Eur. Phys. J. A **15**, 65–68 (2002)
DOI 10.1140/epja/i2001-10227-7

THE EUROPEAN
PHYSICAL JOURNAL A

Coulomb breakup of ^{8}B and the flux of ^{8}B neutrinos from the Sun

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Received: 21 March 2002 /

Abstract. 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}Be(p,γ)^{8}B reaction. A first-order perturbation theory analysis of the reaction dynamics 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 $E_{\rm rel} = 130$ keV to 400 keV, we find $S_{17}(0) = 17.8^{+1.4}_{-1.2}$ eV b. Semiclassical 1st-order perturbation theory and fully quantum-mechanical continuum-discretized coupled-channels analyses yield nearly identical results for the $E1$ strength relevant to solar-neutrino flux calculations, suggesting that theoretical reaction mechanism uncertainties need not limit the precision of Coulomb-breakup determinations of the ^{7}Be(p,γ)^{8}B S-factor. A recommended value of $S_{17}(0)$ based on a weighted average of this and other measurements is presented. This recommendation implies a revised value for the theoretical flux of ^{8}B solar neutrinos, which is also given.

PACS. 25.70.De Coulomb excitation – 26.20.+f Hydrostatic stellar nucleosynthesis – 26.65.+t Solar neutrinos

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 detector at Homestake and the water and heavy water Čerenkov solar-neutrino detectors SuperKamiokande and SNO. In the Sun, ^{8}B is produced via the ^{7}Be(p,γ)^{8}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 small.

Radiative capture cross-sections are often characterized in terms of an energy-dependent cross-section factor, $S(E) = E\sigma(E)\exp[2\pi Z_1 Z_2 e^2/(\hbar v)]$, where the Z_i are the charges and v the relative velocity of the nuclei involved. Hammache *et al.* [2] discuss the discrepancies in the overall normalizations of the direct measurements of the astrophysical S-factor for the ^{7}Be(p,γ)^{8}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}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.

As illustrated in [9], there is a disagreement in the energy dependence of the S-factors extracted from the Coulomb-dissociation experiments at RIKEN and GSI. Furthermore, the radiative capture reaction proceeds almost exclusively by $E1$ transitions at solar energies (≈ 20 keV), but $E2$ and $M1$ transitions also play a role in Coulomb breakup for relative energies less than 1 MeV. $E2$ transitions are particularly important at low and intermediate beam energies, while $M1$ transitions are most significant at high incident beam energies. The contributions of these multipolarities to measured Coulomb-dissociation

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cross-sections must be correctly accounted for in order to obtain the $E1$ yield relevant to the production of ^{8}B 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 to Coulomb-dissociation cross-sections was determined in an experiment by Davids *et al.* [12] in which the longitudinal momentum distributions of ^{7}Be fragments emitted in the Coulomb dissociation of intermediate energy ^{8}B projectiles on a Pb target were measured. In that experiment, we observed an asymmetry in the longitudinal momentum distribution of the emitted ^{7}Be fragments characteristic of interference between $E1$ and $E2$ transition amplitudes [13]. Here we report an exclusive breakup measurement that confirms the presence of $E2$ transitions in the Coulomb breakup, and quantitatively accounts 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 a Pb target at low relative energies. An 83 MeV/nucleon ^{8}B beam delivered by the A1200 fragment separator [14] 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 (MWDCs) were used to measure 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. Using the ion optics code COSY INFINITY [15], we reconstructed the 4-momenta of the breakup fragments from the measured positions in the four detectors and the known magnetic field. The momentum calibration obtained from ^{7}Be and proton 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, 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, *e.g.*, from 100 keV at $E_{\rm rel} = 300$ keV to 250 keV at $E_{\rm rel} = 1.5$ MeV. The 1σ resolution in the reconstructed angle of the dissociated ^{8}B projectile was 4.5 mrad. The dominant contribution to the experimental resolution was the position resolution of the MWDCs. 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 was predicted by the model of ref. [13], and was required to fit the longitudinal momentum distributions of protons measured in the present experiment, and of ^{7}Be fragments measured in [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 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 [16] and distorted-wave Born approximation (DWBA) [17] calculations find that nuclear-induced breakup is negligible up to the grazing angle ($\approx 4°$), so the severe scattering angle cut imposed here gives confidence that nuclear effects are small, and that the point-like projectile approximation is valid. A first-order perturbation theory analysis neglecting nuclear-induced breakup was employed to interpret the results of this experiment. Such an approach is justified by the high beam energy and the restricted angular range covered in the experiment. Higher-order effects are most important at large scattering angles and low incident beam energies [10,13]. Recent continuum-discretized coupled-channels (CDCC) calculations [18] suggest that nuclear excitations account for less than 4% of our measured breakup cross-section below 500 keV, and that higher-order electromagnetic processes have little effect on $\mathrm{d}\sigma/\mathrm{d}E_{\rm rel}$ for the angles and energies covered in this experiment [19].

