Evolution of the pygmy dipole resonance in nuclei with neutron excess

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There are experimental evidences that in nuclei with neutron excess, in addition to the well known Giant Dipole Resonance (GDR), a new type of dipole resonance appears [1–3]. Since this resonance has smaller strength than that of the GDR and exhausts only a small fraction of the energy weighted sum rule is called Pygmy Dipole Resonance (PDR). The PDR appears at lower energy with respect to the GDR but it is not its low-energy tail, since it has an isoscalar (IS) character and is dominated by neutron excitations, while the GDR has isovector (IV) character with almost equal contribution of proton and neutron excitations.

We have studied how the PDR rises when neutrons become more numerous than protons in various nuclei belonging to different regions of the nuclear isotope table, from oxygen to lead [4]. The nuclear model adopted in our calculation is the traditional phenomenological discrete Random Phase Approximation (RPA). In our study we have defined some indeces which enable us to distinguish PDR and GDR. First, for a given excited state, we have calculated the relative contribution of protons and neutrons to the relation of normalization for RPA amplitudes

$$\sum_{ph=1,N_{ph}} \left[X^2_{ph}(\omega) - Y^2_{ph}(\omega)\right] = 1 \ . \tag{1}$$

These contributions, indicated as N(π) and N(ν) in the following, have been obtained from Eq. (1) by summing over ph pairs for protons, or, respectively, neutrons only. Second, we have defined an index to measure the degree of collectivity of a specific excited state. In the RPA framework, in the ideal collective state all the $X^2_{ph}(\omega) - Y^2_{ph}(\omega)$ terms of Eq. (1) would contribute $1/N_{ph}$. From these considerations we define a collectivity index as:

$$\mathcal{D} = \frac{N^*}{N_{ph}} \tag{2}$$

where N* is the number of states with $[X^2_{ph}(\omega) - Y^2_{ph}(\omega))] \geq 1/N_{ph}$. Finally, we have characterized each state by its B(E1) value and by the ratio $\mathcal{R}$ between the B(E1) value of the specific state and the total B(E1) strength.

We have tested the validity of these investigation tools in the ^{208}Pb nucleus where we have an experimental evidence of the PDR.

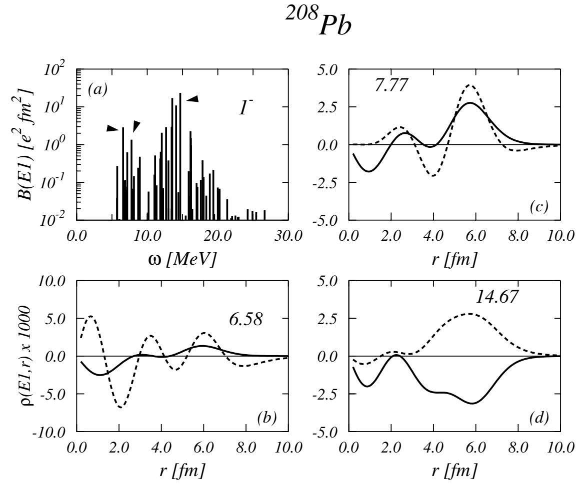

Figure 1. Dipole solution for the ^{208}Pb nucleus. In panel (a) the B(E1) values as a function of the excitation energy are shown. In the other panels, the protons, full lines, and neutrons, dashed lines, transition densities (in fm$^{1/3}$ units) for the states indicated by the arrows, whose excitation energy is given in panel, are shown.

The Fig. 1 panel (a) clearly shows the GDR region which has its maximum at 14.67 MeV and in addition a set of peaks at lower energy. The energy values of the first state is 6.58 MeV. For this state we found $\mathcal{D}$=0.049 and N* =10, N(π) =0.026 and N(ν) =0.974. The characteristics of the other state are ω=7.77 MeV, $\mathcal{D}$=0.049, N* =10, N(π) =0.238 and N(ν) =0.762. For both the states, the proton and neutron transition densities show the *in phase* structure, typical of the IS excitation (panels (b) and (c)). These features are rather different from those of the states forming the GDR. As typical example, we discuss here only the state at 14.67 MeV. For this state we obtain $\mathcal{D}$=0.073, and N* =15, indicating a slightly higher collectivity with respect to that of the PDR and N(π) =0.682 and N(ν) =0.318, values rather similar to those of the 7.77 MeV. The transition densities show an *out of phase* behaviour (panel (d)) which indicates the IV nature of the excitation. Photon scattering experiments on ^{208}Pb have identified, in addition to the well known GDR peaked at 13.5 MeV [5], a small dipole resonance around 7.35 MeV which has been interpreted as PDR [2]. In our calculations we found a large resonance above 13.5 MeV which contributes for about the 70% of the total dipole strength, and a tiny resonance with centroid energy at about 7.2 MeV which carries about the 5% of the total strength.

