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The ^{7}Be(p,γ)^{8}B Reaction and its Future

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The experimental landscape for the ^{7}Be+p radiative capture reaction is rapidly changing as new high precision data become available. We present an evaluation of existing data, detailing the treatment of systematic errors and discrepancies, and show how they constrain the astrophysical S factor (S_{17}), independent of any nuclear structure model. With theoretical models robustly determining the behavior of the sub-threshold pole, the extrapolation error can be reduced and a constraint placed on the slope of S_{17}. Using only radiative capture data, we find $S_{17}(0) = 20.7 \pm 0.6(stat) \pm 1.0(syst)$ eV b if data sets are completely independent, while if data sets are completely correlated we find $S_{17}(0) = 21.4 \pm 0.5(stat) \pm 1.4(syst)$ eV b. The truth likely lies somewhere in between these two limits. Although we employ a formalism capable of treating discrepant data, we note that the central value of the S factor is dominated by the recent high precision data of Junghans et al., which imply a substantially higher value than other radiative capture and indirect measurements. Therefore we conclude that future progress will require new high precision data with a detailed error budget.

1. Introduction

The formalism adopted for the analysis of the ^{7}Be(p,γ)^{8}B data has been discussed elsewhere [1–3]. We comment that the formalism requires intimate knowledge of experimental data and their associated error budgets. For simplicity, the formalism assumes the dominant systematic error is due to the normalization uncertainty. Also, intrinsic to this formalism is a robust and quantitative assessment of the quality of fit, which takes into account intrinsic normalization errors as well as discrepant datasets.

Naively, one may consider a simple polynomial expansion in energy about $E = 0$. However, this simple form does not properly treat the behavior of the subthreshold pole, known to exist at $E = -Q$, where $Q = 137.5$ keV. We therefore, adopt the form recommended by [4].

$$S_{17}(E) = S_{17}(0) + \alpha\frac{E}{Q(E+Q)} + \beta E$$

This form is valid for $E \lesssim 425$; much beyond this energy, higher order terms become important (e.g. $\propto E^2$). By keeping the fit linear in the parameters, $S_{17}(0)$, α, and β, we ensure they are gaussian distributed. They are easily transformed into the non-linear parameters of [4] through $a = -\alpha/S_{17}(0)$ and $c = \beta/S_{17}(0)$. We can see the α-term

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accounts for the subthreshold pole behavior, while β represents the slope at larger energies (i.e. "slope" parameter).

We find that the data alone are not sufficient to put strong constraints on these parameters. We therefore use several theoretical models to fix the "universal" subthreshold pole behavior, by fitting theory predictions to the form in eqn. 1, with $S_{17}(0) = 1$.

Table 1
Best fit parameters for several theoretical models below $E_{cm} = 425$ keV. We adopt $a = 45 \pm 1$ keV for our quasi-theory independent fits.

Model	a (keV)	c (MeV^{-1})
DT ^{7}Li + n potential [5]	45.7 ± 0.5	0.553 ± 0.007
DT ^{7}Be-potential [5]	45.0 ± 0.6	0.433 ± 0.007
DB Volkov II [6,7]	45.5 ± 0.1	0.434 ± 0.001
DD Minnesota [8,9]	44.5 ± 0.1	0.404 ± 0.002

2. The Data

We now discuss the data available to constrain the astrophysical S factor of the ^{7}Be(p,γ)^{8}B reaction. In some cases there is sufficient reason to exclude data sets from the analysis. We consider only low energy data, $E_{cm} < 425$ keV, when determining the best fits to $S_{17}(E)$, as nuclear structure uncertainties complicate and render more uncertain the extrapolation when higher energy data are included [4,5,19].

2.1. Radiative Capture Data

We consider the data sets of Kavanagh [10], Parker [11], Vaughn *et al.* [12], Filippone *et al.* [13], Strieder *et al.* [14], Hammache-2 [16], Hammache-1 [15], Hass *et al.* [17], Junghans-BE1 [18], Junghans-BE3 [19], and Baby *et al.* [20]. We exclude Kavanagh [10], Parker [11] and Vaughn *et al.* [12] because they do not present enough information to adequately determine a normalization error. We do not use Hass *et al.* [17] simply because the data lie above our 425 keV energy cutoff.

The Hammache-2 [16] data consist of 3 data points, two of which are measured relative to the third. Ideally, one would like to include all 3 points, but not enough information is given on the third point to determine an intrinsic normalization error. We thus adopt the 2 relative measurements as the data set, using the third to determine the normalization error. Ref. [19] presents renormalized data from their BE1 measurement. We believe that underlying systematics are different enough between the BE1 and BE3 data sets that this renormalization and common error assignment is inappropriate, and unphysically reduces the dispersion between the two data sets. Thus, we adopt the original Junghans-BE1 data [18], in additional to the Junghans-BE3 data [19].

2.2. Coulomb Dissociation Data

We consider the Coulomb dissociation (CD) data of Kikuchi *et al.* [21,22], Iwasa *et al.* [23], Schümann *et al.* [24] and Davids *et al.* [25,5]. We exclude Kikuchi *et al.* [21,22] and Iwasa *et al.* [23] which suffer from substantial $E2$ and nuclear diffraction dissociation contributions and other complications. Hence we include only the CD data of Schümann *et al.* [24] and Davids *et al.* [25,5].

