Coulomb Dissociation of ^{8}B and the ^{7}Be$(p,\gamma)^8$B Reaction at Low Energies

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The cross section for Coulomb dissociation of ^{8}B—the ^{208}Pb(^{8}B, ^{7}Be p)^{208}Pb reaction—was measured using a ^{8}B radioactive beam of 46.5 MeV/nucleon energy, and the cross section for the ^{7}Be$(p,\gamma)^8$B capture reaction was deduced at low energies; $E_{\rm c.m.} = 0.6 - 1.7$ MeV. The extracted astrophysical S_{17} factors were found to be consistent with the values measured by Vaughn *et al.* and Filippone *et al.* This result encourages further experimental studies extended to lower relative energies for a new determination of the S_{17} value relevant to the ^{8}B solar neutrino flux.

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The Coulomb dissociation process at intermediate energies has recently attracted a great deal of attention as an alternative method to study radiative capture reactions of astrophysical interest at low energies. The process can be treated as the absorption of a virtual photon, which is essentially the inverse of the radiative capture process [1]. A typical example is the Coulomb dissociation of ^{14}O—the inverse of the radiative capture ^{13}N$(p,\gamma)^{14}$O reaction—a key reaction of the hot-CNO cycle. Fairly accurate results have been obtained by Coulomb breakup experiments at an incident energy of 87.5 MeV/nucleon at RIKEN [2] and 70 MeV/nucleon at GANIL [3]. The contribution due to nuclear interaction is predicted to be significantly small compared with the dominant Coulomb excitation amplitude at these incident energies. Furthermore, the results agree with that of an experiment at Louvain-la-Neuve using a low energy radioactive ^{13}N beam [4] to measure the ^{13}N$(p,\gamma)^{14}$O reaction directly. The Coulomb breakup process is, however, characterized by a large cross section. The small capture cross section is enhanced by several orders of magnitudes, which helps to compensate for the small intensity of secondary beams.

The present paper reports on the first attempt to study the breakup of ^{8}B in the field of a ^{208}Pb nucleus, which provides information on the ^{7}Be$(p,\gamma)^8$B reaction, a key process in the production of high energy solar neutrinos by the ^{8}B β^+ decay [5]. The pioneering Homestake [6] and recent Kamiokande II and III [7] experiments measure fluxes of neutrinos originating mainly or solely from ^{8}B that are $(33 \pm 3)\%$ and $(49 \pm 6)\%$, respectively, of the prediction of the standard solar model (SSM) of Bahcall and Ulrich [8]. This discrepancy defines the "^{8}B solar neutrino problem."

The ^{7}Be$(p,\gamma)^8$B reaction cross section that was measured at relatively high energies must be extrapolated to lower center-of-mass energies near 20 keV. Bahcall and Ulrich [8] use an S factor ($= \sigma E e^{2\pi\eta}$, where $\eta = e^2 Z_1 Z_2/\hbar v$) at $E = 0$ of $S_{17}(0) = 24.3 \pm 1.8$ eV b, which was derived from an average based on all existing data. Bahcall and Pinsonneault [9] quote a smaller value of $S_{17}(0) = 22.4 \pm 2.1$ eV b. Turck-Chièze *et al.* [10] list as a possible value $S_{17}(0) = 19.5 \pm 2.5$ eV b. Possible sources of uncertainties in the value of $S_{17}(0)$ have been discussed by Barker and Spear [11] and Johnson *et al.* [12]. Six measurements of $S_{17}(E)$ have been reported so far. The four highest precision [$\pm(8-10)\%$] data sets are grouped in two distinct pairs that agree on the energy dependence of the measured $S_{17}(E)$ between 0.1 and 1.5 MeV, but disagree on the absolute values by approximately $(25-35)\%$. Filippone *et al.* [13] and Vaughn *et al.* [14] reported lower $S_{17}(E)$ values which lead to $S_{17}(0) = 19 - 20$ eV b [15] with the extrapolation procedure used in the SSM of Bahcall and Pinsonneault [9]. Higher values reported by Parker [16] and Kavanagh *et al.* [17] correspond to $S_{17}(0) = 25-27$ eV b. Hence, it is of interest to carry out independent measurements of the cross section.

