ELSEVIER

16 September 1999

Physics Letters B 462 (1999) 237–242

PHYSICS LETTERS B

A new measurement of the ^{7}Be(p,γ)^{8}B cross-section with an implanted ^{7}Be target

M. Hass [a,1], C. Broude [a], V. Fedoseev [b], G. Goldring [a], G. Huber [c], J. Lettry [d], V. Mishin [b], H.J. Ravn [d], V. Sebastian [c], L. Weissman [e], ISOLDE Collaboration [d]

[a] *The Weizmann Institute of Science, Rehovot, Israel*
[b] *Institute of Spectroscopy, Troitzk, Russia*
[c] *Johannes Gutenberg University, Institute of Physics, Mainz, Germany*
[d] *ISOLDE, CERN, CH-1211 Geneva, Switzerland*
[e] *Instituut voor Kern-en Stralingsfysica, KU Leuven, Leuven, Belgium*

Received 9 June 1999; received in revised form 21 July 1999; accepted 22 July 1999
Editor: J.P. Schiffer

Abstract

The ^{7}Be(p,γ)^{8}B capture reaction is of major importance to the physics of the sun and the issues of the ‘‘solar neutrino puzzle’’. We report here on a new determination of the absolute cross section of this reaction, using a novel method which overcomes some of the major experimental uncertainties of previous measurements. We utilize a ^{7}Be target implanted into a Cu substrate and a uniformly scanned particle beam larger than the target spot, eliminating issues of target homogeneity and backscattering loss of ^{8}B reaction products. The target was produced using a beam of $1.8 \cdot 10^{10}$/s ^{7}Be nuclei extracted at ISOLDE (CERN) from a graphite target bombarded by 1 GeV protons in a two-step resonant laser ionization source. The ^{7}Be nuclei were directly implanted into a copper substrate to obtain a target of 2 mm diameter with a total of 3.10^{15} atoms. The measurement of the ^{8}B production cross section was carried out at the Van de Graaff laboratory of the Weizmann Institute of Science. We obtain for the *S* factor of the reaction: $S_{17}(E_{cm} = 1.09$ MeV$) = 22.7(1.2)$ eV. barn and $S_{17}(E_{cm} = 1.29$ MeV$) = 23.8(1.5)$ eV. barn, somewhat higher than other recent measurements. The present results can serve as a benchmark for further measurements of this cross section.

PACS: 25.40.Lw; 26.65.+t; 27.20.+m
Keywords: Fusion reactions in the sun; ^{7}Be(p,γ)^{8}B; Solar neutrinos

The subject of cross-section determination for solar fusion reactions has recently come under renewed focus and scrutiny following the successful measurements of terrestrial solar neutrinos at the three major experiments, Homestake [1], Kamiokande [2] and GALEX/SAGE [3,4], which have demonstrated that there is a considerable shortfall of measured solar neutrinos in terrestrial experiments as compared to the standard solar model [5,6]. In a recent review of nuclear reactions in the sun [7] an urgent recommendation was extended to re-measure the cross section of the ^{7}Be(p,γ)^{8}B reaction. The motivation behind this recommendation stems from

---

[1] E-mail: fnhass@wicc.weizmann.ac.il

PII: S0370-2693(99)00926-0

the importance of this reaction as the main source of high energy neutrinos from the sun, thus dominating the predictions for the Homestake and Kamiokande experiment, and from the uncertainties involved in earlier measurements, mostly regarding the thickness and homogeneity of the radioactive ^{7}Be target. As will be described below, we also eliminate the recently discovered [8] possible loss of product nuclei from the target assembly due to backscattering. A recent careful re-measurement of the ^{7}Be(p,γ)^{8}B reaction [9] has also not addressed these issues fully. The present work was undertaken with the aim of obtaining a reliable and accurate value for the cross section at relatively high proton energies which may serve as a benchmark for further measurements.

