Monopole giant resonance in $^{100-132}$Sn, $^{144}$Sm and $^{208}$Pb

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Abstract

The isoscalar giant monopole resonance (GMR) in spherical nuclei $^{100-132}$Sn, $^{144}$Sm and $^{208}$Pb is investigated within the Skyrme random-phase approximation for a variety of Skyrme forces and different pairing options. The calculated GMR strength functions are directly compared to the available experimental distributions. It is shown that, in accordance with the results of other groups, the description of GMR in Sn and heavier Sm/Pb nuclei needs different values of nuclear incompressibility, $K \approx 200$ or $230$ MeV, respectively. Thus, none of the Skyrme forces used can simultaneously describe GMR in these nuclei. The GMR peak energy in open-shell $^{120}$Sn is found to depend on the isoscalar effective mass, which might be partly used to solve the above problem. Some important aspects of the problem, such as discrepancies of available experimental data and proper treatment of the volume and surface compression in finite nuclei, are briefly discussed.

Keywords: giant monopole resonance, Skyrme RPA approach, spherical nuclei

(Some figures may appear in colour only in the online journal)

1. Introduction

In recent decades, the giant monopole resonance (GMR) has been the subject of intense study (see, e.g., [1–3] for recent reviews and discussions). The GMR provides valuable information on nuclear incompressibility [4] since its energy centroid, $E_{GMR}$, can be directly related to the compression modulus, $K_A$, within a collective model [4],

$$E_{GMR}^A = \sqrt{\frac{h^2 K_A}{m \langle r^2 \rangle_0}},$$

where $A$ is the nucleus mass number, $m$ is the nucleon mass, and $\langle r^2 \rangle_0$ is the ground-state mean-square radius. For nuclear matter, the commonly accepted value for incompressibility is $K = 230–240$ MeV, which is confirmed by relativistic as well as nonrelativistic mean-field models [5].

Despite many efforts, the description of GMR still suffers from some persistent problems. For example, the mean-field models with $K = 230–240$ MeV reproduce the GMR experimental data in heavy and medium nuclei like $^{208}$Pb and $^{144}$Sm [6, 7, 9], but fail to describe more recent GMR experiments for lighter nuclei like Sn and Cd isotopes [10–14], which require a lower incompressibility (see, e.g., the discussion in [1, 2, 15, 16]). In other words, none of the modern relativistic or nonrelativistic, self-consistent models can simultaneously describe the GMR in all mass regions. This problem has already been analyzed from different sides. It was shown that GMR centroids can be somewhat changed by varying the symmetry energy at the constant, $K$ [17]. Different Skyrme forces and pairing options (surface, volume, and mixed) were explored [2, 15, 16]. Hartree–Fock–Bogoliubov (HFB) and HF-BCS methods were compared [18]. All these attempts have partly confirmed the description, but they have not solved the problem completely.

The modern GMR experimental data are mainly delivered by two groups: Texas A&M University (TAMU)
and the Research Center for Nuclear Physics (RCNP) at Osaka University [7, 11–14]. Both groups use the \((\alpha, \alpha')\) reaction and the multipole decomposition prescription to extract the E0 contribution from the cross sections. However, these groups provide notably different results, which should be also taken into account in the analysis of the above problem [2, 19].

The present paper also explores the problem of the simultaneous description of the GMR in Sm-Pb and Sn nuclei. With this goal in mind, the E0 strength functions are calculated within the Skyrme random-force approximation (RPA) [23] and directly compared to the available experimental data. Note that in some previous studies [2, 18], the Skyrme forces [20], which cover a wide range of the nuclear pressibility, \(K\), were applied. As shown below, our analysis considers the matter parameters and thus are convenient for a systematic exploration should include a direct comparison of the calculated and experimental strength distributions, which is only available in the present study.

