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Study of the GDH sum rule of ^{3}He at HIGS

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In this talk, we discuss an experiment that has been conducted recently at the High Intensity Gamma Source (HIGS) facility at the Duke Free Electron Laser Laboratory (DFELL) on three-body photodisintegration of circularly polarized photons from a longtudinally polarized ^{3}He target at an incident photon energy of 11.4 MeV. The target was based on the technique of spin-exchange optical pumping with hybrid rubidium and potassium vapors. Neutrons from the three-body photodisintegration process were detected in the experiment using liquid scintillator neutron detectors. We also discuss future prospects at HIGS with the Gerasimov-Drell-Hearn (GDH) integral measurement of ^{3}He.

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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):

$$I^{GDH} = \int_{\nu_{thr}}^{\infty} (\sigma_N^P - \sigma_N^A) \frac{d\nu}{\nu} = \frac{4\pi^2\alpha}{M^2} \kappa_N^2 I \tag{1.1}$$

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.1.1 can be applied directly with N representing the nucleus instead of the nucleon in this case, I being the spin of the nucleus, M being the mass of the target nucleus, and κ_N the anomalous magnetic moment of the 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 for a number of important reasons. It is an important region contributing to the sum rule and as such it is important for the test of the GDH sum rule prediction for ^{3}He. This is also the region that one can test the state-of-the-art three-body calculations. Lastly, it allows for a test of how effective a polarized ^{3}He nucleus is an effective polarized neutron target as polarized ^{3}He nucleus is commonly used as a polarized neutron target. The GDH sum rule for ^{3}He can be written into the following three parts:

$$\int_{\nu_{thr}}^{\infty} GDH_{^3He} = \int_{\nu_{thr}}^{\nu_\pi} GDH_{^3He} + \int_{\nu_\pi}^{2-3GeV} GDH_{^3He} + \int_{2-3GeV}^{\infty} GDH_{^3He} \tag{1.2}$$

In Eqn. 1.2, the first piece is from the two-body breakup threshold of ^{3}He to the pion production threshold, the second piece is due to the contribution from the resonance region, and the last piece is the high energy contribution beyond the resonance region.

The GDH sum rule prediction for ^{3}He, proton and neutron are 496μb, 204μb and 233.5μb, respectively from Eqn.1.1. The second part is estimated to be $247 \pm 38\mu$b extrapolated from the recent inclusive electron scattering data [2]. The uncertainty shown above is the experimental uncertainty only which does not include the model uncertainty. This quantity will become more accurate as new results become available from the inclusive electron scattering data taken at much lower Q^2 [5]. The third part in Eqn. 1.2 can be written into neutron and proton integrals in the plane wave impulse approximation (PWIA) as:

$$\int_{2-3GeV}^{\infty} GDH_{^3He} = P_n \times \int_{2-3GeV}^{\infty} GDH_n + 2P_p \times \int_{2-3GeV}^{\infty} GDH_p \tag{1.3}$$

where GDH_i refers to GDH integral for i, P_n is the effective polarization of the neutron in ^{3}He (87%), and P_p is the effective polarization of proton in ^{3}He (-2.7%) [3]. The factor of two in front of the proton term is to account for the two protons in ^{3}He nucleus. The high energy part of the GDH integral for proton and neutron are $(-26 \pm 7)\mu$b and $(35 \pm 11)\mu$b, respectively based on an analysis by Bianchi and Thomas [4]. So one obtains a value of (31.9 ± 9.6) μb for ^{3}He for the high piece of the integral within PWIA. The first part of the integral in Eqn. 1.2 is therefore estimated to be $\sim (217.1 \pm 39.2)$ μb.

