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^{3}He(α,γ)^{7}Be cross section in a wide energy range

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Abstract. The reaction rate of the ^{3}He(α,γ)^{7}Be reaction is important both in the Big Bang Nucleosynthesis (BBN) and in the Solar hydrogen burning. There have been a lot of experimental and theoretical efforts to determine this reaction rate with high precision. Some long standing issues have been solved by the more precise investigations, like the different S(0) values predicted by the activation and in-beam measurement. However, the recent, more detailed astrophysical model predictions require the reaction rate with even higher precision to unravel new issues like the Solar composition. One way to increase the precision is to provide a comprehensive dataset in a wide energy range, extending the experimental cross section database of this reaction. This paper presents a new cross section measurement between $E_{cm} = 2.5 - 4.4$ MeV, in an energy range which extends above the ^{7}Be proton separation threshold.

1 Introduction

The ^{3}He(α,γ)^{7}Be reaction is the starting point of the ppII and ppIII reaction branches in the solar hydrogen burning pp-chains, therefore its rate has sizeable impact on the solar ^{7}Be and ^{8}B neutrino production. Using the standard solar model [1], the flux of these neutrinos can be calculated. With the known solar parameters and reaction rates, we gain insight into the solar core through comparison of the measured and calculated neutrino spectrum. Recently, the solar neutrino detections reached a precision of a few percent [2, 3], which would allow these investigations. However, now the precision of the nuclear physics input has to catch up to have this unique tool for precise solar core diagnostics.

The reaction has its other major role in the Big Bang Nucleosynthesis (BBN). For a long time it has been a candidate for solving the primordial lithium problem [4]. However, in the last decade the LUNA collaboration measured the reaction cross section directly in the BBN energy range [5–8], excluding this possibility. Even though, the ^{3}He(α,γ)^{7}Be reaction cannot be the solution of the primordial Li problem, its BBN reaction rate has to be known with higher precision to test models using new physics e.g. [9].

There are a few methods to investigate experimentally the ^{3}He(α,γ)^{7}Be reaction. One of the possibilities is the so-called in-beam gamma spectroscopy. In this case the prompt gamma-rays produced in the reaction have to be detected. Anther possibility is the activation method. The reaction product ^{7}Be is radioactive with a half life of 53.22 days [10], and 10.44 % of the ^{7}Be decay goes to an excited state of ^{7}Li producing a 477.6 keV γ-ray. By counting this γ-ray the produced ^{7}Be activity can be derived and the reaction cross section can be determined.

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In the 1998 Solar fusion cross section compilation [11] several cross section measurements were listed for the ^{3}He(α,γ)^{7}Be reaction, however, there was a discrepancy between the cross section values obtained with the two methods. Later the LUNA collaboration performed an experiment, where the reaction cross section was measured simultaneously by both methods [6]. The new data showed perfect agreement between the two methods, indicating some hidden systematic uncertainty in the previous measurements.

Recently a third technique became available to determine the ^{3}He(α,γ)^{7}Be reaction cross section. Namely, the direct detection of the ^{7}Be recoils. This measurement was done by the ERNA collaboration [12], where additionally a few prompt gamma and activation data points were recorded at overlapping energies, and consistent results were found from the three methods. This experiment extended the experimental database up to E_{cm} = 3.1 MeV. Only one former dataset contains data above E_{cm} = 1.5 MeV [13]. These data exhibit a different slope of the the S-factor towards higher energies as pointed out in the 2011 Solar fusion cross section compilation [14]. To resolve the discrepancy two new datasets have been measured at different laboratories [15, 16], and both were in agreement with the ERNA data.

As a summary of the current situation, most of the recent reaction cross section measurements have focused on the low energies below E_{cm} = 1.5 MeV, including the most recent one [17]. However, there is no experimental data above E_{cm} = 3.1 MeV. It was suggested recently, that the R-matrix models have to be tested on higher energy datasets [18]. In addition, there are conflicting datasets for the ^{6}Li(p,γ)^{7}Be reaction [19, 20] having impact on the level scheme of ^{7}Be, which has to be understood for a precise extrapolation toward the solar energies.

To address the need for experimental data outlined above, a new measurement is being performed across a wide energy range, extending the experimental database of the ^{3}He(α,γ)^{7}Be reaction cross section with a dataset in the energy range of E_{cm} = 2.5 – 4.4 MeV.

2 Experimental details

In this work the ^{3}He(α,γ)^{7}Be reaction cross section is measured with the activation technique. The lower energy points overlap with the energy range of the former studies, and spans slightly above the proton separation threshold of ^{7}Be, thus it can be compared also with the ^{6}Li(p,γ)^{7}Be reaction cross sections.

