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 254 A MeV allowed to study 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.

Exciting new results 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 if non-electron flavour neutrinos are taken into account. This again focusses 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 re-determined by new high-precision direct measurements and extrapolated to zero energy with the help of a theoretical model. The resulting zero-energy astrophysical S factors, $S_{17}(0)$, however, do not always agree within their quoted errors: Hammache et al. found $S_{17}(0) = 18.8 \pm 1.7$ eV b, in agreement with other direct-capture data. In contrast, Junghans et al. 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. also favours a rather large value of $S_{17}(0) = 21.2 \pm 0.7$ eV b.

In view of their importance for astrophysical 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, intermediate, and high energies. Alternatively, $S_{17}(0)$ can also be calculated from asymptotic normalization coefficients (ANC) which in turn are determined in low-energy proton-transfer or in proton-removal reactions.

In the present 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,$\gamma$)$^8$B 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 to either 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. and Iwasa et al. 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 and 81 A MeV. The asymmetries in the $p_{||}$ spectra were interpreted to be due to E1-E2 interference in terms of first-order perturbation-theory.

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 GSI with...
FIG. 1: Vector diagram showing the definitions of the angles $\theta_{cm}$ and $\phi_{cm}$ as well as the proton in-plane transverse momentum, $p_t^{in}$, in the frame of the $^8\text{B}$ system.

FIG. 2: In-plane transverse momenta, $p_t^{in}$, of the break-up protons for three different cuts in $\theta_8$. 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.

the aim to measure quantities that should be sensitive to contributions of E2 multipolarity, namely the angular correlations of the $^8\text{B}$ breakup particles, proton and $^7\text{Be}$. Experimentally, this requires high-resolution measurements of the positions and angles of the incident $^8\text{B}$ beam as well as those of the breakup fragments. The $^8\text{B}$ secondary beam was produced at the SIS/FRS radioactive beam facility at GSI [20] by fragmenting a 350 A MeV $^{12}\text{C}$ 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 $^8\text{B}$ beam intensities in front of KaoS were $5 \times 10^4$ per 4 sec spill; the only contaminant consisted of about 20% $^7\text{Be}$ 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 (PPAC) located at 308.5 cm and 71 cm upstream from the target, respectively. The detectors, which were designed at RIKEN [21], had areas of $10 \times 10 \text{cm}^2$ and allowed to track the incident $^8\text{B}$ 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$^2$ $^{208}\text{Pb}$ enriched to 99.0±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 $\mu$m thick, 100 $\mu$m pitch) located at distances of about 14 cm and 31 cm. Proton and $^7\text{Be}$ 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 $^7\text{Be}$ signals resulting from breakup in the $^{208}\text{Pb}$ 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 $^7\text{Be}$ particles allowed to construct the invariant-mass spectrum of the excited $^8\text{B}^*$ system prior to breakup. Fig. [14] shows the coordinate systems used. The angle $\theta_8$ is the laboratory scattering angle of $^8\text{B}^*$ relative to the incoming $^8\text{B}$ beam. The polar angles, $\theta_{cm}$, and the azimuthal angles, $\phi_{cm}$, of the breakup protons are measured in the rest frame of the $^8\text{B}^*$ system, as shown in Fig. 1. In the same way, one can calculate e.g. the transverse proton momentum vector in the reaction plane ($p_t^{in}$).

In the following we will present some angular distributions of the emitted proton in the frame of the $^8\text{B}^*$ system that can be shown to be sensitive to an E2 amplitude in CD. To interprete 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 semi-classical approach [22, 23], using a simple Woods-Saxon potential model for $^8\text{B}$. The potential depth for the ground state of $^8\text{B}$ was adjusted to match the proton binding energy; the potential depths of the scattering states were fitted to the scattering lengths of the $^7\text{Li}+n$ 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 $a^{\text{theo}}_{02} = -8$ fm agrees well with the recently measured value of $a^{\text{exp}}_{02} = -7 \pm 3$ 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 $\theta_8$ 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 $p_t^{in}$ for three different upper limits in $\theta_8$, 0.62°, 1.0°, and 2.5°.
In classical Rutherford scattering, this corresponds to impact parameters of 30 fm, 18.5 fm, and 7 fm, respectively. Relative energies between p and 7Be up to 1.5 MeV were selected. The experimental data for all three \( \theta_q \)-cuts can be reproduced well by a PT calculation that includes only E1 multipolarity (full histograms in Fig. 4). The theoretical curves were normalized individually to the data points. If E1-plus-E2 multipolarity is used in the PT calculation, the different impact-parameter dependences of E1 and E2 multipolarity lead to markedly different shapes for the different \( \theta_q \)-cuts (dashed histograms in Fig. 4). The latter distributions are, however, in clear disagreement with our data points.

