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Davids, B.; Anthony, D. W.; Aumann, T.; Austin, Sam M.; Baumann, T.; Bazin, D.; Clement, R. R. C.; Davids, C. N.; Esbensen, H.; Lofy, P. A.

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$S_{17}(0)$ Determined from the Coulomb Breakup of 83 MeV/Nucleon ^{8}B

B. Davids,[1,2,*] D. W. Anthony,[1,3] T. Aumann,[1] Sam M. Austin,[1,2] T. Baumann,[1] D. Bazin,[1] R. R. C. Clement,[1,2]
C. N. Davids,[4] H. Esbensen,[4] P. A. Lofy,[1,3] T. Nakamura,[1] B. M. Sherrill,[1,2] and J. Yurkon[1]
[1]*National Superconducting Cyclotron Laboratory, Michigan State University, East Lansing, Michigan 48824*
[2]*Department of Physics and Astronomy, Michigan State University, East Lansing, Michigan 48824*
[3]*Department of Chemistry, Michigan State University, East Lansing, Michigan 48824*
[4]*Physics Division, Argonne National Laboratory, Argonne, Illinois 60439*

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A kinematically complete measurement was made of the Coulomb dissociation of ^{8}B nuclei on a Pb target at 83 MeV/nucleon. The cross section was measured at low relative energies in order to infer the astrophysical S factor for the $^7\text{Be}(p,\gamma)^8\text{B}$ reaction. A first-order perturbation theory analysis including $E1$, $E2$, and $M1$ transitions was employed to extract the $E1$ strength relevant to neutrino-producing reactions in the solar interior. By fitting the measured cross section from $E_{\text{rel}} = 130$ to 400 keV, we find $S_{17}(0) = 17.8^{+1.4}_{-1.2}$ eV b.

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The β^+ decay of ^{8}B is the predominant source of high-energy solar neutrinos. These neutrinos produce the most events in the chlorine radiochemical and the water and heavy water Čerenkov solar neutrino detectors. In the Sun, ^{8}B is produced via the $^7\text{Be}(p,\gamma)^8\text{B}$ reaction. Since 1964, the rate of this reaction has been the most uncertain input to the calculated solar neutrino fluxes and the predicted event rates in solar neutrino detectors [1]. Precise knowledge of this reaction rate is essential not only for a detailed understanding of solar neutrino experiments, but also for constraining fundamental properties of neutrinos themselves. Direct measurements of the cross section are difficult because the target is radioactive, and the cross section is small.

Radiative capture cross sections are often characterized in terms of an energy-dependent cross section factor, $S(E)$. Hammache *et al.* [2] discuss the discrepancies in the overall normalizations of the direct measurements of the astrophysical S factor for the $^7\text{Be}(p,\gamma)^8\text{B}$ reaction, S_{17}. The disagreements among the direct measurements make an independent approach desirable. Peripheral transfer reactions that yield asymptotic normalization coefficients [3] and Coulomb breakup [4–10] permit the extraction of S factors with different systematic uncertainties. In the Coulomb breakup of ^{8}B, a virtual photon emitted by a heavy target nucleus such as Pb dissociates an incident ^{8}B projectile into $^7\text{Be} + p$. This is the inverse of the radiative capture reaction. The two reaction rates are related by the detailed balance theorem for photons of a given multipolarity.

At solar energies ($\approx$20 keV), the radiative capture reaction proceeds almost exclusively by $E1$ transitions, but $E2$ and $M1$ transitions also play a role in Coulomb breakup for relative energies less than 1 MeV. The contributions of these multipolarities to measured Coulomb dissociation cross sections must be correctly accounted for in order to obtain the $E1$ yield relevant to ^{8}B production in the Sun. The size of the $M1$ contribution at low relative energies can be gauged from the direct measurement of the radiative capture cross section near the 0.64 MeV 1^+ resonance [11]. The $E2$ contribution was determined [12] by measuring the longitudinal momentum distributions of ^{7}Be fragments emitted in the Coulomb dissociation of intermediate energy ^{8}B projectiles on Pb. In this Letter, we report an exclusive breakup measurement that confirms the presence of $E2$ transitions in the Coulomb breakup and quantitatively account for the measured $E2$ contribution in inferring $S_{17}(0)$.

