EPJ Web of Conferences **260**, 11006 (2022) https://doi.org/10.1051/epjconf/202226011006
NIC-XVI

Measurement of the ^{7}Be(p, γ)^{8}B reaction cross section with the recoil mass separator ERNA

Raffaele Buompane[1,2,*], *Antonino* Di Leva[2,3], *Lucio* Gialanella[1,2], *Antonio* D'Onofrio[1,2], *Mario* De Cesare[4], *Jeremias* G. Duarte[1,2], *Zsolt* Fülöp[5], *Leandro* R. Gasques[6], *György* Gyürky[5], *Lizeth* Morales-Gallegos[2], *Fabio* Marzaioli[1,2], *Giancarlo* Palumbo[2,7], *Giuseppe* Porzio[1,2], *David* Rapagnani[2,3], *Vincenzo* Roca[1,2], *Detlef* Rogalla[8], *Mauro* Romoli[2], *Claudio* Santonastaso[1,2], and *Daniel* Schürmann[1,2].

[1]Dipartimento di Matematica e Fisica, Università della Campania "L. Vanvitelli", Viale Lincoln, 5, Caserta, Italy, EU

[2]Istituto Nazionale di Fisica Nucleare, Sezione di Napoli, Via Cinthia snc, Napoli, Italy, EU

[3]Dipartimento di Fisica "E. Pancini", Università di Napoli "Federico II", Via Cinthia snc, Napoli, Italy, EU

[4]Dipartimento di Metodologie e Tecnologie per le Osservazioni e Misure, Centro Italiano Ricerche Aerospaziali, Capua, Italy, EU

[5]Institute for Nuclear Research (Atomki), H-4001 Debrecen, Hungary, EU

[6]Departamento de Física Nuclear, Instituto de Física da Universidade de São Paulo, São Paulo, SP, Brazil

[7]Dipartimento di Economia, Management Istituzioni - Laboratorio Chimico-Merceologico, Università degli Studi di Napoli "Federico II", Napoli, Italy, EU

[8]RUBION, Ruhr-Universität Bochum, Bochum, Germany, EU

Abstract. The cross section of ^{7}Be(p, γ)^{8}B represents one of the most important nuclear inputs for the prediction of the high energy component of solar neutrinos and it has also a direct impact on the ^{7}Li abundance after the Big Bang Nucleosynthesis. The importance of this reaction triggered an intense experimental work over the last decades, where discrepancies were observed between the results of different measurements. In addition, a question remains about possible common systematic effects, considering that all measurements share the same experimental approach, i.e. an intense proton beam impinging on a ^{7}Be radioactive target. Inverse kinematics, i.e. a ^{7}Be ion beam and a hydrogen target, with the direct measurement of the total reaction cross section by means of the detection of the ^{8}B recoils, can shed light on such systematic effects. Efforts attempted so far were limited by the low ^{7}Be beam intensity. We present here the results of a new measurement at E_{cm}= 376 to 819 keV using a high intensity ^{7}Be beam in combination with a windowless gas target and the recoil mass separator ERNA (European Recoil mass separator for Nuclear Astrophysics) at CIRCE (Center for Isotopic Research on Cultural and Environmental heritage), Caserta, Italy. Our results, including the systematic error, are compatible with previous measurements that yields lower value of $S_{17}(0)$ and are compatible with the currently accepted value from [1] only at a 2-σ level.

*e-mail: raffaele.buompane@unicampania.it

1 Introduction

The solar neutrinos of ^{7}Be to ^{8}B have a great interest, since they represent a large fraction of the high energy solar neutrino flux. The rate of the reaction ^{7}Be(p, γ)^{8}B relative to the ^{7}Be electron capture decay rate in the Sun determines the ratio of these neutrino. The importance of ^{7}Be to ^{8}B neutrinos ratio triggered several experiments to determine cross section of ^{7}Be(p, γ)^{8}B at the relevant astrophysical energies [2–12] and the ^{7}Be half-life in different environments [13–16].

