9 HIGS Facility at the DFELL

9.1 First Experiments

9.1.1 Near-Threshold Photodisintegration of Deuterium at HIGS


A paper which reports the results of our first measurement of the analyzing power for the $^2\text{H}(\gamma,n)p$ reaction at a gamma-ray energy of 3.58 MeV was recently published in [Sch00]. The abstract of this paper follows:

The first measurement of the $^2\text{H}(\gamma,n)p$ 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 $\gamma$-ray beam having an energy resolution of 2.5\% and 100\% linear polarization was incident on an active D\textsubscript{6}D\textsubscript{12} target. Outgoing neutrons were detected parallel and perpendicular to the plane of $\gamma$-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.

We have recently run this experiment again. As before, our gamma-ray beam was generated using a backscattered FEL photon beam, producing a 100\% linearly polarized gamma-ray beam. In this case, the beam energy was lowered to 3.2 MeV. The experimental setup was essentially the same as before. The target was a deuterated liquid scintillator, and the detectors consisted of four new liquid scintillator neutron detectors (provided by W. Tornow), positioned left, right, up and down with respect to the beam direction at a scattering angle of 150 degrees. In this experiment, the neutron detectors were pulled further back (4-inches) from the target in order to reduce the size of the finite-geometry corrections.

The results of these measurements gave a corrected analyzing power of 0.55(0.06). Performing an analysis identical to the one reported in [Sch00] leads to a percent $M1$ contribution of 26.9(2.7)\%, considerably larger than the theoretical values of $\sim$17\% [Are91, Are99, Che99]. Using the theoretical value of the total cross section, this gives an $M1$ cross section at 3.2 MeV of 0.62(0.06)mb, which is also considerably larger than the theoretical value. The results of this and our previous result at 3.58 MeV are shown in Fig. 9.1–1 along with the

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theoretical prediction of [Che99].

Figure 9.1–1: The measured values of the M1 cross section for the $^2\text{H}(\gamma,n)^1\text{H}$ reaction compared to the predictions of [Che99].

These results can also be used to obtain information on the Gerasimov-Drell-Hearn sum-rule for the deuteron. It has been predicted [Are98] that most of the GDH sum rule strength for the deuteron below pion threshold will occur just above photo-disintegration threshold as a result of the $^1S_0$ resonance. The integrand of the GDH sum rule involves the difference of the total absorption cross sections when the spins of the deuteron and the photons are parallel and anti-parallel, respectively. This quantity can be written in terms of the contributing transition matrix elements. If we make the reasonable assumption that the $p$-wave (E1) amplitudes are equal, the $p$-wave terms drop out. Then, by assuming that the M1 strength is dominated by the $^1S_0$ term, we can evaluate the quantity $\sigma_P - \sigma_A$. The results are shown in Fig. 9.1–2, along with the theoretical predictions of [Are98]. Clearly, although our 3.58 MeV data point is in good agreement with theory, the 3.2 MeV result is in serious disagreement.

This preliminary result indicates the need for further studies at these and other energies. Such experiments are planned for the near future, although running below a gamma-ray energy of 3.0 MeV will require further development work on both the beam and the neutron detectors.


Figure 9.1–2: The “deduced” values of $\sigma_P - \sigma_A$ from the HIGS experiment compared to the theoretical predictions of [Are98].


9.1.2 Nuclear Resonance Studies of the $^{13}\text{C}(\gamma,n)^{12}\text{C}$ Reaction at HIGS


As has been previously reported in [Sch98], a resonance study of the $^{13}\text{C}(\gamma,n)^{12}\text{C}$ reaction was conducted last year at the High-Intensity Gamma-ray Source (HIGS) at the Duke Free-Electron Laser Laboratory. The analyzing power $\Sigma(\theta) = (N_\parallel - N_\perp)/(N_\parallel + N_\perp)$ was measured at $\theta = 90^\circ$ as a function of energy, with $E_\gamma$ ranging from 7.7 to 10.26 MeV in 150 keV steps, using a 100% linearly polarized $\gamma$-ray beam. $N_\parallel$ and $N_\perp$ are the number of outgoing neutrons detected in and out of the horizontal $\gamma$-ray polarization plane, respectively. Time-of-flight (TOF) and pulse-shape discrimination (PSD) techniques were used to separate the neutrons of interest from scattered $\gamma$ rays and background neutrons.

Effects due to the finite size of the target and detectors are being simulated in a Monte-Carlo code. Optical-model calculations have been performed for the $^{13}\text{C}(n,n)^{13}\text{C}$ reaction

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using the optical-model code GENOA. The resulting cross sections will be incorporated into
the simulation, which will then be used to correct for finite-geometry and multiple-scattering
effects.

