Deformation-induced splitting of the monopole giant resonance in ²⁴Mg

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Abstract. The strong deformation splitting of the isoscalar giant monopole resonance (ISGMR), recently observed in (α, α') reaction in prolate ²⁴Mg, is analyzed in the framework of the Skyrme quasiparticle random-phase-approximation (QRPA) approach with the Skyrme forces SkM*, SVbas and SkP$^\delta$. The calculations with these forces give close results and confirm that the low-energy $E0$-peak is caused by the deformation-induced coupling of ISGMR with the $K = 0$ branch of the isoscalar giant quadrupole resonance.

1 Introduction

The isoscalar giant monopole resonance (ISGMR) represents the main source of information on the nuclear incompressibility [1] and is a subject of intense studies during last decades, see the book [2] and recent reviews [3, 4]. In deformed nuclei, ISGMR is coupled with the $K^\pi = 0^+$ branch of the isoscalar giant quadrupole resonance (IS-GQR), which leads to a double-bump structure (splitting) of the ISGMR [2]. The energy interval between the bumps is larger than the ISGMR and ISGQR widths [2]. Besides, in well deformed nuclei, both bumps carry a significant monopole strength. These two factors favor an experimental observation of the ISGMR splitting.

In medium and heavy deformed nuclei, the clear IS-GMR splitting has been found only in Sm isotopes [5–8] and ²³⁸U [9]. In this aspect, light deformed nuclei look more promising because some of them demonstrate much stronger deformation (β=0.5-0.60) [10] than well deformed heavier nuclei (β=0.30-0.35). Thus we may expect in light nuclei particularly strong $E0 - E2$ coupling.

The first experimental data of this kind have been recently obtained. Namely, the ISGMR splitting in ²⁴Mg was observed in (α, α') reaction to forward angles [11]. The experiment was performed in the Research Center for Nuclear Physics (RCNP) in Osaka University. The nucleus ²⁴Mg has a huge prolate quadrupole axial deformation with β=0.605±0.008 [10] and thus promises a strong $E0 - E2$ coupling. However, fist attempts to observe a discernible ISGMR splitting in this nucleus using inelastic scattering of α-particles and ⁶Li have failed [6, 12–14]. Only in [11], the experimentalists have managed to reliably discriminate the splitting. It turned out to be huge, with a strong narrow peak at $E_1 \sim 16$ MeV and a broad structure at $E_2 \sim 24$ MeV, see Fig. 1.

The calculations in the framework of the quasiparticle random-phase-approximation (QRPA) with the Skyrme force SkM* [15], presented in Ref. [11], have confirmed the $E0 - E2$ origin of the ISGMR splitting observed in ²⁴Mg. However, it is known that QRPA description of giant resonances can noticeably depend on the applied Skyrme parametrization [16–19]. Such dependence can take place for ISGMR in deformed nuclei as well [20]. In this connection, it is worth to check the Skyrme QRPA results obtained with SkM* in Ref. [11] by using other Skyrme parameterizations. This is just the aim of the present study.

Here, we explore the ISGMR splitting in ²⁴Mg within Skyrme QRPA approach with the forces SkM* [15], SVbas [19] and SkP$^\delta$ [21]. The force SkM* ($K_\infty = 217$ MeV) is used for comparison with the previous calculations [11]. Two other forces are chosen as representatives of essentially different nuclear incompressibilities: K_∞=234 MeV for SVbas and 202 MeV for SkP$^\delta$. As shown below, all three forces give qualitatively close results and confirm that the ISGMR splitting arises just because of the $E0 - E2$ coupling.

2 Model

The calculations are performed with the two-dimensional (2D) QRPA code [22]. As compared to our previous calculations for ISGMR [20], the present code does not use any separable ansatz. The method is fully self-consistent because: i) both the mean field and residual interaction are obtained from the same Skyrme functional, ii) the residual interaction includes all terms of the functional, including Coulomb (direct and exchange) terms. Both time-even and time-odd densities are involved. The code exploits a mesh in cylindrical coordinates with a mesh size of d=0.7 fm and a calculation box of about three nuclear radii.

