New experimental study of the ^{3}He(α,γ)^{7}Be reaction around the E_{cm} = 3 MeV resonance

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Abstract. The total cross section of the ^{3}He(α,γ)^{7}Be reaction was measured by the activation technique in the energy range of E_{cm} = 2.6 – 3.1 MeV, covering the first known resonance in the reaction. Consistent results were obtained with the only one available literature dataset in this energy range.

1 Introduction

The ^{3}He(α,γ)^{7}Be reaction was studied by many groups before the turn of the century. For a compilation, see e.g. the first *Solar fusion cross sections* review [1]. Microscopic calculations successfully described the energy dependence of the experimental datasets, thus robust extrapolation to solar and stellar energies was established. However, the absolute normalization of the theoretical calculations to the experimental data showed different scalings for datasets obtained by in-beam γ-spectroscopy and by activation method. Motivated by this ambiguity pointed out in the review, a new series of cross section data have been measured.

The newer datasets are compiled in the second *Solar fusion cross sections* review [2], where the previously inconsistent scaling was attributed to underestimated experimental uncertainties in the pre-2000 datasets. For the extrapolation to solar energies, only the well documented post-2000 works were considered, from which data only up to E_{cm} = 1.0 MeV were used. The reason behind was that the different theoretical models differ by only a few percent in this energy range, and starts to deviate above. In addition, the new experimental data based on recoil detection [3] disagreed with the only one older in-beam γ-spectroscopy measurement [4] in the slope of the S-factor[1] towards higher energies.

In the last decade there were a few works motivated to solve this tension between the higher energy datasets, and all of them [5–7] supported the newer measurement. These new data also provided a firm basis for updated theoretical calculations also toward higher energies. There is one previous study of the total radiative capture cross section with the activation technique around the ^{7}Be proton separation threshold in the energy range of E_{cm} = 4.0 – 4.4 MeV [8], which was motivated by a proposed level in ^{7}Be which appeared as a resonance in the ^{6}Li(p,γ)^{7}Be reactions [9]. The existence of the level was not confirmed either by the ^{3}He(α,γ)^{7}Be work, or by a newer ^{6}Li(p,γ)^{7}Be investigation [10].

For the precise determination of the reaction rate in different astrophysical scenarios, extrapolation of the cross section is mostly unavoidable. For example, the lowest measured

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[1] S(E)=E$e^{(2\pi\eta)}\sigma$(E), where η is the Sommerfeld parameter

experimental cross section is at E_{cm} = 93 keV [11], while the solar Gamow peak (the energy range that gives the most contribution to the reaction rate) centers at about 23 keV. Because of the Coulomb barrier, between these two energies the cross section drops by about 7 orders of magnitude, making it impossible with the present days techniques to be measured.

Beside the direct reaction studies, indirect methods are also used to infer the solar reaction cross section. For example, with transfer reactions, the ^{3}He(α,γ)^{7}Be ANC (asymptotic normalization coefficient) can be determined [12], which directly sets the magnitude of the zero-energy S-factor extrapolation. An other possibility is to use the Standard Solar Model and the experimental solar neutrino fluxes to extract the reaction rates [13].

For the extrapolation, one of the widely used possibilities is the R-matrix theory, where multi-channel, multi-level fits can be performed, taking into account almost all the experimental information about a compound nucleus [14]. However, the fit is highly dependent on the precision and consistency of the datasets used in the analysis. For example, a new precise determination of the scattering cross section changed the extrapolation in such a way, that the previously discrepant (or off scale) low energy capture data became consistent with the fit [15]. To strengthen the predictive power of the fits, a new study is following up the one at high energy with the same setup [8]. The aim is to cover the energy range of the first resonance, where only one experimental dataset exist, and close the energy gap lacking experimental data. Even thought the new data will have minor influence on the S(0) extrapolation, it is worth while to cross validate different R-matrix calculations. A previous cross validation work [16] concentrated only on scattering data, however the treatment of the radiative capture may differ in the codes, which should also be validated.

