Giant and Pygmy Dipole Resonances in neutron-rich nuclei: their excitation via Coulomb and nuclear fields

A Vitturi (1,2), EG Lanza (3), MV Andrés (4), F Catara (3,5) and D Gambacurta (3,5)
(1) Dipartimento di Fisica, Padova, Italy
(2) INFN, Sezione di Padova, Italy
(3) INFN, Sezione di Catania, Italy
(4) Departamento de FAMN, Facultad de Física, Sevilla, Spain
(5) Dipartimento di Fisica, Catania, Italy
E-mail: vitturi@pd.infn.it

Abstract. We study the excitation of low-lying dipole states in very-neutron rich nuclei (so called Pygmy Dipole Resonances). The states are described within the Hartree-Fock plus RPA formalism, using different parametrizations of the Skyrme interaction. We show how the combined information from reaction processes involving the Coulomb and different mixtures of isoscalar and isovector nuclear interactions can provide a clue to reveal the characteristic features of these states.

1. Introduction
A great deal of interest has been raised in the last few years by the presence of dipole strength at low excitation energy in neutron-rich nuclei. This strength (typically of the order of few per cent of the corresponding Energy Weighted Sum Rule) has been often associated to the possible existence of a collective mode of new nature, corresponding to the oscillation of the valence neutron skin against the proton plus neutron core (Pygmy Dipole Resonance, PDR).

The presence of this low-lying strength is predicted by almost all microscopic models, ranging from Hartree-Fock plus RPA with Skyrme interactions to relativistic Hartree-Bogoliubov plus relativistic quasiparticle RPA. All these approaches [1, 2, 3, 4] predict similar amounts of strength, but often disagree on the collective (or not) nature of these states, on their fragmentation and on their isoscalar/isovector contents. Information on the precise nature of these states must come from experimental data [5]. Heavy-ion high-energy Coulomb excitation processes provide values of the multipole B(Eλ) transition rates, being instead unable to provide further information on wave functions and transition densities. We suggest in this talk that a part of this information can be obtained by resorting to reactions where the nuclear part of the interaction is involved. By tuning masses, charges, bombarding energies and scattering angles one can alter the relative role of the nuclear and Coulomb components, as well as of the isoscalar and isovector contributions.

Along this line, we present the predictions for the excitation of the low-lying (PDR) and high-lying (GDR) dipole states in the neutron-rich $^{132}$Sn by different projectiles ($\alpha$, $^{40}$Ca, $^{48}$Ca)
at different bombarding energies. The dipole states, their wave functions and the corresponding transition densities have been obtained within the Hartree-Fock plus discrete RPA with Skyrme interactions. Inelastic formfactors have then been obtained by double-folding the M3Y nucleon-nucleon interaction with the microscopic densities and transition densities and then used to describe the quantal evolution of the system along classical ion-ion trajectories. The excitation probabilities turn out to be sensitive to the details of the transition densities (and not simply to the B(E1) values) and therefore these can be probed by comparing different processes.

Figure 1. Isovector strength distributions for dipole states for tin isotopes calculated with the SGII interaction. The bars are the RPA B(E1) values. The solid curves represent $dB(E1)/dE$ as obtained by adopting a smoothing procedure described in the text. In the lower right figure we report the same continuous lines shown in the other frames.

2. RPA dipole strength, transition densities and formfactors
Dipole states and corresponding dipole response have been calculated using the simple discrete non-relativistic RPA approach with Skyrme interactions. An example of the evolution of the dipole response with the neutron number is shown in Fig. 1, where the three isotopes $^{100,120,132}$Sn are separately considered (from Ref.[4]). Note that the bars are the discrete response of the RPA calculation while the continuous lines are generated by a smoothing procedure using a Lorentzian with a 1 MeV width. For a better comparison the three distributions of dipole strength are shown together in the lower right frame. Together with the usual lowering of the energies of the dominant Giant Dipole Resonance with increasing mass number, we can notice the appearance of some low-lying strength (carrying a fraction of the EWSR of the order of few per cent) below 10 MeV. These are precisely the states that are candidates to be interpreted as Pygmy Dipole Resonances, associated with the occurrence of a neutron skin in the nuclear densities and its oscillation with respect to the proton+neutron core.
More precise information on the specific nature of the states is embedded in the corresponding transition densities. As an example we show in Fig. 2 the RPA transition densities associated with the GDR (right frame) and with a state in the “PDR” region (left frame) in $^{132}$Sn. Neutron and proton components of the transition densities are separately shown, together with their isoscalar and isovector combinations. The two cases clearly display very different behaviours. The one associated with the GDR shows the usual opposite-phase behaviour of the proton and neutron components, leading to the usual predominant isovector character. The situation is rather different in the case of the other state at lower energy. Here neutron and proton components seem to oscillate in phase in the interior region, while having a pure neutron oscillation (with opposite phase) in the surface region. This may favor the interpretation of this state as a Pygmy Dipole Resonance, macroscopically described as the oscillation of the neutron skin with respect to the proton+neutron core, although a full interpretation in terms of the PDR is not obvious (cf. e.g. ref.[4]).

