Effects of Self-Consistency Violations in HF-RPA Calculations for Giant Multipole Resonances

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The study of collective modes in nuclei provides very important information for understanding the structural and bulk properties of nuclear systems. In particular, the isovector giant dipole (IVGDR) mode is sensitive to the symmetry energy and the centroid energy $E_{\text{cen}}$ of the isoscaler giant monopole resonance (ISGMR) allows us to extract the value of the incompressibility modulus $K$ of symmetric nuclear matter. These quantities are important ingredients not only for the description of the finite nuclei but also for the study of heavy-ion-collisions, supernovae and neutron stars. Recent developments in high precision experimental facilities in our Cyclotron Institute make it possible to measure the centroid energy of ISGMR with an error of $\delta E_{\text{cen}} \sim 0.1$-$0.3$ MeV. This leads to an error of $7$ MeV for $K=230$ and $E_{\text{cen}}=13.96\pm0.20$ MeV for $^{208}$Pb, since one has $(\delta K)/K = 2(\delta E_{\text{cen}})/E_{\text{cen}}$. Therefore the theoretical calculation should be highly accurate so that the error in the calculated value of $E_{\text{cen}}$ is less than the experimental error.

The basic theory for the microscopic description of modes of giant resonances is the Hartree-Fock (HF) based random phase approximation (RPA). A very accurate calculation within HF+RPA demands self-consistency, i.e., exactly the same interaction has to be used in carrying out the HF and the RPA calculations. Most of the presently available HF+RPA calculations are contaminated by the problem of self-consistency violation (SCV) caused by neglecting the particle-hole (ph) spin-orbit and Coulomb interactions in carrying out the RPA calculations. In Ref. [1], results of elaborate studies of the effects of (SCV) on the constrained energy ($E_{\text{con}}$) and scaling energy ($E_{s}$) have been reported only for the ISGMR. In order to estimate the error due to SCV, $E_{\text{con}}$ and $E_{s}$ were calculated in HF+RPA with some of the interactions (spin-orbit or Coulomb) turned on in HF calculation but missing in the RPA level and the results were compared with those obtained using the fully self-consistent constrained or scaling approaches within Hartree-Fock. It was pointed out [1] that the violation of self-consistency through spin-orbit and Coulomb interactions between the HF and RPA levels might cause an error in $E_{\text{con}}$ of the ISGMR as large as 5 times the experimental error. We note that in Ref. [1] the effect of SCV on the $E_{\text{con}}$ could not be estimated, since fully self-consistent HF-RPA calculation, with the ph spin-orbit and Coulomb interactions included in the RPA, was not carried out. In this work, we investigated the effects of SCV on $E_{\text{con}}$, obtained by carrying out highly accurate fully self-consistent HF-RPA calculations of the response functions and their energy moments. Moreover, we have not restricted our investigation to the ISGMR and considered the isoscalar and isovector modes of multi-polarities $L=0-3$ in a wide range of nuclei.

We have quantified very accurately [2] the effects of self-consistency violations in the calculations of the energies of giant resonances of nuclei within the Hartree-Fock based random phase approximation. We have studied the cases of SCV due to the omission of the spin-orbit (LS) or/and Coulomb (CO) ph interactions and mainly focus on their effects on the centroid energy $E_{\text{cen}}$. Here we
consider both isoscalar and isovector modes of multipolarities $L=0$-3. It is found, for the wide range of nuclei considered here, that the effects of violations of self-consistency due to the ph LS or CO interactions are most significant for the ISGMR. For the ISGMR, the absence of the ph LS interaction tends to increase $E_{\text{cen}}$, whereas the violation due to ph CO interaction decreases $E_{\text{cen}}$. For the spin unsaturated nuclei (such as $^{56}\text{Ni}$, $^{100}\text{Sn}$), the shift of $E_{\text{cen}}$ is robust ($\sim 1.5$ MeV) which is almost 5 times larger than the experimental uncertainty. For other higher multi-polarities, the individual effects of the ph LS and CO interactions are somewhat smaller than those for the ISGMR. But for the quadrupole and octopole modes, the LS and CO self-consistency violations both tend to reduce the centroid energy. Hence, the effect of SCV on $E_{\text{cen}}$ in these modes is significant ($\sim 0.5$ MeV) if one neglects the ph spin-orbit and Coulomb interactions simultaneously in the RPA calculation.