The main feature of the present measurement is the use of a small-size target, implanted into a low-Z material and a uniformly scanned particle beam larger than the target. In general, and as described also in [8], the reaction yield is given by:

$$Y = \sigma \int \frac{dn_b}{dS} \frac{dn_t}{dS} dS \tag{1}$$

where n_b, n_t are the total numbers of beam and target particles, respectively, and $dn_b/dS, dn_t/dS$ are areal densities.

Only when the target is known to be uniform and the beam is smaller than the target can Eq. (1) be simplified to:

$$Y = \sigma \frac{dn_t}{dS} \int \frac{dn_b}{dS} dS = \sigma \frac{dn_t}{dS} n_b \tag{2}$$

In such a case, the evaluation of the cross section is independent of the areal distribution of the particle beam. In other cases – e.g. for radiochemically produced ^{7}Be targets – the target cannot be assumed to be strictly uniform and the full relation (1) has to be used in the evaluation. The inherent uncertainties in the distributions dn_b/dS and dn_t/dS may thus lead to considerable uncertainties in the value of the integral and hence in the deduced cross section. We have addressed this problem by reversing the arrangement: we use a homogeneous beam – produced by raster scanning – impinging on a target *smaller* than the beam. The relation (1) then reduces to:

$$Y = \sigma \frac{dn_b}{dS} n_t \tag{3}$$

requiring only a determination of the total number of target nuclei and of the areal distribution of the beam.

The ^{7}Be target was prepared at ISOLDE/CERN by direct implantation at 60 keV of a radioactive ^{7}Be beam into a copper substrate. The ^{7}Be ions are produced via 1 GeV proton-induced spallation reactions in a graphite target which is connected to a laser ion source, using a two-step resonant laser ionization inside a high temperature cavity. A two step excitation scheme with laser light at a wavelength of $\lambda = 235$ nm and $\lambda = 297$ nm has been developed [10]. Using the $2p^2\ ^1S_0$ auto-ionizing state, an ionization efficiency for beryllium of 0.034(7) was achieved. The yield of ^{7}Be from a standard graphite target was $1.8 \cdot 10^{10}$ atoms/s and allowed the implantation, in a few shifts of ISOLDE beam time, of $3 \cdot 10^{15}$ ^{7}Be atoms into a copper substrate on a beam spot of 2 mm diameter. The implanted ^{7}Be target also contained about an equal amount of ^{7}Li which could not be eliminated at the ISOLDE implantation. This, and the amount of ^{7}Li accumulated subsequently through the decay of ^{7}Be does not affect our experiment in any significant manner.

The Cu matrix was chosen after test experiments at the ion-implantation machine of the Technion, Haifa [11]. A test implanted target in copper was made using a stable ^{9}Be beam at 60 keV in order to investigate the implanted-target properties after a prolonged bombardment with an intense proton beam. Comparison of SIMS measurements of the implanted target before and after proton irradiation and comparison to SRIM simulations [12] demonstrated that the Be nuclei are deposited at an average depth of 11 000 nm into the Cu and remain stable under these conditions.

In the course of earlier work in this program on the ^{7}Li(d,p)^{8}Li reaction [8] we noticed a process which was not appreciated before and may have affected earlier measurements: the loss of product nuclei from the target through backscattering which can become significant when using a high-Z substrate like Pt. Backscattering losses were calculated with the aid of the SRIM code [12] and confirmed by a direct measurement, comparing α yields from the ^{7}Li(d,p)^{8}Li reaction using Pt and Al backed targets [8]. These measurements have recently been repeated and extended to lower deuteron energies [13]. For the $_{7}$Be reaction, the backscattering loss for a Pt substrate can also be significant, depending on the detailed (often unknown) target composition. The use of a ^{7}Be target implanted in Cu eliminates the backscattering loss: for an infinitely thin Be target on the surface of a Cu substrate, the loss from the surface for $E_p = 1.2$ MeV is estimated to be 1.8% (as compared to 8.8% for a Pt substrate) [8,12]. Since the Be nuclei are deposited at a depth of about 1100 A in Cu and the backscattered ^{8}B nuclei are of rather low energy, the loss of ^{8}B from the implanted target is negligible.

