A coupled-channels study of ^{11}Be Coulomb excitation

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Abstract

We study the effects of channel coupling in the excitation of ^{11}Be projectiles incident on heavy targets. The contribution to the excitation from the Coulomb and the nuclear fields in peripheral collisions are considered. Our results are compared with recent data on the excitation of the $\frac{1}{2}^-$ state in ^{11}Be projectiles. We show that the experimental results cannot be explained, unless very unusual parameters are used.

Unstable nuclei are often studied in reactions induced by secondary beams. Examples of such reactions include elastic scattering, fragmentation and Coulomb excitation in collisions with very heavy targets [1]. Coulomb excitation is especially useful, since the interaction mechanism is well known. The cross sections for Coulomb excitation of radioactive beams yield precious information on the intrinsic electromagnetic moments of these nuclei. Such information is hard to obtain with other methods due to the short lifetime of unstable projectiles. Recently, the Coulomb excitation of the halo nucleus ^{11}Be has been

investigated [2,3]. In Ref. [2] the transition from the ground state (a parity-inverted $\frac{1}{2}^+$ state) of ^{11}Be to the continuum (with threshold at 504 keV) was studied and a good agreement with the theory was found. On the other hand, in Ref. [3] the Coulomb excitation of the $\frac{1}{2}^-$ state at 320 keV (the only excited state in ^{11}Be [4]) was studied in collisions of 45 MeV A ^{11}Be beams on ^{208}Pb targets. Amazingly, it was found that the measured cross section, 191±26 mb, is a factor 2 smaller than that expected from first order perturbation theory, using $B(E1) = 0.116\pm0.012$ e^2 fm^2. This $B(E1)$-value is an average over three distinct experiments which yield a lifetime of 166±15 fs for this state.

It has been suggested that the reason for the above mentioned discrepancy could be the coupling of the bound states in ^{11}Be and the continuum, or the contribution from nuclear excitation causing a destructive Coulomb-nuclear interference [3,5]. We will investigate these possibilities here using a semiclassical

coupled-channels approach to the Coulomb and nuclear excitation of the $\frac{1}{2}^{-}$ state in ^{11}Be. The spin and parities of the states involved imply that the Coulomb dipole excitation corresponds to the largest contribution to the cross section. This has been experimentally observed [2,3] and is theoretically understood [7].

We treat the Coulomb excitation in the semiclassical formalism, assuming a straight-line trajectory for the projectile, and including relativistic effects in the interaction. The matrix element for the Coulomb dipole potential in a collision with impact parameter b is

$$\langle k|V_{(E1)}(t)|i\rangle = \sqrt{\frac{2\pi}{3}}\, \gamma \left\{ \mathcal{E}_1(\tau)\, \left[\mathcal{M}_{ki}(E1,-1) \right.\right.$$
$$\left. - \mathcal{M}_{ki}(E1,1) \right] + \sqrt{2}\,\gamma\,\tau\, \left[\mathcal{E}_1(\tau) \right.$$
$$\left.\left. - i\frac{\omega v b}{c^2}\,\left(1+\tau^2\right)\, \mathcal{E}_2(\tau) \right] \mathcal{M}_{ki}(E1,0) \right\}, \qquad (1)$$

where γ is the Lorentz factor, $\tau = (\gamma v/b)\, t$, $\hbar\omega$ is the excitation energy, and

$$\mathcal{E}_1(\tau) = \frac{Z_T e}{b^2\,[1+\tau^2]^{3/2}}, \quad \mathcal{E}_2(\tau) = \frac{Z_T e \tau}{b\,[1+\tau^2]^{3/2}} \qquad (2)$$

are respectively the transverse and longitudinal electric fields generated by the target nucleus. The matrix elements for electric dipole excitations are given by $\mathcal{M}_{ki}(E1,m) = e\,\langle k|rY_{1m}|i\rangle$, where e is the electron charge.

