A New Proposal to the High Intensity Gamma-Ray Source (HIγS) PAC-09

Three-body photodisintegration of ^{3}He with double polarizations for E_γ from 10-40 MeV

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Abstract

We propose to use a circularly polarized photon beam at an incident photon energy range of 10 MeV to 40 MeV on a high-pressure polarized ^{3}He target to carry out a spin-dependent differential cross section measurement from three-body photodisintegration of ^{3}He. Such measurements will allow for a test of the state-of-the-art three-body calculations and represent an important study towards the ultimate goal of determining the GDH integral on ^{3}He from the two-body breakup threshold to the pion production threshold. We request a total beam time of 240 hours with 100% efficiency at a minimum photon flux of 5×10^7/s [1] for a photon energy spread of 3.0%.

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[1] We will postpone the running of the experiment at photon energies higher than 20 MeV if the minimum flux has not been demonstrated.

1 Introduction

An important sum rule known as the Gerasimov-Drell-Hearn (GDH) sum rule [1] is expressed using the total helicity-dependent nucleon real photo-absorption cross sections σ_N^p (nucleon spin parallel to the spin of the photon)and σ_N^A(nucleon spin anti-parallel to the spin of the photon):

$$I^{GDH} = \int_{\nu_{thr}}^{\infty} (\sigma_N^P - \sigma_N^A) \frac{d\nu}{\nu} = \frac{4\pi^2 e^2}{M^2} \kappa_N^2 I \tag{1}$$

where κ_N is the anomalous magnetic moment of the nucleon, M is the mass of the nucleon and I is the spin. This sum rule is based on low energy theorems and the validity of the unsubtracted dispersion relation for the spin-flip amplitude. The GDH sum rule also applies to nuclei. It relates the total cross section of circularly polarized photons on a longitudinally polarized nucleus to the anomalous magnetic moment of the nucleus. Eqn.(1) can be applied directly with N representing the nucleus instead of the nucleon in this case, I being the spin of the nucleus, and M being the mass of the target nucleus. The lower limit of the integration is the photo-nuclear disintegration threshold.

The experimental determination of the GDH integral on ^{3}He from the two-body breakup to the pion production threshold is particularly interesting due to the fact that polarized ^{3}He nucleus is commonly used as an effective neutron target. It can be written into three parts:

$$\int_{\nu_{thr}}^{\infty} GDH_{^3He} = \int_{\nu_{thr}}^{\nu_\pi} GDH_{^3He} + \int_{\nu_\pi}^{2-3GeV} GDH_{^3He} + \int_{2-3GeV}^{\infty} GDH_{^3He} \tag{2}$$

The GDH sum rule prediction for ^{3}He, proton and neutron are 496μb, 204 μb and 233.5 μb, respectively from Eqn(1). The second part is about 247 ± 38 μb extrapolated from the recent experimental data [2], and the third part can be written into neutron and proton integrals in the plane wave impulse approximation (PWIA) as:

$$\int_{2-3GeV}^{\infty} GDH_{^3He} = P_n \times \int_{2-3GeV}^{\infty} GDH_n + P_p \times \int_{2-3GeV}^{\infty} GDH_p \tag{3}$$

where GDH_i refers to GDH integral for i, P_n is the effective polarization of the neutron, 87%; and P_p is the effective polarization of proton, -2.7% [3]. The high energy part of the GDH integral for proton and neutron are -26 ± 7 μb and 35 ± 11 μb, respectively [4]. So one obtains 31.9 ± 9.6 μb for ^{3}He for this part in PWIA. The first part of the integral is therefore estimated as being about 217.1$\pm$39.2 μb based on the experimental data and the PWIA picture. However, the state-of-the-art three-body calculations predict a value between 16μb to 136μb [5][6]. Fig. 1 shows theoretical predictions of the ^{3}He GDH integral from 20 MeV up to the pion production threshold from [5] and [6] (magenta and black)

In [5] (green, blue and yellow lines), in addition to Siegert, which assumes current conservation and replaces dominant parts of electric multipoles by the Coulomb multipoles, explicit

