Self-consistent continuum Random Phase Approximation calculations of ^{4}He electromagnetic responses

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Abstract

We study the electromagnetic responses of ^{4}He within the framework of the self-consistent continuum Random Phase Approximation theory. In this approach the ground state properties are described by a Hartree-Fock calculation. The single particle basis constructed in this manner is used in the calculations of the continuum responses of the system. Finite-range interactions are used in the calculations. We compare our results with photon absorption cross sections and electron scattering quasi-elastic data. From this comparison, and also from the comparison with the results of microscopic calculations, we deduce that our approach describes well the continuum excitation.

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One of the crucial ingredients in the description of the nuclear excitation in the continuum is the re-interaction between the emitted nucleon, and the remaining nucleus. The Continuum Random Phase Approximation (CRPA) theory describes this effect, commonly called Final State Interaction (FSI), as linear combination of particle-hole and hole-particle excitations. Recently, we have developed a technique to solve CRPA equations with finite-range interactions by considering, without approximations, the excitation to the continuum [1]. The application of our approach to medium-heavy nuclei produces satisfactory descriptions of the experimental data. The positions of the peaks in the excitation of the electromagnetic giant dipole and quadrupole resonances are well reproduced, even though the widths of the resonances are too narrow and their heights to high. There are strong indications that these problems are related to the hypotheses underlying the RPA theory which is limited to consider one-particle one-hole excitations only [2].

In this article, we study the ability of our CRPA calculations to describe the electromagnetic responses of the ^{4}He nucleus. The application of the CRPA approach to the ^{4}He nucleus is quite unusual, since the number of particles composing the system is too small to consider the mean-field hypotheses, on which the RPA theory is based, to be reliable. On the other hand, for the ^{4}He nucleus we have the possibility of comparing our results with those of a fully microscopic approach, based on the Lorentz Inverse Transform (LIT). This approach uses nucleon-nucleon interactions constructed to describe the two-nucleon systems and solves the Schrödinger equation without approximations, contrary to the CRPA, which is an effective theory where the many-body effects are considered by changing the parameters of the interaction.

We have constructed the single particle basis by doing Hartree-Fock calculations. We tested the validity of our description of the ^{4}He ground state, by using three effective interactions: two different parameterizations of the Gogny interaction, the more traditional D1S [3] interaction and the more modern D1M force [4], which produces a reasonable neutron matter equation of state, and an old finite-range effective interaction constructed to reproduce at best the ^{4}He binding energy, the B1 interaction of Brink and Boeker [5].

The binding energies and the proton and neutron separation energies obtained by using the three different interactions are given in Table I. The experimental values have been taken from the compilation of Ref. [6]. The performances of the HF theory in the description of the ^{4}He ground state properties are quite unsatisfactory. The values of the binding energies generated by the two Gogny interactions are too large with respect to the experimental value. By construction, the B1 interaction makes a better job in this case. The situation is reversed when the proton and neutron separation energies are considered. In this case, the two Gogny interactions provide a better description than the B1 force.

We compare in Fig. 1 our charge distributions with the empirical one [7]. The discrepancies are remarkable especially if compared with the good description of the charge distributions of medium-heavy nuclei obtained by using the D1M and D1S interactions [1]. In the present case, the charge distributions are more extended than the experimental one. In effect, the values of the root mean squared radii of these charge distributions are 2.04 and 2.02 fm for the D1S and D1M interactions, respectively, and 1.92 fm for the B1 interaction, while the experimental value is 1.68 fm.

The results we have just presented confirm the inadequacy of the mean-field description of the ^{4}He ground state. In any case, we are interested in investigating the capacity of our approach to describe the excitation of the ^{4}He nucleus in the continuum.

As a first test of the CRPA results we have calculated the total photoabsorption cross section. We compare in Fig. 2 our results with the available experimental data [8–10], We have obtained the total cross section by summing the contribution of the 1^- and of the 2^+ excitations, this last one contributes to the total cross section only for about the 2%. Panels (a), (b) and (c) show the results obtained with the D1S, D1M and B1 interactions, respectively. With the dashed lines we show the results of the Independent Particle Model (IPM) calculation, i.e. those obtained by switching off the residual interaction in the RPA calculation. The solid lines show the CRPA results.

The results of Fig. 2 indicate that the behaviour of the experimental data is reasonably well described by the CRPA calculations, while the IPM results are clearly off the data. The performances of the results obtained with the D1M interaction are slightly better than those obtained with the D1S and B1 interaction. The two Gogny forces are able to reproduce the position of the peak, but this is not the case for the B1 interaction.

