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Studying the Pygmy Dipole Resonances with isoscalar and isovector probes

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Abstract. We present a short review of the properties of the so-called Pygmy Dipole Resonance (PDR) which can be studied with both isovector and isoscalar probes. This is possible due to the particular property of this new mode where the isoscalar and isovector characters are mixed. The use of both probes unveils new features which otherwise will remain hidden. It is of paramount importance the use of a proper description of these modes, taking into account their main features, in order to have a good description of the experimental data.

1. Introduction

The Pygmy Dipole Resonances are dipole states located at much lower energy than the Giant Dipole Resonances (GDR). They were called pygmy because their strength is much smaller than the GDR one and they exhaust a small fraction of the Energy Weighted Sum Rule. They are present in all nuclei with neutron excess and therefore they are more evident in nuclei lying far from the stability line. The low-lying dipole states we are dealing with here are then different from the ones present in nuclei with neutron halo where the peak at low energy of the dipole state is due to the very low binding energy of the last neutrons. In this case, in fact, the dipole states at low energy is generated by the long tail of the less bound neutrons wave functions. In nuclei with neutron excess the low-lying dipole states are instead strictly related to a kind of neutron skin and they are produced, in a Random Phase Approximation (RPA) approach, by many particle-hole (p-h) configurations. These configurations do not contribute coherently though and therefore they cannot be considered to form a collective mode. These modes have been studied at length experimentally as well as theoretically and an almost complete description of their properties can be found in many review papers that have been written in the last years[1, 2, 3, 4, 5]. Although this mode is interesting by itself, the interest to study it extensively comes also for its relevance in other field of physics. Since it is generated by the neutron excess it must have a connection with the symmetry energy parameter of the Equation Of State[6, 7]. In addition, the location of this strength in proximity of the neutron separation threshold has an impact on neutron capture rates in astrophysical processes. In the r-process the neutron capture competes with gamma decay, which is of E1 type, and originates at excitation energy around the neutron binding energy. The amount of E1 strength and its energy position has therefore a consequence in the astrophysical r-process, that proceeds via neutron rich nuclei, and it is expected to be enhanced by the presence of this low-lying E1 peak[8, 9, 10].

2. Studying the Pygmy Dipole Resonance: Theory

The theoretical studies of the PDR can be classified in two different approaches: macroscopic and microscopic models. Among the first ones we can quote a tentative theoretical description given within an approach like the incompressible three fluid model[11] (proton, neutron of the core, and neutron excess) build upon the same spirit of the well known Steinwedel-Jensen model. The low-lying dipole state arises in a natural way but the calculated PDR strength was too weak. A similar version of the model considered only two incompressible fluids[12], namely core and neutron excess. Similar results have been found when the well known Goldhaber-Teller prescription was used[13] and it was found that the ratio of the PDR to the GDR sum rule was close to the one obtained before.

However, a better description of this mode is obtained within microscopic many-body models which have been very successfully used in the description of the collective excitations. Here there is a list of the main models exploited in the description of the PDR: the Hartree-Fock plus Random Phase Approximation (RPA) with Skyrme interactions; the Hartree-Fock-Bogoliubov (HFB) theory plus the Quasi-Particle RPA (QRPA) with Skyrme or Gogny effective interactions; the relativistic RPA (RRPA) and a relativistic quasi-particle RPA (RQRPA); the so-called Quasi-particle Phonon Model (QPM) and the Relativistic Quasi-particle Time Blocking Approximation (RQTBA), in the last two approaches the coupling to up to three phonons are taken into account. More details can be found in the review paper of refs. [1] and [5].

Some of the features of the PDR have been found by almost all the quoted approaches implying that these features can be thought as fundamental characteristic of the mode. In Fig. 1 there are shown the electromagnetic (panel a) and isoscalar (panel b) dipole strength distributions for the ^{68}Ni isotope obtained with a discrete HF plus RPA with a SGII Skyrme interaction[14, 15]. The electromagnetic dipole response is generated by the following isovector operator:

$$O^{(EM)}_{1M} = \frac{eN}{A}\sum_{p=1}^{Z} r_p Y_{1M}(\hat{r}_p) - \frac{eZ}{A}\sum_{n=1}^{N} r_n Y_{1M}(\hat{r}_n)\,. \tag{1}$$

and an isoscalar operator

$$O^{(IS)}_{1M} = \sum_{i=1}^{A}(r_1^3 - \frac{5}{3} < r^2 > r_i) Y_{1M}(\hat{r}_i)\,. \tag{2}$$

This is a second order dipole transition operator which generates a $3\hbar\omega$ dipole nuclear transition with the modification introduced to eliminate the spurious dipole state. In Fig. 1 the curves are generated by a smoothing procedure using a Lorentzian with a 1 MeV width.

