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THE HIγS FACILITY: A FREE-ELECTRON LASER GENERATED GAMMA-RAY BEAM FOR RESEARCH IN NUCLEAR PHYSICS

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The High Intensity Gamma-ray Source (HIγS) is a joint project between Triangle Universities Nuclear Laboratory (TUNL) and the Duke Free Electron Laser Laboratory (DFELL). This facility utilizes intra-cavity back-scattering of the FEL photons in order to produce a γ-flux enhancement of approximately 10^3 over the existing sources. At present, gamma-ray beams with energies ranging from 2 to 50 MeV are available with intensities of 10^5–10^7 γ/s, energy spreads of 1% or better (with lower intensities), and 100% linear polarization. An upgrade is presently underway which will allow for the production of γ rays up to an energy of about 225 MeV having intensities in excess of 10^8 γ/sec. The primary component of the upgrade is a 1.2 GeV booster-injector which will provide for efficient injection at any chosen operating energy of the storage ring from 300 MeV to 1.2 GeV. In addition, an upgrade of the present OK-4 FEL to a helical undulator system (OK-5) is underway. This new system has many advantages over the present one, including making switchable linear and circularly polarized beams available, an increase in power and a decrease in mirror-damaging radiation. The full system, including the booster injector, is expected to be ready for use by 2006. TUNL researchers, in collaboration with outside theoretical and experimental colleagues, have proposed a broad based research program in nuclear physics which is designed to exploit the unique flux, energy resolution and polarization of the HIγS beams. A description of the presently available facility and the anticipated facility following the present upgrades will be given in this review, along with a description of recent and planned experiments.

Keywords: Free-electron laser; laser Compton backscattering, γ-rays.

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1. The High Intensity γ-Ray Source (HIγS)

There are at present a number of facilities which produce polarized γ rays for nuclear physics studies. All of those facilities which employ Compton backscattering

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techniques operate by scattering conventional laser light from electrons circulating in a storage ring. In our scheme, intracavity scattering of the FEL photons produces a γ-flux enhancement of approximately 10^3 over the existing sources. The Duke storage ring was designed to operate at energies from 250 MeV to 1.2 GeV. The Duke OK-4 storage ring XUV FEL can presently produce FEL photons up to 6.4 eV, with an upgrade underway which will increase this to 12.5 eV. This will allow for the production of γ rays up to an energy of about 225 MeV having an average flux in excess of 10^8/sec. This can be obtained with a modest beam having an average-stored current of only about 100–150 mA.

The major components of the HIγS facility are the OK-4 XUV FEL and the Duke 1.2 GeV electron storage ring with its 280 MeV linac injector. These facilities are located in the Duke University Free-Electron Laser Laboratory (DFELL). A diagram showing the γ-ray production scheme is presented in Fig. 1. In the case shown here, the two electron bunches contained in the ring can be thought of as a *lasing* bunch and a *scattering* bunch. The lased photons from one electron bunch are reflected from the downstream mirror, then collide head on with the second electron bunch at the *collision point*, producing gamma rays.[1] The flux of γ rays can be increased by increasing the current in the target bunch and/or by operating eight electron bunches. The present OK-4 FEL will soon be upgraded to a helical undulator system (OK-5[2]). The performance characteristics of the OK-4 XUV FEL are described in other publications.[3,4]

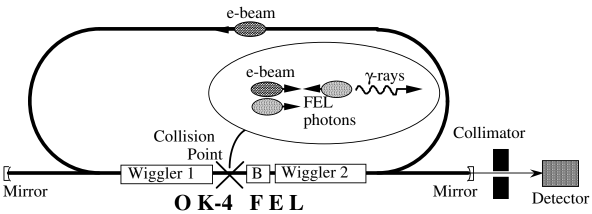

Fig. 1. Schematic diagram of the HIγS – the DFELL-TUNL γ-ray facility.

There are a number of distinct advantages of this system as compared to presently available ones. The first is the high flux which is already allowing us to measure nuclear processes with low cross-sections with good precision in realistic times. The second advantage is the fact that tagging is not needed. The high-quality of the electron beam permits energy definition by the use of collimation alone. This means that, unlike many tagged sources, there will be NO untagged high-energy γ rays. In addition, the energy of these beams can be currently tuned from 2 to 50 MeV, and up to 225 MeV when the upgrade is complete. The energy resolution of these beams is exceptional. For example, for a 10 MeV γ ray beam, a 3 mm radius collimator located 70 meters from the collision point provides an energy spread (FWHM) of less than 100 keV ($\sim$ 1%). These γ-ray beams are 100% linearly polarized, and the beam environment is exceptionally clean; backgrounds are negligibly small.

The present system can support the HIγS operation in the "no loss" mode up to 20 MeV. Total beam intensities on the order of 10^6–10^7 γ/s are available between 2 and 20 MeV. For γ-ray energies above 20 MeV, the recoil electrons exceed the energy acceptance of the storage ring. However, beams on target with intensities of $\sim 10^6$ γ/s are presently available up to 48 MeV. Higher energy γ-ray production requires that the electrons be replaced at full-energy.

The current electron source for the ring is a 280 MeV S-band radio-frequency linear accelerator. This system consists of 11 accelerator sections and an electron gun, all driven by three klystrons and is adequate to support the initial stage of operation during the construction of a 1.2 GeV booster injector. The construction of the booster will not interfere with normal operation of the HIγS facility. The booster injector utilizes standard technology and will provide for efficient injection at any chosen operating energy of the storage ring from 200 MeV to 1.2 GeV. Parts of the existing linac injector will be used for injection into the booster. The transition period from the existing linac injector to the full-energy booster injector will take about two months once the booster is completed. The proposed layout of the HIγS facility with the full-energy booster injector and the new helical undulator (OK-5) is shown in Fig. 2. A summary of the present and the anticipated total beam intensities is given in Table 1 below.

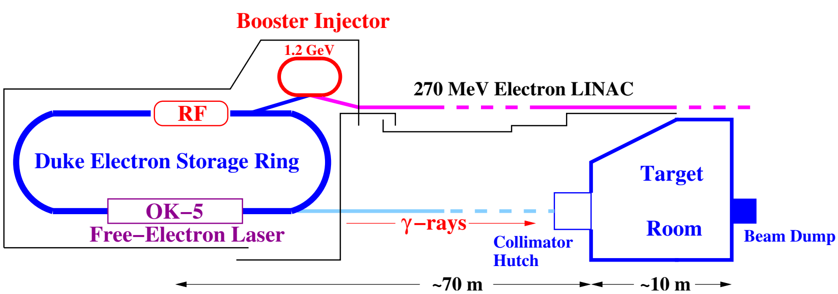

Fig. 2. Proposed layout of the HIγS facility with full-energy booster injector.

Table 1. Summary of the intensities at the HIγS facility.

E_γ	Intensity	Date
2–50 MeV	10^6–10^7 γ/s	Spring 2001
2–50 MeV	10^7–10^8 γ/s[a]	By 2005
	(with circular polarization[b])	
2–225 MeV	$> 10^8$ γ/s[c]	By 2006

[a]This anticipated intensity increase is a result of OK-5 and the RF upgrade.
[b]OK-5, the helical-undulator system will be operating by 2005.
[c]This follows the completion of the installation of the Booster-Injector.

