Investigation of the Giant Monopole Resonance in the Cd and Pb Isotopes: The Asymmetry Term in Nuclear Incompressibility and the MEM Effect

U. Garg

Physics Department, University of Notre Dame, Notre Dame, IN 46556, USA

The giant monopole resonance (GMR) has been investigated in the even-A Cd and Pb isotopes $^{112-124}$Cd, and $^{204-208}$Pb, with the aim of obtaining a confirmatory "experimental" value for the asymmetry term in nuclear incompressibility, K_τ, and to test the Mutual Enhancement Magicity (MEM) effect in nuclear incompressibilities. The latter was advanced as a possible explanation of the puzzling "softness" of the Sn and Cd nuclei, as evidenced by their low GMR energies as compared to theoretical predictions. The GMR results in the Cd isotopes give a value $K_\tau = -490 \pm 100$ MeV, in close agreement with the value obtained previously from the Sn isotopes. Our results rule out the MEM effect as an explanation of the aforementioned "softness" observed for the Sn and Cd nuclei.

The asymmetry term of nuclear incompressibility, K_τ, associated with the neutron-excess $(N - Z)$, is crucial in obtaining the radii of neutron stars in the equation of state (EOS) calculations.[1)–4)] It has been suggested that the radius of a neutron star whose mass is between about 1.0 and 1.5 solar masses ($M_\odot$) is mostly determined by the density dependence of the symmetry-energy term.[5),6)]

In recent measurements on the giant monopole resonance (GMR) in the even-A Sn isotopes ($A = 112 - 124$), we had obtained an "experimental" value for this term, $K_\tau = -550 \pm 100$ MeV.[7),8)] This number is in agreement with the value $K_\tau = -500^{+125}_{-100}$ MeV, obtained by Centelles et al.[9)] from constraints put by neutron-skin data from anti-protonic atoms across the mass table; $K_\tau = -500 \pm 50$ MeV obtained by Sagawa et al.[10)] by comparing our Sn GMR data with calculations using different Skyrme Hamiltonians and RMF Lagrangians; and, $K_\tau = -370 \pm 120$ MeV obtained from an analysis of the isotopic transport ratios in medium-energy heavy-ion reactions.[11)] Combined with the value of $K_\infty = 240 \pm 10$ MeV extracted from data on GMR and the other compression-mode, the isoscalar giant dipole resonance (ISGDR),[12),13)] this value for K_τ may provide a means of selecting the most appropriate of the interactions commonly used in nuclear structure and EOS calculations.

To confirm the value of K_τ obtained from the GMR in the Sn isotopes, we have investigated the GMR in the another series of isotopes, viz. ^{106,110,112,114,116}Cd using inelastic scattering of 400-MeV α particles at extremely forward angles, including 0°. The measurements were performed at the Research Center for Nuclear Physics (RCNP) at Osaka University, Japan, using the Grand Raiden spectrometer. The experimental techniques and data analysis procedures were identical to those in the measurements described previously for the Sn isotopes.[7),8)]

The GMR strength distributions for the Cd isotopes are presented in Fig. 1. The $L = 0$ strength distributions were fitted with a Lorentzian function to determine the centroid energies and widths of the GMR; these fits are shown superimposed in Fig. 1.

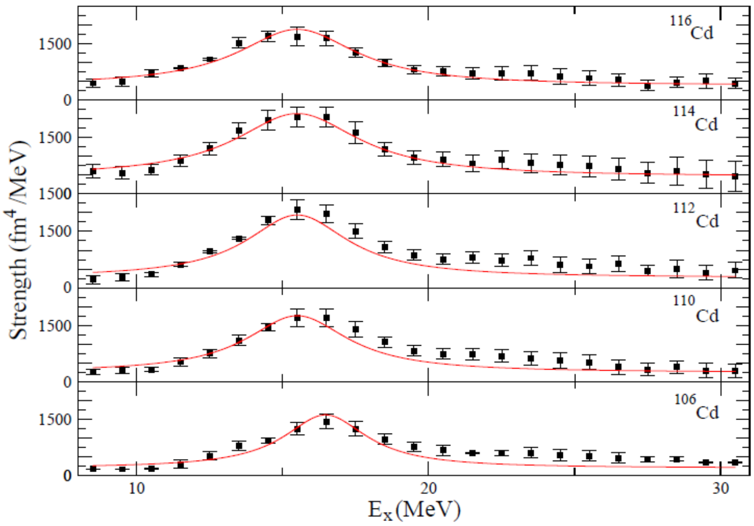

Fig. 1. ISGMR strength distributions obtained for the Cd isotopes in the present experiment. Error bars represent the uncertainties from fitting the angular distributions in the MDA procedure. The solid lines show Lorentzian fits to the data. **These results should be considered preliminary**.