We made a kinematically complete measurement of the cross section for the Coulomb dissociation of ^{8}B on Pb at low relative energies. An 83 MeV/nucleon ^{8}B beam delivered by the A1200 fragment separator [13] at the National Superconducting Cyclotron Lab impinged on a 47 mg cm^{-2} Pb target. The ^{8}B beam intensity was approximately 10^4 s^{-1}; nearly 4 billion nuclei struck the target. A 1.5 T dipole magnet separated the breakup fragments ^{7}Be and p from each other and from the elastically scattered ^{8}B nuclei, and dispersed the fragments according to their momenta. Four multiwire drift chambers measured the positions and angles of the breakup fragments after they passed through the magnet. An array of 16 plastic scintillators was used for particle identification. A thin scintillator at the exit of the A1200 provided continuous measurements of the beam intensity. In conjunction with the plastic scintillator array, it was also used to measure times of flight and to make intermittent beam transmission and purity measurements. A stainless steel plate prevented most of the direct ^{8}B beam from reaching the detectors. We reconstructed the 4-momenta of the breakup fragments using the ion optics code COSY INFINITY [14]. The momentum calibration obtained from ^{7}Be and p beams of known momenta was verified by checking that the fragment velocity distributions were centered about the beam velocity.

The detection efficiency and experimental resolution were determined by means of a Monte Carlo simulation,

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accounting for the beam emittance, energy loss, and multiple scattering in the target and detectors, and the detector position resolution. The 1σ relative energy resolution ranged from 100 keV at $E_{\text{rel}} = 300$ keV to 250 keV at $E_{\text{rel}} = 1.5$ MeV. The 1σ resolution in the reconstructed angle of the dissociated ^{8}B projectile was 4.5 mrad. The simulation of the angular distribution of the breakup fragments included both $E1$ and $E2$ transitions and anisotropic breakup in the ^{8}B center-of-mass system. Such an anisotropic angular distribution, predicted by the model of Ref. [15], was required to fit the longitudinal momentum distributions of protons measured in the present experiment, and of ^{7}Be fragments measured previously [12]. The anisotropy is a consequence of interference between $E1$ and $E2$ transition amplitudes.

The results of [12] imply that a proper theoretical description of a ^{8}B Coulomb breakup experiment must include $E2$ transitions. In Ref. [12], the analysis of the ^{7}Be momentum distributions assumed first-order perturbation theory (FOPT) using the pointlike projectile approximation for the Coulomb dissociation and neglecting nuclear-induced breakup. This was reasonable for the experimental conditions, namely, for small scattering angles of the ^{8}B center of mass. The analysis employed the $E1$ and $E2$ matrix elements predicted by the model of Ref. [15], scaled independently in order to reproduce the data. The best fits for both incident beam energies, 44 and 81 MeV/nucleon, were obtained when the ratio of the $E2$ and $E1$ matrix element scaling factors was 0.7. This was incorrectly reported as the ratio of the scaling factors for the $E2$ and $E1$ strength distributions; the correct value for this ratio is $0.7^2 = 0.49$. As a consequence, the reported [12] ratio of $E2$ and $E1$ S factors at $E_{\text{rel}} = 0.6$ MeV should be replaced by $4.7^{+2.0}_{-1.3} \times 10^{-4}$. The $E2$ strength extracted from the inclusive breakup measurement [12] is a factor of 10 to 100 larger than the upper limits reported in other experimental studies [7,9]. However, it is only slightly smaller than or in good agreement with recent theoretical calculations [15–19] and is consistent with the measurement of [20]. That the extracted experimental value should be somewhat smaller than the theoretical values is consistent with the idea that FOPT overestimates the $E2$ contribution to the cross section [15].