Our calculations are performed using the family of SV Skyrme forces [20], which cover a wide range of the nuclear matter parameters and thus are convenient for a systematic investigation. Both surface and volume pairing options are applied. As shown below, our analysis confirms that incompressibility, \(K \approx 230\) MeV, is suitable to describe E0 strength in heavier nuclei (\(^{208}\)Pb and \(^{144}\)Sm), while lighter Sn isotopes need lower values, \(K \approx 200\) MeV. In connection to this problem, a significant discrepancy between TAMU and RCNP experimental data is discussed. In addition, we inspect the dependence of the GMR peak energy on various nuclear matter variables in three representative Sn isotopes: neutron-deficient doubly magic \(^{100}\)Sn, stable semi-magic \(^{120}\)Sn, and neutron-rich doubly magic \(^{132}\)Sn.

The paper is organized as follows. In section 2, the theoretical framework and calculation details are sketched. In section 3, the results are discussed. Lastly, we provide a summary of the paper’s findings.

2. Theoretical framework

The calculations of the E0 strength function are performed within the RPA based on the Skyrme energy functional (see, e.g., [20])

\[
\hat{\varepsilon}(\rho, \tau, \vec{J}, \vec{\sigma}, \vec{T}) = \varepsilon_{\text{kin}} + \varepsilon_{\text{Sk}} + \varepsilon_{\text{Coul}} + \varepsilon_{\text{pair}}
\]

depending on a couple of local densities \((\rho(\vec{r})\): nucleon, \(\tau(\vec{r})\): kinetic energy, \(\vec{J}(\vec{r})\): spin-orbit, \(\vec{\sigma}(\vec{r})\): current, \(\vec{T}(\vec{r})\): vector kinetic energy). Here, \(\varepsilon_{\text{kin}}, \varepsilon_{\text{Sk}}, \varepsilon_{\text{Coul}},\) and \(\varepsilon_{\text{pair}}\) are kinetic energy, Skyrme, Coulomb, and pairing terms, respectively. The explicit expressions for these terms are found elsewhere [20].

Using Hartee-Fock (HF) with BCS treatment of the pairing, we obtain the effective Hamiltonian as a sum of the quasiparticle mean field, \(\hat{h}_{\text{HF+BCS}}\), and residual interaction, \(\hat{V}_{\text{res}}\) [20–22]:

\[
\hat{H} = \hat{h}_{\text{HF+BCS}} + \hat{V}_{\text{res}}
\]

where

\[
\hat{h}_{\text{HF+BCS}} = \int d^3r \sum_{d+} \frac{\delta \varepsilon}{\delta \rho_d(\vec{r})} \hat{J}_d(\vec{r}),
\]

\[
\hat{V}_{\text{res}} = \frac{1}{2} \sum_{d,d'} \int d^3r \int d^3r' \frac{\delta^2 \varepsilon}{\delta \rho_d(\vec{r}) \delta \rho_{d'}(\vec{r}')} : \hat{J}_d(\vec{r}) \hat{J}_{d'}(\vec{r}'):.
\]

The \(\hat{h}_{\text{HF+BCS}}\) involves only time-even densities \((\rho, \tau, \vec{J})\), while in \(\hat{V}_{\text{res}}\), all the densities are embraced. The symbol \(:\) in (5) represents the normal product of the involved operators with respect to the quasiparticle creation, \(\alpha^+\), and annihilation, \(\alpha\), operators [22]. Then, using the standard RPA procedure, we obtain the RPA equation

\[
\begin{pmatrix}
A & B \\
B^* & A^*
\end{pmatrix}
\begin{pmatrix}
\rho^{(0)}(\vec{r}) \\
\tau^{(0)}(\vec{r})
\end{pmatrix}
= \begin{pmatrix}
E_0 & 0 \\
0 & -E_0
\end{pmatrix}
\begin{pmatrix}
\rho^{(0)}(\vec{r}) \\
\tau^{(0)}(\vec{r})
\end{pmatrix}
\]

for the two-quasiparticle (2qp) forward and backward amplitudes, \(\rho^{(\pm)}\), of the phonon creation operator

\[
Q^+_{\vec{p}}(\lambda \mu) = \sum_{i \neq j} C_{ijkl}^{j*} n_{ij}^{(0)}(\alpha_i^{(0)} \alpha_i^{(0)} - \delta_{ij}) \alpha_j \alpha_j.
\]

