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The Coulomb Dissociation of ^8B; A Triumph of Good Science [1].

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Abstract. The GSI1, GSI2 (as well as the RIKEN2 and the corrected GSI2) measurements of the Coulomb Dissociation (CD) of ^8B are in good agreement with the most recent Direct Capture (DC) $^7Be(p,\gamma)^8B$ reaction measurement performed at Weizmann and in agreement with the Seattle result. Yet it was claimed that the CD and DC results are sufficiently different and need to be reconciled. We show that these statements arise from a misunderstanding (as well as misrepresentation) of CD experiments. We recall a similar strong statement questioning the validity of the CD method due to an invoked large E2 component that was also shown to arise from a misunderstanding of the CD method. In spite of the good agreement between DC and CD data the slope of the astrophysical cross section factor (S_{17}) can not be extracted with high accuracy due to a discrepancy between the recent DC data as well as a discrepancy of the three reports of the GSI CD data. The slope is directly related to the d-wave component that dominates at higher energies and must be subtracted from measured data to extrapolate to zero energy. Hence the uncertainty of the measured slope leads to an additional uncertainty of the extrapolated zero energy cross section factor, $S_{17}(0)$. This uncertainty must be alleviated by future experiments to allow a precise determination of $S_{17}(0)$, a goal that so far has not be achieved in spite of strong statement(s) that appeared in the literature.

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1. Introduction

The Coulomb Dissociation (CD) method was developed in the pioneering work of Baur, Bertulani and Rebel [1] and has been applied to the case of the CD of ^8B [2, 3, 4, 5] from which the cross section of the $^7Be(p,\gamma)^8B$ reaction was extracted. This cross section is essential for calculating the ^8B solar neutrino flux. The CD data were analyzed with a remarkable success using only first order Coulomb interaction that includes only E1 contribution. An early attempt (even before the RIKEN data were published) to refute this analysis by introducing a non-negligible E2 contribution [6] was shown [7] to arise from a neglect of the angular acceptance of the RIKEN1 detector and a misunderstanding of the CD method. Indeed the CD of ^8B turned out to be a testing ground of the very method of CD. Later claims by the MSU group for evidence [8] of non-negligible E2 contribution in **inclusive measurement** of an asymmetry, were disputed in a recent **exclusive measurement** of a similar asymmetry by the GSI2 collaboration [5].

In contrast, Esbensen, Bertsch and Snover [9] recently claimed that higher order terms and an E2 contribution are an important correction to the RIKEN2 data [3]. It is claimed that "S_{17} values extracted from CD data have a significant steeper slope as a function of E_{rel}, the relative energy of the proton and the ^7Be fragment, than the direct result". However they find a substantial correction only to the RIKEN2 CD data and claim that this correction(s) yield a slope of the RIKEN2 data in better agreement with Direct Capture (DC) data. In addition it is stated [9] that "the zero-energy extrapolated $S_{17}(0)$ values inferred from CD measurements are, on the average 10% lower than the mean of modern direct measurements". The statements on significant disagreement between CD and DC data are based on the re-analyses of CD data presented in [10]. In this paper we demonstrate that an agreement exists between CD and DC data and the statements in [10] are based on misunderstanding (as well as misrepresentation) of CD data.

In spite of the general agreement between CD and DC data, still the the slope of astrophysical cross section factor measured between 300 - 1,500 keV can not be extracted with high accuracy. This hampers our ability to determine the d-wave contribution that dominates the cross section of the $^7Be(p,\gamma)^8B$ reaction at higher energies and must be subtracted for extrapolating the s-wave to zero energy. Lack of accurate knowledge of the d-wave contribution to data (even if measured with high accuracy), precludes accurate extrapolation to zero energies. We show that this leads to additional uncertainty of the extrapolated $S_{17}(0)$. We doubt the strong statement that $S_{17}(0)$ was measured with high accuracy (see for example [10]).

