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Cross section measurements of the ${}^3\text{He}(\alpha, \gamma){}^7\text{Be}$ reaction using DRAGON at TRIUMF

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Abstract. We present our initial efforts with the DRAGON separator at TRIUMF facility towards obtaining the energy dependence of the astrophysical S-factor for ${}^3\text{He}(\alpha, \gamma){}^7\text{Be}$ reaction in the energy range of $E_{cm} = 2$ to 3 MeV that was recommended by the recent evaluations. A comparison between the existing data and our new complementary Madrid data, together with the recent theoretical calculations, is also given in the context of our ongoing work.

1. Introduction

The ${}^3\text{He}(\alpha, \gamma){}^7\text{Be}$ reaction was first studied half a century ago sparking interest in different fields of physics including solar neutrinos and big bang nucleosynthesis calculations [1, 2]. Since then, there have been a number of efforts both on the experimental and theoretical fronts, often resulting in disagreements in the absolute values of cross sections [2]. Obtaining accurate information on this reaction has become increasingly important in the recent years as the reaction, among the nuclear inputs, has become the second largest contributor to the uncertainty in calculating the high energy solar neutrino flux. As it is practically impossible to carry out measurements in the laboratories around the astrophysically most effective energy, 23 keV, theoretical extrapolations of the data taken at higher energies become necessary. From a recent compilation and critical analysis of the astrophysical S-factor variation with energy, it is clear that no model can give an accurate fit to all the available data and differences in the theoretical energy dependence contribute up to a 6% error in the extrapolated value of the S-factor. In particular, the models differ in energy dependence of the S-factor seen in the range of $E_{cm} = 2$ to 3 MeV [3, 4]. Clearly, precise data should also be obtained at medium energies. Such efforts, when combined with the measurements at lower energies, will allow an accurate model independent shape analysis of the S-factor curve and will help constraining theoretical models. Currently, data from Refs. [3] and [5] extend well above 1 MeV and disagree with each other at these medium energies. The available data on the astrophysical S-factor, S_{34} , were obtained by using different methods: the detection of prompt γ rays from ${}^7\text{Be}$, of the

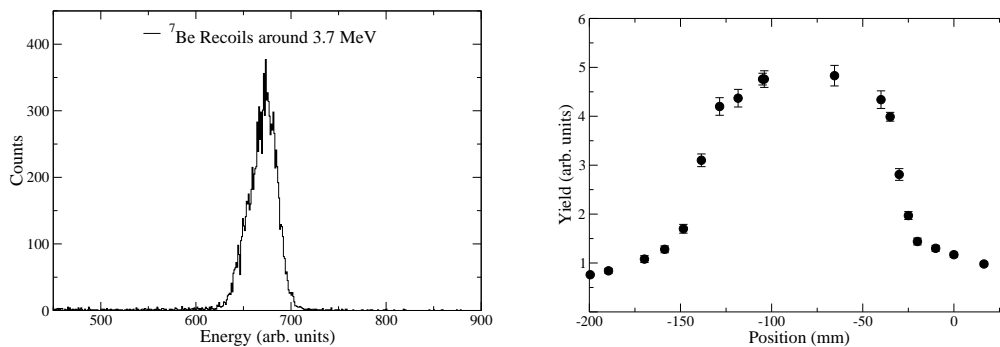


Figure 1. Left: The DSSSD spectrum showing around 11,000 ${}^7\text{Be}$ nuclei having recoil energies of 3.7 MeV with essentially no interference from background or the ${}^4\text{He}$ beam with 300 nA current at a bombarding energy of 6.5 MeV. No collimator was used between the gas target and the separator. Right: The measured target profile shows that the effective target length is 140mm; with a pressure of 8 Torr this leads to $\Delta E=14.8$ A keV within the gas that was verified by measuring the exit energies of the beam after the gas at different pressures between 2 and 9 Torr. This is different from that of 12.3 cm for H_2 gas at 4 Torr [10]. In addition, the yield profile does not go to zero at extremes. As the gas mixture with only 3.5% of ${}^3\text{He}$ was used, the statistical accuracies and the quality of the γ spectra detected with a collimated BGO detector can be improved by using pure gas.

ensuing activity from ${}^7\text{Be}$, and of produced ${}^7\text{Be}$ nuclei [2, 3, 4, 5, 6, 7, 8, 9]. In this paper, we present our initial work towards obtaining new data using the recoil detection method utilizing the DRAGON setup [10]. Our ongoing work, in relation to our new Madrid activity data and the recent calculations presented at this conference, is also discussed [11, 12].

