Nuclear and Coulomb excitations of low-lying dipole states in exotic and stable nuclei

E G Lanza (1,2,*), A Vitturi (3,4), M V Andrés (5)

1 INFN Sezione di Catania, Catania, Italy
2 Dipartimento di Fisica e Astronomia, Università di Catania, Italy
3 Dipartimento di Fisica, Università di Padova, Italy
4 INFN Sezione di Padova, Padova, Italy
5 Departamento de FAMN, Facultad de Física, Sevilla, Spain

E-mail: (*)lanza@ct.infn.it

Abstract. Nuclei with a consistent neutron excess show the presence of dipole strength at low excitation energy. This strength, carrying few per cent of the isovector EWSR, has been often associated to the so called Pygmy Dipole Resonance (PDR). In this mode the isoscalar and isovector components are strongly mixed and therefore there is a possibility to study these low-lying dipole states by using both isoscalar and isovector probes. We show that valuable informations on the nature of the PDR can be obtained by excitation processes involving also the nuclear part of the interaction. The use of different bombarding energies, of different combinations of colliding nuclei involving different mixture of isoscalar/isovector components, together with the mandatory use of microscopically constructed formfactors, can provide the clue to reveal the characteristic features of these states. The relative population of the PDR with respect to the GDR may change by changing the parameters of the reactions. In particular, at low incident energy the excitation probability of the PDR state is sensibly higher than the GDR one. Our conclusion is that the best conditions to reveal the PDR can be achieved at relatively low incident energies (few tens of MeV per nucleon), where the interplay between the Coulomb and nuclear interactions plays a fundamental role in singling out these states.

1. Introduction

Approaching the neutron dripline a concentration of neutron density, partially decoupled from the core nucleons, develops in nuclei giving rise to the so called neutron skin. Evidence of new phenomena associated with these neutron rich nuclei has been accumulated in the past years[1]. Previous calculations[2] have shown that in the dipole strength distribution some strength appears at low energies when the number of neutrons increases. This strength is located well below the dipole giant resonance, carries few per cent of EWSR, it is present in many isotopes and it has been associated to the so called Pygmy Dipole Resonance (PDR). Such a low-lying dipole strength has been widely studied within several microscopic models[1]. More recent references are quoted in ref. [3] where part of the work reported here has already been presented. Apart from some details the different models coincide on the description of the main features of the PDR, in particular they all consistently agree on the strong isoscalar response of these states.

The experimental information has been obtained mainly by mean of the Coulomb excitation by various groups and can be roughly separated into two sectors. Relativistic energy Coulomb
excitation processes with heavy ion collisions have been performed at GSI on $^{132}$Sn[4] as well as on $^{68}$Ni[5]. The information obtained with this technics is above the neutron separation threshold. On the other hand, information on energy below the neutron separation threshold is obtained by the well-established method of nuclear resonance fluorescence (or real photon-scattering experiments) performed on semimagic nuclei at Darmstadt[6]. Recently, experiments with polarized protons (p,p') allowed to extract E1 transition strength on $^{208}$Pb by mean of the MDA (multipole decomposition analysis) below and above the neutron threshold[7].

The experimental information for these states comes therefore essentially from Coulomb excitation processes which provide information only on the multipole B(E\lambda) transition rates. If one wants to investigate further the nature of these states one has to envisage different reactions which can provide further information on wave functions and transition densities. Due to their strong isovector/isoscalar mixing some information can be obtained by resorting to reactions where the nuclear part of the interaction is also involved. The interplay between the nuclear and Coulomb interaction, as well as the isoscalar and isovector contributions, can be modified by choosing the projectile mass, charge, bombarding energy and scattering angle of the reaction in an appropriate way. These aspects have been partly investigated[8, 3] and here we present some new results embedded in a summary of the main results already obtained.

The use of a isoscalar probe to investigate the PDR has been applied to some semi-magical nuclei like the ones studied in ref. [9]. There, by means of (α,α'γ) coincidence method, a splitting of the low-lying dipole bump has been found out. Namely, it was shown that with this method only the low lying part of the bump is populated while the remnant is excited only by a (γ, γ') experiment. However, all theoretical calculations and analyses done until now within several microscopic many body models indicates that the PDR transition densities have a strong isoscalar contribution. Therefore, the interpretation of the two components is not clear and further investigations are in order. However, this indicates that comparing the results obtained by using different probes one can get valuable information on the structure underlying the peaks observed experimentally.

