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Interference effects in the Coulomb dissociation of ^{8}B

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Abstract

The interference between E1 and E2 in the Coulomb breakup of ^{8}B strongly affects the angular distribution of the decay proton. Thus this measurement could provide empirical information on the magnitude of the E2 contribution, which has been the subject of recent controversy.

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There has been much recent interest in using Coulomb breakup reactions to infer capture cross sections at very low energy, following the suggestion of Ref. [1]. In particular, the reaction (^{8}B,^{7}Be+p) has been measured [2] with the aim of determining the cross section for the reaction ^{7}Be+p $\rightarrow$ ^{8}B. This reaction is important for the flux of high energy neutrinos from the sun [3].

A simple analysis is possible only when a single multipole, in this case E1, dominates the cross section. One problem with using Coulomb breakup in the ^{8}B reaction is that the E2 multipole is not negligible [4] and so detailed balance cannot be used without some further assumptions or information. We will show in this Letter that the angular distribution of decay protons in the ^{7}Be +p final state following Coulomb excitation of ^{8}B is sensitive to interference between E1 and E2 amplitudes, and can therefore be used to resolve the question of the importance of E2.

Because of the nonzero spin of ^{8}B ($J = 2$), there are many interfering channels produced by E1 and E2 excitation, and it only seems possible to analyze the angular distribution by comparing to specific models. We will thus carry out a model calculation to demonstrate the sensitivity. The model and its predictions are discussed in greater detail in Ref. [5]. Here we summarize the main ingredients:

(a) *Coulomb excitation amplitudes.* We write the probability amplitude $a_{\rm fi}$ to excite with the effective charge multipole field $\mathcal{M}_{\lambda,\mu} = e_\lambda r^\lambda Y_{\lambda,\mu}(\theta,\phi)$ as

$$a_{\rm fi} = -i \sum_{\pi\lambda\mu} F_{\lambda\mu} \, \langle {\rm f}|\mathcal{M}_{\lambda\mu}|{\rm i}\rangle \, . \qquad (1)$$

The F depends on impact parameter, beam velocity, and excitation energy. We use the formulas of Winther and Alder [6], which assumes that the projectile moves in a straight-line trajectory. The geometry is here opposite to that used in radioactive beam experiments: the ^{8}B nucleus is the target and it is excited by the Coulomb field from projectile nuclei. In the notation of Winther and Alder, the F field associated with electric Coulomb excitation is given by

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$$F_{\lambda\mu} = \frac{Z_P e}{\hbar v \gamma} \sqrt{2\lambda+1} \left(\frac{\omega}{c}\right)^{\lambda} G_{E\lambda\mu} \, K_\mu(\xi) \, . \qquad (2)$$

(b) *Multipole matrix elements.* We follow Robertson [7] and use a simple particle-core model for ^{8}B. The core has angular momentum $I_c = 3/2$, and the states are labeled by the angular momenta of the particle, (ℓ, j), and the total angular momentum J. The ground state is assumed to be a pure configuration, $\ell_0(j_0 I_c)_{J_0} = (p_{3/2} 3/2)_2$. The matrix elements of the multipole operator are calculated for the particle alone, neglecting the core contribution except for its influence on the effective electric multipole charge e_λ. The angular momentum recoupling to express the many-particle reduced matrix element in terms of the single-particle reduced matrix element gives the formula

$$\begin{aligned}&\langle E\ell(jI_c)J \| \mathcal{M}_\lambda \| \ell_0(j_0 I_c)J_0\rangle \\ &\quad = (-1)^{j+I_A+J_0+\lambda}[(2J+1)(2J_0+1)]^{1/2} \\ &\quad \times \left\{ \begin{matrix} j J I_A \\ J_0 j_0 \lambda \end{matrix} \right\} \langle E\ell j \| \mathcal{M}_\lambda \| \ell_0 j_0\rangle_J \exp(i(\delta^J_{\ell j} - \ell\pi/2)) \, .\end{aligned} \qquad (3)$$

Note that the final state is in the continuum and we label it also by E, the final state kinetic energy in the ^{8}B cm frame. Note also that we have included a phase-shift factor for the final state, $\exp(i(\delta^J_{\ell j} - \ell\pi/2))$, in the definition of the many-particle reduced matrix element. This has no consequences for the multipole response but it is an important factor for angular distributions.