Here, \(C_{ijkl}^{j*}\) are Clebsch–Gordan coefficients, \(\nu\) numerates the RPA states, \(E_0\) is the RPA energy, \(A\) and \(B\) stand for the RPA matrices with the elements

\[
A_{ij} = \delta_{ij} \delta_{\vec{p}_i \vec{p}_j} e_{ij}
\]

\[
+ \sum_{d,d'} \frac{(-1)^{j'} +1}{2 \lambda +1} \int_0^{\infty} \rho^{(L+1)}(\vec{r}) J^{(ij)}_{d,d'}(\vec{r}) J^{(ij')}_{d,d'}(\vec{r}) \rho^{(L')}(\vec{r}) \rho^{(L')}_{d,d'}(\vec{r}) \rho^{(L')}(\vec{r}) \rho^{(L')}_{d,d'}(\vec{r})
\]

\[
B_{ijkl} = \sum_{d,d'} \gamma_d(1)^{j'} +1 \int_0^{\infty} \rho^{(L+1)}(\vec{r}) J^{(ij)}_{d,d'}(\vec{r}) J^{(ij')}_{d,d'}(\vec{r}) J^{(ij')}_{d,d'}(\vec{r}) \rho^{(L')}(\vec{r}) \rho^{(L')}_{d,d'}(\vec{r}) \rho^{(L')}(\vec{r}) \rho^{(L')}_{d,d'}(\vec{r})
\]

\[
\frac{1}{\sqrt{2 \lambda + 1}} \sum_{ijLM} C_{ijLM}^{LM} Y_{LM}(\vec{r}) \alpha_i^{(0)} \alpha_j^{(0)} - \gamma_d \alpha_i \alpha_j,
\]

where \(C_{ijLM}^{LM}\) are spherical harmonics. (More complicated radial parts for the vector and tensor densities can be found in [22].) Diagonalization of the RPA matrix gives amplitudes \(c_{ij}^{(\pm)}\) and phonon energies \(E_0\).
By using the structure and energies of one-phonon states, the strength function
\[ S(E_0, E) = \sum_{\nu} \left| \langle \nu | \hat{M}(E_0) | 0 \rangle \right|^2 \xi_\Delta(E - E_\nu) \] (11)
for the monopole transition operator, \( \hat{M}(E_0) = r^2 Y_{00} \), is calculated. The Lorentz weight
\[ \xi_\Delta(E - E_\nu) = \frac{1}{2\pi} \frac{\Delta}{(E - E_\nu)^2 + \frac{\eta^2}{4}} \] (12)
with the averaging parameter, \( \Delta = 2\text{ MeV} \), is used. Such averaging is found to be optimal for simulating the smoothing effects beyond RPA (escape widths and coupling to complex configurations). This allows a convenient comparison of the calculated and experimental strengths.

The calculations exploit a set of Skyrme SV forces [20] consisting of groups of parameterizations with variations in one of the nuclear matter variables: incompressibility modulus, \( K \), isoscalar effective mass, \( m_0/m \), TRK sum-rule enhancement, \( \kappa \) (related to the isovector effective mass), and the symmetry energy, \( a_{\text{sym}} \). Thus, SV forces are convenient for the systematic investigation of the dependence of the results on the basic nuclear matter features. For comparison, some other Skyrme parameterizations with essentially different incompressibilities are used: SKP\(^\ast\) (\( K = 202 \text{ MeV} \)) [24], SKM\(^*\) (\( K = 217 \text{ MeV} \)) [25], SLy6 (\( K = 230 \text{ MeV} \)) [26], and SkI3 (\( K = 258 \text{ MeV} \)) [27].

In our strength distributions, the spurious mode related to the pairing-induced nonconservation of the particle number lies at 4–6 MeV, which is safely below the GMR peak at 14–16 MeV. To minimize the impact of the spurious mode, only the strength at the excitation energy, \( E > 9 \text{ MeV} \), is considered.