In order to minimize the role of $E2$ transitions and possible nuclear diffraction dissociation contributions to the breakup cross section measured in this experiment, only events with ^{8}B scattering angles of 1.8° or less were analyzed, corresponding classically to an impact parameter of 30 fm. Eikonal model [21] and distorted-wave Born approximation [22] calculations find that nuclear-induced breakup is negligible up to the grazing angle ($\approx 4°$), so the scattering angle cut imposed here gives confidence that nuclear effects are small and that the pointlike projectile approximation is valid. A FOPT analysis neglecting nuclear-induced breakup was employed to interpret the results of this experiment, an approach justified by the high beam energy and the restricted angular coverage. Higher-order effects are most important at large scattering angles and low incident beam energies [10,15]. Recent continuum-discretized coupled channel calculations [23] suggest that nuclear excitations account for less than 4% of the measured breakup cross section below 500 keV and that higher-order electromagnetic processes have little effect on $d\sigma/dE_{\text{rel}}$ for the angles and energies covered here [24].

A particular strength of our analysis is that it includes all of the relevant electromagnetic multipole contributions, $E1$, $E2$, and $M1$. The $E1$ and $E2$ contributions were calculated using the structure model of Ref. [15], quenching the $E2$ matrix elements as discussed earlier. The $M1$ contribution at the 0.64 MeV 1^+ resonance was calculated by folding the measured $M1$ S factor [11] with the $M1$ photon spectrum [25]. The contributions of the different multipolarities and their sum are shown in Fig. 1(a). By requiring $\Theta_{^8B} \leq 1.8°$ and $E_{\text{rel}} \geq 130$ keV, we have ensured the dominance of $E1$ transitions. Except for a narrow range surrounding the $M1$ resonance, $E1$ transitions represent over 90% of the cross section in FOPT. Figure 1(b) shows the fraction of the cross section accounted for by $E1$ transitions in the present experiment.

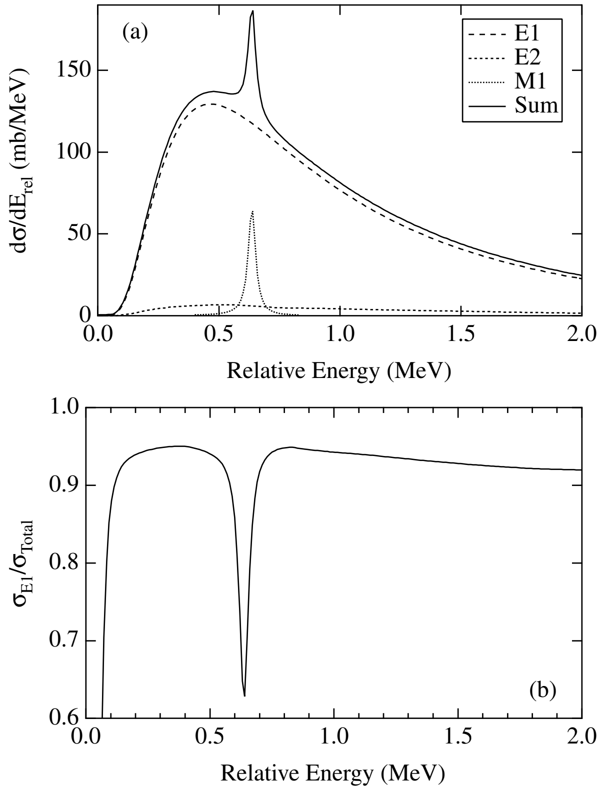

FIG. 1. (a) Contributions of $E1$, $E2$, and $M1$ transitions to the cross section for the Coulomb dissociation of 83 MeV/nucleon ^{8}B on Pb with ^{8}B scattering angles of 1.8° or less in FOPT. (b) Fraction of the calculated cross section for the Coulomb dissociation of 83 MeV/nucleon ^{8}B on Pb with ^{8}B scattering angles $\leq 1.8°$ ($b \geq 30$ fm) accounted for by $E1$ transitions in FOPT.

