EPJ Web of Conferences 66, 07003 (2014)
DOI: 10.1051/epjconf/20146607003

^{3}He(α,γ)^{7}Be cross section measured using complementary techniques

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Abstract. The astrophysical S-factor for the ^{3}He(α,γ)^{7}Be reaction plays an important role in the Solar Standard Model and in the Big Bang Nucleosynthesis scenario. The advances from two recent experiments performed using complementary techniques at center of mass (C.M.) energies between 1 and 3 MeV are discussed.

1 Introduction

Since the first measurement in 1956 by Holmgren and Johnston [1], the cross section of the astrophysical direct capture reaction ^{3}He(α,γ)^{7}Be has been widely studied from theoretical and experimental fronts. See reference [2] and references therein for an overview. The cross section of this reaction plays an important role in estimating solar neutrino fluxes. Specifically, the ^{3}He(α,γ)^{7}Be reaction opens the ppII and ppIII chains which are responsible for the solar neutrinos from the ^{7}Be and ^{8}B decays. Indeed, the large theoretical uncertainties in these neutrino fluxes, 10.5% and 16% respectively [3], are highly influenced by the uncertainty in the cross section of the ^{3}He(α,γ)^{7}Be reaction, e.g., for the ^{7}Be neutrinos, the S-factor of the ^{3}He(α,γ)^{7}Be reaction contributes the second largest error [2, 3]. This reaction rate is also an important input parameter to the Big Bang Nucleosynthesis (BBN) calculations and the open problem related to the primordial ^{7}Li abundance. The BBN predictions for the primordial ^{7}Li abundance is a factor ~3 higher than the inferred abundances from observations in globular cluster of stars. Different types of solutions have been suggested including physics beyond the standard model. Although it is not thought that a nuclear rate revision will solve the problem an accurate determination of the ^{3}He(α,γ)^{7}Be cross section is needed, see for example reference [4].

2 Experimental techniques

As the cross section falls off very rapidly with decreasing energy, the direct experimental determination of the cross section at energies of astrophysical interest, (such as the Gamow peak in the Sun of 23 keV), is currently impossible due to technical limitations. Thus, data at higher energies together

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with the theoretical models are used to obtain the extrapolated values for the S-factor at astrophysical energies. The measurements by the ERNA collaboration [5] at C.M. energies between 1 and 3 MeV show discrepancies when comparing with the data of Parker and Kavanagh [6]. Further, the *ab initio* calculation by T. Neff [7] reproduced the capture cross section measured by ERNA and the scattering phase shifts, disagreeing with previous theoretical models (see e.g. [8]), not only in the magnitude of the cross section but also in the energy dependence. In order to resolve the experimental discrepancies and to constrain the theoretical model extrapolations, two experiments using complementary techniques have been performed by our collaboration aiming to determine the cross section at C.M. energies between 1 and 3 MeV. In the following subsections we give details of the two experimental techniques, followed by the results and discussion. For more technical details see reference [9].

2.1 Activation Method

The ^{7}Be recoils are unstable nuclei and decay by electron capture (EC) with a half life of 53.22(6) days. Therefore, instead of measuring directly either the recoils or the prompt-γ from the reaction, the reaction products can be collected and the subsequent EC-delayed γ radiation measured. This method, known as the *Activation Method* was chosen in the first experiment performed at the Centro de Microanálisis de Materiales in Madrid (CMAM). A ^{3}He$^+$ beam impinged onto a ≈12 cm of ^{4}He gas target at ≈60 Torr through a Ni foil window. The target chamber, originally used for the Weizmann experiment [10], was electrically isolated from the beam line, and the number of incoming particles was determined by integrating the total charge in the chamber with typical uncertainties of ∼2%. As a cross check, the number of beam particles were also estimated with typical uncertainties of ∼5%, from the scattered beam with the Ni foil using a silicon detector placed at 44.9(4)^o. The target density was determined with <1% uncertainty by continuously monitoring the pressure inside the chamber. The ^{7}Be recoils were forward focused and completely deposited in a Cu catcher foil placed at the end of the chamber. The subsequent EC-delayed γ rays from the de-excitation of the first excited state (populated with a known branching ratio of 10.44(4)%) to the ground state in the ^{7}Li daughter were measured using a low background HPGe detector station. Typical activation measurement times between 7 to 10 days were performed in order to get ∼1000 counts in the 478 keV γ peak. Measurements were made at three different C.M. energies, namely 1.05, 2.07 and 2.80 MeV. The results of these measurements are detailed in reference [11] and are discussed in section 3.

