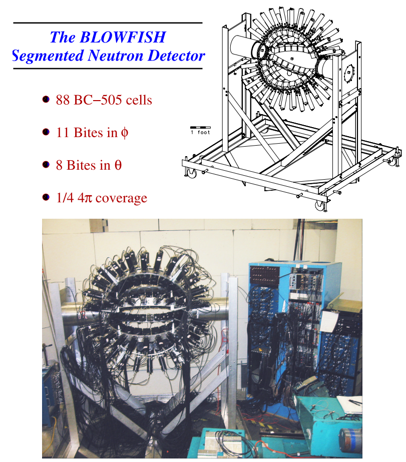

Figure 4. The BLOWFISH segmented detector array.

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. When a γ-ray is absorbed by a deuteron, its energy tears the proton and neutron apart. Due to the polarized nature of the photon, the neutron and proton have a greater probability of been ejected in the plane of the photon's electric field. At our energies, the proton (being charged) stops almost instantly inside the target, but the neutron is able to escape and may be detected in the BLOWFISH array.

† keV$_{ee}$ is keV *electron-equivalent*, a unit that normalizes a detector's energy response to heavier particles (protons, neutrons, etc.) to the energy deposited by an incident electron.

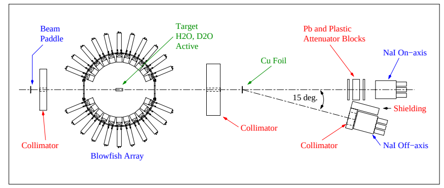

Figure 5. Diagram of the experimental apparatus used for the $d(\vec{\gamma},n)p$ measurement.

The degree to which the neutrons (and protons) tend to favor being ejected in one direction (or plane) than another is quantified by calculating the **Asymmetry** (Fig. 6). The 11 rings in BLOWFISH allow us to calculate 11 independent asymmetries at each γ energy. The magnitude of these asymmetries and how they vary as a function of θ and energy reflect the nature of the force binding the two nucleons together.

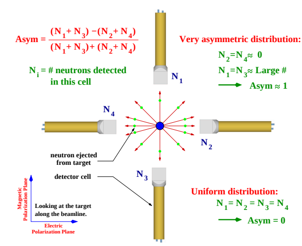

Figure 6. How the **Asymmetry** is computed.

What did we discover?

Data for three of the four energy settings has been analyzed. Figure 8 provides a comparison of our data against the predictions of a Potential Model (Arenhövel et al. 1998), and an Effective Field Theory (Chen and Savage 1999). The agreement between our data and theory is generally good with the notable exception of a systematic divergence at backward angles ($\theta \geq 120°$) in the 6 MeV data set. At $\theta = 157.5°$ the discrepancy is more than five standard deviations. **Interesting!**

As it happens, the results of a $d(e,e'p)n$ experiment done at the Darmstadt electron LinAc were recently published (von Neumann-Cose et al. 2002). This experiment differs in many ways from our own, but it does provide a test of the same nuclear system and theoretical models at energies comparable to what we used. (E_x is the energy transfered to the deuteron by the electron. It is roughly equivalent to E_γ in our $d(\vec{\gamma},n)p$ measurement.) Figure 7 shows plot of the double-differential cross sections extracted from their data plotted against a calculation from Arenhövel's theory. Note the discrepancy between data and theory popping up again back angles. This is a log plot so the difference is larger than it appears at first glance – 30% or more around $\theta = 160°$ (well outside several standard deviations).

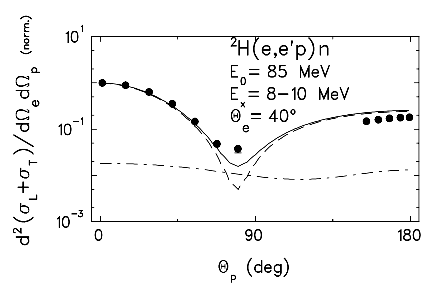

Figure 7. Results from Darmstadt von Neumann-Cose et al. (2002). Sum of the double-differential longitudinal and transverse cross sections of the $d(e,e'p)$ reaction at incident electron energy $E_0 = 85$ MeV for an excitation energy bin $E_x = 8$–10 MeV as a function of polar proton emission angle θ_p. The dashed and dash-dotted lines are theoretical predictions for σ_L and σ_T, and the solid line is the sum of both. Error bars are typically hidden beneath the data points.

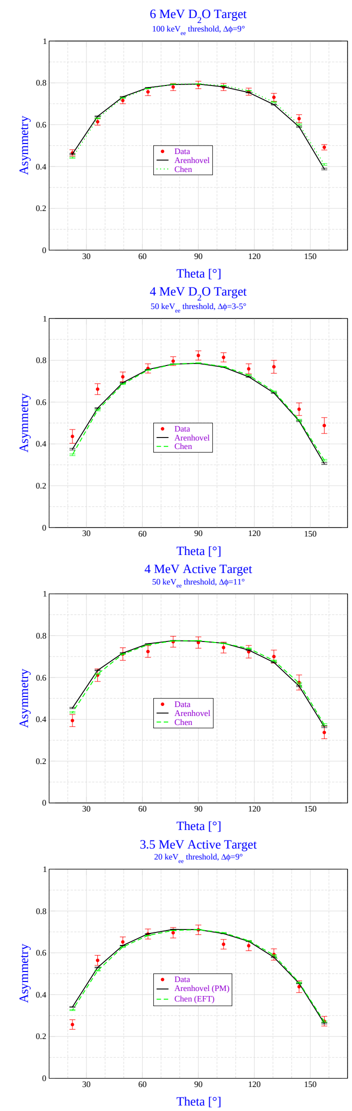

Figure 8. Asymmetry vs. θ for $d(\vec{\gamma},n)p$. Note the discrepancy at backward angles at $E_\gamma = 6.0$ MeV.

Perhaps there is more to this most basic nuclear system than we thought? Work is in progress to upgrade the BLOWFISH hardware and plans are being made to revisit this experiment at both higher (E_γ =6–15 MeV), and lower ($E_\gamma \leq 2.6$ MeV) energies in the near future.

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.

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

von Neumann-Cose, P., Richter, A., Schrieder, G., Shevchenko, A., Stiller, A., & Arenhövel, H. 2002, Phys. Rev. Lett., 88, 202304.

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