(c) *Single-particle matrix elements.* These are calculated using the single-particle wave functions of a Coulomb potential plus a nuclear interaction of the form

$$\begin{aligned}V(r) &= V_0\left(1 - F_{\text{s.o.}}\, \boldsymbol{l}\cdot\boldsymbol{s}\, \frac{1}{r}\frac{d}{dr}\right) \\ &\quad \times [1 + \exp((r-R)/a)]^{-1} \, .\end{aligned} \qquad (4)$$

The parameters of this interaction are taken as R = 2.391 fm, a = 0.52 fm, and $F_{\text{s.o.}}$ = 0.439 fm^2. The well depth, V_0, is adjusted separately for the $p_{3/2}$ state in the J = 1,2,3 channels to reproduce the proton separation energy of the J = 2 ground state and the energies of the J = 1,3 resonances. The other single-particle states are calculated with the $J = 1^+$ potential, as suggested in Ref. [7]. The potential well depths are quoted in Table 1, together with the single-particle matrix elements and phase-shifts for a final state kinetic energy of E = 0.6 MeV. The continuum states are normalized so that the excitation strength per unit energy satisfies $dB(E\lambda)/dE = \sum_J \langle J\|\mathcal{M}_\lambda\|J_0\rangle^2/(2J_0+1)$.

Table 1
Single-particle reduced matrix elements for the E1 and E2 multipole operators, $M = \langle E\ell j \| \mathcal{M}_\lambda \| p_{3/2}\rangle_J$, for a final state kinetic energy of E = 0.6 MeV

	(ℓ, j)	V_0	J	M	δ
E1	$s_{1/2}$			0.558	160°
	$d_{3/2}$			−0.129	41°
	$d_{5/2}$			0.382	41°
E2	$p_{3/2}$	−42.14	1	−32.6	53°
		−44.65	2	14.6	199°
		−36.80	3	−16.63	21°
	$p_{1/2}$			16.4	21°
	$f_{7/2}$			18.1	55°
	$f_{5/2}$			−7.4	55°

The units are e fm MeV$^{-1/2}$ and e fm^2 MeV$^{-1/2}$ for E1 and E2, respectively. Also shown are the associated (Coulomb plus nuclear) phase-shifts δ, and the well depths V_0.

The ultimate objective for studying this reaction is the astrophysical S-factor for the capture reaction. Our model gives $S \approx 17$ mb keV at the energy relevant for solar physics.

We calculate the Coulomb excitation cross sections in two steps. The first is to calculate the excitation probability at a fixed impact parameter. The probability for all emission angles is given by

$$\frac{dP(E,b)}{dE} = \sum_{\lambda\mu} |F_{\lambda\mu}|^2 \, \frac{1}{2\lambda+1} \, \frac{dB(E\lambda)}{dE} \, . \qquad (5)$$

In the example below we follow the experimental conditions of the recent measurement [2] and take the beam energy to be 46.5 MeV/u and consider excitation by the Coulomb field of a lead nucleus. The E1 and E2 dissociation probabilities obtained from Eq. (5) are shown separately in Fig. 1, for different impact parameters and as functions of the proton energy E. At the smallest impact parameter, the E1 and E2 probabilities are of similar magnitude but the E2 probability falls off faster as a function of impact parameter. In order to suppress the E2 contribution in a measurement it is therefore important to avoid the smaller impact parameters, as it was done in the experiment [2]. The ratio of E2 and E1 probabilities is larger than

