Self-consistent continuum Random Phase Approximation with finite-range interactions for charge-exchange excitations

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In this work [1] we have extended the formalism of the Continuum Random Phase Approximation (CRPA) theory [2] which treats, without approximations, the continuum part of the single particle (s.p.) spectrum, to describe charge-exchange excitations. The basic idea of our formalism is to rewrite the usual RPA secular equations [3], where the unknown variables are the X and Y amplitudes, in terms of new unknowns, called channel functions, defined as

$$f_{ph}^{p_0h_0}(r) \;=\; \sum\!\!\!\!\!\!\int_{\epsilon_p} X_{ph}^{p_0h_0}(\epsilon_p)\, R_p(r,\epsilon_p)$$

and

$$g_{ph}^{p_0h_0}(r) \;=\; \sum\!\!\!\!\!\!\int_{\epsilon_p} \left[Y_{ph}^{p_0h_0}(\epsilon_p)\right]^* R_p(r,\epsilon_p)$$

where the symbol $\sum\!\!\!\!\!\!\int$ indicates the sum on discrete s.p. energies and the integration on the continuum part of the spectrum, and R_p is the radial part of the particle wave function. The label p_0h_0 indicates the *elastic channel*, defined as the specific channel where the particle is emitted. The CRPA equations are solved by imposing, every time, that the particle is emitted in a different elastic channel. In order to obtain the CRPA solutions, we have expanded our channel function on a Sturm functions basis [4], as we have done in the charge-conserving case [2, 5].

Charge-exchange excitations can be classified as isospin lowering one T$_-$, when the hole is a neutron and the particle is a proton, and isospin rising one T$_+$, in the opposite case. We use the convention of indicating with π and ν proton and a neutron particle states, respectively, and with a bar a hole state. Therefore, we have $\pi\overline{\nu}$ pairs in T$_-$, and $\nu\overline{\pi}$ pairs in T$_+$ excitations. We show in Ref. [1] that charge-exchange CRPA secular equations for T$_-$ excitations can be expressed as

$$\begin{bmatrix} A^{\mu+}_{\pi\overline{\nu},\pi'\overline{\nu}'} & -B^{\mu+}_{\pi\overline{\nu},\nu'\overline{\pi}'} \\ -(B^{\mu-}_{\nu\overline{\pi},\pi'\overline{\nu}'})^* & (A^{\mu-}_{\nu\overline{\pi},\nu'\overline{\pi}'})^* \end{bmatrix} \begin{bmatrix} c^{\mu+}_{\pi'\overline{\nu}'} \\ (c^{\mu-}_{\nu'\overline{\pi}'})^* \end{bmatrix} = \begin{bmatrix} C_{\pi\overline{\nu},\pi_0\overline{\nu}_0} \\ (D_{\nu\overline{\pi},\pi_0\overline{\nu}_0})^* \end{bmatrix} ,$$

and for T$_+$ excitations as

$$\begin{bmatrix} A^{\mu+}_{\nu\overline{\pi},\nu'\overline{\pi}'} & -B^{\mu+}_{\nu\overline{\pi},\pi'\overline{\nu}'} \\ -(B^{\mu-}_{\pi\overline{\nu},\nu'\overline{\pi}'})^* & (A^{\mu-}_{\pi\overline{\nu},\pi'\overline{\nu}'})^* \end{bmatrix} \begin{bmatrix} c^{\mu+}_{\nu'\overline{\pi}'} \\ (c^{\mu-}_{\pi'\overline{\nu}'})^* \end{bmatrix} = \begin{bmatrix} C_{\nu\overline{\pi},\nu_0\overline{\pi}_0} \\ (D_{\pi\overline{\nu},\nu_0\overline{\pi}_0})^* \end{bmatrix}$$

where A and B are the interaction matrices and depend on the excitation energy ω and $c^{\mu\pm}$ the expansion coefficients of the channel functions. The above expressions indicate inhomogeneous sets of linear algebraic equations. They have solutions, different from the trivial one, for each value of ω above the nucleon emission threshold. For a given excitation energy, and for each elastic channel, the knowledge of the channels functions f and g allows us to calculate the nuclear response induced by an external operator.

Our approach is self-consistent, meaning that we use a unique, finite-range, interaction in the Hartree-Fock (HF) calculations which generate the s. p. basis and in the CRPA which describes the excitation. We used four Gogny-like finite-range interactions: the D1M force [6], the more traditional D1S [7] parameterization, and also the D1MT2c and the D1ST2c forces [8] which we built by adding tensor terms to the two basic D1S and D1M parameterizations. We have carried out calculations for the ^{12}C, ^{16}O, ^{22}O, ^{24}O, ^{40}Ca, ^{48}Ca, ^{56}Ni and ^{68}Ni. In these nuclei the hole s.p. levels are fully occupied and this fact eliminates deformations and minimizes pairing effects. We studied excitations induced by the Fermi, Gamow-Teller and Spin-Dipole operators and payed particular attention to the tensor effects.