In Fig. 3 we compare our CRPA results obtained with the D1S (dotted curve), D1M (solid curve) and B1 (dashed-dotted curve) interactions with those of the microscopic calculation of Refs. [11] (dashed curve) based on the LIT technique. The agreement between our results and those of the microscopic calculation is remarkable. However, there are some differences which is worth to point out. The results of our calculations are higher in the peak and drop more quickly in the high energy tails. Even though the experimental situation is still quite controversial, the microscopic calculations give a better description of the data.

We used our computational scheme to calculate the quasi-elastic electron scattering responses. We have done calculations with all the three interactions mentioned before. However, since the results are rather similar, we present in Fig. 4 only those results we have obtained with the D1M interaction.

The calculations of the quasi-elastic responses have been done by summing the contribution of all the electric and magnetic multipole excitations up to numerical convergence was reached. This has been achieved by considering multipole excitations up to angular momentum $J = 6$ for the results at momentum transfer value $q = 200$ MeV/c, and up to $J = 8$ for $q = 500$ MeV/c. In our calculations we have considered only one-body electromagnetic currents.

In Fig. 4 the results of the CRPA calculations are indicated by the full lines, while with the dashed-dotted curves we show the IPM results. We have performed also calculations were the FSI has been totally switched off, that is, we have calculated the responses in IPM and we have substituted the mean-field wave functions of the emitted nucleon with plane waves. We have indicated as Plane Wave Impulse Approximation (PWIA) these results and we present them by using dotted lines. The dashed lines indicate the LIT results of Refs. [12–14]. The data for q=200 MeV/c are those of Ref. [15], while for the other values of the momentum transfer the black squares indicate the data of Ref. [16] and the white circles those of Ref. [17].

We observe first that the agreement between the CRPA results and the experimental data is quite good for all the values of the momentum transfer considered in the case of the longitudinal responses (left panels). This confirms the results of the photoabsorption cross section. In the case of the transverse response, our calculations slightly underestimate the data.

A second point is that CRPA effects become smaller with increasing value of the momentum transfer in the longitudinal response. This can be seen by comparing the CRPA results with those of the IPM. The full and dashed-dotted lines are quite different for 200 and 300 MeV/c, but they become closer at 400 MeV/c, and almost overlap at 500 MeV/c. Transverse responses are more sensitive to the presence of CRPA correlations. The differences with the IPM results grow slightly with the momentum transfer. On the other hand, the comparison with the PWIA results, the dotted lines, indicates that the mean field is taking into account a large part of FSI for all the momentum transfer values considered. It is interesting to remark again the good agreement between our CRPA results and those obtained with the fully microscopic calculations done with the LIT technique, shown by dashed lines.

While the HF theory gives a poor description of the ^{4}He ground state, the self-consistent CRPA theory describes well the excitation of the continuum, for both photoabsorption and quasi-elastic inclusive electron scattering data. We may say that our CRPA calculations are able to describe well the FSI between the emitted nucleon and the remaining nucleus. This good description of the FSI is obtained for a wide range of values of the momentum transfer.

It is surprising that the performances of the CRPA are superior in ^{4}He than in medium-heavy nuclei, where the theory is supposed to be tailored. In medium-heavy nuclei a spreading width should be added to have reasonable description of the excitation data in the continuum. As it is shown in Ref. [1], the difficulties of the CRPA in describing the responses of medium-heavy nuclei are due to the fact that excitations more complex than one-particle one-hole are not considered. The effects of these excitations are almost absent in ^{4}He, and for this reason the CRPA works very well in this case.

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	binding energy	separation energies protons	separation energies neutrons
D1S	30.28	19.39	20.09
D1M	29.54	18.25	18.96
B1	28.48	26.00	26.00
exp	28.29	19.81	20.58

Table I: Binding energies and proton and neutron separation energies, in MeV, obtained for the three different interactions considered in this work. The experimental values are taken from Ref. [6].

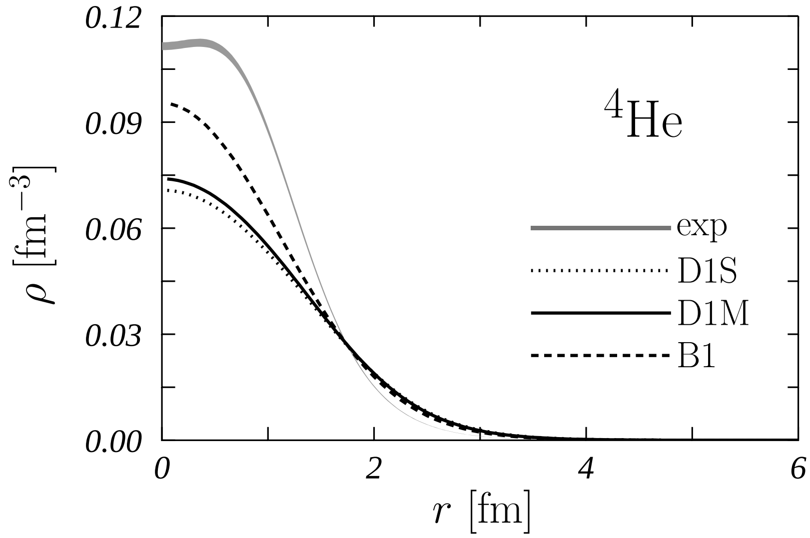

Figure 1: Charge density distributions calculated with the D1S (dotted line) and D1M (solid line) parameterizations of the Gogny interaction and with the B1 interaction (dashed line) compared to the empirical density taken from Ref. [7] (gray curve).