2 Experimental aspects

For the experiment the activation technique was employed. Since the ^{7}Be reaction product is radioactive and decays by electron capture with a half-life of 53.22 days [17], it is well suited for this technique. The decay is followed by the emission of a 478-keV γ ray with 10.44 % branching [17]. This γ radiation makes it possible to measure the activity created by the irradiation via γ-ray detection.

Since the target is a noble gas, it forms no solid compound, which could be used as a reaction target. Solid target from helium can be created by implantation, which has already been used for studying the ^{3}He(α,γ)^{7}Be [18, 19]. However, the determination of the absolute amount of nuclei captured in the crystal structure of the host material, and the stability of such target under beam bombardment require extensive target characterization techniques. In most cases, helium targets in gas form are used. Either in a differential pumped windowless gas target (e. g. [3, 20]), or in gas-jet target, or enclosed in a cell (e. g. [6]). All of them may have their own difficulties, e. g. in the determination of the number of target atoms, the beam current measurement, or the overlap of the beam and target, just to mention a few. In the present work, the investigated energy range allowed to employ a gas cell closed by thin window, thus no differential pumping was necessary, and the number of projectiles was possible to be determined by measuring the electric current hitting the target. Here, the window itself may cause some problems, which has to be tackled for a precision measurement.

The continuously developed thin-windowed gas-cell setup of Atomki [6, 8, 21, 22] contains for the present study two 10 μm thick aluminium windows, which separate the ^{3}He gas volume from the beamline vacuum. The beam was produced by the Atomki cyclotron accelerator. For the targeted center-of-mass energy range, the α particles had an energy around 8 MeV. The beam lost about 1-1 MeV energy in both the entrance and exit foils, and a few keV in the gas volume. All the energy of the beam particles passing through the windows, and later the energy of the created ^{7}Be recoils passing through the gas was determined by

simulations using the SRIM software package [23]. With this double-window configuration sizable portion of the total energy is dumped outside the gas cell (in a water cooled tantalum sheet), thus any temperature effect caused by the heating of the gas is reduced. The target areal density was determined from the initial temperature (≈24 °C), pressure (≈100 mbar) and the length of the cell (≈4 cm) using the ideal gas law. The real gas behavior of helium deviates less than 0.005 % from the ideal gas low in this pressure and temperature regime [24], thus this effect is negligible compared to other uncertainties. Since the cell is closed, the number of target atoms did not change during the irradiation even if the temperature and pressure may increase as a consequence of the beam power deposition in the cell or gas desorption from the cell walls. The foils expected to be bent because of the pressure difference between its two sides. The size of this effect was tested in an off-site setup [22], and found to be in the order of 0.3 mm at the center of the foil. Additional to the foil bending effect, a slight offset between the beamline and cell axes may cause a maximum 0.1 mm effective length change. Because of the two foil configuration, a conservative 1 mm uncertainty in the cell length was adopted, which includes the possibility of a slightly higher foil deformation while it is heated by the beam. There was a maximum 0.2 mbar and 2 °C fluctuation observed in the initial pressure and temperature, respectively, thus these values were used as a conservative estimate in the calculation of the number of target atoms. In total, 2.5 % uncertainty is assigned to the areal number density of the target.

The whole cell was attached to an electrically isolated activation chamber serving as a Faraday-cup. At the entrance of the chamber, a beam defining aperture ensured that only those α particles enter the chamber, which also hit the gas volume. Electrons that may emerge from the entrance aperture, or would escape from the chamber, are suppressed by employing -300 V on an aperture right behind the beam defining one. Since the gas volume was inside the Faraday-cup, charge exchange inside the gas did not affect the current measurement. An overall current reading accuracy of 3 % is taken into account as a systematic uncertainty.

