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PHYSICS LETTERS B
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Physics Letters B 547 (2002) 205–209
www.elsevier.com/locate/npe

Coupling of giant resonances to soft E1 and E2 modes in ^{8}B

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Received 28 August 2002; accepted 1 October 2002

Editor: W. Haxton

Abstract

The dynamic coupling between giant resonance states and "soft" low-energy excitation modes in weakly-bound nuclei is investigated. A coupled-channels calculation is reported for the reaction $^8\text{B} + \text{Pb} \to \text{p} + {}^7\text{Be} + \text{Pb}$ at 83 MeV/nucleon. It is shown that the low-energy response is only marginally modified by transitions to the isovector giant dipole and isoscalar giant quadrupole resonances.

PACS: 21.10.Pc; 24.10.Eq; 24.30.Cz

Keywords: Electromagnetic response; Giant resonances; Soft dipole modes

The nuclear response to external electromagnetic fields is one of the main probes of the structure of nuclei far from the stability valley [1]. The Coulomb excitation of rare isotopes in high energy collisions ($E_{\text{Lab}} \gtrsim 50$ MeV/nucleon) has revealed the existence of "soft" excitation modes [2,3]. However, it is still an open question if these modes represent a new type of collective motion, or a resonance in the continuum, as predicted by some theories [4]. These soft modes can also been explained as a simple consequence of the phase-space availability of transitions from a bound-state to a structureless continuum [5]. These questions are of extreme relevance for experimental strategies, since the Coulomb dissociation method has become a powerful experimental alternative to access information on the radiative capture processes occurring in numerous astrophysical scenarios [6,7].

It is not known if the low energy peak in the Coulomb excitation cross sections of ^{11}Li [3] is due to the existence of a resonant state close to threshold. But, the Coulomb breakup of ^{8}B is well explained by a direct transition of a bound particle state ($p_{3/2}$ proton) to a structureless continuum. This transition is caused by the action of the time-dependent electric dipole (E1) and electric quadrupole (E2) fields of the target nucleus. The resonance state at 630 keV in ^{8}B, which plays an important role in magnetic dipole (M1) transitions of the radiative capture reaction $^7\text{Be}(p,\gamma)^8\text{B}$ occurring in the sun, is imperceptible in Coulomb dissociation experiments [8].

The E1 and E2 response in ^{8}B is reasonably well described by a proton + ^{7}Be-core model with an spectroscopic factor close to unity [9]. This model yields an astrophysical S-factor $S_{17} = 18$ eV b at

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PII: S0370-2693(02)02771-5

$E_{17} = 20$ keV, where E_{17} is the relative energy of the proton–beryllium system in the solar environment. This value of S_{17} is the most recommended value, based on the average of numerous direct and indirect experiments [10].

Thus, it seems that the low-energy response in ^{8}B is due entirely to the promotion of a valence proton from the $p_{3/2}$ level into the continuum [11]. This excitation process decouples from the higher energy excitations, except in a situation where multi-step processes are relevant. Hence, with no configuration mixing, the electromagnetic response coincide with the free response (with no residual interaction) in the low energy region. Although more elaborate models exist in the literature [12,13], I will adopt the proton + ^{7}Be-core model to obtain the E1 and E2 low-energy response of ^{8}B ($E_x \lesssim 5$ MeV).

Giant resonances (GRs) are collective vibrations in nuclei and have been known for a long time (for a review, see Ref. [14]). Their energies and widths have been studied for a large number of nuclei. Some experimental data have been obtained with real photons, which are well suited for (isovector) E1 excitation modes. Isoscalar E2 and higher modes have been best studied with α or proton scattering. E0 (breathing) modes have also been studied with electron and nucleus–nucleus scattering. Nowadays a great effort is underway [15] to understand the structure of double giant resonances, i.e., giant resonances excited on another giant resonance state [16]. Such studies have been performed with stable nuclear species. We have practically no information about giant resonances in very light nuclei (e.g., ^{9}Be), or in neutron or proton-rich nuclei (e.g., ^{8}B, or ^{11}Li) although theoretically one expects them to exist [17].