In this Letter we intend to first establish the usefulness of the Coulomb dissociation method for studying the ^{7}Be$(p,\gamma)^8$B reaction at low energies. We report on data for 600 keV–1.7 MeV center-of-mass energies that are consistent with the values of Filippone *et al.* [13] and Vaughn *et al.* [14]. The present work represents the first results in our program to determine $S_{17}(0)$ through the Coulomb dissociation at lower relative energies. The advantage of a large cross section in the Coulomb

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dissociation process is quite significant in the ^{8}B case. Its very small binding energy of 137 keV leads to a large kinematical factor, $(k_p/k_\gamma)^2 \approx 1000$, and to a high virtual photon flux at low energies. Consequently, the small direct capture cross section of 1–100 nb is enhanced to the level of 0.1–10 mb breakup cross section per 20 keV energy bin.

The current method for analyzing Coulomb dissociation data assumes a one-step Coulomb excitation mechanism. Corrections due to nuclear excitation and higher order Coulomb interactions, known as Coulomb postacceleration effects, have been studied in various theoretical models [18–21]. For the specific case measured here, Bertulani predicts a small Coulomb postacceleration effect, which yields a spread of the measured relative energy by no more than 20 keV for our kinematical conditions [21], considerably smaller than the experimental resolution (see below). In the same analysis, the nuclear amplitudes are also predicted to be negligibly small. These features are due to the high incident energy (46.5 MeV/nucleon) of the present experiment and to the small binding energy (137 keV) of ^{8}B. Very low energy virtual photons are sufficient to excite ^{8}B into the continuum, and hence trajectories with very large impact parameters of approximately 25–90 fm make significant contributions to the measured data.

The experiment was performed at RIKEN (the Institute of Physical and Chemical Research). A primary ^{12}C beam of 91 MeV/nucleon bombarded a ^{9}Be target of 1.4 g/cm^2 thickness. Reaction products were analyzed by the projectile fragment separator RIPS [22] to obtain a radioactive ^{8}B beam. A typical ^{8}B beam intensity was 2×10^4 s^{-1}. A 50 mg/cm^2 ^{208}Pb target with 99.5% enrichment was placed in the air at the focal point of the RIPS system and was bombarded with an averaged incident energy of 46.5 MeV/nucleon in the target.

The products of the ^{208}Pb(^{8}B, ^{7}Be p)^{208}Pb reaction (protons and ^{7}Be) were detected in coincidence by a plastic scintillator hodoscope with 1×0.96 m^2 active area placed 5 m downstream of the target. It consists of a 5 mm thick ΔE plane and a 60 mm thick E plane. A helium bag was inserted between the target and the hodoscope to reduce the reactions due to the air. The hodoscope was placed with its symmetry axis along the beam line, and the central part of 15 cm in diameter was covered by an aluminum plate of 4 mm thickness to stop the beam. The ΔE plane is subdivided horizontally into ten strips, and the E plane consists of sixteen scintillators set perpendicular to the ΔE strips, dividing the hodoscope into 10×16 segments. The energy of the breakup fragments was determined by the time of flight (TOF) over the 5 m flight path. The calibration of the TOF was carried out by using both proton and ^{7}Be beams extracted from RIPS at several energies around 47 MeV/nucleon, with an accuracy of 1% in its absolute value. The particle identification was performed using the ΔE-E and TOF-E methods. The complete kinematics of the breakup products was determined from the TOF data and the positions of their hits, and thus the p-^{7}Be relative energy (essentially invariant mass) spectrum was constructed.