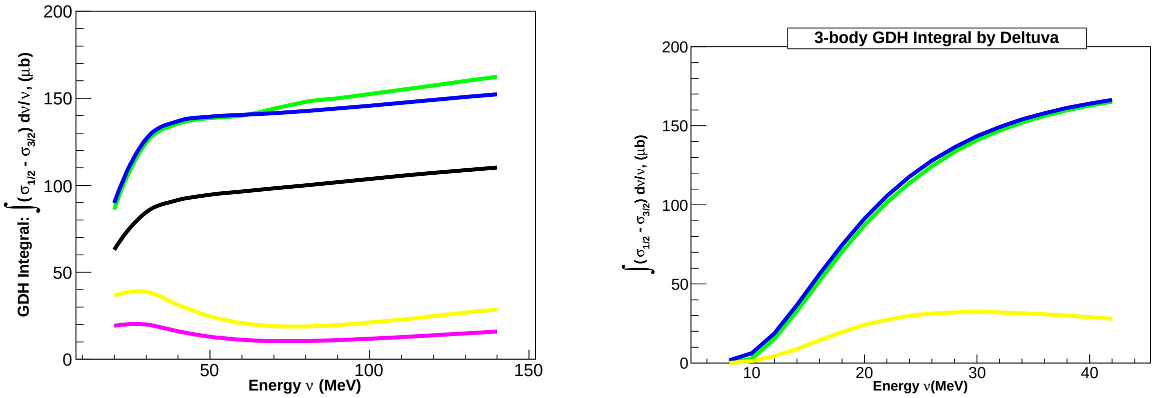

Figure 1: (Theoretical predictions of the ^{3}He GDH integral from 20 MeV up to the pion production threshold (left), and the corresponding contribution due to the three-body breakup channel only (right). The curves with different colors are (from bottom to top) (left): magenta line: AV18 + implicit MEC via Siegert theorem; yellow line: CD Bonn + Siegert + MEC(h.o.); black line: AV18 + explicit MEC; blue line: CD Bonn + Siegert including RCO + MEC(h.o.); green line: CD Bonn+Δ (potential) + Siegert including RCO + MEC(h.o.). The same color designation applies to the right panel.

MECs are used for magnetic multipoles and higher order (h.o.) terms of electric multipoles not accounted for by Siegert. In the relativistic charge operator (RCO) calculations the Coulomb multipoles additionally include contribution from the relativistic corrections of the charge operator. The green line uses the CD Bonn + Δ potential [7], plus Siegert including RCO, and explicit MEC(h.o.); the blue line uses CD Bonn plus the Siegert including RCO and MEC(h.o.); and the yellow line is from CD Bonn, the Siegert theorem and MEC(h.o.). Details of these calculations can be found in [8]. The calculations by Golak *et al.* [6] using the AV18 potential are shown as the black line with explicit MECs and the magenta line using the Siegert theorem, respectively. The right panel in Fig. 1 shows the contribution due to the three-body breakup channel only based on the calculation by Deltuva *et al.* [5].

There is an enormous strength in the first part of the integral (can be as large as 212 μb) if a polarized ^{3}He nucleus is indeed a very effective polarized neutron. Further, the dominant contribution is due to the three-body breakup channel (see Fig. 1 and Fig. 2), which is the focus of this proposal. Our proposed measurements will allow for stringent tests of the state-of-the-art three-body calculations including effective field theory calculations in the future. Future complete measurements from the two-body photodisintegration threshold to the pion threshold can be used to study how effective a polarized ^{3}He is as a polarized neutron target. Such measurements in combination with the $Q^2 \rightarrow 0$ GDH integral measurement above the pion threshold from JLab will provide a test of the GDH sum rule on the ^{3}He nucleus for the first time.

