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Studies of Nucleons and Nuclei at TUNL/HIγS: From Hadron Structure to Exploding Stars

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An overview of the nuclear physics research program at the High Intensity Gamma-Ray Source (HIγS) of Triangle Universities Nuclear Laboratory (TUNL) is presented. This program, across the distance scales include studies of hadron structure to measure the electromagnetic and spin polarizabilities, precision measurement of photonuclear cross sections of reactions on light nuclei, and measurements of key nuclear reaction rates relevant to helium burning in stars.

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1. Introduction

Since the production of the first Compton backscattered γ ray beams at the High Intensity γ-Ray Source (HIγS) nearly fifteen years ago, a diverse program using photonuclear reactions has produced a wealth of quality data. These data have contributed significantly in the understanding of nuclear systems ranging from relatively large distance scales, such as establishing the spectral structure of Pygmy Dipole Resonance (PDR) [1] , discovery and spin-parity assignment of more than 1000 new nuclear levels in actinides, and unambiguous identification of second 2^+-state in ^{12}C [2], to short distance scales such as the first measurement of the Gerasimov-Drell-Hearn (GDH) sum-rule integrand for ^{3}He at two energies below pion production threshold [3], and recently commissioned program of nucleon Compton scattering to determine model independent electromagnetic polarizabilities of the proton and neutron, as well as the their spin polarizabilities.

There have been recent theoretical advances such as ab-initio Effective Field Theory Lattice (EFT-L) calculations describing alpha-cluster states in light nuclei [4] and Bayron χPT calculations [5] of proton's electromagnetic polarizabilities, which demand precision measurements to be carried out at energies, γ-ray polarization, and beam intensities only available at the HIγS facility. These measurements have begun with with the Compton scattering program and a first measurement of the photon scattering differential cross sections on ^{6}Li at 60 and 80 MeV. Initial photon scattering beam tests on proton and ^{3}He targets have been carried out at 80 MeV to study the active scintillating targets and backgrounds. In addition, the HIγS Frozen Spin Target (HIFROST) installation will be completed in the summer of 2013 with the first GDH experiment on deuterium scheduled for early fall of 2013. The installation of the HIFROST will also enable the next phase of the Scintillating-HIFROST (S-HIFROST) to be tested for the proton spin polarizability measurements at 100 MeV.

An additional future direction of the program, though not discussed in this paper, is the extensive program on pion photoproduction which has been described in detail in the review article [6]. We anticipate to start the photo-pion production program with the availability of γ-ray beams above 150 MeV in 2015. Therefore, the Compton scattering program would contribute a significant fraction of the nuclear physics program at HIγS along with nuclear structure and nuclear astrophysics measurements. The HIγS facility is described in detail in Ref. [6]. The recent accomplishments at HIγS, the Compton scattering program, and the future directions are presented in this paper.

2. Compton Scattering

In nucleon Compton scattering, the electromagnetic field of frequency ω induces multipoles in the nucleon, which in turn radiates with the same frequency. The stiffness of the internal degrees of freedom of the nucleon against the deformation of a particular multipolarity is called polarizability. In the case of experiments at HIγS with energies below pion production threshold, we can limit ourselves to the lowest order dipole polarizabilities. As outlined in [7], the field-theoretical Lagrangian which describes the interaction between a nucleon field N with spin $\vec{\sigma}/2$ can be written in terms of these polarizabilities:

$$\begin{aligned}\mathscr{L} &= 2\pi N^\dagger[\alpha_{E1}(\omega)\vec{E}^2+\beta_{M1}\vec{B}^2(\omega)+\gamma_{E1E1}(\omega)\vec{\sigma}\cdot(\vec{E}\times\dot{\vec{E}})+\gamma_{M1M1}(\omega)\vec{\sigma}\cdot(\vec{B}\times\dot{\vec{B}}) \\ &- 2\gamma_{M1E2}(\omega)\sigma B_j E_{ij}+2\gamma_{E1M2}(\omega)\sigma E_j B_{ij}, \qquad (2.1)\end{aligned}$$

