Physics Letters B 757 (2016) 553–557

Contents lists available at ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

Dynamical coupling of pygmy and giant resonances in relativistic Coulomb excitation

N.S. Brady [a], T. Aumann [b,c], C.A. Bertulani [a,d,*], J.O. Thomas [a]

[a] Department of Physics and Astronomy, Texas A & M University-Commerce, Commerce, TX 75429, USA
[b] Institut für Kernphysik, Technische Universität Darmstadt, Schlossgartenstr. 9, 64289 Darmstadt, Germany
[c] GSI Helmholtzzentrum für Schwerionenforschung, Planckstr. 1, 64291 Darmstadt, Germany
[d] Department of Physics and Astronomy, Texas A & M University, College Station, TX 77843, USA

A R T I C L E I N F O

Article history:
Received 18 January 2016
Received in revised form 8 April 2016
Accepted 16 April 2016
Available online 20 April 2016
Editor: V. Metag

A B S T R A C T

We study the Coulomb excitation of pygmy dipole resonances (PDR) in heavy ion reactions at 100 MeV/nucleon and above. The reactions ^{68}Ni + ^{197}Au and ^{68}Ni + ^{208}Pb are taken as practical examples. Our goal is to address the question of the influence of giant resonances on the PDR as the dynamics of the collision evolves. We show that the coupling to the giant resonances affects considerably the excitation probabilities of the PDR, a result that indicates the need of an improved theoretical treatment of the reaction dynamics at these bombarding energies.

The existence of collective vibrations in neutron-rich nuclei at low energies was suggested by Kubono, Nomura, and collaborators in a 1987 proposal for the Japanese Hadron project which eventually became the J-PARC facility [1]. This proposal was later given theoretical support by Ikeda [2] and collaborators. It took nearly two decades for experimental evidences of the existence of a collective low energy response to be found in neutron-rich nuclei, far from the valley of stability. It is worthwhile mentioning that direct breakup of light and loosely-bound projectiles, such as ^{11}Be and ^{11}Li were initially thought to be indicative of a collective nuclear response but it was shown to be a direct Coulomb dissociation of the weakly-bound valence nucleons [3]. Nowadays it is known as the Pygmy Dipole Resonances (PDR), which is the strength at low-lying energies due to the fragmentation of the nuclear response [4]. The energy spectrum is typically obtained with the experimental probe of choice, i.e., relativistic Coulomb excitation of projectiles produced and accelerated in radioactive beam facilities (for related reviews, see Refs. [5,6]). In such a process, the identification of pygmy resonances is done via their decay modes, usually via gamma or neutron emission, and the energy spectrum is obtained by invariant mass reconstruction from the energy of the fragments [4]. PDRs are typically interpreted as due to the oscillation of the excess neutrons against a more tightly bound core.

Theories for giant resonances date back to when a simple hydrodynamical interpretation of protons oscillating against the neutrons was used [7,8]. Later on microscopic calculations were developed based on the linear response theory [9]. Nowadays, an effort is being undertaken to describe nuclear collective motion with more elaborated models such as the time-dependent superfluid local density approximation [10,11]. Similarly, theoretical studies of the pygmy resonances have been developed based on the improvements of the hydrodynamical model [12–14], and with microscopic theories such as the random phase approximation (RPA) and its variants [15–18]. When reactions with radioactive beams became the focus of nuclear research in the last decades, it was soon realized that slight modifications of the linear response theory predict a considerable concentration at low energies of the excitation strength in neutron-rich nuclei [19,20]. As a word of caution, the amount of the sum rule exhausted by the nuclear response at low energies strongly depends on how the nuclear interaction, pairing, and other physical phenomena are incorporated in the theory [15–20]. As an example, the public code of Ref. [21] has been used to calculate the E1 strength function, defined as

$$S(E) = \sum_{\nu} | \langle \nu || \mathcal{O}_L || 0 \rangle |^2 \delta(E - E_\nu), \quad (1)$$

defined for an RPA configuration space in terms of delta-function states ν, where $\mathcal{O}_L$ is an electromagnetic operator. A 1 MeV smearing of the fragmented strength function is introduced to yield a continuous distribution, shown in Fig. 1 for the E1 response in ^{68}Ni. In this case we used the option $\mathcal{O}_L = j_L(qr)$ in Eq. (1), where