2.2 Direct recoil detection method

The *Direct Recoil Detection Method* consists of the direct counting of the ^{7}Be recoils. This approach was firstly employed by the ERNA collaboration [5], where they separated the recoils from the beam before detecting them in a detector placed at the focal plane of the separator. In our case, the experiment was performed using DRAGON ("Detector of Recoils and Gammas of Nuclear Reactions") spectrometer at TRIUMF facility in Vancouver [12]. For our ^{4}He beam energies raging from 3.5 to 6.5 MeV, ^{7}Be are expected to recoil in the forward direction with cone angles of ∼20 mrad. This is at the limit of the acceptance of DRAGON, therefore careful simulations have been employed to obtain the number of ^{7}Be produced in the reaction from those detected.

A ^{4}He beam at three different C.M. energies, 1.5, 2.2 and 2.8 MeV and a windowless ^{3}He gas target at ≈6 Torr with a recirculating gas system were used. The ^{7}Be recoils were detected in a DSSSD (Double Sided Silicon Strip Detector) placed in the focal plane at the end of the spectrometer, with a beam suppression better than 10^{14} [13]. The ^{7}Be recoils leaving the gas target are produced with characteristic charge state distributions (CSD) and just one charge state is selected by the separator.

Therefore, the CSD were experimentally measured by using the same target and a ^{9}Be pilot beam at the corresponding velocities to the ^{7}Be recoils from the ^{3}He(α,γ)^{7}Be reaction. In Figure 1 the CSD for 534 A·keV beam energy measured at 5.25 and 0.95 Torr pressures shows that charge state equilibrium was reached at pressures as low as 1 Torr. On the other hand, considering the reaction kinematics,

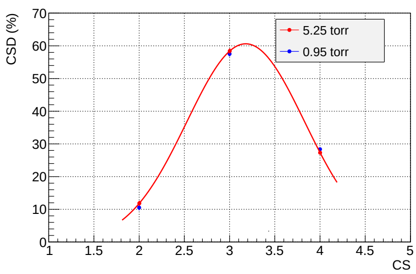

Figure 1. Preliminary 534 AkeV ^{9}Be^{2+} charge state distribution onto 0.95 and 5.25 Torr ^{3}He gas target pressures (corresponding to the recoil energy for 2.8 MeV C.M. energy of the ^{3}He(α,γ)^{7}Be reaction) . The x-axis shows the ^{9}Be charge state selected with the separator, and the y-axis the charge fraction after passing through the gas target. The Gaussian fit is used to estimate systematic error contribution due to different recoils energy depending of where they are created.

and additional effects as straggling or the beam spot size, the reaction cone angle falls slightly out of the geometrical acceptance of the separator. Thus, the transmission efficiency for this reaction has been obtained by simulating the reaction and the separator with the well tested DRAGON-GEANT3 code, using as input parameters measured experimental properties such as the target density profile [9] and beam emittance. Assuming an isotropic γ ray distribution and a branching ratio from the direct state to the first excited state (S_1) and to the ground state (S_0) of S_1/S_0=45%, the recoil angle and energy distribution from the simulations shows that the acceptance is limited by the spread in the recoil energy more than in the recoil angle (see Figure 2).

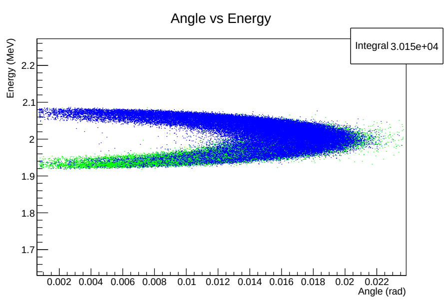

Figure 2. Angle vs energy recoil distribution for the ^{3}He(α,γ)^{7}Be simulated reaction at 1.5 MeV C.M. energy. In blue appear all recoils which reach the end DSSSD, and in green those stopped throughout the path of the the separator. As can be seen, the difference between them depends more on the energy rather than the angle.