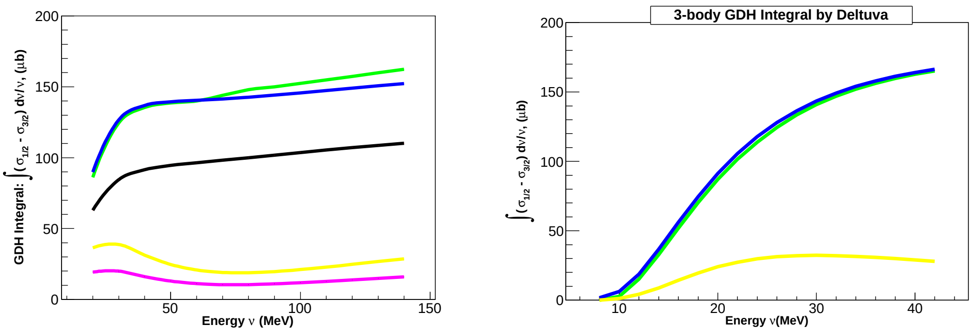

Figure 1: Theoretical predictions of the ^{3}He GDH integral from 20 MeV up to the pion production threshold (left), and the corresponding contribution due to the three-body break-up channel only (right). The curves with different colors are (from bottom to top) (left): magenta line: AV18 + implicit 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.

Fig. 1 shows the state-of-the-art three-body calculations of the GDH integral on ^{3}He as a function of the incident photon energy from 20 MeV to the pion production threshold by Deltuva *et al.* [6], and by Golak *et al.* [7] (magenta and black). In Ref. [6] (green, blue and yellow lines), in addition to the use of Siegert theorem, which assumes current conservation and replaces dominant parts of electric multipoles by the Coulomb multipoles, explicit meson exchange currents (MEC) 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, the Δ potential [8], Siegert including RCO, and explicit MEC(h.o.). The blue line uses CD Bonn plus the Siegert including RCO and MEC(h.o.). The yellow line is from CD Bonn, Siegert theorem and MEC(h.o.). Details of these calculations can be found in Ref. [9]. The calculations by Golak *et al.* [7] using the AV18 potential are shown as the black line with explicit MECs, and the magenta line using the Siegert theorem. The predicted values for the GDH integral on ^{3}He from the two-body break-up threshold to the pion production threshold is below the estimated value discussed previously. Therefore, a precise measurement of the integral in this energy region will provide excellent testing grounds for theories.

The HIGS facility at Duke FEL Lab is an ideal place for such a measurement. The experiment requires measurements of the total two-body and three-body break-up cross sections as a function of incident photon energy starting from the two-body break-up threshold of ^{3}He to the pion production threshold. 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 break-up channel. The three-body photodisintegration process dominates the integral in this energy region as shown in the right panel of Fig. 1 based on the calculation by Deltuva *et al.* [6]. Therefore, the initial phase of our program focuses on the three-body break-up channel. Recently, we carried out a first measurement at 11.4 MeV using a circularly polarized photon beam from HIGS and a longitudinally polarized, high-pressure polarized ^{3}He target.

2. The Experiment

This experiment was carried out at Duke University Free Electron Laser Laboratory (DFELL) which houses the HIGS facility. The γ-rays were 100% circularly polarized with an average flux on target of $\sim 5\times 10^7$/s, and an energy spread of $\sim$3% at an incident energy of 11.4 MeV using a collimator of 22 mm (i.d.). The γ rays were delivered at a rate of 5.5 MHz. This timing structure of the beam is useful to the time-of-flight (TOF) technique employed to identify neutrons and to determine the energy of the neutron.

The beam was incident on a high-pressure polarized ^{3}He target. The target holding field was provided by a pair of Helmholtz coils, 58 inches in diameter. To flip the target spin direction relative to the incident photon momentum direction in order to measure the helicity dependent photodisintegration cross section, the target spin was periodically flipped during the experiment together with the adiabatic fast passage (AFP) technique for spin rotation. The polarized ^{3}He target used in this experiment was a Rb-K hybrid cell consisting of an upper pumping chamber and a lower target chamber, connected by a short transfer tube between the two, all made of GE180 glass. The target was polarized based on the spin-exchange optical pumping (SEOP) technique [10]. The pumping light was from two 60W Coherent diode lasers. The ^{3}He polarization process started with heating the pumping chamber to 238° C. The Rb atoms were optically pumped and polarized, which in turn transferred their polarization to the K atoms. Then spin exchange collisions between K and ^{3}He atoms transfer the polarization to ^{3}He nuclei more efficiently than spin-exchange collisions between Rb atoms and ^{3}He nuclei [11]. The ^{3}He density was determined to be 7.27±0.07 amagats [1] using the laser absorption technique [12]. In addition, about 75 Torr of N_2 gas (room temperature) was contained in the target cell as the buffer gas. More detailed description of the polarized ^{3}He target can be found in Ref. [13]. During the experiment, a N_2-only GE180 reference cell with identical dimensions as those of ^{3}He target, containing the same amount of N_2 gas, was used to measure the background from the N_2 buffer gas and the target cell itself. Two independent techniques were employed to measure the ^{3}He polarization. The first was based on the Nuclear Magnetic Resonance-Adiabatic Fast Passage (NMR-AFP) technique [14], in which the absolute ^{3}He polarization was determined by a calibration to a water NMR measurement to an accuracy of 3.5%. The second one was based on the technique of Electron Paramagnetic Resonance (EPR) [15, 16, 17, 18]. It works in the following way. In an external magnetic field, a Rb atomic $(F=3)$ state splits into seven sub-levels. The frequency of the $m_F=-3\rightarrow m_F=-2$ transition is proportional to the external magnetic field applied plus the field created by polarized ^{3}He nuclei. One can determine the absolute polarization of ^{3}He by measuring this frequency shift. These two methods agreed to 4% and the ^{3}He polarization during our experiment was determined to be $\sim$42%.