Previous measurements [Woo79, Hol79] of this reaction suggest the presence of states at
7.70 MeV ($\frac{3}{2}^+$), 7.95 MeV ($\frac{3}{2}^+$), and 8.95 MeV ($\frac{5}{2}^-$). These measurements were made using
$\gamma$ rays from unpolarized bremsstrahlung sources, and resonance information was extracted
from the measured $n_0$ angular distribution. The following treatment assumes that the
resonance states are pure $d$-wave E1 and pure $p$-wave M1.

To extract the relative percentage of the $d$-wave E1 and the $p$-wave M1 contributions
to the cross section after correcting for finite geometry and multiple scattering, the cross
section and analyzing power are expressed in terms of Legendre functions and transition
matrix elements (TMEs). Using the formalism for ($\gamma, X$) reactions described in [Wel92],
the cross section can be written as

$$
\sigma(\theta, \phi) = \frac{\lambda^2}{16\pi} \left[ |P|^2 + \left( \frac{3}{2} \sin^2 \theta (1 + \cos 2\phi) + 1 \right) |D|^2 \right],
$$

where $\lambda$ is the wavelength of the incident $\gamma$ ray, $|P|^2$ is the $p$-wave M1 intensity, and $|D|^2$
is the $d$-wave E1 strength. The analyzing power can then be expressed as

$$
\Sigma(\theta) = \frac{[\sin^2 \theta] |D|^2}{\frac{2}{3}|P|^2 + [\sin^2 \theta + \frac{2}{3}] |D|^2}.
$$

Preliminary results show tentative agreement with the previously inferred $J^\pi$
assignments of the $^{13}$C resonances mentioned above. In particular, the analyzing power near the
7.95 MeV ($\frac{3}{2}^+$) E1 resonance is approximately 0.6, while the analyzing power near the 8.95
MeV ($\frac{5}{2}^-$) M1 resonance is approximately zero, as expected from Eq. 9.1 (see Fig. 9.1–3).
A resonance plus direct-capture calculation will help extract the resonance parameters by
incorporating the analyzing power data into the fit.


Figure 9.1–3: Neutron asymmetries in the TOF spectra as a function of energy. $N_h$ and $N_v$ are the number of neutrons detected in the horizontal and vertical detector positions, respectively. The error bars are statistical.

9.2 Detector Developments

9.2.1 Construction of a NaI Detector Mount for Compton Scattering from Protons

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We have designed and constructed an apparatus to hold the detectors and anti-coincidence shields needed for our experiment which will measure the electric and magnetic polarizabilities of the proton. This experiment will involve Compton scattering of ~50 MeV 100% linearly polarized γ rays, produced by the DFELL/TUNL High-Intensity Gamma-Ray Source (HIGS), from the protons of a liquid hydrogen target.

Our plan is to measure the relative scattering cross sections of γ rays scattered in the plane of polarization and perpendicular to the plane of polarization at several different scattering angles using four 25 cm × 25 cm NaI detectors surrounded by plastic anti-coincidence shields. This plan required an apparatus with several important features:

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1. The four steel arms, with a 1.5 m radius of curvature, support two detectors (with shields) in the plane of polarization (left and right) and two detectors (with shields) perpendicular to the plane of polarization (up and down). Due to the nature of the polarized beam it is expected that the scattering will exhibit left-right symmetry as well as up-down symmetry. Therefore, we increase our statistics two-fold by having two detectors in each scattering plane.

2. Each detector is mounted on a trolley wheel assembly which allows the detectors to be moved along the steel arms, thereby allowing them to be placed between $\theta = 90^\circ$ and $\theta = 28^\circ$ with respect to the beam axis. Simulations have shown that $30^\circ$ is a critical angle for measuring the polarizabilities of the proton.

3. The entire assembly is mounted on an angle iron frame which, in turn, is mounted on wheels. This allows our entire setup to be rotated by $180^\circ$ so that we can measure back-angle scattering between $\theta = 90^\circ$ and $\theta = 152^\circ$. A more spherical design in which the steel arms had an arc length which encompassed the entire angular spread, both forward and backward scattering, was not possible due to space restrictions in the experimental area.

4. All four steel arms can be completely rotated about the beam axis with an angular spread of $\Delta\phi = 2\pi$. This ability to rotate about $\phi$ is necessary so that we can cancel out possible detector asymmetries by interchanging the various detectors.