2. The Physics Program at HIγS

2.1. *Studies of the nucleon*

The availability of high-intensity beams of polarized γ rays below 225 MeV will allow for a series of measurements which will test some of the most basic theories of nuclear and particle physics. At present, Quantum Chromodynamics (QCD) is the most fundamental theory of the strong force.[5] However, a treatment which allows for a direct solution of the QCD Lagrangian for the nucleus has not been discovered. Recently, however, a great deal of progress has been made in understanding low-energy interactions of pions, nucleons, and photons using Chiral Perturbation Theory (CPT). Chiral Perturbation Theory is an effective field theory which exploits the chiral symmetry of QCD in order to make rigorous contact with low-energy nuclear and particle-physics phenomenology. Calculations done within this framework allow one to test whether low-energy descriptions of strong-interaction phenomena are consistent with CPT, or more generally, with the standard model. Working within this framework assures us that the results will connect to the direct solution of the QCD Lagrangian, if and when it is discovered.

In the limit of vanishing u, d and s quark masses, the QCD Lagrangian admits a global chiral symmetry: $\mathrm{SU}(3)_L \times \mathrm{SU}(3)_R$. This symmetry is broken spontaneously, which implies the existence of eight pseudoscalar massless Goldstone bosons. Furthermore, since the quark masses are finite (but small), these Goldstone bosons acquire a small mass and are identified with the pions, the kaons and the eta. It is the fact that the interaction of these Goldstone bosons with themselves or matter fields, e.g., the nucleons, is weak, which allows for a systematic low-energy expansion in terms of small momenta and quark masses: Chiral Perturbation Theory. Chiral Perturbation Theory is a low-energy procedure, expected to be able to deal with reactions below about 500 MeV.[6] Consequently, CPT allows us to test our understanding of the spontaneous and explicit chiral-symmetry breaking and isospin-symmetry breaking contained in QCD.

The quark masses are important input parameters in the Standard Model. The determination of the light quark masses has, however, proven to be extremely difficult. CPT offers the framework to precisely determine the quark mass ratios.[5] The currently accepted values (at a renormalization scale of 1 GeV) are:

$$m_u \approx 5\ \text{MeV} \qquad \text{and} \qquad m_d \approx 9\ \text{MeV}$$

with $m_d/m_u \approx 2$. This large ratio might lead one to expect large isospin-violating effects. These effects are, however, efficiently masked since $(m_d - m_u)/\Lambda$ is, with $\Lambda = 1$ GeV, less than or equal to about 0.01. Note that Λ is the typical scale of the hadronic (chiral) interactions. For reactions involving only pions, effects related to the quark-mass difference $m_u - m_d$ cannot appear in leading order (G-parity). This is different in the three-flavor case (e.g., in $\eta \to 3\pi$) or in the presence of nucleons. In this latter case, the HIγS facility could provide an important contribution. To be specific, pion-photo-production offers two ways of observing effects due to isospin violation. The first one consists of a precise measurement of all four photo-pion production s-wave amplitudes $\gamma p \to \pi^+ n$, $\gamma p \to \pi^0 p$, $\gamma n \to \pi^- p$, and $\gamma n \to \pi^0 n$, where the latter two cases would be observed via coherent production from the deuteron. A recent TRIUMF experiment (E643) attempted to extract the s-wave amplitude for the process $\gamma n \to \pi^- p$ from the measurement of the total and differential cross-sections of the inverse reaction $\pi^- p \to \gamma n$. To be quantitative, the s-wave amplitude for the charged-particle channels should be determined to within an accuracy of 1%, and to within 5% for the neutral channels. Accurate predictions for all four channels exist[7] making use of the conventional isospin symmetric basis of three independent amplitudes. The theoretical framework of consistently including operators related to the quark-mass difference and to virtual photons is currently being developed at Bonn.[9] A determination of the (absolute) total cross-section for the charged channels with a 2% accuracy appears to be sufficient to give a consistency check on the quark-mass ratio m_d/m_u extracted from mesonic processes. A more quantitative assessment of the effect is still lacking, but further study is underway.[9]

Recently, there have been two independent claims that isospin has been violated at the $\approx$ 7% level in medium energy πN scattering.[10] As pointed out by Bernstein,[21] a very precise determination of the phase of $\gamma p \to \pi^0 p$ below the secondary $\pi^+ n$ threshold would allow for a determination of the s-wave πN scattering length $a_{\pi N}(\pi^0 p)$ via a generalized three-channel Fermi–Watson analysis. As shown by Weinberg,[22] the difference $a_{\pi N}(\pi^0 p) - a_{\pi N}(\pi^0 n)$ is very sensitive to the quark-mass difference $m_u - m_d$. A measurement of $\mathrm{Im}(E_{0+})$ is equivalent to a measurement of the corresponding πN phase shift. It is important to map out this quantity in the region of the so-called unitary cusp (150–170 MeV)[21]: the discontinuity in E_{0+} which results from the fact that the $\pi^0 p$ and $\pi^+ n$ thresholds are different (a result of isospin breaking). It is clear that a measurement of $\mathrm{Im}(E_{0+})$, performed using a polarized target, can be obtained using the intensity and energy resolution of the HIγS facility with an accuracy which will easily display isospin violation if it is present at the level claimed above. These important experiments can only be performed at the level of accuracy needed using a facility such as HIγS. These experiments involve the use of polarized-proton targets, a technology at which TUNL excels.

The analyzing power for a spin-1/2 polarized target will be called $T(\theta)$. The prediction from CPT for $T(\theta)$ at $E_\gamma = 158$ MeV is shown as the solid curve in Fig. 3.[7,9] The other two curves in Fig. 3 are the predicted values for $T(\theta)$ when the (Im E_{0+}) amplitude is halved or doubled, respectively.

We have made a count-rate estimate for this study based on the expected γ-ray flux from the upgraded facility and the modified TUNL dynamically polarized proton target. The three data points shown in Fig. 3 represent the accuracy which we would obtain if all three angles were measured simultaneously in just 90 hours of beam time. A 4π-spectrometer would, of course, allow us to obtain a full angular distribution in the same amount of time.

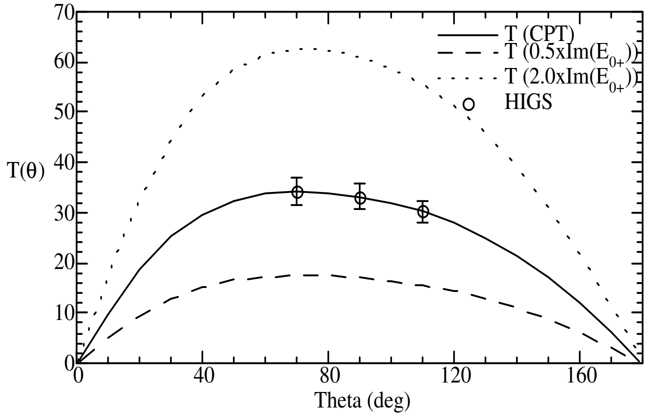

Fig. 3. CPT prediction for $T(\theta)$ for a polarized proton target at $E_\gamma = 158$ MeV for various values of $\mathrm{Im}(E_{0+})$. The data points indicate the uncertainity which is expected from the HIγS beam in 90 hours of running time.

