Astrophysical S factor for the $^4\text{He}(^3\text{He},\gamma)^7\text{Be}$ reaction at medium energies

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Abstract. The astrophysical S factor for the $^4\text{He}(^3\text{He},\gamma)^7\text{Be}$ direct capture reaction plays a major role in determining the primordial $^7\text{Li}$ abundance in the universe from the $^7\text{Be}$ disintegration. Furthermore, the high energy solar neutrino flux depends strongly on the $^8\text{B}$ abundance due to the $^7\text{Be}$ proton capture, and thus on the formation of $^7\text{Be}$, which mainly occurs via the direct capture reaction $^3\text{He}(^4\text{He},\gamma)^7\text{Be}$. Currently, this reaction is one of the remaining major sources of uncertainty among the nuclear inputs required to calculate the high energy solar neutrino flux [1]. Present work is also timely in view of new results of the detection of solar anti-neutrinos with the BOREXINO detector at Gran Sasso laboratory [2]. Precise measurements of the cross section $\sigma$ are therefore necessary. The astrophysical S factor is extracted from $\sigma$ via: $\sigma(E) = \frac{1}{2} \cdot S(E) \cdot e^{-2\pi \eta(E)}$, where $E$ is the energy and $\eta$ is the Sommerfeld parameter. The $S(E)$ gives the nuclear dependence of the astrophysical reaction rate and theoretical models use the extrapolation of $S(E)$ for the $^4\text{He}(^3\text{He},\gamma)^7\text{Be}$ reaction at zero energy ($S_{34}(0)$) as an input parameter in determining the solar neutrino flux and $^7\text{Li}$ abundance. Presently, there are serious discrepancies between the existing measurements of $S_{34}$ using different methods [3-7]. We focus mainly on the striking differences in the centre of mass (C.M.) energy range of 1.6 MeV to 3 MeV, where only data from Ref. [3] from 1963 and Ref. [4] from 2009 exist. Our measurements would help to constrain the experimental shape of $S_{34}(E)$ at medium energy and thus validate the theoretical calculations.

1. Introduction
The $^4\text{He}(^3\text{He},\gamma)^7\text{Be}$ reaction rate plays an important role in determining the primordial $^7\text{Li}$ abundance in the universe from the $^7\text{Be}$ disintegration. Furthermore, the high energy solar neutrino flux depends strongly on the $^8\text{B}$ abundance due to the $^7\text{Be}$ proton capture, and thus on the formation of $^7\text{Be}$, which mainly occurs via the direct capture reaction $^3\text{He}(^4\text{He},\gamma)^7\text{Be}$. Currently, this reaction is one of the remaining major sources of uncertainty among the nuclear inputs required to calculate the high energy solar neutrino flux [1]. Present work is also timely in view of new results of the detection of solar anti-neutrinos with the BOREXINO detector at Gran Sasso laboratory [2]. Precise measurements of the cross section $\sigma$ are therefore necessary. The astrophysical S factor is extracted from $\sigma$ via: $\sigma(E) = \frac{1}{2} \cdot S(E) \cdot e^{-2\pi \eta(E)}$, where $E$ is the energy and $\eta$ is the Sommerfeld parameter. The $S(E)$ gives the nuclear dependence of the astrophysical reaction rate and theoretical models use the extrapolation of $S(E)$ for the $^4\text{He}(^3\text{He},\gamma)^7\text{Be}$ reaction at zero energy ($S_{34}(0)$) as an input parameter in determining the solar neutrino flux and $^7\text{Li}$ abundance. Presently, there are serious discrepancies between the existing measurements of $S_{34}$ using different methods [3-7]. We focus mainly on the striking differences in the centre of mass (C.M.) energy range of 1.6 MeV to 3 MeV, where only data from Ref. [3] from 1963 and Ref. [4] from 2009 exist. Our measurements would help to constrain the experimental shape of $S_{34}(E)$ at medium energy and thus validate the theoretical calculations.
used for the extrapolation towards zero energy, thereby providing the accurate information
needed for calculating solar neutrino and the $^7$Li primordial abundances.

