

Precision Measurement of the ${}^7\text{Be}(p, \gamma){}^8\text{B}$ Cross Section with an Implanted ${}^7\text{Be}$ Target

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The ${}^7\text{Be}(p, \gamma){}^8\text{B}$ reaction plays a central role in the evaluation of solar neutrino fluxes. We report on a new precision measurement of the cross section of this reaction, following our previous experiment with an implanted ${}^7\text{Be}$ target, a raster-scanned beam, and the elimination of the backscattering loss. The new measurement incorporates a more abundant ${}^7\text{Be}$ target and a number of improvements in design and procedure. The point at $E_{\text{lab}} = 991$ keV was measured several times under varying experimental conditions, yielding a value of $S_{17}(E_{\text{c.m.}} = 850 \text{ keV}) = 24.0 \pm 0.5$ eV b. Measurements were carried out at lower energies as well. Because of the precise knowledge of the implanted ${}^7\text{Be}$ density profile, it was possible to reconstitute both the off- and on-resonance parts of the cross section and to obtain from the entire set of measurements an extrapolated value of $S_{17}(0) = 21.2 \pm 0.7$ eV b.

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The study of fusion reactions in the Sun, relevant to the observed solar neutrino shortfall, has been the subject of intensive research [1,2]. Recently, this subject has acquired additional significance with the new results of the Super-Kamiokande [3] and Sudbury Neutrino Observatory (SNO) [4] experiments. The ${}^7\text{Be}(p, \gamma){}^8\text{B}$ reaction and the accurate determination of the astrophysical $S_{17}(0)$ factor is of great importance to these and other astrophysical studies [5–7] since ${}^8\text{B}$ is the major source of the high-energy solar neutrinos. In previous publications [8,9], we have demonstrated a new method for measuring the cross section of the ${}^7\text{Be}(p, \gamma){}^8\text{B}$ reaction by overcoming several of the recognized potential systematic errors in earlier measurements (see, e.g., [1]). Our method involves a small diameter implanted ${}^7\text{Be}$ target from ISOLDE (CERN), incorporating the elimination of backscattering loss of ${}^8\text{B}$ through the use of an implanted target, and a raster-scanned beam over an area larger than the target spot, avoiding the difficulties encountered with targets of poorly known areal distribution. Several experiments [10–12] have recently published $S_{17}(0)$ values of (3–10)% accuracy, two of those [11,12] using similar methods to [9]. However, there still exist large, up to 20%, discrepancies among experimental results as well as the extracted $S_{17}(0)$ values of these measurements. The present work has been undertaken in order to address these discrepancies and to provide a new, firm input for the determination of this cross section by exploiting fully the advantages of the implanted target: full knowledge of the target composition and the ${}^7\text{Be}$ profile, target robustness, and the ability to produce a secondary target of reduced activity to improve the conditions for the γ

calibration of the target. Another feature of the present work is a thin α detector and a relatively small solid angle, providing clean α spectra.

The general scheme of the experiment follows that of our previous publications [8,9]. For the case of a homogeneous beam impinging on a target smaller than the beam, the reaction yield Y , in terms of the cross section σ , is given by

$$Y = \sigma \frac{dn_b}{dS} n_t, \quad (1)$$

where dn_b/dS is the beam density and n_t is the total number of ${}^7\text{Be}$ atoms in the target spot. The target was switched periodically between a position in the proton beam and a position in front of the β delayed- α detector. The counting efficiency for the entire cycle is $\eta_{\text{cycle}} = 0.390 \pm 0.001$. In terms of the experimental parameters, this can be written as

$$\sigma(E_{\text{c.m.}}) = \frac{N_\alpha}{n_t} \left(\frac{A}{N_p} \right) \frac{1}{\eta_{\text{Be}} \eta_{\text{cycle}}}, \quad (2)$$

where N_α is the number of measured α particles, N_p/A is the integrated current density through a collimator hole of area A , and η_{Be} is the geometrical detection efficiency of ${}^8\text{Be}$, which is twice the detection efficiency of α 's: $\eta_{\text{Be}} = 2\Omega_\alpha/4\pi$.

