Coulomb Dissociation of ^{8}B and the Low-Energy Cross Section of the ^{7}Be$(p, \gamma)^8$B Solar Fusion Reaction

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An exclusive measurement of the Coulomb breakup of ^{8}B into ^{7}Be + p at 254A MeV allowed the study of the angular correlations of the breakup particles. These correlations demonstrate clearly that $E1$ multipolarity dominates and that $E2$ multipolarity can be neglected. By using a simple single-particle model for ^{8}B and treating the breakup in first-order perturbation theory, we extract a zero-energy S factor of $S_{17}(0) = 18.6 \pm 1.2 \pm 1.0$ eV b, where the first error is experimental and the second one reflects the theoretical uncertainty in the extrapolation.

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Exciting new results [1] from the Sudbury Neutrino Observatory (SNO) have proven for the first time that the measured high-energy neutrino flux from the Sun agrees well with the one calculated from standard solar models [2,3] if nonelectron flavor neutrinos are taken into account. This again focuses attention onto the ^{7}Be$(p, \gamma)^8$B reaction which provides almost exclusively the high-energy neutrinos measured in the SNO experiment. Their flux depends linearly on the ^{7}Be$(p, \gamma)^8$B cross section at solar energies. Very recently, the latter has been redetermined by new high-precision direct measurements [4–7] and extrapolated to zero energy with the help of a theoretical model [8]. The resulting zero-energy astrophysical S factors, $S_{17}(0)$, however, do not always agree within their quoted errors: Hammache *et al.* [4] found $S_{17}(0) = 18.8 \pm 1.7$ eV b, in agreement with other direct-capture data [5,9,10]. In contrast, Junghans *et al.* [6] report a considerably larger value, $S_{17}(0) = 22.3 \pm 0.7 \pm 0.5$ eV b. The very recent result of Baby *et al.* [7] also favors a rather large value of $S_{17}(0) = 21.2 \pm 0.7$ eV b.

In view of their importance for astro- and elementary-particle physics, these conflicting results should be verified and cross-checked by other, indirect measurements that have different systematic errors. One possibility is Coulomb dissociation (CD) of ^{8}B in the electromagnetic field of a high-Z nucleus. Such measurements have been performed at low [11], intermediate [12,13], and high [14] energies. Alternatively, $S_{17}(0)$ can also be calculated from asymptotic normalization coefficients which in turn are determined in low-energy proton-transfer or in proton-removal reactions [15–17].

In this Letter, we focus on a crucial question that must be answered if one wants to use the CD method to derive a precise value for $S_{17}(0)$. The astrophysical S factors of the ^{7}Be(p, γ) reaction can only be calculated reliably from the energy-differential CD cross sections if the electromagnetic multipole components relevant for direct capture and the time-reversed process have the same strength. In low-energy proton capture the $E1$ contribution by far dominates the cross section. While $E1$ is the dominant multipolarity also in CD, one can show easily that the equivalent photon field emitted from a high-Z target nucleus contains a strong $E2$ component. This is particularly true for CD at low energies. At higher energies (see Ref. [14]) the relative amount of $E2$ multipolarity is expected to be reduced, but may still be substantial enough to affect the final result. To remove this ambiguity, it is indispensable either to determine the $E1/E2$ ratio in CD experimentally or to extract S_{17} with such cuts that any $E2$ contribution is negligible.

Experimental limits for a possible $E2$ contribution were extracted in the work of Kikuchi *et al.* [12] and Iwasa *et al.* [14]. Both papers found negligible $E2$ contributions. Recently, Davids *et al.* have reported positive experimental evidence for a finite $E2$ contribution in CD of ^{8}B, mainly from the analysis of *inclusive* longitudinal momentum ($p_{||}$) spectra of ^{7}Be fragments measured at 44*A* and 81*A* MeV [13]. The asymmetries in the $p_{||}$ spectra were interpreted to be due to *E*1-*E*2 interference in terms of first-order perturbation theory [18].