2. The Slope of S_{17} Above 300 keV

Early on it was recognized that s-wave capture alone yields an s-factor with a negative slope. This is due to the Coulomb distortion of the s-wave at very low distances. The observation of a positive slope of S_{17} measured at energies above 300 keV was recognized as due to the d-wave contribution. It was also recognized that

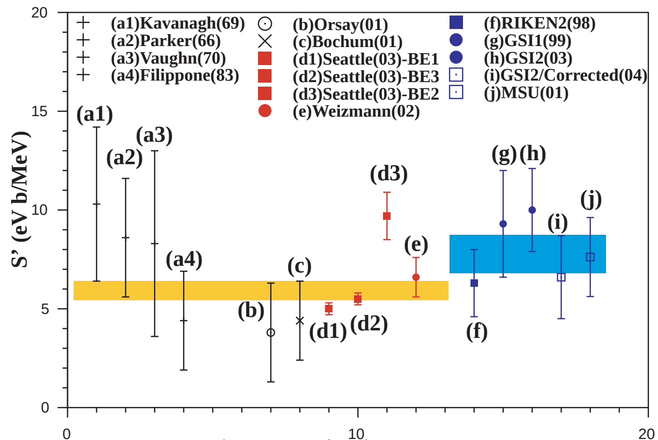

Fig. 1. The measured slopes (S' = dS/dE) of world data measured between 300 and 1500 keV, as discussed in the text. The range of "average values" is indicated and discussed in the text.

the d-wave contribution is very large at measured energies and in fact it dominates around 1.0 MeV. The d-wave contribution must be subtracted to allow an accurate extrapolation of the s-wave to zero energy (where the d-wave contribution is very small, of the order of 6%). The (large) contribution of the d-wave at energies above 300 keV leads to a linear dependence of S_{17} on energy (with a positive slope). An accurate extrapolation of S_{17} must rely on an accurate knowledge of the d-wave contribution or the slope at energies above 300 keV.

In Fig. 1 we show the slope parameter (S' = dS/dE) extracted from both DC and CD data in the energy range of 300 - 1500 keV. We refer the reader to [11] for detailes on data used to extract the slope shown in Fig. 1. We conclude from Fig. 1 that the slope parameter can not be extracted from DC data [10, 13, 14, 15, 16, 17, 18, 19] with high accuracy as claimed. The DC data are not sufficiently consistent to support this strong statement [10]; for example there is not a single data point measured by the Bochum group [14] that agrees with that measured by the Seattle group [10], where we observe that some of the individual data points disagree by as much as five sigma. The disagreement of the three slopes measured by the Seattle group and the disagreement with the Weizmann slope are most disturbing. In the same time the dispersion among slopes measured in CD is also of concern. However, it is clear that the over all agreement between CD and DC data (1.7 sigma) is better than the agreement among specific DC data. We do not support the strong claim of substantial disagreement between slopes measured in DC and CD [10].

The lack of evidence for substantial difference between CD and DC results leads to doubt on the very need to reconcile these data [12]. Furthermore, in Fig. 2 we show the slope obtained by EBS after their attempt to reconcile the slope of CD with the slope of DC data. Clearly the original slope of the RIKEN2 data obtained using only first order E1 interactions is in considerably better agreement with DC

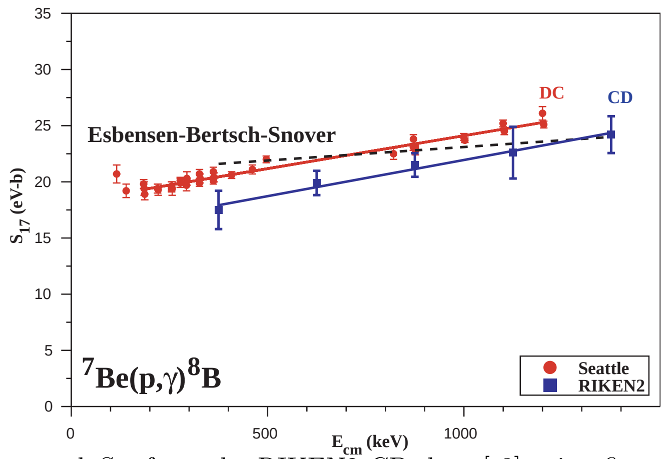

Fig. 2. Extracted S_{17} from the RIKEN2 CD data [3] using first order electric dipole interaction as shown in [5], compared to the DC capture data published by the Seattle group [10] and the so called reconciled slope calculated by EBS [9]. The shown RIKEN2 data include systematic uncertainties (equal or slightly smaller) as published [3].

data than the so called reconciled slope.

3. $S_{17}(0)$ Extracted From CD Data

In Fig. 20 of the Seattle paper [10] they show extracted $S_{17}(0)$ from CD using the extrapolation procedure of Descouvemont and Baye [20], and based on this analysis it is stated [9] that "the zero-energy extrapolated $S_{17}(0)$ values inferred from CD measurements are, on the average 10% lower than the mean of modern direct measurements". The extracted $S_{17}(0)$ shown in Fig. 20 [10] are only from data measured at energies below 425 keV and the majority of CD data points that were measured above 425 keV were excluded in Fig. 20 [10].