The proton beam from the Weizmann Institute 3 MV Van de Graaff accelerator was scanned by an electronically controlled electrostatic raster scanner over a rectangular area in order to get a beam of uniform areal density [13] passing through a 3 mm collimator placed

in front of the target. A vacuum of $\approx 6 \times 10^{-7}$ mbar was maintained in the chamber. A liquid nitrogen cooled cryofinger was used to reduce carbon buildup. The 2 mm diam target spot was aligned with a set of interchangeable collimators downstream from the target, used to measure the beam density and homogeneity. A 150 mm², 25 μ m silicon surface barrier detector recorded the β delayed α particles from the decay of ^8B . The target was mounted on an arm which was periodically rotated by a microstep motor out of the beam to face the detector at distances of 7–10 mm. The time sequence of the cycle was similar to the one used in [9]. The scanned beam density dn_b/dS , typically of about 1–1.5 μA through a 2 mm aperture, was measured by integrating the beam in an electron suppressed Faraday cup. The current was digitized and recorded in a gated scaler. Beam integration with and without suppression yielded results similar to a fraction of a percent. The beam homogeneity was checked by measuring the α yield from the $^7\text{Li}(d, p)^8\text{Li}$ reaction versus integrated beam current for various downstream collimators. This procedure was repeated at various energies to obtain the corresponding scan voltage. The $^7\text{Li}(d, p)^8\text{Li}$ reaction was also used to determine the solid angle of the Si detector by comparing the α yield of the $^7\text{Li}(d, p)^8\text{Li}$ measurement (“close” geometry) with the yield in a “far” geometry where the detector was collimated and far removed from the target for the solid angle to be established directly. The proton energy from the Van de Graaff accelerator was calibrated with the help of the known resonances of the $^{27}\text{Al}(p, \gamma)^{28}\text{Si}$ reaction at energies 991.2, 773.7, 632.6, and 504.9 keV.

A high activity ^7Be target was prepared at ISOLDE (CERN) in a manner similar to that described in [9] by direct implantation of ^7Be at 60 keV in a copper substrate. The main new component in the present implantation was the primary source of ^7Be for ISOLDE: a graphite target from the Paul Scherrer Institute (PSI) [14], used routinely at PSI for the production of π mesons. A large number of spallation products are accumulated in the target, including ^7Be . The graphite target was placed inside an ISOLDE ion-source canister and brought to ISOLDE for an off-beam implantation. The number of ^7Be atoms at production was 1.17×10^{16} on an implantation spot of 2 mm in diameter. The major characteristics of such a target — the deposition depth of 1220 nm, the stability of the Cu-Be matrix, and the negligible backscattering loss — are described in [9]. In order to test the simulated profile of the Be implants, we measured the resonance curve in the $^7\text{Be}(p, \gamma)^8\text{B}$ reaction. The position of the resonance peak indicated a proton energy of $E_{\text{lab}} = 741$ keV, consistent with the energy loss in 1220 \AA of Cu, the mean deposition depth obtained from simulation. The results, summarized in Fig. 3, yield $\Gamma_{\text{c.m.}} = 35 \pm 3$ keV for the resonance width, in agreement with the value 37 ± 5 keV of Ref. [16]. The full width at half

maximum of the ^7Be simulated profile is 1200 \AA and the second moment is $2.5 \times 10^5 \text{\AA}^2$.