Although it is a controversial discussed issue, it seems there exist a strong relationship between the PDR strength and the neutron skin[10]. Since the neutron skin can be related to the energy symmetry parameter $a_4$ the knowledge of the PDR strength may have consequences on the investigations on neutron stars and r-process. For an exhaustive discussion on these aspects see Piekarewicz’s contribution to this conference[11].

2. The pygmy dipole strength

By using an Hartree-Fock plus a discrete RPA calculation with Skyrme interaction (in particular the SGII[12]) we are able to get the dipole states, their wave functions and the corresponding transition densities. In figure 1 the dipole strength distribution is reported for the nucleus $^{68}$Ni; the curves are generated by a smoothing procedure using a Lorentzian with a 1 MeV width. In the upper (lower) frame one can find the response to an isovector (isoscalar) probe. In particular they are generated by the action of the following two operators

$$O_{1m}^{IV} = \sum_{i=1}^{A} r_i Y_{1m}(\hat{r}_i) r_{i\tau}^\dagger; \quad O_{1m}^{IS} = \sum_{i=1}^{A} r_i^3 Y_{1m}(\hat{r}_i)$$

(1)

In the second case the spurious term due to the translational mode can be eliminated by adding to the operator the term $-r_i Y_{1m}(\hat{r}_i) 5 < r_2 > /3$ as shown in ref. [13]. The problem of the spurious state related with the center-of-mass motion has been explicitly discussed in ref. [14] (at page 3) and our conclusion was that the mixing of the spurious state with the other dipole states is small. Similar distributions for the nuclei $^{132}$Sn and $^{208}$Pb are shown in figures 2 and 3. In all the cases we note the presence of a small peak around or below 10 MeV in the isovector
distribution and a relative strong peak in the isoscalar distribution in correspondence of the same energy region.

The low lying peaks have all the same features and these can be put in evidence by looking to their transition densities. In figure 4 they are shown for the three nuclei under study: in the upper frames (a, b, c) there are the proton (dashed line) and neutron (solid line) transition densities; in the lower frames the corresponding isoscalar (dashed line) and isovector (solid line) ones. One can notice that, a apart for some small detail, they look very much the same: The neutron and proton transition densities are in phase inside the nucleus and at the surface only the neutron part survives. These features can be taken as a sort of theoretical definition of the PDR. At the interior the isoscalar part is much more pronounced that the isovector one and at the surface both of them have almost the same strength. The isovector parts have more nodes as we increase the nucleons number. This may be related to the different major shell of the nuclei and may be a first indication of the non collective character of these states.

Figure 1. RPA strength distributions for isovector (a) and isoscalar (b) response for $^{68}$Ni.
Figure 2. RPA strength distributions for isovector (a) and isoscalar (b) response for $^{132}$Sn.
Figure 3. RPA strength distributions for isovector (a) and isoscalar (b) response for $^{208}$Pb.
Figure 4. Transition densities for the three nuclei under study. In the upper parts (a, b, c) are shown the transition densities for the proton (dashed line) and neutron (solid line) components. In the lower frames (d, e, f) the isoscalar (dashed line) and isovector (solid line) transition densities are shown for the three nuclei.
Figure 5. Isovector (a, b) and isoscalar (c, d) partial contribution $b_{ph}(E1)$ (see eq. 2) for two dipole states at $E=7.98$ MeV (a, c) and $E=12.49$ MeV (b, d) for $^{208}$Pb, as function of the RPA p-h configurations (The order goes from the most to the less bound ones.). The bars corresponds to the individual $b_{ph}$ contributions while the continuous line is the cumulative sum of the contributions. The upper (lower) frames correspond to the response to an isovector (isoscalar) probe.

One way to see whether a state may considered collective is to look at its reduced transition probability \[14\], which can be written as:

$$B(E\lambda) = \left| \sum_{ph} b_{ph}(E\lambda) \right|^2 = \left| \sum_{ph} (X_{ph}^\nu - Y_{ph}^\nu) T_{ph}^\lambda \right|^2$$

