The Isoscalar Giant Dipole Resonance in $^{208}$Pb and the Nuclear Incompressibility

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Abstract. The isoscalar giant dipole resonance (ISGDR) has been investigated in $^{208}$Pb using inelastic scattering of $400$ MeV $\alpha$ particles at extremely forward angles, including 0°. Using the superior capabilities of the Grand Raiden spectrometer, it has been possible to obtain inelastic spectra devoid of any “instrumental” background. The ISGDR strength distribution has been extracted from a multipole-decomposition of the observed spectra. The implications of these results on the experimental value of nuclear incompressibility are discussed.

Nuclear Incompressibility is a crucial component of the nuclear equation of state and, as such, has very important bearing on diverse nuclear and astrophysical phenomena: for example, strength of supernova collapse, the emission of neutrinos in supernova explosions, and collective flow in medium- and high-energy heavy-ion collisions. The only direct experimental measurement of nuclear incompressibility is possible via the compressional-mode giant resonances in nuclei. Of the two important compressional modes, the isoscalar giant monopole resonance (GMR) is the better known and has been studied now for more than 20 years. The other mode, the isoscalar giant dipole resonance (ISGDR), is an exotic oscillation—to first order, isoscalar dipole mode represents simply the motion of the center-of-mass which, in itself, cannot lead to any nuclear excitation—which has remained somewhat elusive, even though initial (although inconclusive) evidence for the mode was reported as long ago as the early 80’s.

The ISGDR can be thought of a hydrodynamic density oscillation in which the volume of the nucleus remains constant and a compressional wave—akin to a sound wave—traverses back and forth through the nucleus. The mode has generally been referred to as the “squeezing mode” in analogy with the mnemonic “breathing mode” for the GMR. A general description of this mode, along with the relevant transition densities and sum-rules, has been provided in Refs. [1, 2]. The energy of this resonance is related to the nuclear incompressibility via the scaling relation:

$$E_{\text{ISGDR}} = \hbar \sqrt{\frac{7 K_A + 27 \epsilon_F}{3 m < r^2>}}$$

where $K_A$ is the incompressibility of the nucleus, $m$ is the nucleon mass, and $\epsilon_F$ is the Fermi energy [3].

As mentioned above, indications of the ISGDR were reported as early as the beginning of the 1980’s. However, the first conclusive evidence for this mode, based on the differences in angular distribution of the ISGDR from that of the nearby high-energy octupole resonance (HEOR), was provided by Davis et al. [4], who demonstrated that in inelastic scattering of 200 MeV $\alpha$’s at angles near 0°, the giant resonance “bump” at 3 $\hbar \omega$ excitation energy could be separated into two components, with the higher-energy component corresponding to the ISGDR. Further evidence for
the ISGDR has since come from 240 MeV $\alpha$ inelastic scattering measurements, using the multipole-decomposition technique [5, 6]. For reviews of the status of the ISGDR work, the reader is referred to Refs. [7, 8, 9].

We have undertaken a detailed investigation of this resonance using inelastic scattering of 400 MeV $\alpha$’s at forward angles, including $0^\circ$. The experiments are being carried out at the Research Center for Nuclear Physics (RCNP), Osaka University. The ring-cyclotron facility at RCNP provided high-quality $\alpha$-particle beams of 400 MeV energy which were momentum analyzed in a recently-installed beam-analysis system and were incident on thin (typically 2–10 mg cm$^{-2}$), self-supporting, metallic targets. Data were obtained on $^{58}$Ni, $^{90}$Zr, $^{116}$Sn, $^{144,148,150,152,154}$Sm, and $^{208}$Pb over several angles between $0^\circ$ and $13^\circ$. In addition, spectra were measured for $^{12}$C targets for energy-calibration purposes. In this report, we will concentrate on the results for $^{208}$Pb; preliminary results on the Sm isotopes have been presented previously [10].

Inelastically scattered particles were analyzed by a versatile, high-resolution, magnetic spectrometer, Grand Raiden [11]. The focal-plane detector system [12, 13] consists of two multi-wire drift chambers (MWDC) and two plastic scintillation counters. The MWDC’s provided the position and angle information which was used, by ray-tracing technique, to subdivide the full angular opening of the spectrometer ($\sim 2^\circ$) into several angular bins and to construct energy spectra for the corresponding scattering angles. Particle identification was provided by the energy-loss signals from the plastic scintillators. For the $0^\circ$ measurements, the primary beam, after passing through the spectrometer, was guided through a hole in the high-momentum side of the detector system, and was stopped in a Faraday cup placed several meters downstream from the focal plane. For the extremely forward angles ($2^\circ$–$5^\circ$), the beam was stopped just behind the first quadrupole magnet of Grand Raiden (about 160 cm downstream from the target); for all other angles, a Faraday cup was placed inside the target chamber.

Small-angle measurements, as is well-known, require extra care in beam-preparation and transport through the system. Several innovative measures were adopted to ensure a halo-free beam and, ultimately, the “blank-target” rate in the focal-plane detector system was typically only $\sim 10$/second, compared with count rates of several thousand per second with the targets in place. The typical energy resolution was $\sim 250$ keV, more than sufficient to investigate the giant resonances which are typically several-MeV wide.

![FIGURE 1](image)

**FIGURE 1.** Vertical ($y$) position spectrum in the “$0^\circ$” inelastic scattering measurement on $^{208}$Pb. The peak represents “true” events; the flat part emanates from non-physical (“background”) events.