We will solve numerically the coupled-channels equations

$$\frac{da_k}{dt}(t) = \sum_i \langle k|V(t)|i\rangle\, \exp\left\{ i(E_k - E_i)t/\hbar \right\}\, a_i(t)\,, \qquad (3)$$

where the $|k\rangle$ denote the (discrete) nuclear states. For the Coulomb coupling, the Wigner-Eckart theorem allows us to write the matrix elements $\langle k|V(t)|i\rangle$ in terms of the $B(E1;M\lambda)$-values for the electromagnetic multipole transitions. For the transition $\frac{1}{2}^{+} \rightarrow \frac{1}{2}^{-}$ we use the previously mentioned B(E1)-value. The Coulomb dipole transitions to the continuum are treated by means of a discretization procedure. In Refs. [2,7] it was shown that the dipole response for the transitions from the bound-state to the continuum can

be appreciably well accounted for by neglecting final state interactions and using the asymptotic value of the ground state wave function, represented by an Yukawa tail. This dipole response is given by [1]

$$\frac{1}{e^2}\frac{dB(E1;\,E_x)}{dE_x} = C\,\frac{\sqrt{S}\,(E_x - S)^{3/2}}{E_x^4}\,, \qquad (4)$$

where E_x is the excitation energy, and S is the separation energy of the valence neutron in ^{11}Be. C is a normalizing constant, which the two-body ($n + ^{10}$Be) model predicts to be independent of the separation energy. In the experiment of Ref. [2] it was found that the best fit to the data corresponds to $C = 3.73 \pm 0.7$ fm^2/MeV. We also use this value for the transition $\frac{1}{2}^{-} \rightarrow$ continuum.

The continuum is discretized so that the B(E1)-values from the bound states to the nth state in the continuum are given by

$$B(E1;\,i \rightarrow n) = \Delta E_x \cdot \left.\frac{dB(E1,\,E_x)}{dE_x}\right|_{E_x = E_n}\,,$$

which can be calculated with help of Eq. (4). Above, ΔE_x is the spacing in the continuum energy mesh. In our numerics we use $\Delta E_x = 0.3$ MeV, and a total of 10 discretized continuum states. This mesh covers the most important part of the continuum dipole response function in ^{11}Be [2]. A phase convention for the nuclear states can be found so that the reduced matrix elements $\langle I_f M_f || \mathcal{M}(E;M\lambda)||I_i M_i\rangle$ are real [6]. We noticed that in the present problem the sign of the matrix elements do not appreciably affect the results. We then set all matrix elements as positive.

With the above described procedure, the matrix elements for the transitions from the bound states to the continuum are fixed. We neglect the coupling between the continuum states, since it corresponds to reacceleration effects, which has been shown to be small for this system [7]. The integrated dipole response in the continuum is obtained from Eq. (4) as

$$B(E1;\,i \rightarrow \text{cont.})/e^2 = \frac{\pi C}{16S}\,, \qquad (5)$$

where i stands for one of the two bound states in ^{11}Be. Using the experimental value of C, we get $B(E1;\,\frac{1}{2}^{+} \rightarrow \text{cont.}) = 1.45\,e^2$ fm^2, for the ground state, and $B(E1;\,\frac{1}{2}^{-} \rightarrow \text{cont.}) = 4.06\,e^2$ fm^2 for the first excited state.

Table 1
Experimental and theoretical cross sections for ^{11}Be excitation in the ^{11}Be (45 MeV A)+^{208}Pb reaction

	Exp.	Theory (1)	Theory (2)	Theory (3)	Theory (4)
$\sigma_{1/2-}$ (mb)	191 ± 26	405.81	405.80	388.2	390.2
$\sigma_{cont.}$ (mb)	–	–	–	334.5	335.2

In "Theory (1)" the coupled-channel calculation was restricted to the $\frac{1}{2}^+$ and $\frac{1}{2}^-$ channels. In "Theory (2)" the reorientation effect caused by the M1-transition $\frac{1}{2}^+ \rightarrow \frac{1}{2}^+$ was introduced. In "Theory (3)" we included the coupling between the $\frac{1}{2}^+$ and $\frac{1}{2}^-$ states with the continuum. Finally, in "Theory (4)" we included nuclear coupling effects.