All direct ^{7}Be(p, γ)^{8}B cross section measurements producing results with sufficient precision to constrain astrophysical models are measured in direct kinematics i.e. using an intense proton beams on radioactive targets. The complicated target stoichiometry and its modification under beam bombardment, as well as the difficulties of the detection of the reaction products are possibly the origin of the discrepancy between different data sets, that persists even if a selection based on a careful review of the experiments is done as proposed in [1]. An alternative approach using a radioactive ion beam and a hydrogen gas target was attempted in [12], and later in [17]. In both cases a recoil mass separator was employed to detect the ^{8}B recoils. However, those experiments could not achieve a sufficient precision because of the low ion beam intensity ($\approx 10^7$ pps). We present here a new experiment exploiting the same method with the much higher ion beam intensity available at the Tandem Accelerator Laboratory at CIRCE (Center for Isotopic Reasearch on Cultural and Environmental heritage), Dept. of Mathematics and Physics, University of Campania "L. Vanvitelli", Italy, where a ^{7}Be ion beam is routinely produced [18] with an intensity up to 10^9 pps.

2 Experimental setup

Until 2009 the recoil mass separator ERNA was installed at the Dynamitron Tandem Laboratorium of the Ruhr Universität Bochum, Germany. In 2009 ERNA was moved to the Tandem accelerator laboratory at CIRCE, University of Campania "L. Vanvitelli", Caserta, Italy. The new installation gave the opportunity to upgrade the experimental setup. In particular, a new windowless hydrogen gas target was built [19] and an additional magnet (Charge State Selection Magnet, CSSM in the following) was inserted between the gas target and the first focusing element of the separator. The experimental apparatus has been described in details in [19–22]. The measurements are performed in inverse kinematic, the ^{8}B nuclei formed in the reaction emerge from the target at forward angles together with the beam ions in an intensity ratio of 10^{-11} to 10^{-13}, depending on the cross section. The mass separator ERNA filter the recoils that are then directly detected in the $\Delta E - E$ telescope detector [22], example of matrices obtained is shown in figure 1. The number of ^{8}B recoils N_r observed in the final detector having an efficiency ϵ is given by:

$$N_r = N_b \cdot T_{RMS} \cdot \Phi_{q_r} \cdot \epsilon \cdot \int_{E_b - \Delta E_b}^{E_b} \frac{\sigma(E)}{|dE/dN_t|} dE \tag{1}$$

where N_b is the number of ^{7}Be projectiles measured by the elastic scattering of beam ions in the target region, Φ_{q_r} is the probability of the charge state q_r selected for the separation, T_{RMS} is the transmission of the recoils from the target to the final detector. The interaction cross section $\sigma(E)$ is integrated over the beam energy loss in the target ΔE_b at the beam energy E_b, that is determined by the beam ions stopping power in the target $\frac{dE}{dN_t}$, where N_t is the number of nuclei per unit target area. All the relevant quantities have been determined experimentally, the systematic uncertainty in the determination of cross section is about 4%, stemming from the systematic uncertainties in the determination of the target thickness (2%),