The general scheme of the experiment is shown in Fig. 1. A proton beam from the Weizmann Institute 3 MV Van de Graaff accelerator is raster scanned over a rectangle of 4.5 mm × 3.5 mm. The purpose of the scan is to obtain a beam of uniform areal density, as demonstrated in detail in [8,14]. The scanned proton beam is collimated by a 3 mm diameter hole and impinges on the ^{7}Be target of 2 mm diameter. A liquid nitrogen cooled cryofinger is placed close to the target area to protect the target surface from contamination. The target spot is aligned with a set of adjustable collimators downstream from the target. The target is mounted on an arm which is periodically rotated by a step motor out of the beam and in front of a 40 micron surface barrier detector registering the delayed α's following the β decay of $_{8}$B. The time sequence of the entire cycle, similar to the cycle used for the ^{7}Li(d,p)^{8}Li experiment [8] is: 1.5 s beam-on-target; 100 ms rotation; 1.5 s target in the counting position; 100 ms rotation back to the beam position. In the counting position a signal from the motor-control unit enables the ADC for α counting and the gated scaler for Faraday-cup beam monitoring.

The beam density dn_b/dS was measured by integrating the beam, collimated by a downstream aperture, in an electron-suppressed Faraday cup and counting the digitized counts in a gated scaler. The current digitizer and the scaler were checked during the experiment with a calibrated current source. The beam homogeneity was ensured by the nature of the raster operation: a low frequency triangular y scan and a high frequency triangular x scan, in small, digitally controlled voltage steps in clock-fixed time intervals. The beam homogeneity was checked directly in two ways: 1. the areal density of x-rays from a tin foil scanned by the proton beam was measured in a phosphor image plate [14], 2. α yields from the ^{7}Li(d,p)^{8}Li reaction versus integrated protons for different downstream collimators were compared [8]. The collimator hole areas were measured to an accuracy of 0.5% by a microscope and by monitoring counts from an α source in front of the

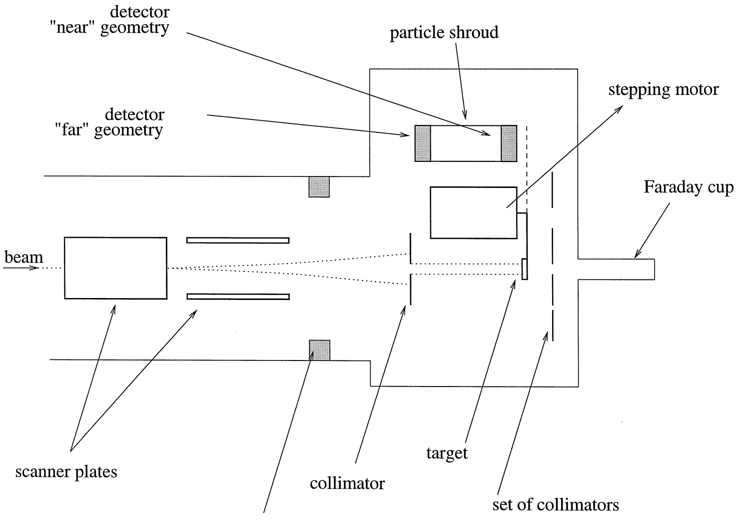

Fig. 1. A schematic view of the experimental apparatus. The ‘‘close’ and ‘‘far’’ geometries refer to the two positions of the particle detector (see text).

collimator-detector assembly. The number n_t of ^{7}Be's in the target was determined by counting γ's from the decay branch to the 478 keV state in ^{7}Li (see below).

A detailed account of the various factors affecting the accuracy of a similar measurement of the ^{7}Li(d,p)^{8}Li reaction can be found in [8]. We present here the features and parameters which have to be addressed for the ^{7}Be(p,γ)^{8}B measurement.