where $T_{ij} \equiv \frac{1}{2}(\partial_i T_j + \partial_j T_i), \vec{T} = \vec{E}, \vec{B}$. This response can be characterized by six independent structure functions, $A_i(\omega, z = cos\theta)$, which are linear combinations of electromagnetic polarizabilities α and β, and spin polarizabilities $\gamma_{ll'}$ with multipolarities l and l'. For the case of forward scattering and in the limit $\omega \to 0$ these amplitudes contain terms describing the coupling of photons to the charge eQ (Thompson term) and anomalous magnetic moment κ. These structure functions can be separated into *structure* and *non-structure* parts as:

$$A_i(\omega, z) = A_i^{Born}(\omega, z) + \overline{A}_i(\omega, z). \tag{2.2}$$

The six structure amplitudes $\overline{A}$ contain linear combinations of α_{E1}, β_{M1} in ω^2 and $\gamma_{ll'}$ in ω^3. The Compton scattering program at HIγS will contribute significantly towards the understanding of each one of these structure functions by the following measurements:

- The Gerasimov-Drell-Hearn (GDH) sum rule which connects the helicity structure of the photo-absorption cross section to the anomalous magnetic moment of the nuclear target. The GDH measurements are being performed on the deuteron and ^{3}He;
- A sum rule independent measurement of the proton's electric and magnetic polarizabilities;
- Spin-polarizabilities of the proton and the neutron.

2.1 The GDH sum rule measurements

The Gerasimov-Drell-Hearn (GDH) sum rule connects the helicity structure of the photo-absorption cross section to the anomalous magnetic moment of the nuclear target. It is derived using Lorentz and gauge invariance, crossing symmetry, causality and unitarity of the forward Compton scattering amplitude, and is given explicitly by

$$I_T = \int_{\omega_{\rm th}}^{\infty} d\omega \frac{\sigma_P(\omega) - \sigma_A(\omega)}{\omega} = 4\pi^2 \alpha s_T \left(\frac{\kappa_T}{m_T}\right)^2, \tag{2.3}$$

where σ_P and σ_A are the cross sections for absorption of polarized photons of energy ω and helicities parallel and antiparallel to the target spin s_T, $\omega_{\rm th}$ is the threshold photon energy for inelastic processes, α is the fine-structure constant, and m_T and κ_T are the target mass and anomalous magnetic moment, respectively.

2.1.1 ^{3}He

There have been worldwide efforts to determine the GDH sum rule on the proton [8], neutron [9] and deuteron [10, 11] using real photons, the GDH integrand for ^{3}He, $I_{^3He}$, has never been measured prior to the experiments at HIγS below pion production threshold. The GDH sum rule prediction based upon the anomalous magnetic moment for ^{3}He is 496 μb. The first measurement of the three-body photodisintegration of longitudinally-polarized ^{3}He with a circularly-polarized γ-ray beam was carried out at incident photon energies of 12.8 and 14.7 MeV [3]. The contributions from the three-body photodisintegration to the ^{3}He GDH integrand were measured and found in agreement with state-of-the-art three-body calculations.

The circularly polarized γ-ray beams of energies 12.8 and 14.7 were incident on a longitudinally-polarized, 39.6 cm long ^{3}He target. Neutrons from the $^3\vec{He}(\vec{\gamma}, n)pp$ process were detected using sixteen BC-501A-based neutron detectors. The total cross sections were extracted for both energies and the two spin-helicity states, in order to determine the values of the GDH integrand. The HIγS data are in very good agreement with predictions of Ref. [12] and consitute the first measurement of the GDH sum rule contribution from the 3-body channel below the pion production threshold. Details of the experiment and results can be found in Ref. [3].

2.1.2 Deuteron

The recent interest in the nucleon and deuteron GDH sum rules stems from the study of the spin dependent structure functions in deep inelastic scattering. Since the proton and neutron have relatively large anomalous moments ($\kappa_p = 1.793$ and $\kappa_n = -1.913$, respectively), the corresponding values of I obtained from Eq. (2.3) are large, $I_p = 204.8\mu$b and $I_n = 232.5\mu$b, while the deuteron, for which $\kappa_d = -0.143$, has a comparatively small $I_d = 0.652\mu$b. One should expect to observe the sum of the proton and neutron strengths (and more) in the deuteron above pion threshold, indicating that a large negative contribution of about this size (-436 μb) should exist below this threshold. Indeed, Arenhövel [14] and others point out that the photodisintegration channel, which is the only photo-absorption process below the pion threshold, gives a large negative contribution arising from the M1 transition to the resonant $^1S_0$ state just above the deuteron breakup threshold.

