^{7}Be$(p,\gamma)^8$B Astrophysical S Factor from Precision Cross Section Measurements

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We measured the ^{7}Be$(p,\gamma)^8$B cross section from $\bar{E}_{\text{c.m.}} = 186$ to 1200 keV, with a statistical-plus-systematic precision per point of better than $\pm 5\%$. All important systematic errors were measured including ^{8}B backscattering losses. We obtain $S_{17}(0) = 22.3 \pm 0.7(\text{expt}) \pm 0.5(\text{theor})$ eV b from our data at $\bar{E}_{\text{c.m.}} \leq 300$ keV and the theory of Descouvemont and Baye.

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It is now known that electron neutrinos (ν_e's) from the decay of ^{8}B in the Sun oscillate into ν_μ's and/or ν_τ's, and possibly into sterile ν_x's [1]. The ν_e production rate is based on solar-model calculations that incorporate measured reaction rates for most of the solar burning steps, the most uncertain of which is the ^{7}Be$(p,\gamma)^8$B rate. Improved production rate predictions are very important for limiting the allowed neutrino mixing parameters, including possible contributions of sterile neutrinos. The astrophysical S factor $S_{17}(0)$ for this reaction must be known to $\pm 5\%$ in order that its uncertainty not be the dominant error in predictions of the solar ν_e flux [2].

$S_{17}(0)$ values based on previous direct measurements have quoted uncertainties of typically $\pm 9\%$ or larger [3–10] (see also the quoted $\pm 5\%$ results of Ref. [11]), while for many of these experiments there are unsettled issues such as possible ^{8}B backscattering losses. Indirect $S_{17}(0)$ determinations based on Coulomb dissociation and peripheral transfer reactions are also available [12], but it is difficult to determine all of their important systematic errors.

We have made a precise determination of $S_{17}(0)$ using a technique that incorporates several improvements over traditional methods. We avoided a major difficulty in most previous experiments due to uncertain and nonuniform target areal density by using a $\sim$1 mm diameter beam magnetically rastered to produce a nearly uniform flux over a small $\sim$3 mm diameter target. We directly measured the energy loss profile of the target using a narrow ^{7}Be$(\alpha,\gamma)^{11}$C resonance and we determined all important sources of systematic error including the first direct measurement of ^{8}B backscattering losses.

We used a 106 mCi ^{7}Be metal target fabricated at TRIUMF and deposited on a molybdenum backing. The cross sections were measured using the University of Washington FN tandem accelerator with a terminal ion source. A proton beam, typically 10 μA, passed through an LN$_2$-filled cold trap directly upstream of the target. Cryopumps were used for high-vacuum pumping, and sorption pumps were used for roughing. The water-cooled target and a plate with precision-sized circular apertures were mounted on opposite ends of a rotating arm. Rotating the arm 180° from its horizontal bombardment position placed a 3 mm aperture in the beam, and the target $\sim$4.5 mm from a 450 mm^2 40 μm Si detector that counted β-delayed α's from ^{8}B decay. In each measurement, the arm was rotated through many complete cycles.

We integrated three different beam currents: the current striking the target during the bombardment phase, and, during the α-counting phase, the current striking the aperture and the current collected in a Faraday cup after passing through the aperture. The target arm was biased to +300 V. The neutral H content of the beam was found to be $<10^{-4}$, and the cup current changed by $<0.5\%$ for a cup suppressor bias in the range -300 ± 45 V. We estimated a $\pm 0.8\%$ beam flux integration uncertainty based on the difference of the good geometry (Faraday cup) and poor geometry (biased target arm) results. The beam was rapidly deflected from the target prior to and during arm movement. The timing cycle intervals [7] were $t_1 = t_3 = 1.50021$ s, $t_2 = 0.24003$ s, and $t_4 = 0.26004$ s, and the (inverse) timing efficiency $\beta(^8\text{B}) = 2.923 \pm 0.005$ assuming $t_{1/2}(^8\text{B}) = 770 \pm 3$ ms [13].

In the limit of uniform beam flux, the ^{7}Be areal density is unimportant, and the cross section is given by

$$\sigma(\bar{E}_{\text{c.m.}}) = \frac{Y_\alpha(E_p)F_\alpha(E_p)\beta(^8\text{B})}{2N_p N_{\text{Be}}(t)\Omega/4\pi} \tag{1}$$

where $\bar{E}_{\text{c.m.}}$ is discussed below, E_p is the bombarding energy, $Y_\alpha(E_p)$ is the α yield above a threshold energy of 895 keV, $F_\alpha(E_p)$ is a correction for the fraction of the α spectrum that lies below the threshold, N_p is the integrated number of protons per cm^2, $N_{\text{Be}}(t)$ is the number of ^{7}Be atoms, and Ω is the solid angle of the α detector.