* Corresponding author.
E-mail addresses: nbrady@leomail.tamuc.edu (N.S. Brady), t.aumann@gsi.de (T. Aumann), carlos.bertulani@tamuc.edu (C.A. Bertulani), jamesothomas@gmail.com (J.O. Thomas).

http://dx.doi.org/10.1016/j.physletb.2016.04.038

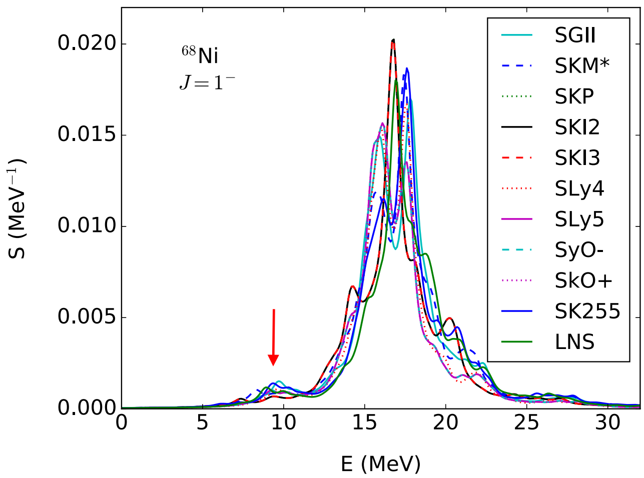

Fig. 1. Strength function for the E1 RPA response in ^{68}Ni calculated with formalism described in Ref. [21]. The calculation is performed for several Skyrme interactions, shown in the figure inset. The arrow shows the location of the pygmy resonance. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

$q = 0.1$ fm^{-1} was taken as representative of the momentum transfer. See Ref. [21] for more details. In this case, the strength function has dimensions of MeV^{-1} and in the long-wavelength approximation, $qr \ll 1$, it is proportional to the usual response for electric multipole operators. The calculation is performed for several Skyrme interactions, as listed in the figure inset. The arrow shows the location of the expected pygmy dipole resonance. The results presented in the literature, e.g., in Refs. [15–20] show a larger response in the PDR energy region due to adaptations in the model space and interactions. As of now, there is not a clear prediction of the precise location of the pygmy strength. It could be in the range of 7–12 MeV for medium mass nuclei such as Ni isotopes. The amount of the sum rule exhausted by the pygmy resonance is also relatively unknown, although some models based on nuclear clusterization can yield up to a 10% of the total strength [22].

One of the effects overseen in the experimental analysis of Coulomb excitation of pygmy resonances is the large excitation probability in Coulomb excitation at small impact parameters, leading to a strong coupling of pygmy and giant resonances. This coupling is manifested in dynamical effects such as the modification of transition probabilities and cross sections for the excitation of the PDR. This has been observed in the past in the context of the excitation of double giant dipole resonances (DGDR) [23–25]. The observation of the DGDR in experiments is a consequence of higher-order effects in relativistic Coulomb excitation and arises because the large excitation probabilities of giant resonances in heavy ion collisions at small impact parameters. The dynamical coupling between the usual giant resonances and the DGDR is very strong, as shown, e.g., in Ref. [26]. In the present work we make an assessment of this effect on the excitation of the PDR using the relativistic coupled channels (RCC) equations introduced in Ref. [27].

The S-matrix, $S_\alpha(z,b)$, for Coulomb excitation is obtained from the RCC equations [27]

$$iv\frac{\partial S_\alpha(z,b)}{\partial z} = \sum_{\alpha'} \left\langle \alpha \left| \mathcal{M}_{EL} \right| \alpha' \right\rangle S_{\alpha'}(z,b) e^{-i(E_{\alpha'}-E_\alpha)z/\hbar v}, \qquad (2)$$

where v is the projectile velocity and $\mathcal{M}_{EL}$ is the electromagnetic operator for electric dipole (E1) and quadrupole (E2) transitions connecting states α and α' satisfying the selection rules of their intrinsic angular momenta and parities. The ground state is denoted by $|0\rangle = |E_0 J_0 M_0\rangle$ and the excited states by $|\alpha\rangle = |E_\alpha J_\alpha M_\alpha\rangle$, where $|EJM\rangle$ labels intrinsic energy and angular momentum quantum numbers. In the long-wavelength approximation the electromagnetic operators are given by [27]