The γ activity of the ^7Be target was too intense to be assayed in a standard γ calibration setup due to the problems associated with large dead times in the γ counting. We therefore prepared a target identical to that used in the experiment but ≈ 300 times weaker. An accurate measurement of the relative intensities of the 478 keV γ rays from the decay of ^7Be for the two targets was carried out at the low background γ counting laboratory of Nuclear Research Center (NRC)-Soreq by placing both at the same distance from the Ge counter, yielding a ratio of 317.8 ± 0.8 . This ratio was determined several times with consistent results. The absolute intensity of the weak target was measured at NRC-Soreq and also at Texas A&M University. Both measurements followed calibration procedures involving up to 13 high-precision standard sources of ten radio nuclides. The Texas A&M procedure is discussed in detail in Ref. [17]. These two determinations yield a (weak) target ^7Be atom number of $(2.667 \pm 0.018) \times 10^{13}$ and $(2.650 \pm 0.018) \times 10^{13}$, respectively. We determine the number of ^7Be nuclei in the target at a date corresponding to the end of implantation at ISOLDE to be $n_t = (1.168 \pm 0.008) \times 10^{16}$. The branching ratio for γ emission in the decay of ^7Be was taken to be $(10.52 \pm 0.06)\%$ [18] and the half-life 53.29 ± 0.07 days [19]. The activity of the Be target was monitored throughout the experiment and revealed that there was no significant loss of ^7Be over the entire measurement (Fig. 1). A conservative limit on the loss is $\Delta(^7\text{Be}) < 1\%/C$ of integrated beam flux, except for a specific event in the last phase of the experiment (see below). The ^7Li content of the target also exhibited a similar long term stability.

The 25 μm thick Si detector provided a sufficient depletion layer to stop the α particles from the reaction

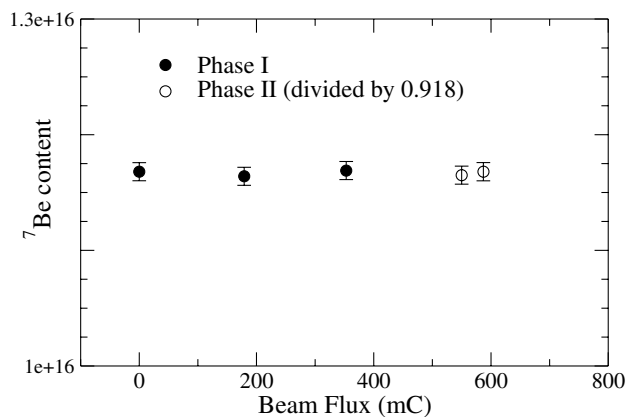


FIG. 1. The ^7Be content monitored by a Ge detector as a function of the accumulated integral charge on target, normalized to the total number of ^7Be just after implantation at ISOLDE and corrected for the decay of ^7Be . The open circles are scaled by a factor of 0.918 (see text).

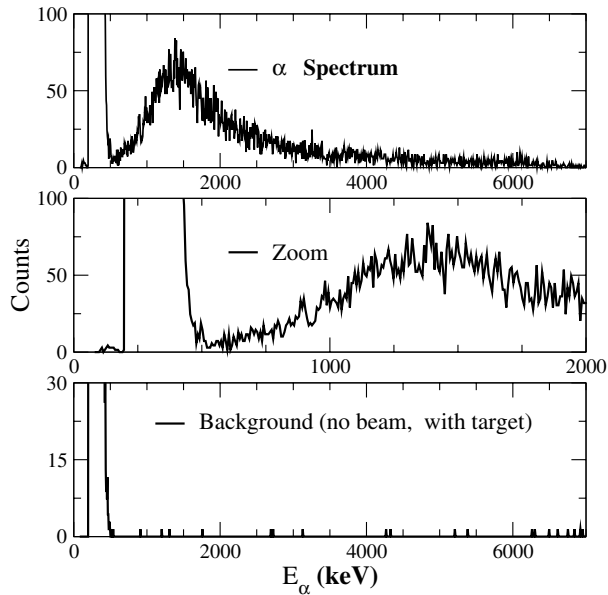


FIG. 2. Top: an α spectrum obtained at $E_{\text{lab}} = 991$ keV. Middle: an expanded view of the top panel. This spectrum was collected over a time of ≈ 80 h. Bottom: a background spectrum collected for ≈ 65 h with the target in the counting position and without beam. The top and middle panels show the clear separation between the α and noise part of the spectrum. The noise cutoff is at E_{α} of ≈ 525 keV.

but minimized the interaction with γ rays from the ${}^7\text{Be}$ activity. Figure 2 shows an α spectrum at $E_{\text{lab}} = 991$ keV. The α counts, N_{α} , were obtained by integrating the spectrum of Fig. 2 in the region of interest. The number of α counts in the region of the fast rising noise peak is very small. For the data at $E_{\text{lab}} = 991$ keV (Table I), this contribution has been determined as $(0.3 \pm 0.3)\%$ to $(0.8 \pm 0.8)\%$ of the total.