2. Experiment and Results

As can be seen from the work by Di Leva *et al.* [3] the recoil detection method needs fairly complex setups which employ a differentially pumped windowless gas target cell, a recoil separator and a detection system at the focal plane. We utilized the two stage DRAGON recoil separator at the TRIUMF laboratory in Vancouver with ${}^4\text{He}$ beams of energies in the range of 3.5 MeV to 6.5 MeV and a ${}^3\text{He}$ windowless gas target at 8 Torr. Details on the separator can be found in Ref. [10]. Cross section measurements with an accuracy better than 10% using such a setup demand a good knowledge of, the acceptance of the separator, the charge state distributions and the background expected in the focal plane detectors for the produced ${}^7\text{Be}$ recoils, as well as the total numbers of beam and target particles. As we are addressing the most symmetric reaction studied ever at this separator and the recirculation of the ${}^3\text{He}$ gas target was required, a few modifications or developments for various components of our setup needed to be done and extensive careful tests have been performed to characterize our setup. It should be pointed out that due to the limitation in the acceptance of the separator, the reaction can best be studied in inverse kinematics, i.e. using ${}^4\text{He}$ as a beam and ${}^3\text{He}$ as a gas target.

The acceptance tests were initially carried out using an α source in conjunction with collimators that are aligned with the gas target and have geometric half-angles of 17,19 and 21 mrad. The α particles passed through the collimator and the separator before being detected in the Double Sided Si Strip Detector (DSSSD) at the focal plane typically at a rate of 1 Hz. The position information from the DSSSD and the event rates observed with collimators allowed us to infer that the separator has an acceptance cone half-angle of 21.0(6) mrad. In addition we measured the $d({}^{16}\text{O},n){}^{17}\text{F}$ reaction which has a threshold beam energy of 908.06 AkeV at

which the maximum angle for the resulting ~ 12.0 MeV ^{17}F recoils is 0° and increases gradually with the energy. Our measurements at 971, 952, 922 AkeV utilizing the collimators mentioned before, helped us to confirm our source tests.

The existing differentially pumped gas target design was modified to adapt it for the recirculation of the ^3He gas avoiding any possible leaks. Since a pure gas was not available at the time of our tests, we used a gas mixture of ^3He (3.5%) and ^4He (96.5%). The He gas pressure was maintained in the target chamber at 8 Torr. The recoiling ^7Be nuclei were separated from the beam by DRAGON and subsequently detected by the DSSSD at the focal plane. Figure 1 (left) shows the energy spectrum of recoils detected in the DSSSD at $E_{cm}=2.8$ MeV. The total number of ^4He beam particles striking the gas target during this data collection was $\sim 2.5 \times 10^{16}$. Based on background measurements without beam, we expect a mean background at and below the beam energy of 38.1 events. We observed 31 events during the measurement of recoils and therefore infer a 90% confidence level lower limit on the beam suppression factor of $\sim 3 \times 10^{15}$. This result confirms the suitability of the DRAGON set up to study our symmetric reaction.

The target density profile was measured using the $^3\text{He}(^{12}\text{C}, p \gamma)^{14}\text{N}$ reaction at the $E_{cm}=2.389$ MeV resonance having 40 AkeV width (Γ). A ^{12}C beam at 100 pA current and 11.985 MeV energy was delivered onto the ^3He target gas at a pressure of 8 Torr. Prompt- γ -rays at energies of 3.38, 3.89, 5.11 and 6.44 MeV from this reaction were detected using a BGO detector, that is a part of the DRAGON γ detection setup, which was collimated using 4 inch Pb blocks with a 5 mm gap. The detector was mounted on a movable table that could be controlled remotely. For each position we acquired data to obtain at least 1000 counts for the 6.44 MeV line in the γ spectrum. Figure 1 on the right gives the measured target profile. Although we expect the yield to fall off to zero at the extremes of the target profile, our measurements do not give such a result. Therefore, we plan for future measurements to understand this. For more details see the caption. The beam intensity was measured at regular intervals of 2 hrs. with a Faraday cup. This allows us to normalize the continuous measurement of the elastically scattered target particles detected in the two Si surface barrier detectors with precise collimators placed at 30° and 57° with respect to the beam. This provided us a way of monitoring the relative beam intensity during the course of the experiment [10]. Indeed utilizing, the target profile, the ^7Be observed in the DSSSD, the characteristics of the setup after the modifications mentioned above and the capture cross section from Ref. [5], we confirmed the composition of the gas mixture. Although these checks were done with uncertainties somewhat larger than 10%, this is a big step forward towards obtaining the S-factor in the medium energy range, since future tests as discussed below will lead us to better or similar accuracies compared to those from Ref. [3].