The calculations use a radial coordinate-space grid with a step size of 0.1 fm. The large configuration space involving a 2qp spectrum up to 140 MeV is exploited. The energy weighted sum rule, \( \text{EWSR}(E_0) = \frac{\mu^2}{2m^2} A(r_0^2) \), estimated at the energy interval 9–45 MeV, is exhausted by 98–105%. The excess of EWSR arises in nuclei with pairings due to the remaining weak tail of the spurious mode.

Proton and neutron pairing are taken into account in semimagic \(^{144}\text{Sm}\) and \(^{112,116,120,124}\text{Sn}\), respectively. The pairing potential reads
\[ V_{\text{pair}}(\vec{r}, \vec{r}') = V_{\text{pair}} \left[ 1 - \eta \left( \frac{\rho(\vec{r})}{\rho_0} \right) \delta(\vec{r} - \vec{r}') \right], \] (13)
where \( q \) stands for protons or neutrons, \( V_{\text{pair}} \) and \( V_{\text{pair}} \) are the pairing strengths, \( \rho(\vec{r}) \) is the nucleon density, and \( \rho_0 \) is the density of symmetric nuclear matter at equilibrium. The parameter, \( \eta \), switches the pairing options between the volume delta-interaction (DI) for \( \eta = 0 \) and the surface density-dependent delta-interaction (DDDI) for \( \eta = 1 \). Both options are used in the calculations. Pairing is treated at the BCS level. This means that at each HF iteration for single-particle wave functions, the Bogoliubov coefficients, \( u_i \) and \( v_i \), are determined within the BCS and then introduced to the Skyrme densities. However, unlike the HFB case, the HF iterations exploit the single-particle Hamiltonian without the pairing term [28]. The RPA calculations take into account the pairing particle-particle channel.

3. Results and discussion

Figure 1 shows the RPA results for isoscalar (\( T = 0 \)) GMR in doubly magic \(^{208}\text{Pb}\), neutron semimagic \(^{144}\text{Sm}\), and proton semimagic \(^{112,116,120,124}\text{Sn}\). The SV parameterizations with different values of the incompressibility, \( K \) (as indicated at the figure), are used. The calculated strength functions are compared with TAMU [6, 9, 10] and RCNP [7, 8, 11] experimental data. For the convenience of comparison, the TAMU data, which are initially presented in units of the fraction of the EWSR, are transformed to the units fm\(^4\) MeV\(^{-1}\) used by RCNP. In the calculated strength function, the Lorentz averaging parameter, \( \Delta = 2 \text{ MeV} \), is used as the most convenient option to compare the calculated and RCNP strengths. Such averaging produces GMR amplitudes and widths similar to one found by RCNP. Then, the actual model output is reduced to the GMR shape, integral strength, and energy. As seen in figure 1, the calculated GMR integral strength is close to the RCNP integral strength expressed in the same units.

Before further comparison of the theory and experiment, the significant discrepancy between RCNP and TAMU data should be discussed. Figure 1 shows a large difference at the left wing of the GMR strength. In principle, this difference can be reduced by a proper rescaling of the TAMU data. However, scaling cannot conceal two other apparent differences. First, when compared to RCNP, TAMU gives a somewhat lower energy position of the GMR peak in Sm and Sn. Second, the RCNP data exhibit a long, uniform tail above the GMR. Only the onset of this tail at 19 MeV < \( E < 23 \) MeV is seen in figure 1, though actually it continues at least up to 33 MeV [11]. This tail is absent in the TAMU data (see the discussion in [9]). This difference can affect determination of the experimental GMR centroids, which are usually estimated through the sum rules and thus depend on the chosen energy intervals. Altogether, these two RCNP/TAMU discrepancies should be taken into account when comparing the calculated GMR with the experiment.