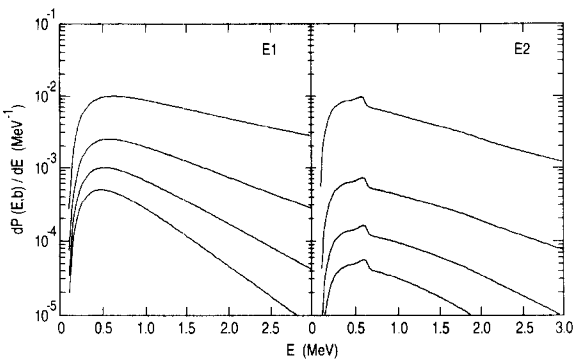

Fig. 1. The excitation probabilities for E1 and E2 as functions of the kinetic energy in the proton+^{7}Be final state. The four curves show (in decreasing order) the results at impact parameters between 15 and 60 fm, in steps of 15 fm.

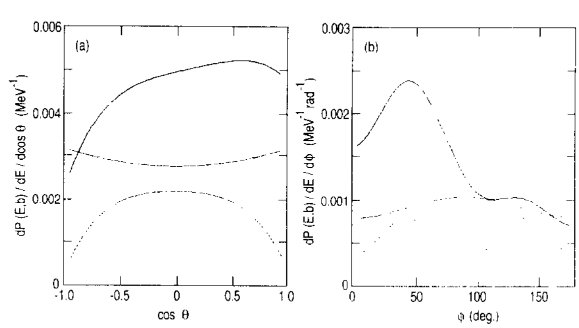

Fig. 2. Projections of the angular distribution of decay protons in the ^{8}B cm frame, for a final state kinetic energy of 0.6 MeV and an impact parameter of 20 fm with respect to a lead nucleus. The solid line shows the full distribution. The dashed lines are the separate E1 and E2 contributions, where the E1 result is the larger.

those obtained by Typel and Baur [8] (about 40% at 0.5 MeV), essentially because they ignored the final state f-waves. The total excitation cross sections that we obtain from all impact parameters larger than 20 fm are 282 mb for the E1 and 58 for the E2, giving a total of 340 mb for the breakup reaction.

We now come to the angular distribution. The formula for the differential probabilities is given by [5]

$$\frac{dP(E,b)}{dEd\Omega} = \frac{1}{4\pi}\sum_{\lambda_1\mu_1\lambda_2\mu_2}\sum_{\Lambda M}{}' F_{\lambda_1\mu_1}F^*_{\lambda_2\mu_2}\langle\lambda_1\mu_1\Lambda M|\lambda_2\mu_2\rangle \times \left(\mathcal{D}^{\Lambda}_{M0}(\hat{k})\right)^* A^{\Lambda}_{\lambda_1\lambda_2}, \tag{6a}$$

where the sum with the prime is restricted to Λ-values such that $\lambda_1 + \Lambda - \lambda_2$ is even, and $\mathcal{D}(\theta,\phi)$ is the Wigner rotation matrix with polar angles (θ,ϕ) measured with respect to the beam axis and the reaction plane. The coefficient $A^{\Lambda}_{\lambda_1\lambda_2}$ is given by the product of reduced matrix elements and angular recoupling coefficients as

$$A^{\Lambda}_{\lambda_1\lambda_2} = \sum_{\ell_1 j_1 J_1}\sum_{\ell_2 j_2 J_2}\langle J_1\|\mathcal{M}_{\lambda_1}\|J_0\rangle\langle J_2\|\mathcal{M}_{\lambda_2}\|J_0\rangle^* \times(-1)^{J_0+J_1-J_2-I_a-j_1-\lambda_1-1}\frac{2\Lambda+1}{2J_0+1} \times\left(\frac{(2J_1+1)(2J_2+1)(2j_1+1)}{2\lambda_2+1}\right)^{1/2} \times\langle j_1\tfrac{1}{2}\Lambda 0|j_2\tfrac{1}{2}\rangle\begin{Bmatrix}J_2\lambda_2J_0\\ \lambda_1J_1\Lambda\end{Bmatrix}\begin{Bmatrix}J_2j_2J_0\\ j_1J_1\Lambda\end{Bmatrix}. \tag{6b}$$

