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Nuclear excitation of Pygmy Dipole Resonance

Edoardo G Lanza[1,2], Andrea Vitturi[3,4], M Victoria Andrés[5], Francesco Catara[2,1]

[1] INFN - Sezione di Catania, 95123 Catania, Italy
[2] Dipartimento di Fisica e Astronomia, 95123 Catania, Italy
[3] Dipartimento di Fisica e Astronomia, 35131 Padova, Italy
[4] INFN - Sezione di Padova, 35131 Padova, Italy
[5] Departamento de Física Atomica, Molecular y Nuclear, 41080 Sevilla, Spain

E-mail: lanza@ct.infn.it

Abstract. Excitations of Pygmy Dipole Resonance (PDR), generated by a nuclear field, are studied within a semiclassical RPA based model. This is possible since the PDR, present in almost all nuclei with neutron excess, has a strong isoscalar character. Our results show that the employ of isoscalar probes finds its best use at incident energies below 50 MeV/u. The structural splitting of the low-lying E1 strength, found in recent $(\alpha, \alpha'\gamma)$ experiments, is corroborated by our cross section calculations.

1. Introduction

Collective states play an important role in the varied panorama of nuclear phenomena. Their role has been strengthened with the advent of the studies of nuclei far from the stability line. In particular, the low lying excitation dipole strength, present in almost all the nuclei with neutron excess, has arisen a lot of attention and many experimental [1] and theoretical [2] studies have been devoted to it. The interest in the Pygmy Dipole Resonance (PDR) states is enhanced by the fact that there is a connection between their strength and the neutron skin as well as with the symmetry energy in the equation of state of nuclear matter [1, 2]. Although there is a controversial debate about whether they can be considered collective, most of the theoretical studies coincide in the description of their transition densities whose behaviour "defines" this new mode: The neutron and proton transition densities are in phase inside the nucleus and at the surface only the neutron part considerably contributes. This property manifests in a strong mixing of isospin character which eventually allows the excitation of these states by means of both isoscalar and isovector probes.

In this paper we will describe the excitation of the PDR via the nuclear interaction at low incident energies within a semiclassical framework and we essentially will concentrate in two aspects. In our previous studies it was shown that these states are not collective, therefore it is not possible to apply the usual standard model to calculated the form factors to be employed in, for instance, distorted-wave Born approximation (DWBA) calculations. Therefore it is of paramount importance the use of a microscopic description of these states both for the transition densities as well as for the form factors. The other aspect regards the comparison with experimental data. Recently, experiments with isoscalar probes have become available [3, 4, 5, 6]. Combining the $(\alpha, \alpha'\gamma)$ coincidence method with high-resolution γ-ray spectroscopy [7] on several


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semi-magic stable nuclei, a splitting of the low lying dipole strength has come in evidence. The strength separates in two groups: the low lying part is excited by both isoscalar and isovector probes while the high energy group is excited only by electromagnetic probes. Some microscopic nuclear structure calculations show, for the isoscalar and isovector B(E1) response, a qualitative agreement with the experimental findings. Our cross section calculations agree very well with the data reproducing the experimental observed splitting.

