Eur. Phys. J. A **7**, 303–305 (2000)

THE EUROPEAN PHYSICAL JOURNAL A

Short note

Absolute cross section of p(^{7}Be,γ)^{8}B using a novel approach*

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Received: 8 February 2000
Communicated by B. Povh

Abstract. The absolute cross section σ(E) of the radiative capture reaction p(^{7}Be,γ)^{8}B at the center-of-mass energy E = 992 keV has been measured using a radioactive ^{7}Be ion beam and a windowless gas target system filled with H_2 gas. The ^{8}B residual nuclides were detected with a recoil separator consisting of momentum and velocity filters and a ΔE-E detector telescope. The ^{8}B yield was observed concurrently with the ^{7}Be+p elastic scattering yield, relating σ(E) to the Rutherford scattering cross section. The resulting value, $\sigma(E) = 0.41 \pm 0.11$ μb, leads to an S(E) factor at zero energy of S(0) = 16 ± 4 eV b, in fair agreement with recommended values.

PACS. 26.65.+t Solar neutrinos – 25.60.Dz Interactions and reactions cross sections

The observed solar neutrino fluxes on the earth provide no unique picture of the microscopic processes in the sun ([1] and references therein). Neutrino oscillations have been invoked to explain the discrepancy between observation and model predictions (solar neutrino problem), but nuclear inputs to solar models play still an important role [2]. In particular, the astrophysical S(E) factor at the Gamow energy E_0 = 18 keV of the radiative capture reaction ^{7}Be(p,γ)^{8}B (Q = 0.14 MeV) influences sensitively the calculated flux of high-energy solar neutrinos and must therefore be known with adequate precision (better than 5%).

As the cross section drops exponentially at subcoulomb energies, σ(E) could not be measured yet at E_0. Instead, σ(E) was determined at higher energies and extrapolated to E_0 with the help of nuclear reaction models. The present knowledge of the cross section is based essentially on measurements of the β-delayed α-decay of ^{8}B ($T_{1/2}$ = 770 ms) performed using a radioactive ^{7}Be target ($T_{1/2}$ = 53 d), which was produced by hot chemistry on a heavy backing (always Pt). The measurements [3–9] provided σ(E) data – covering the center-of-mass energy range E = 0.12 to 8.75 MeV – which show however a considerable scatter, predominantly in the absolute values. Omitting some data sets and using different model calculations [10,11], values of S(0) = 19 eV b [12] and 21 ± 2 eV b [13] have been recommended for the astrophysical S(E) factor at zero energy.

In 1998 Weissman et al. [14] suggested – on the basis of TRIM simulations – that a significant backscattering of the recoiling ^{8}B nuclides out of the target could occur affecting significantly the deduced cross section values: a loss of up to 15% was predicted depending on the backing material (large effects for heavy backings such as Pt) and on the thickness of the target (large effects for thin targets). Similar predictions for the loss of ^{8}Li recoil nuclei in ^{7}Li(d,p)^{8}Li have been confirmed experimentally [15], which could also influence the ^{7}Be(p,γ)^{8}B results when the former reaction is used for normalization. It was thus suggested [15] that the reported σ(E) values should include an additional systematic uncertainty of the order of 15%.

In 1995 we have started at the 3 MV tandem accelerator in Naples [16] a renewed measurement of the absolute σ(E) value of p(^{7}Be,γ)^{8}B (inverted kinematics) in the non-resonant energy region, i.e. at E = 1 MeV (E_{lab} = 8 MeV). The study involved a ^{7}Be radioactive ion beam, a windowless H_2 gas target, and a recoil mass separator for the detection of the ^{8}B recoils. The approach avoided the problems of ^{7}Be target stoichiometry and allowed to identify the ^{8}B recoils on the basis of their energy and

* Supported in part by DFG (Ro429/21-4 and 436UNG113), DAAD-Vigoni/Crui, INFN, Hungarian OTKA (T025465), and Social European Fund

ΔE-E characteristics (using a telescope placed at the end of the separator). Since the ^{8}B yield was measured concurrently with the ^{7}Be+p elastic scattering yield, the method related ultimately σ(E) to the elastic scattering cross section. Since all previous experiments had used essentially the same technique, the aim of the present different technique was to search for possible systematic uncertainties, such as those reported by Weissman et al. [14] during the course of our experiment. Details of the equipment and experimental procedures have been described [16] and the first direct observation of ^{8}B nuclides has been also reported [17]. In this note we describe the present status of this novel approach.