The measured longitudinal momentum distribution of protons emitted in the Coulomb breakup of 83 MeV/nucleon ^{8}B on Pb with ^{8}B scattering angles of 1.8° or less is shown in Fig. 2. The 1σ proton momentum resolution was estimated from the simulation to be 4 MeV/c. Since the statistical significance of these data is less than that of the inclusive measurement reported in Ref. [12], we shall not use them to extract the $E2$ strength. Nevertheless, the asymmetry of this distribution is manifest. Also shown in the figure are calculations done with the model of Ref. [15], one with the full $E2$ strength, one with $E2$ matrix elements scaled as described above, and another with no $E2$ matrix elements. The asymmetry observed in [12], taken together with momentum conservation, implies that the proton longitudinal momentum distribution must have a complementary asymmetry. We observed such an asymmetry for the first time in this measurement, confirming the presence of $E2$ transitions in the Coulomb breakup of ^{8}B.

In analyzing $d\sigma/dE_{\text{rel}}$, we convoluted the sum of the calculated $E1$, $E2$, and $M1$ contributions with the experimental resolution and scaled the magnitude of the $E1 + E2$ contribution in order to minimize χ^2 for the data points within two energy intervals, 130 keV–2 MeV and 130–400 keV. The factor by which the $E1 + E2$ contribution was multiplied will be referred to as the normalization factor. At energies below 100 keV, our calculations show that the $E2$ component dominates, so these data were excluded from the fits. A correction for the feeding of the 429 keV excited state of ^{7}Be was made using the results of [7]. This correction is small, ranging from less than 1% at the lowest relative energies to about 10% around 2 MeV.

The best-fit normalization factor obtained for the data between 130 keV and 2 MeV was $1.00^{+0.02}_{-0.06}$. The 1σ error includes energy-dependent contributions from statistics, momentum and angular acceptance, detector efficiency, and the ^{7}Be excited state feeding correction. The various sources of systematic uncertainties include beam intensity (1%), target thickness (2.6%), momentum calibration (4.2%), and the theoretical uncertainty (5.6%), resulting in a total systematic uncertainty of 7.5%. The theoretical uncertainty includes contributions from the size of the $E2$ component (2.5%) and from the extrapolation to zero energy (5%). Thus the analysis of data from 130 keV–2 MeV yields $S_{17}(0) = 19.1^{+1.5}_{-1.8}$ eV b.

A more reliable result can be obtained by analyzing a smaller relative energy range. Jennings *et al.* [26] point out that nuclear structure uncertainties increase significantly above $E_{\text{rel}} = 400$ keV. Hence we also fit only the data from 130–400 keV. The theoretical extrapolation uncertainty is only 1% for this energy range [26]. The best-fit normalization factor for these data was $0.93^{+0.05}_{-0.04}$, resulting in $S_{17}(0) = 17.8^{+1.4}_{-1.2}$ eV b, with all sources of uncertainty added in quadrature. This result is consistent with the value extracted from all the data up to 2 MeV, implying that the potential model of Ref. [15] describes the physics well even at large relative energies, within the uncertainties. The data and the best-fit FOPT calculations for all the data between 130 keV and 2 MeV, and for the data from 130–400 keV, are shown in Fig. 3.

The present result is in good agreement with three of the capture measurements [2,11,27], and with The Institute of Physical and Chemical Research (RIKEN) (18.9 ± 1.8 eV b) and Gesellschaft für Schwerionenforschung Darmstadt m.b.H. (GSI) (20.6 ± 1.2 ± 1.0 eV b) Coulomb breakup measurements [8,9]. It is also in excellent agreement with the results of asymptotic normalization coefficient determinations (17.3 ± 1.8 eV b) [3]. Although the results agree within the errors, the $E1$ strength found here is about 15% smaller than reported in the GSI Coulomb breakup measurement [9]. This might be ascribed to the neglect of $E2$ transitions in the analysis of the GSI measurement. The fraction of the breakup cross section attributable to $E2$ transitions depends on the