Figure 1 shows the experimental relative energy spectrum of the proton and ^{7}Be from the ^{208}Pb(^{8}B, ^{7}Be p)^{208}Pb reaction together with the corresponding detection efficiency obtained by a Monte Carlo simulation calculation. The loss of coincidence events due to reactions in the scintillator material (7%) has been corrected for. Contributions of breakup reactions occurring in the material other than the target (e.g., mainly the helium) were subtracted by using the data measured with no target in place. Because of the large contribution from breakup in the helium gas in the low relative energy region, typically 3 times the yield due to the ^{208}Pb target, only upper limits (not shown here) could be extracted for the cross sections below $E_{\rm rel}$ = 500 keV, and the lowest data point includes yield from 500 to 700 keV. The relative-energy resolution is 100 keV at $E_{\rm rel}$ = 0.6 MeV and 130 keV at $E_{\rm rel}$ = 1.7 MeV. These values were calculated by a Monte Carlo simulation, taking into account the multiple scattering of the fragments in the target (0.3°), the detector angular resolution (0.3°), and the TOF resolution (0.24 nsec). The simulation includes also the angular spread, $\delta\theta = 0.85°$, and the finite size, $\delta x = \delta y = 8.3$ mm, of the secondary (^{8}B) beam. Note

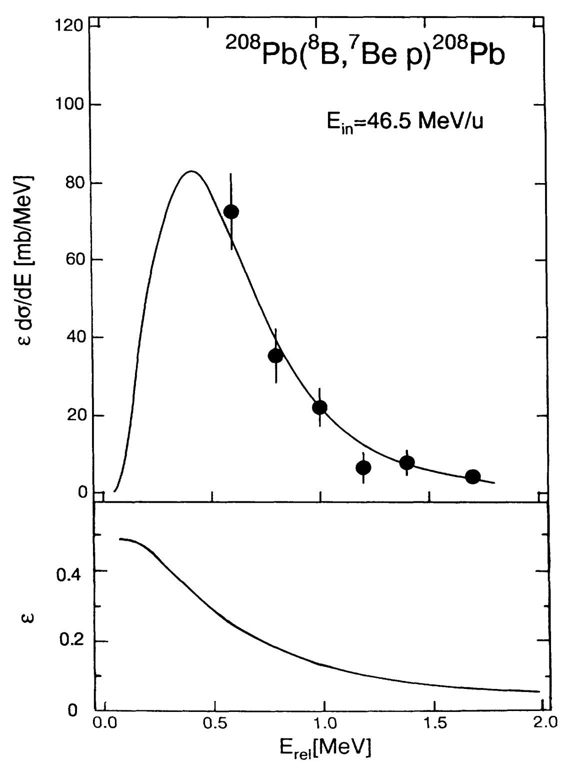

FIG. 1. The ^{8}B Coulomb dissociation yield [(differential cross section) $\times$ efficiency] as a function of relative energy (upper part). The solid curve is the result of a simulation with a constant S factor of 15 eV b. The detection efficiency is shown in the lower part.

that all the resolutions are quoted at their 1σ values. The curve in Fig. 1 represents the predictions of the Monte Carlo simulation with a constant S factor $S_{17} = 15$ eV b. A semiclassical formula proposed by Baur, Bertulani, and Rebel [1] was used to calculate the $E1$ Coulomb breakup cross section from the assumed S_{17}. The formula was shown to be accurate in the measured angular range where nuclear absorption is negligible. The p-^{7}Be relative angular distribution in their rest frame is calculated by the prescription given by Baur and Weber [23] for a mixture of relative s and d states as predicted by Kim, Park, and Kim [24]. As seen in Fig. 1, the energy dependence of the present data resembles the prediction resulting from assuming a constant S factor for the ^{7}Be$(p,\gamma)^8$B reaction over the measured energy range.