Briefly, the ^{7}Be nuclides were produced using the ^{7}Li(p,n)^{7}Be reaction. In a first phase of the experiment, Li_2O cathodes were activated and placed directly in the sputter ion source of the Naples tandem. This technique was then modified irradiating metallic Li samples with a 11.4 MeV proton beam (20 μA) from the cyclotron in Debrecen, whereby for each sample a ^{7}Be activity of about 20 GBq was achieved over an irradiation time of about 2 weeks. Using hot chemistry, the activated samples were transformed into nearly pure ^{7}BeO+Ag pills to be used as cathodes in the sputter ion source of the Naples tandem. The procedures applied in the irradiation and hot chemistry will be described elsewhere [18]. In the sputter source, the ^{7}Be nuclides were extracted in form of a ^{7}BeO$^-$ molecular ion beam. Setting the 35° injection magnet to mass-23 ions, this beam was accompanied by a ^{7}LiO$^-$ molecular beam.

Both beams were focused by a gridded lens and accelerated to the terminal voltage U = 2.42 MV of the tandem. After stripping in a 5 μg/cm^2 thick C foil, the 8.0 MeV ions of ^{7}Be^{3+} (probability Φ_{3+} = 15%) and ^{7}Li^{3+} emerging from the accelerator were focused by a magnetic quadrupole doublet on the object slits of the 90° analysing magnet. Inserting a post-stripper C foil (10 μg/cm^2 thick) near the object slits, fully stripped ^{7}Be^{4+} ions were produced with a 67% probability. The ^{7}Be^{4+} ions were selected by the analysing magnet, while the accompanying ^{7}Li^{3+} ions were filtered. Other contaminant beams were suppressed using a Wien filter before the analysing magnet. A high purity of the resulting ^{7}Be^{4+} beam (25 ppA maximum current) was verified [17].

The number of ^{8}B nuclides from p(^{7}Be,γ)^{8}B as observed in the ΔE-E telescope of the recoil separator, IB, can be related to the ^{7}Be+p elastic scattering yield (i.e. the number of the proton recoils), Iel, observed with a particle detector placed at an angle $\theta_{\rm lab}$ in the gas target chamber, by the expression [16]:

$$I_B/I_{el} = \Phi_5 \varepsilon_B l_B \sigma(E)/(l_{el}\Omega_{lab}\sigma_{cm}(\theta,E)\Omega_{cm}/\Omega_{lab}). \quad (1)$$

The quantity Φ_5 is the probability of the ^{8}B recoils emerging from the gas target with a 5$^+$ charge state, $\varepsilon_{\rm B}$ = 100% (3% error) represents the transmission of the ^{8}B^{5+} recoils through the separator, $l_{\rm B}$ is the effective target length along the beam axis producing ^{8}B nuclides, $l_{\rm el}$ is the effective target length seen by the particle detector, $\sigma_{\rm cm}(\theta, {\rm E})$ is the elastic scattering cross section at the as-