With respect to the nuclear interaction in peripheral collisions, we expect that the most relevant contributions arise from the monopole and quadrupole isoscalar excitation modes. Isovector excitations are strongly suppressed [8] due to the approximate charge independence of the nuclear interaction. We adopt the folding optical potential of Ref. [9]. For the ground state density of ^{11}Be we use the results [9] of the Hartree-Fock formalism with Skyrme interaction, and for ^{208}Pb we take a Fermi density with radius $R = 6.67$ fm and diffuseness $a = 0.55$ fm. The monopole and quadrupole transition potentials were calculated with the Tassie model, as explained in Ref. [9]. In terms of the optical potential $U_{opt}(r)$, they can be written

$$V_N(r) = \begin{cases} \alpha_0 \left[3U_{opt}(r) + r \, dU_{opt}(r)/dr \right] \\ \quad \text{for monopole;} \\ (\delta_2/\sqrt{5}) \left[dU_{opt}(r)/dr \right] \\ \quad \text{for quadrupole,} \end{cases} \quad (6)$$

where α_0 and δ_2 are parameters to fit inelastic scattering data. Since there are no such data on ^{11}Be, we arbitrarily choose $\alpha_0 = 0.1$ and $\delta_2 = 1$ fm. These values correspond to about 5% of the energy-weighted sum rule, if a state at 1 MeV excitation energy is assumed, and should be reasonable for a qualitative calculation. The nuclear couplings are given a time-dependence though the application of a Lorentz boost on the system. This amounts to multiplying Eq. (6) by the Lorentz factor γ, and using $r = \sqrt{b^2 + \gamma^2 v^2 t^2}$.

The cross section to excite the state k are calculated from the relation

$$\sigma_k = 2\pi \int db \, b \, |a_k(b)|^2$$

$$\times \exp\left((2/\hbar v) \, \text{Im}\left\{ \int dz \, U_{opt}(r) \right\} \right), \quad (7)$$

where $r = (b, z)$. The exponential term accounts for the strong absorption along the classical trajectory.

In Table 1 we present the results of our calculations. In the column "Theory (2)", reorientation effects caused by the magnetic dipole transitions $\frac{1}{2}^+ \rightarrow \frac{1}{2}^+$ are included. For this purpose, we use the Schmidt value $B(M1, \frac{1}{2}^+ \rightarrow \frac{1}{2}^+) = 0.087 \, e^2 \, fm^2$, and calculate the magnetic dipole coupling through the same procedure as that employed for V_{E1} [10]. We observe that this effect can be neglected, since it causes a negligible change in the cross sections. On the other hand, the inclusion of the coupling to the continuum yields more sizeable effects. The cross section for the excitation of the $\frac{1}{2}^-$ state decreases by about 4%. This reduction is, however, still too small to explain the discrepancy between experiment and theory. Finally, in the column "Theory (4)", we present effects of nuclear excitation. These effects are also very small. The reason is that the nuclear interaction is limited to a very small impact parameter region, around the grazing value, as illustrated in Fig. 1. The cross sections for the nuclear excitation of monopole and quadrupole states are respectively 7.07 mb and 6.22 mb. A second reason for this fact is that Coulomb-nuclear interference only appears for high-order transitions, i.e., those involving many excitation steps. This occurs because the Coulomb coupling is dominated by the dipole term while the nuclear coupling is dominated by monopole and quadrupole. In Table 1 we also show the dissociation cross section, $\sigma_{cont.}$. It is of the same magnitude as $\sigma_{1/2-}$.