It should be noted here that the predicted Coulomb dissociation yield has only a moderate energy dependence for $E_{\rm rel} = 300$–700 keV, and hence to the S_{17} value. As shown in Fig. 1, possible uncertainties in the relative energy determination do not strongly affect the cross section. For example, a shift of +100 keV at $E_{\rm rel} =$ 600 keV (corresponding to the relative energy resolution) yields an increase of 9% in S_{17}. This moderate energy dependence is due to the convolution of the (γ, p) cross section, which decreases rapidly with decreasing energy, and the virtual photon flux, which increases rapidly with decreasing energy.

The data are plotted in Figs. 2(a)–(c) as a function of the scattering angle of the excited ^{8}B (center of mass of the p + ^{7}Be system) for three relative energy bins, 0.5–0.7, 0.7–0.9, and 0.9–1.1 MeV. The solid curves are the predicted $E1$ angular distributions with S factors which give the best fits to the data.

In Fig. 3 we show the astrophysical S factors extracted from the fits shown in Fig. 2, together with the existing (p,γ) data as renormalized by Filippone [15], based on a compiled value for the ^{7}Li(d,p) reaction cross section used in the target thickness determinations. The $M1$ resonance peak at 633 keV from the direct (p,γ) data is suppressed in the Coulomb dissociation data because of the low magnetic dipole virtual photon intensity. The nonresonant continuum of the (p,γ) cross section is also expected to contain a certain amount of $M1$ (p-^{7}Be relative p wave) amplitude in addition to the dominant $E1$ (s and d waves) component [13], whereas the Coulomb dissociation is essentially insensitive to the $M1$ transition. On the other hand, an $E2$ (p and f waves) contribution, which is suppressed in the capture reaction, is expected in the Coulomb dissociation data due to the high $E2$ virtual photon flux [25]. Many theoretical studies on the nuclear structure of ^{8}B have been performed [24,26–29]. The predicted $M1$ contribution varies considerably, depending on the models, from 4% to 15% at $E_{\rm rel} =$ 1 MeV. Predicted $E2$ yields for the ^{7}Be$(p,\gamma)^8$B reaction also differ by a factor of 4. The corresponding yield in the present Coulomb dissociation data was extracted by a simulation calculation taking account of the detector

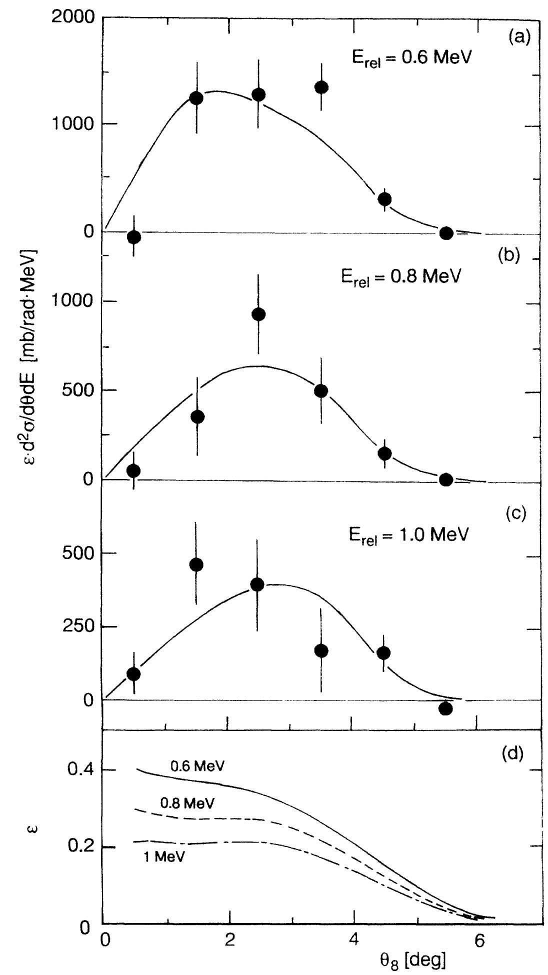

FIG. 2. The Coulomb dissociation yield as a function of the ^{8}B (θ_8) scattering angle, in 1° angular bins, for (a) a 500–700 keV bin, (b) a 700–900 keV bin, and (c) a 900–1100 keV bin. The solid curves represent the best fits of the simulation to the data. The detection efficiencies corresponding to above three energy bins are shown in (d). Note that the efficiency is not averaged over the experimental angular resolution.