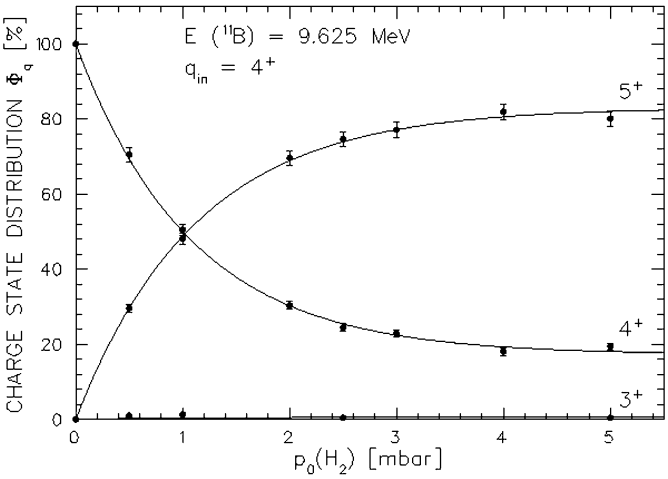

Fig. 1. Charge state distributions of 9.625 MeV ^{11}B projectiles in H_2 gas for an incident charge state $q_{\rm in}$ = 4$^+$. The curves through the data points are fits using exponential functions

sociated center-of-mass angle θ, and $\Omega_{\rm cm}/\Omega_{\rm lab}$ is the ratio of center-of-mass solid angle to laboratory solid angle.

The windowless (differentially pumped) gas target system is described in [16], where also the measurement of the H_2 pressure profile along the beam axis is reported. The following features were observed: a constant pressure plateau at the central region of the target chamber and a pressure drop near the apertures, leading to an effective length $l_{\rm B}$ = 376 ± 8 mm. Calibration of the analysing magnet and energy loss calculations performed by the program SRIM2000 [19] led to the effective energy $E_{\rm eff}$ = E = 992 ± 0.4 keV at the center of the target chamber.

Silicon particle detectors were placed at the scattering angles $\theta_{\rm lab}$ = 44.87° ± 0.06° and −44.94° ± 0.06° (measured in a way as described previously [16]) and collimated by a slit-hole combination. From the geometry and these angles one obtains $l_{\rm el}\Omega_{\rm lab}$ = 11.3 ± 0.4 mm msr and $\Omega_{\rm cm}/\Omega_{\rm lab} = 4\cos\theta_{\rm lab}$ = 2.833 ± 0.003. For the ^{7}Be+p scattering system, we have adopted the Rutherford scattering cross section for the following reasons: the energy E = 992 keV is far below the Coulomb barrier, E/E_c = 0.7, and interference effects with the 39 keV broad resonance at E_R = 632 keV (p-wave formation) are absent at θ = 90° ($\theta_{\rm lab}$ = 45°) assuming a predominance of s-waves in the non-resonant scattering channel. An experimental verification of the adopted Rutherford scattering law at E = 992 keV is in progress.

The ^{8}B recoils emerge from the gas target with an energy $E_{^8B}$ = 7.0 MeV and several charge states q. The fully stripped ^{8}B^{5+} recoils were selected and tuned in the separator, since for this charge state the intensity of the leaky ^{7}Be beams should be minimised [16]. Their charge state probability Θ_5 in the H_2 was measured using a ^{11}B^{4+} beam with the same energy per amu, i.e. $E_{^{11}B}$ = (11/8) $E_{^8B}$ = 9.625 MeV. The Φ_q results are shown in Fig. 1 as a function of H_2 pressure. The mean value of the relevant 5$^+$