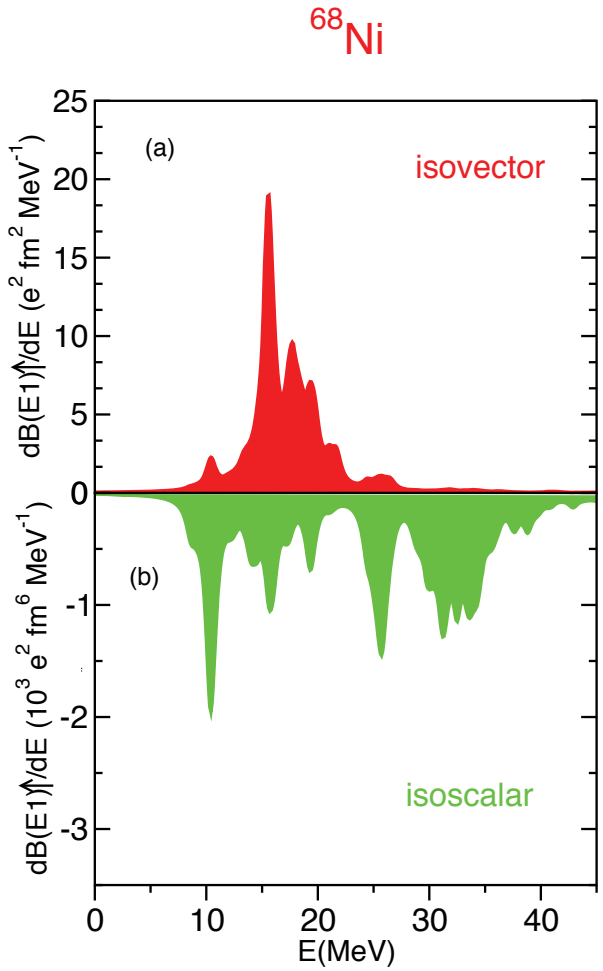

Figure 1. (Color online) RPA strength distributions for isovector (a) and isoscalar (b) response for ^{68}Ni.

2. Semiclassical model

The inelastic cross section calculations are performed within a semiclassical model which has been developed along the years and it has been applied to several nuclear reactions between heavy ions. The idea is that the trajectory of the partners of the reactions can be described classically, while their internal structure and excitation can be described microscopically according to quantum mechanics. These conditions are valid for grazing collisions. Details of the model are given in Ref. [8] and references therein, here we only emphasize the most salient points.

The Hamiltonian describing each of the two colliding nuclei is given by the sum of one term which describes the structure of the nucleus and another one which is responsible, through its mean field, of the excitation of the other partner. The Schrödinger equation for the time dependent wave functions of the states taken into consideration can be written in terms of

coupled equations for the probability amplitudes. The solutions of these coupled equations can then be used to calculate cross sections, for each state taken into consideration, as an integral of the excitation probabilities over the impact parameters. The structure of the nucleus under study is obtained by means of an HF + RPA calculation which allows us to select the states with an important EWSR percentage among the RPA states with multipolarities from 0 to 3. For each of these states the transition densities are obtained and they are used to construct the real part of the nuclear optical potential as well as the form factors by the double folding procedure. The classical trajectory is then determined by the Coulomb potential together with the real part of the nuclear potential.

In a previous work we have analyzed in detail the nature of the PDR (see for example Refs. [9, 10]). There we have shown that the dipole responses for an isoscalar and isovector probe are quite different. As an example we show in figure 1 the strength distribution for the isovector (above) and isoscalar (below) response for the isotope ^{68}Ni. The isovector response shows the well known peak of the isovector Giant Dipole Resonance (IVGDR) at about 15 MeV and the small peak at about 10 MeV of the PDR. In the lower frame the response for the isoscalar probe shows a very strong peak in correspondence of the PDR energy and the well known ISGDR peak at around 33 MeV. The transition density for the PDR shows its characteristic pattern: at the surface only the neutron transition density contributes. In order to establish whether these states are collective we have analyzed them in detail. The RPA results tell us that they are formed by many particle-hole configurations and most of them come from the shell occupied by the excess neutrons. But the analysis of the coherence, the other property that has to be satisfied to be called collective, gives different results for the isoscalar and isovector response. While the isoscalar response shows a clear feature of coherence, as in the case of the high lying ISGDR, the isovector one is manifestly not coherent [10].

This implies that the usual standard prescription to calculate the form factor for the collective states cannot be applied in this case. A microscopic construction of the form factors is in order. This can achieved by means of the double folding prescription [11] where a microscopic RPA transition density is double folded with the density of the nucleus responsible of the excitation and with a nucleon nucleon interaction. In our calculation we have chosen an M3Y-Reid type [12]. Examples of the radial form factors are shown in figure 2 where the Coulomb (dashed blue) and the nuclear (full red) contributions are separately presented together with their sum for the system ^{68}Ni + ^{12}C. These states are the results of RPA calculations with SGII interaction [13]. In the upper first frame on the left, we observe the known property of the GMR which can not be excited by the Coulomb interaction. In the other cases, the Coulomb form factor shows clearly its proportionality to the squared root of the B(Eλ). This is manifestly evident if one looks at the dipole form factors, namely the one for PDR and GDR, for which the B(Eλ) values are almost an order of magnitude different. The other thing to be noted is that for the dipole states the nuclear and Coulomb contribution are interfering negatively in the interior region and positively at the surfaces of the nuclei. This depends on the fact that the isoscalar transition densities for the dipole states display a node as it has been shown and discussed in Refs. [8, 14]. For the quadrupole and octupole states one can notice a slight negative interference at the surface region. The interference in the form factors reveals itself also in the inelastic cross section as it will be shown in the following. Another aspect, even more interesting, is the fact that the nuclear form factor for the PDR has a very different slope with respect to the other ones. The prescription of the collective model or the scaling assumption for the radius [15] to calculate the transition densities and hence the form factors seems not to work for the PDR states. For these states a more microscopic description, like the one sketched here, for the construction of the form factor seems to be more appropriate.