The isovector response in panel a) of Fig. 1 is dominated by the very well known peak of the IVGDR at around 15 MeV while in the isoscalar one, in panel b), the ISGDR at around 30 MeV has a large width. The peak at about 10 MeV in the upper panel corresponds to the PDR with a very prominent peak in the isoscalar strength part. These three different peaks at different excitation energies correspond to different excitation modes. This can be better evidenced by giving a look to their transition densities. In Fig. 2 we plot the proton (black dashed line), neutron (red, dot-dashed line), isoscalar (blue solid line) and isovector (green solid line) transition densities for the three states of interest. In the middle panel b) the proton and neutron transition densities show an out of phase oscillation typical of the ISGDR giving rise to a strong isovector transition density (panel e). The curves shown in panel c) of Fig. 2

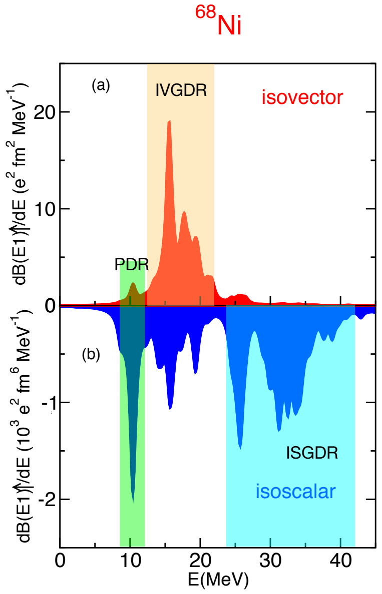

Figure 1. RPA isovector (a) and isoscalar (b) response for the ^{68}Ni isotope. The shaded areas show the three different excitation modes, as indicated in the figure.

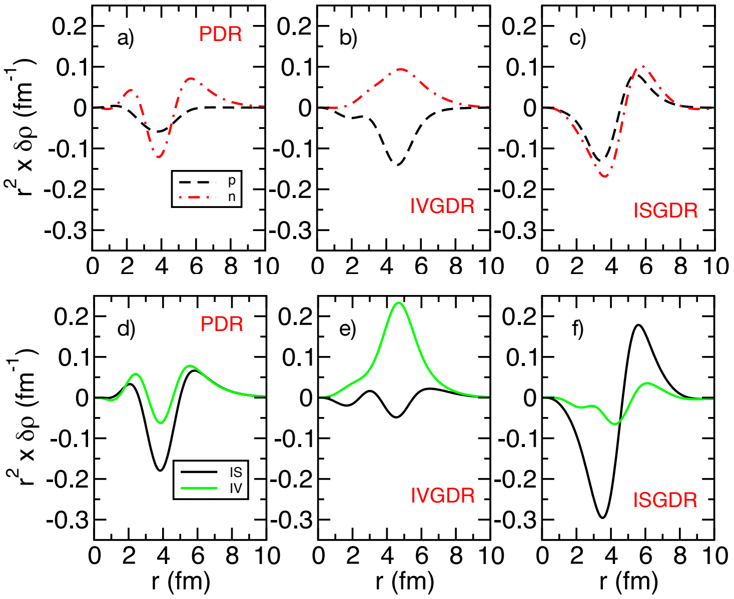

Figure 2. Transition densities for the low-lying dipole state (PDR) (a,d), for the IVGDR (b,e) and for the ISGDR (c,f) for the ^{68}Ni isotope. We show the proton, neutron, isoscalar and isovector components (as indicated in the legend).

indicate that proton and neutron transition densities are in phase producing a strong isoscalar transition density for the ISGDR (panel f) with a node at the interior of the nucleus, typical of a compressional mode. The transition densities of panel a) of Fig. 2 show a different and novel behaviour: the ones for neutrons and protons are in phase inside the nucleus and at the surface only the neutron contributions survive. This implies that the isoscalar and isovector transition densities (panel d) have the same intensity at the nuclear surface. These features were found in all the many-body theory calculations cited above and therefore can be considered as the theoretical definition of the PDR. The strong mixing of isoscalar and isovector components allows the population of these states by means of both isoscalar and isovector probes.