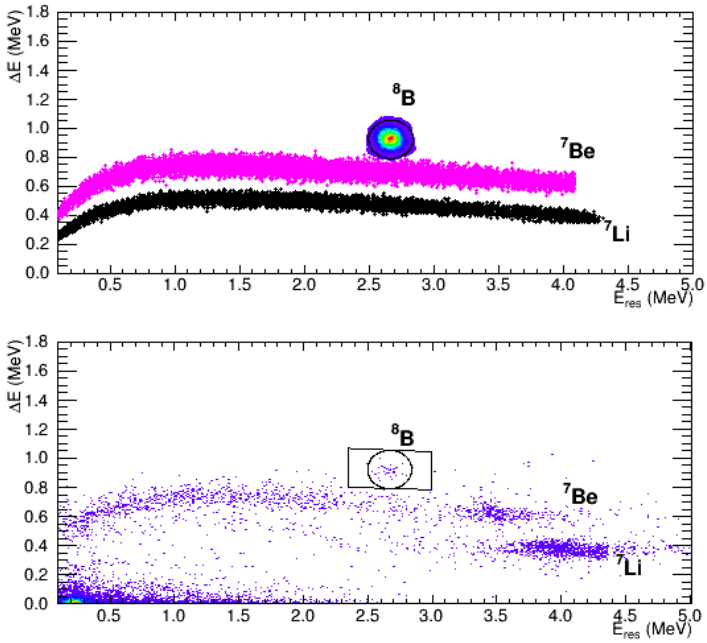

Figure 1. $\Delta E - E_{res}$ matrices of the end detector of ERNA for $^7Be(p,\gamma)^8B$ at E_b=675.5 keV. The upper matrix represent the predictions of a Monte Carlo simulation for the different ion species. The lower matrix the experimental results. Both ^{7}Li and ^{7}Be leaky beam ions are visible with long low energy tails. The rectangular region around the elliptical area where the ^{8}B recoils are expected is used to estimate the background.

number of projectiles (2%), transmission of the recoils (2%), recoil detection efficiency (1%), and charge state probability (2%). A detailed discussion of measurements and of the uncertainties affecting the relevant quantities is given in [20]. The beam energy has a systematic uncertainty of 0.06% [26].

3 Results

The resulting cross sections are shown in figure 2. The data are compared with a fit function obtained summing the nonresonant component S_{MN} from Table V of [23] and a resonant component S_{res}:

$$S_{factor}(E) = A \cdot S_{MN}(E) + \pi \lambda\!\!\!^{-2} \cdot \frac{2J+1}{(2J_p+1)\cdot(2J_t+1)} \cdot \frac{\Gamma_p(E)\cdot\Gamma_\gamma(E)}{(E-E_{res})^2 + (\Gamma_{tot}(E)/2)^2} \cdot E \cdot e^{2\pi\eta(E)} \tag{2}$$

where A is a scaling factor for the nonresonant component. $J_p = 1/2$, $J_t = 3/2$, and $J = 1$ are the spin of the ^{1}H, ^{7}Be, and ^{8}B relevant states for the resonant capture, respectively. The energy dependent widths $\Gamma_p(E)$ and $\Gamma_\gamma(E)$ are calculated using the approximations given in [24]:

$$\Gamma_p(E) = \Gamma_p(E_{res}) \frac{e^{2\pi\eta(E)}}{e^{2\pi\eta(E_{res})}} \tag{3}$$

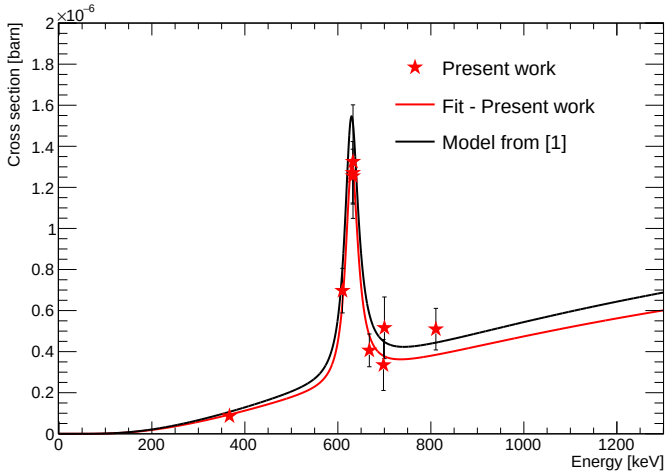

Figure 2. The red stars represent the cross section values obtained in the present work. The dotted black line represents the fit of [1]. The solid red line represents the model from equation 2 fitted to present work data.