The effect of continuum–continuum transitions on the low-energy response of weakly-bound nuclei was first mentioned and studied in Ref. [18]. More recently, intensive theoretical studies have been performed [8,9, 19] to access the relevance of continuum–continuum transitions in the breakup reactions of ^{8}B, ^{11}Li, and other exotic light nuclei. But besides the low energy continuum–continuum couplings, the giant resonances located at much higher energies could also have some influence on the low-lying states through a dynamic coupling during the reaction process. This assumption is based on the known fact that the giant resonances exhaust the largest part of the electromagnetic response in heavy stable nuclei (see, e.g., [20]). This often leads to a large excitation cross section of giant resonance states in Coulomb excitation at high bombarding energies [7]. This hypotheses is worth investigation in the case of light-neutron- or proton-rich nuclei.

In this Letter I report a study of the influence of the GR states on the soft modes. A continuum discretized coupled-channels calculation (CDCC) was done which includes nuclear and Coulomb induced breakup of ^{8}B projectiles incident on heavy (large-Z) targets. A microscopic description of the GRs in very light nuclei, using, e.g., the random phase approximation, probably leads to unreliable results. Thus, a more conservative approach is adopted, describing the giant dipole resonance (GDR, $\lambda = 1$) and the giant quadrupole (isoscalar) resonance (GQR, $\lambda = 2$) by means of a Breit–Wigner function,

$$f_{E\lambda}(E) = \frac{C_\lambda}{(E - E_\lambda)^2 + \Gamma_\lambda^2/4}, \tag{1}$$

centered on the energy E_λ of the resonance. The continuum is discretized with an energy mesh around the resonances, using Eq. (1) as reference. In terms of $f_{E\lambda}(E)$, the total response function is given by

$$B(E\lambda) = \sum_k f_{E\lambda}(E_k)\Delta E_k, \tag{2}$$

where $E\lambda = E1,\ E2$, and $\Delta E_k = E_k - E_{k-1}$ is the energy interval. The reduced matrix elements for the excitation of the energy state at $E = E_k$ from the ground state, or from a low-lying state in the continuum ($E_i \leqslant 5$ MeV), are given by $\langle k\| O(E\lambda)\| i\rangle = (2I_i + 1)\sqrt{f_{E\lambda}(E_k)\Delta E_k}$, where I_i is the spin of the initial state i. Typical values were adopted for their widths, $\Gamma_{\lambda=1,2} = 4$ MeV, and for their energy centroids, $E_{\lambda=1} = 30$ MeV and $E_{\lambda=2} = 20$ MeV, respectively.

The constants C_λ are obtained by assuming that the GRs exhaust 100% of the energy-weighted sum-rule. This yields

$$C_1 = \frac{9}{16\pi^2}(2I_i + 1)\frac{\Gamma_1}{E_{\lambda=1}}\frac{\hbar^2}{m_N}\frac{NZ}{A}e^2 \quad \text{and}$$
$$C_2 = \frac{15}{8\pi^2}(2I_i + 1)\frac{\Gamma_2}{E_{\lambda=2}}\frac{\hbar^2}{m_N}R_m^2\frac{Z^2}{A}e^2, \tag{3}$$

where N, Z, and A are the neutron, charge, and mass numbers of the excited nucleus, m_N is the nucleon mass, and $R_m = \sqrt{\langle r^2 \rangle}$ is the ground-state density matter radius. For ^{8}B the value $R_m = 2.38$ fm, obtained by a Skyrme–Hartree–Fock calculation [21], is used.

The values of the normalization constants in Eq. (3) follow from the energy weighted-sum-rules (EWSR):

$$S_{E\lambda} = \int B(E\lambda; E)\, dE = \int f_{E\lambda}(E_x)\, dE_x$$
$$= \begin{cases} \dfrac{9}{4\pi}\dfrac{\hbar^2}{2m_N}\dfrac{NZ}{A}e^2, \\ \quad \text{for E1 isovector excitations,} \\ \dfrac{30}{4\pi}\dfrac{\hbar^2}{2m_N}\langle r^2 \rangle \dfrac{Z^2}{A}e^2, \\ \quad \text{for E2 isoscalar excitations.} \end{cases} \tag{4}$$

The contribution of nuclear excitations have been included using the collective vibration model [20, 22,23]. In this model the structure input are the deformation parameters δ_1 and δ_2, obtained from the EWSR, Eq. (4). That is,

$$\delta_1^2 = \pi \frac{\hbar^2}{2m_N}\frac{A}{NZ}\frac{1}{E_{GDR}} \quad \text{and}$$
$$\delta_2^2 = \frac{20\pi}{3}\frac{\hbar^2}{m_N}\frac{1}{AE_{GQR}}. \tag{5}$$

To account for the width of the GRs, Eq. (5) is multiplied by f_λ given by Eq. (1), with $C_\lambda = \Gamma_\lambda/2\pi$. In this way, the deformation parameters acquire an energy dependence.