The above discussion indicates that the most important factor leading to the reduction of $\sigma_{1/2-}$ is the coupling between the bound states and the continuum. We cannot be sure that the adopted $B(E1; \frac{1}{2}^- \rightarrow$ cont.)-value is accurate, since the form of Eq. (6) has
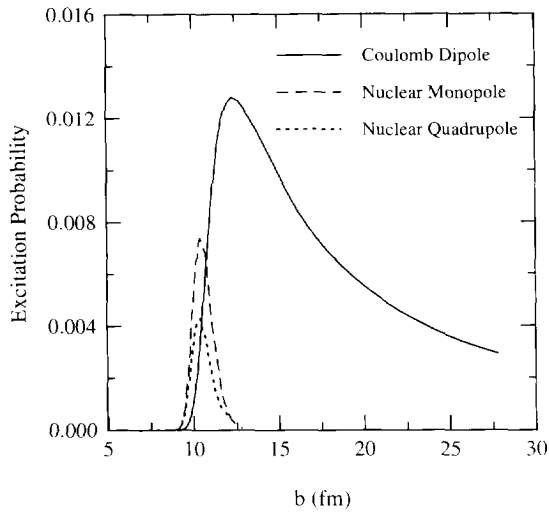
Fig. 1. Excitation probabilities of the $\frac{1}{2}^-$ state by the Coulomb field, and of hypothetical low-lying monopole and quadrupole states by means of the nuclear interaction as a function of the impact parameter b. The reaction ^{11}Be $+^{208}$Pb at 45 MeV A is considered.

been shown to be appropriate for transitions from the ground state [2,7]. It is therefore worthwhile to let the strength $B(\text{E1}; \frac{1}{2}^- \rightarrow \text{cont.})$ vary and study the effects on the $\sigma_{1/2-}$ cross section. This is shown in Fig. 2, where we plot the quantity

$$\Delta = \frac{\sigma_{\frac{1}{2}-}(\xi) - \sigma_{\frac{1}{2}-}(\xi = 1)}{\sigma_{\frac{1}{2}-}(\xi = 1)}, \qquad (8)$$

where ξ is a renormalization factor multiplying the strength given by Eq. (6). We see that, increasing this strength reduces the cross section $\sigma_{1/2-}$. However, this reduction is much smaller than the factor 2 needed for an agreement with the data. We point out that, even assuming the complete exhaustion of the energy-weighted dipole sum-rule for this state (corresponding to the indicated ξ-value in Fig. 2), the reduction still falls very short.

We conclude that taking into account nuclear coupling and multistep coupled-channel processes cannot improve appreciably the disagreement between the experiment of Ref. [3] and the theory. The depopulation of the state $\frac{1}{2}^-$ arising from its coupling to the continuum, is not large enough. This result is not surprising, since the $\frac{1}{2}^+ \rightarrow \frac{1}{2}^-$ transition probability is very small, even for grazing collisions (see Fig. 1).
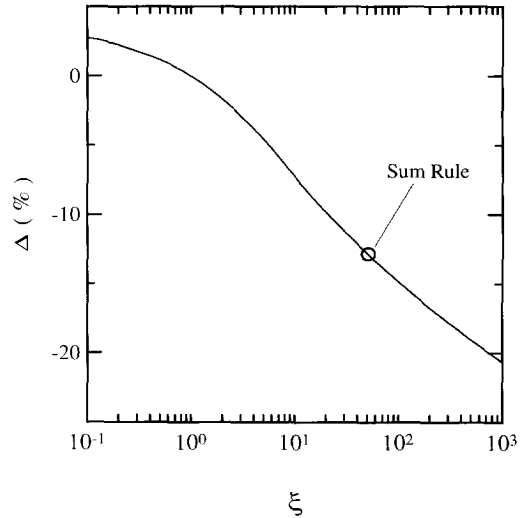

Fig. 2. The ratio $\Delta = \left[\sigma_{\frac{1}{2}-}(\xi) - \sigma_{\frac{1}{2}-}(\xi = 1) \right] / \sigma_{\frac{1}{2}-}(\xi = 1)$ for the excitation of the $\frac{1}{2}^-$ state in ^{11}Be is shown as a function of the strength parameter ξ.

Thus, first order perturbation theory is appropriate to calculate the cross sections. A further increase of the transition probability from the excited state to the continuum would occur in the presence of a resonance in ^{11}Be close to the threshold. However, presently, this hypothesis lacks experimental evidence [2]. Further studies are needed to clarify this matter.

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