The GDH collaboration at HIγS is dedicated to measuring the integrand of this sum rule. There are two main phases to this work. The first phase has recently been completed. It consisted of using the linearly polarized gamma-ray beams and unpolarized targets to measure the near-threshold contribution to the GDH sum-rule integral of the deuteron. The results of this study have been published in Refs. [11, 15]. Although these indirect measurements have been very instructive, the continuation of this method to higher energies is not practical since the number of contributing TMEs is known to grow. The number of unknowns will therefore be too great to be able to obtain meaningful solutions. For this reason we will make direct measurements of the GDH integrand for the deuteron at energies between 5 and 20 MeV during 2013 and up to 100 MeV by 2015.

The measurement will use the Blowfish neutron detector array, the HIγS frozen-spin polarized deuterium target (HIFROST), and circularly polarized gamma rays. The GDH collaboration anticipates starting this experiment in the fall of 2013.

2.2 A Sum Rule Independent Measurement of Proton's Static Electric Polarizability

The Compton @ HIγS collaboration is measuring the static electric (α) dipole polarizability of the proton using Compton scattering of linearly polarized gamma rays from unpolarized protons. We will measure α using a different approach in which a photon asymmetry measurement at a laboratory scattering angle of 90° yields a sum-rule, model independent measurement of α with an uncertainty of ~ 5 %. The goal of this α measurement is not to so-much to improve on the statistical uncertainty in the currently accepted value, but to provide a direct measurement of α from a method which does not have uncertainties associated with the extraction of α using dispersion relations. These measurements will be carried out at a gamma ray energy of 82 MeV using the HIγS NaI detector Array (HINDA).The target will be a plastic scintillator, 10 cm long. A 300 hours experiment will provide an independent measurement of α and the point cross section for the first time.

Studies of nucleon Compton scattering in the framework of subtracted dispersion relations [18], and model-independent effective field theory (EFT) [19] have been performed. At photon energies below $\sim$ 100 MeV, the low energy expansion (LEX) of the Compton scattering cross section relates the static polarizabilities (α, β) to the cross section. Historically, the Baldin Sum rule, which constrains the value of $\alpha + \beta$ and relates it to the total photoabsorption cross section (σ_γ), has been invoked to extract individual polarizabilities [17, 20, 21].

The validity of the LEX starts to fail beyond $\sim$ 100 MeV of photon energy and the effect of finite polarizabilities is weak below 100 MeV and measuring their values has required precision measurements of absolute cross sections. The dispersion relation (DR) calculations have been used to extract the polarizabilities since most of the experimental data on proton Compton scattering is above 100 MeV. Therefore, in addition to statistical uncertainties, these extractions of polarizabilities have systematic and model dependent errors [20]. The experimental status of proton electric and magnetic dipole polarizabilities is summarized in Refs. [20, 21, 18]. A global fit yields the current accepted values of the proton's electric- and magnetic-dipole polarizabilities [18]:

$$\begin{aligned} \alpha &= [12.1 \pm 0.3(\text{stat}) \mp 0.4(\text{syst}) \pm 0.3(\text{model})] \times 10^{-4}\ \text{fm}^3 \\ \beta &= [1.6 \pm 0.4(\text{stat}) \pm 0.4(\text{syst}) \pm 0.4(\text{model})] \times 10^{-4}\ \text{fm}^3 \end{aligned} \tag{2.4}$$

There has been recent interest in the measurement of the EM polarizabilities in-part due to Baryon-Chiral Perturbation Theory (BχPT) calculations with the inclusion of Δ indicating values for α and β which are significantly different from the accepted values listed above [5]. The situation is shown in fig. 1. An in-depth theoretical and experimental review of the field is available in [7].