3 Results and Discussion

Our results are shown in Figure 3 together with those from previous experiments. The two theoretical models [8, 16] presented in the figure together with the Neff calculations and an R-matrix fit [17] are normalized to the value of S(0)=0.553 keV·b taken from reference [5]. As can be seen the disagreement in the energy dependence between the different models is significant, especially for the energy range discussed here. Our results from the activation method experiment in Madrid agree with the ERNA data points as well as with the Neff calculation, but disagree with the Parker and Kavanagh data [cf. Fig. 3]. However, the Neff calculations do not reproduce the cross section for the mirror reaction ^{3}H(α,γ)^{7}Li. For this reaction the calculation is 15% larger than the experimental data, although the energy dependence agrees fairly well. New measurements for this reaction are therefore recommended. New measurements using the activation method have been recently published by Bordeanu and collaborators [18], which also show agreement with the results of our Madrid experiment.

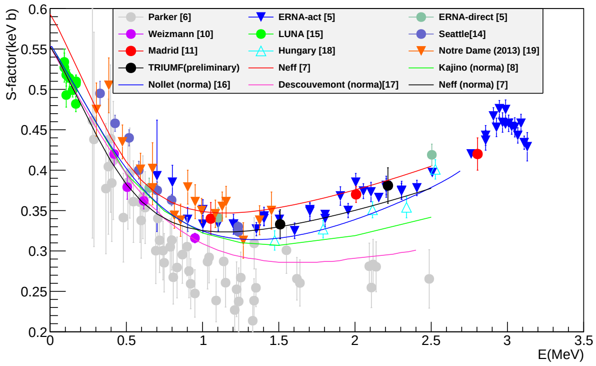

Figure 3. Astrophysical S-factors. In red are the measurements performed in Madrid using the *"Activation Method"*, and in black the **preliminary results** from TRIUMF using the *Direct Recoil Method*. The red curve shows the Neff *ab initio* calculations. The other curves show the theoretical models from references [7], [8], [16], [17], normalized to 0.553 keV·b taken from [5]. See text for discussion.

Our preliminary results with the *Direct Recoil Method*, [cf. Fig. 3], show agreement with our Madrid data for the two lowest energies. At the highest measured energy the angular distribution of the emitted gamma rays may be quite anisotropic due to the presence of the nearby $7/2^-$ resonance. We are carefully evaluating the dependence of the recoil transmission efficiency on the assumed angular distribution.

Acknowledgements

The work was partly financed by the Spanish Research Funding Agency CICYT under Project FPA2012-32443 and was supported by the UK STFC. Further M.C.G. acknowledges his CSIC-JAEpredoc grant partly funded by the European Social Funds.

References

[1] H.D. Holmgren and R.L. Johnston, Phys. Rev. **113**,1556 (1959)
[2] E.G. Adelberger et al., Rev. Mod. Phys. **83**, 195 (2011)
[3] J.N. Bahcall et al., Astrophys. J. **621**, L85 (2005)
[4] R.H. Cyburt et al., J. Cosmol. Astropart. Phys. **11**, 012 (2008)
[5] A. Di Leva et al., Phys. Rev. Lett. **102**, 232502 (2009)
[6] P.D. Parker and R. W. Kavanagh, Phys. Rev. **131**, 2578 (1963)
[7] T. Neff, Phys. Rev. Lett. **106**, 042502 (2011)
[8] T. Kajino and A. Arima, Phys. Rev. Lett. **52**, 739 (1984)
[9] B.S. Nara Singh, Acta Physica Polonica B. **44**, 511 (2013)
[10] B.S. Nara Singh et al., Phys. Rev. Lett. **93**, 262503 (2004)
[11] M.Carmona-Gallardo et al., Phys. Rev. C. **86**, 032801(R) (2012)
[12] D.A. Hutcheon et al., Nucl. Instrum. Methods Phys. Res. **A498**, 190 (2003)
[13] S.K.L. Sjue et al., Nucl. Instrum. Methods Phys. Res. **A700**, 179 (2013)
[14] F. Confortola et al., Phys. Rev. *C75*, 065803 (2007)
[15] T.A.D. Brown et al., Phys. Rev. *C76*, 055801 (2007)
[16] Kenneth M. Nollet, Phys. Rev. C **63**, 054002 (2001)
[17] P. Descouvemont et al., At. Data Nucl. Data Tables **88**, 203 (2004)
[18] C. Bordeanu et al., Nucl. Phys. A **908**, 1-11 (2013)
[19] A. Kontos et al., Phys. Rev. C **87**, 065804 (2013)