Precision Measurements of the $^7\text{Be}(p,\gamma)^8\text{B}$ Reaction With Radioactive Beams and the $^8\text{B}$ Solar Neutrino Flux *

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Abstract

The $^7\text{Be}(p,\gamma)^8\text{B}$ reaction is one of the major sources of uncertainties in estimating the $^8\text{B}$ solar neutrino flux and is critical for understanding the Solar Neutrino Problem and neutrinos. The main source of uncertainty is the existence of conflicting data with different absolute normalization. Attempts to measure this reaction rate with $^7\text{Be}$ beams are under way by the UConn-LLN collaboration, and we discuss a newly emerging method to extract this cross section from the Coulomb dissociation of the radioactive beam of $^8\text{B}$. We discuss some of the issues relevant for this study including the question of the E2 contribution to the Coulomb dissociation process which was measured to be small. The Coulomb dissociation appears to provide a viable alternative method for measuring the $^7\text{Be}(p,\gamma)^8\text{B}$ reaction rate, with a weighted average of the RIKEN1, RIKEN2 and GSI1 published results of $S_{17}(0) = 19.4 \pm 1.3$ eV-b.

1 Introduction: The $^7\text{Be}(p,\gamma)^8\text{B}$ Reaction at Low Energies

The solar neutrino problem [1, 2] may allow for new breakthroughs in our understanding of the standard model [3, 4]. The precise knowledge of the astrophysical $S_{17}$-factor of the $^7\text{Be}(p,\gamma)^8\text{B}$ reaction at the Gamow peak, about 20 keV, is of crucial importance for interpreting terrestrial measurements of the solar neutrino flux [3]. This is particularly true for the interpretation of results from the Homestake, Kamiokande, SuperKamiokande and SNO experiments [2] which measured high energy solar neutrinos mainly or solely from $^8\text{B}$ decay.

Eight direct measurements were reported for the $^7\text{Be}(p,\gamma)^8\text{B}$ reaction [3, 7, 8, 9, 10, 11, 12, 13]. Since the cross section at $E_{cm} \approx 20$ keV is too small to be measured, the $S_{17}$-factors at low energies have to be extrapolated from the experimental data with the help of theoretical models (see e.g. Johnson et al. [15], Jennings et al. [14]). But also in the energy range above $E_{cm} \approx 100$ keV, where measurements can be performed, experimental difficulties, mainly connected with the determination of the effective target thickness of the radioactive $^7\text{Be}$ target, hamper the derivation of accurate results. These difficulties are reflected in the fact that the six precise measurements [7, 8, 9, 10, 11, 12] can be grouped into two distinct data sets which agree in their energy dependence but disagree in their absolute normalization by about 30%. Since this discrepancy is larger than the error of adopted $S_{17}$ in the standard solar model, experimental studies with different methods are highly desirable for improving the reliability of the input to the standard solar model [17].

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In Fig. 1 we show the world data including our new GSI measurement of $S_{17}$ [14]. It is clear from this figure that if we are to quote $S_{17}(0)$ with an accuracy of ±5%, many more experiments using different methods are required.

![Figure 1: World data on $S_{17}$ as reported by our GSI collaboration [14].](image)