A particular strength of our analysis is that it includes all of the relevant electromagnetic multipole contributions, $E1$, $E2$, and $M1$. The procedure was the following. The $E1$ and $E2$ contributions were calculated using the structure model of ref. [13], quenching the $E2$ matrix elements as described in ref. [19]. 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 calculated in 1st-order perturbation theory [20]. By requiring $\Theta_{^8\mathrm{B}} \leq 1.8°$ and $E_{\rm rel} \geq 130$ 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 first-order perturbation theory.

The 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 was measured [21]. 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 do not use them to extract the $E2$ strength. Nevertheless, the asymmetry of this distribution is manifest. 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 the measured decay energy spectrum, 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 to 2 MeV, and 130 to 400 keV. The factor by which the $E1 + E2$ contribution was multiplied will be referred to as the normalization factor. The data above 2 MeV were excluded from the fit due to the presence of a 3^+ resonance at 2.2 MeV that was not included in the theoretical calculation, and because the statistics there are poor. At energies below 100 keV, our calculations show that the $E2$ component dominates, so these data were also excluded from the fit. A correction to the data 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 a percent 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 with this procedure 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%). Hence the result of the perturbation theory analysis of data from 130 keV to 2 MeV is $S_{17}(0) = 19.1^{+1.5}_{-1.8}$ eV b.

A more reliable result can be obtained by analyzing a smaller relative energy range. Jennings *et al.* [22] point out that nuclear-structure uncertainties increase significantly above $E_{\mathrm{rel}} = 400$ keV. In order to minimize this model dependence, we also fit only the data between 130 keV and 400 keV. The theoretical extrapolation uncertainty is only 1% for this energy range [22]. 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 simple potential model of ref. [13] describes the physics well even at large relative energies, within the uncertainties.

We have performed continuum-discretized coupled-channels calculations of the Coulomb dissociation of ^{8}B. These calculations employ a slightly simplified version of the structure model of ref. [13], and provide a means of gauging the importance of nuclear-induced breakup and higher-order electromagnetic effects; the $E1$ and $E2$ reduced transition probabilities predicted by the two structure models agree at the 1% level. The fully quantum-mechanical CDCC calculations include both nuclear and Coulomb interactions, and have not been renormalized. The two reaction models describe the data between 130 keV and 2 MeV equally well, implying that the theoretical uncertainties in the reaction mechanism are smaller than or comparable to the experimental uncertainties here. In large measure, this is due to the experimental conditions of the exclusive measurement. By limiting the angular acceptance as we did, we probed large impact parameters where the $E2$ and nuclear contributions are small. The CDCC calculations indicate that nuclear-induced breakup is negligible at relative energies less than 400 keV. Higher-order electromagnetic effects are also smallest at the largest impact parameters [10,13]. The fact that the zero-energy S-factors implicit in the CDCC calculation (18.9 eV b) and the best-fit 1st-order perturbation theory calculation for the data up to 2 MeV (19.1 eV b) agree within 1% gives confidence that 1st-order perturbation theory adequately describes the underlying physics of the breakup reaction under these experimental conditions, provided the $E2$ matrix elements are appropriately quenched [19]. A comparison between the CDCC calculations and (1st-order) DWBA calculations using the same structure model indicates that the reduction in $E2$ strength caused by higher-order dynamical effects does not exhibit any significant relative energy dependence. Hence the approach we have adopted, namely scaling the $E2$ matrix elements by the same factor for all relative energies in 1st-order perturbation theory, is justified.

The present result is in good agreement with three of the capture measurements [2,11,23], and with the RIKEN (18.9 ± 1.8 eV b) and GSI ($20.6 \pm 1.2 \pm 1.0$ 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) [3,24]. The concordance of our measurement and the other Coulomb-breakup measurements conceals an underlying difference in interpretation. The analyses of refs. [8,9] have treated the contributions of $E2$ transitions as negligible, while our data imply they are not. Since these experiments covered angular ranges larger than this measurement, they probed smaller impact parameters where $E2$ transitions are relatively more important. If $E2$ transitions are considered, 1st-order perturbation theory calculations imply that the astrophysical S-factor inferred from the RIKEN Coulomb-breakup measurement should be reduced by 4–15% [25], and that of the GSI measurement by 15–20%. Such a reduction would bring these measurements into even better agreement with the present work. If we were to analyze our measured Coulomb-breakup cross-section between 130 and 400 keV without considering $E2$ transitions, the extracted $E1$ strength would be 5% greater, and the inferred value of $S_{17}(0)$ would increase to 18.7 ± 1.3 eV b. The small $E2$ correction is the result of restricting the angular range covered in this experiment, making the $E2$ contribution to the breakup cross-section comparable in magnitude to the statistical uncertainty of the measurement.