response and the predicted $E2$ virtual photon numbers [1]. The (4–15)% $E2$ contribution in the present result at 1 MeV is smaller than that calculated in Ref. [25] and is comparable to the predicted $M1$ contribution to the (p,γ) data. Therefore the present Coulomb dissociation results [$E1$+ (4–15)% of $E2$] are consistent with the the direct (p,γ) results [$E1$+ (4–15)% of $M1$] of Filippone *et al.* [13] and Vaughn *et al.* [14] within the errors (see Fig. 3). The S_{17} factors from our data yield a very preliminary value of $S_{17}(0) = 16.7 \pm 3.2$ eV b, if the extrapolation procedure used in Ref. [13] is employed. Note that the error assigned is an experimental one only.

In summary, the coincidence cross section has been measured for the breakup reaction ^{208}Pb(^{8}B, ^{7}Be p)^{208}Pb in a kinematical domain predicted to be dominated by the Coulomb dissociation mechanism. The astrophysical S factor of ^{7}Be$(p,\gamma)^8$B was deduced from 0.6 to 1.7 MeV

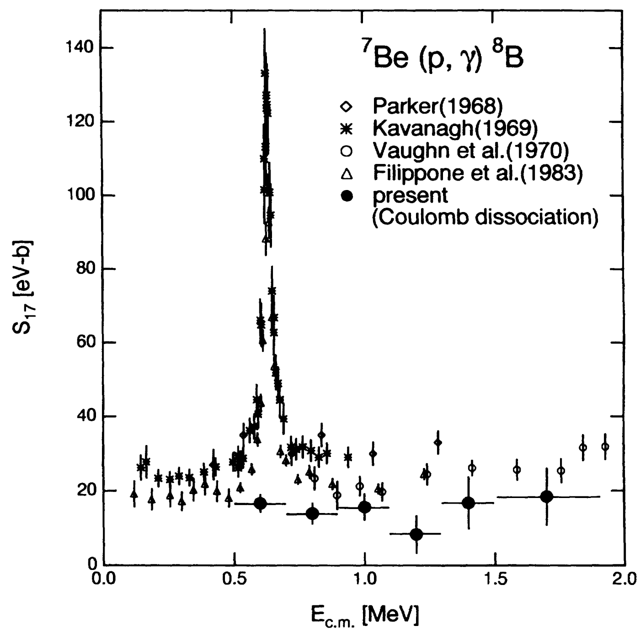

FIG. 3. Comparison of S_{17} extracted from the Coulomb dissociation of ^{8}B and the previous highest precision results. The horizontal bars indicate the range of E_{rel} over which the S factor is averaged.

center-of-mass energy. The Coulomb dissociation results are consistent with the values of the $^7\mathrm{Be}(p,\gamma)^8\mathrm{B}$ reaction cross section measured by Filippone *et al.* and Vaughn *et al.* Coulomb postacceleration effects are predicted to require only a relatively insignificant correction to the S factors.

The present results are encouraging for further studies. As shown in Fig. 1 considerable yield is expected even below a relative energy of 100 keV, which can be reached by improving the present experimental setup for better energy resolution and better signal-to-noise ratio. We emphasize that the angular distributions for the $E1$ and $E2$ Coulomb dissociation are sufficiently different that these amplitudes can be decomposed from data with a wider angular range. We intend to improve the present result to allow for an independent determination of $S_{17}(0)$ from future Coulomb dissociation data. We are also continuing our experimental efforts to extend the measurements to higher incident ^{8}B beam energies, in an attempt to reduce the uncertainty due to the $E2$ mixture and possible higher order processes which depend on the incident energy.