Fig. 3 depicts the experimental \( \phi_{cm} \) and \( \theta_{cm} \) distributions for three different \( E_{rel} \) bins, as indicated in the figure. A “safe” \( \theta_q \) limit of 1° was chosen. As expected, these distributions are mostly isotropic at low \( E_{rel} \) (indicative of s-waves) and become increasingly anisotropic for larger values (contributions from d-waves). For the \( \phi_{cm} \) distributions, which are most sensitive 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 \( E_{rel} \), 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 (\( \theta_{cm} \)) distributions are shown. The low-\( E_{rel} \) bins show little sensitivity to E2 multipolarity, whereas inclusion of E2 leads to a marked discrepancy near \( \cos(\theta_{cm}) = 1 \) for the highest \( E_{rel} \) 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 \( \theta_q \) 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 to interpret the relative-energy distributions of the breakup particles in an easy way. In the following, we have restricted the angles \( \theta_q \) 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 two electromagnetic multipole components: a resonant M1 contribution located at \( E_{rel} = 0.63 \) MeV with resonance parameters taken from Filippone et al. 10, and the non-resonant 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 7Be at 429 keV using the measurements of Kikuchi et al. 12. Subtracting the small M1 contribution (that affects only a narrow \( E_{rel} \) region around the resonance), the remaining \( d\sigma/dE_{rel} \) distribution can be converted to the E1 astrophysical S factor \( S_{17}(E_{rel}) \).

The resulting \( S_{17} \) factors (averaged over \( E_{rel} \) bins 0.2 to 0.3 MeV wide) are visualized in Fig. 3. The error bars do not include a common systematic error of 5.6%. The top panel (a) compares our results to those of other CD experiments 12, 13, 14 (the data of Refs. 13 represent their E1-S\( S_{17} \) factors after subtraction of the E2-contribution). At low \( E_{rel} \), the CD \( S \) factors are in good agreement, though the Davids et al. 13 data are systematically lower. The bottom panel (b) compares our data to those of the \( ^7\text{Be}(p,\gamma)^8\text{B} \) measurements where the authors have subtracted the contribution from the M1 resonance (Refs. 13, 14). At low energies the \((p,\gamma)\) data of Refs. 13, 14 and ours are in good agreement, whereas the Seattle data 14 deviate considerably. The opposite behaviour is noted above the M1 resonance: our data and those of Refs. 13, 14 match excellently, whereas the other \((p,\gamma)\) experiments 13, 14, 10, 11 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-
The theoretical curves are described in the text. Ref. [12], open squares Ref. [13] (E2 contribution subtracted). Present (previous) GSI CD experiment. Open stars depict dissociation experiments. The full (open) circles indicate the position of the M1 resonance by the authors.

**FIG. 4:** 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], 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. [2] (squares), Ref. [3] (stars), and Ref. [4] (open circles). The latter data were corrected for the contribution of the M1 resonance by the authors.

To extrapolate to zero energy, all recent (p,γ) experiments have chosen the cluster model of Descouvemont and Baye [5]. 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 $S_{17}(0) = 20.8 ± 1.3$ 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], $S_{17}(0) = 19.6 ± 1.4$ eV b is obtained. Our potential model, however, reproduces the data over the entire energy range up to 1.5 MeV, yielding $S_{17}(0) = 18.6 ± 1.2$ 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, $S_{17}(0) = 18.1 ± 0.3$ eV b. Clearly, still much 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 $\theta_8$ 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 to reproduce the data in first-order perturbation theory with remarkable accuracy up to about $E_{rel} = 1.5$ MeV.

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