Solar Fusion and The Coulomb Dissociation of $^8B$; What Have We Learned and Where Do We Go From Here?

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Abstract. The much needed nuclear input to the Standard Solar Model, $S_{17}(0)$, has now been measured with high precision (±5% or better) by different groups and good agreement is found, even when very different methods are employed. We review the decade long research program to measure the cross section of the $^7Be(p,\gamma)^8B$ reaction using the Coulomb dissociation method, including the pioneering RIKEN1 experiment carried out during March 1992, followed by RIKEN2, GSI1, GSI2 and an MSU experiment. Our RIKEN and GSI data allow us to rule out the much tooted large E2 contribution to the Coulomb dissociation of $^8B$. Specifically recent results of the MSU experiment are not confirmed. The GSI1 and GSI2 high precision measurements are in good (to perfect) agreement with the newly published high precision measurements of direct capture with $^7Be$ targets. From these GSI-Seattle-Weizmann high precision data we conclude that the astrophysical cross section factor, $S_{17}(0)$, is most likely in the range of 20 - 22 eV-b. We point out to an additional large uncertainty (-10% +3%) that still exists due to uncertainty in the measured slope of the S-factor and the theoretical extrapolation procedure which may still lower $S_{17}(0)$ down to approximately 18.5 eV-b. For quoting $S_{17}(0)$ with an uncertainty of ±5% or better, yet another measurement needs to be performed at very low energies, as recently discussed by the UConn-Weizmann-LLN collaboration for the CERN/ISOLDE facility.

Keywords: Solar Neutrinos, Solar Fusion, Nuclear Astrophysics, Astrophysical Cross Section factor, Coulomb Dissociation, Virtual Photons.

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1. Introduction

The discovery of solar neutrino oscillations [H] opens a window of opportunity for the study of neutrino masses with very small mass differences. While the SNO result [H] for the measured total solar neutrino flux is rapidly approaching the
accuracy of ±5%, the uncertainty in the Standard Solar Model is still dominated by nuclear inputs, with the most disturbing uncertainty in the astrophysical cross section factor of the $^7$Be$(p, \gamma)^8$B reaction, $S_{17}(0)$ [2]. It is desirable to measure $S_{17}(0)$ with accuracy comparable to the design goal accuracy of the SNO experiment of ±5%. For example a significantly smaller total neutrino flux measured by SNO as compared to an accurate prediction of the Standard Solar Model may teach us about oscillation of solar neutrinos into sterile neutrinos.

2. The Coulomb Dissociation of $^8$B

The Coulomb dissociation of $^8$B [3] has been suggested as a viable method to measure the cross section of the $^7$Be$(p, \gamma)^8$B reaction. After the pioneering experiment of the RIKEN1 group [4] several experiments were carried out at medium energy heavy ion facilities [5, 6, 7, 8] using a variety of kinematical regions and different experimental techniques. While already the data of RIKEN1 suggest a small if not negligible E2 contribution [9] to the Coulomb dissociation of $^8$B, the MSU group claimed to have measured a large effect [7] in the measured asymmetry. The MSU model dependent claim has now been tested with the new GSI2 data [8], including a test of the claim of a measured large asymmetry due to E2 contribution. No large E2 contribution was observed in the GSI2 data [8], as summarized in Table 1. Note that while the RIKEN-GSI results for the astrophysical cross section factors were measured with increasingly higher accuracy, reaching the accuracy of ±5% or better, the quoted central value has risen over the years and stabilized around 20.5-20.8 eV-b, as can be seen in Table 1. The smaller value for $S_{17}(0)$ quoted by the MSU group, see Table 1, is almost entirely due to their model dependent assumption (and not a measurement) of large E2 contribution to the Coulomb dissociation of $^8$B.

| Experiment | $S_{17}(0)$ (eV-b) | $S_{E2}/S_{E1}(0.6$ MeV) |
|------------|-------------------|--------------------------|
| RIKEN1(94) | 16.9 ± 3.2 | < 7 × 10$^{-4}$ |
| RIKEN2(98) | 18.9 ± 1.8 | < 4 × 10$^{-5}$ |
| GSI1(99)   | 20.6 ± 1.2 - 1.0 | < 3 × 10$^{-5}$ |
| GSI2(03)   | 20.8 ± 0.5 ± 0.5 | < 3 × 10$^{-5}$ (Yield < 1%) |
| MSU(01)    | 17.8 + 1.4 - 1.2 | (4.7 + 2.0 - 1.3) × 10$^{-4}$ |
3. Comparison of Results

The recent large number of direct capture measurements of the $^7\text{Be}(p, \gamma)^8\text{B}$ reaction with $^7\text{Be}$ targets [10, 11, 12, 13], at specific energies allow us to perform a detailed comparison. At first we focus our attention on comparing data points measured at a specific energy, $S_{17}(E)$. In Figure 1 we show a comparison of the GSI2(03) [8], GSI1(99) [6], Weizmann(03) [13], Orsay(01) [10], and Bochum(01) [11] data. The GSI1(99), GSI2(03) and Weizmann(03) data are measured with high accuracy ($\pm 5\%$ or better) and are in very good agreement among themselves. Unfortunately this is not the case for the Orsay(01) and Bochum(01) data that at some energies exhibit more than $3\sigma$ deviation from the GSI-Weizmann data, see Figure 1.