3. Studying the Pygmy Dipole Resonance: Experiment

From the experimental point of view, the low-lying dipole states have been extensively studied with several isovector and isoscalar probes. Among the isovector ones there are the pioneering works on ^{132}Sn[16] and later on ^{68}Ni[17] at GSI with relativistic Coulomb excitation. The most extensive work on stable nuclei with neutron excess have been performed with the (γ, γ') reaction, or Nuclear Resonance Fluorescence (NRT) technique, at Darmstadt University. More recently a Coulomb excitation by (p,p') reaction at zero degrees have been employed at the Research Center for Nuclear Physics, Osaka University, and was then also widely used at iThemba LABS. Proton beams in the energy interval 300-400 MeV are used at RCNP while at iThemba LABS beams have an energy of 200 MeV.

Measurements using inelastic scattering and gamma-decay have been extensively used in recent years to study the excitation of dipole states via nuclear interaction and to learn on their isospin character. The most common isoscalar probe being the $(\alpha, \alpha'\gamma)$ which have been widely used at KVI laboratory, Groningen. There have been a considerable number of experiments done at the INFN Legnaro laboratory where an ^{17}O projectile at a beam energy of 20 MeV/u has been employed in a (^{17}O, ^{17}O' γ) reaction. A much more detailed descriptions of these experimental method can be found in the review papers quoted above.

For the low-lying dipole states below the neutron emission threshold, the use of both isoscalar and isovector probes has unveiled a distinctive feature of this mode. The dipole states split in two different distinct parts: one at lower energy, whose states have a strong isospin mixing probed by the fact that they can be populated by both isoscalar and isovector probes, and one at higher energy with predominant isovector character.

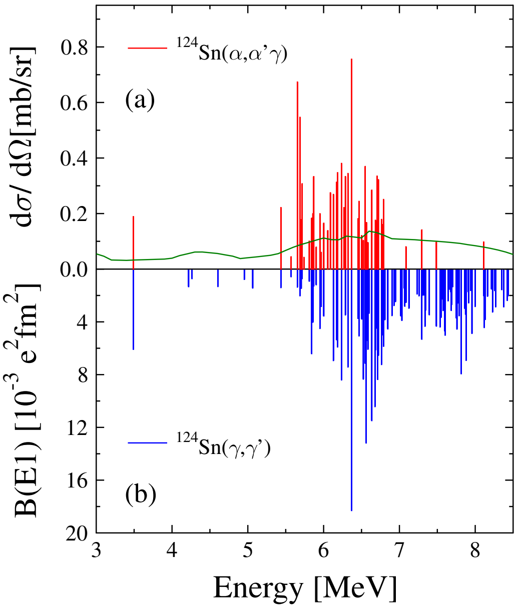

Figure 3. In panel a) it is shown the singles cross section for the excitation of the dipole states in ^{124}Sn obtained in the $(\alpha, \alpha'\gamma)$ coincidence experiment. In panel b) the dipole strength distribution measured with the (γ, γ') reaction. (adapted from ref. [18]

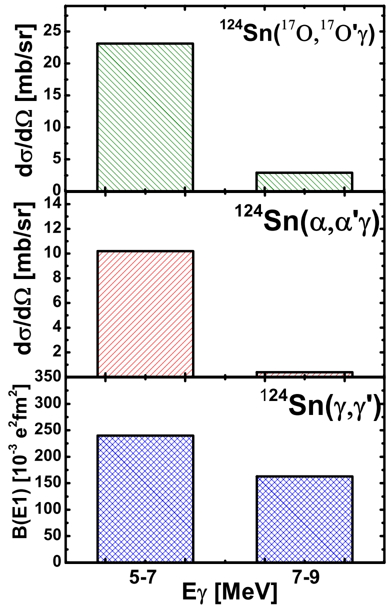

Figure 4. Differential cross sections measured in the ^{124}Sn(^{17}O, ^{17}O' γ) experiment, integrated in two regions 5-7 and 7-9 MeV (top panel). For comparison, the corresponding strengths measured in α-scattering (middle panel) and photon-scattering (bottom panel), shown in Fig. 3, are shown. Adapted from ref. [19].