It appears that the three techniques used to infer $S_{17}(0)$, direct radiative capture measurements, asymptotic normalization coefficient determinations, and Coulomb breakup, yield consistent results with different systematic uncertainties. In light of these facts, we take a weighted average of these measurements to obtain a recommended value. We include in this average the recent direct measurements of ref. [2], the weighted mean [24] of the two published asymptotic normalization coefficient results [3], and the present Coulomb-breakup measurement. Including the radiative capture measurement of Filippone *et al.* [11], which was deemed the only reliable measurement at the 1997 workshop on solar nuclear fusion cross-sections [26], makes no difference in the weighted average. It has been excluded because lack of knowledge about the target composition prevents accurate correction for the escape of ^{8}B recoils out of the target [2]. Similarly, although the data of refs. [23,27] are in general consistent with the Hammache *et al.* and Filippone *et al.* measurements, the fact that these data were taken at high energies (~ 1 MeV), means that one must contend with substantial extrapolation uncertainties when inferring $S_{17}(0)$ from them. Since there is a significant dispersion in the inferred values of $S_{17}(0)$ from such high-energy data depending on the ^{8}B structure model used, we have excluded these studies from our weighted average. Among the direct measurements, that of Hammache *et al.* [2] is unique in its careful treatment of both ^{8}B backscattering and theoretical extrapolation errors. We do not include the other Coulomb-breakup measurements [8,9] in this average because we lack sufficient information to precisely correct for the $E2$ component neglected in the published analyses of these data. The uncertainties in the considered measurements all contain theoretical contributions, including extrapolation uncertainties for the radiative capture and Coulomb-breakup measurements. These extrapolation uncertainties are derived from the spread in the values obtained using different ^{8}B structure models for the extrapolation to zero energy [2,22], and vary with the relative energy ranges considered. The weighted average we obtain is $\langle S_{17}(0)\rangle = 18.0 \pm 0.9$ eV b. This value of $S_{17}(0)$ implies a reduction of both the predicted ^{8}B solar-neutrino flux and its 1σ uncertainty from the values given in ref. [1]. The revised theoretical ^{8}B solar-neutrino flux is 4.78×10^6 (1.00 ± 0.15) cm^{-2} s^{-1}.

In summary, we made an exclusive measurement of the Coulomb dissociation of 83 MeV/nucleon ^{8}B on a Pb target using a dipole magnet to separate the beam from the breakup fragments. Measuring the differential Coulomb-breakup cross-section at low relative energies and small ^{8}B scattering angles yielded the astrophysical S-factor for the ^{7}Be$(p,\gamma)^8$B reaction with minimal complications from $E2$ transitions, higher-order electromagnetic effects, and nuclear-induced breakup. Interpreting this exclusive measurement in the context of a 1st-order perturbation theory description of the reaction dynamics and a single-particle potential model of ^{8}B structure, we obtained $S_{17}(0) = 17.8^{+1.4}_{-1.2}$ eV b. We checked the validity of the perturbative approach through continuum-discretized coupled-channels calculations that assume an essentially identical model of ^{8}B structure. The two reaction theories describe the data up to relative energies of 2 MeV equally well within the experimental uncertainties, implying that a slightly modified 1st-order perturbation theory is adequate for understanding the Coulomb breakup of ^{8}B at intermediate beam energies and small angles.

This measurement agrees well with other recent experimental determinations of $S_{17}(0)$, and shows that the uncertainties associated with the Coulomb-breakup technique, unwanted multipolarities, higher-order electromagnetic effects, and nuclear-induced breakup, can be controlled well enough to obtain a precise value for the ^{7}Be$(p,\gamma)^8$B cross-section. Direct radiative capture measurements, asymptotic normalization coefficient determinations, and Coulomb-breakup measurements yield consistent results for $S_{17}(0)$, despite their different systematic uncertainties, giving confidence that this quantity is now well determined. We recommend a weighted average of measurements using these 3 different techniques, $\langle S_{17}(0)\rangle = 18.0 \pm 0.9$ eV b, for use in solar modeling. This value of $S_{17}(0)$ implies that the theoretical ^{8}B solar-neutrino flux is 4.78×10^6 (1.00 ± 0.15) cm^{-2} s^{-1}.

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