1.1 Extrapolation Procedures

The discrepancy in the measured absolute value of the cross section of the $^7Be(p, \gamma)^8B$ reaction is quite possibly best addressed with a $^7Be$ radioactive beam and a hydrogen target, allowing for a direct measurement of the beam-target luminosity as we propose to do at LLN. However, additional uncertainty exists in the theoretical extrapolation of the measured cross section to solar energies (approximately 20 keV). A few theoretical studies suggest an extrapolation procedure that is accurate to approximately ±1% [16]. Without discussing these rather strong statements we consider a similar situation that haunted Nuclear Astrophysics a few years back— the S-factor of the $d(d, \gamma)^4He$ reaction. It was assumed that in this case d-waves dominate and no nuclear structure effects should play a role at very low energy, as low as 100 keV. Much in the same way, it is stated today that s-waves dominate the $^7Be(p, \gamma)^8B$ reaction and we do not expect nuclear structure effects to play a role at low energies in the $^7Be(p, \gamma)^8B$ reaction. In Fig. 2 we show Fowler’s extrapolated d-wave S-factor that is a mere factor of 32 smaller than measured, due to a small non d-wave component in the d + d interaction [18]. A small nuclear structure effect, namely the d-wave component of the ground state of $^4He$, gives rise to a change by a factor of 32 in the predicted astrophysical S-factor. Similarly we may ask whether a small non s-wave component in the low energy interaction of p + $^7Be$ could alter the extrapolated $S_{17}(0)$ value by considerably more than one percent. A measurement of $S_{17}(0)$ with an accuracy of ±5% mandates that the cross section be measured at low energies, as low as possible, so as to also test the extrapolation procedures.
Fig. 2: Extrapolation of d-wave S-factor of the $d(d, \gamma)^4He$ reaction\[18\]. Note the presence of small non d-wave components that yield a discrepancy from Fowler’s extracted S-factor by a factor of 32.

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

The Coulomb Dissociation (CD) \[19, 20\] is a Primakoff \[21\] process that could be viewed in first order as the time reverse of the radiative capture reaction. In this case instead of studying for example the fusion of a proton plus a nucleus (A-1), one studies the disintegration of the final nucleus (A) in the Coulomb field, to a proton plus the (A-1) nucleus. The reaction is made possible by the absorption of a virtual photon from the field of a high Z nucleus such as $^{208}Pb$. In this case since $\pi/k^2$ for a photon is approximately 1000 times larger than that of a particle beam, the small cross section is enhanced. The large virtual photon flux (typically 100-1000 photons per collision) also gives rise to enhancement of the cross section. Our understanding of the Coulomb dissociation process \[19, 20\] allows us to extract the inverse nuclear process even when it is very small. However in Coulomb dissociation since $\alpha Z$ approaches unity (unlike the case in electron scattering), higher order Coulomb effects (Coulomb post acceleration) may be non-negligible and they need to be understood \[22, 23\]. The success of CD experiments \[24\] is in fact contingent on understanding such effects and designing the kinematical conditions so as to minimize such effects.

Hence the Coulomb dissociation process has to be measured with great care with kinematical conditions carefully adjusted so as to minimize nuclear interactions (i.e. distance of closest approach considerably larger than 20 fm, or very small forward angles scattering), and measurements must be carried out at high enough energies (many tens of MeV/u) so as to maximize the virtual photon flux.

2.1 The RIKENII Results at 50 AMeV

The RIKENII measurement \[25\] of detailed angular distributions for the Coulomb dissociation of $^8B$ allowed us to extract the E2 amplitude in the CD of $^8B$. The same data also allowed us to extract values for $S_{17}$ as recently published \[26\]. The $^{208}Pb$ target and $^8B$ beam properties in this experiment were as in Ref. \[27\], but the detector system covered a large angular range up to around 9° to be
sensitive to the E2 amplitude. The E1 and E2 virtual photon fluxes were calculated\cite{25} using quantum mechanical approach. The nuclear amplitude is evaluated based on the collective form factor where the deformation length is taken to be the same as the Coulomb one. This nuclear contribution results in possible uncertainties in the fitted E2 amplitude. Nevertheless, the present results lead to a very small E2 component at low energies, below 1.5 MeV, of the order of a few percent, even smaller than the low value predicted by Typel and Baur\cite{23} and considerably below the upper limit on the E2 component extracted by Gai and Bertulani\cite{28} from the RIKENI data. These low values of the E2 amplitude were however recently challenged by the MSU group\cite{29} that used interference between E1 and E2 components to observe an asymmetry of the longitudinal-momentum distribution of $^7$Be\cite{30}. They\cite{29} claim: $S_{E2}/S_{E1} = 6.7^{+2.8}_{-1.9} \times 10^{-4}$ at 0.63 MeV. These results are considerably larger than reported by Kikuchi et al.\cite{25}, and just below the upper limit reported by Gai and Bertulani\cite{28}. A recent analysis of the RIKENII data\cite{25} as well as the negligible nuclear contribution. Note that in this analysis\cite{31} the acceptance of the RIKENII detector is taken into account using the matrix generated by Kikuchi et al.\cite{25}. Recently a possible mechanism to reduce the E2 dissociation amplitude was proposed by Esbensen and Bertsch\cite{30}.