Figure 1 also shows that, in accordance with previous studies (see [1, 2] and references therein), the calculated energy position of the GMR noticeably depends on the the incompressibility, \( K \). The larger \( K \) is, the higher the GMR is. For instance, in \(^{144}\text{Sm}\), the force SV-K241 with \( K = 241 \text{ MeV} \) gives the GMR maximum at 16.2 MeV, while SV-K218 with \( K = 218 \text{ MeV} \) downshifts this maximum to 15 MeV. It is also seen that the forces with a large \( K \), like SVbas, provide a good agreement with TAMU and RCNP data in heavy nuclei \(^{144}\text{Sm}\) and \(^{208}\text{Pb}\), but they certainly overestimate the GMR energy in lighter Sn isotopes. The description of GMR in Sn needs forces with a much smaller incompressibility; even the force SV-K218 is not enough. In other words, Sn isotopes...
demonstrate a remarkable softness to the compression, and this is valid for both RCNP and TAMU data.

These conclusions are corroborated in figure 2, where Skyrme parameterizations beyond the SV-family (SkP$^\delta$[24], SkM*$[25]$, SLy6$[26]$, SkI3$[27]$) with a broader incompressibility range, $K = 202 \div 258$ MeV, are applied. Figure 2 shows that the best description of the GMR energy, $E_{\text{GMR}}$, in Sn isotopes is obtained with the low-$K$ SkP$^\delta$ and SkM* forces, but these forces noticeably underestimate the GMR energy in $^{144}$Sm and $^{208}$Pb. For the latter nuclei, the parametrization SVbas with a large $K = 234$ MeV is best, but it fails in Sn isotopes. The force, SkI3, with the highest incompressibility, $K = 258$ MeV, overestimates $E_{\text{GMR}}$ in all the considered nuclei. Both pairing options, DI and DDDI, give similar results.

It is instructive to compare the sensitivity of the centroid energy, $E_{\text{GMR}}$, both to $K$ and to other nuclear matter variables. Figure 3 shows the dependence of $E_{\text{GMR}}$ on the isoscalar effective mass, $m_0/m$, isovector enhancement factor, $\kappa$, incompressibility, $K$, and the symmetry energy, $a_{\text{sym}}$, for neutron-deficit doubly magic $^{100}$Sn, stable semimagic $^{120}$Sn, and neutron-rich doubly magic $^{132}$Sn. One finds that $E_{\text{GMR}}$ indeed depends most strongly on $K$; the difference in $E_{\text{GMR}}$ for $K = 218$ and 243 MeV reaches 1 MeV. The $E_{\text{GMR}}$ decreases from $^{100}$Sn to $^{132}$Sn in general agreement with the empirical estimation, $E_{\text{GMR}}^\text{emp} \approx 78A^{-1/3}$ MeV$[29]$.

The dependence of $E_{\text{GMR}}$ on $\kappa$ and $a_{\text{sym}}$ is generally weak (for the exception of the neutron-rich nucleus, $^{132}$Sn). However, $^{120}$Sn demonstrates a significant dependence on the isoscalar effective mass: the less $m_0/m$ is, the higher $E_{\text{GMR}}$ is. This is because a decrease of $m_0/m$ makes the single-particle spectrum more dilute, and thus results in higher $E_{\text{GMR}}$. In $^{120}$Sn, this effect seems to be enhanced by the neutron pairing. Dependence on $m_0/m$ can be used for a further conformance of the GMR description in Pb/Sm and Sn nuclei.

Finally, note that the problem of the simultaneous description of the GMR in Pb/Sm and Sn can occur for various reasons. Perhaps available Skyrme parameterizations and paring treatments are not yet optimal enough. It is also possible that the accuracy of the Skyrme-like energy density functionals has already reached its limits (see the discussion in $[30]$) and some essential modifications of the functionals, such as a richer density dependence $[31]$, are in order. Note that there are also other cases when Skyrme forces cannot simultaneously describe nuclear excitations in closed- and open-shell nuclei. For example, no Skyrme parametrization can simultaneously reproduce the spin-flip M1 GR in closed-shell spherical $^{208}$Pb and open-shell rare-earth deformed nuclei $[32, 33]$. More versatile density dependence would also

Figure 1. $E_0(T = 0)$ strength functions in $^{144}$Sm, $^{208}$Pb, and $^{112,116,124}$Sn, calculated with SV forces SV-K218, SV-K226, SV-bas, and SV-K241. The incompressibility moduli, $K$, are indicated for each force in MeV. In Sm and Sn, the DDDI pairing is used. The Lorentz averaging parameter is $\Delta = 2$ MeV. The results are compared with TAMU data for Sm/Pb $[6, 9]$, and Sn $[10]$ and RCNP data for Sm $[7]$, Pb $[8]$, and Sn $[11]$. 


