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$E2$ contribution to the ^{8}B $\rightarrow p + {}^7$Be Coulomb dissociation cross section

K. Langanke and T. D. Shoppa
W. K. Kellogg Radiation Laboratory, 106-38, California Institute of Technology, Pasadena, California 91125
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We have calculated the $E1$ and $E2$ contributions to the low-energy $^8\mathrm{B} + {}^{208}\mathrm{Pb} \rightarrow p + {}^7\mathrm{Be} + {}^{208}\mathrm{Pb}$ Coulomb dissociation cross sections using the kinematics of a recent experiment at RIKEN. Using a potential model description of the $^7\mathrm{Be}(p,\gamma)^8\mathrm{B}$ reaction, we find that the $E2$ contributions cannot *a priori* be ignored in the analysis of the data. Its inclusion reduces the extracted $^7\mathrm{Be}(p,\gamma)^8\mathrm{B}$ S-factor at solar energies by about 25%.

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The $^7\mathrm{Be}(p,\gamma)^8\mathrm{B}$ reaction plays a crucial role in the solar neutrino puzzle, as its rate is directly proportional to the flux of those high-energy neutrinos to which the ^{37}Cl and Kamiokande detectors are particularly sensitive [1]. While the energy dependence of the low-energy $^7\mathrm{Be}(p,\gamma)^8\mathrm{B}$ cross section is believed to be sufficiently well known [2], the absolute cross section at solar energies ($E \approx 20$ keV) is rather uncertain as the two measurements of the cross section that extend lowest in energy disagree by about 25% in magnitude [3,4]. The recent availability of radioactive beam facilities offers the possibility of resolving this discrepancy indirectly by measuring the Coulomb dissociation of a ^{8}B nucleus in the field of a heavy-target nucleus like ^{208}Pb. Performing such an experiment at carefully chosen kinematics to minimize nuclear-interaction effects and assuming the breakup as a one-step process in which a single virtual photon is absorbed, the Coulomb dissociation is the inverse of the radiative capture process [5].

Recently an experiment at RIKEN measured the $^8\mathrm{B} + {}^{208}\mathrm{Pb} \rightarrow p + {}^7\mathrm{Be} + {}^{208}\mathrm{Pb}$ dissociation cross section at the high incident energy of 46.5 MeV/nucleon [6]. Using the semiclassical formulas of Ref. [5], the Coulomb dissociation cross section was translated into S factors for the $^7\mathrm{Be}(p,\gamma)^8\mathrm{B}$ radiative capture process. From this it was concluded that the $^7\mathrm{Be}(p,\gamma)^8\mathrm{B}$ S factor at solar energies is likely to be smaller than 20 eV b, supporting the lower [4] of the two direct $^7\mathrm{Be}(p,\gamma)^8\mathrm{B}$ measurements.

In Ref. [6] the Coulomb dissociation was analyzed as a pure $E1$ breakup process, ignoring possible $E2$ contributions. This assumption is certainly valid for the radiative capture reaction, in which the $E1$ cross section is estimated to dominate $E2$ captures by nearly 3 orders of magnitude at low energies [7]. However, as the number of virtual photons strongly favors $E2$ transitions, the ratio of $E2$-to-$E1$ Coulomb dissociation cross sections ($\sigma^{cd}_{E2}/\sigma^{cd}_{E1}$) is significantly different, relatively enhancing the importance of $E2$ transitions. As has been shown in studies of the $^6\mathrm{Li} + {}^{208}\mathrm{Pb} \rightarrow d + \alpha + {}^{208}\mathrm{Pb}$ [8], $^7\mathrm{Li} + {}^{208}\mathrm{Pb} \rightarrow t + \alpha + {}^{208}\mathrm{Pb}$ [9], and $^{16}\mathrm{O} + {}^{208}\mathrm{Pb} \rightarrow \alpha + {}^{12}\mathrm{C} + {}^{208}\mathrm{Pb}$ [10] reactions, this enhancement can amount to more than two orders of magnitude, depending on the kinematics of the breakup process.