2.2. *Compton scattering*

2.2.1. *Compton scattering from the proton*

Chiral Perturbation Theory (CPT) predicts a number of observables which the HIγS facility will be ideally suited to testing.[23] These include the polarizabilities of the nucleons.[23] The electric and the magnetic polarizabilities are defined as the first nontrivial moments in the energy expansion of the Compton scattering amplitude:

$$T(\gamma N \to \gamma N) = \frac{e^2 Z^2}{4\pi m} + \bar{\alpha}\omega'\omega\boldsymbol{\varepsilon}' \cdot \boldsymbol{\varepsilon} + \bar{\beta}\omega'\omega(\boldsymbol{\varepsilon}' \times \mathbf{k}) \cdot (\boldsymbol{\varepsilon} \times \mathbf{k}) + O(\omega^4)\,, \qquad (1)$$

where the first term is the well-known Thomson limit which is only sensitive to global parameters like the charge Z and the mass m of the particle from which the photon scatters. The nontrivial structure information is encoded in the polarizabilities $\bar{\alpha}$ and $\bar{\beta}$. In a nonrelativistic picture, these quantities measure the response of a system to external electric and magnetic fields: the ability to induce an electric and a magnetic dipole moment, respectively. They have been determined to date by Compton scattering from the free proton[24,19,25] and the quasi-free neutron (bound in deuterium) as well as by scattering slow neutrons in the field of a heavy nucleus.[26–28] The results have large uncertainties and depend upon the use of a sum rule for the value of $\bar{\alpha} + \bar{\beta}$ which is derived from the optical theorem. The proposed intense polarized beam will allow for a new precise determination of $\bar{\alpha}$ and $\bar{\beta}$ which is independent of the dispersion sum rule for $\bar{\alpha} + \bar{\beta}$. The equations below illustrate how Compton scattering data with polarized γ rays will provide a direct determination of $\bar{\alpha}$ and $\bar{\beta}$.

$$\left[\frac{d\sigma_\perp}{d\Omega} - \frac{d\sigma_\perp^{pt}}{d\Omega}\right]^{\frac{1}{2}} - \cos\theta\left[\frac{d\sigma_\parallel}{d\Omega} - \frac{d\sigma_\parallel^{pt}}{d\Omega}\right]^{\frac{1}{2}} = +\bar{\alpha}\sin^2\theta\left(\frac{E_\gamma}{hc}\right)^2, \qquad (2)$$

$$\cos\theta\left[\frac{d\sigma_\perp}{d\Omega}-\frac{d\sigma_\perp^{pt}}{d\Omega}\right]^{\frac{1}{2}}-\left[\frac{d\sigma_\parallel}{d\Omega}-\frac{d\sigma_\parallel^{pt}}{d\Omega}\right]^{\frac{1}{2}}=-\bar{\beta}\sin^2\theta\left(\frac{E_\gamma}{hc}\right)^2, \qquad (3)$$

where $\perp$ and $\parallel$ refer to having the photon polarization vector perpendicular or parallel to the reaction plane, respectively. σ^{pt} is the exact Born cross-section for a nucleon with an anomalous magnetic moment, but no other structure.

The intensity and quality of the proposed polarized beam will allow for an order of magnitude improvement in our knowledge of these quantities. The measurement for the proton using the proposed γ-ray source was simulated[29] using the following parameters:

- $E_\gamma = 120$ MeV (and others)
- target thickness = 80 mg/cm^2
- Flux = $10^7 \gamma$/sec
- Running time = 280 hours

The results indicate that our measurements will determine $\bar{\alpha}$ to within $\pm 2\%$ and $\bar{\beta}$ to within $\pm 5\%$ *without* the use of the sum rule. This represents a significant improvement in our knowledge of these quantities.

2.2.2. *Compton scattering from the deuteron*

The intense beams of (polarized) γ rays available at HIγS are ideally suited to measurements of Compton scattering from nuclei and nucleons. Recent developments in theory[14–17] indicate that precision low energy Compton scattering experiments can provide important new information on the iso-scalar, scalar electric and magnetic-nucleon polarizabilities. These quantities represent the average values of the proton and neutron electric and magnetic polarizabilities, respectively. While the scalar-proton polarizabilities are well measured from Compton scattering off the proton,[19,24,25] the lack of free neutron targets has led to a large uncertainty in the corresponding values for the neutron. Recently, a low energy nuclear Effective Field Theory (EFT) without dynamical pions calculation[11–13] has been performed[14] and indicates that precision Compton scattering data from the deuteron at and below 50 MeV can lead to a determination of the neutron electric and magnetic polarizabilities. The sensitivity of the angular distribution of the cross-section to the values of the polarizabilities at $E_\gamma = 49$ MeV are shown in Fig. 4 along with previously existing data.[18] We are proposing to measure the cross-section and analyzing powers for Compton scattering from the deuteron at energies between 20 and 50 MeV. The detection system consists of four 25.4 cm $\times$ 25.4 cm NaI detectors which are contained in plastic anti-coincidence shields and mounted in a device which makes it possible to place the detectors in the up-down-left and right positions at scattering angles of from 20 to 160 degrees. The targets for these experiments will be liquid deuterium, obtained from collaborators at the University of Saskatchewan.[20] With gamma intensities of 10^8 γ/s, count rates for cross-sections of 15 nb/sr are

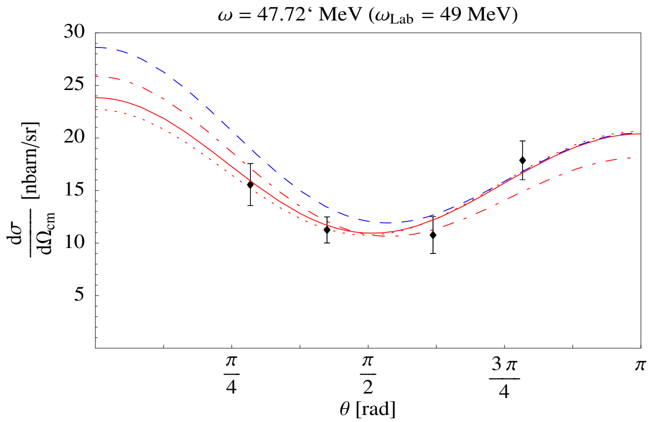

Fig. 4. EFT result for the differential cross-section fitted to data. Dashed: $\alpha_0 = \beta_0 = 0$; dot-dashed: $\beta_0 = 0$; dotted: α_0 and β_0 fitted; solid: α_0 and β_0 constrained by the Baldin sum rule.