In the collective vibration model the nuclear excitation is induced by the deformed potentials

$$U_1(r,E) = \delta_1(E)\frac{3}{2}\frac{\Delta R}{R_m}\left(\frac{dU_{\text{opt}}}{dr} + \frac{1}{3}R_m \frac{d^2U_{\text{opt}}}{dr^2}\right)$$
$$\text{and} \quad U_2(r,E) = -\delta_2(E)\frac{dU_{\text{opt}}}{dr}, \tag{6}$$

where $\Delta R = R_p - R_n = (2.54 - 2.08)\,\text{fm} = 0.46$ fm is the difference between the proton, R_p, and the neutron, R_n, radius in ^{8}B [21]. The optical potentials U_{opt} are constructed from the ground state densities of the colliding nuclei and the "t–$\rho\rho$" approximation, as explained in Ref. [24].

The electromagnetic matrix elements for the excitation of soft E1 and E2 modes were calculated with the potential model of a proton $+^7$Be-core, as presented in Ref. [8]. The 2^+ ground state of ^{8}B is described as a $p_{3/2}$ proton coupled to a $3/2^-$ ground state of the ^{7}Be core. The E1 soft excitations consist of transitions from the ground state to $s_{1/2}$, $d_{3/2}$ and $d_{5/2}$ continuum single-particle states. The E2 excitations consist of transitions to $p_{1/2}$, $p_{3/2}$, $f_{5/2}$ and $f_{7/2}$ states. Continuum–continuum transitions between the low-lying states have been considered in Ref. [8] and are not taken into account here, as we want to isolate the effect of the giant resonances. The form of the nuclear response for the soft-modes within this model, and for the GRs according to the parametrization described by Eqs. (1) and (2), are plotted in Fig. 1. One observes that the assumption that the GRs fully exhaust the EWSRs is an overestimation. An appreciable part of the sum rule goes to the excitation of the soft modes, specially for the case of E2 excitations. Indeed, for ^{8}B the EWSR given in Eq. (4) yield $S_{\text{E1}}^{\text{total}} = 28\, e^2\,\text{fm}^2$ MeV and $S_{\text{E2}}^{\text{total}} = 890\, e^2\,\text{fm}^4$ MeV, respectively. These values should be compared to the energy integrated multipole response of the soft modes: $S_{\text{E1}}^{\text{SD}} = 0.546\, e^2\,\text{fm}^2$ MeV and $S_{\text{E2}}^{\text{SD}} = 396\, e^2\,\text{fm}^4$ MeV, respectively. Although the E1 soft mode corresponds to a very small part of the total sum-rule, it is responsible for large Coulomb dissociation cross sections, since low energy E1 virtual photons are much more

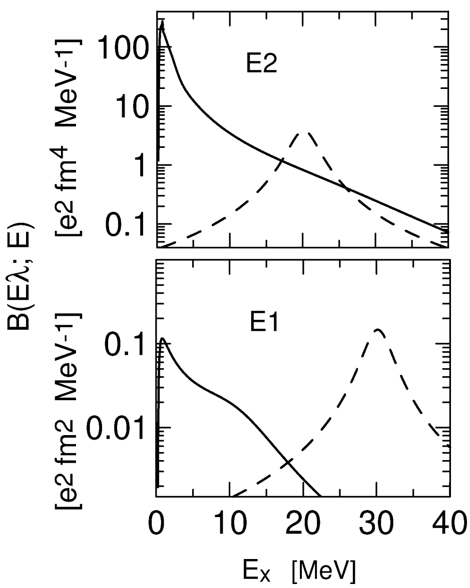

Fig. 1. E2 (upper figure) and E1 (lower figure) response in ^{8}B. The low energy response (solid curves) was calculated with a potential model. The high energy response (dashed curves) for the giant resonances was parametrized in terms of Breit–Wigner functions.

abundant. In contrast, the E2 soft mode as obtained with the potential model, exhausts 44% of the EWSR. This is a hint that the potential model overestimates the magnitude of the E2 response function. Indeed, a recent experiment [25] has suggested that the momentum distributions following the Coulomb breakup of ^{8}B can only be explained if the E2 response obtained from the proton + ^{7}Be-core model is quenched by a factor 2.