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[1] G. Baur, C. A. Bertulani, and H. Rebel, Nucl. Phys. **A458**, 188 (1986).
[2] T. Motobayashi *et al.,* Phys. Lett. B **264**, 259 (1991).
[3] J. Kiener *et al.,* Nucl. Phys. **A552**, 66 (1993).
[4] P. Decrock *et al.,* Phys. Rev. Lett. **67**, 808 (1991).
[5] J. N. Bahcall, *Neutrino Astrophysics* (Cambridge University Press, New York, 1989).
[6] R. Davis, in *Proceedings of the 7th Workshop on Grand Unification, Toyama, Japan, 1986,* edited by J. Arafune (World Scientific, Singapore, 1987); K. Lande, Bull. Amer. Phys. Soc. **38**, 1797 (1993).
[7] K. S. Hirata *et al.,* Phys. Rev. Lett. **63**, 16 (1989); K. Inoue, in Proceedings of the 28th Rencontres de Moriond Electro Weak Interaction and Unified Theories, Les Arcs, Savoie, France, 1993 (unpublished).
[8] J. N. Bahcall and R. K. Ulrich, Rev. Mod. Phys. **60**, 297 (1988).
[9] J. N. Bahcall and M. H. Pinsonneault, Rev. Mod. Phys. **64**, 885 (1992).
[10] S. Turck-Chièze *et al.,* Phys. Rep. **230**, 57 (1993).
[11] F. C. Barker and R. H. Spear, Astrophys. J. **307**, 847 (1986).
[12] C. W. Johnson, E. Kolbe, S. E. Koonin, and K. Langanke, Astrophys. J. **392**, 320 (1992).
[13] B. W. Filippone, S. J. Elwyn, C. N. Davids, and D. D. Koetke, Phys. Rev. Lett. **50**, 412 (1983); Phys. Rev. C **28**, 2222 (1983).
[14] F. J. Vaughn, R. A. Chalmers, D. Kohler, and L. F. Chase, Jr., Phys. Rev. C **2**, 1657 (1970).
[15] B. W. Filippone, Ann. Rev. Nucl. Part. Sci. **36**, 717 (1986).
[16] P. D. Parker, Phys. Rev. **150**, 851 (1966).
[17] R. W. Kavanagh, T. A. Tombrello, T. A. Mosher, and D. R. Goosman, Bull. Am. Phys. Soc. **14**, 1209 (1969); R. W. Kavanagh, *Cosmology, Fusion and other Matters* (Colorado Assoc. Univ. Press, Boulder, 1972), p. 169.
[18] G. F. Bertsch and C. A. Bertulani, Nucl. Phys. **A556**, 136 (1993).
[19] G. Baur, C. Bertulani, and D. M. Kalassa, Nucl. Phys. **A550**, 527 (1992).
[20] S. Typel and G. Baur, Phys. Rev. C **49**, 379 (1994).
[21] C. Bertulani, Phys. Rev. C **49**, 2688 (1994).
[22] T. Kubo *et al.,* Nucl. Instrum. Methods Phys. Res., Sect. B **70**, 309 (1992).
[23] G. Baur and M. Weber, Nucl. Phys. **A504**, 352 (1989).
[24] K. H. Kim, M. H. Park, and B. T. Kim, Phys. Rev. C **35**, 363 (1987).
[25] K. Langanke and T. D. Shoppa, Phys. Rev. C **49**, R1771 (1994).
[26] F. C. Barker, Aust. J. Phys. **33**, 177 (1980); F. C. Barker, Phys. Rev. C **37**, 2920 (1988).
[27] H. Krauss, K. Grün, and H. Oberhummer, Ann. Physik (Leipzig) **2**, 258 (1993).
[28] P. Descouvemont and D. Baye, Nucl. Phys. **A567**, 341 (1994).
[29] S. Typel and G. Baur (to be published).