The HIγS facility at Duke Free Electron Laser Laboratory (DFELL) is an ideal place for such a measurement. The experiment requires measurements of the total two-body and three-body breakup cross section as a function of incident photon energy starting from the two-body breakup threshold of ^{3}He. For relatively low incident photon energies, the detection of the proton is sufficient to separate the two-body process from the three-body process for which the neutron will be detected. For higher incident energies, coincidence detection of both neutron and proton is necessary for the three-body breakup channel. The high pressure polarized ^{3}He target used will have a much thinner wall thickness so that the low energy charged particles can exit. We have built a thin-walled high-pressure polarized ^{3}He target with a wall thickness of 500 μm for the future two-body breakup experiment. In this request, we focus on the 3-body 10-40 MeV part of the GDH Integral measurement on ^{3}He. We note that most of the contribution to the GDH integral below the pion production threshold is from the proposed photon energy range and below, and from the three-body breakup channel.

2 Experiment Description

2.1 Overview

We propose measurements using a high-pressure polarized ^{3}He target and a circularly polarized photon beam with an incident beam energy in the range of 10-40 MeV. The ^{3}He nuclear spin will be aligned parallel and anti-parallel to the incident photon momentum direction. The 3-body photodisintegration process will be studied by detecting the neutrons from the 3-body breakup channel. An improved polarized ^{3}He target system has been developed for this experiment following our experience gained from running this target at HIγS in spring of 2008. A neutron detection system consists of 7 detectors will be used for this experiment.

2.2 Polarized Photon Beam at HIγS

HIγS is an ideal place to carry out nuclear physics experiments which require high photon flux, and high ($\sim$ 100%) beam polarization. Currently, the upgrade of HIγS is successfully completed, and the Optical Klystron (OK-5) is able to deliver circularly polarized γ-ray up to energy of 100 MeV and a total flux of 10^8/s. For the lower range of the requested photon energies, the HIγS facility is capable of delivering the requested photon flux of 5×10^7/s for an energy spread of 3.0%. We hope that future beam developments will allow for the required photon flux in the higher photon energy range of this proposal. The spin-dependent measurement will be carried out by flipping the target spin direction during the experiment since the overhead for flipping the photon beam helicity is quite large (it takes hours to flip the helicity). Therefore, it is crucial to the proposed experiment to have excellent photon flux measurement and monitoring system.