In the following we will estimate the $E2$ contribution to the $^8\mathrm{B} + {}^{208}\mathrm{Pb} \rightarrow p + {}^7\mathrm{Be} + {}^{208}\mathrm{Pb}$ cross section at the kinematics used in the RIKEN experiment. As in the analysis of Ref. [6] we will use the semiclassical formalism of Baur *et al.* [5] to connect the breakup cross section to the radiative capture cross section. We adopt the $E1$ and $E2$ capture cross sections from the $^7\mathrm{Be}(p,\gamma)^8\mathrm{B}$ potential model calculation of Kim *et al.* [7], which has also served as a theoretical guideline in Ref. [6].

The RIKEN experiment [6] has measured the double differential cross section for the $^8\mathrm{B} + {}^{208}\mathrm{Pb} \rightarrow p + {}^7\mathrm{Be} + {}^{208}\mathrm{Pb}$ Coulomb dissociation reaction as a function of the Rutherford scattering angle θ_R and the center-of-mass energy in the $p + {}^7$Be system, E_{17}. One has [5]

$$\frac{d^2\sigma}{d\Omega_R dE_{17}} = \sum_{J_f,\lambda} \left(\frac{Z_{\mathrm{Pb}}e}{\hbar v_i}\right)^2 a^{-2\lambda+2} B(E\lambda, J_i \rightarrow J_f, E_{17}) \times \frac{df_{E\lambda}(\theta_R,\xi)}{d\Omega_R}\,, \tag{1}$$

where

$$a = \frac{Z_{\mathrm{B}} Z_{\mathrm{Pb}} e^2}{\mu v_i v_f} \tag{2}$$

is the half distance of closest approach and

$$\xi = \frac{Z_{\mathrm{B}} Z_{\mathrm{Pb}} e^2}{\hbar}\left(\frac{1}{v_f} - \frac{1}{v_i}\right) \tag{3}$$

is the adiabaticity parameter. Here, v_i, v_f denote the relative velocities between projectile and target in the initial and final channels, while Z_k is the atomic number of the fragment k. The reduced mass μ is defined between the ^{8}B and the ^{208}Pb nuclei. The quantity $\frac{df_{E\lambda}(\theta_R,\xi)}{d\Omega_R}$ can be calculated in the straight-line approximation from the formulas given in Ref. [11]. Finally, the $B(E\lambda)$ matrix elements are related to the respective partial $^7\mathrm{Be}(p,\gamma)^8\mathrm{B}$ cross sections via

$$\sigma_{E\lambda}^{J_f\rightarrow J_i}(p + {}^7\mathrm{Be} \rightarrow {}^8\mathrm{B} + \gamma) = \frac{16\pi^3(\lambda+1)}{\lambda[(2\lambda+1)!!]^2}\left(\frac{E_\gamma}{\hbar c}\right)^{2\lambda+1} \times \frac{\hbar^2}{2\mu_{17}E_{17}} B(E\lambda, J_i \rightarrow J_f, E_{17})\,, \tag{4}$$

where J_i, J_f are the total angular momenta of the initial and final states in the Coulomb dissociation reaction, μ_{17}

is the reduced mass of the $p + {}^7$Be system, and E_γ denotes the photon energy. We have calculated the $B(E\lambda)$ matrix elements from the partial ^{7}Be$(p,\gamma)^8$B $E1$ and $E2$ cross sections as given in Ref. [7]. This $E1$ cross section agrees well with the measured ^{7}Be$(p,\gamma)^8$B data. Due to the lack of better experimental constraints, the initial scattering states for the $E2$ cross section have been calculated by using the same l-independent radial optical potential fitted to the $M1$ resonance at 633 keV. It should be noted that the $E2$ cross section is not tested directly against experimental data and might thus be viewed as somewhat uncertain. Nevertheless, the potential model estimate given in Ref. [7] is probably accurate enough to determine whether $E2$ contributions can be ignored in the ^{8}B + ^{208}Pb $\to p + {}^7$Be + ^{208}Pb cross sections.

