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PRECISE DETERMINATION OF THE ISOVECTOR GIANT QUADRUPOLE RESONANCE IN NUCLEI*

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The intense, nearly mono-energetic, 100% linearly polarized beams available at the HIγS facility, along with the realization that the $E1$–$E2$ interference term that appears in the Compton scattering polarization observable has opposite signs in the forward and backward angles, has been shown to make it possible to obtain an order-of-magnitude improvement in the determination of the parameters of the isovector giant quadrupole resonance (IVGQR). The first nucleus which was studied was ^{209}Bi. One surprise was that only 56% of the Isovector $E2$ Energy Weighted Sum Rule was observed. Preliminary results have now been obtained for the case of ^{89}Y. The parameters in this case suggest an A-dependence for the energy, width, and sum-rule fraction which is quite intriguing. The method and the results for ^{209}Bi and ^{89}Y will be presented, along with plans for future systematic studies. The possible impact of these results on the nuclear equation of state, which is important for our understanding of nuclear matter under extreme conditions, will be discussed.

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1. Introduction

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

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term which appears in the nuclear equation of state and is a key parameter for describing neutron rich astrophysical systems such as neutron stars [1]. 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.

Measurement of the IVGQR presents several experimental challenges due to the large width of the resonance, the small cross section compared to the dipole excitation, and the availability of a suitably selective probe. Inelastic proton scattering strongly favors the nonspin-flip isoscalar mode [2], while (e,e') measurements, though equally sensitive to isoscalar and isovector transitions [3], report large uncertainties due to significant non-resonant backgrounds and model dependencies [4].

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 [5–7]. The first experiment to exploit the polarization degree of freedom was performed by Dale [8] using a linearly polarized bremsstrahlung beam. Systematic uncertainties from Thomson scattering were minimized by comparing the ratio of cross sections parallel and perpendicular to the plane of polarization (the polarization ratio) at a single backward angle, while the effects of Delbrück scattering were shown to be minimal at the measurement angle for the relevant energies. The data were interpreted using a model of the scattering process consisting of $E1$ (GDR) and $E2$ (IVGQR) amplitudes as well as the aforementioned Thomson and Delbrück terms. The neglect of higher order effects, such as the possible excitation of the double IVGDR, was justified on the basis of the fact that the simple model used was able to accurately reproduce the data.

We have expanded on this technique and measured the IVGQR in ^{209}Bi with enhanced precision at HIγS [9]. A phenomenological model of polarized Compton scattering [10] 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 [11] and were not included. Similarly, contributions from Delbrück scattering were also considered negligible at these energies [10]. The polarization ratio then takes the form

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

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 $\cos^2\theta$. The remaining term in equation (1) is the $E1$–$E2$ interference term. The experimental setup (Fig. 1) employed an array of six NaI detectors, known as HINDA, arranged at $\theta = 55°$ and $125°$, where the interference term is maximal, with 4 detectors parallel to the plane of incident polarization and 2 perpedendicular to it.

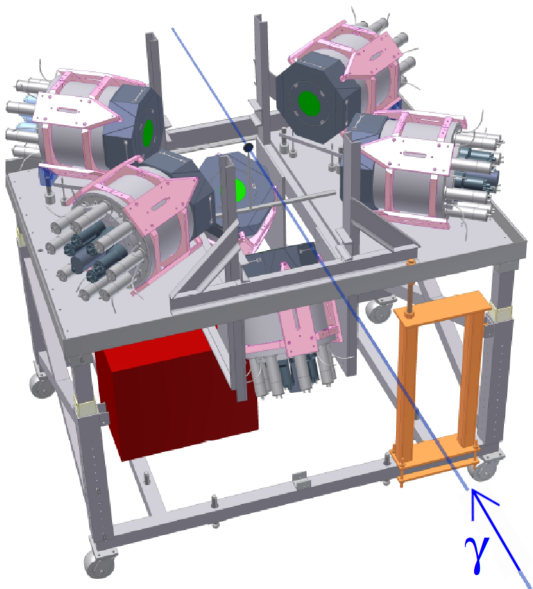

Fig. 1. Experimental setup for the ^{209}Bi measurement at HIγS [9], using a total of 6 NaI detectors. Two additional out of plane detectors were used for the subsequent ^{89}Y measurement.

This setup offers several advantages leading to improvements in the extraction of the IVGQR parameters. The $\sim 100\%$ 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 (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 location of the $E1$ line. Any deviation in the polarization ratio from this line is an unambiguous indication of $E2$ strength. Results for the case of ^{209}Bi are shown in Fig. 2 along with the fits to the data using equation (1) [9]. The resulting parameters for the IVGQR of ^{209}Bi were $E_{\rm res} = 23 \pm 0.13$ MeV, $\Gamma = 3.9 \pm 0.7$ MeV, and exhaustion of the Isovector $E2$ Energy Weighted Sum Rule of $56. \pm 4.\%$, where the errors given are statistical only. This experiment was spotlighted by APS as 'exceptional research'.