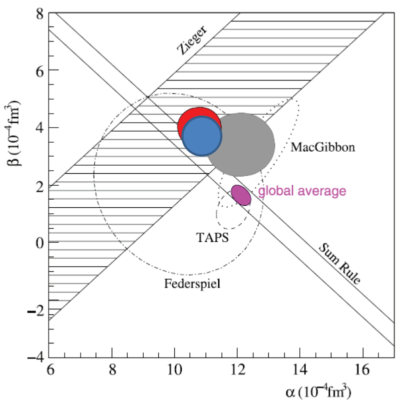

Figure 1: The value of α and β for the proton. The global accepted value is shown in purple, whereas the recent BχPT predictions are shown by the blue circle.

We present here a sum rule and model independent approach to measuring the proton's electric polarizability at 82 MeV using linearly polarized gamma rays and an unpolarized proton target.

The scattering of linearly polarized γ-rays from unpolarized protons is described by the formalism outlined in [22]. In this formalism, the polarization dependent low-energy expansion of the cross section can be viewed as a combination of a point scattering term and a dipole-only term:

$$\frac{d\sigma(\varepsilon)}{d\Omega} = \left(\frac{d\sigma(\varepsilon)}{d\Omega}\right)_{point} + \left(\frac{d\sigma(\varepsilon)}{d\Omega}\right)_{dipole} \tag{2.5}$$

where ε is the incoming polarization direction.

These cross sections parallel and perpendicular ($\frac{d\sigma_{\parallel}}{d\Omega}$ and $\frac{d\sigma_{\perp}}{d\Omega}$) to the initial polarization can be separately stated as:

$$\frac{d\sigma_{\perp}}{d\Omega} = (\frac{d\sigma_{\perp}}{d\Omega})_{point} - \underbrace{\left[\frac{e^2}{Mc^2}\right]\left[\frac{\omega'}{\omega}\right]^2 \omega\omega'(2\alpha + 2\beta\cos\theta)}_{d\sigma_{\perp}^{dipole}} \tag{2.6}$$

and

$$\frac{d\sigma_{\parallel}}{d\Omega} = (\frac{d\sigma_{\parallel}}{d\Omega})_{point} - \underbrace{\left[\frac{e^2}{Mc^2}\right]\left[\frac{\omega'}{\omega}\right]^2 \omega\omega'(2\alpha\cos^2\theta + 2\beta\cos\theta)}_{d\sigma_{\parallel}^{dipole}} \tag{2.7}$$

where κ is the proton anomalous magnetic moment and the cross sections are defined in the laboratory system. The 90° parallel cross section is independent of α and β and the the cross section asymmetry can be defined as:

$$A(\omega,\theta) = \frac{d\sigma_{\perp} - d\sigma_{\parallel}}{d\sigma_{\perp} + d\sigma_{\parallel}}, \text{ and} \tag{2.8}$$

at 90° this asymmetry yields a pure α measurement:

$$A(\omega, 90^{\circ}) = \frac{C_1(\omega) - C_2(\omega)\alpha}{C_3(\omega) + C_2(\omega)\alpha} \tag{2.9}$$

where $C_{1,2,3}$ are energy dependent constants.

We will measure the value of α by measuring the cross section asymmetry (Eq. 2.8) at a laboratory scattering angle of 90°. We will use the HIγS NaI Detector Array (HINDA) which has now been used for multiple Compton scattering experiments, for photon detection. Four detectors will be placed left, right, up, and down with respect to the polarization plane of the beam at a scattering angle of 90°. A plastic scintillating target with proton density of 5.21×10^{22} protons/cm^2 was recently test in the HIγS beam at 85 MeV. A count rate and sensitivity calculation was performed to predict the error in the measurement of α using an asymmetry measurement. In this case the uncertainties due to flux determination, target thickness, detector efficiencies and solid angle corrections do not play a role. A 300 hour experiment will yield an asymmetry error of 0.25%, which will provide a measurement of α with an uncertainty $\sim$ 5%. This uncertainty will not improve the currently stated global uncertainty in the value of α, but will provide a first ever model/sum-rule independent measurement of this quantity.