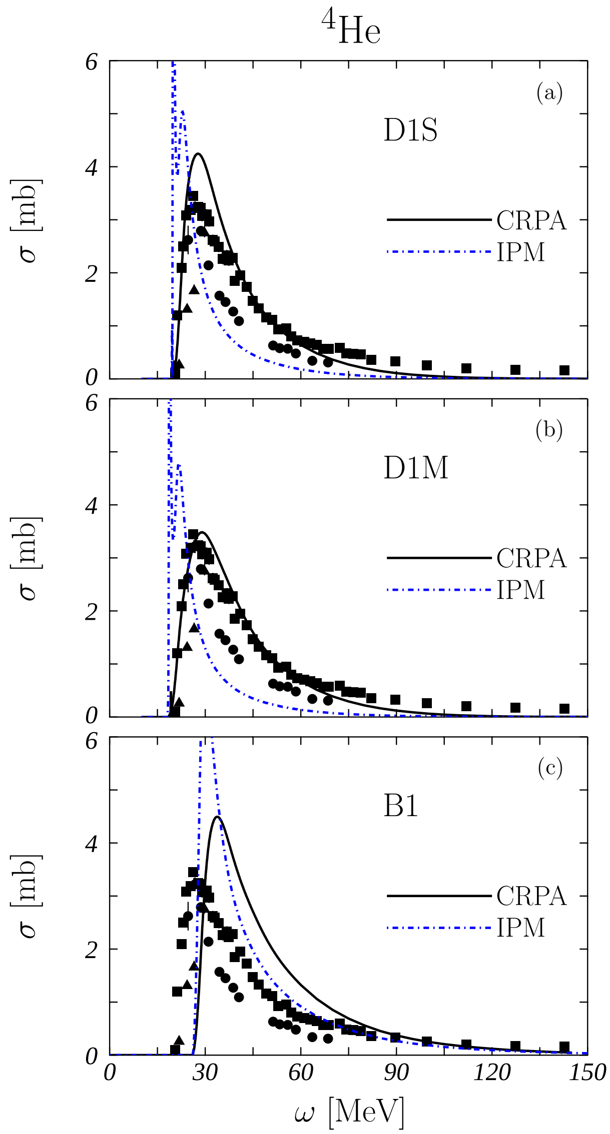

Figure 2: (color on line). Total photoabsorption cross sections obtained with the three interactions used in this work. The full lines show the results of the self-consistent CRPA calculations and the, blue, dashed lines show the IPM results based on the HF calculations done with the various interactions. The experimental data are from Refs. [8], squares, [9], triangles, and [10], circles.

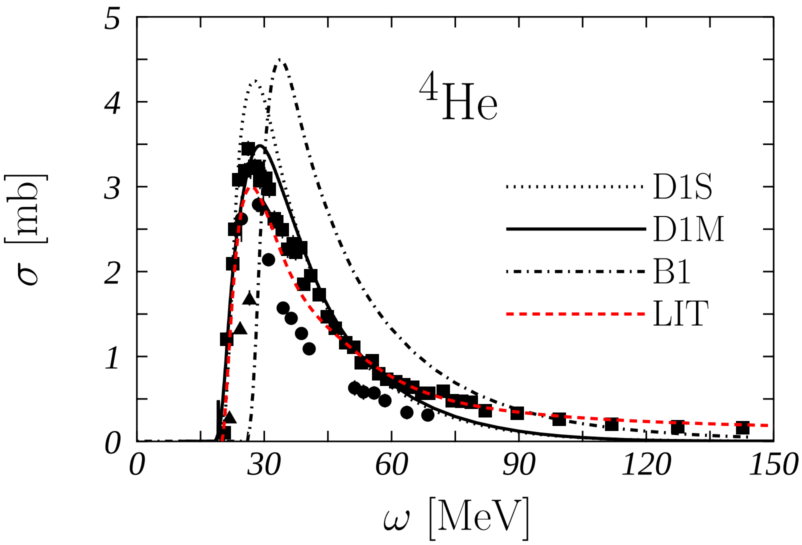

Figure 3: (color on line). Comparison of the total photoabsorption cross sections obtained in the self-consistent CRPA calculations with the LIT results of Ref. [11]. The experimental data are from Refs. [8–10].

