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The contribution of the $^3\vec{He}(\vec{\gamma}, n)pp$ reaction to the GDH integrand below pion production threshold

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Abstract. The first measurements of the three-body phototdisintegration of ^{3}He polarized parallel and anti-parallel to a circularly polarized γ-ray beam were carried out at the High Intensity γ-ray Source (HIγS) facility located at Triangle Universities Nuclear Laboratory (TUNL). A high pressure ^{3}He target, polarized via spin-exchange optical pumping with alkali metals, was used in the experiments. The neutrons from the three-body photodisintegration were detected with sixteen 12.7 cm diameter liquid scintillator detectors. The spin-dependent cross sections and the contributions from the three-body photodisintegration to the ^{3}He Gerasimov-Drell-Hearn sum rule integrand were extracted and compared with state-of-the-art three-body calculations at the incident photon energies of 12.8, 14.7, and 16.5 MeV. The calculations, which include the Coulomb interaction are in good agreement with the results of the measurements at 12.8 and 14.7 MeV but deviate from the results at 16.5 MeV.

1 Introduction

Sum rules involving the spin structure of the nucleon and nuclei offer an important opportunity to study QCD. Among spin sum rules, the Gerasimov-Drell-Hearn (GDH) sum rule [1] is particularly interesting. It connects long distance behavior of the nucleon (nucleus), i.e. static property, to the entire excitation spectrum. The GDH sum rule relates the energy-weighted difference of the spin-dependent total photo-absorption cross sections σ^P (for target spin and beam helicity parallel) and σ^A (for target spin and beam helicity anti-parallel) to the anomalous magnetic moment of the target nucleus/nucleon as follows:

$$I^{GDH} = \int_{\nu_{thr}}^{\infty} (\sigma^P - \sigma^A) \frac{d\nu}{\nu} = \frac{4\pi^2\alpha}{M^2}\kappa^2 I, \tag{1}$$

where ν is the photon energy, ν_{thr} is the pion production/photodisintegration threshold on the nucleon/nucleus, κ is the anomalous magnetic moment, M is the mass and I is the spin of the nucleon or the nucleus. This sum rule is based on fundamental principles such as Lorentz and Gauge invariance, crossing symmetry, causality and unitarity, and an assumption of unsubtracted dispersion relation. A detailed derivation of the GDH sum rule based on the aforementioned principles can be found in Ref. [2].

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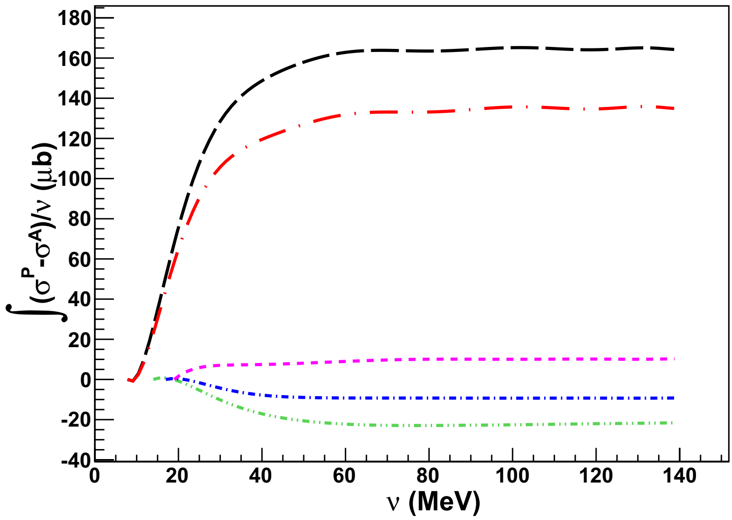

Figure 1. (Color online) Theoretical predictions of two- and three-body channel contributions to the ^{3}He GDH Integral below pion production threshold. The curves from top to bottom are: (i) long-dashed (black) curve: three-body channel contribution by Deltuva *et al.* (ii) long-dashed dotted (red) curve: three-body channel contribution by Skibiński *et al.* (iii) short-dashed (purple) curve: two-body channel contribution by Skibiński *et al.* (explicit MEC) (iv) short-dashed dotted (blue) curve: two-body channel contribution by Skibiński *et al.* (implicit MEC via Siegert theorem) (v) short-dashed double dotted (green) curve: two-body channel contribution by Deltuva *et al.*