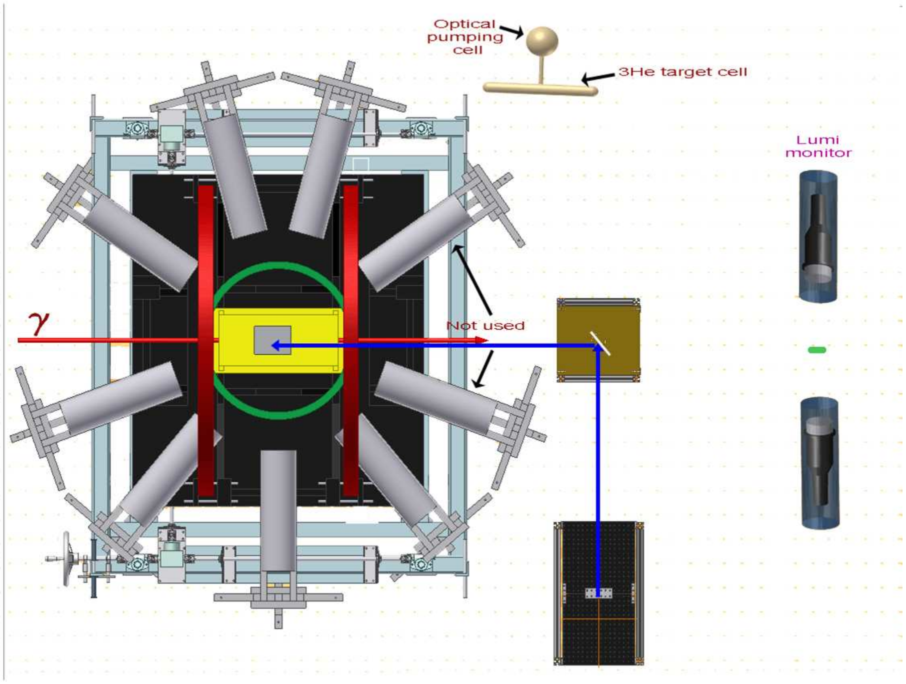

Figure 2: The target room setup during May 2008

2.3 Neutron Detectors

We plan to use seven BC-501A liquid organic scintillating detectors for neutron detection, with additional two placed down-stream the HIγS target room together with a D_2O target for flux monitoring. The specifications of these neutron detectors are: the inner diameter is 12.69 cm and the interior depth is 5.08 cm. The density of scintillator is 0.874 g/cm^3, and hydrogen to carbon ratio is 1.212. The neutrons interact with protons in hydrogen through the strong force, and the protons knocked out interact with scintillating materials. The emitted light will then be collected and converted into a usable signal through a Photomultiplier Tube(PMT). Light output response plays a crucial role in determining the efficiency of the scintillator to convert ionization energy to photons. More details can be found in [9]. Fig. 2 shows the experimental setup at HIγS in May, 2008 and we propose to use the same detector setup for the proposed measurements.

2.4 A High Pressure Polarized ^{3}He Target

In spring of 2008, we carried out a first experiment at HIγS using a circularly polarized photon beam and a high pressure polarized ^{3}He target. The ^{3}He gas target was made of Aluminosilicate (GE180) glass due to its less magnetic impurities and more impermeability to ^{3}He atoms than regular pyrex glass. However, much higher background rates (a factor of several) were observed from a reference nitrogen cell made of GE180 glass than those from a reference cell made of pyrex glass. To improve the situation for future experiments, a new high pressure ^{3}He cell made of pyrex glass coated with a thin layer of pure aluminosilicate glass has been built and tested in our target lab in the last several months.

The coating technique was first invented by G. Cates' group at University of Virginia (UVA) by doping the aluminum nitrate nonahydrate ($Al(NO_3)_3{\cdot}9H_2O$) to the solution produced by the Sol-gel process [10]. Several smaller single pyrex cells produced using the Sol-gel technique yielded longer relaxation time than uncoated cells. This is the first time that this technique is applied to a high pressure ^{3}He target, a double cell system. The smooth paramagnetic-free aluminosilicate glass coated surface reduces ^{3}He relaxation from magnetic impurity at the sites on the wall. And its low ^{3}He permeability helps prevent loss of ^{3}He atoms for long term operation at typical temperatures of spin exchange optical pumping (180 degree C for Rb-only-cells and 230 degree C for Rb-K hybrid cells). The high background rates from GE180 glass will be highly suppressed since the coating thikcness is on the order of microns. The cell was coated by G. Cates' group at UVA and filled by Todd Averett's group at College of William and Mary. This new Rb-K hybrid ^{3}He gas target cell has the same dimensions as the GE180 cell previously used at HIγS and will be tested for background rates in late May, 2009 at HIγS.

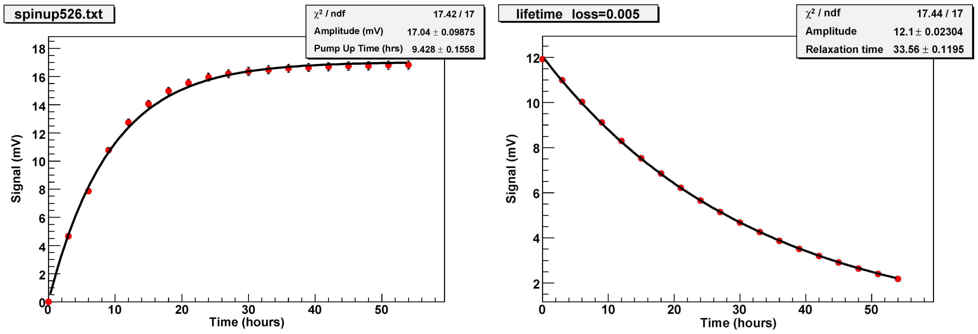

Figure 3: The spin up curve and the curve of the relaxation time measurement.