### 2.2 The GSI Results at 254 A MeV

An experiment to measure the Coulomb dissociation of $^8$B at a higher energy of 254 A MeV was performed at GSI\cite{14}. The present experimental conditions have several advantages: (i) forward focusing allows us to use the magnetic spectrometer KaoS\cite{32} at GSI for a kinematically complete measurement with high detection efficiency over a wider range of the $p-^7$Be relative energy; (ii) because of the smaller influence of straggling on the experimental resolution at the higher energy, a thicker target can be used for compensating the weaker beam intensity, (iii) effects that obscure the contribution of E1 multipolarity to the Coulomb dissociation like E2 admixtures and higher-order contributions are reduced\cite{22,23}. The contribution of M1 multipolarity is expected to be enhanced at the higher energy, but this allows to observe the M1 resonance peak and determine its $\gamma$ width.

A $^8$B beam was produced by fragmentation of a 350 A MeV $^{12}$C beam from the SIS synchrotron at GSI that impinged on a beryllium target with a thickness of 8.01 g/cm$^2$. The beam was isotopically separated by the fragment separator (FRS)\cite{33} by using an aluminum degrader with a thickness of 1.46 g/cm$^2$ with a wedge angle of 3 mrad. The beam was transported to the standard target-position of the spectrometer KaoS\cite{32}. The average beam energy of $^8$B in front of the breakup target was 254.5 A MeV, a typical $^8$B intensity was $10^4$/spill ($7s$/spill). Beam-particle identification was achieved event by event with the TOF-$\Delta E$ method by using a beam-line plastic scintillator with a thickness of 5 mm placed 68 m upstream from the target and a large-area scintillator wall discussed later placed close to the focal plane of KaoS. About 20% of the beam particles were $^7$Be, which could however unambiguously be discriminated from breakup $^7$Be particles by their time of flight.

An enriched $^{208}$Pb target with a thickness of 199.7 ($\pm$ 0.2) mg/cm$^2$ was placed at the entrance of KaoS. The average energy at the center of the target amounted to 254.0 A MeV. The reaction products, $^7$Be and proton, were analyzed by the spectrometer which has a large momentum acceptance of $\Delta p/p \approx 50\%$ and an angular acceptance of 140 and 280 mrad in horizontal and vertical directions, respectively. For scattering-angle measurement or track reconstruction of the two reaction products, two pairs of silicon micro-strip detectors were installed at about 14 and 31 cm downstream from the target, respectively, measuring either x- or y-position of the products before entering the KaoS magnets. Each strip detector had a thickness of 300 $\mu$m, an active area of $56 \times 56$ mm$^2$, and a strip pitch of 0.1 mm.

The measured complete kinematics of the breakup products allowed us to reconstruct the $p-^7$Be relative energy and the scattering angle $\theta_s$ of the center-of-mass of proton and $^7$Be (excited $^8$B) with respect to the incoming beam from the individual momenta and angles of the breakup products.

To evaluate the response of the detector system, Monte-Carlo simulations were performed using the code GEANT\cite{34}. The simulations took into account the measured $^8$B beam spread in energy, angle,
and position at the target, as well as the influence of angular and energy straggling and energy loss in the layers of matter. Losses of the products due to limited detector sizes were also accounted for. Further corrections in the simulation are due to the feeding of the excited state at 429 keV in $^7$Be. We used the result by Kikuchi et al. [25] who measured the $\gamma$-decay in coincidence with Coulomb dissociation of $^8$B at 51.9 A MeV.