An analysis of the GMR centroids in the Cd isotopes identical to that performed in case of the Sn isotopes[7),8)] gives a preliminary value of $K_\tau = -490 \pm 100$ MeV (see Fig. 2), in excellent agreement with the value obtained from the Sn isotopes.

Thus, a very reasonable "experimental" value for this parameter is $K_\tau = -500 \pm 100$ MeV.

Another important finding from the investigations of the GMR in the Sn isotopes was that the experimentally observed GMR energies in these nuclei were significantly lower (by almost 1 MeV in the case of the higher-A's) than the values predicted by recent theoretical calculations that reproduce the GMR energies in the "standard" nuclei, ^{90}Zr and ^{208}Pb, very well. This disagreement, also observed in case of GMR in the Cd isotopes, has posed a big challenge for theory and the question of why Sn (and Cd) isotopes are so "soft"[14)] has engendered a lot of activity and debate in the field about the possible theoretical interpretation and implications;[15)–19)] indeed, this has been identified as one of the "open" problems in nuclear structure theory in a recent major compilation.[20)] The effects of pairing (superfluidity) in these open-shell nuclei account for only a small part of the difference between the experiment and theory.[15),18)]

A most intriguing suggestion has been made in this connection that this might be analogous to the so-called Mutual-Enhancement-Magicity (MEM) effect observed in predictions of masses with different energy-density functionals. It has been noted that the ability of these models to predict masses of doubly-closed shell nuclei is significantly poorer than that for nuclei over the rest of the nuclear chart.[21),22)] The implication, then, is that the nuclear incompressibility value obtained from the GMR in the doubly-closed nucleus, ^{208}Pb, would necessarily overestimate the GMR

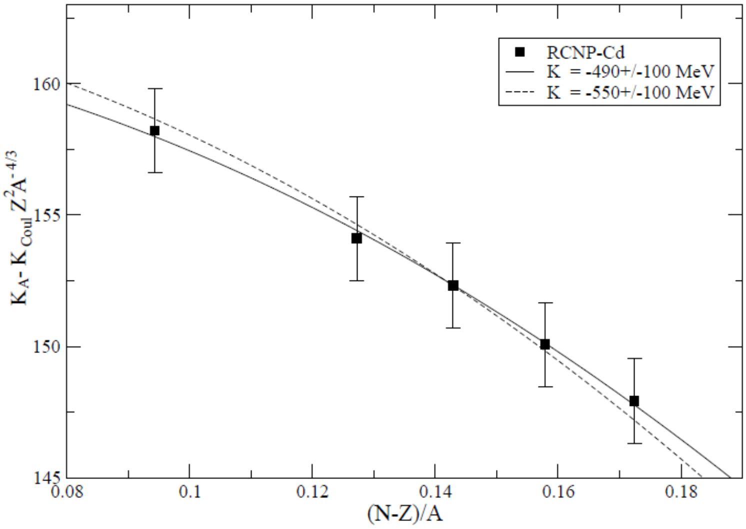

Fig. 2. Systematics of the difference $K_A - K_{Coul} Z^2 A^{-4/3}$ in the Cd isotopes as a function of the "asymmetry-parameter" $((N-Z)/A)$; $K_{Coul} = -5.2 \pm 0.7$ MeV.[10] The solid line represents a least-square quadratic fit to the data. The dashed line shows, for comparison, results with the value $K_\tau = -550$ MeV previously obtained from the Sn data. **These results should be considered preliminary**.

energies in the open-shell nuclei,[18),23)] accounting for the observed behavior of the GMR in the Sn and Cd isotopes. An essential prediction of this conjecture was that the GMR energy in the doubly-magic nucleus, ^{208}Pb, would be significantly, and measurably, larger than that in the neighboring Pb isotopes: ^{204,206,210,212}Pb.[23]

In order to test this conjecture, we have measured the GMR in the Pb isotopes, ^{204,206,208}Pb. Inelastic α scattering data with high statistics were obtained for all the three nuclei in the same experiment—this way, it was possible to maintain as "constant" experimental conditions as possible so that the systematic errors, if any, are the same for all nuclei. Elastic scattering was also measured for the ^{204,206}Pb targets to obtain the optical model (OM) parameters to be used in DWBA calculations employed in multipole-decomposition-analysis (MDA) of the inelastic scattering data, to extract the various multipole strengths;[7),8)] the OM parameters for ^{208}Pb have been known from our previous measurements on ISGDR.[24]

Figure 3 shows the "0°" inelastic α-scattering spectra for the three Pb isotopes investigated in this work (the GMR cross sections are maximal at 0°). It is clear, even from a cursory look, that the three spectra are practically identical, contrary to the expectation from the application of MEM effect to GMR's.