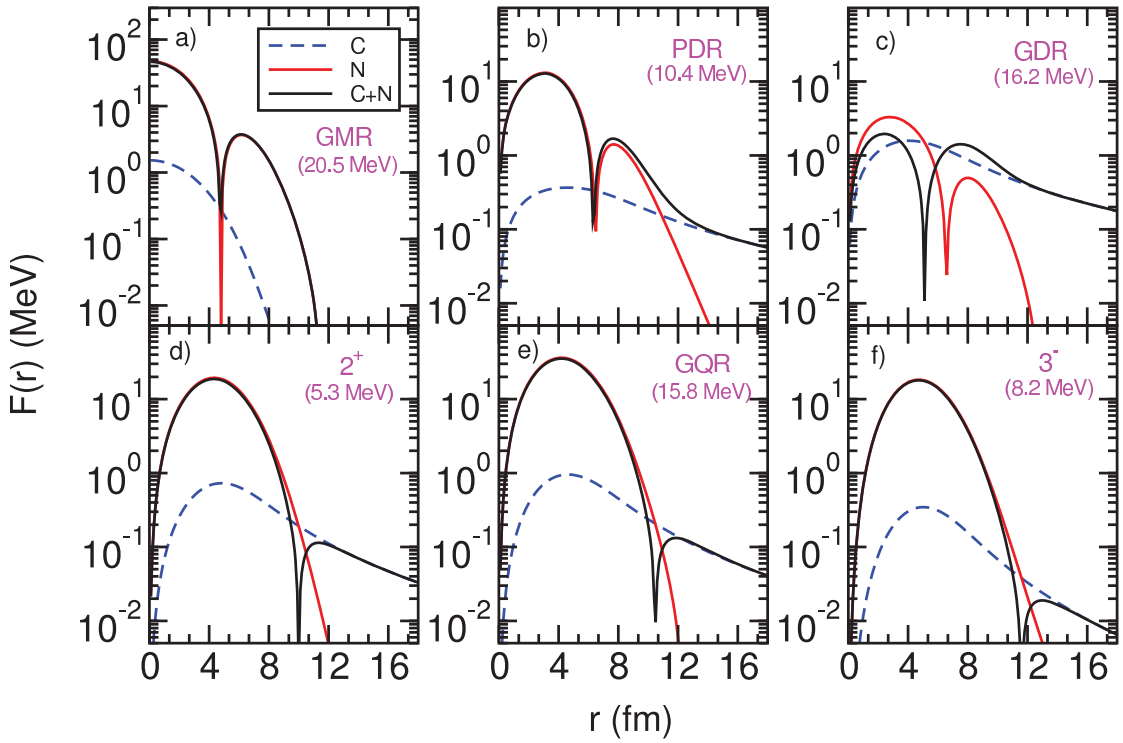

Figure 2. (Color online) Radial form factors, in absolute values, for the states used in the cross section calculations for the system ^{68}Ni + ^{12}C. In each frame is reported the Coulomb (dashed blue) and nuclear (full red) contributions as well as their sum. The states and their energies are also shown.

3. The inelastic cross section

We have performed calculations for the inelastic excitation of various systems with the aim of putting in evidence the appropriate incident energies and/or partners of the reaction that allow the best results for the detection of the PDR via the nuclear interaction. As an example we report here the results referring to calculations performed for the ^{68}Ni + ^{12}C at several incident energies. The dependence of the excitation process on the incident energies for each of the states involved in the reaction can be seen in figure 3 where the inelastic cross sections for each of the states are reported as a function of the incident energy. The contributions due to the two terms of the interactions are separately reported in first two panels of the figure. We note that the PDR is mainly excited by the nuclear interaction as well as the pure isoscalar states. The Coulomb interaction is almost not contributing to the excitation process due to the small electric charge of ^{12}C. The high multipolarities are depleted in Coulomb excitation and that is why the 2^+ low lying state is more excited than the 3^- one. When both interactions are acting (right frame) one can appreciate strong interference effects for the dipole states and this is related to the form factor properties we were discussing above. Therefore, although the Coulomb interaction alone is not producing a strong excitation, because of the small charge of ^{12}C, it is important in the reaction process for the interference effect.