The transition densities are the basic ingredients to construct the nuclear formfactors describing nuclear excitation processes. These formfactors can be obtained by doublefolding the transition densities with the density of the reaction partner and the nucleon-nucleon interaction (M3Y interaction, in our case), including both isoscalar and isovector terms. The relative role of isoscalar and isovector formfactors depends on the corresponding mixture in the transition density of the specific state but also on the nature of the specific reaction partner (being purely isoscalar in the case of $\alpha$-particle or other $N = Z$ nuclei, and both isoscalar and isovector for $N \neq Z$ nuclei). The change of reaction (and of the bombarding energy), with the consequent change of the relative role of nuclear and Coulomb components as well as of the isoscalar/isovector nuclear components) will have therefore the consequence of altering the relative population of the different states. We will consider here the excitation of the Pygmy and Giant dipole states in $^{132}$Sn by different partners: $\alpha$, $^{40}$Ca and $^{48}$Ca. The square of the corresponding formfactors (nuclear and Coulomb) at the surface for the excitation of different

![Figure 2](image-url). Transition densities for the low-lying dipole state (PDR) (left) and for the GDR (right) for the $^{132}$Sn isotope calculated with the SLY4 interaction. We show the proton, neutron, isoscalar and isovector components.
Figure 3. Square of the formfactor around the surface for different systems $^{132}$Sn + $\alpha$, $^{40}$Ca, $^{48}$Ca (the surface has been assumed to be at 7.7 fm, 11.0 fm and 11.3 fm for the three cases). The continuous lines are obtained with the same smoothing procedure used previously. Coulomb and nuclear contributions to the total formfactors are separately shown.

states and shown in Fig. 3. One can see how the different reactions and the different interplay of isoscalar and isovector contributions alter the relative “intensities” of PDR and GDR states.

3. Cross sections

With ion-ion potential and formfactors we can now proceed to the next step and calculate the inelastic cross sections. This is done within a semiclassical model where the relative motion is treated classically. These assumptions are usually well justified for grazing collisions. The Hamiltonian describing the colliding nucleus can be separated into two parts: the internal Hamiltonian describing the structure of the nucleus and an external field which is responsible of the excitation of one of the partner of the collision through the mean field of the other one. The time dependent Schrödinger equation is cast into a set of coupled differential equations for the different excitation amplitudes which are integrated along the classical relative motion trajectories. For each state considered the associated cross section is obtained by integrating the corresponding excitation probability over the whole impact parameters range modulated by the transmission coefficient [6]. The resulting energy differential total cross sections for $^{132}$Sn on different targets ($\alpha$, $^{40}$Ca and $^{48}$Ca) at E=10 MeV/u are shown in Fig. 4. The different contributions from Coulomb and nuclear formfactors are separately show. It is clear that the balance between PDR and GDR changes in the different reactions. The ratios can be further modified by selecting different scattering angles, that are associated to different ranges of impact parameters. For example nuclear contributions are known to be enhanced at grazing angles, corresponding to "surface" impact parameters. An alternative possibility is to consider the total cross sections but varying the bombarding energy, so altering the relative role of nuclear and Coulomb contributions. This is better shown in Fig. 5 where we show the cross sections for the case $^{132}$Sn + $^{40}$Ca at different bombarding energies.
Figure 4. Differential cross sections as function of the excitation energy for the systems $^{132}$Sn + α, $^{40}$Ca, $^{48}$Ca at 10 MeV per nucleon. Coulomb, nuclear and total contributions are separately shown.

Figure 5. Differential cross sections as function of the excitation energy for the systems $^{132}$Sn + $^{40}$Ca at different bombarding energies.
4. Conclusions
The interpretation of the low-lying dipole strength in very-neutron rich nuclei as a pygmy dipole state of collective nature needs to be carefully checked. Valuable information on the nature of these states can be obtained by excitation processes involving the nuclear part of the interaction, which are sensitive to the shape of the transition densities. 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 towards the solution of the problem.

[1] Catara F, Lanza E G, Nagarajan M A and Vitturi A Nucl. Phys. A 614 86 (1997); Nucl. Phys. A 624 449 (1997).
[2] Paar N, Vretenar D, Khan E and Colò G, Rep. Prog. Phys. 70, 691 (2007) and references therein.
[3] Tsoneva N and Lenske H, Phys. Rev. C 77 024321 (2008).
[4] Lanza E G, Catara F, Gambacurta D, Andres M V and Chomaz Ph, Phys. Rev. C 79 054321 (2009).
[5] Adrich P, et al. (LAND-FRS Collaboration), Phys. Rev. Lett. 95 132501 (2005); Klimkiewicz A, et al. (LAND Collaboration) Nucl. Phys. A 788 145 (2007); Klimkiewicz A, et al. (LAND Collaboration) Phys. Rev. C 76 051603(R) (2007).
[6] Andrés M V, Catara F, Lanza E G, Chomaz Ph, Fallot M and Scarpaci J A, Phys. Rev. C 65 014608 (2001).