In order to resolve these discrepancies, we decided to perform an *exclusive* CD experiment at high energy (254*A* MeV) at the kaon spectrometer KaoS at Gesellschaft für Schwerionenforschung (GSI) [19] with the aim to measure quantities that should be sensitive to contributions of *E*2 multipolarity, namely, the angular correlations of the ^{8}B-breakup particles, proton, and ^{7}Be. Experimentally, this requires high-resolution measurements of the positions and angles of the incident ^{8}B beam as well as those of the breakup fragments. The ^{8}B secondary beam was produced at the SIS/FRS radioactive beam facility at GSI [20] by fragmenting a 350*A* MeV ^{12}C beam in a 8 g/cm^2 Be target and separating it from contaminant ions in a 1.4 g/cm^2 wedge-shaped Al degrader placed in the FRS intermediate focal plane. Typical ^{8}B beam intensities in front of KaoS were 5×10^4 per 4 s spill; the only contaminant consisted of about 20% ^{7}Be ions which could be identified event by event with the help of a time-of-flight measurement.

Positions and angles of the secondary beam incident on the Pb breakup target were measured with the help of two parallel-plate avalanche counters located at 308.5 and 71 cm upstream from the target, respectively. The detectors, which were designed at RIKEN [21], had areas of 10×10 cm^2 and allowed one to track the incident ^{8}B beam with about 90% efficiency and with position and angular resolutions of 1.3 mm and 1 mrad, respectively. Downstream from the Pb target (which consisted of 50 mg/cm^2 ^{208}Pb enriched to $99.0\% \pm 0.1\%$), the angles and positions as well as the energy losses of the outgoing particles were measured with two pairs of Si strip detectors (300 μm thick, 100 μm pitch) located at distances of about 14 and 31 cm. Proton and ^{7}Be momenta were analyzed with the KaoS spectrometer which was set up almost identical to our previous experiment [14], except for a newly constructed plastic-scintillator wall near the KaoS focal plane with 30 elements (each 7 cm wide and 2 cm thick) used for trigger purposes.

The coincident *p* and ^{7}Be signals resulting from breakup in the ^{208}Pb target were identified by reconstructing their vertex at the target; this removed all breakup events in layers of matter other than the target. The measured momentum vectors of the outgoing *p* and ^{7}Be particles allowed one to construct the invariant-mass spectrum of the excited ^{8}B* system prior to breakup. Figure 1 shows the coordinate systems used. The angle θ_8 is the laboratory scattering angle of ^{8}B* relative to the incoming ^{8}B beam. The polar angles, $\theta_{\rm cm}$, and the azimuthal angles, $\phi_{\rm cm}$, of the breakup protons are measured in the rest frame of the ^{8}B* system, as shown in Fig. 1. In the same way, one can calculate, e.g., the transverse proton momentum vector in the reaction plane ($p_t^{\rm in}$).

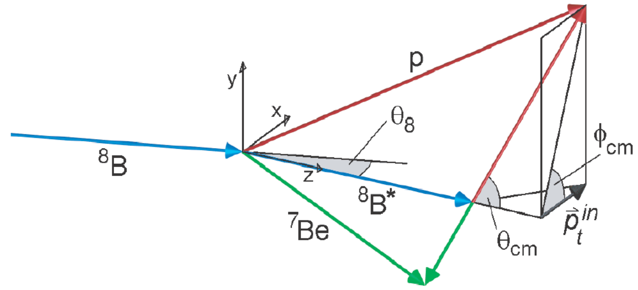

FIG. 1 (color online). Vector diagram showing the definitions of the angles $\theta_{\rm cm}$ and $\phi_{\rm cm}$ as well as the proton in-plane transverse momentum, $p_t^{\rm in}$, in the frame of the ^{8}B* system.

In the following we will present some angular distributions of the emitted proton in the frame of the ^{8}B* system that can be shown to be sensitive to an *E*2 amplitude in CD. To interpret the measured distributions we need guidance by a theoretical model. To this end, we have performed standard first-order perturbation-theory (PT) calculations of the CD process in the semiclassical approach [22,23], using a simple Woods-Saxon potential model for ^{8}B. The potential depth for the ground state of ^{8}B was adjusted to match the proton binding energy; the potential depths of the scattering states were fitted to the scattering lengths of the ^{7}Li + *n* mirror system [24]. We used a radius parameter of $r_0 = 1.25$ fm and a diffuseness of $a = 0.65$ fm. For channel spin $I = 2$ (the dominant contribution) we obtained a potential depth of $V_2 = 52.60$ MeV. The resulting scattering length for this channel of $a_{02}^{\rm theo} = -8$ fm agrees well with the recently measured value of $a_{02}^{\rm exp} = -7 \pm 3$ fm (Angulo *et al.* [25]).