1. *The solid angle.* The measurement was carried out with the α detector situated 8 mm from the target (''close'' geometry of Fig. 1). The detector solid angle was measured by comparing the ''close geometry'' of the ^{7}Be experiment with the absolute measurement of the ''far geometry'' similar to that of [8] using the ^{7}Li(d,p)^{8}Li reaction on the same implanted target, yielding a ratio of 192.8(4) between the solid angles of the two geometries. For the far geometry, the solid angle was defined by a collimator of diameter d = 8.14(3) mm at a distance ℓ = 82.60(10) mm from the target in the counting position. The solid angle at the ''far geometry'' is given by: $\Omega_{\mathrm{far}} = \frac{1}{16}\frac{d^2}{\ell^2} = 6.07(2) \cdot 10^{-4}$ of 4π and the solid angle for the ^{7}Be experiment (''close geometry'') is: $\Omega_{\mathrm{near}} = 192.8 \times 6.07(2) \cdot 10^{-4} = 0.1170(6)$ of 4π.
2. *The beam scan.*
   In order to reduce the scan amplitude as much as possible (and thus increase the beam density), the α yield from the ^{7}Li(d,p)^{8}Li reaction at 770 keV [8] was measured as a function of scan voltage and was found to be constant over a wide range. The operating voltage for the Be experiment was chosen as 250 V. (cf. Fig. 2).
3. *Proton-beam intensity.* We have used a proton beam density of about 60 μA/cm^2. The beam intensity was limited by radiative heating of the detector from the target assembly. The current density n_p was determined by the integrated counts in the Faraday cup after the beam scan. The construction of the Faraday cup, including the suppressor, ensures a reliable monitoring of the current. A high precision current source was used to calibrate the current integrator.
4. *The time-sequence efficiency – η(cycle).* This factor relates to the time fraction of the α counting out of the entire irradiation-counting cycle. From the above description this factor is calculated to be: η(cycle) = 0.390(1). The time intervals of the rotation cycle were measured by counting a time-reference pulse signal in the scaler gated by the cycle time windows.

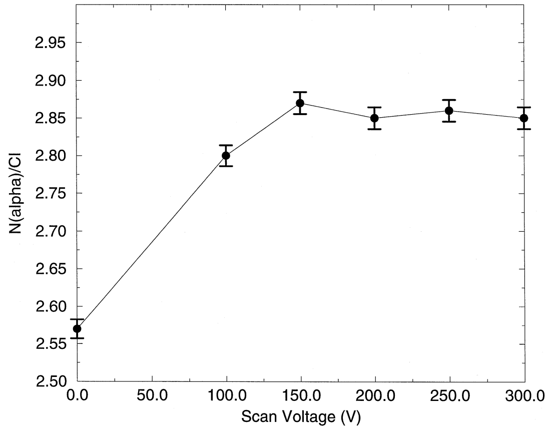

Fig. 2. α yield normalized to the current integration from the ^{7}Li(d,p)^{8}Li reaction as a function of scan voltage, demonstrating the scanned-beam uniformity for the voltage used in the ^{7}Be experiment, 250 V.

5. *The α spectrum – N_α.* The cross section determination was carried out at two energies: E_{cm} = 1.09 MeV and E_{cm} = 1.29 MeV. The α spectrum at E_{cm} = 1.09 MeV, together with a background spectrum obtained by bombarding the reversed Cu disk with the ^{7}Be target on the downstream side, is presented in Fig. 3a. The background spectrum includes the electronic noise, pulses induced by the ^{7}Be target (the major part) and general background. Bombardment of a blank target (no ^{7}Be) demonstrated that there are no low-energy scattered protons within the region relevant to the α integration. The α counts, N_α, were obtained by integrating the net spectrum of Fig. 3b above the line indicated in the figure. While the measured background can not reliably reproduce the fast rising counts below the indicated channel because of low-level thresholds etc., the background contribution in the region relevant to the α measurement is much less sensitive to these effects. A probable error of 30% has been assigned to the background in this region, equivalent to 2% of the total α count.
   We have carried out a numerical simulation of the α spectrum to check the possibility that low-en-