expected to be about 400 counts/s. The pulsed nature of the HIγS beam will permit the use of time-of-flight to separate neutron and gamma events. Another feature of the HIγS beam, which turns out to be extremely useful, is the ability to produce Giant High-Peak Power Pulses (GHPP) in the storage ring FEL. This is accomplished using the gain modulation technique[38] and allows the user to have a beam of gamma rays which has bursts of gamma rays with a duration of, for example, 100 μs and a separation between bursts of, say, 100 ms. The total intensity of the gamma-ray beam on average is only reduced by a factor of 3 or less, and the high frequency time structure is maintained. This mode of operation reduces room and cosmic ray generated backgrounds by a factor of more than 1,000.[39]

Our goal is to measure angular distributions with relative statistical errors of 1% or better, and overall absolute uncertainties of 3–5%. Since our beam is 100% linearly polarized, we will also obtain the analyzing powers ($A(\theta)$) at all angles and energies with a precision of better than 1%. The sensitivity of the analyzing powers to the isoscalar nucleon polarizabilities is shown in Fig. 5. The calculations shown here are the same EFT calculations shown in Fig. 4. It seems clear that precision measurements of $\sigma(\theta)$ and $A(\theta)$, along with the precise EFT calculations, will lead to accurate values of the isoscalar nucleon polarizabilities. Since the proton polarizabilities are experimentally well determined,[19,24,25] this will lead to a determination of the neutron polarizabilities.

2.2.3. *Compton scattering from* ^{16}O

The first Compton scattering experiment performed at HIγS consisted of a measurement of the asymmetries ($\Sigma(\theta)$) for Compton scattering from ^{16}O at $E_\gamma = 40$ MeV. In this work the target consisted of a 25.4 cm long water sample, while the scattered γ rays were detected using four 25.4 $\times$ 25.4 cm NaI detectors. The 100%

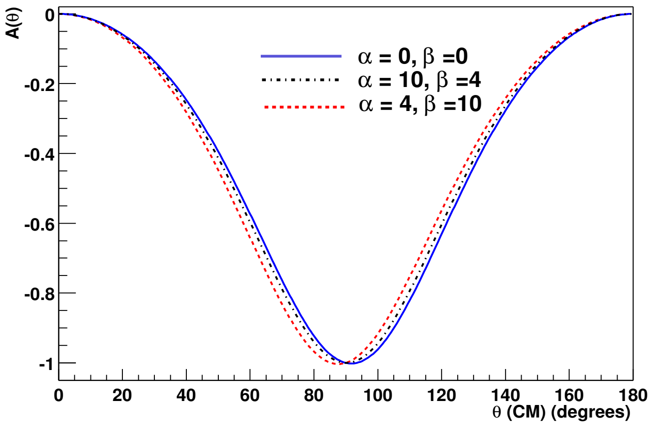

Fig. 5. Angular sensitivity of the deuteron Compton scattering analyzing power to the nucleon polarizabilities.

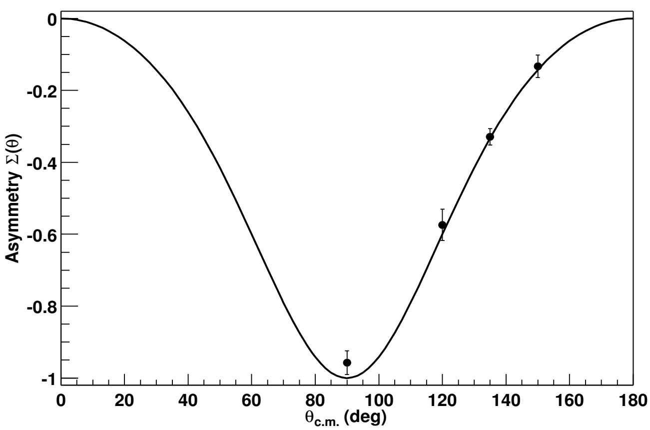

Fig. 6. The analyzing power for $^{16}O(\boldsymbol{\gamma},\gamma)^{16}O$ as a function of scattering angle at $E_\gamma = 40$ MeV. The solid curve shows the theoretical calculation for pure electric-dipole scattering through the GDR.

linearly polarized γ-ray beam had its polarization vector in the horizontal plane, with the NaI detectors positioned in the left, right, up and down positions at each scattering angle θ. The use of the GHPP pulse mode of running, which was previously described, along with a time-of-flight condition (a 10 ns gate width was used with one bunch every 175 ns) lead to an overall background reduction by a factor of $\sim$ 1,700.[39] The results of our measurements of $\Sigma(\theta)$ performed at 40 MeV are shown in Fig. 6. The solid curve is the prediction for the case of pure E1 scattering through the high energy tail of the Giant Dipole Resonance (GDR) ^{16}O. The results of preliminary measurements of $\Sigma(\theta)$ as a function of energy at two angles (135° and 120°) are shown in Fig. 7. The solid curves represent what would be expected for pure electric-dipole scattering through the GDR. While a full report

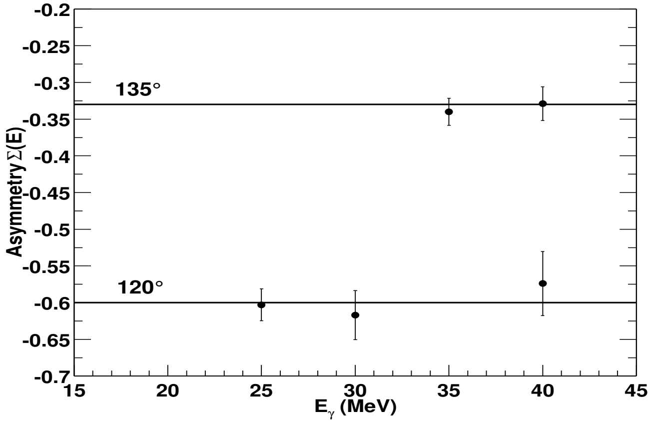

Fig. 7. Analyzing power as a function of the γ-ray energy in ^{16}O Compton scattering. The top plot is for a scattering angle of 135° (Lab.) and the bottom is for 120° (Lab.). The solid curves are the predictions for pure electric dipole scattering through the GDR.

of this experiment and the calculations being described here is in preparation, the results presented here are intended to illustrate not only the sensitivity of these measurements to the existence of the GQR in ^{16}O, but to show the precision with which measurements of analyzing powers in Compton scattering reaction can be obtained at the HIγS facility. It seems clear that precision measurements of $\sigma(\theta)$ and A(θ) for the case of Compton Scattering from the deuteron will be able to, using EFT results, determine the values of the isoscaler nucleon polarizabilities.

2.2.4. *Compton scattering from* ^{4}He

Recent theoretical progress in the mass-4 system has generated a new interest in the electric polarizability of the ^{4}He nucleus. For example, Orlandini[40] has calculated a value of $\alpha_E = 0.075$ fm^3 for the ^{4}He nucleus. If one considers the amplitude for Compton scattering up to $O(\omega^2)$, and determines the cross-section for detectors placed at $\theta = 90°$ and colinearly with respect to the direction of the incident linear polarization vector of the beam, it is found that the cross-section vanishes (except for finite geometry effects).[41] On the other hand, for detectors at right angles with respect to the polarization vector, one finds that:

$$\frac{d\sigma}{d\Omega} = \frac{1}{2}\left(\frac{\alpha}{M}\right)^2 \left[1 - 2M\omega^2 \frac{\alpha_E}{\alpha}\right], \tag{4}$$

where α is the fine structure constant. Thus, a measurement of the cross-section at $\theta = 90°$ with detectors placed above and below a horizontally polarized incident gamma-ray beam, as a function of ω^2, determines α_E. Actually, after performing numerical calculations, it is apparent that one must carry out the calculation to $O(\omega^4)$ in order to obtain accurate results. This task remains to be completed.