A very important aspect of these measurements has been the elimination of all “instrumental background” from the final spectra. This “background” results primarily from multiple scattering of the beam on the target, as well as from rescattering by the yoke and the walls of the spectrometer. For the purpose, we utilized the vertical-position
spectrum at the double-focused position of the spectrometer. As shown in Fig. 1, the “true” events (those coming from inelastically scattered α particles) focus well at the focal plane due to the ion-optics of the spectrometer (the peak in Fig. 1); the “background” events, on the other hand, have a poor focus and the distributions of the vertical positions of such events is “flat”. The “background” events were, then, subtracted from the final spectra by gating on the peak in Fig. 1 and subtracting the events corresponding to the underlying background which can be estimated by setting gates on both sides of the peak.

Fig. 2 shows the results of these cuts. The top left part of the figure shows the spectrum for $^{208}\text{Pb}$ at “0°” (the actual angle is 0.77°) resulting from a gate on the peak in Fig. 1. The top right part shows the spectrum with gate on the background. In the bottom part of the figure is shown the spectrum with the background subtracted. As noted above, this ability to eliminate all instrumental background from singles inelastic scattering spectra has been achieved for the first time in such studies and has led to observation of GR strength in the excitation-energy region up to $\sim 30$ MeV; in previous measurements, all this strength at the higher excitation energies has, generally, been part of the overall empirical background subtraction. The “flat” part at the upper end of the excitation-energy spectrum, we believe, is the true physical continuum.

![Figure 2](image)

FIGURE 2. (Top Left): Position spectrum gated on the “peak” in Fig. 1. (Top Right): Position spectrum gated on the corresponding “background”. (Bottom): “Background-free” position spectrum obtained by subtracting the Top Right spectrum from the Top Left spectrum.

The strength distributions for the various modes has been extracted from these spectra using a multipole-decomposition analysis, similar to that used previously by Bonin et al. [14] and, more recently, also by Youngblood et
The contribution of the isovector giant dipole resonance (IVGDR), which is excited because of Coulomb interaction, is subtracted from the spectra, using the precisely-known IVGDR strength distributions from previous photoabsorption work [15]. In this analysis, the “continuum” has not been subtracted out; instead, the entire spectrum has been fitted with a combination of multipoles (up to $l=5$; the available angular-range for these measurements is not sufficient to clearly distinguish the higher-order multipoles from those already employed).

The resulting ISGDR strength distribution is shown in Fig. 3. While these results must be considered preliminary at this stage, pending complete data analysis, the observed ISGDR distribution clearly has two components, centered at about 13 MeV and 23 MeV, respectively. Results of a two-Gaussian fit to the strength distribution are shown superimposed in the figure and are presented in Table 1.1 Also shown in Table 1 are the results from other recent measurements on ISGDR as well as the theoretical results from various recent calculations.

This “bi-modal” ISGDR strength distribution is most interesting and, as discussed below, has crucial bearing on the determination of nuclear incompressibility using the excitation energy of the ISGDR. The lower-energy component, at about the energy of the GMR and IVGDR, has now been observed in several nuclei and also appears in several of the more recent calculations of ISGDR strength (see, for example, Refs. [16, 17, 18]).2 All the cited calculations clearly establish that only the higher-energy component depends on the value of nuclear incompressibility employed in the calculations; the position of the lower-energy component is completely independent of the $K_\infty$’s, pointing to its “non-bulk” origin. Further, Vretenar et al. [17] have identified the dynamics of this mode as resulting from surface effects. We note, however, that the observed centroid for this low-energy component is higher than the theoretical predictions by several MeV.

The extraction of a value for the nuclear incompressibility using simultaneously the excitation energies of the two compressional modes, the GMR and ISGDR, has been problematic so far [9]. Until recently, it appeared that all the calculations, using nuclear incompressibility that reproduced the GMR energies well, substantially overpredicted

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1 The errors quoted for the present work are primarily statistical. There are additional uncertainties associated with extraction of ISGDR strength from DWBA calculations.

2 Incidentally, this is not the expected $\hbar \omega$ component of the ISGDR, discussed in detail previously by Poelhekken et al. [19]. The $\hbar \omega$ strength would be expected near or below the lower-excitation-energy bound of our experiment.
TABLE 1. ISGDR excitation-energies obtained in the present work. Also shown are results from other recent measurements and predictions from recent theoretical work.

|                         | High-energy component | Low-energy component |
|-------------------------|-----------------------|----------------------|
| This work               | 23.0 ± 0.5 MeV        | 13.0 ± 0.5 MeV       |
| Davis et al.*           | 22.4 ± 0.5            |                      |
| Youngblood et al.†      | 19.9 ± 0.8            | 12.2 ± 0.6           |
| Colo et al.**           | 23.9                  | 10.9                 |
| Vretenar et al.‡        | 26.01                 | 10.4                 |
| Piekarewicz§            | 24.4                  | ~8                   |

* Ref. [4]  † Ref. [6]  ** RPA with SGII, K∞ = 215 MeV [16]  ‡ RRPA with NL3, K∞ = 271.8 MeV [17]  § RRPA with NL-C, K∞ = 224 MeV [18, 20]

the excitation energy of the ISGDR. With the results reported herein, this “problem” has been alleviated to a great extent. First, with the “background-free” spectra obtained in the present work, it has been possible to identify ISGDR strength up to higher excitation energies. Second, based on the theoretical work, it is clear that only the higher-energy component of the observed ISGDR strength needs to be taken into account for the purposes of extracting the nuclear incompressibility. The combination of these two factors leads to the centroid of the experimental ISGDR strength in 208Pb being close to the theoretical predictions of Colò et al.[16] and of Piekarewicz [18]. The first of these employs a value for nuclear incompressibility, K∞ = 215 MeV, and the second uses K∞ = 224 MeV. With both, the GMR energies are also well reproduced over a range of nuclei. It may be concluded, then, that a value of K∞ ≈ 220 MeV is consistent with the observed properties of both the compressional modes in 208Pb.

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