In practice it is impossible to produce a completely uniform beam flux. To understand the error associated with this approximation, one needs to know both the beam and target uniformities. It is particularly important that the target be confined within a small central area.

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This was ensured by depositing the ^{7}Be on a Mo backing consisting of a 4 mm diameter raised post surrounded by a mask tightly pressed around the post, with post plus mask machined flat as one piece. After evaporation the mask was removed, eliminating unwanted tails on the ^{7}Be radial distribution [14].

The beam uniformity was determined by measuring the transmissions through 2, 3, and 4 mm apertures as functions of the (equal) amplitudes of the x and y triangular raster waveforms. Figure 1 shows measurements with a 770 keV deuteron beam, and curves calculated by folding a Gaussian with a rectangular function. The uniformity of the product of the beam and target densities was determined by the raster-amplitude dependence of the $^{7}\mathrm{Li}(d,p)^{8}\mathrm{Li}$ yield from the ^{7}Be target at $E_d = 770$ keV, shown in Fig. 1. The curve is a 1-parameter folding of the target density estimated from γ-activity scans, and the beam profile determined by the transmission ratios, including a fitted target-aperture misalignment of 0.5 mm. The point at which this yield flattened out determined the minimum safe raster amplitude, and is similar to the point at which the aperture ratio data flattened out. We chose 0.42 as the safe raster amplitude for 770 keV deuterons, and assigned a conservative $\pm 1\%$ nonuniformity uncertainty here. Aperture-transmission curves, measured at most proton energies, determined the minimum raster amplitude for each energy and tune for which the beam-target nonuniformity was $<1\%$. Independent estimates of the safe raster amplitudes were made by folding the target density distribution [14] with beam-flux distributions determined from the proton aperture-transmission data.

$N_{\mathrm{Be}}(t)$ was determined with the target arm vertical by counting 478 keV γ rays *in situ* using a collimated Ge detector located on top of the target chamber. We assumed $t_{1/2} = 53.12 \pm 0.07d$ [13] and a $10.52 \pm 0.06\%$ branch [13] to the 478 keV level. The Ge efficiency ϵ_{478} was determined to $\pm 1.3\%$ from a fit to 14 lines from ^{125}Sb, ^{134}Cs, ^{133}Ba, ^{137}Cs, and ^{54}Mn sources calibrated typically to $\pm 0.8\%(1\sigma)$ [15], with $\chi^2/\nu = 2.2$. We obtained a second ^{137}Cs source calibrated independently to $\pm 0.4\%(1\sigma)$ [16]. The relative activity of the two ^{137}Cs sources agreed within $\pm 0.1\%$. As can be seen in Fig. 2, 2.5 mCi of ^{7}Be