Fig. 3 shows the curve for the polarization pump-up and the curve for relaxation time measurement. The spin up time is on the order of 10 hours and the relaxation time is ~34 hours. Two methods have been incorporated to measure the ^{3}He polarization in the target chamber, the water calibration [12] and the electron paramagnetic resonance (EPR) techniques [13]. The highest polarization of the ^{3}He target is ∼64.4% from EPR and is consistent with the water calibration data. This outperforms the best result from [14], though the target density is slightly on the lower side.

During the experiment, a reference cell with the same dimension as that of the target cell but with N_2 gas only will be used to measure the background from the N_2 and target cell itself. The ^{3}He target and the reference cell will be interchanged frequently during the data taking at HIγS. This was done manually in the previous run last spring, which was inconvenient and inefficient. A computer controlled target motion system is being designed and will be built and tested this summer. The ^{3}He target and the reference cell can move together up and down, in and out of the gamma beam by a motor-controlled support. When the reference cell is in the gamma beam line, the ^{3}He target is $\sim$ 4.5 in. above it and being polarized by the laser system at the same time, significantly reducing the overhead of the data taking.

3 Preliminary Results from April-May of 2008

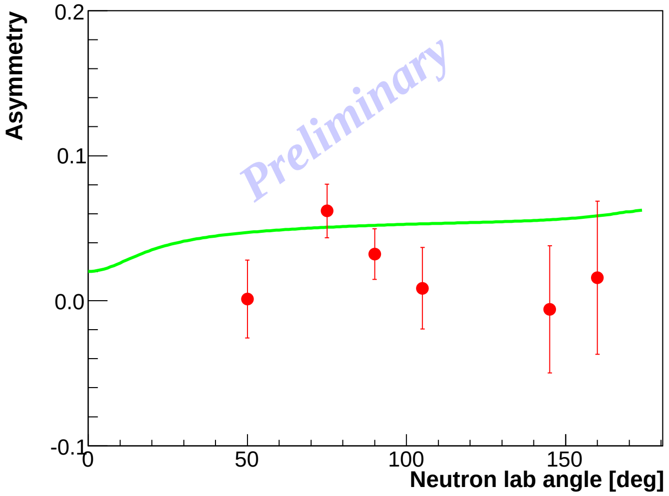

Figure 4: Preliminary asymmetry results at $E_\gamma = 11.4$ MeV with statistical uncertainties only. The red curve represents Deltuva's theoretical calculation using CD Bonn plus Δ (potential) (see text in Introduction). The neutrons are integrated over a kinetic energy range of 1.5 to 2.5 MeV.

Preliminary results from the 11.4 MeV data we took last spring at HIγS are presented here. Fig. 4 shows the extracted physics asymmetry as a function of the neutron scattering angle in the lab frame, integrated over a neutron kinetic energy range of 1.5 to 2.5 MeV. The rather

E_γ (MeV)	Flux (/sec)	$\frac{\Delta E}{E}$(%)	P_{beam} (%)	P_{target} (%)	Beam time (hrs)
11.4	8×10^7	3.0	100.0	60.0	60
20.0	8×10^7	3.0	100.0	60.0	60
30.0	5×10^7	3.0	100.0	60.0	60
40.0	5×10^7	3.0	100.0	60.0	60

Table 1: Parameters for the projection of the proposed measurements.

large statistical uncertainties are due to the fact that the polarized ^{3}He cell "Linda" used in the experiment was made of GE180 glass and very high background rates were seen from the target (see the discussion in the target section). While these results are preliminary, rather different behaviors in our data are seen from those predicted by the theory. More precise measurements are essential in testing the state-of-the-art three-body calculations.

4 Projection and Beam Request

In table 1, we list all the parameters for beam and target that we use in making the projection together with the requested beam time. For each photon energy setting, we include 10 hours of beam time for nitrogen background measurement. We propose to use a 0.75-inch beam collimator. A ^{3}He target density of 5.27 Amags is used in the projection based on that of the "Bolts" cell discussed in the target section.

