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Compton Scattering at the HIγS Facility

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The Compton scattering program at the HIγS facility has made significant progress in recent years. Accomplishments of this program include the development of a novel technique for performing precise measurements of the Isovector Giant Quadrupole Resonance (IVGQR) in nuclei. This technique utilizes the nearly 100% linearly polarized photon beams of the HIγS facility along with the realization that the sign of the E1-E2 interference term can be flipped by measuring the ratio of the Compton-scattered cross sections parallel and perpendicular to the plane of polarization in a backward vs. a forward angle. A second experiment has measured the angular distribtuion of Compton-scattered γ rays from ^{6}Li at 60 MeV for the first time. These data have been shown to be sensitive to the *isoscalar* nucleon polarizabilities. Future experiments will focus on obtaining precise values of the electric polarizability of the proton using 100% linearly polarized beams, and of the neutron using Compton scattering from a deuterium target. In addition a double polarization experiment using circularly polarized beams and a frozen-spin polarized target will be performed in order to determine the spin polarizabilities of the proton.

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1. The HIγS Facility

The HIγS facility utilizes Compton backscattering of free-electron laser light from relativistic electrons inside an optical cavity to produce intense, nearly mono-energetic γ rays with 100% linear or circular polarization. This requires operating three accelerators: the first accelerator is a 180 MeV Linac which injects into a 1.2 GeV booster Synchrotron. The beam is then injected into a 1.2 GeV storage ring where the total current is maintained by operating in *top-off* mode.

The facility is normally operated in the two-bunch mode. Photons generated by one bunch are timed so that they collide head on with the second bunch, producing the desired γ-ray beam. Collimators are used to determine the beam spot size and the energy spread in the beam. A typical operating condition utilizes a 1 cm diameter beam spot on target with an energy spread of $\sim$2.5%. At the present time γ rays can be produced between 1.0 and 100 MeV with intensities as great as 2×10^8 γ/s on target (after collimation). Future plans call for increasing the beam energy up to 160 MeV in order to access pion-threshold physics. Further details on this facility and the research program underway can be found in [1] and in the paper in these proceedings by M. W. Ahmed *et al.*

2. Study of the Isovector Giant Quadrupole Resonance in Nuclei

The isovector giant quadrupole resonance (IVGQR) is a collective mode of the nucleus characterized by the out-of-phase quadrupole oscillation of protons against neutrons. The restoring force is due to the symmetry energy term which appears in the nuclear equation of state and is a key parameter for describing neutron-rich astrophysical systems such as neutron stars [2]. A systematic determination of the IVGQR parameters (energy, width, and sum-rule depletion) can provide important constraints on the magnitude and the density dependence of this term.

Nuclear photon scattering is an ideal tool for studying the IVGQR. The E2 contribution can be observed via its interference with the tail of the giant dipole resonance (GDR). This interference term gives rise to a fore/aft asymmetry from which the IVGQR parameters can be obtained [3, 4, 5]. We have expanded on this technique and measured the IVGQR in ^{209}Bi with enhanced precision at HIγS [6]. A phenomenological model of polarized Compton scattering [7] consisting of GDR and IVGQR resonant terms as well as a term representing Thomson scattering, modified by the charge form factor of the target nucleus, was used to extract the IVGQR parameters. The effects of higher-order terms in the Thomson amplitude due to nucleon polarizabilities and meson-exchange currents have been shown to be negligible over the relevant energy range and were not included. The polarization ratio then takes the form

$$\frac{\sigma_\perp}{\sigma_\parallel} = \left[\cos^2\theta + \frac{2|f_{E2}|\cos(\phi_{E2}-\phi_{E1})[\cos^3\theta - \cos\theta]}{|f_{E1}+D(E_\gamma,\theta)|}\right]^{-1} \tag{2.1}$$

where f_{E1} and f_{E2} are the complex scattering amplitudes for the GDR and the IVGQR respectively, ϕ_{E1} and ϕ_{E2} are their phases, and $D(E_\gamma,\theta)$ is the modified Thomson amplitude. In the absence of an E2 component, the polarization ratio is constant and equal to $1/\cos^2\theta$. The remaining term in Equation 2.1 is the E1-E2 interference term. The experimental setup employed an array of

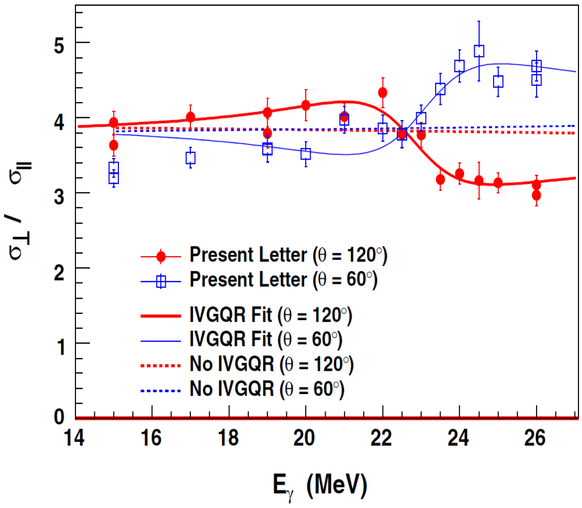

Figure 1: Measured polarization ratios for ^{209}Bi obtained at HIγS [6]. The solid curves were obtained using Equation 2.1 and a three-parameter fit to the energy, width, and strength of the IVGQR. The dotted curves are the 'no-E2' results from Equation 2.1 including a correction factor for detector misalignment.

six NaI detectors, known as HINDA, arranged at θ=55° and 125° where the interference term is maximal, with 4 detectors parallel to the plane of incident polarization and 2 perpendicular to it.