The Monte Carlo simulations yielded relative-energy resolutions from the energy and angular resolutions of the detection system to be 0.11 and 0.22 MeV (1$\sigma$) at $E_{\text{rel}} = 0$ and 1.8 MeV, respectively. The total efficiency calculated by the simulation was found to be larger than 50% at $E_{\text{rel}} = 0 - 2.5$ MeV due to the large acceptance of KaoS.

Fig. 3: (a,b,c) Yields of breakup events plotted against $\theta_8$, the scattering angle of the excited $^8$B, for three relative energy bins. The full histograms show the results of a simulation taking into account the measured angular spread of the incident $^8$B beam (shown in d) and assuming E1+M1 multipolarity. The dashed histograms show the simulated results for E2 contribution according to the calculations of Bertulani and Gai [31].

In Fig. 3, the experimental yield is plotted against the scattering angle of the excited $^8$B for three relative-energy bins, 0.3–0.5 (a), 0.5–0.7 (b), and 1.0–1.2 (c) MeV, together with results of the Monte Carlo simulations assuming E1 excitation. The M1 transition also contributes to the 0.5–0.7 MeV bin with the same angular dependence. Since we did not measure the incident angle of $^8$B at the target, the experimental angular-distributions represent the $\theta_8$ distributions folded with the angular spread of the incident beam shown in Fig. 3d. The angular resolution was estimated to be 0.35° (1$\sigma$), smaller than the observed widths. As seen in Fig. 3 the experimental distributions are well reproduced by the simulation using only E1 multipolarity, in line with the results of Kikuchi et al. [25].

To study our sensitivity to a possible E2 contribution, we have added the simulated E2 angular distribution from the E2 Coulomb dissociation cross section calculated by Bertulani and Gai [31]. Note that nuclear breakup effects are also included in the calculation. By fitting the experimental angular distributions to the simulated ones, we obtained 3$\sigma$ upper limits of the ratio of the E2- to E1-transition amplitude of the $^7$Be(p,$\gamma$)$^8$B reaction, $S_{E2}/S_{E1}$ of $0.06 \times 10^{-4}$, $0.3 \times 10^{-4}$ and $0.6 \times 10^{-4}$ for $E_{\text{rel}} = 0.3–0.5$, 0.5–0.7 and 1.0–1.2 MeV, respectively. These numbers agree well with the results of Kikuchi et al. [25], and suggest that the results of the model dependent analysis of Davids et al. [29] needs to be checked.
2.3 Conclusion: The Coulomb Dissociation Method

In conclusion we demonstrated that the Coulomb dissociation (when used with "sechel") provides a viable alternative method for measuring small cross section of interest for nuclear-astrophysics. First results on the CD of $^8B$ are consistent with the lower measured values of the cross section and weighted average of all thus far data is: $S_{17}(0) = 19.4 \pm 1.3 \text{ eV} - b$, see Table 1. The accuracy of the extracted S-factors are now limited by our very understanding of the Coulomb dissociation process, believed to be approx. $\pm 10\%$. The value of the E2 S-factor as extracted from both the RIKEN and GSI experiments are consistent and shown to be very small, $S_{E2}/S_{E1}$ of the order of $10^{-5}$ or smaller, see Table 1.

Table 1: Measured S-factors in Coulomb dissociation experiments.

| Experiment | $S_{17}(0)$ eV-b | $S_{E2}/S_{E1}(0.6 \text{ MeV})$ |
|------------|------------------|-------------------------------|
| RIKEN1     | 16.9 ± 3.2       | $< 7 \times 10^{-4}$          |
| RIKEN2     | 18.9 ± 1.8       | $< 4 \times 10^{-5}$          |
| GSI1       | 20.6 ± 1.2 ± 1.0 | $< 3 \times 10^{-5}$          |
| MSU        |                  |                               |
| ADOPTED    | 19.4 ± 1.3       | $< 3 \times 10^{-5}$          |