The entire setup is approximately 3.6 m tall, 3.4 m wide, and 2.4 long and is currently set up in the Gamma Vault of DFELL. Presently, we are in the process of installing the shields and working on getting the liquid hydrogen target ready, which will hopefully be available by the fall. Our immediate plans are to run a preliminary experiment with an active scintillating target and $\sim50$ MeV $\gamma$ rays beginning in early September.

### 9.2.2 Development of a Compton Scattering Beam-Flux Monitor for the HIGS Facility at the DFELL


A beam-flux monitor is being developed for use with the $\gamma$-ray beam at the DFELL/TUNL High-Intensity Gamma-Ray Source (HIGS). At the higher beam intensities and energies which will soon become available, new methods for beam-flux measurements are required. One such method is the use of a NaI detector placed at a small angle relative to the beam.

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axis, which detects the photons that are Compton-scattered from a thin Pb target located downstream from any other experimental apparatus. This method allows monitoring of the beam flux in parallel with experimental data acquisition. The feasibility and accuracy of this method at relevant energies is under investigation.

Initial tests have been performed with a HPGe detector directly in the HIGS beamline to measure the beam flux, and two NaI detectors slightly off the beam axis, for beam energies of 3.2, 3.6, and 4.0 MeV. The HPGe detector was located 2.22 m downstream of a 1/8” thick Pb scatterer. A 5” × 6” NaI detector was at 4.6° from the beam axis, and a 10” ×
A 10" NaI detector was at 6.7° from the beam axis, as shown in Figure 9.2-3.

![Diagram showing setup for measuring Compton-scattering flux with respect to total beam flux. Not shown in this figure are an upstream beam collimator and apparatus for an experiment running in parallel with these measurements.](image)

These measurements were made concurrently with data acquisition of the reaction \( ^2\text{H}(\gamma,n)^3\text{H} \), with the beam collimator and experimental apparatus (not shown) located approximately 3 m upstream of the Pb scattering target. The lead bricks shown in the figure were positioned to shield the two NaI detectors from the upstream collimator and apparatus. Initially, lead was also used to shield the NaI detectors from background caused by scattering from the HPGe detector. However, Monte-Carlo simulations indicated the count rate and energy of this backscattering would be low enough to not interfere with our measurements. This was verified by in-beam tests. Therefore, the lead shielding was removed from around the NaI detectors, in order to place the detectors at as small an angle to the beam as possible.

The HPGe efficiencies were obtained from [Sch96]. In that work, the measured efficiencies were fitted using the equation:

\[
\epsilon = a + \exp \left[ b \ln \left( \frac{1.022}{E_{\gamma}} \right) + c \left( \ln \left( \frac{1.022}{E_{\gamma}} \right) \right)^2 \right],
\]

where \( E_{\gamma} \) is in MeV, and the values obtained for the parameters \( a, b, \) and \( c \) are \(-0.7075 \pm 0.0002, 0.185 \pm 0.0017, \) and \( 0.0320 \pm 0.0013, \) respectively. The relative efficiencies of the two NaI detectors have been carefully measured with respect to the HPGe detector, using \(^{241}\text{Am}, ^{137}\text{Cs}, \) and \(^{22}\text{Na} \) sources (see Figure 9.2-4).

Preliminary comparisons with EGS4 simulations indicate that the relative efficiencies can be accurately predicted using Monte-Carlo calculations, and thus the beam flux can be
Figure 9.2-4: Relative efficiency of NaI detector with respect to the HPGe efficiency, as a function of energy. For the lower two data points, the error bars are too small to show up on this scale. A least-squares fit was performed.

determined. Continued studies are underway using GEANT simulations.

Current measurements indicate the beam flux determined by Compton scattering agrees with direct beam flux measurements to 2–3%. Further beam studies are planned for September 2000 at higher γ-ray beam energies.

9.3 Polarized Target Development

9.3.1 A Frozen Spin Deuteron Target for the DFELL

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The proposed measurement of the Drell-Hearn-Gerasimov sum rule at the HIGS facility requires a specific type of frozen spin deuteron target - one with a long, cylindrical target volume, polarized parallel to the cylindrical axis, and with close access for detectors to measure low-energy neutrons produced in photo-induced deuteron breakup. We have completed design specifications of the target, and with support of a DOE equipment grant, have begun assembling components for the target refrigerator gas handling system and the 2.5 Tesla polarizing magnet. The TUNL-designed, commercially-constructed magnet system should arrive at TUNL in August, 2000, and will be tested in the Fall. This year we will complete detailed shop drawings for the dilution refrigerator components and assemble the gas handling and target support structures.