Background spectra were collected throughout the experiment with the target in the counting position, both with beam-on and beam-off, and also with the target in the beam-through (current integration) position. The background consists of four parts: the electronic noise, pileup events from γ activity, multiple scattering of the beam, and general background (no beam, no target). The electronic noise was appreciably reduced by water cooling the detector and it yielded no contribution to the recorded spectra. The contribution to the background from multiple scattering was minimized by tight shielding of both the detector and the proton beam path. It was determined to be negligibly small in a number of measurements, e.g., one in which the target was replaced by a blank target. The general background was measured frequently; the individual rates range from 0.4 to 0.6 ± 0.06 /h. The α counts from the reaction ranged from 100 /h to 6 /h.

The cross section measurements were carried out at the energies of $E_{\text{c.m.}} = 1078, 850, 415, 356,$ and 302 keV and also around the 633 keV resonance. The carbon buildup on

TABLE I. The measured $S_{17}(E)$ values along with the details of the estimated error. The * indicates the set of measurements carried out at $E_{\text{lab}} = 991$ keV; the slightly different values of $E_{\text{c.m.}}$ are due to gradual carbon buildup, monitored by repeated measurements of the resonance. Points indicated by ** were measured after the thermal episode as described in the text. Columns 3–7 represent the contributions to the error from counting statistics, background, beam energy, correction for α loss below the region of interest, and a set of common errors: the error on the number of ${}^7\text{Be}$ atoms, solid angle, timing efficiency, and the area of the beam collimator.

$E_{\text{c.m.}}$ (keV)	$S_{17}(E)$ (eV b)	Stat.	B.G	Energy	α cutoff	Common
1078	25.5 ± 0.8	0.49	0.03	0.08	0.20	0.52
856*	24.3 ± 0.6	0.29	0.03	0.07	0.08	0.45
853*	23.8 ± 0.6	0.24	0.03	0.07	0.08	0.48
849*	$23.8 \pm 0.8^{**}$	0.44	0.03	0.10	0.08	0.54
844*	$23.6 \pm 0.8^{**}$	0.54	0.03	0.10	0.14	0.44
415	$20.2 \pm 1.5^{**}$	1.36	0.16	0.36	0.06	0.45
356	$18.8 \pm 1.1^{**}$	0.90	0.19	0.37	0.06	0.42
302	$18.1 \pm 1.8^{**}$	1.50	0.21	0.80	0.06	0.40

the target and the subsequent (small) energy degradation was monitored throughout the course of the experiment by repeating the resonance measurement at regular intervals. The energy point at $E_{\text{c.m.}} = 850$ keV, corresponding to the ${}^{27}\text{Al}(p, \gamma){}^{28}\text{Si}$ resonance at $E_p = 991.2$ keV, was measured several times in the course of this experiment under varying conditions of solid angle and target strength in order to serve as a benchmark (see Table I).

In the last phase of the measurements, the target was subjected to a thermal episode and was heated to a high temperature. Following this event, the ${}^7\text{Be}$ content of the target dropped to 0.918 ± 0.003 of the previous value. Before and after the event the values were constant (taking into account the ${}^7\text{Be}$ decay). A ${}^7\text{Be}(p, \gamma){}^8\text{B}$ resonance curve measurement revealed that the second moment of the ${}^7\text{Be}$ distribution was broadened by the “event” by a factor of 9. For most of our measurements the target is sufficiently thin so that the integration of the cross section over the density distribution can be inferred to the requisite accuracy by correlating each measurement with the proton energy at the centroid of the ${}^7\text{Be}$ distribution. This energy was derived from the measurement of the peak of the 633 keV resonance. Only at the 302 keV energy is there an additional increase in the cross section of 0.8% because of the broadening.