2.3 Neutron α_n and β_n

We are measuring the electric and magnetic polarizabilities, α_n and β_n respectively, of the neutron by Compton scattering a circularly polarized beam of photons on an unpolarized, liquid deuterium target. Using the "known" values of the proton's polarizabilities, the neutron polarizabilities can be extracted. With a 1" beam collimation we'll have a flux of $1\times10^7\ \frac{\gamma}{s}$ at 65 and 100 MeV. Eight 10"×10" NaI detectors will be paired beam left and beam right at 45°, 80°, 115°, and 150°. The ratio $\frac{\sigma_{45^\circ}}{\sigma_{150^\circ}}$ varies by ±2% at 65 MeV, and by ±4% at 100 MeV, for $\Delta\beta_N = \pm1\times10^{-4}\ fm^3$. The average cross section at those angles is 17 $\frac{nb}{sr}$ at 65 MeV, and 13 $\frac{nb}{sr}$ at 100 MeV. Using this ratio alone we would obtain enough statistics to resolve each variation in 300 hours of beam-time at 65 MeV and 100 hours at 100 MeV. The additional detectors at 80° and 115° will allow us to fit over the angular distribution, further improving the results. Our goal is to supplement the experimental data with a measurement at HIγS and then fit these data with the (χEFT) cross sections in order to ultimately extract α_n and β_n.

2.4 Spin Polarizabilities (SP) of the Proton

As presented earlier, at $O(\omega^3)$ four new structure dependent terms enter the Compton scattering amplitude which are linear combinations of dipole spin polarizabilities. In the multipole basis the spin-polarizabilities are given as γ_{E1E1}, γ_{M1M1},γ_{E1M2}, and γ_{M1E2}, where the multipoles define the initial and final state photon states. Relatively little is known about the spin-polarizabilities of the nucleon. In general terms, they describe the response of the nucleon's spin to the photon polarization. The "stiffness" of the spin can be thought of as arising from the nucleon's spin interacting with the pion cloud. The most model-independent way to measure the SPs is double-polarized Compton scattering at energies below pion threshold with longitudinal and transverse polarized targets, and circularly polarized photons. At the present time there are no measurements of individual SPs below pion production threshold. The first experiment measuring the beam-target asymmetry (Σ_{2x}), which is sensitive to γ_{E1E1}, has been carried out at Mainz at photon energy of 285 MeV. The results of the measurements at Mainz are discussed in detail by R. Miskimen in his contribution to these proceedings.

The sensitivity of Σ_{2x} to γ_{E1E1} is shown in Figure 2 at 100 MeV for a transverse polarized target from the dispersion model of Ref.[27]. In this figure the polarizabilities γ_0 and γ_π are held fixed at the experimental values, and γ_{E1E1} and γ_{M1M1} are varied by $\pm2\times10^{-4}$ fm^4 from the values of Ref.[27]. The black (blue) curve shows the effect of varying γ_{E1E1} by $\pm2\times10^{-4}$ fm^4 from the value of Ref.[27], holding the other SPs fixed at their nominal values, and the red (orange) curve shows the effect of varying γ_{M1M1} by $\pm2\times10^{-4}$ fm^4 from the value of Ref.[27]. The width of the curves is from the uncertainty in γ_0 and γ_p. At angles near 90° the sensitivity to γ_{M1M1} is weak, and most of the sensitivity in the beam-target asymmetry is due to γ_{E1E1}. *We are exploiting this sensitivity to make a relatively pure measurement of γ_{E1E1} at HIγS.*

We are constructing a scintillating, polarized target for this measurement to reduce the background from heavy nuclear recoils from materials in target. The scintillating target foils were cast to be ∼0.8 mm thick and have high clarity. About 60 of these foils will be strung together on 4 thin graphite rods to get a total target length of approximately 5 cm. Scintillation light produced in the target foils escapes through the quartz target cell wall, and the light is captured in a blue-to-