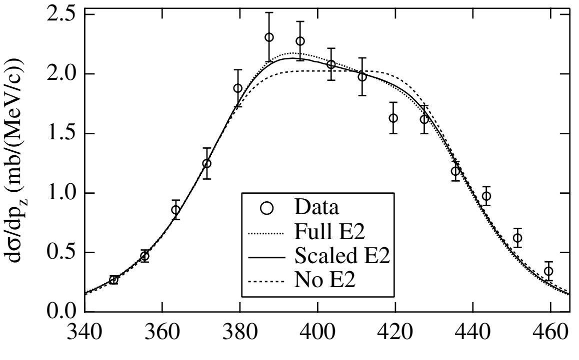

FIG. 2. Longitudinal momentum distribution of protons emitted in the Coulomb dissociation of 83 MeV/nucleon ^{8}B on Pb with ^{8}B scattering angles of 1.8° or less. The curves are FOPT calculations using the model of Ref. [15] modified as described in the text, convoluted with the experimental resolution. The error bars indicate the size of the relative uncertainties.

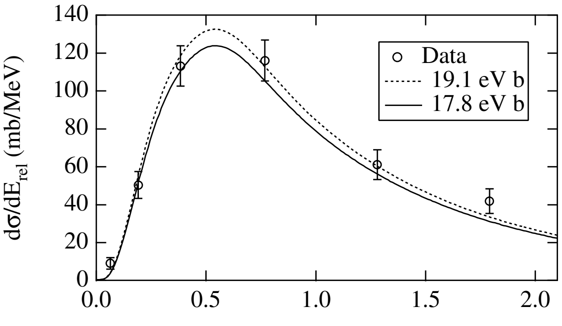

FIG. 3. Measured cross section for the Coulomb dissociation of 83 MeV/nucleon ^{8}B on Pb with ^{8}B scattering angles ≤1.8°. Only relative errors are shown. Also depicted are the best-fit FOPT calculations for the data between 130 keV and 2 MeV, and for the data between 130 and 400 keV, convoluted with the experimental resolution. The data point at 64 keV was excluded from the fits because of a large $E2$ contribution.

energies and angles covered. In the present measurement, the experimental conditions were tailored to minimize the role of $E2$ transitions. The GSI measurement probed smaller impact parameters, implying in FOPT a σ_{E2}/σ_{E1} ratio about 4 times larger than in this measurement. Since the $E2$ contribution to the present measurement is about 5%, this could account for the difference between the extracted $E1$ components. Similarly, the S factor inferred from the RIKEN Coulomb breakup measurement [8] must be reduced by 4%–15% [28] in order to account for the $E2$ contribution in FOPT.

In summary, a kinematically complete measurement of the Coulomb dissociation of 83 MeV/nucleon ^{8}B on Pb was carried out using a dipole magnet to separate the breakup fragments from the beam. The Coulomb breakup cross section was measured at low relative energies and small ^{8}B scattering angles in order to infer the astrophysical S factor for the $^7\mathrm{Be}(p,\gamma)^8\mathrm{B}$ reaction with minimal complications from nuclear-induced breakup, $E2$ transitions, and higher-order electromagnetic effects. A FOPT description of the reaction that included $E1$, $E2$, and $M1$ transitions and a single-particle ^{8}B structure model were used to interpret the measurement. The longitudinal momentum distribution of the emitted protons was measured and found to be asymmetric, consistent with our prior inclusive measurement of the ^{7}Be fragments, confirming the role of $E2$ transitions in the Coulomb breakup. Although we obtained data below 100 keV, they were excluded from the analysis because $E2$ transitions dominate at these energies. In order to minimize the theoretical uncertainties, the $E1$ strength in the Coulomb breakup was extracted from 130 to 400 keV, yielding $S_{17}(0) = 17.8^{+1.4}_{-1.2}$ eV b. Having for the first time properly accounted for the $E2$ component, the dominant theoretical uncertainty in ^{8}B Coulomb breakup measurements, we have shown that direct radiative capture, Coulomb breakup, and asymptotic normalization coefficient determinations give consistent values of $S_{17}(0)$.

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*Present address: Kernfysisch Versneller Instituut, Groningen, The Netherlands.
Email address: davids@kvi.nl

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