We are proposing, in a collaboration with Dr. John Calarco of the University of New Hampshire, to perform Compton scattering measurements from ^{4}He using 100% linearly polarized gamma rays. Data will be taken at 5, 15, 25 and 35 MeV in order to cover a reasonable range in ω^2. We propose to use four NaI detectors placed at $\theta = 90°$, two in the up and down positions and two in the left and right, relative to the linear photon polarization vector. The target will be a 20 cm long liquid He cell having a diameter of about 3 cm. With an expected beam intensity of 10^9 γ/s, we find a count rate at 5 MeV of 190 cts/hour for each of the up and down detectors, assuming a solid angle of 50 msr each. A 1% statistical measurement will require about 50 hours of beam time. Points at 15, 25 and 35 MeV will require 6 days, 6 days and 1 day respectively, for a total of about 15 days. This will provide four points along a parabolic distribution, each with about 1% uncertainty. A fit to this distribution should yield α_E to the same statistical accuracy: 1%.

2.2.5. *Compton scattering from* ^{3}He

As previously noted the electric ($\bar{\alpha}$) and magnetic ($\bar{\beta}$) scalar polarizabilities, which describe the response of the nucleon to external electric and magnetic field, respectively, enter in terms which are second order in photon energy. At the third order, four new parameters, γ_1 to γ_4, of the spin polarizabilities appear.[42] While spin polarizabilities do not have as clear a physical interpretation as the electric and magnetic polarizabilities, they are nevertheless just as fundamental. These parameters are related to the classical Faraday rotation, wherein the linear polarization of the photon passing longitudinally through a magnetized medium exhibits a rotation due to the difference in index of refraction for photons with circular polarization anti-parallel and parallel to the direction of magnetization.[42] The spin polarizabilities can be thought of as measuring the transient dipoles that are induced in the nucleon due to the rearrangements of constituents interacting with the photon fields.[43]

While the proton electric and magnetic polarizabilities are known relatively well, little is known about its spin polarizabilities. Recently, the backwards spin polarizability γ_π has been extracted from unpolarized Compton scattering data from the proton.[24] However, the extracted value $\gamma_\pi = -27.1 \pm 2.2$ is in disagreement with the TAPS result,[25] $\gamma_\pi = -35.8 \pm 2.4$, the latter result being in excellent agreement with theoretical results obtained using chiral perturbation theory. Since it is known that the pion-pole contribution gives a value of ~ -45,[44] the interesting descrepancy is actually between the differences with this value: -28 versus -9, or a factor of 3. The clarification of the situation will benefit from double polarization Compton scattering[25] in which circularly polarized photons are scattered off a polarized proton target.

In the case of the neutron, there is no information on the spin polarizabilities due to the fact that there is no free neutron target in nature. While deuterium targets have been used in the past in quasifree Compton scattering for the extraction of the neutron electric and magnetic polarizabilities, a polarized ^{3}He target is advantageous in probing the neutron spin polarizabilities. The sensitivity of spin-dependent quasifree Compton scattering from ^{3}He to the structure of the neutron originates from the cancellation of the proton spins in the dominant spatially symmetric S wave of the ^{3}He ground state. Double polarized elastic Compton scattering from ^{3}He is a fundamental measurement in its own right. Combining measurements of both photon helicities, one can access the ^{3}He electric, and magnetic polarizabilities as well as the spin polarizabilities of ^{3}He. The comparison between the ^{3}He spin polarizabilities and the extracted neutron spin polarizabilities will allow us to test our understanding of a polarized ^{3}He target as an effective neutron target as well as to test few-body calculations.

With the intense photon source at the HIγS facility and a high-pressure spin-exchange optically pumped ^{3}He target,[46] such a double polarization experiment is feasible at photon energies both below and above the pion production threshold. A target thickness of $1.0 \times 10^{22}/\text{cm}^2$ and a polarization of 45% is routine with the high-pressure spin-exchange optically pumped polarized ^{3}He target in Hall A at Jefferson Lab for electron scattering experiments.[46] A group at TUNL led by Professor Haiyan Gao plans to build a high-pressure polarized ^{3}He target based on the same technique for these studies at HIγS. Such a target can also be used for the spin polarizability study of the ^{3}He nucleus itself and the Gerasimov–Drell–Hearn integral measurement on ^{3}He.

The quasifree Compton scattering cross-section from ^{3}He at a photon energy of 100 to 150 MeV is expected to be about 15 nb/sr. For a single measurement which detects the scattered photons only, the expected counting rate is about 0.2 Hz. This rate estimate is based on a photon flux of 3×10^9/sec, a ^{3}He target thickness of $1.0 \times 10^{22}/\text{cm}^2$, and a large acceptance detection system with a solid angle acceptance of 500 msr. This solid angle acceptance can be achieved by (i) reconfiguring the existing HIγS Blowfish detection system to increase the azimuthal angular acceptance: (ii) using the Neutral Meson Spectrometer (NMS); (iii) using the combination of the Blowfish detection system and the NMS system. With a rate of 0.2 Hz, a photon beam polarization of 100% and a ^{3}He target polarization of 45%, a double polarization asymmetry measurement with a statistical uncertainty of 0.005 can be accomplished in $\sim$ 300 hours.

2.3. *The Gerasimov–Drell–Hearn sum rule for the deuteron*

Measurements of the Gerasimov–Drell–Hearn integral on the proton and neutron to test the Gerasimov–Drell–Hearn (GDH) Sum Rule have been and are being performed at Mainz, LEGS,[45] GRAAL and TJNAF.[31,32] For the LEGS measurements the SPHICE target composed of molecular HD will be used, with the deuteron providing the "neutron target". The GDH sum rule for a nucleon is

$$\int_{k_\pi}^{\infty} (\sigma_P(k) - \sigma_A(k)) \frac{dk}{k} = 2\pi^2 \alpha \left(\frac{\kappa_N \hbar}{M_N c} \right)^2 , \qquad (5)$$

where k_π corresponds to the threshold energy for pion production from the nucleon, σ_P (σ_A) is the total inelastic photon cross-section when the nucleon and the circularly polarized photon spins are parallel (anti-parallel), and κ_N is the anomalous magnetic moment of the nucleon. Significantly, this sum rule is based upon very general principles: causality, unitarity, gauge and Lorentz invariance. In addition, it involves the reasonable assumptions that an unsubtracted dispersion relation can be used in calculating the forward-angle contribution from Compton scattering and that the LETs give the correct low-energy limits. It was subsequently pointed out by Hosada and Yamamoto[33,34] and Gerasimov[32] that these arguments could be applied equally well to the deuteron. That is, the deuteron could be treated as the object of the sum rule rather than simply as a source of neutrons. The resultant "GDH" sum rule is given by

$$\int_{k_2}^{\infty} (\sigma_P(k) - \sigma_A(k)) \frac{dk}{k} = 4\pi^2 \alpha \left(\frac{\kappa_d \hbar}{M_d c} \right)^2 , \tag{6}$$

where k_2 corresponds to the threshold not for pion production ($\approx$ 145 MeV) but for photodisintegration ($\approx$ 2.2 MeV), and M_d (κ_d) is the mass (anomalous magnetic moment) of the deuteron. The sum rule values for the proton, neutron and deuteron are given in Table 2:

Table 2.