Table 1. Fit results to our data using the function in eq. 2. ν indicates the number of degrees of freedom.

Data set	ν	χ^2	A	E_{res}(keV)	Γ_p(keV)	Γ_γ(meV)	$S_{17}(0)$(eV · b)
Present work	6	3.8	0.67±0.09	630[c]	33±6	20±4	16.6± 2.1

[c] Fixed from [25].

$$\Gamma_\gamma(E) = \Gamma_\gamma(E_{res})\left(\frac{E_\gamma}{E_{\gamma res}}\right)^3 \tag{4}$$

The fit function included one parameter (A) for the nonresonant component and three parameters (E_{res}, Γ_p and Γ_γ) for the resonant component. The data on the resonance were not sufficient to fix the E_{res} that is fixed to the values from [25]. The free parameters were obtained using Maximum Likelyhood minimizing the least square function through the routine MINUIT (Cernlib). Best fit values based on our experimental data are reported in table 1.

4 Conclusion

The total cross section of ^{7}Be(p, γ)^{8}B was measured in the energy range E_{eff}=367.2 keV to 812.2 keV using a radioactive ^{7}Be beam and a recoil mass separator. For the first time, this approach provides results with adequate precision to determine the cross section of ^{7}Be(p, γ)^{8}B at astrophysical energy. Our result, including the 4% systematic error combined in quadrature, yields $S_{17}(0)$=16.6±2.2 eV·b compatible only with a part of previous measurements that yields lower value of $S_{17}(0)$. Our $S_{17}(0)$ is compatible with the currently accepted range $S_{17}(0)$=20.8±0.7 eV·b [1] only at a 2-σ level, thus strengthening the discrepancy between existing data sets. A detailed analysis including all datasets [2–12] is be presented in [26].

References

[1] E.G. Adelberger, A. García, R.G.H. Robertson, K.A. Snover, A.B. Balantekin, K. Heeger, M.J. Ramsey-Musolf, D. Bemmerer, A. Junghans, C.A. Bertulani et al., Rev. Mod. Phys. **83**, 195 (2011)

[2] B.W. Filippone, A.J. Elwyn, C.N. Davids, D.D. Koetke, Phys. Rev. C **28**, 2222 (1983)

[3] L.T. Baby, C. Bordeanu, G. Goldring, M. Hass, L. Weissman, V.N. Fedoseyev, U. Köster, Y. Nir-El, G. Haquin, H.W. Gäggeler et al. (ISOLDE Collaboration), Phys. Rev. C **67**, 065805 (2003)

[4] L.T. Baby, C. Bordeanu, G. Goldring, M. Hass, L. Weissman, V.N. Fedoseyev, U. Köster, Y. Nir-El, G. Haquin, H.W. Gäggeler et al. (ISOLDE Collaboration), Phys. Rev. Lett. **90**, 022501 (2003)

[5] F. Hammache, G. Bogaert, P. Aguer, C. Angulo, S. Barhoumi, L. Brillard, J.F. Chemin, G. Claverie, A. Coc, M. Hussonnois et al., Phys. Rev. Lett. **80**, 928 (1998)

[6] F. Hammache, G. Bogaert, P. Aguer, C. Angulo, S. Barhoumi, L. Brillard, J.F. Chemin, G. Claverie, A. Coc, M. Hussonnois et al., Phys. Rev. Lett. **86**, 3985 (2001)

[7] M. Hass, C. Broude, V. Fedoseev, G. Goldring, G. Huber, J. Lettry, V. Mishin, H. Ravn, V. Sebastian, L. Weissman et al., Physics Letters B **462**, 237 (1999)

[8] F. Strieder, L. Gialanella, G. Gyürky, F. Schümann, R. Bonetti, C. Broggini, L. Campajola, P. Corvisiero, H. Costantini, A. D'Onofrio et al., Nuclear Physics A **696**, 219 (2001)