From our results it is evident that the more promising incident energy to study the PDR is around 30 MeV/u. At these energies the value of the cross section for the PDR is smaller than the ones for the other multipole states. But its detection may be possible because they are located in

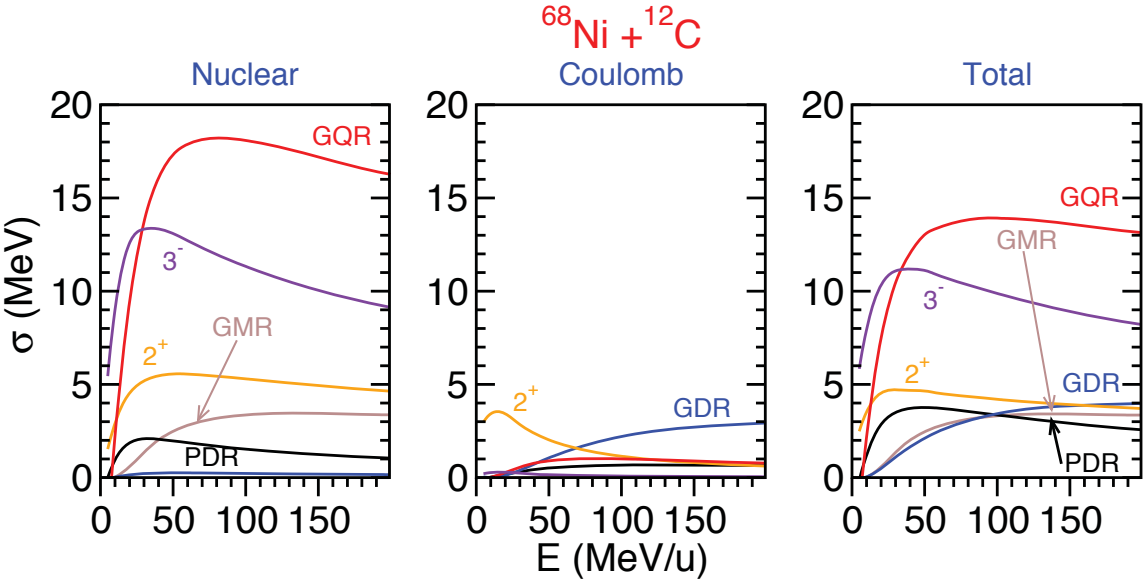

Figure 3. (Color online) Inelastic cross section for the system ^{68}Ni + ^{12}C as a function of the incident energy per nucleon and for all the states involved in the reaction. The contribution of each state is indicated in figure. On the left frame the cross section due to only the nuclear interaction is reported. The middle panel show the contribution of the Coulomb interaction and in the right one are shown the results when both interactions are acting.

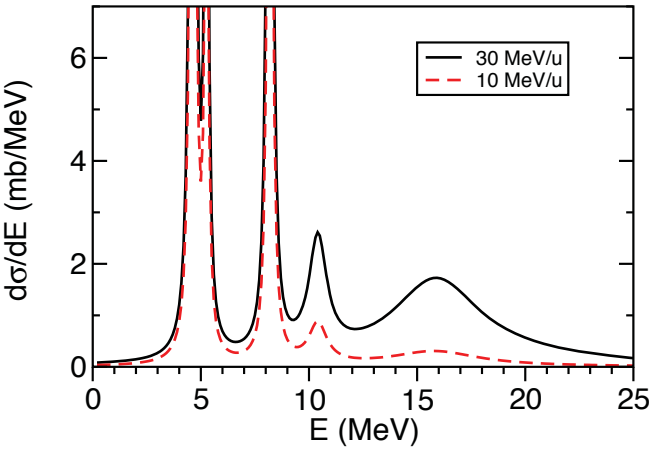

Figure 4. (Color online) Inelastic cross section for the system ^{68}Ni + ^{12}C for two incident energies as a function of the excitation energy. The figure is obtained with a folding procedure as explained in the text.