The ^{7}Be formed in the reaction had a forward momentum with an energy of 4.15 – 3.83 MeV and a maximum angle of about 1°. Recoils may lose maximum about 0.4 MeV energy in the gas volume, when they arrive to the exit foil serving as a catcher. Since the implantation occur with a minimum of 3.4 MeV, negligible backscattering is expected. The implantation depth of ^{7}Be with these energies is about 5 μm, thus sputtering of the already implanted activity by the unreacted α beam is also negligible.

The catchers were extracted and replaced after each irradiation, and their activity was determined using a lead shielded high purity germanium (HPGe) detector. The detection efficiency of the HPGe was determined by using multi-line γ-ray standards at far geometry (detector-source distance of 27 cm). From the calibration, the detection efficiency at 478-keV was interpolated. The actual, low activity samples created by the ^{3}He(α,γ)^{7}Be reaction were measured in close geometry (detector-source distance of 1 cm). To determine the ratio of the far and close geometry efficiencies, a stronger ^{7}Be source created via the ^{7}Li(p,n)^{7}Be reaction was used. With this approach the true coincidence summing effect relevant for multi-line calibration sources in close geometry is avoided. The final uncertainty assigned to the γ detection efficiency is 3 % incorporating the uncertainty of the activity of the γ-ray standards, and that of the interpolation and the scaling.

For the center-of-mass energy determination, the thickness of each entrance foil was precisely measured after the irradiation in a setup consisting of a triple nuclide alpha source and a particle detector. From the energy loss of the α particles passing through the foils, their thickness was determined. For the conversion between the energy loss and thickness, the SRIM tables [23] were used. Each foil was measured at several points. No significant thickness variation was observed between the region where the beam hit the foils and those which where unexposed to the beam or to the tension created by the pressure difference.

3 Preliminary results

The work is in progress, however, a few preliminary data points are shown in Fig. 1. The newly obtained results are inline with the literature data. Additional to the statistical uncertainty plotted in the figure, a systematic uncertainty of about 5 % has to be considered, which affects the absolute scale of the whole dataset. This systematic uncertainty accounts for the uncertainty of the γ branching, γ detection efficiency (3 %), current reading (3 %), cell-length (2.4 %); common for each data point.

The horizontal error bar shows the absolute energy uncertainty. It stems from the uncertainty of the entrance foil thickness, and the uncertainty of the stopping power of the incoming α particles in aluminium, and the energy uncertainty of the initial beam.

The dataset will be extended towards higher energies, to close the gap between $E_{cm} = 3.1 - 4.0$ MeV, where experimental data are lacking.

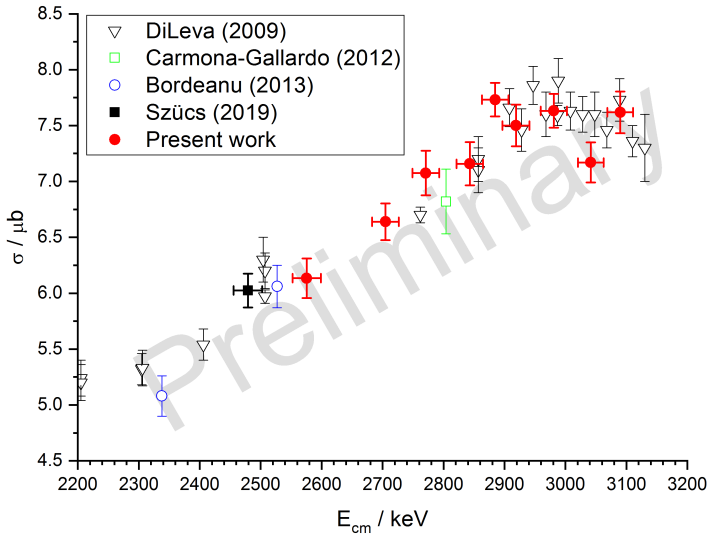

Figure 1. The new preliminary data is compared with literature datasets in a similar energy range [3, 5, 6, 8]. Only the statistical uncertainties are plotted on each datapoint. The horizontal error bars show the beam energy uncertainty in the gas.

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