The measured $S_{17}(E)$ values are shown in Fig. 3 and in Table I. The four measurements at $E_{\text{lab}} = 991$ keV, with the corresponding η_{Be} values of $0.1783, 0.2879, 0.2324,$ and $0.1752,$ yield an average value of $S_{17} = 24.0 \pm 0.5$ eV b at the nominal energy of $E_{\text{c.m.}} = 850$ keV. This value provides a reference, regardless of possible extrapolation uncertainties, for comparison to other measurements.

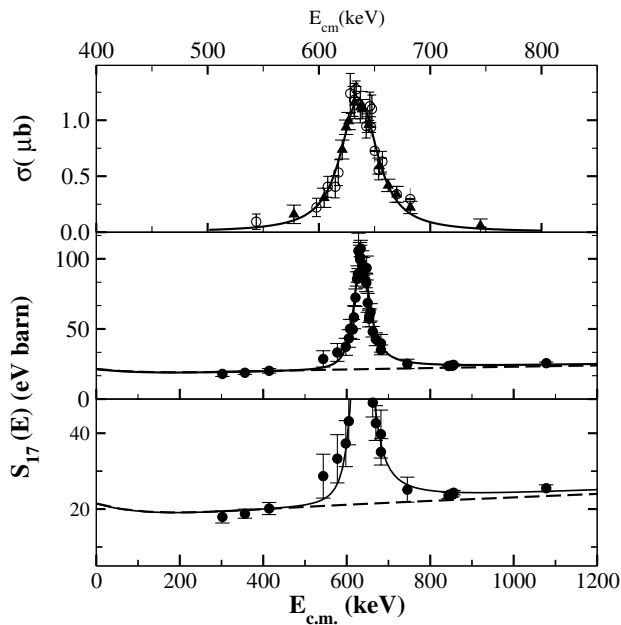


FIG. 3. Top: the measured resonance at 633 keV. The points are the measured cross section after subtraction of the non-resonant part. The energy axis gives an expanded view of the resonance in comparison to the middle panel. The two symbols represent the resonance measurements carried out at two different times. The continuous curve represents the convolution of a Breit-Wigner resonance with the simulated ${}^7\text{Be}$ distribution in Cu. Middle: $S_{17}(E)$ at different energies. The continuous line shows the scaled function of Descouvemont and Baye (DB) [15] plus a Breit-Wigner resonance with an energy dependent width. The dashed line shows the scaled DB model. Bottom: an expanded view of the middle figure.

The standard procedure at present is to employ theoretical models for the extrapolation of $S_{17}(E)$ to solar (“zero”) energy. This procedure is reasonable, as the nuclear physics processes involved are rather simple and well understood. The practice of employing a generally adopted extrapolation model is supported by the observation that the disagreements among experiments are mostly in factors of proportionality in the cross section while the measured energy dependence is largely consistent. The present experiment utilizes a thin target with a quite accurately known density profile. We have therefore adopted the procedure of including all measurements, off and on the resonance, in a fit with the values of σ_{max} and Γ of the resonance and the overall normalization of the generally used Descouvemont-Baye (DB) [15] theory as free parameters (Fig. 3). We arrive in this way at a value of $S_{17}(0) = 21.2 \pm 0.7$ eV b. We quote for completeness also the value derived from the low energy points (below the resonance) only as $S_{17}(0) = 20.8 \pm 1.3$ eV b. The quoted $S_{17}(0)$ values of all recent direct capture mea-

surements using a ${}^7\text{Be}$ target are 20.3 ± 1.2 eV b, 18.8 ± 1.7 eV b, 22.3 ± 0.7 eV b, and 18.4 ± 1.6 eV b (Refs. [9–12], respectively). The mean of these values is $S_{17}(0) = 21.1 \pm 0.4$ eV b with $\chi^2/\nu = 2.0$, suggesting a discrepancy. If we omit the value of Ref. [11] (which is being revised) from the list, we get a mean value: $S_{17}(0) = 20.5 \pm 0.5$ eV b with $\chi^2/\nu = 1.2$. If we add to this in quadrature an “error in theory” of (± 0.5) , as suggested in Ref. [11], we get a consistent common value: $S_{17}(0) = 20.5 \pm 0.7$ eV b.

A full account of this work will be published elsewhere.

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