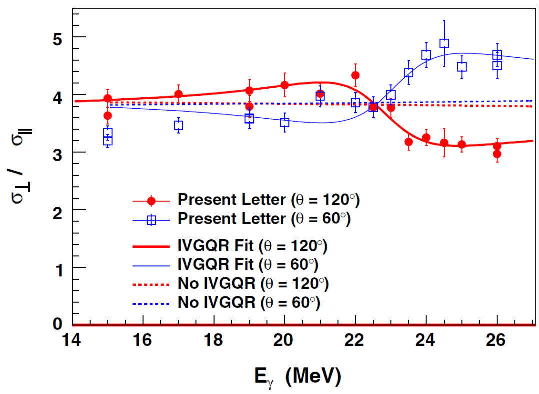

Fig. 2. Measured polarization ratios for ^{209}Bi obtained at HIγS [9]. The solid curves were obtained using equation (1) and a three-parameter fit to the energy, width, and strength of the IVGQR. The dotted curves are the 'no-$E2$' results from equation (1) including a correction factor for detector misalignment.

2. New results

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 $E_{\rm IVGQR} = 135/A^{1/3} \approx 30$ MeV for ^{89}Y. The measured polarization ratios, along with a preliminary extraction of the resonance parameters, are displayed in Fig. 3. 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 $E_{\rm res} = 26.3 \pm 0.4$ MeV and a sum rule exhaustion of $128.5 \pm 11.1\%$ 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 $\sim 2\%$ statistical accuracy. This supplemental data will provide 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.

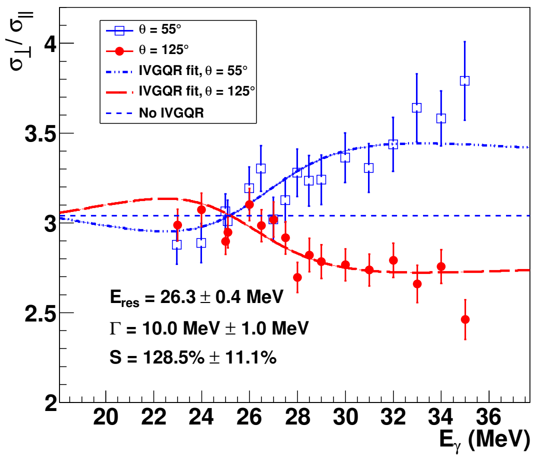

Fig. 3. Polarization ratios from the ^{89}Y run, along with extracted resonance parameters.

The IVGQR parameters obtained for ^{209}Bi and ^{89}Y using this new technique are compared to a compilation of previous results in Fig. 4. The present results appear to confirm the trends suggested by the previous data.

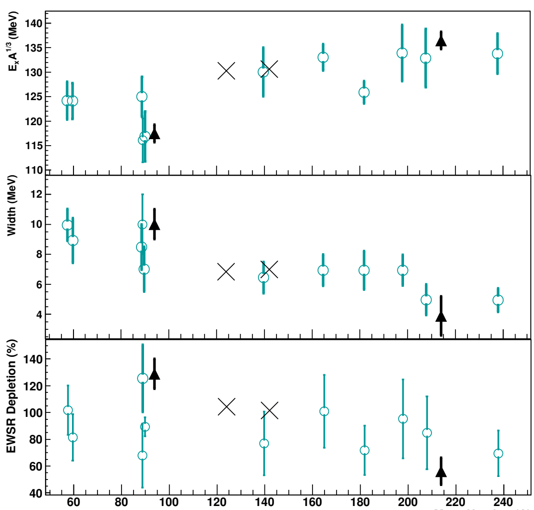

Fig. 4. Systematics of the IVGQR parameters. The open circles are data compiled by Pitthan [12], and the triangles are the results of HIγS measurements. Planned IVGQR measurements at HIγS for $A = 124$ and $A = 142$ are indicated by the xs.

3. Future studies

3.1. Target selection

In considering candidate nuclei for which to measure the IVGQR, nuclear structure must be considered. The excitation spectra of nuclei with intrinsic ground state deformation will contain rotational bands, contributing an inelastic component to the total scattering cross section through a process known as Raman scattering [13]. To avoid complications from unfolding this component from the collected data, good candidate nuclei should have spherically symmetric ground states, as reflected in the intrinsic quadrupole moment Q_0. Large values of Q_0 indicate deformed nuclei ($Q_0 = 11.0$ barns for ^{238}U), while nuclei with values of Q_0 close to 1 are spherical ($Q_0 = 1.7$ barns for ^{208}Pb). Keeping in mind the need for an isotopically pure target, the natural abundance of a particular isotope should be sufficiently large to keep fabrication costs reasonable. We have identified ^{124}Sn and ^{142}Nd as nuclei satisfying these conditions, summarized in Table I.