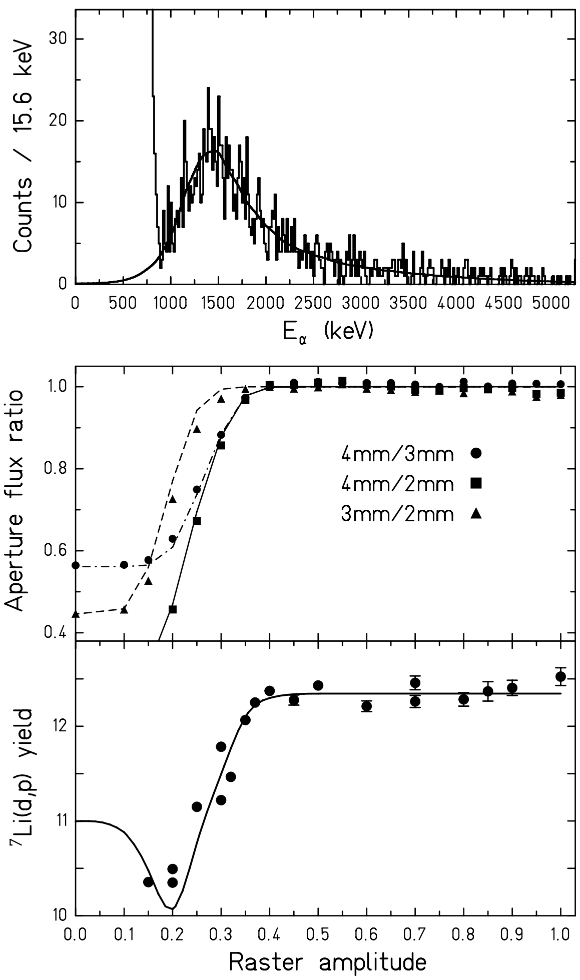

FIG. 1. Top panel: α spectrum from $^{7}\mathrm{Be}(p,\gamma)^{8}\mathrm{B}$ at $\bar{E}_{\mathrm{c.m.}} = 186$ keV. Middle panel: 770 keV deuteron beam transmission ratios through different apertures, vs raster amplitude. Bottom panel: $^{7}\mathrm{Li}(d,p)^{8}\mathrm{Li}$ yield at 770 keV, normalized to the integrated beam flux through a 3 mm aperture, vs raster amplitude, measured with the same tune as the aperture ratio data.

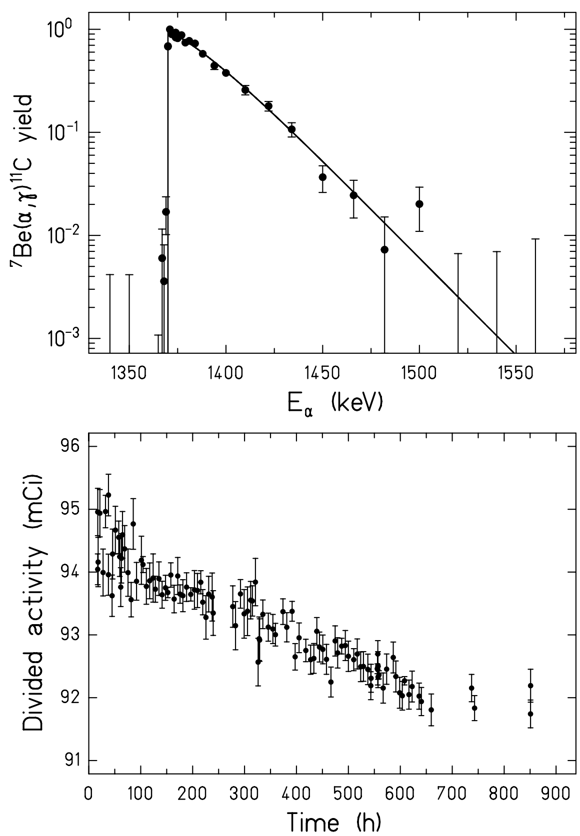

FIG. 2. Top panel: $^{7}\mathrm{Be}(\alpha,\gamma)^{11}\mathrm{C}$ resonance profile corrected for small backgrounds due to cosmic rays and a nonresonant yield from $^{9}\mathrm{Be}(\alpha,n)^{11}\mathrm{C}$. Bottom panel: ^{7}Be activity divided by the ^{7}Be decay curve, showing sputtering losses.

was lost due to beam sputtering during the cross section measurements.

We inferred Ω with the aid of a "far" Si detector [7] located 47.42 ± 0.09 mm from the target and collimated to an area of $248.8 \pm 0.4\ \mathrm{mm}^2$. From geometry, $\Omega_{\mathrm{far}} = 0.1078 \pm 0.0004$ sr, where the zero of the distance scale was checked using a ^{148}Gd α source. $\Omega/\Omega_{\mathrm{far}}$ was determined using the $^7\mathrm{Li}(d,p)^8\mathrm{Li}$ reaction. A differential correction for α particles lost below the threshold was applied based on the (d,p) angular distribution [17] and SRIM [18] calculations including ^{8}Li straggling. We obtained $\Omega = 3.82 \pm 0.04$ sr. This result was checked using different detectors and different size collimators for Ω_{far}.

The yields $Y_\alpha(E_p)$ were corrected for a small beam-off background (3.9% at the lowest E_p). The beam-related background was checked at several energies and found to be negligible. The α-spectrum cutoff factors for $^7\mathrm{Be}(p,\gamma)^8\mathrm{B}$ were estimated from SRIM calculations, including ^{8}B straggling, fitted to 23 different spectra. $F_\alpha(E_p)$ varied linearly from 1.039 ± 0.007 at $E_p = 221$ keV to 1.086 ± 0.008 at 1379 keV. The accelerator energy calibration was determined to $\pm 0.17\%$ from $^{19}\mathrm{F}(p,\alpha\gamma)^{16}\mathrm{O}$ resonances at $E_p = 340.46 \pm 0.04$, 483.91 ± 0.10, and 872.11 ± 0.20 keV [19].

