Pygmy and giant electric dipole responses of medium-heavy nuclei

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The pygmy dipole resonance (PDR) is an electric dipole excitation located at energies close to the nucleon emission threshold, and called pygmy since its strength is much smaller than that of the well studied giant dipole resonance (GDR).

In addition to the genuine nuclear structure interest for this new type of resonance, there are motivations to study the PDR related to nuclear astrophysics. The presence of PDR in neutron rich nuclei would increase the rate of nucleosynthesis r-process by orders of magnitude, and, furthermore, from the PDR structure is possible to infer information about neutron matter at out of equilibrium densities, useful to understand supernovae explosions.

From the nuclear structure point of view, there are many aspects of this excitation to be clarified. For example, if the PDRs are present in all the medium and heavy nuclei or if this type of excitation is peculiar of neutron rich nuclei only. Another question to be answered is whether these resonances are the low energy tail of the GDR or if they represent a different type of excitation.

Recently [1] we have studied the electric dipole excitation of various spherical nuclei in different regions of the nuclear chart by using a self-consistent Hartree-Fock (HF) plus Random Phase Approximation (RPA) approach. The first step of our procedure consists in constructing the single particle (s.p.) basis by solving the HF equations. In the second step, the wave functions obtained in the HF calculation are used to solve the RPA equations by considering, without approximations, the fact that the main part of the s.p. wave functions above the Fermi surface lies in the continuum. We have labeled continuum RPA (CRPA) the results obtained in these calculations. Unfortunately, CRPA calculations have two drawbacks. A first one is that the CRPA equations are formulated with very involute expressions which make very difficult to disentangle the role of the various ingredients of the calculations, for example the relevance of specific particle-hole (p-h) excitations. The second problem is that the calculations are numerically very involved and, for large nuclei our technique suffers of numerical instability. For these reasons, together with the CRPA calculations, we carried out RPA calculations where only a discrete set of s.p. wave functions is used. We call discrete RPA (DRPA) this last type of calculations. The discrete configuration space is obtained in the HF calculation when the iterative procedure has reached the minimum value of the binding energy. This calculation is done by assuming that the system is confined in a spherical box with infinite walls. Our calculations have been carried out by using two different parametrizations of the finite-range Gogny interaction. Since the results are very similar we discuss those obtained with the D1M [2] force.

As typical example of the results we have obtained, we show in Fig. 1 the total photoabsorption cross sections for the oxygen isotopes we have selected. The full lines indicate the results of the CRPA calculations and the vertical bars those of the DRPA calculations. In the latter results we have indicated with red bars located at $\omega_{\rm PDR}$ and $\omega_{\rm GDR}$ the states we have selected to be representative of the pygmy and giant resonance regions, respectively. The vertical dotted lines indicate the energy $\omega_{\rm sep}$ chosen to separate the pygmy and giant resonance regions. In ^{16}O the results of our calculations are compared with the experimental data of Ref. [3]. In the panel (b), showing the ^{22}O results, the gray area indicates the empirical PDR region found in Ref. [4].

The figure shows the level of the agreement between discrete and continuum RPA results and the capacity of these calculations to reproduce the experimentally detected position of the peak of the GDR. The PDR appears at lower energies, with respect to that of the peak of the GDR. The size of the PDR cross section is much smaller than that of the GDR, and increases with increasing neutron number. In reality, in ^{16}O where $N = Z$, the PDR is absent.

We have studied in more detail the structure of the states identified with the red bars, and we found that