This setup offers several advantages leading to improvements in the extraction of the IVGQR parameters. The ∼100% linearly polarized photon beam eliminated corrections due to the partial polarization of bremsstrahlung beams. Furthermore, the HIγS photon beam is *mono-energetic* and tunable, so that the resonance region can be scanned in energy steps as fine as 0.5 MeV. The E1-E2 interference term in Equation 2.1 changes sign between forward and backward angles, and the HIγS measurement was the first to exploit this feature by simultaneously measuring the polarization ratio at forward and backward angles, which clearly identifies the value of the ratio for pure E1 radiation. Any deviation in the polarization ratio from this value is an unambiguous indication of E2 strength. Results for the case of ^{209}Bi are shown in Figure 1 along with the fits to the data using Equation 2.1 [6]. The resulting parameters for the IVGQR of ^{209}Bi are E_{res}=23±0.13 MeV, Γ=3.9±0.7 MeV, and exhaustion of the Isovector E2 Energy Weighted Sum Rule of 56±4%, where the errors given are statistical only. This experiment was spotlighted by APS as 'exceptional research'.

Data using approximately 40 hours of beam on a 1.25 cm thick ^{89}Y target have recently been obtained, with a measured beam on target intensity of 3×10^6 γ/s. The polarization ratio was measured at 16 energies, and data were taken with a circularly polarized beam at 3 additional energies to correct for any instrumental asymmetries. The measurement points were chosen based on an expected resonance energy of E_{IVGQR} = 135/$A^{1/3}$ ≈ 30 MeV for ^{89}Y. The measured polarization ratios, along with a preliminary extraction of the resonance parameters, are displayed in Figure 2. The fitted values were obtained by fixing the width (Γ) at 10 MeV and allowing the resonance energy and sum-rule depletion to vary freely. This results in a resonance energy of E_{res}=26.3±0.4 MeV and a sum-rule exhaustion of 128.5±11.1% of the Isovector E2 Sum Rule.

This data set will be augmented with additional beam time to measure the transition region between 23 and 30 MeV with ∼2% statistical accuracy. This supplemental data set will provide

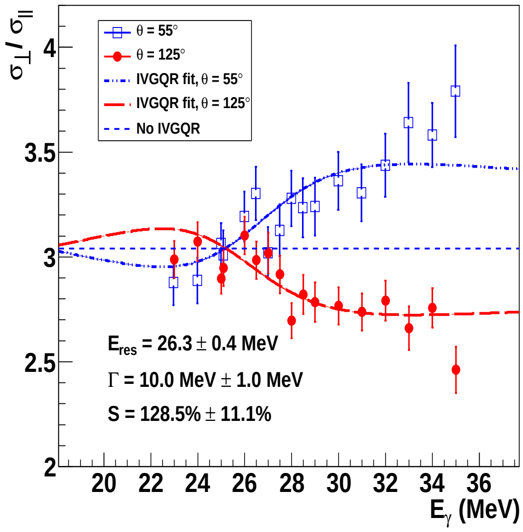

Figure 2: Polarization ratios from the ^{89}Y run, along with extracted resonance parameters.

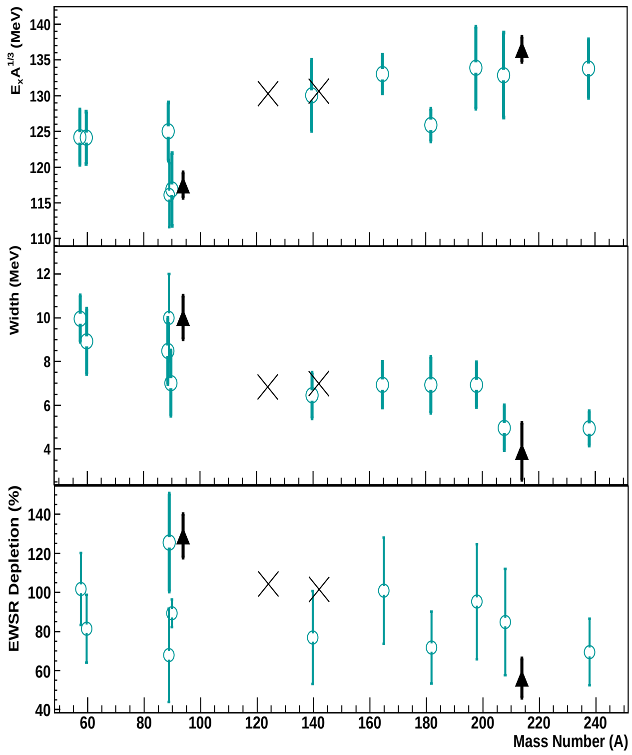

Figure 3: Systematics of the IVGQR parameters. The open circles are data compiled by Pitthan [8], and the triangles are the results of HIγS measurements. Planned IVGQR measurements at HIγS for A=124 and A=142 are indicated by the x's.

the necessary constraints to obtain an accurate value for the width of the IVGQR in this nucleus. The quoted uncertainty of 1.0 MeV for the width is the anticipated statistical error once the full data set has been collected.