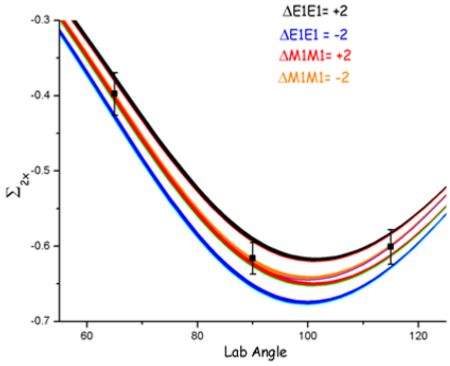

Figure 2: The double-spin asymmetry Σ_{2x} from Ref.[27] plotted as a function of lab angle at 100 MeV. The black(blue) curve shows the effect of increasing γ_{E1E1} from the nominal values of Ref.[27] by $\pm\, 2\times10^{-4}$ fm^4. The red(orange) curve is the same for increasing γ_{M1M1} by $\pm\, 2\times10^{-4}$ fm^4. The data points show projected errors for this experiment.

green wavelength shifting (WLS) tube that covers 270° in azimuth angle. Green-to-orange WLS fibers attached along the open edge of the WLS tube capture and transport light to a photo-detector. Radiation Monitoring Devices Inc. (RMD) in Watertown MA has developed a CMOS solid-state photomultiplier (SSPM) for use in the active polarized target. The transverse holding coil is now ready and was tested at TUNL and performed as expected. The measurement will use the already commissioned HINDA system.

The sensitivity of the double-asymmetry Σ_{2x} to the spin polarizabilities at lab angles of 65°, 90° and 115° have been calculated. At these kinematics we're largely sensitive to γ_{E1E1}, with a $\sim$10% sensitivity to γ_{M1M1}. Projected absolute errors in the effective polarizabilities are calculated assuming an 800 hour run, 80% transverse target polarization and a relaxation time of 4 days. Experimental errors in γ_0 and γ_π have little effect on the accuracy of extracting the weighted sum of γ_{E1E1} and γ_{M1M1}. Assuming that γ_{M1M1} makes a negligible contribution to the effective polarizabilites, the projected error for γ_{E1E1} is $\approx 1.0\times10^{-4}$ fm^4. This would constitute the first measurement of the γ_{E1E1} below pion production threshold.

Compton scattering on heavier targets, such as ^{6}Li, to extract isoscaler polarizabilities of the nucleons is discussed by H. R. Weller in his contribution to these proceedings. In addition, a program on the nuclear Compton scattering to extract precision isovector giant quadrupole resonance (IVGQR) paraemters is also discussed in his contribution.

3. Nuclear Astrophysics: The Direct Observation of the New 2^+ State in ^{12}C

This topic is discussed in detail by W. R. Zimmerman in his contribution to these proceedings. A summary is presented here.

Stellar synthesis of elements heavier than helium, such as carbon and oxygen, is thought to occur through the triple-α process. The observed abundance of carbon led Hoyle [28] to predict a resonance near the ^{8}Be$+\alpha$ threshold which was subsequently observed [29, 30]. This was the first time that an astrophysical argument correctly predicted specific attributes of nuclear structure,

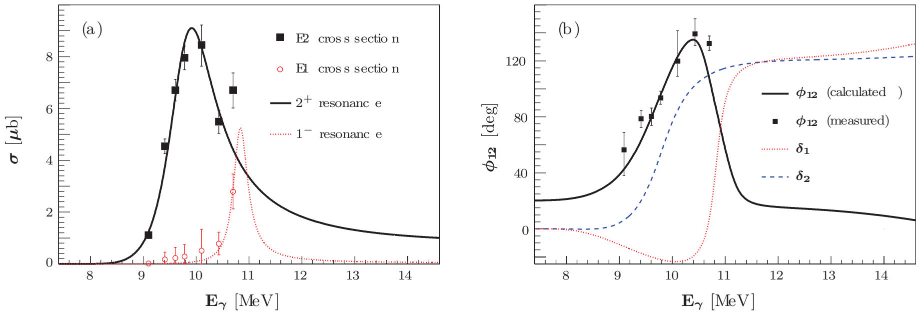

Figure 3: Measured ^{12}C(γ,α_0)^{8}Be cross section and relative phase angle. (a) shows the E1 and E2 components of the cross section. The E2 data are fit to a 2^+ resonance, and the E1 data are fit to a 1^- resonance of known width and energy. (b) shows the measured phase difference ϕ_{12}, along with calculations from a two-resonance model