A thin window gas cell target was used for the investigations. The cell was slightly modified, but it is similar to the one used in Atomki for a previous measurement campaign [16]. The ^{3}He gas is confined between two aluminium foils with 10 μm nominal thickness. The first one served as an entrance foil for the beam, the second one was used as an exit and catcher foil for the produced ^{7}Be. After the exit foil the beam was stopped in a water cooled beam stop. With this double window configuration less beam power is absorbed in the gas volume, therefore less pressure change was observed during the irradiations.

The number of target atoms is determined from the initial gas pressure and temperature knowing the length of the cell. Without beam the gas pressure was constant over several days. During the irradiations the gas pressure was continuously monitored, and a slight increase was observed. This additional pressure did not decrease after the beam was stopped, therefore it is assumed to be outgassing of internal surfaces of the cell. The additional pressure was considered in the effective energy calculation.

The thickness of the entrance foil was measured by α-energy loss. A triple isotope alpha source was placed below the foil in an α-spectrometer, and the energy of the α-particles penetrating through the foil was measured by an ion-implanted silicon detector. From the measured energy loss, the thickness was determined using SRIM [21].

The beam energies varied between 7.3 − 11.3 MeV to measure at the targeted center-of-mass energies. The energy loss of the particles in the entrance foil and the target gas itself was calculated from SRIM [21].

After the beam defining aperture the whole irradiation chamber and gas cell was isolated to allow the beam current measurement by charge integration. Typical irradiation length was 20 − 22 hours with an α^{++} current of 1 μA.

After the irradiation the catcher foil was transported to a HPGe detector with 100 % relative efficiency in a commercial 10 cm thick 4π lead shielding. For the countings 1 cm sample to detector end-cap distance was used. The activity of a given catcher was measured multiple times to check the activity decrease. The half-life of the reaction product was consistent with the literature half-life of ^{7}Be. The detector efficiency calibration was done with calibrated multi-line gamma sources at far geometries, where the true coincidence summing is negligible. Then the close distance efficiency was determined by a stronger ^{7}Be source. A scaling factor was derived between the two geometries, and used later in the analysis.

3 Preliminary results and outlook

The obtained cross sections range between between 6 − 12 μbarn. In Fig. 1. a few preliminary data points are shown together with the data from [12]. In the overlapping energy region the agreement between the new and former data is clearly seen.

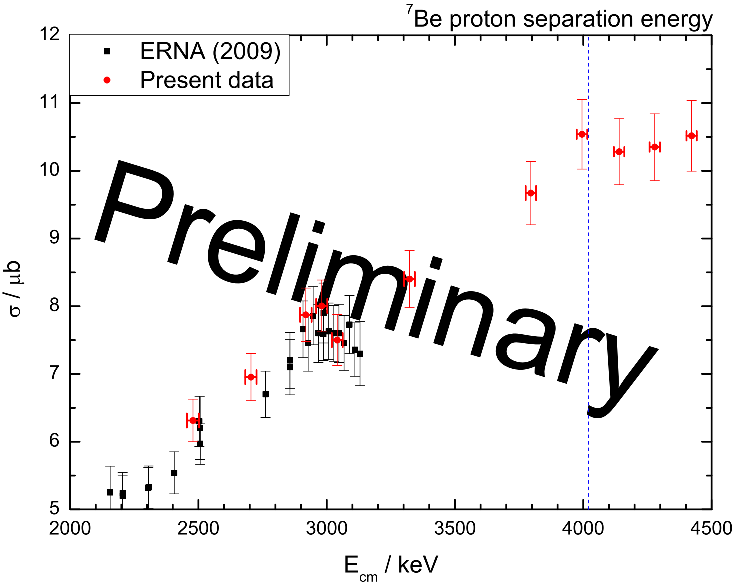

Figure 1. Preliminary cross section data are indicated by red dots, black points are the data from [12]. Horizontal error bars represent the energy uncertainty. Vertically the total uncertainties are displayed including statistical and systematic ones.

The average trend of the data is following the lower energy trend up to the ^{7}Be proton separation threshold. Above the threshold, the excitation function becomes more flat. The opened ^{3}He(α,p)^{6}Li reaction channel is not strong close to the threshold, and does not take away sizeable yield.

The data taking and analysis is ongoing. The whole energy range will be populated with additional points, especially above the threshold energy, where a new ^{6}Li(p,γ)^{7}Be resonance was suggested [20]. The energy region of the resonance measured by the ERNA collaboration [12] will also be investigated and populated with more data points.

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