The structure inputs as described above were used in a calculation using the coupled-channels code DWEIKO [24] that includes relativistic dynamics, important for bombarding energies of 84 MeV/nucleon. As the main interest is for the low energy region, the energy mesh for the continuum discretization was taken as 10 energy states equally spaced in the energy interval of 0–2 MeV. To account for the effect of the GR, 20 energy states equally spaced in the interval 10–40 MeV were taken. The results of the coupled-channels calculations were matched to results of first-order perturbation calculations at impact parameters larger than 50 fm.

The results are plotted in Fig. 2. The solid curve shows the cross section for the Coulomb dissociation reaction $^8\mathrm{B} + \mathrm{Pb} \to \mathrm{p} + {^7\mathrm{Be}} + \mathrm{Pb}$ at 84 MeV/nucleon using first-order perturbation (PT) theory [8]. The numerical results have been normalized to the data. The same normalization factor was used for the coupled-channels results, shown by the dashed line.

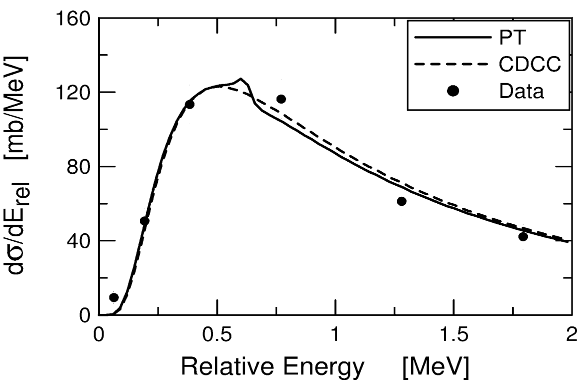

Fig. 2. Energy dependence of the cross section for $^8\mathrm{B} + \mathrm{Pb} \to \mathrm{p} + {^7\mathrm{Be}} + \mathrm{Pb}$ at 84 MeV/nucleon. First-order perturbation calculations (PT) are shown by the solid curve. The dashed curve is the result of a CDCC calculation including the coupling between the ground state and the low-lying states with the giant dipole and quadrupole resonances. The data points are from Ref. [10].

The first order perturbation calculation shows a small peak at $E_{\mathrm{rel}} = E_x - 0.134$ MeV $= 640$ keV due to the excitation of the 1^+ resonance. This peak is washed-out in the coupled-channels calculations due to the mesh size used. The coupled-channels calculation is slightly different than the first-order perturbation results, only for energies above 0.7 MeV. However, the correction is very small, being no larger than 2% for the whole energy interval.

We conclude that the effect of the giant resonances on the Coulomb dissociation cross sections of ^{8}B projectiles is small and can be neglected. A similar conclusion is expected to hold for the breakup reactions of other weakly-bound nuclei. The total excitation cross sections of soft modes in ^{8}B for the reaction studied here are $\sigma_{\mathrm{E1}}^{\mathrm{SD}} = 370$ mb $\sigma_{\mathrm{E2}}^{\mathrm{SD}} = 236$ mb, while the cross sections for the excitation of GRs are $\sigma_{GDR} = 2.5$ mb and $\sigma_{GQR} = 6.5$ mb, respectively. This is the reason for the small relevance of the GRs in the dynamic coupling. The situation can be very different for the heavier nuclei which have a larger response to the electromagnetic excitation in the region of giant resonances. Although they have not yet been studied in details experimentally, the electromagnetic response of heavy neutron- or proton-rich nuclei close to the dripline will probably contain soft multipole modes. These are very likely to be influenced by the dynamic coupling to the much higher-lying giant resonance states.

Acknowledgements

I would like to thank Sam Austin for suggesting this problem and to Alex Brown for providing the ^{8}B density distribution parameters. This research was supported in part by the US National Science Foundation under Grants No. PHY-007091 and PHY-00-70818.

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