(2)

where $T_{ph}^\lambda$ are the $2^\lambda$ multipole transition amplitudes associated with the elementary p-h configurations and the $X$ and $Y$ are the RPA amplitudes. In Figure 5 we plot the partial contributions $b_{ph}$ for two dipole states versus the order number (from the most bounded to the higher ones) of the p-h configurations used in the RPA calculations for two states of the $^{208}$Pb. The bars correspond to the individual values of the $b_{ph}$ while the continuous thin line is the cumulative sum of the contributions. The dashed lines divide the protons from the neutron configurations. The two figures on the left side (frames a and c) are for the low-lying dipole state while the ones on the right are for the state at 12.49 MeV which belongs to the GDR peak. In both cases the lower frames (c and d) correspond to the isoscalar response while the frame a) and b) show the isovector response. In all the four cases there are several p-h configurations participating to the formation of the $B(E1)$ but while for the isoscalar ones and the GDR isovector the contributions sum up coherently for the low lying isovector some of the contributions have opposite sign giving rise to a final value which is small. From our analysis, it emerges that the response of the PDR has a collective behaviour to an isoscalar probe while it is not collective for an isovector one. Similar results have been found also for the other two nuclei analyzed here and are very similar to that ones found by using a fully self-consistent relativistic RPA\[15\].
3. Semiclassical model of the excitation process

The reaction mechanism is described according to a semiclassical model (valid for grazing collisions) which assumes that nuclei move on classical trajectories, while the internal degrees of freedom are treated quantum mechanically (see for instance ref. [16] and references quoted therein). The Hamiltonian can be considered then as a sum of two Hamiltonians describing the projectile and the target. Each one of them is formed by two parts: one describing the internal properties and the other one responsible of the excitation process. This comes through the mean field of the other partner of the reaction. The Schrödinger equation is cast in a set of coupled equations for the probability amplitude of the states taken into consideration. Then the cross section for the excitation of each of the states is obtained by making an integration over the impact parameter once the the excitation probabilities are calculated. The calculation includes the states with a strong EWSR percentage among the RPA ones. Details can be found in ref. [16].

Table 1. Four dipole states for $^{68}$Ni. The energies of the states are displayed in the first column; in the next two columns the RPA isoscalar and isovector reduced transition probabilities are shown.

| Energy (MeV) | $B_{is}(E1)$ ($e^2$fm$^6$) | $B_{iv}(E1)$ ($e^2$fm$^2$) |
|--------------|-----------------------------|-----------------------------|
| 10.36        | 2324.7                      | 0.47                        |
| 15.45        | 6.6                         | 3.26                        |
| 15.63        | 997.6                       | 3.51                        |
| 17.80        | 2.8                         | 0.10                        |

The real part of the nuclear optical potential, which together with the Coulomb interaction determines the classical trajectory, is constructed with the double folding procedure[17]. The form factors are obtained by double folding the RPA transition densities of the state in consideration and the ground density of the reaction partner with the nucleon-nucleon interaction. If we take into account also the isospin dependent part of the nucleon-nucleon interaction then the form factors as well as the folding potential will be formed by two parts, one of them depending of the isospin degree of freedom. This part will go to zero when one of the two reaction partner has $N = Z$[17]. Then the explicit expression for the form factors are

$$F_0 = \int \int [\delta \rho_p(r_1) + \delta \rho_p(r_1)] v_0(r_12) [\rho_T(r_2) + \rho_T(n(r_2))],$$

$$F_1 = \int \int [\delta \rho_p(r_1) - \delta \rho_p(r_1)] v_1(r_12) [\rho_T(n(r_2)) - \rho_T(p(r_2))],$$

where the central part of the local effective interaction $v_{12}$ as been written as sum of two terms, the isoscalar part $v_0$ generating an isoscalar form factor and an isovector term $v_1$ giving an isospin dependent form factor[17].

Let us consider first some dipole states for $^{68}$Ni (the ones presented in table 1) whose form factors with $^{208}$Pb for the first three of them are shown in figure 6. The two states around 15 MeV belonging to the GDR peak have been chosen to have very different isoscalar reduced transition probabilities. In frame a) of the figure 6 the Coulomb form factors display the well known proportionality to the $B_{iv}(E1)$: the ones of the GDR’s are indistinguishable because
their $B_{iv}(E1)$ values are very close. The same happens for the isovector part of the nuclear form factor (frame c). The situation is not so clear for the isoscalar part although one can notice how the form factors corresponding to states with bigger $B_{is}(E1)$ are predominant over the others especially at the surface region. This relation is not proportional as in the Coulomb case but it can still be appreciated. Finally in frame d) we plot the total form factors where some positive interference between the two contributions can be noticed in the peripheral region.