The sum rule for ^{3}He can be written as the sum of two terms:

$$496\mu b = \int_{\nu_{thr}}^{\infty} GDH_{^3He} = \int_{\nu_{thr}}^{\nu_\pi} GDH_{^3He} + \int_{\nu_\pi}^{\infty} GDH_{^3He} \tag{2}$$

where the first term is from the two-body breakup threshold of ^{3}He (~ 5.5 MeV) to the pion production threshold (~ 140 MeV) and the second term is for the energy region from the pion production threshold to infinity. The first term can be measured experimentally by carrying out double-polarized two-body and three-body photodisintegration experiments in this energy region and it can also be estimated based on the state-of the-art three-body calculations.

The state-of-the-art three–body calculations which can estimate the first part of the integral in Eq. (2) are performed mainly through the machinery of Faddeev [6] and Alt-Grassberger-Sandhas equations (AGS) [7], and have been carried out for both two-body and three-body photodisintegration of ^{3}He with double polarizations. These calculations [8, 9] use a variety of nucleon-nucleon (NN) potentials like Argonne V18 (AV18) [10] or charge dependent (CD) Bonn [11, 12] and three-nucleon forces (3NFs) like Urbana IX (UIX) [13] or CD Bonn + Δ [8], with the latter yielding an effective 3NF through the Δ-isobar excitation. The calculations by Deltuva *et al.* are based on AGS equations and employ the CD Bonn+Δ [8] with the corresponding single-baryon and meson-exchange electromagnetic currents plus relativistic single-nucleon charge corrections [8]. The proton-proton Coulomb force is included using the method of screening and renormalization [8]. Skibiński *et al.* solve the Faddeev equations by using the AV18 potential and the UIX 3NF accounting for single-nucleon currents and the two most important meson-exchange electromagnetic currents, the seagull and pion-in-flight terms [9].

Figure 1 shows the GDH integral for the two- and three-body photodisintegration of ^{3}He below pion production threshold. The short-dashed double dotted (green) and the long-dashed (black) curves are the estimations of the GDH integral for the two- and three-body photodisintegration from Deltuva *et al.* Their sum amounts to 142 μb. The short-dashed (purple) and short-dashed dotted (blue) curves are two different estimations by Skibiński *et al.* of the two-body channel contribution to the GDH integral taking into account explicitly or implicitly the MEC via the Siegert theorem. The long-dashed dotted curve is the estimation of the three-body contribution to the GDH integral coming from the same group. The maximum estimation of the GDH integral below pion threshold according to Skibiński *et al.* is 145 μb. Both theoretical calculations predict that the contribution to the GDH sum rule below pion production threshold is 140–150 μb which is an important part of the overall GDH integral (496 μb). This contribution lays mainly below the incident photon energy of 40 MeV. Therefore, a spin-dependent study of $^3\vec{He}(\vec{\gamma},n)pp$ below 40 MeV not only provides a stringent test of modern three-body calculations, but also serves as an important step towards an experimental test of the GDH sum rule on the ^{3}He nucleus.

2 The Experiment

The first experiments [14, 15] on the three–body photodisintegration of ^{3}He using a longitudinally polarized ^{3}He target and a circularly polarized γ-ray beam took place at the HIγS facility [17] of TUNL at the incident photon energies of 12.8, 14.7 and 16.5 MeV. A nearly mono-energetic, ~100% circularly-polarized pulsed γ-ray beam was used. The beam was collimated using a 12 mm diameter collimator resulting in on-target intensities of (0.7-2.0)$\times10^8\gamma/s$ and an energy spread of $\Delta\nu/\nu$ ~3.0-5.0%. The on-target intensity of the beam was determined using the well-known d(γ,n)p cross section [18] and two BC501A liquid scintillator neutron detectors mounted at a scattering angle of 90° degrees downstream of the ^{3}He target.