3. Discussion

In future we will perform more accurate measurements of the ^3He target density profile using better shielding for the BGO detectors and with an arrangement that will allow a bigger range of distances for the movement to get better definition at the falling parts of the profile. Geant simulations, using detailed geometry of the separator including any estimated misalignments of its components, particularly of the differentially pumped gas target, the capture reaction mechanisms and the resulting γ -ray angular distributions, are being developed to compare with our tests. The acceptance measurements will also be improved upon using an arrangement which will allow movements of an α source in all the three spatial directions scanning the entire gas target in a controlled manner. We also plan to carry out charge state distribution measurements using stable Be beam which will be crucial for the final analysis. As the rigidities of ^4He and ^7Be charge states are very different, online beam monitoring by collecting the unreacted beam on a Faraday cup at the far-side of the dipole magnet of the separator is also contemplated.

This ongoing TRIUMF work is complemented by our new Madrid measurements carried out using the activity method [11]. Figure 2 shows the existing data together with our new data

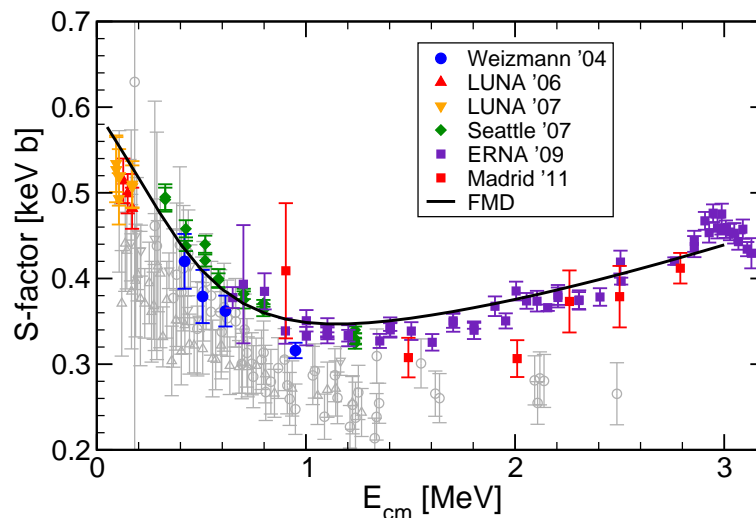


Figure 2. Existing data and new Madrid work (Madrid '11) compared with the calculations by T. Neff (FMD) [12]. Data are taken from Refs. [6] (Weizmann '04), [7, 8] (LUNA '06, LUNA '07), [9] (Seattle '07), [3] (ERNA '09). Old data (shown in grey, for details see e.g. Ref. [12]) also included data from Parker *et al.* at medium energies those do not agree with new data.

from this experiment. Although the uncertainties are large, our data clearly disagree with the energy dependence seen by Parker *et al.* [5], but agrees somewhat with that of Ref. [3]. The latter results could not be explained consistently by any of the theories when analyzed together with the other modern data [3]. This situation is somewhat changed after the work by Neff [12] that agrees with all of the modern data including that from the ERNA data and our new Madrid work. These fully microscopic calculations using a realistic effective interaction reproduce the nucleon-nucleon scattering data and do not require adjustment of any theoretical parameters including the absolute scale of the S-factor curve and gives an extrapolated value of 0.593 keVb for $S_{34}(0)$. However, we would like to stress that the current situation should be treated with a caution because these new calculations do not completely agree with the data for ${}^3\text{H}(\alpha,\gamma){}^7\text{Li}$ reaction. Since the data was obtained a few decades ago and has a scope for some improvement, future accurate measurements may change the scenario. Even though future calculations in different approaches will be helpful, there is still much work needed such as ours at TRIUMF on the experimental side to extract the shape of the S-factor curve in a model independent way from the data obtained in a wide energy range and using complementary techniques.

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