To take into account absorption due to nuclear overlap in CD, we have introduced a diffuse absorptive nuclear potential with a depth of 20 MeV and a radius of 9.91 fm, i.e., the sum of the projectile and target radii. This choice reproduces well the integral θ_8 angular distribution. Technically, the results of the PT calculations were returned as a statistically distributed ensemble of 500 000 CD-"events" that were analyzed in the same way as the experimental data, thus imposing the experimental cuts.

We first present in Fig. 2 the distribution of $p_t^{\rm in}$ for three different upper limits in θ_8, 0.62°, 1.0°, and 2.5°. In classical Rutherford scattering, this corresponds to impact parameters of 30, 18.5, and 7 fm, respectively. Relative energies between *p* and ^{7}Be up to 1.5 MeV were selected. The experimental data for all three θ_8 cuts can be reproduced well by a PT calculation that includes only *E*1 multipolarity (full histograms in Fig. 2, the theoretical curves were normalized individually to the data points). If *E*1-plus-*E*2 multipolarity is used in the PT calculation, the different impact-parameter dependences of *E*1 and *E*2 multipolarity lead to markedly different shapes for the different θ_8 cuts (dashed histograms in Fig. 2). The latter distributions are, however, in clear disagreement with our data points.

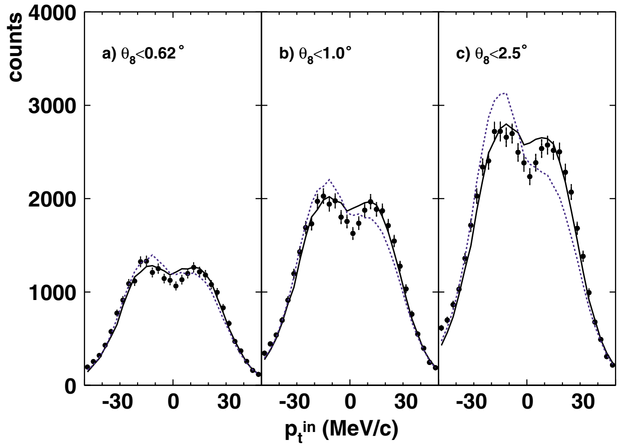

FIG. 2 (color online). In-plane transverse momenta, $p_t^{\rm in}$, of the breakup protons for three different cuts in θ_8. The theoretical curves (full lines: $E1$ multipolarity; dashed lines: $E1 + E2$ multipolarity) have been calculated in first-order perturbation theory. They were normalized individually to the data points in each frame.

Figure 3 depicts the experimental $\phi_{\rm cm}$ and $\theta_{\rm cm}$ distributions for three different $E_{\rm rel}$ bins, as indicated in the figure. A "safe" θ_8 limit of 1° was chosen. As expected, these distributions are mostly isotropic at low $E_{\rm rel}$ (indicative of s waves) and become increasingly anisotropic for larger values (contributions from d waves). For the $\phi_{\rm cm}$ distributions, which are most sensistive to $E2$ admixtures, the calculations for pure $E1$ multipolarity clearly fit best; inclusion of an $E2$ component shifts the maxima away from 90° and 270° with increasing $E_{\rm rel}$, while at the same time the anisotropy is reduced. Similar conclusions can be drawn from the bottom part of Fig. 3, where the proton polar angular ($\theta_{\rm cm}$) distributions are shown. The low-$E_{\rm rel}$ bins show little sensitivity to $E2$ multipolarity, whereas inclusion of $E2$ leads to a marked discrepancy near $\cos(\theta_{\rm cm}) = 1$ for the highest $E_{\rm rel}$ bin. More detailed calculations show that at most $E2$ amplitudes of $\lesssim 0.3$ times the theoretical one from our simple model are simultaneously compatible with all our measured observables. Since this would correspond to $E2$ contributions to the cross sections of less than 1%, much less than the errors of the data points, we neglect the effect of $E2$ multipolarity. This is in line with conclusions drawn by Kikuchi *et al.* [12] and by Iwasa *et al.* [14] from their respective θ_8 distributions (which are, however, less sensitive to a small $E2$ component than the present angular correlations). Our findings contradict the conclusions of Davids *et al.* [13] that a substantial $E2$ cross section has to be subtracted from the total measured CD cross section.