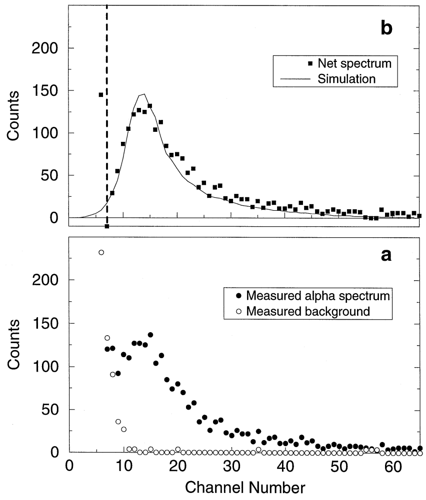

Fig. 3. 3a: An α spectrum at $E_{\mathrm{cm}} = 1.09$ MeV together with the background spectrum obtained with the implanted target placed so that the ^{7}Be spot is on the downstream side of the Cu substrate. 3b: The net α spectrum together with the results of the SRIM simulation (see text). The lower limit of the integration region used to obtain the number N_{α} is indicated; the channels below this point are dominated by the exponentially-rising background.

ergy α's could be lost in the spectrum integration. The depth distribution of the decaying ^{8}B nuclei i.*e.* the source, was taken from the distribution of the implanted ^{7}Be target as calculated by SRIM [12] (and confirmed by a SIMS measurement, see above), transposed to a depth corresponding to the range of the ^{8}B recoils after the capture reaction. The intrinsic α spectrum from the source was taken from the tabulation of Warburton [15]. The energy of the α particles emerging from the target in the direction of the detector was obtained using the alpha-particle ranges from the SRIM program. The simulated spectrum is shown in Fig. 3b, superimposed on the measured net spectrum. We note that no attempt was made to fit the simulation to the measured spectrum. Our conclusion is that the implanted target exhibits no major distortion of the spectral shape of α's at low energies. Based on the simulation, we estimate that the possible loss of α's at low energy is 2(1)% and correct N_{α} for this. The statistical errors are 2.2% and 4.5% for the two proton energies, respectively. With these uncertainties and the 2% error arising from the background subtraction, the integrated number of counts, N_{α}, is determined to an accuracy of 3% and 5% for the two energies of $E_{\mathrm{cm}} = 1.09$ MeV and $E_{\mathrm{cm}} = 1.29$ MeV, respectively.

6. *Absolute calibration of the* ^{7}Be *activity – N_{γ}, η_{γ}.* The activity of the ^{7}Be 478 keV γ-ray source was determined by comparison with calibrated ^{22}Na, ^{137}Cs and ^{133}Ba γ sources at a standard distance from a Ge detector, shielded for low-background, at the γ-counting laboratory of NRC-Soreq. [2] The decrease in activity measured before and after the proton bombardment was in complete agreement with the radioactive decay of ^{7}Be, demonstrating that there has been no significant loss of implanted ^{7}Be nuclei from the target matrix due to the proton bombardment. The absolute intensities of the γ sources used are known to within 2–3%. The number of 478 keV γ rays: N_{γ}, the γ branch of the decay of ^{7}Be to the first excited state of ^{7}Li: $b_r = 0.1052(6)$ [16], the mean life of ^{7}Be: τ and the efficiency of the Ge detector: η_{γ} determine the number of ^{7}Be nuclei in the target, n_t, to an accuracy of 3%:

$$n_t = \frac{N_{\gamma}}{\eta_{\gamma}} \frac{\tau}{b_r}. \qquad (4)$$

7. *Proton-energy calibration.* The accelerator voltage was calibrated using the known resonance of the ^{27}Al(p, γ)^{28}Si at 990 keV as well as the known thresholds of the ^{13}C(p, $\gamma = 9.17$ MeV)^{14}N capture at 1.746 MeV and the ^{7}Li(p,n)^{7}Be reaction at 1.88 MeV. The mean energy loss of the protons in the target is small and was taken into account in the evaluation of the S factor.