The authors of Ref. [6] have studied the ^{8}B + ^{208}Pb $\to p + {}^7$Be + ^{208}Pb reaction at various relative energies E_{17} between 600 keV and about 2 MeV and at Rutherford scattering angles $\theta_R \leq 6°$. In Fig. 1 we show the ratio of virtual photon numbers for $E2$ and $E1$ transitions in the ^{8}B + ^{208}Pb $\to p + {}^7$Be + ^{208}Pb reaction covering the experimental energy range and at some typical θ_R values. We observe that the $E2/E1$ enhancement increases with angle, while it decreases with relative energy. While the enhancement is smaller than 100 at all experimentally relevant energies at the smallest angles data have been taken, it already amounts to more than 100 at $\theta_R = 2°$ for the astrophysically important energy range $E_{17} \leq 1$ MeV. Considering that the ratio of partial $E1$ to $E2$ ^{7}Be$(p,\gamma)^8$B cross sections is estimated [7] to be less than about a factor 1000, we expect that the $E2$ contribution to the ^{8}B + ^{208}Pb $\to p + {}^7$Be + ^{208}Pb

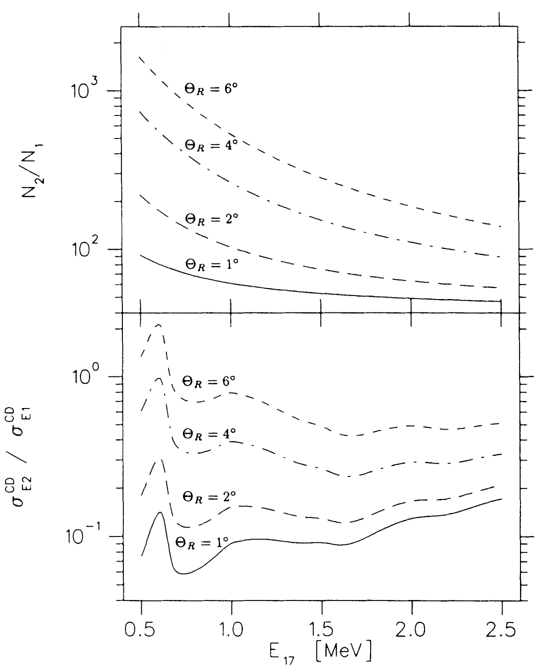

FIG. 1. $E2/E1$ ratio of virtual photon numbers (upper panel) and of partial double-differential cross sections (lower panel) for the ^{8}B + ^{208}Pb $\to p + {}^7$Be + ^{208}Pb breakup process as a function of energy E_{17} and for various Rutherford angles.

cross section cannot be ignored at angles $\theta_R \geq 2°$ and energies $E_{17} \leq 1$ MeV. This conjecture is confirmed in Fig. 1 where we have plotted $\sigma^{cd}_{E2}/\sigma^{cd}_{E1}$. The maximum of this ratio at around $E_{17} = 633$ keV is related to the lowest 1^+ resonance in ^{8}B. The main electromagnetic decay of this state is by $M1$ transition to the ^{8}B ground state with $J^\pi = 2^+$. While an $E1$ Coulomb excitation of this resonance is forbidden by parity, an $E2$ excitation is allowed leading to a particularly large $E2$ contribution around the resonance energy. With the partial $E1$ and $E2$ cross sections of Ref. [7], one finds that the $E2$ process dominates the total ^{8}B + ^{208}Pb $\to p + {}^7$Be + ^{208}Pb cross section at angles $\theta_R \geq 4°$.