The IVGQR parameters obtained for ^{209}Bi and ^{89}Y using this new technique are compared to a compilation of previous results in Figure 3. The present results appear to confirm the trends suggested by the previous data. Also shown in Figure 3 are the mass numbers of nuclei (^{124}Sn and ^{142}Nd) identified as suitable candidates for further IVGQR measurements.

3. Compton Scattering from ^{6}Li at 60 MeV

A measurement of Compton scattering from ^{6}Li at 60 MeV was performed in order to commission the Compton scattering program at HIγS using high-energy γ rays [9]. This choice was motivated by the ease of providing a relatively thick, isotopically pure target (5.8 g/cm^2 of enriched ^{6}Li) and a high counting rate. From the physics perspective, this experiment was motivated by the idea that the angular distribution of the elastically-scattered γ rays would be sensitive to the nucleon isoscalar electromagnetic polarizabilities.

The experiment was performed using eight of the HINDA detector assemblies arranged at angles between 40° and 160°. The 60 MeV unpolarized beam on target had an energy spread of $\sim$4.5% and an on-target intensity of $\sim 10^7$ γs/s. Additional experimental details can be found in [9].

The Compton scattering cross section from ^{6}Li in this energy regime is dominated by the giant electric dipole and quadrupole resonances and the quasideuteron (QD) amplitudes. One must also include the one- and two-body seagull amplitudes which are dependent upon the isoscalar nucleon electric and magnetic polarizabilities (which are the average of the neutron and proton electric and magnetic polarizabilities, respectively). It is also necessary to include the one- and two-body form factors which modulate the seagull amplitudes. These can be obtained from electron scattering data which determines the charge density distribution function. As shown in [9], this phenomenological model can be used to study the sensitivity of the Compton scattering cross section data to the values of the isoscalar polarizabilities.

The resulting data are shown in Figure 4 along with the results of a fit using the phenomenological model. The nominal values of the isoscalar polarizabilities were assumed and the data were fitted by adjusting the strengths of the giant resonances. The QD amplitude values were taken from previous studies of Compton scattering from light nuclei, and the form factors were generated using results from electron elastic scattering data. The two dotted curves shown in Figure 4 were generated by varying the polarizabilities by +/-2 units under the constraint that their sum is equal to 14.5×10^{-4} fm^3. By fixing all of the parameters and fitting the data allowing only the values of the polarizabilities to vary, it was found that the uncertainties in both the electric and the magnetic isoscalar polarizabilities were equal to 0.7, comparable to the results obtained from all previous studies of Compton scattering from deuterium.

This study illustrates the sensitivity of these data to the isoscalar polarizabilities. Future studies in this energy region will be performed in an attempt to fix the model parameters so that absolute values of the polarizabilities can be extracted.

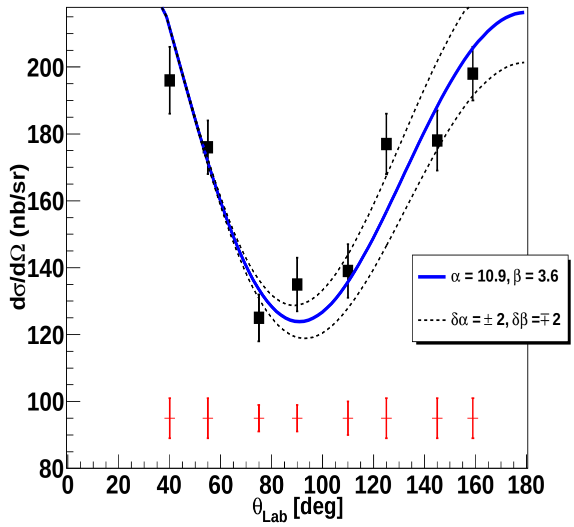

Figure 4: The scattering cross section of ^{6}Li obtained at HIγS. Statistical errors are shown on the data points. Systematic errors for this measurement are shown under the data by the red bars. The curves are results from fitting the data to a phenomenological model.

4. Future Directions

An extensive Compton scattering program is being developed at HIγS. One of the first measurements will utilize the 100% linearly polarized beams at $\sim$90 MeV in order to perform a sum-rule model-independent measurement of the electric and magnetic polarizabilities of the proton. In addition, a frozen-spin target is nearly installed at HIγS. This target will be used in a double polarization Compton scattering measurement using circularly polarized beams at $\sim$120 MeV in order to determine the four spin polarizabilities of the proton. Clearly, the Compton@HIγS program is just beginning.

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