We have, further, extracted the $\Delta L = 0$ strength in all three Pb isotopes using the MDA technique; as shown in many previous examples, this procedure allows determination of strength distributions associated with various multipoles with very good accuracy. Preliminary results from MDA for the $\Delta L = 0$ strength distributions for the three Pb isotopes are shown in Fig. 4; also shown are Lorentzian fits to the extracted strength distributions. The centroids for the Lorentzians are at 13.9 MeV,

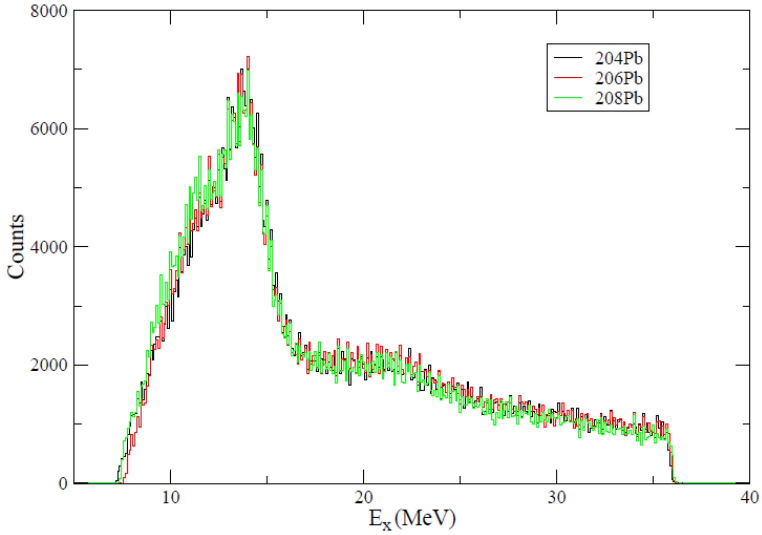

Fig. 3. (Color online) Inelastic α-scattering spectra at 0° for ^{204}Pb (black), ^{206}Pb (red), and ^{208}Pb (green).

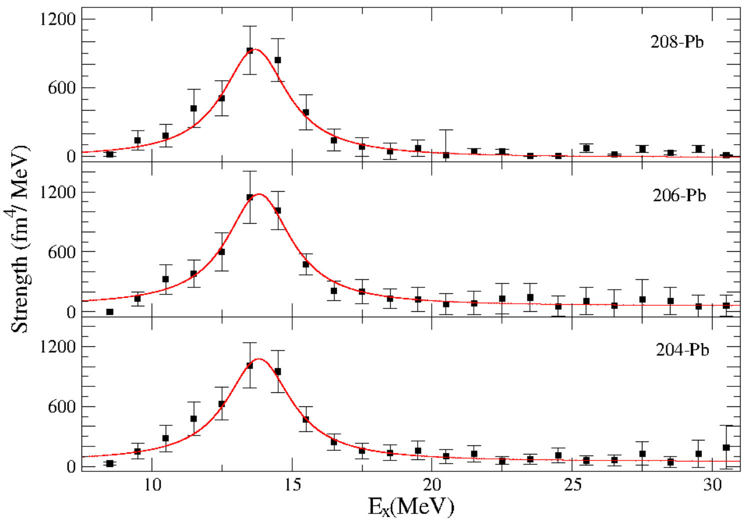

Fig. 4. Preliminary $\Delta L = 0$ strength distributions for ^{204}Pb (bottom panel), ^{206}Pb (middle panel), and ^{208}Pb (top panel) as extracted from Multipole Decomposition Analysis (MDA) of 400-MeV inelastic α-scattering spectra. Lorentzian fits to the distributions are also shown (solid lines). **These results should be considered preliminary**.

13.8 MeV, and 13.7 MeV, respectively, for ^{204}Pb, ^{206}Pb, and ^{208}Pb. While these numbers are very preliminary, it is clear, again, from the GMR strength distributions that, quite contrary to the expectation that the energy of the GMR would be largest in ^{208}Pb, the GMR energies in the three cases are nearly identical.

Indeed, the variation in GMR energy corresponds to what one would normally expect from the standard $A^{-1/3}$ dependence for all giant resonances.

These results would imply, then, that the MEM effect does not hold for the Pb isotopes and, consequently, does not provide a good explanation for the observed "softness" of the Sn and Cd nuclei, as indicated by their GMR energies. As such, this remains an open problem, a challenge to theorists.

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