Figure 2. The same as in figure 1, but for the Skyrme forces SkP$^\delta$, SkM$^*$, SLy6, SV-bas, and SkI3. The incompressibility moduli, K, (in MeV) and pairing options (DI or DDDI) are indicated for each force.

Figure 3. Dependence of the GMR peak energies in $^{100,120,130}$Sn on the nuclear matter values: (a) isoscalar effective mass ($m_0^*/m = 0.7, 0.8, 0.9, 1.0$), (b) isovector enhancement factor ($\kappa = 0, 0.2, 0.4, 0.6$), (c) incompressibility modulus ($K = 218, 226, 234, 243$ MeV) and (d) symmetry energy ($a_{sym} = 28, 30, 32, 34$ MeV). The RPA calculations [23] are performed with the family of SV Skyrme forces [20].
allow one to distinguish between the bulk incompressibility, $K$, and the surface incompressibility, $K_{A}^{\text{surf}}$. Note that the incompressibility in finite nuclei can be different at the nuclear surface and in the interior because these regions have different nucleon densities. Besides, at the nuclear surface, the impact of pairing is most essential. Thus, the separate consistent estimations of the volume, $K_{A}^{\text{vol}}$ (to be associated with the nuclear matter incompressibility $K$), and surface, $K_{A}^{\text{surf}}$, incompressibility might be useful, as seen in the analysis of the lepton-dense expansion of $K_{A}$ in [3].

As mentioned previously, the discrepancy between RCNP and TAMU experimental data also hampers the solution of the problem. Note that RCNP/TAMU data also deviate in deformed nuclei. For example, TAMU gives (in agreement with recent Skyrme RPA calculations [19]) a clear two-bump GMR structure in $^{154}$Sm [9], explained by the deformation-induced coupling between $E0(T = 0)$ and $E2(T = 0)$ modes. Instead, RNCP data give a one-bump GMR structure in this nucleus [7]. In this connection, note that TAMU and RCNP experiments use $\alpha$-particle beams with different incident energies. Since ($\alpha$, $\alpha$) experiments use a peripheral reaction, the TAMU and RCNP experiments can probe different surface slices and thus exhibit different compression responses, which may be resolved by distinguishing bulk and surface incompressibility, $K_{A}^{\text{vol}}$ and $K_{A}^{\text{surf}}$, respectively. Certainly these discrepancies call for more accurate measurements and analysis of the GMR.

4. Conclusions

The GMR was explored in $^{100,120,132}$Sn, $^{144}$Sm, and $^{208}$Pb in the framework of the Skyrme RPA with different Skyrme forces and pairing options. The calculations confirmed the results of numerous previous studies [1] that GMR in $^{208}$Pb ($^{144}$Sm) and Sn isotopes cannot be simultaneously described with the same Skyrme parametrization. The analysis calls for more accurate experiments to match the TAMU and RCNP experimental data.

Dependence of GMR peak energies on the nuclear matter variables (incompressibility, $K$, isoscalar effective mass, $m_0^*/m$, isovector enhancement factor, $\kappa$, and symmetry energy, $\alpha_{\text{sym}}$) was examined in $^{100,120,132}$Sn. The calculations confirmed the well-known strong dependence of the results on $K$. In addition, a sensitivity to the isoscalar effective mass, $m_0^*/m$, was revealed. The latter opens another window for further arrangement of the problem of the simultaneous GMR description in Sm/Pb and Sn nuclei. Some possible next steps in the solution of this problem (further experimental progress, proper treatment of the ratio between the volume and surface incompressibility in finite nuclei, etc) were briefly discussed.

Acknowledgments

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