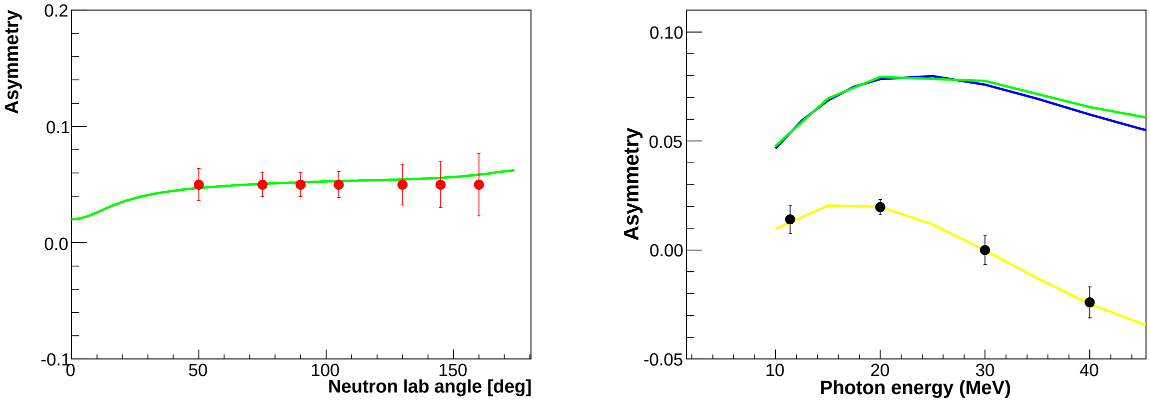

Figure 5: (Left) Projection for asymmetry measurements at $E_\gamma = 11.4$ MeV. (Right) Projection for total asymmetry measurement as a function of incident photon beam energy. The theory curves are labeled in the same way as in Figure 1.

In summary, we request a total of 240 hours of 100% efficient photon beam with a minimum photon flux of 5×10^7/sec [2] with a photon energy spread of 3%. In addition we request 5 days for equipment setup and alignment; 2 days for setup commissioning and instrumentation calibration without beam; 1 day for post-measurement calibrations without beam (1 day) and 2 days for decommissioning (removal of equipment from beam line).

References

[1] S. D. Drell and A. C. Hearn, Phys. Rev. Lett. **16** (1966) 908; S. B. Gerasimov, Sov. J. Nucl. Phys. **2** (1966) 430.

[2] (Jefferson Lab E94010 Collaboration) M.Amarian, et.al Phy. Rev. Lett. **89**, 242301, 2002

[3] J. L. Friar *et al.*, Phys. Rev. C **42**, 2310 (1990)

[4] N. Bianchi, E. Thomas, Phys. Lett. B **450**, 439 (1999)

[5] A. Deltuva *et al.*, Phys. Rev. C **69**, 034004(2004); A. Deltuva and P. Sauer, private communications.

[6] J. Golak *et al.*, Phys. Rept. **415**, 89 (2005); J. Golak, private communications.

[7] A. Deltuva, R. Machleidt and P.U. Sauer, Phys. Rev. C **68**, 024005 (2003).

[8] A. Deltuva, A.C. Fonseca and P.U. Sauer, Phys. Rev. C **71**, 054005 (2005); Phys. Rev. C **72**, 054004 (2005) and Nucl. Phys. A **790**, 344c (2007).

[9] D.E. Trotter *et al.* Nuclear Instruments and Methods in Physics Research A, **599**, 234, 2009

[10] C. J. Brinker and G. W. Scherer, *Sol-Gel Science*, Academic Press, 1990.

[11] M. V. Romalis *et al.*, Phys. Rev. A, **56**, 4569, 1997.

[12] W. Lorenzon *et al.*, Phys. Rev. A, **47**, 468, 1993.

[13] Erin McGuire Buckley, B. S. thesis, College of William and Mary, May, 2005.

[14] K. Kramer *et al.*, Nuclear Instruments and Methods in Physics Research A, **582**, 318, 2007.

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[2] We will postpone the running of the experiment at photon energies higher than 20 MeV if the minimum flux has not been demonstrated.