Target	κ	$\int GDH$
p	1.79	204.0 μb
n	−1.91	232.0 μb
d	−0.14	0.6 μb

The GDH integral for the deuteron can be separated into two pieces

$$\int_{k_2}^{\infty} GDH_d = \int_{k_2}^{k_\pi} GDH_d + \int_{k_\pi}^{\infty} GDH_d = 4\pi^2 \alpha \left(\frac{\kappa_d \hbar}{M_d c} \right)^2 = 0.6\ \mu\text{b} . \tag{7}$$

The second term on the right-hand side will be measured at LEGS and GRAAL. Its value can be estimated from the GDH integrals for the nucleons under the assumption that the impulse approximation is valid (this assumption is useful to obtain this estimate but is not significant to the basic argument since what will actually be measured at Mainz, LEGS, GRAAL, and TJNAF is the GDH integral for the deuteron). Thus,

$$\int_{k_\pi}^{\infty} GDH_d = (204\ \mu\text{b}) + (232\ \mu\text{b}) = 436\ \mu\text{b} . \tag{8}$$

Therefore, the previous equation predicts that

$$\int_{k_2}^{k_\pi} GDH_d \cong -436\ \mu\text{b} . \tag{9}$$

That is, if the assumptions underlying the GDH sum rules are generally valid, then asymmetries in the total cross-sections dominated by high energy pion production and resonance excitation processes give a firm prediction for asymmetries in a very low-energy process, namely photodisintegration below pion threshold. This is a connection that merits testing.

The connection between the GDH sum rule for the nucleons and that for the deuteron is potentially more interesting. There are suggestions that the GDH sum rule may be violated for nucleons. If this turns out to be true, then the immediate question will be, "What is the origin of the violation?" Possible explanations include a failure of the GDH integral to converge, the need to use a subtracted dispersion relation in calculating the forward-angle Compton amplitudes, or a breakdown of the LETs. Measurements on the deuteron would help to differentiate among these possibilities. For example, if the discrepancy in the GDH sum rule for the nucleons arises from a failure of the integral to converge as E_γ approaches infinity, then one would conclude that some very short range phenomena have not been accounted for accurately, a potentially very exciting result. On the basis of the nucleon data alone one could not determine whether this was indeed the cause. However, noting that at very high energies the deuteron can be treated as a free proton plus a free neutron (with very small corrections) one can use the nucleon data to determine a "correction" to the GDH sum rule for the deuteron. If one were to find that this "corrected" sum rule was satisfied for the deuteron when integrated from photodisintegration threshold up to the same cutoff as the nucleon data, then one could reasonably infer that the source of the discrepancy for the nucleons is in the high-E_γ behavior of the integrands. Note that, since the experiments at Mainz, LEGS, GRAAL and TJNAF will use a deuterium target to measure the sum rule for the neutron, deuteron data above pion threshold will be available. These data, when combined with the lower energy data of the present proposal, will provide data over the complete energy range needed. In summary, the measurement of the GDH integral for the deuteron will be a valuable complement to measurements on the nucleons which are currently underway or in preparation.

The cross-section, total and differential at a few angles, for low-energy photodisintegration of the deuteron has been studied since the 1950s (see Arenhövel and references therein).[35] Very few measurements involving polarization observables have been made. Moreover, only the quantities P_y (nucleon polarization), Σ^l (photon linear polarization), and A_y (analyzing power) have been extracted. No measurement of the asymmetries contained in the GDH integrals has ever been attempted.

Figure 8 shows the results of a calculation[36] of difference between the total cross-section when the helicity of the incident photon and the spin of the target are parallel (σ_P) and that when they are antiparallel (σ_A) divided by their sum. The dominant contribution comes from the near threshold ${}^1S_0$ resonance. A measurement between threshold and $E_\gamma = 10$ MeV will be the crucial component of the total measurement. This asymmetry shows a surprisingly large sensitivity to

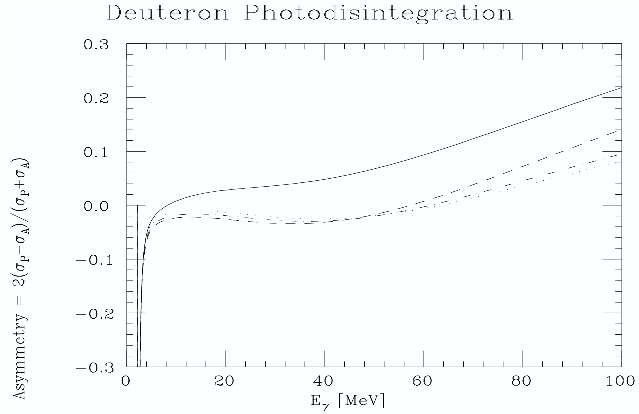

Fig. 8. The asymmetry $2(\sigma_P - \sigma_A)/(\sigma_P + \sigma_A)$ in the total cross-section for deuteron photodisintegration where $\sigma_P(\sigma_A)$ is the total cross-section when the photon helicity and target spin are parallel (antiparallel). Dotted curve includes N–N potential only, dot-dashed adds MEC, dashed adds isobar currents, and solid adds relativistic effects as well.[36]

relativistic effects, a result meriting serious investigation especially since the positive contribution it creates is important to cancel some of the negative contribution (~ 550 μb) which is present near threshold if the sum-rule integral is going to result in the theoretical value.

The HIγS facility will be ideally suited to the task of obtaining these measurements. In fact, since the major part of the GDH integral as well as the predicted onset of significant relativistic effects both occur at energies below 60 MeV, these will constitute the initial program of experiments at HIγS. Intense beams having energies below 40 MeV should be available prior to the injector upgrade. The production of circularly polarized FEL photons, and hence circularly polarized γ rays, will be accomplished using the helical undulator (OK-5). Preliminary calculations indicate that a statistical accuracy of better than 5% in the GDH integral up to an energy of 50 MeV can be obtained in less than 200 hours of running.

The HIγS facility has been used to perform measurements of the photodisintegration of the deuteron in the threshold region using 100% linearly polarized γ rays on an unpolarized target. Our initial measurements were performed using four neutron detectors.[37] The analyzing power was measured at $E_\gamma = 3.58$ MeV, and used to determine the percentage M1 strength at this energy. Our results indicated that the M1 contribution to the total cross-section was $9.2 \pm 1.8\%$, which is in good agreement with the theoretical prediction of Arenhövel.[36] More recently, we have made a high precision measurement of these analyzing powers for E_γ between 2.6 and 10 MeV using the 88-neutron detector array BLOWFISH.[47] This detector system is shown in Fig. 9. The data from this experiment are currently being analyzed.