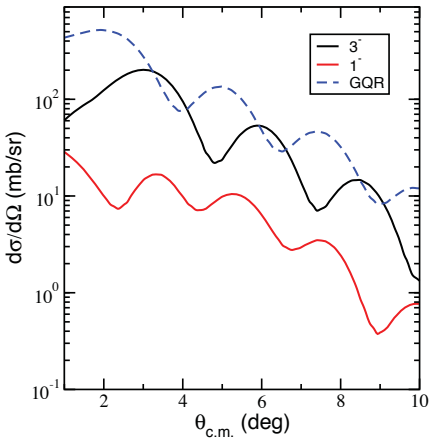

Figure 5. (Color online) Angular distribution for the system ^{68}Ni + ^{12}C at 30 MeV/u for the states indicated in the legend.

the spectrum at different regions of excitation energies. The predicted theoretical shape for the spectrum of the reaction ^{68}Ni + ^{12}C at 30 MeV/u incident energies is shown in figure 4 where the total cross sections for each of the states taken into consideration have been smoothed out

by folding them with a Lorentzian shape with a width of 0.2, 1 and $0.026\times E^{1.9}$ MeV for the low lying states, PDR and giant resonances, respectively. For comparison the result corresponding to 10 MeV/u of incident energy is also reported. As one can see, even in this case the PDR cross section should be measurable, even if in both cases the PDR peak could be masked by the presence of the other states like the giant resonance at higher energies, which are not strongly excited due to the choice of the incident energy, or the low lying octupole state at lower energies. The latter, however, should be lower in energy in the real nuclei, since it is well known that the RPA overestimates the energies of the low lying states of higher multipole. Nevertheless, angular distributions should be able to disentangle the competition between the dipole and octupole cross sections. Indeed, as it is shown in figure 5, the angular distributions for the PDR and the low lying 3^- state have different behaviour at forward angles. For completeness also the angular distribution for the GQR is shown.The angular distributions are calculated for the system ^{68}Ni + ^{12}C at 30 MeV/u incident energies with the DWUCK4 code [16] using our microscopic form factors and potential; for the imaginary part we assume the same geometry of the real part with half strength. We are aware of the fact that for exotic nuclei with neutron excess, this choice may be inaccurate because of the possible incorrect estimation of other channels, as nucleons transfer or breakup, typical surface reactions. Therefore, if one wants to compare, with precise absolute magnitude, calculations of this sort with experimental data, one should use an optical potential which is deduced from elastic scattering experimental data and possibly within the same experimental set-up. On the other hand, our aim here is to show the possibility to discriminate between excitations of states of different multipolarities by means of the shape of the angular distribution at forward angles, and this has been clearly manifested here. Indeed, the shape of the angular distribution depends on the angular momentum of the state while the choice of the correct optical potential, together with the strength deformation parameter, will determine the absolute value of the distribution.

4. Splitting of the PDR

One of the most recent aspects of the problematics related to the low lying dipole states is the so called splitting of the PDR. This comes out when the investigation of the PDR on the same nucleus by means of isovector (IV) as well as isoscalar (IS) probes is carried out in order to put in evidence the strong mixing of isospin character. These studies have been performed on various stable nuclei and here we analyze the α +^{124}Sn reaction at 136 MeV incident energy [5, 6]. The comparison of the high resolution γ ray spectroscopy [7] (nuclear resonance fluorescence (NRF)) with the results obtained applying the $(\alpha, \alpha'\gamma)$ coincidence method on the same nucleus shows a splitting of the low lying dipole strength below the neutron threshold into two groups: The one at lower energy is excited by both isovector and isoscalar probes while the group at higher energy is excited only by the electromagnetic probe. This can be seen in figure 6 where the results from the $(\alpha, \alpha'\gamma)$ coincidence method [6] are plotted (a) together with the NRF results [17] (b). A closer inspection of the figures confirm the existence of the two separate regions. Similar behaviour of the low-lying E1 strength has been reported in the experimental inelastic scattering of ^{17}O off ^{208}Pb at low bombarding energies [18].

The internal structure of the nucleus ^{124}Sn is calculated within the relativistic quasiparticle time blocking approximation (RQTBA) developed in Refs. [19, 20]. The details of the calculations, performed by E. Litvinova, for ^{124}Sn are given in Ref. [6]. The electromagnetic B_{em}(E1) values for the nucleus ^{124}Sn are displayed in frame d) of figure 6. These can be compared directly with the experimental results in the frame b). For the same set of states the isoscalar Bis(E1) has been calculated and its distribution show a pattern which recall the structure of the experimental cross section in frame a) (see figure 2 of Ref. [5]). This qualitative agreement between the experimental $(\alpha, \alpha'\gamma)$ cross section and the B_{is}(E1) distribution is not satisfactory. In fact, while the Coulomb excitation cross section and the B_{em}(E1) distribution

are proportional, the relation between the cross section and the $B_{is}(E1)$ is not so clear. So a calculation of the inelastic cross section for the low lying dipole states with a isoscalar probe is in order.

