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^{3}He(α,γ)^{7}Be cross section measurement around ^{7}Be known energy levels

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Abstract. The ^{3}He(α,γ)^{7}Be reaction plays an important role in two astrophysical scenarios. It is a key reaction in lithium production during the Big Bang Nucleosynthesis and one of the central reaction in the p-p chain in stars. In the case of the former event, the Gamow energy of the reaction is around 0.2 MeV, while in the case of the p-p chain in the Sun, an order of magnitude less, around 0.023 MeV. Experimental investigation at such low energies is very difficult, if possible at all, thus low energy extrapolation inevitable to predict the reaction rate at these energies. The extrapolation and its uncertainty are influenced by the precision and covered energy range of the data used. There are many precision datasets between $E_{c.m.}$ = 0.3–3.1 MeV, but only one below and one above. At higher energies known levels of ^{7}Be exist, which motivates the study of that energy range. Therefore, we performed investigations in the energy range of $E_{c.m.}$ = 4.3–8.3 MeV, where the radiative cross section has not been studied so far. For the cross section determination, the activation technique was used utilising a thin-windowed gas cell and the MGC-20 cyclotron of ATOMKI.

1 Introduction

The study of nuclear reaction cross sections is of interest in various aspects of astrophysics, such as the formation of the elements, stellar evolution, the formation of the solar system and the evolution of the early universe. The ^{3}He(α,γ)^{7}Be nuclear reaction is important in two different astrophysical scenarios. On the one hand, it plays an important role in the production of elements in the Big Bang Nucleosynthesis (BBN), through the production of ^{7}Li. On the other hand, it is one of the branching reactions of the proton-proton chain therefore significantly affects the flux of neutrinos from the Sun's core. It is very important to know the cross section of the reaction with as little uncertainty as possible, because this reduces the uncertainty of the model calculations, which are currently less precise than the experimental solar neutrino flux determinations.

In the relevant energy range in stars, the so-called Gamow window, experimental data are difficult to provide because of the extremely low cross sections caused by the Coulomb barrier between the interacting charged particles.

A part of the energy range for the BBN has been experimentally determined by the LUNA Collaboration in the range of $E_{c.m.} = 0.09 - 0.17$ MeV [1, 2, 3, 4]. Currently, this is the only measurement that has been performed within the Gamow window of this reaction.

However, if we have experimental data at higher energies, it is possible to extrapolate to the low energy range and predict the reaction rate. There are many experimental data available in the $E_{c.m.} = 0.3 - 3.1$ MeV range [5, 6, 7, 8, 9, 10]. In 2019, the reaction cross section was measured around the proton separation energy of the compound ^{7}Be nucleus in $E_{c.m.} = 4.0 - 4.4$ MeV [11].

To ensure the accuracy of the extrapolation, experimental data are needed not only around the relevant energy range, but also at higher energies. In our experiment, we investigated the cross section of the reaction around the known energy levels of ^{7}Be, covering the energy range of $E_{c.m.} = 4.3 - 8.3$ MeV.

2 Experimental details

The cross section of the ^{3}He(α,γ)^{7}Be reaction was determined using the activation technique [12]. Usually the first step is to create radioactive reaction products by irradiation and then detect the yield of radiation emitted after the decay of these nuclei. The experiments were carried out with a thin-windowed gas cell. High putiry Al foils served as entrance and exit windows for the cell of 4.19-cm active lengths. The thickness of the entrance foils used was 10 μm, while that of the exit foils was 10, 20 and 25 μm, depending on the energy of the ^{7}Be produced during irradiation. Despite the foil high purity, its contains some impurities (Cu, Fe, Mg, Si...). On these impurities can undergo (α,n) reactions, which can produce nuclei with short half-lives ($<$ 1 day). The decay of these nuclei increases the undesirable background in the spectrum.

High purity (99.999 %) ^{3}He gas was used as the target, with an initial pressure of about 100 mbar during the irradiations. In the cell, an appropriately sized O-ring was placed under the foil, clamped down with a metal plate and secured with screws, giving the foil a diameter of 12 mm.