$$\mathcal{M}_{E1m} = \sqrt{\frac{2\pi}{3}}\xi Y_{1m}(\hat{\boldsymbol{\xi}}) \frac{\gamma Z_T e^2}{\left(b^2+\gamma^2 z^2\right)^{3/2}} \begin{cases} \mp b \ \ (\text{if} \ \ m=\pm 1) \\ \sqrt{2}z \ \ (\text{if} \ \ m=0) \end{cases} \qquad (3)$$

where $\boldsymbol{\xi}$ is the intrinsic coordinate of the excited nucleus and Ze is the charge of the nucleus giving rise to the electromagnetic field (in our case, the target). For E2 transitions the electromagnetic operator is [27]

$$\mathcal{M}_{E2\mu} = \sqrt{\frac{3\pi}{10}}\xi^2 Y_{2\mu}(\hat{\boldsymbol{\xi}}) \frac{\gamma Z_T e^2}{\left(b^2+\gamma^2 z^2\right)^{5/2}} \times \begin{cases} b^2 \quad (\text{if} \quad \mu=\pm 2) \\ \mp 2\gamma^2 bz \quad (\text{if} \quad \mu=\pm 1) \\ \sqrt{2/3}\left(2\gamma^2 z^2 - b^2\right) \quad (\text{if} \quad \mu=0). \end{cases} \qquad (4)$$

Note that $\mathcal{M}_{ELm} = f_{ELm}(\mathbf{r})\mathcal{O}_{ELm}$, where $\mathcal{O}_{ELm} = \xi^L Y_{Lm}(\hat{\boldsymbol{\xi}})$ is the usual electric operator, and $f_{ELm}(\mathbf{r})$ is a function of the projectile-target relative position $\mathbf{r} = (\mathbf{b}, z)$.

The coupled equations (2) are solved by using $S_\alpha(z \to -\infty) = \delta_{\alpha 0}$. For high energies and very forward angles, the cross sections for the $|0\rangle \longrightarrow |\alpha\rangle$ transition are given by

$$\frac{d\sigma_\alpha}{dE} = 2\pi\, w_\alpha(E) \int db\, b \exp\left[-2\chi(b)\right] \left|S_\alpha(z\to\infty, b)\right|^2, \qquad (5)$$

where $w_\alpha(E)$ is the density of final states, b is the impact parameter in the collision, and $\chi(b)$ is the eikonal absorption phase given by

$$\chi(b) = \frac{\sigma_{NN}}{4\pi} \int dq\, q \rho_1(q) \rho_2(q) J_0(qb), \qquad (6)$$

where σ_{NN} is the experimental value of the total nucleon–nucleon cross section with medium corrections added according to Refs. [28,29] and $\rho_i(q)$ is the Fourier transform of the ground state densities of the nuclei obtained from fitting to electron scattering experiments [30] for ^{197}Au and using Hartree–Fock–Bogoliubov calculations for ^{68}Ni with the SLy4 interaction. It is worth mentioning that the use of the eikonal absorption phase to cut down the Coulomb excitation mechanism at small impact parameters has been introduced in Ref. [31] for the first time to calculate cross sections relevant to GDR and DGDR excitations. The effects of nuclear excitation have been subtracted in the experiments [32–34]. Therefore, we did not include nuclear excitations, and possible interferences, in these calculations.

We consider the excitation of ^{68}Ni on ^{197}Au and ^{208}Pb targets at 600 and 503 MeV/nucleon, respectively. These reactions have been experimentally investigated in Refs. [32,33]. In the first experiment a pygmy dipole resonance in ^{68}Ni was identified at $E_{PDR} \simeq 11$ MeV with a width of $\Gamma_{PDR} \simeq 1$ MeV, exhausting about 5% of the Thomas–Reiche–Kuhn (TRK) energy-weighted sum rule. The identification was done with the analysis of the excitation and decay via gamma emission. In the second experiment the PDR centroid energy was found to be at 9.55 MeV, with a 2.8% fraction of the TRK sum rule, a width of 0.5 MeV, and the PDR identification was done by measuring the neutron decay channel of the PDR. In this work our objective is to study the effects of the coupling between the several giant resonances with the PDR, and therefore we will only calculate the excitation function $d\sigma/dE$ without concern for the decay channels.

One needs a model for bound and continuum discretized wavefunctions entering the matrix elements $\langle \alpha | \mathcal{M}_{EL} | \alpha' \rangle$ in Eq. (2). The wavefunctions can also be used to calculate the response