and the 7.65 MeV, $J^\pi = 0^+$ state in ^{12}C is now known as the 'Hoyle state.' Even though carbon is primarily produced via the Hoyle state in red giant stars at temperatures of 10^8–10^9 K, during core-collapse supernovae, γ-ray bursts and other astrophysical phenomena, the temperature rises well above 10^9 K, and higher energy states in ^{12}C could have a significant effect on the triple-α reaction rate [31, 32]. In particular, a second $J^\pi = 2^+$ state (written 2_2^+) was predicted in 1956 as an excitation of the Hoyle state [33]. The exact energy, width, and strength of the 2_2^+ state are needed to determine the influence of this state on the triple-α reaction rate at high temperatures [31].

Recently, *ab initio* EFT lattice calculations [4] have been performed in order to understand the structure of the Hoyle state. Further calculations [34] have identified a 2^+ excitation and predicted its electromagnetic decay widths. These ab initio EFT lattice calculations are described by D. Lee in his contribution to these proceedings. An unambiguous identification of the 2_2^+ state would be an important test for the *ab initio* EFT lattice calculations as well as for other models of light nuclei.

A search for the 2_2^+ state in ^{12}C was carried out at HIγS and a second 2^+ state was unambiguously identified with at E_{res} = 10.03(11) MeV with a total width of Γ(res) = 800(130) keV, and a γ-decay width to the ground state of Γ_{γ_0}(res) = 60(10) meV. Figure 3 shows the measured cross section and the relative phase. A detailed discussion on the implications of this resonance are discussed in the contribution by W. R. Zimmerman.

4. Few-Body Studies on ^{4}He

The ^{4}He nucleus is the lightest few-body system with excited states, unlike the deuteron, triton, and ^{3}He. Therefore, in contrast to the theoretical advances of 2- and 3-body calculations, only recently it became possible to calculate the total photoabsorption cross section of ^{4}He using the Lorentz integral transform (LIT) method [35] with a realistic nucleon-nucleon (NN) potential and a three-nucleon force (3NF), and an *ab initio* no-core shell model calculation based upon χ-EFT [36, 37].

The two recent experiments discussed in this paper were performed to provide precision data on the total photodisintegration cross sections of ^{4}He(γ,p)^{3}H and ^{4}He(γ,n)^{3}He reactions. A significant amount of experimental data exists for the total cross section of these reactions in the energy region of the giant dipole resonance. However, the data shows a considerable scatter and contradiction.

The experiments at HIγS were performed using a high-pressure scintillating gas cell target. For the case of the ^{4}He(γ,p)^{3}H reaction the target cell was filled with a ^{4}He-Xe mixture having a total pressure of 51 atms. The ratio of ^{4}He to Xe pressure was adjusted to provide the stopping power needed for maximum energy protons to have a maximum range of 1.5 cm and thus avoiding any wall effects from the target cell. The data were collected between γ-ray beam energies of 22.0 and 29.5 MeV. The results of this measurement are described in detail in Ref. [38] and shown in Fig. 4. These data are found in good agreement with the predictions of the Trento group [35].

The data for the total photoabsorption cross section of the ^{4}He(γ,n)^{3}He reaction was collected in a similar fashion. The data were collected for 27.0, 27.5, and 28.0 MeV γ-ray beam energies, near the peak of the giant dipole resonance. This measurement and the results are described in detail in Ref. [39] and shown in Fig. 4. These data are also found in good agreement with the predictions of the Trento group [35]. Further discussion on the results of both of these experiments and comparison with older data sets can be found in Refs. [38, 39].