Experiments on several nuclei with neutron excess have been performed showing this splitting of the PDR. As an example, in Fig. 3, the results for (γ, γ') (panel b)) and for $(\alpha, \alpha'\gamma)$ (panel a)) coincidence reactions are presented. The comparison between the two results obtained with the two different probes shows clearly the different behaviour of the states belonging to the two energy region between 5-7 and 7-9 MeV. These different responses are evidenced in Fig. 4 where the sum over the two intervals is performed. Moreover, in the upper panel the results obtained with a different isoscalar probe, namely with the ^{124}Sn(^{17}O, ^{17}O' γ) experiment, confirm the splitting of the PDR. It will be interesting to investigate whether this feature, which has been observed in all the stable nuclei with neutron excess studied until now, it is also present for the PDR states observed above the neutron emission threshold and for nuclei far from the stability line. Recently, an experiment performed at LNS-INFN Catania has been devoted to explore this aspect for the case of the nucleus ^{68}Ni, far from the stability line, impinging on a ^{12}C target at an incident energy of 28 MeV/A[20]. The aim was also to demonstrate experimentally that also the dipole states lying just above the neutron emission threshold have the characteristic isospin mixing of the dipole states lying below the threshold. The experiment devoted to investigate the presence of an isoscalar component in the pygmy region for the nucleus ^{68}Ni was performed at the fragmentation facility of LNS-INFN with the set up CHIMERA plus FARCOS to measure the scattered particles and the emitted gamma-rays whose angular distribution shows the behaviour of the E1 transitions[20].

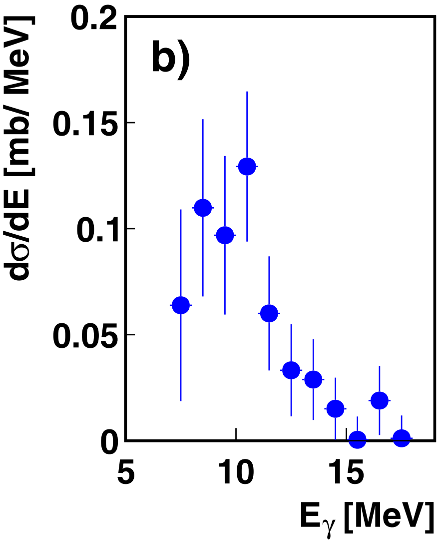

Figure 5. Energy γ spectrum for the reaction (^{68}Ni, ^{68}Ni' γ) on a ^{12}C target at 28 MeV/A obtained with the CHIMERA plus FARCOS set up at LNS-INFN Catania. Adapted from [20].

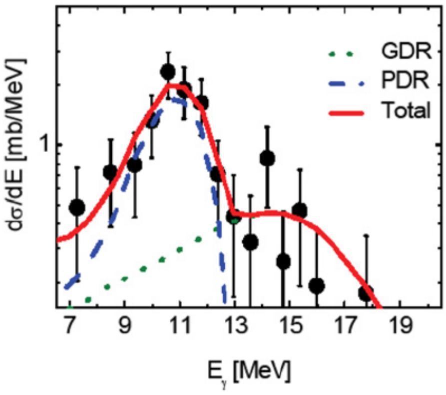

Figure 6. Energy γ spectrum for the reaction (^{68}Ni, ^{68}Ni' γ) on an Au target, at a bombarding energy of 600 MeV/A, performed at the Laboratory GSI using the RISING set up. The experimental setup was designed to detect scattered particles at 0 degrees for Coulomb excitation selection. Adapted from [17].

The energy γ spectrum for the reaction (^{68}Ni, ^{68}Ni' γ) on a ^{12}C target at 28 MeV/A obtained with the CHIMERA plus FARCOS set up at LNS-INFN Catania is shown in Fig. 5. This has to be compared with the results of a previous experiment, Fig. 6, where the same reaction (^{68}Ni, ^{68}Ni' γ) on an AU target and at much higher bombarding energy of 600 MeV/A was performed at the GSI with the RISING set up. The almost one order of magnitude difference between the two cross sections is probably caused by the different reactions regimes. Within the small statistics and the relatively scarce energy resolution of the two measurements this comparison seems to indicate that the outcome of the excitation process due to the two isoscalar and isovector probes is similar along the PDR energy region. Therefore the isospin splitting seems not to be observed at the energy above the neutron emission threshold; however more precise measurements are necessary to prove this observation. The splitting of the PDR states is still not very well understood and further works have therefore to be dedicated to this study.

4. Summary

We have reviewed the main features of the so-called Pygmy Dipole Resonances from both the experimental and theoretical point of view. The main characteristic is the isotopic mixing shown by the experimental and theoretical investigations where both isoscalar and isovector probes can excite these low-lying states. The use of both probes on the same nucleus with neutron excess has unveiled a new feature which is still not very well understood, the so-called PDR splitting.

While this new characteristic is well established for the low-lying dipole states below the neutron emission threshold, for the dipole states lying above this threshold the results coming from a recent experiment seems to indicate that this is not the case. Further experimental as well as theoretical studies have to be devoted to this aspect.

4.1. Acknowledgments

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