Corrections for energy averaging of the proton beam due to finite target thickness are important, particularly at low E_p. We directly measured the beam energy loss profile in the target using the narrow ($\Gamma \ll 1$ keV) $^7\mathrm{Be}(\alpha,\gamma)^{11}\mathrm{C}$ resonance [20] which we found at $E_\alpha = 1378 \pm 3$ keV. The mean α-energy loss was 26 ± 2 keV, based on the average of three measurements, one of which is shown in Fig. 2. The excellent reproducibility of the apparent $^7\mathrm{Be}(\alpha,\gamma)^{11}\mathrm{C}$ resonance energy measured in the middle of and after the $^7\mathrm{Be}(p,\gamma)^8\mathrm{B}$ measurements ($\Delta E_\alpha = 1 \pm 3$ keV), indicated negligible carbon buildup and target damage due to bombardment.

An important error in some previous experiments was loss of ^{8}B from the target due to backscattering (and loss of ^{8}Li when $^7\mathrm{Li}(d,p)^8\mathrm{Li}$ was used for absolute cross section normalization) [21,22]. These losses may be sizable when a high-Z backing is used, or if there are high-Z contaminants in the target. We made the first direct measurements of the ^{8}B backscattering losses in the $^7\mathrm{Be}(p,\gamma)^8\mathrm{B}$ reaction using our ^{7}Be target in a fixed mount and large-diameter water-cooled Cu catcher plates on each end of the rotating arm. A 4 mm hole in the center of each plate allowed the beam to pass through. We found small backscattering losses of $1.3 \pm 0.3\%$ and $0.9 \pm 0.2\%$ at $E_p = 724$ and 1379 keV, respectively, and made a constant $1.0 \pm 0.5\%$ correction to our data for this effect.

Figure 3 shows our S factors calculated from the relation $S_{17}(\bar{E}_{\mathrm{c.m.}}) = \sigma(\bar{E}_{\mathrm{c.m.}})\bar{E}_{\mathrm{c.m.}}\exp[(E_G/\bar{E}_{\mathrm{c.m.}})^{1/2}]$ (see, e.g., [7]) with $E_G = 13799.3$ keV. We computed $\bar{E}_{\mathrm{c.m.}}$ by inverting the expression $\sigma(\bar{E}_{\mathrm{c.m.}}) = \bar{\sigma}$, where $\bar{\sigma}$ was obtained by fitting the cross section data, including averaging over the target profile, and σ is the corresponding unaveraged cross section. These $\bar{E}_{\mathrm{c.m.}}$ values are very close to the mean proton energy in the target, except near the resonance where they differ by $<1\%$. Figure 3 also shows a fit to all our data of the (scaled) cluster model theory of Descouvemont and Baye (DB) [23] plus an $\bar{E}_{\mathrm{c.m.}} = 630 \pm 2$ keV Breit-Wigner resonance (with energy-dependent Γ_p and Γ_γ). This fit yields $S_{17}(0) = 22.5 \pm 0.6$ eV b and $\chi^2/\nu = 1.3$ ($\nu = 25$) [24], where the quoted uncertainty includes the scale factor error of $\pm 2.7\%$ (Table I). Fits with other theories [25] did not reproduce our measured energy dependence as well ($\chi^2/\nu = 1.7$–16).

The theoretical uncertainty in the energy dependence of S_{17} decreases with beam energy below the resonance,