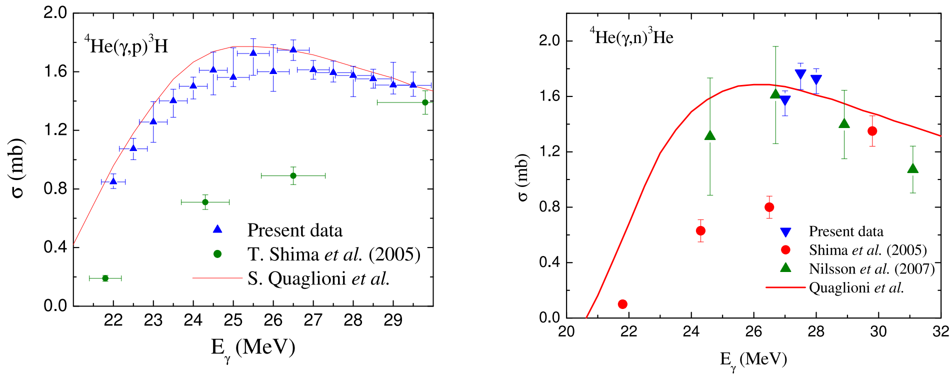

Figure 4: Left: HIγS results (triangles with error bars) for the total cross section of the reaction ^{4}He(γ,p)^{3}H in comparison to the data of Shima *et al.*[40] (dots with error bars), and the theoretical calculation of the Trento group [36]. The horizontal error bars are a measure of the energy spread of the incident mono-energetic photon beams. Our data at energies above 27.0 MeV were corrected for events originating from the three-body and four-body photodisintegration reactions ^{4}He(γ,pn)^{2}H and ^{4}He($\gamma,2p2n$), respectively, which are estimated to contribute to the measured yield between 27.5 MeV and 29.5 MeV at the 0.5% to 2.5% level, respectively. Right: Comparison of the most recent HIγS data and available calculation for the angle-integrated cross section of the reaction ^{4}He(γ,n)^{3}He.

5. Future Outlook

The future nuclear physics program at the HIγS facility can be divided into two categories: 1) the near future program, which will focus on the measurements of the GDH sum rule for the deuteron from 5 to 20 MeV, and electromagnetic and spin polarizabilities of the nucleons, and 2) the program beyond the next three years, which will focus on the photopion physics and the physics which could be performed at the upgraded HIγS2 facility. The near-future experiments will include:

- The first direct measurement of the GDH sum rule integrand near photodisintegration threshold, where most of the sum-rule strength is predicted below the pion production threshold;
- A sum-rule and model independent measurement of proton's electric polarizability (α) using linearly polarized beams at 80 MeV;
- A measurement of the α, β of the neutron using a liquid deuterium target; and
- A first measurement of the spin polarizability (γ_{E1E1}) of the proton below pion production threshold using the S-HIFROST and 100 MeV γ-ray beams.

These measurements will be followed with spin polarizability measurements of the neutron using a polarized ^{3}He target.

A program on studying the Chiral Dynamics in photopion physics has been developed for the HIγS facility [6]. The program requires beams near and above the pion production threshold which are anticipated by the year 2015. This program will use the Neutral Meson Spectrometer (NMS), and the Crystal Box (XBox) detectors to provide a near 4π solid angle coverage for π^0 detection. The HIFROST with both longitudinal and transverse polarizations will be required for these measurements. The holding coils for these polarizations have been successfully tested at TUNL. We anticipate start of this program upon the successful production of γ-ray beams $\sim$ 150 MeV in year 2015.

Lastly, a new initiative to produce γ-ray beams of intensity two-orders of magnitude higher than the current intensities has been taken in the form of the HIγS2 concept. The HIγS2 is a proposed complementary gamma-ray source to the existing FEL driven gamma-ray source at the HIγS facility. This next-generation Compton gamma-ray source will add to the gamma-ray capabilities at the HIγS in the energy range of about 2 to 12 MeV. Driven by a high average-power Fabry-Perot resonator, the HIγS2 will produce gamma-ray beams with intensities more than two orders of magnitude and with better energy resolution than the current source at HIGS. The HIγS2 will offer highly polarized beams of circular polarization with the capability of rapid helicity switching. Once installed, the HIGγ2 capabilities will be available to experimentalists in addition to the beam capabilities of the existing FEL driven source. The three foci of the nuclear physics program at the HIγS2 facility are 1) Nuclear Astrophysics, 2) Hadronic Parity Violation, and 3) Physics Beyond the Standard Model.

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