The term in the integrand of the GDH sum rule, $(\sigma_P - \sigma_A)$, can be written in terms of the contributing transition matrix elements. In the threshold region,

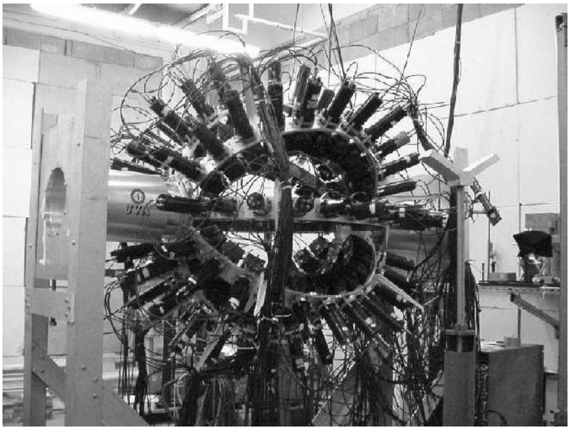

Fig. 9. The BLOWFISH neutron detector array at HIγS. This array was built and commissioned for the UVA-USASK HIγS-GDH collaboration.

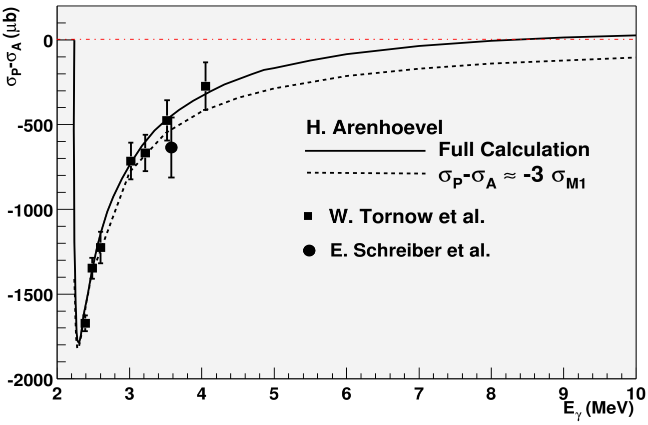

Fig. 10. The theoretical prediction[36] for $\sigma_P - \sigma_A$ as a function of E_γ for the deuteron along with the preliminary results deduced from recent HIγS data.

there are only five matrix elements which are expected to contribute. Three of these are the E1 matrix elements. If we assume, as expected based on the small differences in the p-wave n–p scattering phase shifts at these energies, that the reduced E1 matrix elements are not j-dependent, then they do not contribute to the value of $(\sigma_P - \sigma_A)$. There are also two M1 matrix elements. One of these has the same quantum numbers as the ground state, and is therefore expected not to contribute to the M1 strength due to orthogonality. This result permits us to relate the M1 strength measured in Schreiber *et al.*[37] to the quantity $(\sigma_P - \sigma_A)$, the result being that $\sigma_P - \sigma_A = -3\sigma(\mathrm{M1})$. The resulting value of $(\sigma_P - \sigma_A)$ obtained from our experiment is in excellent agreement with the calculated value at this energy (3.58 MeV), as shown in Fig. 10.

Recently, Tornow *et al.*[57] used the HIγS beam and four neutron detectors to measure the analyzing power at $\theta = 90^\circ$ for the $d(\boldsymbol{\gamma}, n)p$ reaction from $E_\gamma = 2.4$ to 4.05 MeV. An analysis similar to that performed in Ref. 37 leads to values of σ(M1) and therefore to values of $\sigma_P - \sigma_A$, using the approximation given above. The preliminary results of this work are shown in Fig. 10, along with the theoretical results of Ref. 36. The theoretical result obtained using the same approximation as in the data analysis is also shown in Fig. 10, and indicates that the approximation is as good as the uncertanities in the data below 4 MeV.

2.4. *Nuclear-structure studies*

The proposed high-intensity gamma-ray source at the Duke Free-Electron Laser Laboratory will present unique opportunities for the study of nuclear structure. As will be shown below, the high intensity beams of essentially 100% linearly polarized γ rays in the energy range $2 \leq E_\gamma \leq 10$ MeV are ideal for the development of a program to study low-spin, collective excitations of nuclei.

The study of excited nuclear states by nuclear-resonance-fluorescence (NRF) has for many years made important contributions to the understanding of nuclear structure. Recently, a great deal of excitement has followed the discovery of the so-called magnetic dipole "scissors" mode (see the review by Kneissl[48] and references therein). Up to the present time, the majority of these studies have been performed using electron generated bremsstrahlung beams. While bremsstrahlung photon sources have many useful characteristics, they suffer from the serious drawback that the photon energy spectrum is continuous and has an exponentially increasing intensity with decreasing photon energy. It is clear that there are a number of significant advantages to NRF studies offered by the HIγS facility. In particular, the nearly monochromatic photon energies will allow the selective population of resonant states of interest with much less uncertainty due to feeding from higher-lying states. The background from nonresonant scattering will be substantially lower in the energy region where branches to lower-lying excited states would occur. Furthermore, due to the essentially 100% linear polarization of the photon beam, there will be much greater sensitivity in performing parity measurements.

Among the open questions that we have begun or are planning to investigate using the NRF technique at the HIγS facility are:

- Magnetic dipole strength and fragmentation in odd-A nuclei.
- Deformation dependence of M1 strength in transitional even–even nuclei.
- Two-phonon dipole excitations and decay to one-phonon states, coupling with particle excitations.
- Electric dipole transitions in deformed nuclei, octupole degree of freedom.

The first NRF experiment at HIγS, performed in collaboration with Pietralla and Berant of Yale University, involved a target of ^{138}Ba with the incident beam tuned to 5.65 MeV.[59] Four HPGe detectors were used to observe the left, right,

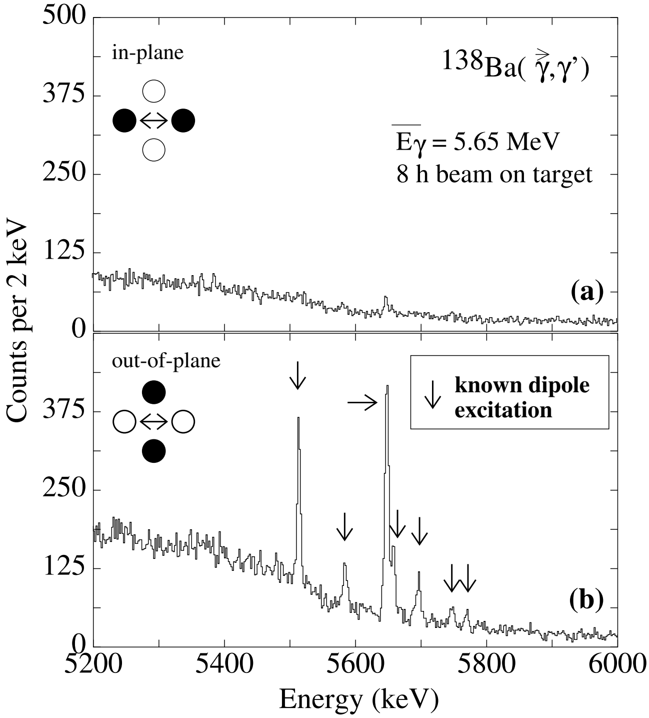

Fig. 11. Photon scattering spectra off a $BaNO_3$ sample observed at a polar angle $\theta = 90°$ in the polarization plane of the incident γ-ray beam (top) and perpendicular to the polarization plane (bottom). The arrows mark known[58] dipole excitations of ^{138}Ba.