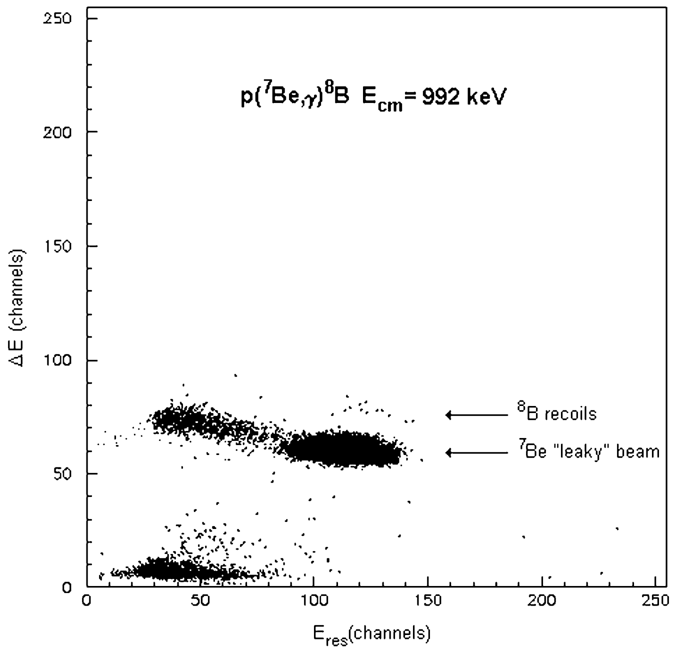

Fig. 2. Two dimensional density plot of the ΔE-E telescope with the recoil separator tuned to the $^8B^{5+}$ nuclides from p(^{7}Be,γ)^{8}B reaction. The observed structures are identified

charge state is $\Phi_{5+} = 65 \pm 2\%$, derived from integration of the $q = 5^+$ curve.

The recoil separator includes a magnetic quadrupole triplet, a 30° switching magnet, a magnetic quadrupole doublet, a Wien filter, and a conventional ΔE-E ionization chamber [16]). For the tuning of the separator, a pilot $^7Li^{3+}$ beam ($E_{^7Li} = 2.880$ MeV) with the same rigidity as the $^8B^{5+}$ recoils was used. After this tuning, hydrogen gas ($p_0 = 5.0$ mbar) was filled into the gas target system and the $^7Li^{3+}$ beam was retuned through the separator (to take into account the energy loss of the ^{7}Li beam in the gas) leading to a set of optimum values for the magnetic field of the switching magnet, the Wien filter, and the magnetic quadrupoles. The resulting values were then corrected for differences (1.0%) in energy loss for the pilot ^{7}Li beam, the actual ^{7}Be beam and the ^{8}B recoils. Finally, the magnetic field of the Wien filter was scaled down to account for the different velocities between $^7Li^{3+}$ and $^8B^{5+}$. The same procedure was repeated using other pilot beams (e.g. $^7Be^{4+}$ at 5.12 MeV) leading to the same final optimum values for the transport parameters within the acceptance of the separator.

The resulting identification matrix of the telescope obtained using a total of five ^{7}Be cathodes (10 GBq each) is shown in Fig. 2. The ^{8}B events, $I_B = 13 \pm 4$, are well resolved from a band of counts due to leaky ^{7}Be beams, which correspond to a suppression factor of about 1×10^{-10} for the incident ^{7}Be projectiles. The corresponding elastic scattering yield is $I_{el} = 345 \pm 15$. These yields together with equation (1) (including the parameters given above) lead to $\sigma(E) = 0.41 \pm 0.11\ \mu$b for the absolute cross section of p(^{7}Be,γ)^{8}B at E = 992 keV. This value, together with the calculated S(E) dependence of [11], gives $S(0) = 16 \pm 4$ eV b. Within the present statistical uncertainty the result is consistent with the values recommended recently [12,13]. However, a closer comparison with individual data sets considered in the above compilations shows an agreement at the level of 1σ just with the lowest S(0) values obtained in the most recent measurements [6,8–9], in spite of the systematic uncertainties discussed above.

The present work demonstrates the feasibility of the techniques used in the study of this reaction so critical for the solar-neutrino-puzzle. An improvement of the statistical uncertainty attainable with the present technique could be achieved - besides the possibility of using a prohibitive amount of activity of the order of 1 TBq – by increasing the accelerator transmission and/or by using a more probable charge state for the accelerated ^{7}Be ions (i.e. $q = 2^+$ with $\Phi_{2+} = 70\%$), which would require a terminal voltage not accessible to our accelerator.

The authors thank the Isotopenlabor at the Ruhr-Universität Bochum (M.Roth) for support in the hot chemistry, and the Kernforschungszentrum Karlsruhe and the Cyclotron Laboratory at Louvain-la-Neuve for the initial ^{7}Be activations. The technical staff of the Tandem Laboratory in Naples (M.Borriello) is gratefully acknowledged.

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