Excitation of pygmy dipole resonance in neutron-rich nuclei via Coulomb and nuclear fields

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Abstract. We study the nature of the low-lying dipole strength in neutron-rich nuclei, often associated with the pygmy dipole resonance. The states are described within the Hartree–Fock plus RPA formalism, using different parametrizations of the Skyrme interaction. We show how the information from combined 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.

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1. Introduction

The study of the evolution of the properties of collective states in neutron-rich nuclei has drawn a great deal of interest in the last few years. Besides the usual giant multipole resonances (as the giant dipole state (GDR)), special attention has been focussed on the presence of dipole strength at low excitation energy, of the order of few per cent of the corresponding energy weighted sum rule (EWSR) [1]. This strength has been often associated with the possible existence of a collective mode, corresponding to the oscillation of the valence neutron skin against the proton plus neutron core (pygmy dipole resonance (PDR)) (see, for example ref. [2] and references therein).

From a theoretical point of view, 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 quasi-particle RPA. All these approaches predict similar amounts of strength, but often disagree on the collective (or not) nature of these states, their fragmentation and their isoscalar/isovector contents [2].
From an experimental point of view the pulling evidence for these states has come from high-energy Coulomb excitation processes [3]. As known, these can only provide values of the multipole \( B(E\lambda) \) transition rates, but cannot provide further information on wave functions and transition densities, which are the necessary ingredients to characterize the nature of these states. A part of this information can be obtained by resorting to reactions where the nuclear part of the interaction is involved. By tuning the projectile mass, charge, bombarding energy and scattering angle, one can alter the relative role of the nuclear and Coulomb components, as well as the isoscalar and isovector contributions.

Here, 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 ($^4$He, $^{40}$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. Form factors have then been obtained by double-folding the M3Y $N$–$N$ interactions, and then used to describe the quantal evolution of the system along the classical ion–ion trajectories. We will show how the excitation probabilities are sensitive to the details of the transition densities (and not simply to the \( B(E1) \) values) and how these can be probed by a combination of different processes.

2. RPA dipole strength distribution and Coulomb excitation probabilities

Predictions for the dipole response in many-body systems are provided by different approaches. At the level of particle–hole plus ground-state correlations, a notable role has always been played by theories based on the random phase approximation,
both in their non-relativistic and relativistic versions. We will use here the results obtained in the simplest discrete non-relativistic RPA approach with Skyrme interactions, consistently used both at the level of mean-field Hartree–Fock and RPA. An example of the evolution of the dipole response with the neutron number is shown in figure 1, where the three isotopes \(^{100,120,132}\text{Sn}\) 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. The continuous lines are drawn only to easily see where the major strength is located. To better appreciate the isotope dependence, the three distributions of dipole strength are shown together in the lower (right) frame in figure 1. As one can see, together with the usual lowering of the energies of the dominant giant dipole resonance with the increased mass number, we have 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 neutron skins in the nuclear densities and their oscillations with respect to the proton+neutron cores.

The dipole strength distribution can be directly tested in Coulomb excitation processes. Calculated \(Q\)-value distributions \(d\sigma_C/dE\) of total Coulomb excitation cross-sections for the \(^{132}\text{Sn} + ^{208}\text{Pb}\) reaction at different bombarding energies are shown in figure 2. As expected, at high bombarding energies the cross-sections just follow the \(B(E1)\) strength distribution but at lower energy the kinematical cut-off enhances the role of the states with lower energies. As apparent from the lower frame (right) where the different cross-sections are combined, at very low bombarding energy the probability of exciting the ‘PDR’ region becomes even larger than the probability exciting the GDR.

3. Isoscalar and isovector transition densities and excitation of dipole states via nuclear fields

Excitation processes via the Coulomb field can only test the \(B(E\lambda)\)-values, i.e. integrated electromagnetic matrix elements. More precise information on the specific nature of the states is instead embedded in the corresponding transition densities. As an example we show in figure 3 the RPA transition densities associated with the GDR (right frame) and with a state in the ‘PDR’ region (left frame) in \(^{132}\text{Sn}\). 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 a dominant isovector character. As known [5], however, in these very-neutron rich nuclei the presence of different radii for the proton and neutron densities leads to non-vanishing isoscalar transition densities, opening the possibility of exciting the GDR also via isoscalar probes. 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 score a point in favour of the
Figure 2. Coulomb excitation cross-section for the system $^{132}\text{Sn} + ^{208}\text{Pb}$ at several incident energies as indicated in each frame. The bars correspond to the calculations done for each of the RPA states while the continuous lines are obtained with the smoothing procedure described in the text. In the frame on the right we put together the solid lines in order to show the relative evolution of the states as a function of the incident energies.