Despite possible uncertainties in the potential model calculation, the $E2$ contribution will contribute significantly to the total Coulomb breakup cross section in the vicinity of the resonance and has to be taken into account in the data analysis. A precise measurement of the Coulomb dissociation cross section at the resonance energy and at angles $\theta_R > 2°$ will determine the strength of the partial $E2$ capture cross section at this energy and thus place an important constraint on the theoretical modeling of this cross section. Of course, it would be desirable to measure the triple-differential Coulomb dissociation cross section $\frac{d^3\sigma}{d\Omega_R d\Omega_{17} dE_{17}}$, where Ω_{17} defines the angle of the proton and the ^{7}Be nucleus out of the scattering plane. This quantity is sensitive to the interference of $E1$ and $E2$ Coulomb breakup transitions [12].

In Ref. [6] the ^{7}Be$(p,\gamma)^8$B S factors at different relative energies (binned into intervals of 200 keV width) have been determined by fitting the double-differential ^{8}B + ^{208}Pb $\to p + {}^7$Be + ^{208}Pb yields for fixed energy as a function of Rutherford scattering angle (binned into intervals of width 1°). As mentioned above, only $E1$ Coulomb breakup has been considered. We will now discuss how significantly $E2$ breakup might contribute to the data of Ref. [6]. As we do not know the detector efficiency function, a direct calculation of the yields is not possible. Assuming that the detector efficiency is the same for $E1$ and $E2$ contributions, we take the yield curves in Fig. 2 of Ref. [6] and multiply by $(\sigma^{cd}_{E1} + \sigma^{cd}_{E2})/\sigma^{cd}_{E1}$. Here we have averaged the cross sections over the same angular and energy bins as in Ref. [6]. We find that the ratio is rather robust against this averaging. The relative importance of the $E2$ contribution can be seen as the difference between the dashed $(E1+E2)$ and dotted $(E1)$ curves in Fig. 2. As expected, $E2$ Coulomb breakup is most important at the energy interval centered around $E_{17} = 0.6$ MeV, which covers the 1^+ resonance at 633 keV. Here we find a noticeable change of the yield curve in both magnitude and shape. At the higher energies, the effect of the $E2$ breakup is less pronounced than at the resonance energy leading to no significant change in the yield pattern.

As the $E1$ and $E2$ breakup parts add in the double-differential cross section (1), the presence of the $E2$ component in the data will reduce the partial $E1$ cross section compared to the one deduced in Ref. [6], which ignored possible $E2$ contributions. We have fitted the data of Ref. [6] to our $(E1 + E2)$ yield curves by multiplying the calculated yields with a parameter $\alpha(E_{17})$ which has

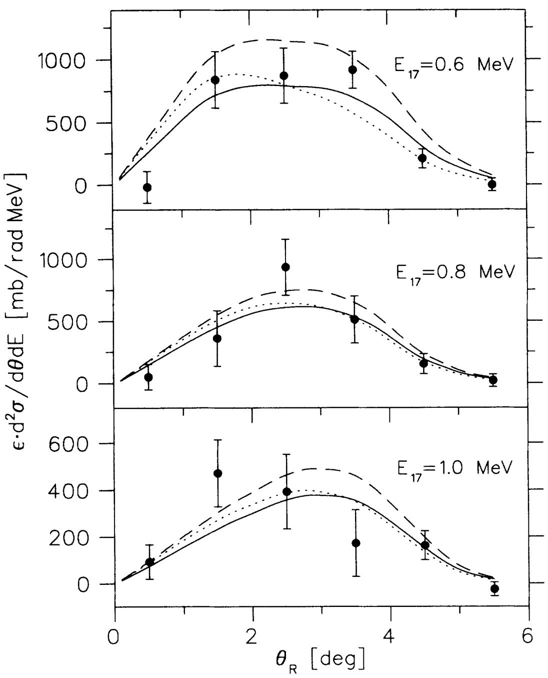

FIG. 2. Comparison of the $E1$ (dotted curve) to the total $E1+E2$ (dashed curve) Coulomb dissociation yield as a function of the Rutherford angle at three different energies E_{17}. The data and the $E1$ contributions are from Ref. [6]. The solid curve shows the best-fit to the data, including $E1$ and $E2$ contributions, as described in the text.