up and down γ rays. The parity of the state at 5.644 MeV had been previously (tentatively) assigned to be positive on the basis of a measurement made using a bremsstrahlung beam and a Compton polarimeter.[48] This was a difficult measurement due to backgrounds and the low-sensitivity of the Compton polarimeter at this energy. On the other hand, the HIγS result was clean and totally unambiguous. In just eight hours of beam on target, the analyzing power was found to be -0.90 ± 0.05, clearly indicating a negative parity (positive parity would give $+1.0$, negative gives -1.0; the -0.90 has not been corrected for finite geometry effects. All told, in just under 20 hours of running at HIγS, unambiguous parity assignments were made to 18 dipole excitations in ^{138}Ba between 5.3 and 6.5 MeV. The quality of these results are illustrated in Fig. 11. This result demonstrates the powerful new tool which HIγS represents. Another HIγS study of several states in ^{88}Sr was recently performed and published.[60]

In order to enhance our sensitivity for weak branches even further, we plan to construct Compton suppression shields for the HPGe detectors mentioned above. The technique of using the GHPP pulse timing will also be extremely valuable in reducing room and cosmic-ray backgrounds. Together, these will serve to greatly reduce the background in the measured spectra at γ-ray energies below that of the resonance to ground-state transition energy. The delineation of such decay pathways will shed light on questions regarding the fragmentation of collective modes and on the degree of harmonicity of multi-phonon vibrational states.

2.5. *Studies in nuclear astrophysics*

As previously discussed, γ-ray fluxes on the order of 10^8 photons per second are available below $E_\gamma = 20$ MeV. These fluxes are essentially 100% linearly polarized. Such intense beams of polarized γ rays open the door to new studies which can answer some of the most important questions in the field of nuclear astrophysics. As an example of this, we consider the problem of helium burning and the $^{12}\mathrm{C}(\alpha,\gamma)^{16}\mathrm{O}$ reaction.[50]

In order to understand the process of helium burning in stars, and in particular the oxygen-to-carbon ratio at the end of the burning, one must understand the $^{12}\mathrm{C}(\alpha,\gamma)^{16}\mathrm{O}$ reaction at the most effective energy for helium burning, which is ~ 300 keV. At this energy, the cross-section is estimated to be about 10^{-8} nbarn, clearly non-measurable in laboratory experiments. The cross-section has been measured at various levels of precision down to 1.2 MeV. It must be extrapolated from there, down to 300 keV.[51]

One of the major uncertainties in performing the extrapolation arises from the fact that there are several resonances which contribute to the cross-section at alpha-particle energies in the vicinity of 1 MeV. Above 1 MeV, the elastic scattering and capture reactions are dominated by a broad 1^- resonance at an excitation energy of 9.59 MeV and a narrow 2^+ state at 9.85 MeV. However, a 1^- state at 7.12 MeV, just 42 keV below threshold, determines the capture cross-section in the astrophysically relevant energy region both by itself and by its interference with the higher lying 1^- and 2^+ levels. In addition, broad high-lying states and direct processes produce a coherent background which affects the energy dependence of the cross-section and thereby its extrapolation.

Direct measurements of the $^{12}\mathrm{C}(\alpha,\gamma)^{16}\mathrm{O}$ reaction cross-section at energies below 2 MeV have been attempted for over 30 years. The major difficulty encountered in these experiments is the intense neutron background which arises from the $^{13}\mathrm{C}(\alpha,n)$ reaction which tends to swamp the γ rays from the capture reaction at these low energies. We have determined that the intense and narrow beam of γ rays which can be produced in the region of 8 to 10 MeV will be able to resolve this problem by studying the inverse reaction: $^{16}\mathrm{O}(\gamma,\alpha)^{12}\mathrm{C}$ with γ rays at the appropriate energies.[52] It is the large flux and the small beam diameter which makes this possible. For example, if we assume that an incident gamma-ray beam having an energy of 9.58 MeV (which is on top of the first 1^- resonance), and an intensity of 5×10^9 γ/sec, then a 100 μg/cm^2 ^{16}O target will produce 6,200 α-particles per day having an energy of 3.32 MeV. Likewise, a γ-ray beam at 8.8 MeV will produce α-particles at 1.6 MeV at the rate of six counts per day. We are proposing to make a developmental run using parameters such as these and detecting the outgoing α-particles in Silicon Strip detectors which can cover most of the 4π steradians surrounding the target. If such runs are successful, techniques to increase the count rate and extend the measurements to even lower energies will be developed. A gas filled time-projection-chamber using an optical-readout is being developed for this purpose.[52]

Studies of supernovae have suggested that the ejecta of certain supernovae might be the site where the r-process nuclei are synthesized. Critical paths in synthesizing the medium mass nuclei ($A < 120$) are the bridges across the unstable mass gaps at $A = 5$ and 8. One of the principle bridges across this gap in forming ^{12}C from ^{4}He is $^{4}\text{He}(\alpha n, \gamma)^{9}\text{Be}(\alpha, n)^{12}\text{C}$.

The cross-section for the $^{9}\text{Be}(\gamma, n)$ reaction has been measured using γ rays from two sources, either from a standard bremsstrahlung source[53,54] or from radioactive isotopes.[55,56] The shape of the data suggests that there may be a resonance near threshold energies, but the data are inadequate to determine the precise location and the value of the cross-section at the resonance energy. We are proposing to measure the $^{9}\text{Be}(\gamma, n)$ cross-section in the energy range from 1660 to 2200 keV in order to determine the cross-section over the probable resonance in the near threshold region. Preliminary designs of this experiment indicate that a neutron count rate of about 100 Hz can be obtained at the highest proposed energy using a gamma flux of 10^7 γ/s with an energy spread of 1%. While encouraging, further simulations are required before a detailed proposal for this experiment can be constructed. These studies are underway.[61]

This brief description of some possible nuclear physics experiments is meant only to give an idea of the potential power of this beam in nuclear physics studies. At present, linearly polarized beams between 2 and 20 MeV are available with total intensities as high as 10^8 γ/s. Beams with energies up to 48 MeV are available with total intensities of 10^6 to 10^7 γ/s. Upgrades presently underway are expected to increase these intensities by one-to-two orders of magnitude and to provide both linear and circular polarizations by early 2005. The full-flux at energies as high as 225 MeV is scheduled to be available by mid-2006, following the commissioning of the booster-injector. Proposals from outside users are welcome.

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