Are there nuclear structure effects on the isoscalar giant monopole resonance and nuclear incompressibility near $A \sim 90$?

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Nuclear incompressibility (K_∞) is a fundamental quantity characterizing the equation of state (EOS) of nuclear matter. A number of important phenomena such as the radii of neutron stars, the strength of supernova explosions, transverse flow in relativistic heavy-ion collisions, the nuclear skin thickness, etc. require a good understanding of the EOS of nuclear matter [1]. K_∞ can be determined experimentally from the compressional "breathing modes", the isoscalar giant monopole and dipole resonances (ISGMR and ISGDR) in finite nuclei [1]. The energy of these resonances are directly related to the nuclear incompressibility of the finite nucleus, K_A. For example, the ISGMR energy is related to K_A as:

$$E_{\rm ISGMR} = \hbar\sqrt{\frac{K_A}{m\left\langle r^2\right\rangle_0}}, \qquad (1)$$

where $\left\langle r^2\right\rangle_0$ is the ground state mean square radius, and m is the nucleon mass. Determination of infinite nuclear matter incompressibility, K_∞ from K_A is achieved within a framework of self-consistent RPA calculations, using the widely accepted method described by Blaizot et al. [1, 2]. The presently accepted value of K_∞, determined from ISGMR in "standard" nuclei such as ^{90}Zr and ^{208}Pb, is 240±20 MeV [3].

Because the compressional modes are collective phenomena, the determination of K_∞ should be independent of the choice of the nucleus, provided that approximately 100% of the energy weighted sum rule (EWSR) fraction is exhausted in the resonance peak; this condition is satisfied for sufficiently heavy nuclei ($A \geq 90$) [1]. In recent work by the Texas A & M group [4], it has been claimed that the ISGMR strength distributions vary in a rather dramatic manner in nuclei around A ∼90, yielding significantly different K_A values in neighboring nuclei. These results, if correct, imply significant nuclear structure contribution to the nuclear incompressibility in this mass region. Such nuclear structure effects have not been observed in any of the investigations of ISGMR going back to its first identification in the late 1970's and, indeed, would be contrary to the standard hydrodynamical picture associated with this mode of collective oscillation. In this paper, I report on the compressional modes in the ^{90,92}Zr and ^{92}Mo nuclei from inelastic α-scattering measurements, free from "instrumental background", at an energy of 385 MeV.

Measurements were carried out at the ring cyclotron facility of the Research Center for Nuclear Physics (RCNP), Osaka University, Japan. Inelastically scattered α particles were momentum analyzed with the high-resolution magnetic spectrometer "Grand Raiden", and their horizontal and vertical positions were measured with a focal-plane detector system composed of two position-sensitive multiwire drift chambers and two plastic scintillators. The vertical-position spectrum obtained in the double-focusing mode of the spectrometer was exploited to eliminate the instrumental background. Further experimental details can be found in Ref. [5] and reference therein.

The spectra near 0° scattering angle exhibit predominantly the monopole strength, and in the present work these are very similar for the three nuclei; in particular, for excitation energies beyond 20 MeV, these are nearly identical whereas the results in Refs. [4] had shown marked differences in this excitation-energy region. The minor differences are observed in the low-energy part of the spectra (below 16 MeV) which are attributed to the different contributions from L=1 and L=2.

The "difference-spectrum", obtained from subtracting the inelastic spectrum at the first minimum of the expected ISGMR angular distribution from that at 0° (maximal ISGMR strength), essentially represents only the ISGMR strength. In the present work, the difference spectra for the angles of 0.7° (maximal ISGMR strength) and 2.0° (first minimum of ISGMR strength) for all the three nuclei are also almost identical, again indicating similar ISGMR response in the three nuclei.

Quantitative strengths for different multipolarities have been determined by employing the standard multipole-decomposition procedure [5]. The experimental cross sections are expressed as linear combinations of calculated (DWBA) double-differential cross sections associated with different multipoles. The DWBA calculations are performed by following the method of Satchler and Khoa, see Ref. [5, 6]. The optical model parameters (OMPs) used in the DWBA calculations are determined for each nucleus from elastic scattering angular distributions. Using the $B(E2)$ and $B(E3)$ transition probabilities from the literature, and the OMPs thus obtained, the angular distributions for the 2^+ and 3^- states for each nucleus are calculated within the same DWBA framework. Good agreement between the calculated and experimental angular distributions for the 2^+ and 3^- states for each nucleus establishes the appropriateness of the OMPs [5].

The ISGMR strength distributions for the three nuclei, each consisting of a single broad peak at E_x ∼16.5 MeV, coincide with each other within experimental uncertainties. The ISGMR strength in the high-excitation-energy range for ^{92}Zr and ^{92}Mo is identical to that in ^{90}Zr; the results in Refs. [4] had shown marked deviations instead, leading to quite different E_{ISGMR} values. Similar to the ISGMR, another compressional breathing mode, the ISGDR strength distributions for the three nuclei also coincide with each other. Various moment ratios for ISGMR as well as ISGDR for all three nuclei, are also identical, as are the K_A values obtained therefrom (∼170 MeV in all cases). The present results, thus, establish strongly, that determination of nuclear incompressibility in nearby medium-heavy to heavy nuclei is not influenced in any appreciable manner by the choice of specific nucleus, or by the underlying nuclear structure.

Determination of the nuclear incompressibility from the ISGMR and ISGDR is based on the assumption that the resonance energies do not depend on detailed structure of the nuclei involved. In fact, there had been no report prior to the results presented in Refs. [4] of any "shell effects" leading to significant differences between ISGMR energies in nearby nuclei. For instance, measurements on three Lead isotopes, ^{204,206,208}Pb, had resulted in very similar ISGMR energies [7]. Detailed experimental techniques, data analysis, and results would be presented. The question, why the present results are so different from those obtained by the Texas A & M group [4] would also be discussed.

I acknowledge the efforts of the staff of the RCNP Ring Cyclotron Facility in providing a high-quality, halo-free α beam and all my collaborators, listed in Ref. [5], for their significant contributions. This work has been supported in part by the U.S. National Science Foundation (Grant No. PHY-1419765).

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