TABLE I

Summary of candidate nuclei. The natural abundance is listed to provide a rough metric for how difficult/expensive isolation of a particular isotope may be.

Nucleus	Natural abundance (%)	Q_0 (barns)	$135/A^{1/3}$ [MeV]
^{124}Sn	32.6	1.292	27.1
^{142}Nd	27.2	1.632	25.9

An isotopically pure ^{124}Sn target has already been used at HIγS by a separate collaboration investigating Pygmy dipole resonances, and they have agreed to allow us use of their target. Inquiries have been made at Oak Ridge Isotopes concerning ^{142}Nd target, and they are able to fabricate a target according to the required specifications.

3.2. Count rate estimates

The counting rate Y of one of the HINDA cores for a particular target can be estimated by

$$Y = \frac{d\sigma}{d\Omega}\, N_\gamma\, t\, d\Omega\, \epsilon\,, \tag{2}$$

where $\frac{d\sigma}{d\Omega}$ is the differential cross section for Compton scattering, N_γ is the photon flux over the same time period, t is the target mass thickness, ϵ is the lineshape efficiency, and $d\Omega = 0.051\,\mathrm{sr}$ is the solid angle subtended by one of the HINDA cores.

The differential cross section can be estimated based on previously published data for $^{208}_{82}$Pb [6] with the assumption that the cross section scales approximately as Z^2. This relationship can be tested against the calcium data obtained in [10], which shows that the Z^2 dependence seems to underestimate the actual cross section by a factor of two. This underestimation can also be seen in the ^{89}Y data using the observed count rate to obtain a rough calculation of the differential cross section. Consequently, the Z^2 scaling assumption can be used, with the understanding that it provides a conservative lower bound for the expected counting rate. For the present calculations, an average value of 140 μb/sr was used as the value of ^{208}Pb to account for the slight difference at forward and backward angles.

The target mass thickness for a nucleus with mass A is calculated as

$$t = \frac{N_{\mathrm{Avogadro}}}{A}\,\rho\,\Delta x\,, \tag{3}$$

where ρ is the density and Δx is the linear thickness. The existing ^{124}Sn target has a total mass of 12 g and can be recast so that $t = 1.7 \times 10^{22}\,\mathrm{cm}^{-2}$, and a ^{142}Nd target with $t = 2.97 \times 10^{22}\,\mathrm{cm}^{-2}$ can be purchased.

As can be seen in a simulation, mono-energetic photons thrown from the target area towards a detector will not always deposit their full energy in the detector. From an analysis of Lithium Compton scattering data [14], a lineshape efficiency of approximately $\epsilon = 0.5$ can be expected. That is, only 50% of the photons of a given energy incident on a detector will deposit enough energy to appear in the elastic peak.

The total expected counting rate based on 4 HINDA detectors at each lab angle was calculated using these numbers. The results are displayed in Table II.

TABLE II

Summary of target count rate calculations.

Nucleus	Z	$d\sigma/d\Omega$ [μb/sr]	t [cm^{-2}]	Y [counts/hr]
^{124}Sn	50	52	1.70×10^{22}	976
^{142}Nd	60	75	2.97×10^{22}	2452

As seen in equation (1) for pure $E1$ scattering, the ratio of perpendicular to parallel counts $N_\perp/N_\parallel \approx 3$. After 4.5 hours a total of 4400 counts will have accumulated with a ^{124}Sn target, apportioned as $N_\perp = 3300$ and $N_\parallel = 1100$, yielding an uncertainty in the polarization ratio of 3.5%. To achieve the same level of uncertainty with ^{142}Nd, a total of ~ 2 hours is required per energy.

We plan to measure 4 energies (in 1 MeV steps) below the expected resonance position, 7 energies (in 0.5 MeV steps) over the range $E_{\rm res} - 1.0 < E < E_{\rm res} + 2.0$ MeV to scan the resonance and transition regions, and 6 more energies (in 1 MeV steps) up to $E_{\rm res} + 8.0$ MeV, for a total of 17 measurements with linear polarization. We plan to perform another 3 energy measurements with circular polarization for a total of 20 measurement points.

For ^{124}Sn, which requires 4.5 hours/energy, we expect to complete 2 energies per day of running, so that 10 days would be required for the experiment. For ^{142}Nd, which requires ~ 2 hours/energy, we expect to complete 5 energy points per day of running, so that 7 beam days would be sufficient to measure this target. The anticipated results from these two targets are indicated in Fig. 4.

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