2. Experiment
In the $^4$He($^3$He,$\gamma$)$^7$Be capture reaction, prompt $\gamma$-rays from the capture state to ground state
or to the first excited state (at 429 keV), as well as from the first excited state to the ground
state are emitted. Subsequently, the $^7$Be ions decay by electron capture to $^7$Li with a half life
of 53.35 days. Thus, three different alternatives appear for the determination of the amount
of $^7$Be created: direct detection and counting of the $^7$Be ions, detection of prompt $\gamma$-rays,
or detection of delayed 478 keV $\gamma$ ray activity from the first excited state in $^7$Li (Activation
Method). The latter technique was used for the current work, utilizing the experimental setup
from the Weizmann institute [8]. The experiment was carried out at the Nuclear Physics line
of the 5 MV Tandem accelerator at the Centro de Microanálisis de Materiales (CMAM), in
Madrid. Figure 1 shows a schematic of the setup. The $^4$He gas target pressure in the chamber is
isolated from the beam line high vacuum by using 1 $\mu$m thick Ni foil window. A $^3$He beam with
energies between 2.3 MeV and 5.3 MeV of 100 to 200 nA current passed through the Ni foil.
The $^7$Be nuclei, produced via the capture of the beam onto $^4$He, recoiled through the chamber
and were implanted into a Cu catcher placed at the end of the chamber. A silicon detector with
a 0.27 mm radius collimator for monitoring the scattered beam was placed inside a chamber arm
at 44.9°. A pressure gauge was used to maintain the pressure constant using a regulated gas
flow system. The chamber was electrically isolated and a suppressor kept at -180 V upstream
of the Ni-foil made possible to use the chamber as a Faraday cup and thus to directly measure
the charge accumulated during the irradiations.

Figure 1. Sketch of the setup used in the experiment. See the text and Ref. [8] for more details.

3. Experimental analysis
Measurements, resulting in six Cu catchers with implanted $^7$Be nuclei produced at different
beam energies, were carried out in order to determine the reaction rate over a wide energy
range. The amount of $^7$Be recoiling ions, the number of target ions and the total incoming
ion beam was measured precisely. The recoiling $^7$Be atoms were collected onto the Cu catchers
and the subsequent $\beta$ delayed $\gamma$ radiation was measured off-line using a low-background HPGe
detection station at SOREQ laboratory, in Israel, similar to that of Ref. [8]. The measurement
typically was carried out over a few days in order to obtain enough statistics in the 478 keV line
in the $\gamma$ spectrum. Due to the low pressure an ideal gas behaviours is assumed for the gas target
and the number of target atoms can be expressed as: $N_T(^4He) = 9.66 \cdot 10^{18} \cdot l \cdot \frac{P}{T_0+T_c}$, where $P$, $l$
and $T_0$ are pressure in torr, room temperature in $K$ and length between the Ni foil and the Cu
catcher in cm, respectively. $T_c$ is the correction to the temperature due to the beam heating the
$^4$He gas during the measurement. Pressure was kept constant over the different measurements
($\approx$50 Torr). The temperature correction ($T_c$) was interpolated using the data in reference [8]. In
order to determine the number of incident $^3$He ions two complementary techniques were being
used: integration of the charge induced on the chamber and integration (IC) of the elastically
scattered particles in the detector (RS).

4. Preliminary results and ongoing work
The results obtained after data analysis are shown in Table 1. The fourth and fifth columns show
the $S_{34}$ factors by determining the beam particles by charge integration (IC) and Rutherford
scattering (RS), respectively. An agreement between the two methods is observed. Our results show a good agreement with those from ERNA data [4] at the highest energies. Around 2 MeV C.M. energy, the $S_{34}$ factor fall between the results of [1] and [3]. New measurements with the same setup are ongoing at CMAM in order to reduce the statistical error and to check the result around 2 MeV C.M. energy, afterwards extrapolations will be carried out using different theoretical models. For a brief discussion on this data in relation with our TRIUMF work and the recent calculations by T. Neff [9] we refer to Ref. [10].

Table 1. First column gives the C.M. energy $E_{CM} = \frac{1}{2}(E_b - \Delta E_{Ni} - \Delta E_{He})$ where $E_b$ is the incoming beam energy, $\Delta E_{Ni}$ is the energy loss in the Ni foil, and $\Delta E_{He}$ the energy loss in the gas target between the Ni foil and the Cu catcher. As we assume that the reaction takes place in the middle of the gas target, the last term in the equation is divided by two. The fourth and fifth columns show S-factor when the number of incoming particles are obtained from charge integration ($S_{34}(E)^{IC}$) and from Rutherford scattered particles ($S_{34}(E)^{RS}$), respectively. The statical errors associated to the delayed gamma radiation detection are shown. The systematic errors are negligible.

| $E_{CM}$ (keV) | P (Torr) | $^{7}$Be (10$^6$) | $S_{34}(E)^{IC}$ (keV.b) | $S_{34}(E)^{RS}$ (keV.b) |
|----------------|----------|------------------|-------------------------|-------------------------|
| 903.6          | 54.68    | 1.30             | 0.40±0.08               | 0.41±0.08               |
| 1487.5         | 63.77    | 4.02             | 0.31±0.02               | 0.31±0.02               |
| 2010.6         | 50.64    | 5.02             | 0.30±0.02               | 0.31±0.02               |
| 2256.0         | 50.66    | 4.71             | 0.37±0.04               | 0.37±0.04               |
| 2499.0         | 50.83    | 3.17             | 0.37±0.03               | 0.38±0.04               |
| 2791.1         | 56.69    | 6.01             | 0.41±0.02               | 0.41±0.02               |

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