3 The UConn-LLN Experiment With $^7Be$ Radioactive Beam

We propose to measure the cross section of the $^7Be(p, \gamma)^8B$ reaction with the use of $^7Be$ beams produced at Louvain-La-Neuve (LLN) [35]. We intend to perform two experiments, both with $^7Be$ beams at Louvain-La-Neuve. The first one is already approved (PH120) with the use of the old cyclotron for three data points measured at 1.0-0.5 MeV. In a second experiment we propose to use the new cyclotron at LLN for additional measurements below 0.5 MeV. It is however clear that a test of the extrapolation procedures, as discussed above, will require yet a third experiment with an implanted $^7Be$ and low energy proton beams.

![Fig. 4: The Experimental setup of the UConn-LLN Experiment (PH120) to measure the $^7Be(p, \gamma)^8B$ reaction with $^7Be$ beams [35].](image)

The experimental detector setup for the LLN experiment is shown in Fig. 4. By measuring the energy of the emerging $^7Be$ beam, we ensure that the $^8B$ produced in the middle of the target is...
stopped at the end of the first aluminum catcher foil. Due to the finite target thickness, the recoil $^8B$ emerge with a (step) distribution of energies with widths approximately 0.7 MeV, and a stopping spread in aluminum of approximately 0.5 μm. Thus the stopped $^8B$ are designed to be equally spread over the two aluminum catcher foils (0.5 μm each). The beta-delayed alpha-particle emission of $^8B$ will be measured by measuring coincidence between the two back to back equal energy alpha-particles detected in a pair of detectors, see Fig. 4. The large diameter of the central detector (more than twice that of front and back detectors) yield a large coincidence efficiency (better than 98%), as shown by our extensive Monte Carlo simulations. By requiring that the count rates in the front and back pair of detectors are similar we will ensure that the $^8B$ are spread equally on both aluminum foils and thus no $^8B$ escapes the catcher foils and none get stopped in the degrader, yielding nearly 100% collection efficiency.

In the target region, two monitors measure beam intensity by measuring the elastic scattering off a thin Au foil (evaporated onto a very thin carbon backing) and the recoil protons off the target. We plan to measure $\sigma/\sigma_{\text{Rutherford}}$ for $p + ^7Be$ with high precision. Thus the cross section of the $^7Be(p,\gamma)^8B$ reaction will be measured relative to the elastic scattering, thereby removing several systematic uncertainties related to beam-target composition. The hydrogen component of the target will be continuously monitored by measuring the recoil protons from the target. These measurements will allow us to continuously measure and monitor the beam-target luminosity.

Since two alpha-particles are associated with that decay we expect a very large detection efficiency, approximately 50% of $2\pi$. Our extensive Monte-carlo simulations yield a large (98%) coincidence efficiency and thus approximately 50% total coincidence efficiency for two equal energy correlated back to back alpha-particles. For a $^8B$ transfer time of 0.07 sec, every 0.5 sec, we obtain a total alpha-particle detection efficiency of approximately 25%. The closed detection geometry (50% of $4\pi$) with a front and back detectors (a-la calorimetry style) also ensures that the total alpha detection efficiency is nearly independent of the exact location of the collection foils, as long as the two foils remain parallel and at constant distance and the recoil $^8B$ nuclei are spread equally on both catcher foils.

A beam intensity of $5 \times 10^8$ /sec and a 250 μg/cm$^2$ CH$_2$ target ($\Delta E_{cm} = 100$ keV) containing $2 \times 10^{19}$ hydrogens/cm$^2$ yield a luminosity of $10^{28}$ /sec/cm$^2$. With expected cross sections of $\sigma = 0.5$, 0.4 and 0.2 μb, at $E_{cm} = 1.0$, 0.8 and 0.5 MeV, respectively, and alpha-particle detection efficiency of 25%, we obtain count rates of approximately 5, 4, and 2 counts per hour. Thus experiments lasting two to three days at $E_{cm} = 1.0$, 0.8 and 0.5 MeV, respectively, will yield a total count of 240, 192 and 144 counts and statistical uncertainties of 6.4%, 7.2% and 8.3%, respectively. With approved 9 days of experiment we plan to adjust the length of runs to achieve 5% precision at each data point.