Upstream of the flux monitor, the polarized γ-beam was incident on a polarized ^{3}He cell. A N_2 reference cell was used for background subtraction. Details concerning their technical characteristics and the spin exchange optical pumping technique used to polarize the ^{3}He target can be found in Refs. [14, 15, 19–21]. The spin of the ^{3}He target was flipped every 15 mins in order to extract the spin-dependent cross sections and the GDH integrand, $(\sigma^P - \sigma^A)/\nu$. The polarization was measured using the nuclear magnetic resonance-adiabatic fast passage [22] technique calibrated by electron paramagnetic resonance [23]. The latter can measure the absolute ^{3}He target polarization which was found to be between 33% and 45%.

An array of sixteen liquid scintillator BC-501A counters was used to detect the neutrons from the $^3\vec{He}(\vec{\gamma},n)pp$ reaction. The detectors were placed at the horizontal plane every 15°, symmetrically on each side of the beam, at laboratory scattering angles from 30° to 165°. No detectors were placed at the laboratory angles 60° and 120° due to the proximity to a pair of Helmholtz coils which provided the holding field for the polarized ^{3}He target.

Three quantities were recorded for each event: the pulse height (PH), the time-of-flight (TOF) and the pulse shape discrimination (PSD) signals. Initially, a PH cut was applied at 0.162 MeVee to set the detector efficiency. The correlations between the PSD, PH and TOF were utilized to extract the neutron events and to remove the γ-ray events and two-dimensional cuts were applied on these histograms. The same cuts were used for the data taken with the N_2 reference cell to subtract the background contributions. The outgoing neutron energy was determined using the measured TOF of the neutrons assuming they were emitted from the center of the ^{3}He target cell. More details about this analysis can be found in Refs. [14, 15].

3 Results and Discussion

The spin-dependent double-, single-differential and total cross sections, and the contributions of the three–body photodisintegration of ^{3}He to the GDH integrand were obtained [14–16] and compared with the state-of the-art three-body calculations [8, 9] at all incident energies. Fig. 2 [16] shows the GDH integral results including the statistical and systematic uncertainties compared with the theoretical calculations. Although a very good agreement is observed between the measurements [14, 15] and the calculations based on Ref. [8] at 12.8 and 14.7 MeV, a difference between the measured GDH integrand and the calculations can be seen at the incident photon energy of 16.5 MeV. The measured GDH integrand at 16.5 MeV is found to be slightly more than one standard deviation larger than the maximum calculated value based on Ref. [8].

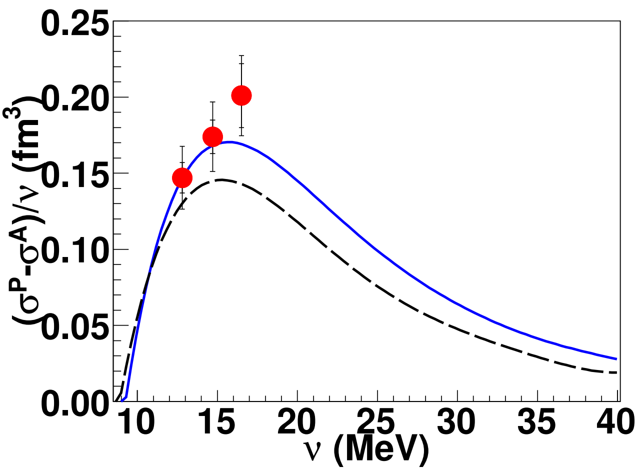

Figure 2. (Color online) The combined GDH integrand results as can be seen in Ref. [16] compared with the theoretical predictions of Ref. [8] (solid-blue curve) and Ref. [9] (dashed-black curve). The inner error bars of the data points represent the statistical uncertainties while the outer include both the statistical and systematic uncertainties added in quadrature.

To investigate whether the larger than expected GDH integrand value at 16.5 MeV is due to statistics and to further quantify the three-body contribution to the GDH integral, measurements above 16.5 MeV for the three-body photodisintegration channel are necessary. These measurements combined with the recently acquired data from the two-body photodisintegration channel [15] will constrain the contribution to the GDH integral for ^{3}He below the pion-threshold.

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