Our results allow one to interpret the relative-energy distributions of the breakup particles in an easy way. In the following, we have restricted the angles θ_8 to values below 0.62° to ensure both dominance of CD and reduction of the effect of any possible $E2$ contribution. The data are compared to a simulation with GEANT that includes

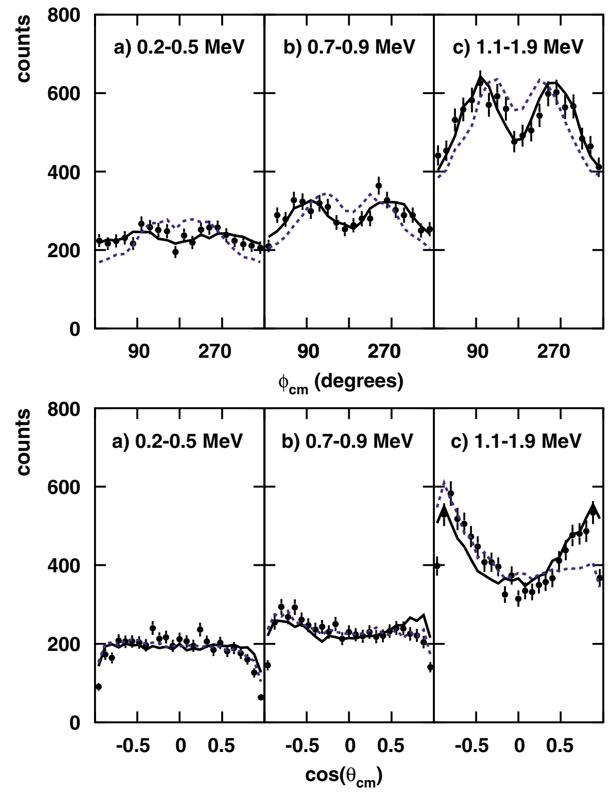

FIG. 3 (color online). Top: Experimental distributions of the proton azimuthal angular ($\phi_{\rm cm}$) distributions for three different bins of the p-^{7}Be relative energy, $E_{\rm rel}$. The full histograms denote a first-order perturbation-theory calculation for $E1$ multipolarity, and the dashed ones for $E1 + E2$. All theoretical curves were individually normalized to the data points in each frame. Bottom: the same for the polar breakup angles, $\theta_{\rm cm}$.

two electromagnetic multipole components: a resonant $M1$ contribution located at $E_{\rm rel} = 0.63$ MeV with resonance parameters taken from Filippone *et al.* [10], and the nonresonant $E1$ contribution from our theoretical model as described above. The latter was scaled by a normalization factor of 0.79. Note that we have added to the GEANT simulation a contribution that feeds the first excited state in ^{7}Be at 429 keV using the measurements of Kikuchi *et al.* [12]. Subtracting the small $M1$ contribution (that affects only a narrow $E_{\rm rel}$ region around the resonance), the remaining $d\sigma/dE_{\rm rel}$ distribution can be converted to the $E1$ astrophysical S factor $S_{17}(E_{\rm rel})$.

The resulting S_{17} factors (averaged over $E_{\rm rel}$ bins 0.2 to 0.3 MeV wide) are visualized in Fig. 4. The error bars do not include a common systematic error of 5.6%. Figure 4(a) compares our results to those of other CD experiments [12–14] (the data of Ref. [13] represent their $E1$-S_{17} factors after subtraction of the $E2$ contribution). At low $E_{\rm rel}$, the CD S factors are in good agreement, though the Davids *et al.* [13] data are systematically lower. Figure 4(b) compares our data to those of the $^7{\rm Be}(p,\gamma)^8{\rm B}$ measurements where the authors have subtracted the contribution from the $M1$ resonance (Refs. [4,6,7]). At low energies the (p, γ) data of Refs. [4,7] and ours are in good