The irradiations were performed by the ATOMKI MGC-20 cyclotron accelerator. To create adequate activity, the length of the irradiations was nearly 20 hours. The activation chamber was isolated from the rest of the beamline. A voltage of -300 V was applied to apertures right between the entrance of the chamber and the beam defining aperture to eliminate the disturbing effect of the generated secondary electrons during irradiation. The function of the collimator is to form the diverging beams. The gas cell is part of the activation chamber, which works as a Faraday cup, so it is possible to determine the number of bombarding particles by charge measurement.

The pressure in the cell has been traced continuously with a pressure gauge. Most of the alpha beam unreacted passed through the cell, those were stopped in a water cooled tantalum sheet. The energy loss of the beam in the entrance foil was calculated with the SRIM program [13]. Depending on the initial beam energy the energy loss varied between 0.65 MeV and 1.0 MeV. The exit foil was used as a catcher foil. The produced ^{7}Be nuclei are implanted in the aluminium foil. Following irradiation, the catcher aluminium foil with the implanted ^{7}Be nuclei was placed in front of a high-purity germanium detector at a distance of 1 cm. To reduce background radiation, the detector was surrounded by 8 cm thick lead. The γ-ray detection of the 477.6 keV γ-transition was started after a cooling time of at least one day, to let the disturbing parasitic activities created on the foil impurities decay out. Each sample was usually measured for 7-12 days, in several periods to achieve good statistics.

The detector efficiency-energy function was determined using calibrated sources of known activity (^{133}Ba, ^{152}Eu and ^{60}Co). To avoid the so called true-coincidence-summing, the calibration measurements were carried out in far geometry. Subsequently, a high activity ^{7}Be source was used to determine the efficiency ratio for the close-far geometry. This ratio was used to determine the efficiency in the 1 cm geometry for the γ-transition under investigation. In this way, the uncertainty of the efficiency could be given with an accuracy of 2%.

The beam loses energy when it passes through the entrance foil, so this must be taken into account when determining the centre-of-mass energy. It is therefore necessary to determine the exact thickness of the entrance foil. This was done using an Ortec Soloist type alpha spectrometer, which includes a silicon ion implanted detector and various collimators. The detector and the radiation source are located in a common vacuum area. The first step of the thickness measurement is to perform the calibration with a mixed alpha source (containing ^{239}Pu, ^{241}Am and ^{244}Cm). Then the arrangement is modified by placing the entrance foil between the alpha source and the detector, and a collimator is placed along the source-foil-

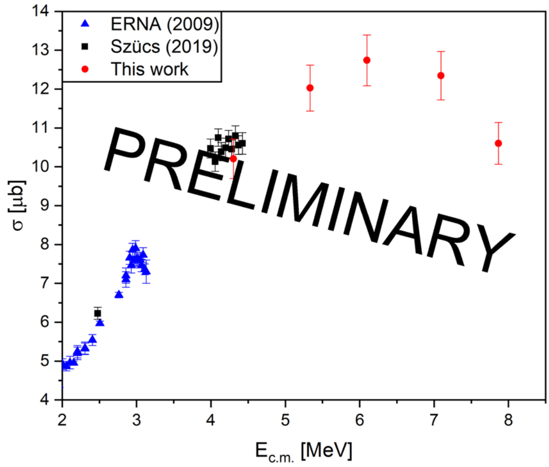

Figure 1. The new preliminary data compared to literature values [7, 11]. The total uncertainty of the data is shown.

detector axis. In this way, different points on the foil (4-5 locations) were tested, and the thickness of the entrance foils were determined with a few percent accuracy.

3 Preliminary results

The cross section of the ^{3}He(α,γ)^{7}Be reaction has been determined over an energy range never investigated experimentally before, around the known energy levels of the ^{7}Be nucleus.

In **Figure 1.**, preliminary cross sections and their associated statistical uncertainties as a function of centre-of-mass energy are provided. The first point was a benchmark test, which shows good agreement with the results of previous measurements. The energy range $E_a = 11 - 20$ MeV is studied in detail. The ATOMKI MGC-20 cyclotron is capable of accelerating twice positively charged alpha particles in the $E_a = 3.5 - 10.4$ and $10.4 - 20$ MeV energy range [14]. Accordingly, irradiation at energies higher than 20 MeV is not possible with this device. The cross section reaches its maximum at 15 MeV and then shows a decreasing trend at higher energies.

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