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### References

[1] John N. Bahcall, Neutrino Astrophysics, Cambridge University Press, New York, 1989.

[2] J.N. Bahcall, F. Calaprice, A.B. McDonald, and Y. Totsuka; Physics Today 30,#7(1996)30 and references therein.

[3] L. Wolfenstein, Phys. Rev. D17(1978)2369, ibid D20(1979)2634.

[4] S.P. Mikheyev, and A.Yu. Smirnov, Yad. Fiz. 44(1985)847.

[5] E.G. Adelberger et al.; Rev. Mod. Phys. 70(1998)1265.
[6] R.W. Kavanagh, Nucl. Phys. 15(1960)411.
[7] P.D. Parker et al., Astrophys. J. 153(1968)L85.
[8] R.W. Kavanagh et al., Bull. Am. Phys. Soc. 14(1969)1209.
[9] F.J. Vaughn et al., Phys. Rev. C 2(1970)1657.
[10] C. Wiezorek et al., Z. Phys. A 282(1977)121.
[11] B. W. Filippone et al., Phys. Rev. C 28(1983)2222.
[12] F. Hammache et al., Phys. Rev. Lett. 80(1998)928.
[13] M. Hass et al., Phys. Lett. B462(1999)237.
[14] N. Iwasa et al.; Phys. Rev. Lett. 83(1999)2910
[15] C.W. Johnson et al., Astrophys. J. 392(1992)320.
[16] B.K. Jennings, S. Karataglidis, and T.D. Shoppa; Phys. Rev. C 58 (1998) 3711
[17] J.N. Bahcall and M.H. Pinsonneault, Rev. Mod. Phys. 64(1992)885.
[18] C.A. Barnes et al.; Phys. Lett. 197(1987)315.
[19] G. Baur, C.A. Bertulani, and H. Rebel; Nucl. Phys. A458(1986)188.
[20] C.A. Bertulani and G. Baur; Phys. Rep. 163(1988)299.
[21] H. Primakoff; Phys. Rev. 81(1951)899.
[22] C.A. Bertulani; Phys. Rev. C49(1994)2688.
[23] S. Typel and G. Baur; Phys. Rev. C50(1994)2104.
[24] Moshe Gai, Nucl. Phys. B(Sup.)38(1995)77.
[25] T. Kikuchi et al.; Phys. Lett. B391(1996)261.
[26] T. Kikuchi et al.; Eur. Phys. J. A3(1998)213.
[27] T. Motobayashi et al.; Phys. rev. Lett. 73(1994)2680. and N. Iwasa et al.; Jour. Phys. Soc. Jap. 65(1996)1256.
[28] Moshe Gai, and Carlos A. Bertulani; Phys. Rev. C52(1995)1706.
[29] B. Davids et al., Phys. Rev. Lett. 81(1998)2209.
[30] H. Esbensen and G.F. Bertsch; Phys. Lett. B359(1995)13 ibid 531 Nucl. Phys. A600(1996)37.
[31] Carlos A. Bertulani and Moshe Gai; Nucl. Phys. A636(1998)227.
[32] P. Senger et al., Nucl. Instr. Meth. A 327, 393 (1993).
[33] H. Geissel et al., Nucl. Instr. Meth. B 70, 286 (1992).
[34] Detector description and simulation tool by CERN, Geneva, Switzerland.
[35] M. Gai, J.E. McDonald, R.H. France III, J.S. Schweitzer, C. Angulo, Ch. Barue, S. Cherubini, M. Cogneau, Th. Delbar, M. Gae lens, P. Leleux, M. Loiselet, A. Ninane, G. Ryckewaert, K.B. Swartz, D. Visser; Bull. Amer. Phys. Soc. 44,II(1999)1529.