Coulomb and spin-orbit interactions in random phase approximation calculations

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The most common approach to the theoretical study of medium and heavy nuclear systems is to describe the ground and excited states with different theories. With self-consistent calculations one indicates Random Phase Approximation (RPA) calculations which use a set of single particle wave functions generated by Hartree-Fock (HF) calculations. The self-consistency consists in using the same nucleon-nucleon interaction in both HF and RPA calculations.

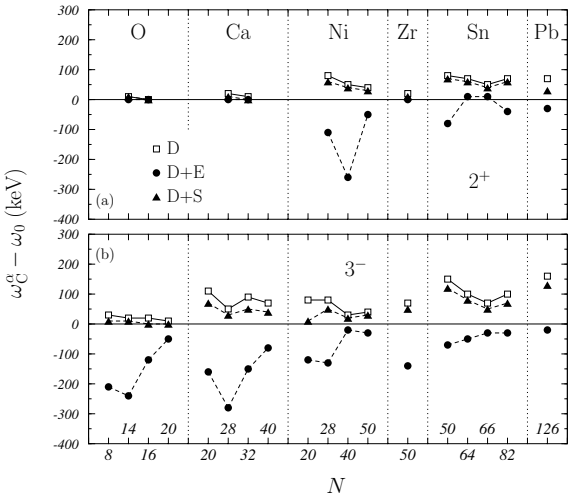

Figure 1. Difference between the RPA energies calculated with and without Coulomb interaction for quadrupole and octupole electric excitations of the nuclei we are investigating. The open squares, $\alpha \equiv$D indicate the results obtained by considering the Coulomb direct term only, the solid circles, $\alpha \equiv$D+E those obtained by considering also the exchange term. The solid triangles, $\alpha \equiv$D+S, show the results obtained by using the Slater approximation to describe the exchange term. All the results of the figure have been obtained without spin-orbit interaction in the RPA calculation. The lines are drawn to guide the eyes.

In actual calculation this self consistency is, usually, not fully accomplished, since the Coulomb and spin-orbits term of the interaction which play an important role in the HF calculations are usually neglected in RPA, with the argument that their effects are small, and, furthermore, since their sign is opposite, they cancel with each other [1]. These are the conclusions of studies done with zero range interactions which, in addition, make use of a simplified treatment of the Coulomb exchange term, called Slater approximation [2].

Since we have developed in these years a HF plus RPA computational approach which uses finite-range interactions, we have implemented the Coulomb and spin-orbit interaction to achieve a fully self consistency between the two theories. We have carried out our investigation by considering various nuclei in different regions of the nuclear chart.

For the various nuclei we have investigated, we present in Fig. 1 the RPA results for low-lying 2^+ and 3^- excited states, panels (a) and (b) respectively, carried out by including the Coulomb interaction. The results presented are the differences between the energies obtained with and without Coulomb interaction, $\omega_C^\alpha - \omega_0$. The open squares, $\alpha \equiv$ D, indicate the results obtained when only the direct terms of the Coulomb matrix elements are considered, and the solid circles, $\alpha \equiv$ D + E, when also the exchange matrix elements are included. The solid triangles, $\alpha \equiv$ D + S, show the results obtained when the Slater approximation of the exchange matrix elements is used.

The results shown in Fig. 1 indicate that the effects of the Coulomb interaction are rather small. We observe maximum differences of the order of few hundreds of keV, in much cases smaller than 100 keV. If only the direct matrix elements are considered the Coulomb interaction is always repulsive: all the nuclei show positive differences, smaller than 100 keV for the 2^+, and smaller than

200 keV for the 3^-. The sign of the difference is reversed when the exchange terms are considered, as the solid circles indicate. The behavior of the complete results strongly depend on the multipolarity and on the nucleus considered. The effects on the 2^+ states of the oxygen and calcium isotopes are negligible, while they become remarkable in the nickel isotopes, more relevant than the effects found in the heavier nuclei we have considered. The situation on the 3^- states is again different. In this case, the isotopes where we observe the largest effects are those of oxygen and calcium, while the effects on the heavier nuclei become gradually smaller.

The results obtained with the Slater approximation strictly follow those obtained by considering only the direct term, and slightly lower the size of the repulsive effect. The Slater approximation is unable to modify the effects of the direct Coulomb matrix elements to reproduce in a reasonable way the effects of the exchange terms.

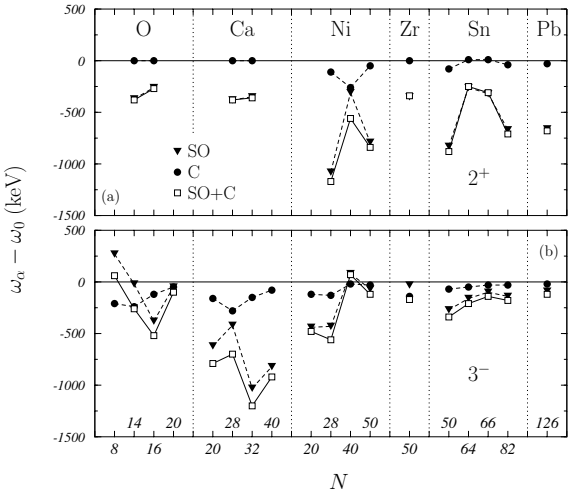

Figure 2. The same as in the previous figure, but now the various symbols represent the RPA energy differences obtained by considering the spin-orbit interaction only (solid triangles), the Coulomb interaction only (solid circles) and both of them (open squares).

We use again the 2^+ and 3^- states considered in the previous section to discuss the effects of the spin-orbit interaction. The results of the calculations done by including the Coulomb and spin-orbit terms of the interactions for the evaluation of the excitation energy of these multipoles are presented in Fig. 2 as a difference with the energies ω_0 obtained without them.

In Fig. 2 the solid triangles indicate the results obtained by using the spin-orbit force only, while the results of the complete calculations, where both Coulomb and spin-orbit terms are considered, are shown by the open squares. For completeness, we show again, with the solid circles, the results obtained by using the Coulomb interaction only.

We first remark that the effects of the spin-orbit force are, in the great majority of the cases, larger than those of the Coulomb interaction. The second remark is that, in general, the spin-orbit interaction is attractive. The exceptions to this trend that we observe are for the 3^- excitations of ^{16}O and of ^{68}Ni. The global effect is essentially given by the simple sum of the two effects separately considered. The largest effects are those found for the 3^- state in ^{52}Ca nucleus and for the 2^+ state in ^{56}Ni nucleus where they reach the values of about 1.2 MeV.

Self-consistent mean-field models are the starting ground to make predictions about the structure of exotic nuclei. The total self-consistency of these calculations is a requirement which reinforces the reliability of these calculations. The exclusion of the Coulomb and spin-orbit terms of the interaction can generate errors up to about 1 MeV on the RPA excitation energies.

A detailed description of our investigation can be found in Ref. [5].

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