This behaviour might be modified by the dynamics of the process. In figure 7 the semiclassical cross section is shown for the system $^{68}\text{Ni} + ^{208}\text{Pb}$ for the four dipole states of table 1 at two incident energies: 50 and 100 MeV/nucleon. In frame a) the Coulomb cross section at low energy shows how the low incident energy inhibits the excitation of the GDR with respect to the low lying dipole state. Increasing the incident energy the cross sections get values which adapt to the different values of the $B_{iv}(E1)$. The nuclear excitation (in frame b) seems to be indifferent to the incident energies and somehow reflects the different values of the $B_{is}(E1)$ in the sense that the only GDR’s state excited in this process is only the one with bigger $B_{is}(E1)$, namely the one at 15.63 MeV. The total cross section show a strong positive interference for the PDR and a moderate one for the GDR’s state which has a larger $B_{is}(E1)$. This may be a direct consequence of the fact that the isoscalar dipole transition density has different sign at small and large radii[2, 3].

We already see at this level how different incident energies may alter the relative intensities of the PDR and GDR states due to the different interplay of their isoscalar and isovector contributions.
Figure 7. Semiclassical cross section for the system $^{68}$Ni + $^{208}$Pb for the four dipole states of Table 1 at two different incident energies as indicated in the legend. The bars corresponding to the lower energy are shifted by 0.5 MeV to the left for a better comparison.

Figure 8. Differential cross sections as a function of the excitation energy for the system $^{132}$Sn + $^{40}$Ca at 30, 60 and 100 MeV/nucleon incident energy. We show separately the nuclear (a) and the Coulomb (b) contributions.
Figure 9. Differential cross sections as a function of the incident energy per nucleon for the systems $^{17}\text{O} + ^{208}\text{Pb}$ for the multipole states used in the calculations. The nuclear (a) and Coulomb (b) contributions, as well as the total one (c), are shown in separate frames. The contributions of each multipole state are indicated with different colors and the corresponding labels.

4. Inelastic cross section

Since other states with different multipolarities are present in the region of interest, we have performed calculations including, besides the dipole states, also quadrupole and octupole states. As usual, we take into account in the coupled-channel calculation only the states with a sizeable EWSR percentage. In order to further reduce their number, we bunch together states with significant strength close in energy. The "bunching" procedure consists in taking as energy the average energy of the states belonging to the group with the condition that the EWSR must be preserved [3, 14].

The calculations were done for several combination of systems at several incident energies. In figure 8 we show the results for the system $^{132}\text{Sn} + ^{40}\text{Ca}$ at three values of incident energies as shown in the legend. We use all the states listed in tables I and II of ref. [3]. The excitation induced by the nuclear part of the interaction (shown in panel a) is almost independent of the incident energy. In the Coulomb case (panel b) the increase of the incident energy enlarges the cross section in the GDR region while it reduces the excitation in the low energy region part. This is due to the well known adiabatic cut-off effect that governs the transition amplitudes for Coulomb excitation. In the lower panel c) the total cross section show clearly the presence of the PDR peak around 9 MeV. Although its strength may be masked by the presence of the low lying high multipole states and of the giant resonance region, it is still evident the positive interference between the Coulomb and nuclear contributions.

In figure 9 we show the nuclear, Coulomb and total inelastic cross section for the system $^{17}\text{O} + ^{208}\text{Pb}$ for the states of different multipolarities used in the calculations as a function of the incident energy. Only the most relevant contribution are shown. In frame a) we show the effects of the excitation due only to the nuclear field: only the pure isoscalar states are populated together with the PDR. We note how after the first increase the cross sections remain almost constant for all the states considered.
The middle panel (b) shows the inelastic cross section produced by the Coulomb field. For the low lying states, after the rapid increase, there is an almost as fast decrease with the increase of the energy. On the contrary the giant dipole resonances maintains its growth with increasing incident energy, at least in the range of energies considered here. Both these features are clearly manifestations of the adiabatic cut-off effect.

If we allow the two interactions to act together then the results for the cross section are the ones shown in frame c). The most noticeable effect is the strong positive interference we observe for the PDR excitation. These results suggest that the investigation of the PDR state can be better carried out at low incident energy (below 50 MeV/nucleon). The higher cross section for the PDR at higher incident energy, may be obfuscated by the strong tail of the giant resonance states. On the other hand the PDR peak at lower energies should compete with the presence of the low lying quadrupole and octupole states whose narrow widths could not hidden their presence. Furthermore, this last system analyzed, has the advantage that, being the partners of the reaction stable nuclei, a great variety of incident energies can be used for getting experimental information.