We have performed a calculation, along the line described above, for the system $\alpha + ^{124}$Sn at 136 MeV incident energy [21]. In particular, the form factors and the real part of the optical potential have been constructed via the double folding procedure by using the already mentioned transition densities provided by E. Litvinova RQTBA calculations. The reaction calculation has been done in the same angular range of the experimental data and the results are shown in frame b) of figure 6. The gross feature of the experimental cross section is retrieved although there is a shift of about 800 keV (due to the RQTBA strength distributions) and a factor of almost ten bigger in the theoretical calculations, both in the cross section and in the $B_{em}(E1)$. Both features seems to be ascribed to the fact that the coupling to higher configurations have to be included. The RQTBA produces strength functions which are less fragmented with respect to the experimental data. Therefore, it may be more appropriate to compare the integral of the experimental and theoretical cross section. The cumulative sums of these quantities are shown in figure 7. Apart from the global energy shift, the experimental and theoretical total cross section are in good agreement.

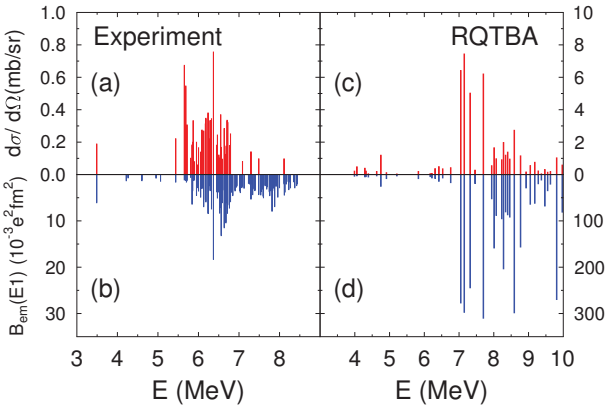

Figure 6. (Color online) Comparison of experimental (a) and RQTBA (c) based cross section for the $(\alpha, \alpha'\gamma)$ reaction and $B_{em}(E1)$ values (b and d) for ^{124}Sn. Experimental values are taken from [6, 17].

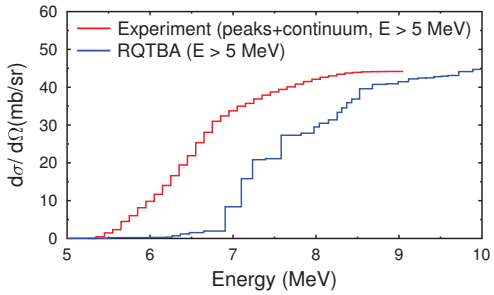

Figure 7. (Color online) Comparison of experimental and RQTBA $(\alpha, \alpha'\gamma)$ cross sections for ^{124}Sn in terms of their cumulative sums.

5. Conclusions

We have presented results where it is shown that the study of the PDR via an isoscalar probe is possible and new features can be envisaged. The study is done within a semiclassical model of the reaction. Important ingredient of this model is the construction of the microscopic form factors that reveals itself of paramount importance for the PDR state which cannot be included among the collective states. Our results show that the proper incident energy to investigate the PDR via isoscalar probes should be below 50 MeV/u. The combination of low incident energies and low charge of the partner of the reaction make the effect of the Coulomb interaction almost negligible, although its contribution to the PDR excitation is important due to a constructive interference effect. To disentangle the low lying dipole state from the other multipole states the use of the DWBA has been proved useful for data taken at very forward angles.

The so called splitting of the PDR has been analyzed with the help of the microscopic structure calculation done within the RQTBA. In the higher part of the low lying dipole peak, the calculated α-scattering cross section is strongly reduced with respect to the isovector channel. Qualitative comparison between the experimental cross section and the isoscalar reduced transition probability was previously done to understand the data. Our proper calculation of the α-scattering excitation cross section confirms the agreement between the experimentally observed splitting of the low-lying E1 strength and the results of the internal structure calculation.

Acknowledgments

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