Before discussing the most important CRPA results we have obtained in this work, we point out some features of our approach related to the need of the proper treatment of the continuum part of the s.p. configuration space. In Fig. 1 we show the charge-exchange excitation transforming ^{24}O in ^{24}F induced by the Spin-Dipole (SD) operator which can excite the 0^-, 1^- and 2^- multipoles. The total strength is shown in the panels (g) and (h) and is obtained by summing the strengths of each individual excitation. The black full lines and the blue vertical dotted lines show the CRPA and DRPA results, respectively. They are repeated in the left and right panels.

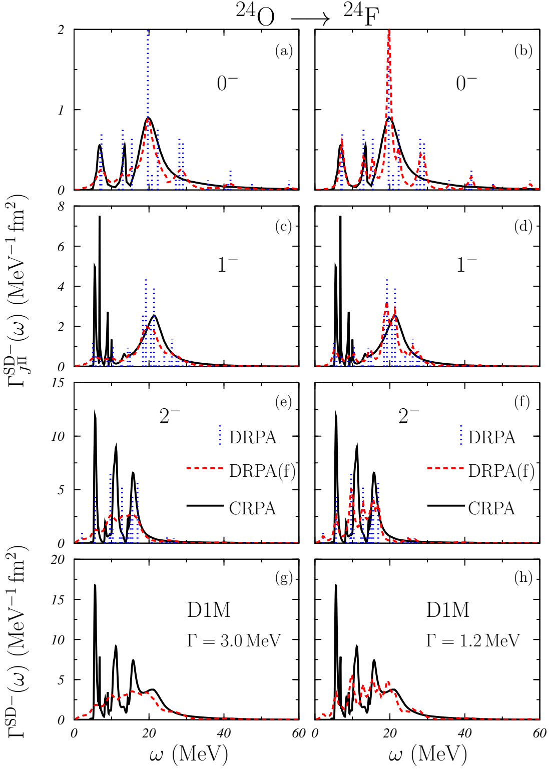

Figure 1. Energy distributions of the T_- for the SD operator strengths for ^{24}O .

Evidently, the DRPA solutions appear at discrete energies and this makes impossible their sum to obtain the global response. The usual procedure consists in folding the various DRPA responses with a Lorentz function which, by definition, conserves the integrated value of the strength. These types of responses are shown in the figure by the red dashed lines. In the left panels they have been obtained by using a value of the Lorentz width of 3.0 MeV, chosen to reproduce the 0^- CRPA strength. In the right panels the Lorentz width is equal to 1.2 MeV and has been selected to reproduce the 2^- CRPA strength. None of the two choices produces satisfactory results. The global CRPA strength is not well reproduced since the good description of one of the multipole excitations makes worst the description of the other ones.

In our work we found interesting results about the SD excitations whose strength develops mainly in the continuum. As example, we show in Fig. 2 the T_- SD strength distributions for the oxygen isotopes considered. We present separately the contribution of each multipole, and also the total strength. The solid black curves have been obtained with the D1M interaction while the dashed red curves with the D1MT2c force. We found that the 2^- excitation is the most important of the multipoles, dominating the total response. On the other hand, the 0^- strength is extremely sensitive to the tensor term. Its inclusion in the CRPA calculations moves the maxima of the 0^- responses towards higher energies. We found these effects for all the nuclei considered. This shift is particularly remarkable in the oxygen isotopes where we found changes of the centroid energies of up to 9 MeV, and a significant widening of the width. We have verified that this large sensitivity of the 0^- to the tensor force is mainly related to the RPA calculations, and not to the modifications of the s.p. energies.

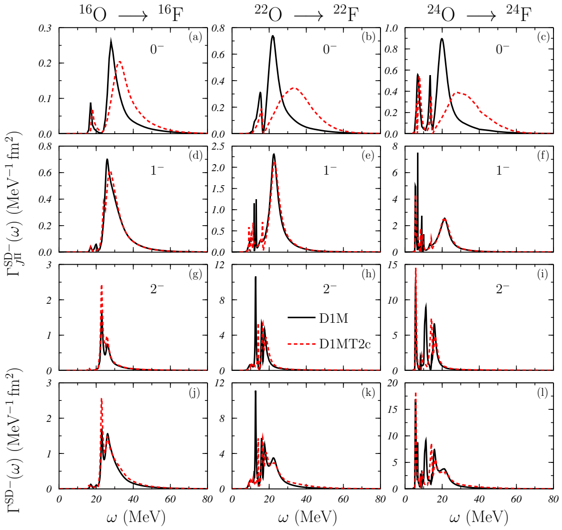

Figure 2. Energy distributions of the T_- for the SD operator strengths for ^{16}O , ^{22}O and ^{24}O nuclei obtained in CRPA calculations.

Our HF+CRPA model is a further step towards the construction of a parameter free mean-field approach describing nuclei in all the regions of the nuclear chart. This offers a great potentiality for the study of neutrino cross sections in the energy region around the emission particle threshold, in analogy to what has been done in Ref. [9] for stable nuclei.

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