We have applied our model to oxygen isotopes where we observed an increase of the E1 strength at low energies but these states did not satisfy the criteria we have designed to identify the PDR: they are a fragmentation of the GDR. This result disagrees with the findings of Ref. [6], where the calculations have been done in a fully self-consistent Hartree-Fock plus RPA approach with Skyrme-like interactions. The problem is still open.

We found instead positive results for all the other isotope chains we have investigated, for example for calcium chain. These results are shown in Figs. 2 and 3.

We observe presence of E1 strength at energies lower than those of the GDR. The states at the peak of the GDR show a high degree of collectivity and they are composed by almost an equal weight of protons and neutrons p-h pairs. The structure of the lower energy states is different. There is a certain degree of collectivity, but it is smaller than for the states just described. In addition it is evident that these states are dominated by neutron p-h excitations. The different structure of these two type of states is emphasized by the transition densities, which are shown in Fig. 3.

The low energy states show an *in phase* behaviour, typical of the *IS* transition, while the higher energy states have the typical *IV out of phase* behaviour. All these remarks indicate that the low energy states are not produced by the fragmentation of the GDR, as it happens in the oxygen isotopes, but they are a new type of excitation. Our calculation for the ^{48}Ca produces strength around 8.5 MeV in agreement with the experimental findings of Ref. [3] and with the results of Ref. [7].

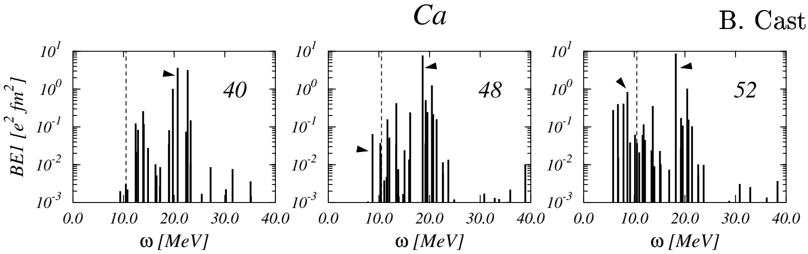

Figure 2. B(E1) distributions for the calcium isotopes we have studied. The numbers in the panels indicate the mass number of the isotope. The units on the y scale are e^2fm^2.

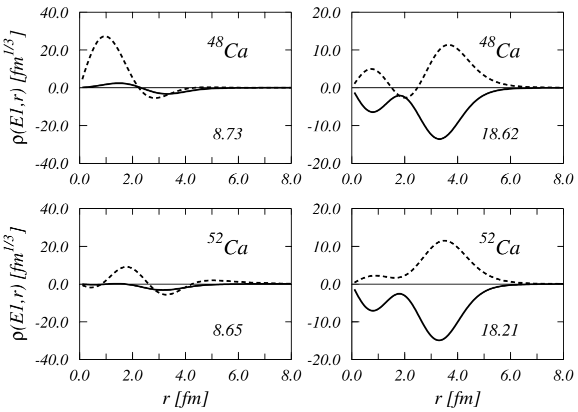

Figure 3. Transition densities, multiplied by a factor 1000, of some 1^- states for various calcium isotopes. The numbers indicate the excitation energy in MeV.

Also the calculations in tin isotopes indicate low energy strength and confirm the experimental finding of Ref. [1].

In the study of the zirconium isotopes we have found a handbook example of the role played by the neutrons in excess around 8.5 MeV.

In conlusion, our calculations indicate that in medium heavy nuclei with neutron excess, a new type of dipole resonance appears, with the characteristics we attribute to the PDR. The presence of this resonance becomes more important with the increase of the neutron number.

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