been determined by χ^2 minimization. As our yields are normalized to the $E1$ yields of Ref. [6], the partial $E1$ ^{7}Be$(p,\gamma)^8$B S factor extracted from the data scales by the same parameter α. We find that at the resonance (E_{17} = 0.6 MeV) the data agree noticeably better with our ($E1$ + $E2$) yield curve than with a pure $E1$ pattern (Fig. 2); the χ^2 between the two fits is reduced by 30%. Thus, the experimental data at this energy show the presence of the 1^+ resonance. We obtain a best-fit value of $\alpha(0.6) = 0.66 \pm 0.08$. At the two other energies our fit procedure results in $\alpha(0.8) = 0.82 \pm 0.16$ and $\alpha(1.0) = 0.77 \pm 0.17$, while the χ^2 values are about the same for pure $E1$ and our $E1 + E2$ yields pattern. The values of the parameter $\alpha(E_{17})$ translate into the partial $E1$ ^{7}Be$(p,\gamma)^8$B S factors of 11.2 ± 1 eV b, 11.5 ± 2.5 eV b, and 12.3 ± 3 eV b at E_{17} = 0.6, 0.8, and 1.0 MeV, respectively. Using the rather reliably known energy dependence of the ^{7}Be$(p,\gamma)^8$B S factor [7,13], these values extrapolate to $S(20$ keV$) = 12 \pm 3$ eV b. This value is about 25% smaller than the S factor derived from the same data in Ref. [6], and it is only 55% (62%) of the S factor adopted in the most recent version of Bahcall's [14] (Turck-Chieze's [15]) Standard Solar Model. We note that such a low value of $S(20$ keV) brings the predicted flux of high-energy neutrinos in agreement with the observation of Kamiokande III [16]. Thus, it is obviously very important to determine the role the $E2$ Coulomb breakup plays in the ^{8}B + ^{208}Pb $\to p$ + ^{7}Be + ^{208}Pb dissociation process at low energies.

The S factor extracted here from the ^{8}B + ^{208}Pb $\to$ p + ^{7}Be + ^{208}Pb data is noticeably smaller and incompatible (within 2 standard deviations) with the one recently derived from the various direct measurements of the ^{7}Be$(p,\gamma)^8$B reaction [2]. As it is important to resolve this apparent difference between the two methods, a precise direct capture experiment at one energy to pin down the overall normalization of the direct capture results is highly desirable. A confirmation of the Coulomb dissociation data and a verification of its assumed relation to the capture cross section is also desirable.

In summary, we have shown that the $E2$ component in the ^{8}B+^{208}Pb $\to p$+^{7}Be+^{208}Pb breakup can have a sizeable effect at low energies, in contrast to the assumption of a previous analysis of ^{8}B + ^{208}Pb $\to p$ + ^{7}Be + ^{208}Pb data, which ignored the $E2$ contributions [6]. If our conjecture is confirmed, the data of Ref. [6] result in a ^{7}Be$(p,\gamma)^8$B S factor at solar energies of 12 ± 3 eV b. This value is noticeably smaller than the S factors obtained in direct capture measurements [2–4] and, if correct, will obviously have important consequences for the understanding of the solar neutrino puzzle. Our present estimate for the $E2$ cross section is based on a simple potential model and clearly calls for an improved treatment. A more reliable microscopic calculation based on the framework of the multichannel resonating group model is currently in progress [17]. However, due its potential importance for the solar neutrino problem, an experimental determination of the $E2$ contribution is indispensable. This can be done by measuring the triple-differential cross section $\frac{d^3\sigma}{d\Omega_R d\Omega_{17} dE_{17}}$, which is sensitive to the interference of $E1$ and $E2$ components and should show sizeable effects of the $E2$ breakup amplitudes, even if it is somewhat smaller than estimated in the presently adopted potential model.

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