The cross section is given by the relation:

$$\sigma = \frac{n(^{8}\mathrm{B})}{n_t\, dn_b/dS}$$

or in terms of the experimental parameters and efficiencies defined above:

$$\sigma(E_{\mathrm{cm}}) = \frac{N_{\alpha}}{n_t} \left(\frac{A}{N_p} \right) \frac{1}{\Omega_{\mathrm{near}}\, \eta(\mathrm{cycle})}$$

where A is the area of the collimating hole into the Faraday cup and N_p/A is the integrated current

---

[2] The laboratory is designated as an International Reference Center for Radioactivity (IRC) by the World Health Organization.

density. Following the detailed discussion above, the two main sources of uncertainty in the measurement are the determination of N_α and the absolute efficiency of the γ sources used to determine η_γ. All other errors are of the order of 0.5% or less. We hence quote the results of the present measurement as: $S_{17}(E_{\mathrm{cm}} = 1.09\ \mathrm{MeV}) = 22.7(1.2)$ eV. barn and $S_{17}(E_{\mathrm{cm}} = 1.29\ \mathrm{MeV}) = 23.8(1.5)$ eV. barn.

These values are somewhat higher than the results of Hammache et al. and of Filipone et al. ([9,17]. They provide a reliable determination of the cross section at a relatively high proton energy for which the S factor remains rather flat as a function of energy. The theoretical extrapolation of the S factor to low energies is still somewhat ambiguous and a major challenge in this field is to extend cross-section measurements down to very low, possibly solar energies. However, following the discussion of [9] were the S factor at solar energies, $S(0)$, is obtained by an extrapolating procedure with one overall parameter, the present results by themselves would indicate a somewhat higher $S(0)$ of about 20.3 eV barn. Concerning further measurements at low proton energies, we note that the backscattering loss of ^{8}B can be appreciable and therefore rather pure ^{7}Be targets and reliable information on the atomic-mass content of the target are required.

Acknowledgements

We wish to acknowledge Prof. R. Kalish of the Technion, Haifa, for his help with the ^{9}Be ion implantation and for helpful discussions. Thanks are due to the technical staff of ISOLDE (CERN) and to Y. Shachar and the technical staff of the Accelerator Laboratory of the Weizmann Institute. We thank O. Even of the NRC-Soreq for his help with the γ-activity measurements.

References

[1] R. Davis Jr., Prog. Part. Nucl. Phys. 32 (1994) 13.
[2] Kamiokande Collaboration, Y. Fukuda, Phys. Rev. Lett. 77 (1996) 1683.
[3] T. Kirsten et al., GALEX Collaboration, in: K. Enqvist, K. Huitu, J. Maalampi (Eds.), Neutrino 96, Proceedings of the 17th International Conference on Meutrino Physics and Astrophysics, Helsinki, World Scientific, Singapore, 1997, p. 3.
[4] V. Gavrin et al., SAGE Collaboration, in: K. Enqvist, K. Huitu, J. Maalampi (Eds.), Neutrino 96, Proc. 17th International Conference on Meutrino Physics and Astrophysics, Helsinki, World Scientific, Singapore, 1997, p. 14.
[5] J.N. Bahcall, M.H. Pinsonneault, Rev. Mod. Phys. 67 (1995) 781.
[6] J.N. Bahcall, S. Basu, M.H. Pinsonneault, Phys. Lett. B 433 (1998) 1.
[7] Adelberger et al., Rev. Mod. Phys. 70 (1998) 1265.
[8] L. Weissman, Nucl. Phys. A 630 (1998) 678.
[9] F. Hammache, Phys. Rev. Lett. 80 (1998) 928.
[10] V. Sebastian et al., Proc. ENAM'98 Conference, Michigan, 1998; J. Lettry et al., Rev. Sci. Instrum. 69 (1998) 761.
[11] R. Kalish, private communication.
[12] H.H. Anderson, J.F. Ziegler, The Stopping and Ranges of Ions in Matter, vol. 3, Pergamon, New York, 1977; SRIM 1998 version.
[13] F. Strieder, Eur. Phys. J. A 3 (1998) 1.
[14] L. Weissman, M. Hass, V. Popov, Nucl. Instr. Meth. A 400 (1997) 409.
[15] E.K. Warburton, Phys. Rev. C 33 (1986) 303.
[16] Table of Isotopes, 8th edition, Wiley, New York, 1996.
[17] B.W. Filippone, Phys. Rev. Lett. 50 (1983) 412.