As an example, we show the E1–E2 interference obtained from Eq. (6) for an impact parameter of 20 fm and a final state kinetic energy of 0.6 MeV in the ^{7}Be+p center-of-mass system. Fig. 2a shows the projected distribution, $dP/dE\,d\cos(\theta)$, as a function of $\cos(\theta)$, where the θ-angle is measured with respect to the beam axis, which in our convention is a lead beam hitting a ^{8}B target. The E1 and E2 longitudinal excitation amplitudes interfere, giving a significant asymmetry with the preferred emission along the direction of motion of the exciting Coulomb field. The sign of the asymmetry agrees with the classical physics argument that a time-dependent field tends to accelerate a particle in the direction of motion of the field. The rescattering associated with the phase shift in the final state wave functions can of course change the interference, but the classical behavior remains in this case.

Fig. 2b shows the other projection of the angular distribution, $dP/dE\,d\phi$, as a function of ϕ which is the azimuthal angle of the proton with respect to the reaction plane. This distribution is symmetric with respect to reflection in the reaction plane so we show it for $0 \le \phi \le 180°$. We note that there is a large enhancement for emission toward the direction of the exciting Coulomb field, near ϕ=0. This interference depends entirely on the wave function distortion in the final state, vanishing if the scattering phase shifts are set to zero. We can perhaps understand the sign of the asymmetry as follows. The E1–E2 interference tends to excite the proton when it is on the side of the ^{8}B nucleus closest to the exciting field. The excited proton on that side is then accelerated by the Coulomb field

Table 2
Multipole coefficients from Eq. (7), as a function of excitation energy

E (MeV)	$a_{1,0}$	$a_{1,1}$
0.3	0.12	−1.10
0.6	0.22	−0.85
0.9	0.29	−0.61

of the ^{7}Be, which gives it a velocity in the direction toward the exciting field.

The multipolarities in the angular distribution can be conveniently tabulated using the parameterization,

$$\frac{dP}{dEd\Omega} = \frac{1}{4\pi}\frac{dP}{dE} \sum_{\Lambda,M\geq 0} a_{\Lambda,M}\,\mathrm{Re}\Big(\mathcal{D}^{\Lambda}_{M0}(\theta,\phi)\Big)$$
$$= \frac{1}{4\pi}\frac{dP}{dE}\Big[1 + a_{1,0}\cos(\theta) - a_{1,1}\sqrt{\tfrac{1}{2}}\sin(\theta)\cos(\phi) + \ldots\Big], \qquad (7)$$

where the monopole coefficient is normalized to $a_{0,0} = 1$. The two $\Lambda = 1$ coefficients, $a_{1,0}$ and $a_{1,1}$, are directly proportional to the E2 amplitude to a good approximation. We show in Table 2 the values of these coefficients for several proton energies. One sees that the asymmetry in the angular distribution is not very sensitive to the excitation energy E, which should be helpful for planning a measurement.

There are several questionable points in this analysis that should be mentioned. The first is that higher-order dynamical processes (beyond first perturbation theory) can also produce asymmetries (see Refs. [8,9]) which could make the quantitative analysis of the E1–E2 interference difficult. However, their relative magnitude is proportional to the target charge. With a fixed beam energy, it is therefore possible to check their importance by using a range of targets with different charges.

The second questionable point is the neglect of nuclear excitation in the analysis. One would like to do the measurement at large impact parameter, where the nuclear excitation is negligible, but the reality of experimental physics is that one can only use the deflection angle of the final state ^{8}B to try to fix the impact parameter. For the experimental conditions we have considered, a scattering angle of 4.5° corresponds to the Coulomb deflection at impact parameter $b = 20$ fm, and nuclear diffractive scattering will be small [10].

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