Figure 3. Transition densities for the low-lying dipole state (PDR) (left) and for the GDR (right) for the $^{132}\text{Sn}$ isotope calculated with the SLY4 interaction. We show the proton, neutron, isoscalar and isovector components (as indicated in the legend).

interpretation of this state as a pygmy dipole resonance, macroscopically described as the oscillation of the neutron skin with respect to the proton+neutron cores. Such behaviour, which has been found also in all the other microscopic approaches [2,6], can be taken as a sort of definition of PDR. A macroscopic description of such a mode assumes a separation of the neutron density into a core part $\rho_N^C$ with $N_C$ neutrons and a valence part $\rho_N^V$ with $N_V$ neutrons ($N = N_C + N_V$), with a proton density $\rho_P$ with $Z$ protons. This leads to neutron and proton transition densities given by
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Figure 4. Transition densities for the low-lying dipole state for the $^{132}$Sn isotope. The left panel shows the macroscopic transition densities according to eq. (1), the one on the right is calculated microscopically with the HF + RPA. We show the proton, neutron, isoscalar and isovector components (as indicated in the legend).

\[
\delta \rho_N(r) = \beta \left[ \frac{N_V}{A} \frac{d\rho_N^C(r)}{dr} - \frac{N_C + Z}{A} \frac{d\rho_N^V(r)}{dr} \right]
\]

\[
\delta \rho_P(r) = \beta \left[ \frac{N_V}{A} \frac{d\rho_P(r)}{dr} \right]
\]

with $\beta$ a proper strength parameter. The microscopic RPA and the macroscopic transition densities, normalized to the same $B(E1)$ value, are compared in figure 4.

Although some similarities are present, a full interpretation of the state in terms of the PDR is not obvious. It should be noted that, besides the requirement of the shape of the transition density, the macroscopic picture should also involve a collective nature of the state, thereby implying some coherent contribution of the different particle–hole in the RPA state. This requirement was not found to be fulfilled at least in the calculations of ref. [4].

The transition densities are the basic ingredients to construct the nuclear form factors describing nuclear excitation processes. These form factors can be obtained by double folding [7] the transition densities with the density of the reaction partner and the $N - N$ interaction (taken in our case as M3Y), including both isoscalar and isovector terms. The relative role of isoscalar and isovector form factors depends on the corresponding mixture in the transition density of the specific state but also on the nature of the specific reaction partner (i.e. purely isoscalar in the case of $\alpha$-particle or other $N = Z$ nuclei, isoscalar+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 alter the relative population of different states. Vice versa, although more tricky, from this different population one can hope to extract the different properties of the transition densities, and hence the different nature of the states.
Figure 5. Form factors for three different systems $^{132}$Sn + $\alpha$, $^{40}$Ca, $^{48}$Ca. The upper parts refer to the PDR states while the lower ones are for the GDR. The different component are shown together with the total one (solid black line).

Figure 6. Square of the form factor for the systems indicated in the figure and for four significative dipole states. The continuous lines are obtained with the same smoothing procedure used previously.

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 corresponding form factors (nuclear, Coulomb and total) and shown in figure 5.

For an easier comparison, we compare in figure 6 the square of the form factors at the surface for the excitation of different states. We have chosen, for simplicity, four significative dipole states which correspond to the four peaks present in the $B(E1)$ strength distributions for $^{132}$Sn of figure 1. One can see how the different reactions alter the relative ‘intensities’ of PDR and GDR states. This is due to the different interplay of isoscalar and isovector contributions.
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Figure 7. Differential cross-sections as a function of the excitation energy for the systems $^{132}$Sn + $\alpha$, $^{40}$Ca, $^{48}$Ca at 10 MeV per nucleon. The Coulomb contribution is shown as dashed line. The black area corresponds to the nuclear contribution.

With ion–ion potential and form factors we can now calculate cross-sections (for example, within the semiclassical approach as done in ref. [4]). The energy differential total cross-sections are shown in figure 7. The different contributions from Coulomb and nuclear form factors are separately shown. It is clear that the balance between PDR and GDR vary in different reactions. The ratios can be further modified by looking at the differential angular distributions. In the semiclassical picture, these are associated with different ranges of impact parameters. Nuclear contributions are known to be enhanced at grazing angles, corresponding to grazing impact parameters. This is clearly evidenced in figure 8, where the partial-wave cross-sections are shown as a function of the impact parameter.

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
Figure 8. Partial wave cross-sections as a function of the impact parameter $b$ for the systems $^{132}\text{Sn} + \alpha$, $^{40}\text{Ca}$, $^{48}\text{Ca}$ at 10 MeV per nucleon. The Coulomb (C) and nuclear (N) contributions are indicated in the figures. The curves with the highest maximum are the total cross-section.

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 form factors, can provide the clue towards the solution of the problem.

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