[9] A.R. Junghans, E.C. Mohrmann, K.A. Snover, T.D. Steiger, E.G. Adelberger, J.M. Casandjian, H.E. Swanson, L. Buchmann, S.H. Park, A. Zyuzin, Phys. Rev. Lett. **88**, 041101 (2002)

[10] A.R. Junghans, E.C. Mohrmann, K.A. Snover, T.D. Steiger, E.G. Adelberger, J.M. Casandjian, H.E. Swanson, L. Buchmann, S.H. Park, A. Zyuzin et al., Phys. Rev. C **68**, 065803 (2003)

[11] A.R. Junghans, K.A. Snover, E.C. Mohrmann, E.G. Adelberger, L. Buchmann, Phys. Rev. C **81**, 012801 (2010)

[12] L. Gialanella, F. Strieder, L. Campajola, A. D'Onofrio, U. Greife, G. Gyurky, G. Imbriani, G. Oliviero, A. Ordine, V. Roca et al., Eur. Phys. J. A **7**, 303 (2000)

[13] C. Santonastaso, R. Buompane, A.D. Leva, L. Morales-Gallegos, N. Itaco, G. Landi, H.C. Neitzert, D. Rapagnani, L. Gialanella, Il Nuovo Cimento **44**, 1 (2021)

[14] E. Segre, C.E. Wiegand, Physical review **75**, 40 (1949)

[15] L. gun Liu, C.A. Huh, Earth and Planetary Science Letters **180**, 163 (2000)

[16] T. Ohtsuki, H. Yuki, M. Muto, J. Kasagi, K. Ohno, Phys. Rev. Lett. **93**, 112501 (2004)

[17] D.W. Bardayan, K.A. Chipps, R.P. Fitzgerald, J.C. Blackmon, K.Y. Chae, A.E. Champagne, U. Greife, R. Hatarik, R.L. Kozub, C. Matei et al., The European Physical Journal A **42**, 457 (2009)

[18] B.N. Limata, L. Gialanella, A.D. Leva, N.D. Cesare, A. D'Onofrio, G. Gyurky, C. Rolfs, M. Romano, D. Rogalla, C. Rossi et al., Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms **266**, 2117 (2008), accelerators in Applied Research and Technology

[19] Schürmann, D., Di Leva, A., Gialanella, L., De Cesare, M., De Cesare, N., Imbriani, G., D´Onofrio, A, Romano, M., Romoli, M., Terrasi, F., Eur. Phys. J. A **49**, 80 (2013)

[20] Buompane, R., De Cesare, N., Di Leva, A., D´Onofrio, A., Gialanella, L., Romano, M., De Cesare, M., Duarte, J. G., Fülöp, Zs., Morales-Gallegos, L. et al., Eur. Phys. J. A **54**, 92 (2018)

[21] A. Di Leva, G. Imbriani, R. Buompane, L. Gialanella, A. Best, S. Cristallo, M. De Cesare, A. D'Onofrio, J. Duarte, L. Gasques et al., Physical Review C **95** (2017)

[22] D. Rogalla, S. Theis, L. Campajola, A. D'Onofrio, L. Gialanella, U. Greife, G. Imbriani, A. Ordine, V. Roca, C. Rolfs et al., Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment **437**, 266 (1999)

[23] P. Descouvemont, Phys. Rev. C **70**, 065802 (2004)

[24] C.E. Rolfs, W.S. Rodney, Physical review (1988)

[25] D. Tilley, J. Kelley, J. Godwin, D. Millener, J. Purcell, C. Sheu, H. Weller, Nuclear Physics A **745**, 155 (2004)

[26] R.Buompane, A.D. Leva, L. Gialanella, A. D'Onofrio, M.D. Cesare, J.G. Duarte, Z. Fülöp, L.R. Gasques, G. Gyürky, L. Morales-Gallegos et al., Physics Letters B (2021), manuscript accepted for publication