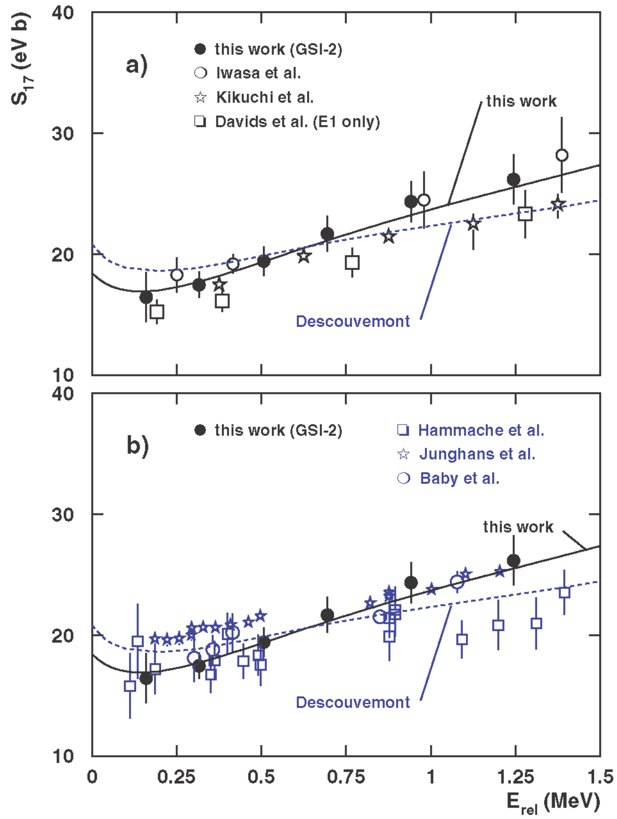

FIG. 4 (color online). (a) Comparison between S_{17} values from Coulomb-dissociation experiments. The full (open) circles indicate the present (previous) GSI CD experiment. Open stars depict Ref. [12], and open squares Ref. [13] ($E2$ contribution subtracted). The theoretical curves are described in the text. (b) S_{17} from this work in comparison with the (p, γ) experiments of Ref. [4] (squares), Ref. [6] (stars), and Ref. [7] (open circles). The latter data were corrected for the contribution of the $M1$ resonance by the authors.

agreement, whereas the Seattle data [6] deviate considerably. The opposite behavior is noted above the $M1$ resonance: our data and those of Refs. [6,7] match excellently, whereas the other (p, γ) experiments [4,5,9,10] consistently report lower values. We want to emphasize the remarkably good agreement of our CD data up to 1.1 MeV with the most recent direct-proton-capture experiment where an ion-implanted ^{7}Be target was used [7].

To extrapolate to zero energy, all recent (p, γ) experiments have chosen the cluster model of Descouvemont *et al.* [8]. When we fit our data points up to $E_{rel} = 1.5$ MeV to this model and add in quadrature a common systematic error of 5.6%, we obtain $S_{17}(0) = 20.8 \pm 1.3$ eV b (dashed lines in Fig. 4). Restricting the fit to energies below 0.6 MeV, where the model dependence has been shown to be weaker [26], $S_{17}(0) = 19.6 \pm 1.4$ eV b is obtained. Our potential model, however, reproduces the data over the entire energy range up to 1.5 MeV, yielding $S_{17}(0) = 18.6 \pm 1.2$ eV b (full lines in Fig. 4). It is interesting to note that a fit of the Baby *et al.* (p, γ) data to our model yields practically the same result, $S_{17}(0) = 18.1 \pm 0.3$ eV b. Clearly, still more high-precision experimental data are needed to resolve the discrepancies between the experimental data sets and to pin down the correct theoretical extrapolation of the measured data to solar energy. In the meantime, an additional "extrapolation error" of ± 1.0 eV b seems appropriate.

We conclude that Coulomb dissociation has been proven to be a valuable method to provide a rather precise value for the low-energy ^{7}Be(p, γ) cross section. Since in CD all energy bins are measured simultaneously, CD provides a reliable measurement of the *shape* of the S_{17} distribution. By setting tight constraints to the scattering angle θ_8 and analyzing p-^{7}Be angular correlations, a significant contribution from $E2$ multipolarity can be excluded. Small modifications of the Woods-Saxon potential parameters allow one to reproduce the data in first-order perturbation theory with remarkable accuracy up to about $E_{rel} = 1.5$ MeV.

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