The neutrons from $^3\vec{He}(\vec{\gamma},n)pp$ reaction were detected using seven liquid scintillating detectors with excellent pulse-shape discrimination properties between γ-rays and neutrons [19]. The

[1] An amagat measures the number density of an ideal gas at 0°C and 1 atmosphere. 1 amg=2.6894×10^{19} atoms/cm^3.

detectors were positioned between 75 and 90 cm from the center of the target. Each detector was enclosed inside a mu-metal shield for magnetic shielding due to the presence of the ^{3}He target holding field. The detectors were placed at neutron angles of 50°, 75°, 90°, 105°, 130°, 145° and 160° in the laboratory frame in the scattering plane with an azimuthal angle ϕ being zero. The detection efficiency was studied [20]. Pulse shape discrimination (PSD) technique was used to separate neutron events from the larger number of photon events. Different from the traditional long/short gate technique, the 4-channel Mesytec MPD-4 module was used for particle identification. It relied on a constant fraction discriminator (CFD) for the rising edge start and a zero-crossing discriminator for tail length detection [21].

To select neutron events from the $^3\vec{He}(\vec{\gamma},n)pp$ process, four cuts were applied in total. A multiplicity cut was applied to select events in which only one detector returned a hit. The second cut was on the pulse shape discrimination in order to select neutron events. The third cut was on pulse height (PH). Due to the hardware threshold of roughly $\frac{1}{4}\times^{137}Cs$ applied during the experiment, a higher software PH threshold of 200 keV$_{ee}$ ($\approx$ 1.0 MeV neutron energy) was applied to ensure that each detector had the same threshold and thus the same efficiency for detecting neutrons [22]. After these three cuts, a significant portion of photon events were eliminated. The last cut was on the TOF window based on the kinematics of the neutrons. By summing over the raw counts within the TOF window, and subtracting the events within an equal length of sideband to subtract background events, neutrons from the $^3\vec{He}(\vec{\gamma},n)pp$ process were finally obtained. Currently the analysis is being finalized and we anticipate to present our final results by the end of 2009.

3. Future Plan

The polarized ^{3}He target used in this experiment was made of Aluminosilicate (GE180) glass due to its fewer magnetic impurities and more impermeability to ^{3}He atoms than regular pyrex glass. However, the rich concentration of barium in the GE180 gave rise to large background neutrons. This made the background subtraction much harder. Recently, a new high-pressure ^{3}He cell made of pyrex glass coated with a thin layer of pure Aluminosilicate glass [23] has been constructed and tested. This coating technique was based on the solution produced by the Sol-Gel process [24] and this is the first time that this technique has been applied to a high pressure ^{3}He target for nuclear physics experiments. This cell was tested in May, 2009 at the HIGS facility and experimental data showed that Sol-Gel coated pyrex glass had 30% fewer background events. The performance of this target together with the beam test results will be reported in a separate paper [26]. Further improvements for future measurements will include the implementation of a vacuum beam pipe, better shielding of the downstream D_2O target and a five-paddle system for absolute flux monitoring [25]. Future high precision measurements will provide more stringent tests of the theory and provide important data towards the ultimate goal of determining the ^{3}He GDH integral in the energy region below the pion production threshold.

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