Table 2
Best fit parameters for data with $E_{cm} < 425$ keV with the functional form of Eq. 1. Here, "All RC" corresponds to all experiments listed in the table, while "More RC" includes datasets that could not be used individually [14,16]. These additional datasets can only be combined when using the correlated normalization method of fitting. The * results exclude the Junghans datasets [18,19]. The first set of rows summarizes individual dataset results, while the follow sets of rows correspond with the normalization independent and correlated normalization analyses.

Data	$S_{17}(0)$ (eV b)	α (eV b MeV)	β (eV b MeV^{-1})	ϵ_{norm}	ϵ_{disc}
Filippone	38.6 ± 15.7	-8.5 ± 5.4	70.6 ± 37.2	11.9%	3.1%
Hammache-1	-2430 ± 2160	-623 ± 554	-2308 ± 2103	4.9%	0.0%
Junghans-BE1	18.4 ± 10.6	-0.0 ± 3.2	7.1 ± 17.5	2.7%	0.7%
Junghans-BE3	24.3 ± 3.9	-2.0 ± 1.3	18 ± 9	2.3%	1.3%
Baby	55.3 ± 213.1	-11.4 ± 56.2	66 ± 229	2.2%	0.0%
All RC*	34.9 ± 13.2	-7.2 ± 4.3	60.2 ± 27.4	—	1.3%
Junghans	23.6 ± 3.4	-1.7 ± 1.1	16.1 ± 7.1	—	0.7%
All RC	23.4 ± 3.3	-1.8 ± 1.1	16.6 ± 6.8	—	3.7%
Coulomb diss.	—	—	—	—	—
All RC*	35.4 ± 13.0	-7.1 ± 4.2	57.2 ± 26.8	6.7%	3.6%
More RC*	29.0 ± 7.9	-5.0 ± 2.9	43.5 ± 21.2	7.7%	5.4%
Junghans	24.1 ± 3.4	-1.9 ± 1.1	18.5 ± 6.9	2.6%	1.3%
More RC	18.9 ± 2.9	-0.1 ± 1.0	5.7 ± 6.1	6.0%	3.2%
Coulomb diss.	-13.5 ± 26.4	9.3 ± 8.6	-5.3 ± 53	6.5%	3.6%

3. Conclusions

The theory-independent constraints on $S_{17}(0)$ are not too constraining. With theory robustly determining the subthreshold pole behavior, much stronger constraints can be placed on the low-energy S-factor. The high-precision Junghans data [18,19] dominates the fit, with marginal discord with other radiative capture and Coulomb dissociation measurements. We remark that the formalism used here is useful in that it (1) parameterizes and quantifies our ignorance, (2) explicitly treats systematic errors and (3) suggests that improvement may be gained with either new precise and accurate data or the exclusion of existing data.The future of S_{17} depends on the confirmation of the Junghans data.

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Table 3
Best fit results using the $a = 45$ keV model for $E_{cm} < 425$ keV. An additional systematic error must be added due to the uncertainty in a; $\Delta S_{17}(0)/S_{17}(0) \approx 0.16\Delta a/a$, and $\Delta\beta/\beta \approx 0.80\Delta a/a$, which for $a = 45 \pm 1$ keV yields $\Delta S_{17}(0)/S_{17}(0) = 0.4\%$ and $\Delta\beta/\beta = 1.8\%$, respectively. The * results exclude the Junghans datasets [18,19].

	Data set	$S_{17}(0)$ (eV b)	β (eV b MeV^{-1})	ϵ_{norm}	ϵ_{disc}
RC	Filippone	16.4 ± 2.8	18.1 ± 7.2	11.9%	4.9%
	Strieder	30.6 ± 17.2	-17.8 ± 37.6	8.3%	4.0%
	Hammache-1	-2.7 ± 16.7	56.2 ± 34.4	4.9%	3.7%
	Hammache-2	-2.3 ± 16.1	$159. \pm 113.$	12.2%	0.0%
	Junghans-BE1	21.4 ± 1.2	12.1 ± 2.6	2.7%	0.7%
	Junghans-BE3	21.4 ± 0.6	11.3 ± 1.6	2.3%	1.3%
	Baby	14.6 ± 8.5	21.9 ± 17.8	2.2%	0.7%
CD	Davids	16.6 ± 2.5	9.1 ± 6.4	7.1%	0.0%
	Schümann	17.5 ± 4.9	12.5 ± 13.2	5.6%	0.0%
indep. norm.	All RC*	16.3 ± 2.3	17.3 ± 5.0	—	3.5%
	Junghans	21.4 ± 0.7	11.6 ± 1.4	—	0.8%
	All radiative capture	20.7 ± 0.6	11.3 ± 1.3	—	4.8%
	Coulomb dissociation	17.5 ± 2.3	9.7 ± 5.8	—	5.1%
corr. norm.	All RC*	17.9 ± 1.4	13.4 ± 3.3	8.0%	5.8%
	Junghans	21.1 ± 0.5	12.3 ± 1.3	2.6%	1.3%
	All radiative capture	21.4 ± 0.5	11.0 ± 1.2	5.7%	3.2%
	Coulomb dissociation	17.4 ± 2.2	8.7 ± 5.7	6.4%	4.8%

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