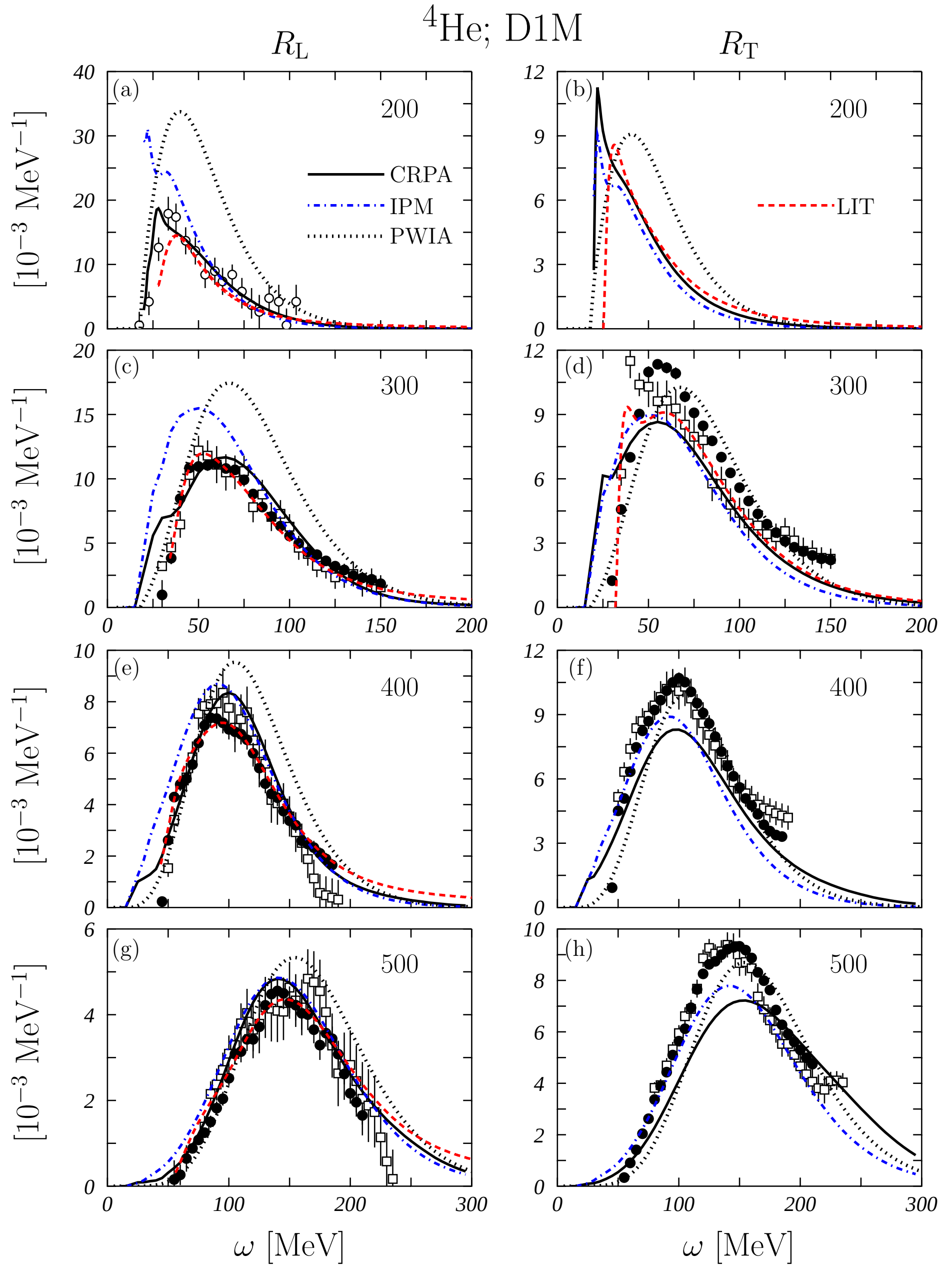

Figure 4: (color on line). Comparison of the longitudinal (left panels) and transverse (right panels) quasi-elastic electron scattering responses obtained with the D1M interaction within the CRPA (solid curves), IPM (dashed-dotted curves) and PWIA (dotted curves) frameworks, with the LIT microscopic results of Ref. [12–14] (red dashed curves). The labels in the panels indicate the values of the momentum transfer in MeV/c. The experimental data for momentum transfer of 200 MeV/c (open circles) are taken from Ref. [15] while those shown in the other panels are taken from Ref. [16] (open squares) and from Ref. [17] (solid circles).