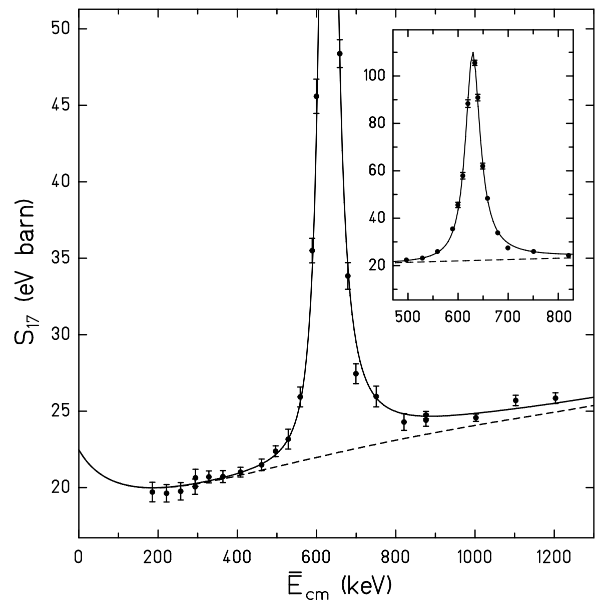

FIG. 3. $S_{17}(\bar{E}_{\mathrm{c.m.}})$ vs $\bar{E}_{\mathrm{c.m.}}$ from this paper. The error bars are statistical plus *varying* systematic errors. Solid curve: DB theory plus a Breit-Wigner resonance. Dashed curve: DB theory. Inset: Resonance region.

TABLE I. Percent uncertainties $\Delta S_{17}/S_{17}$.

Statistical errors	1.0–2.8
Varying systematic errors:	
Proton energy calibration	0.2–0.6
Target thickness	0.0–1.0
Target composition	0.0–1.1
Scale factor errors:	
Beam-target inhomogeneity	1.0
Integrated beam flux	0.8
Target activity	1.9
Solid angle	1.2
α-spectrum cutoff	0.7
Backscattering	0.5
Timing cycle	0.2
Total scale factor error	2.7

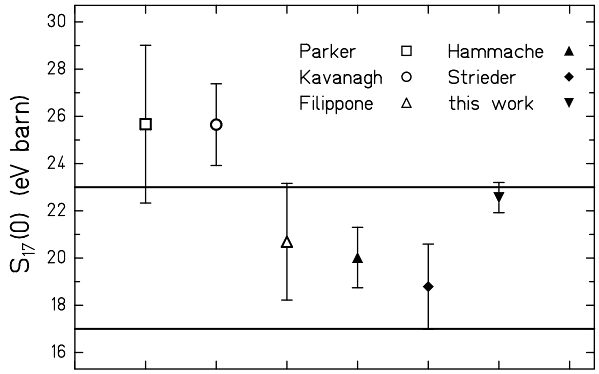

FIG. 4. $S_{17}(0)$ from our fits of the DB theory to $\bar{E}_{\mathrm{c.m.}} \leq 425$ keV data from this and previous measurements. The horizontal lines indicate the 19^{+4}_{-2} eV b range recommended by [29]. Fits over a wider E_p range give similar results but with smaller errors for other experiments.

as the capture becomes increasingly extranuclear. Therefore it is important to determine $S_{17}(0)$ from low energy data. By fitting the DB theory to our data at $\bar{E}_{\mathrm{c.m.}} \leq 300$ keV, we find $S_{17}(0) = 22.3 \pm 0.7$ eV b and $\chi^2/\nu = 0.3$. Here, as above, the error includes statistical plus systematic contributions. In addition, there is an extrapolation uncertainty, which has been estimated to be as small as ± 0.2 eV b [25], and which we estimate conservatively as ± 0.5 eV b from the rms deviation of 11 different theoretical fits to our data for $\bar{E}_{\mathrm{c.m.}} \leq 300$ keV [26]. Thus our final result is

$$S_{17}(0) = 22.3 \pm 0.7(\mathrm{expt}) \pm 0.5(\mathrm{theor})\ \mathrm{eV\,b}. \tag{2}$$

In order to compare all direct measurements below the resonance, we made DB fits to all data at $\bar{E}_{\mathrm{c.m.}} \leq 425$ keV—this work and [3,4,7,8,10,27] renormalized to $\sigma[^7\mathrm{Li}(d,p)^8\mathrm{Li}] = 152 \pm 6$ mb [28], where appropriate. The results are shown in Fig. 4. Results from [3,4,7] may suffer additional errors from ^{8}B and ^{8}Li backscattering losses; in [8], calculated corrections were applied, while in [10], a low-Z backing was used and losses were assumed negligible.

In conclusion, we have reduced the error on $S_{17}(0)$ so that it no longer dominates the uncertainty in the calculated solar ^{8}B ν_e production rate. While our $S_{17}(0)$ value agrees within errors with the previously recommended value of 19^{+4}_{-2} eV b [29], it is 17% larger. Thus 17% more of the ^{8}B solar ν_e's oscillate into other species than given in Ref. [2].

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