We are aware of the fact that the use of the nuclear interaction in the excitation processes does introduce more uncertainties in the calculations. Apart from the ones intrinsic to the nuclear interactions where sometimes it is difficult to separate the effect of the reaction mechanism from the nuclear structure, there are other dubieties which are inherent to our model. We refer in particular to the semiclassical model where the absence of interference among the classical trajectories guaranties reliable results only for the total cross section. Furthermore, the use of nucleon nucleon interaction in the well consolidated double folding procedure introduces a further uncertainty, but most of all it is the imaginary part of the potential which may originate possible erroneous predictions. In most of the case investigated there is no indirect knowledge about the magnitude of the imaginary potential, through the elastic scattering measurement, and therefore only an approximate estimation can be assumed. Our choice was to take as imaginary part a potential with the same geometry of the real one with a half strength, which is a standard assumption.

Nevertheless, we believe that the use of strong probe in the study of PDR may furnish evidences of new features which allow a better knowledge of these states. This believing is corroborated by our calculation as well as by the new findings of experimental results investigated in ref. [9] where a possible splitting of the PDR have been reported.

5. Summary
By mean of a H-F plus a RPA formalism we were able to study the behaviour and the nature of the low lying dipole state known as PDR. These states are present in all nuclei having a neutron excess independently whether they are stable or close to the drip line. We were able to put in evidence the strong response when these states are excited with an isoscalar probe which looks highly collective in contrast to their isovector response. This feature allows an investigation of the PDR al low incident energies where the nuclear field plays an important role. Calculations done with several partners of the reactions at several incident energies permits to choose the proper system to have the proper conditions for a better investigations of these mode. We found that the excitation induced by the nuclear part of the interaction is almost independent of the incident energy. On the contrary, in the Coulomb case the variation of the incident energies produces structurally different results. This is due to the well known adiabatic cut-off effect. Furthermore, there is a strong positive interference between the contributions of the two interactions especially for the PDR state. The relative population of the PDR with respect to the giant resonances region changes with the variation of the parameter of the reaction. In particular, at low incident energy the excitation probability of the PDR state is sensibly higher than the GDR one. Our analysis suggest that the best conditions to study the PDR may be
reached at relatively low incident energies (around 20, 30 MeV per nucleon) where the interplay between nuclear and Coulomb could help in the selection of these states.

References
[1] Paar N, Vretenar D, Khan E and Colò G 2007 Rep. Prog. Phys. 70 691 and references therein.
[2] Catara F, Lanza E G, Nagarajan M A and Vitturi A 1997 Nucl. Phys. A 614 86;
Catara F, Lanza E G, Nagarajan M A and Vitturi A 1997 Nucl. Phys. A 624 449.
[3] Lanza E G, Vitturi A, Andrés M V, Catara F and Gambacurta D 2011 Phys. Rev. C 84 064602.
[4] Adrich P et al. 2005 Phys. Rev. Lett. 100 132501;
Klimkiewicz A et al. (LAND-FRS Collaboration) 2007 Nucl. Phys. A 788 145;
Klimkiewicz A et al. (LAND Collaboration) 2007 Phys. Rev. C 76 051603(R).
[5] Wieland O et al. 2009 Phys. Rev. Lett. 102 092502.
[6] Savran D et al. 2008 Phys. Rev. Lett. 100 232501.
[7] Poltoratska I et al. 2012 Phys. Rev. C 85 041304(R).
[8] Vitturi A, Lanza E G, Andrés M V, Catara F and Gambacurta D 2010 PRAMANA 75 73.
[9] Endres J et al. 2009 Phys. Rev. C 80 034302;
Endres J et al. 2012 Phys. Rev. C 85 064331.
[10] Piekarewicz J 2011 Phys. Rev. C 83 034319;
[11] Piekarewicz J 2012 his contribution to this conference.
[12] Van Giai N and Sagawa H 1981 Phys. Lett. 106B 379.
[13] Van Giai N and Sagawa H 1981 Nucl. Phys. A 371 1.
[14] Lanza E G, Catara F, Gambacurta D, Andrés M V and Chomaz Ph 2009 Phys. Rev. C 79 054615.
[15] Vretenar D, Niu Y F, Paar N and Meng J 2012 Phys. Rev. C 85 044317.
[16] Lanza E G, Andrés M V, Catara F, Chomaz Ph, Fallot M and Scarpacci J A 2006 Phys. Rev. C 74 064614.
[17] Satchler G R 1983 Direct Nuclear Reactions (Oxford University Press).