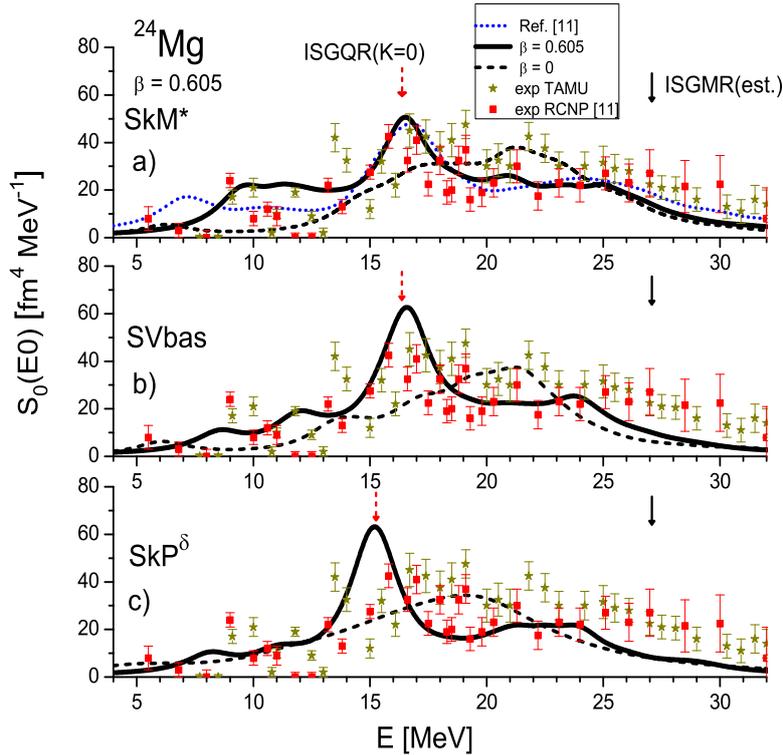---

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Figure 1. (Color online) The QRPA $E0(T=0)$ strength functions in ^{24}Mg, calculated at the experimental quadrupole deformation β=0.605 (black solid curves) and in the spherical limit β=0 (black dash curves) with the Skyrme forces SkM* (a), SVbas (b), and SkP$^\delta$ (c). In the panel a), the SkM* strength function from [11] is also given (blue dotted curve). In all the panels, the TAMU [11, 24] (yellow stars) and RCNP [11] (red squares) experimental data are exhibited. The calculated energy centroids of the ISGQR($K = 0$)-branch are indicated by the red dash arrows. The estimation $E_{ISGMR} = 78A^{-1/3}$ MeV [2] for the ISGMR energy is marked by the black bold arrow.

The experimental value of the deformation β=0.605 [10] is used for all three forces. The δ-force volume pairing is treated at the BCS level [23]. The pairing particle-particle channel in the residual interaction is taken into account.

The ISGMR strength function reads

$$S(E0; E) = \sum_\nu |\langle\nu|\hat{M}(E0)|0\rangle|^2 \xi_\Delta(E - E_\nu) \qquad (1)$$

where $|0\rangle$ is the ground state wave function, $|\nu\rangle$ and E_ν are QRPA states and energies, $\hat{M}_{ISGMR}(E0) = \sum_i^A (r^2 Y_{00})_i$ is the isoscalar (T=0) transition operator, $\xi_\Delta(E - E_\nu) = \Delta/(2\pi[(E - E_\nu)^2 - \Delta^2/4]$ is the Lorentz smoothing with the averaging parameter Δ. The Lorentz function approximately simulates smoothing effects beyond QRPA and makes convenient comparison of the calculated and experimental strengths. The calculations [11] used the smearing 3 MeV. Here, the averaging Δ= 2.5 MeV is found optimal.