This arbitrary exclusion of (CD) data above 425 keV has no physical justification (especially in view of the fact that the contribution of the 632 keV resonance is negligible in CD). For example as shown by Descouvemont [21] the theoretical error increases to approximately 5% at 500 keV and in fact it is slightly decreased up to approximately 1.0 MeV, and there is no theoretical justification for including data up to 450 keV but excluding data between 500 keV and 1.0 MeV.

Thus when excluding the CD data above 425 keV, the Seattle group excluded the data that were measured with the best accuracy and with smallest systematical uncertainty. If in fact one insists on such an analysis of CD data, one must estimate the systematic uncertainty due to this selection of data. This has not been done in the Seattle re-analyses of CD data [10].

Instead we rely here on the original analyses of the authors that published the

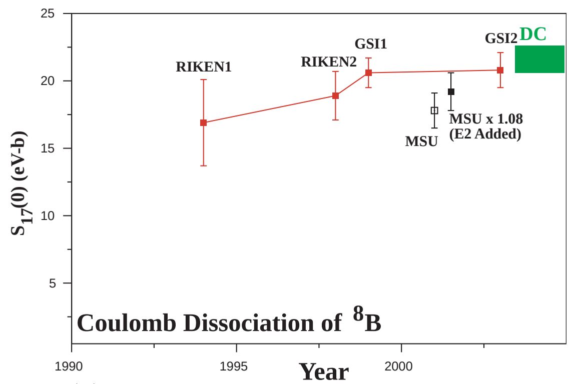

Fig. 3. Measured $S_{17}(0)$ as originally published by the authors who performed the CD experiments. These analyses include all measured data points [2, 3, 4, 5, 8] using the extrapolation procedure of Descouvemont and Baye [20]. We also plot the MSU data as published as well as with the E2 correction ($\approx 8\%$) [8] added back to the quoted $S_{17}(0)$, as discussed in the text. The range of $S_{17}(0)$ results from the measurements of DC by the Seattle [10] and Weizmann groups [15] is indicated.

CD data. In Fig. 3 we show the $S_{17}(0)$ factors extracted by the original authors who performed the CD experiments. These results include all measured data points up to 1.5 MeV, and are analyzed with the same extrapolation procedure of Descouvemont and Baye [20].

We note that the (four) CD results are consistent within the quoted error bars, but they show a systematic trend of an increased $S_{17}(0)$ (to approximately 20.7 eV-b), while the error bars are reduced. We obtain a $1/\sigma$ weighted average of $S_{17}(0) = 20.0 \pm 0.7$ with $\chi^2 = 0.5$, which is in excellent agreement with the measurement of the Weizmann group [15] and in agreement with the measurement of the Seattle group [10].

The current situation with our knowledge of S_{17} and the extrapolated $S_{17}(0)$ is still not satisfactory. The main culprit are major disagreements among DC data. It is clear for example that the systematic disagreements between the Orsay-Bochum [13, 14] and the Weizmann-Seattle [10, 15] results must be resolved before these data are included in a so called "world average". In Fig. 4 we compare the most recent Seattle-Weizmann data (with M1 contribution subtracted) with the GSI1 and GSI2 (as well as corrected GSI2) results. While the data appear in agreement we still observe a systematic disagreement of all measured (DC and CD) slopes. This disagreement does not allow for an accurate extrapolation of $S_{17}(0)$ and must be resolved by future experiments.

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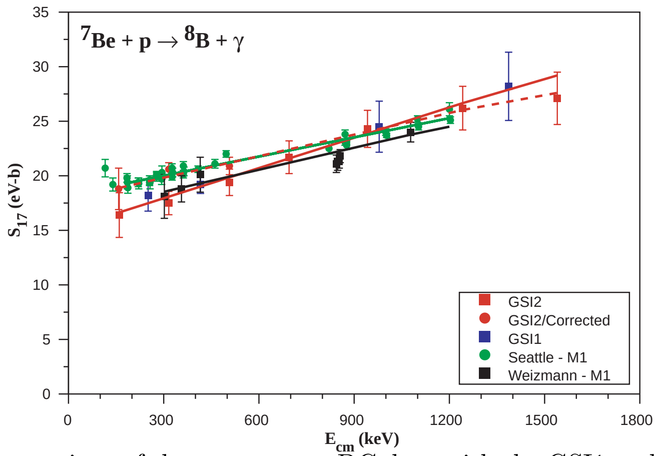

Fig. 4. A comparison of the most recent DC data with the GSI1 and GSI2 results.

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