Fig. 1: Comparison of the recent GSI2(03) [8] data, with the published data of GSI1(99) [6], Weizmann(02) [13], Orsay(01) [10], and Bochum(01) [11].

In spite of the good agreement, the measured slopes of the astrophysical cross section factor are sufficiently different that it precludes an accurate ($\pm 5\%$) extrapolation to zero energy.

Fig. 2: Comparison of the recent GSI2(03) [8] data, with the published data of GSI1(99) [6], Weizmann(03) [13], and Seattle(02) [12].
The Seattle data [12] on the other hand show a remarkable agreement with the GSI-Weizmann data, and it is also measured with high precision. We conclude that the GSI-Seattle-Weizmann data could serve as a benchmark for studying for example the energy dependence and the slope of the measured s-factors. However, as shown in Figure 2, while the data are in fairly good agreement they exhibit sufficiently different slopes, as well as sufficiently different absolute values at low energy, inhibiting an accurate (±5%) extrapolation to zero energy.

Table 2. Extrapolated cross section factors using the theory of Descouvemont and Baye [14]. Only high precision results, $S_{17}(0)$ measured with an error of ±5% or better, are shown, excluding the results of: RIKEN2(98) (18.9 ± 1.8) [9], Orsay(01) (18.8 ± 1.7) [10] and Bochum(01) (18.4 ± 1.6) [11].

| Experiment       | $S_{17}(0)$ (eV-b) |
|------------------|--------------------|
| GSI1(99) [6]     | 20.6 ± 1.2 − 1.0   |
| Seattle(02) [12] | 22.3 ± 0.7         |
| Weizmann(03) [13]| 21.2 ± 0.7         |
| GSI2(03) [8]     | 20.8 ± 0.5 ± 0.5   |

Average: 21.2 ± 0.8 ($\chi^2 = 1.2$)

4. Extrapolation Methods

Fig. 3: The GSI1(99) [6], GSI2(03) [8] and Weizmann(03) [13] data compared to the standard extrapolation of Descouvemont and Baye [14] and the more recent potential model extrapolation of Ref. [8]. The Weizmann(03) data point at approximately 850 keV is plotted with M1 contribution subtracted.

In Figure 3 we show a comparison of the GSI-Weizmann data with the extrapolation
method of Descouvemont and Baye [14] that so far has been used by all current experiments. The slope of the theoretical curve is somewhat flatter than that of the GSI-Weizmann data. The slope of the Seattle data on the other hand is in agreement with the theoretical prediction of Descouvemont and Baye. In the same Figure we also show a more recent theoretical curve of Typel [8] that exhibit a steeper energy dependence, and is consistent with the GSI-Weizmann data, but not with the Seattle data. Using Typel’s extrapolation we deduce $S_{17}(0) = 18.6 \pm 0.5 \pm 1.0 \text{ eV-b}$ [8]. Note that Typel model is a simple potential model with a variation in the potential parameter that yield a different S-factor already for the $s$-wave component without altering the $d$-wave component. The confusion between the different theoretical extrapolations, in addition to the discussion in the previous section, does not allow us to quote $S_{17}(0)$ with the desired accuracy of $\pm 5\%$.

5. Future Experiment: The CERN/ISOLDE project

In order to resolve the issues discussed in section 4 and 3 it is very desirable to perform a precision measurement at low energy as we recently discussed at CERN/ISOLDE [15], where they have developed the most intense $^7\text{Be}$ beam of up to 100 nA. In Figure 4 we show a possible setup discussed for this experiment where the cross section can be measured at $E_{\text{cm}} = 500$-100 keV with a possible extension to 70 keV.

![Fig. 4: The suggested arrangement of the CERN/ISOLDE experiment [15].](image-url)
6. Conclusions

A great deal of progress has been achieved in measuring the cross section of the $^7\text{Be}(p,\gamma)^8\text{B}$ reaction and $S_{17}(E)$, that are now measured with a precision of $\pm 5\%$. But the current state of the extrapolation involving the measured slope as well as the theoretical model used for the extrapolation, still do not allow to extract the relevant nuclear input to the Standard Solar Model, $S_{17}(0)$, with the needed precision of $\pm 5\%$. Instead one may conclude that the value is most likely in the range of 20-22 eV-b, but further study is required to test the possible lowering of $S_{17}(0)$ to approximately 18.5 eV-b due to extrapolation. A measurement of the cross section factor at low energies is needed to resolve the issue of the extrapolation to zero energy.

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