Our calculations use sufficiently large basis. For the SVbas parametrization the single particle (s-p) spectrum includes 750 proton and 920 neutron levels in the energy intervals (-32, +61) MeV and (-37, +85) MeV, respectively. The two-quasiparticle basis involves about 3700 states with the energies up to ~200 MeV. The energy-weighted sum rule for the isoscalar monopole excitations is exhausted by 94%. The similar basis is used for SkM* and SkP$^\delta$.

3 Results and discussion

Results of the calculations are presented in Fig. 1. They are compared with the experimental data from RCNP [11] and TAMU (Texas A&M University) [11, 24]. Following the statement in Ref. [11], RCNP data do exhibit the ISGMR splitting while TAMU data do not.

As seen from Fig. 1, the calculations with SkM*, SVbas and SkP$^\delta$ give a qualitatively similar picture and justify origin of the narrow peak at $E \sim 16$ MeV as a result of the coupling between ISGMR and $K = 0$ branch of ISGQR. Indeed the position of this peak well coincides with the energy of ISGQR($K = 0$) branch, marked by the dash arrows in the figure. The second evidence is that this peak is almost disappears in the spherical limit (β=0) when the $E0 - E2$ coupling is absent. The agreement with the experimental energy $E \sim 16$ MeV is very nice for SkM* and SVbas and somewhat worse for SkP$^\delta$. The latter is explained by a low incompressibility K_∞=202 MeV in SkP$^\delta$.

Our and previous [11] SkM* calculations give about the same description of the peak at $E \sim 16$ MeV (compare the black bold and blue dotted curves in the panel (a)). Both results are also similar for $E0$ strength above the peak. A noticeable difference between two calculations takes place only in a low energy region with $E < 13$ MeV, which is beyond of our interest. Perhaps this difference is partly caused by using variant pairing schemes: (HF+BCS in our case and HFB in [11]).

In Fig. 1, the RCNP experimental data give a high-energy distribution peaked at ~24 MeV. This distribution constitutes the familiar ISGMR. The broad ISGMR structure seems to continue to the low-energy region and form a massive background of the narrow peak at $E \sim 16$ MeV. This is confirmed by the distribution of $E0$ strength calculated in the spherical limit. Note, that the energy $E \sim 24$ MeV gives $E_{\mathrm{ISGMR}} = 69A^{-1/3}$ MeV which is closer to the empirical estimation for ISGQR ($E_{\mathrm{ISGQR}} = 64A^{-1/3}$ MeV) rather than for ISGMR ($E_{\mathrm{ISGMR}} = 78A^{-1/3}$ MeV) [2]. The latter gives for ISGMR in ^{24}Mg the energy $E_{\mathrm{ISGMR}} \sim 27$ MeV.

As seen from Fig. 1, our calculations in general reproduce the ISGMR at ~24 MeV. The forces SkM* and SVbas demonstrate a better performance than SkP$^\delta$ with its very low incompressibility. Note also that present SkM*, SVbas and SkP$^\delta$ calculations, as well as the SkM* results [11], underestimate the observed $E0$ strength at $E > 24$ MeV. Thus the computed ISGMR looks somewhat downshifted as compared to the experimental data. Most probably the QRPA is not enough to describe details of present experimental distribution and we need here the coupling with complex configurations.

4 Summary

The analysis of the recent experimental data for the deformation-induced splitting of the isoscalar giant monopole resonance (ISGMR) in strongly deformed ^{24}Mg [11] has been done within the Skyrme quasiparticle random-phase approximation (QRPA) approach. The Skyrme forces SkM* [15], SVbas [19], and SkP$^\delta$ with different values of nuclear incompressibility were applied. The calculations generally well reproduce the experimental data and confirm the origin of the peak at $E \sim 16$ MeV as a result of the $E0 - E2$ coupling. For a more precise description of the experimental $E0$ distribution, inclusion of the coupling with complex configurations is desirable.

Acknowledgements

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