a) PDRs are less collective than GDRs,

b) the coherence of the excitation is larger in

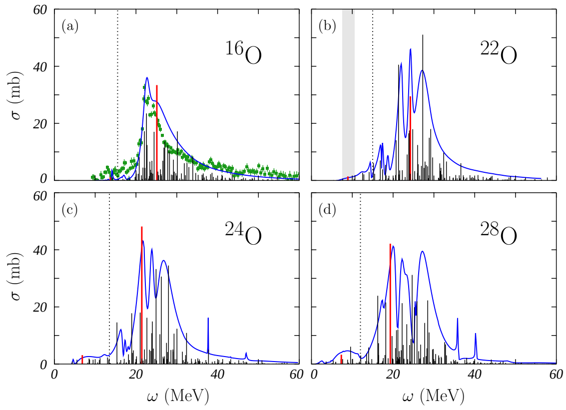

Figure 1. Total photoabsorption cross sections calculated with CRPA (continuous blue lines), and DRPA (solid vertical lines). The dotted vertical lines indicate the energies separating the regions of the pygmy and giant strengths. The meaning of the red lines is explained in the text. The experimental data in the ^{16}O panel have been taken from Ref. [3]. The gray region in the ^{22}O panel indicates the empirical PDR region found in Ref. [4].

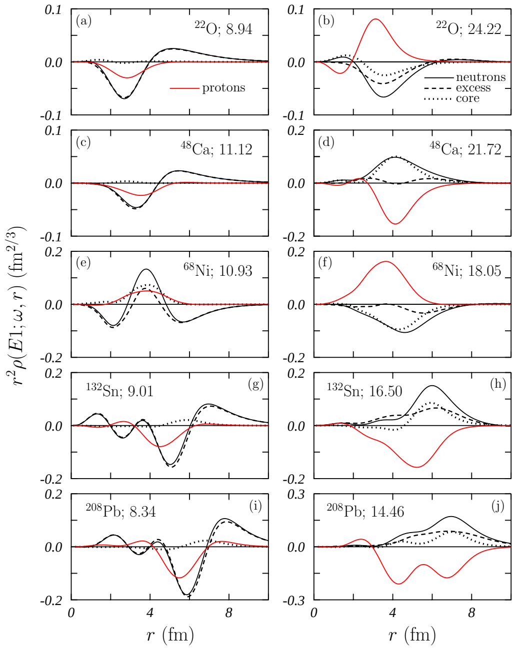

Figure 2. Transition densities for protons, full red lines, and neutrons, full black lines. The black dotted curves show the contributions of the neutrons of the core, while those of the neutrons in excess are shown by the black dashed lines. The number in each panel indicates the excitation energy $\omega_{\rm PDR}$ (left panels) or $\omega_{\rm GDR}$ (right panels), in MeV, of the specific states studied.

GDR than in PDR,
c) the contribution of the neutron excitations is much larger in PDRs than in GDRs.
This study has been extended to Ca, Ni, Zr, Sn and Pb isotopes for a global search of 18 different nuclei, and in all the cases investigated we found the characteristics above mentioned.

We have studied the proton and neutron transition densities in the various states characteristic of pygmy and giant dipole resonance. The transition densities for a selected set of isotopes are shown in Fig. 2. The red lines indicate the proton densities, the full black lines the neutron densities. We observe that for the PDR states, whose transitions are shown in the panels to the left side of the figure, proton and neutron densities are always in phase. In heavier nuclei, such as ^{132}Sn and ^{208}Pb, when the number of nodes of the two transitions is different, their behaviors are coherent on the surface. We observe opposite behaviour in the GDR states, whose transitions are shown in the panels to the right side of the figure. In these cases the proton and neutron transitions are always out of phase.

We have further analyzed the neutron transition densities by separating the contribution of the neutrons of the core from that of neutron in excess. The transition densities of the neutrons of the core, i.e. those which occupy all the s.p. levels with the same quantum numbers of those occupied by the protons, but the isospin third components, are shown by the black dotted lines. The dashed lines indicate the contribution of the other neutrons, those in excess. The neutron transition densities of the PDR are dominated by the neutron in excess, while in those of the GDR the contribution of the neutrons in excess is comparable to that of the neutrons of the core.

Our investigation indicates that
a) the PDR is present in nuclei with neutrons in excess which dominate its excitation,
b) in the PDR proton and neutron excitations are in phase, a feature tipycal of isoscalar character, while in GDR they are out of phase, tipycal of isovector character,
c) the PDR is much less collective than the GDR, therefore its presence seems to be more related to the shell structure of the various isotopes than to a real collective nuclear motion.

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