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Experimental study of ^{6}He Coulomb breakup as an indirect measurement of ^{4}He(2n,γ)^{6}He reaction rate for the astrophysical r-process

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Abstract. In this work, we report the measurement of elastic and Coulomb break-up channels in ^{6}He+^{208}Pb collisions at E_{lab} = 19.3 MeV, close to the Coulomb barrier of this system ∼ 19 MeV. In the context of the astrophysical r-process, the reaction ^{4}He(2n,γ)^{6}He has been proposed to be a key reaction in the path of synthesizing seed nuclei for the r-process, as ^{12}C, in an environment composed mainly of alpha particles and neutrons. Based on a theoretical approach for treating three body reactions by means of which its reaction rate can be inferred, our experimental approach aims to obtain an indirect measurement of the reaction rate of ^{4}He(2n,γ)^{6}He by measuring the Coulomb breakup of ^{6}He under the intense electric field produced by a ^{208}Pb target nucleus. The experiment was carried out at the TriSol facility operated in the Nuclear Science Laboratory of the University of Notre Dame, USA, which delivered a ^{6}He beam together with other contaminants. Particular care must be taken for the alpha particles produced in the production reaction.

1 Introduction

Compact binary mergers have attracted a lot of attention in recent years as the most likely site for the r-process (rapid neutron capture) nucleosynthesis [1, 2] and for the emission of gravitational waves [3, 4]. Recently, experimental evidence of nucleosynthesis of the r process in a double neutron-star merger identified as the origin of the gravitational wave source GW170817 has been reported [5, 6]. In this scenario, the r-process operates in both the material ejected dynamically during the merger [7] and in the outflows from the accretion disc surrounding the merger remnant [8]. The nuclear reactions that describe the evolution of such systems involve thousands of nuclides following a complex network of capture and decay processes [1, 9]. Here, the main parameter determining the feasibility of the astrophysical environment to produce heavy elements by the r-process is the neutron-to-seed ratio. In this context, three-body capture reactions such as ^{4}He(2n,γ)^{6}He are expected to be important in producing heavy seed nuclei, thus playing a relevant role [10, 11]. The temperatures at which alpha particles and heavier elements begin to assemble in these exotic environments range from 1 to 10 GK [7, 8].

The two-neutron capture reaction on alpha particles to produce ^{6}He allows us to bypass the instability gap at A = 5 in neutron-rich environments. Whether ^{4}He(α n,γ)^{9}Be or ^{4}He(2n,γ)^{6}He dominates for the broad range of astrophysical conditions expected in accretion disk ejecta [8, 12] is not clear. As shown in Fig. 1, the relative importance of the generation of ^{9}Be and ^{6}He in an environ-

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ment rich in ^{4}He and neutrons, depends on the temperature T and the concentration of alpha particles Y_α. However, the key factor determining the balance of these nuclei is the corresponding reaction rates. The production of ^{9}Be, a stable nucleus, can be studied through direct photodissociation experiments [13, 14] by assuming a sequential process. However, for exotic nuclei such as ^{6}He, this technique is not feasible. Several theoretical estimations of the ^{4}He(2n,γ)^{6}He reaction rate have been carried out [10, 11, 15], with noticeable differences between them.

The reaction rates for the ^{4}He(2n,γ)^{6}He process obtained from different models are presented in Fig. 2. Four results are depicted: i) two derived in Ref. [16] using two different three-body calculations of the B(E1) distribution [11, 15] (solid line and dotted line, respectively) ; ii) the corresponding reaction rate obtained by integrating the experimental $B(E1)$ [17] taking into account uncertainties (dot-dashed line); iii) and a sequential estimate assuming a dineutron capture [10] (dashed line). The need for new experimental data is apparent to solve the discrepancies between different models.

Experimental data on ^{6}He inclusive Coulomb breakup at small scattering angles can provide a robust estimation of the reaction rate, according to the work in ref. [16]. In the proposed experiment, charged reaction products resulting from ^{6}He+^{208}Pb collisions and emitted at very forward angles will be identified and their energy registered. Following the receipt in Ref. [16], the ratio of the alpha particles resulting from the breakdown of ^{6}He divided by the sum of it plus elastically scattered ^{6}He, will allow us to compute the reaction rate of interest for the r-process in a range of temperatures.

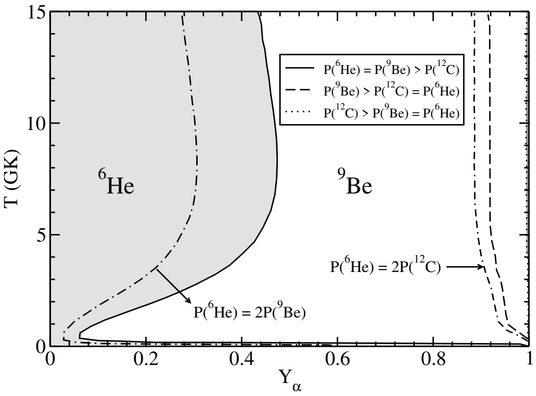

Figure 1. Relative production of ^{6}He, ^{9}Be and ^{12}C in a temperature versus Y_α phase diagram. Taken from [11],

2 Experiment

The experiment was performed at the Nuclear Science Laboratory (NSC) of the University of Notre Dame. The radioactive facility at NSC, formerly operated with two superconducting solenoids (named TwinSol), was recently upgraded with the addition of a third solenoid [18] and it operates today under the name TriSol.

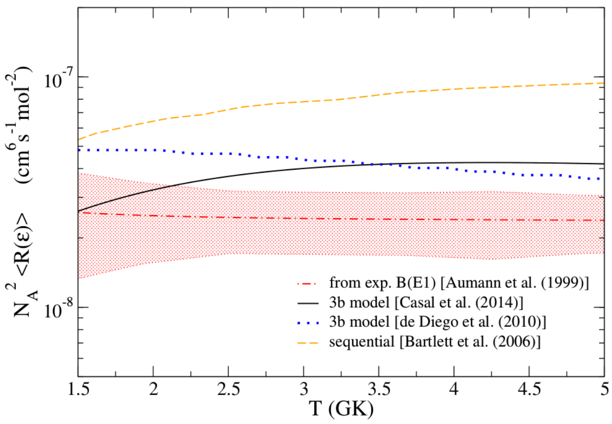

Figure 2. Predictions of the reaction rate of ^{4}He(2n,γ)^{6}He from different models. See the text for details.

^{6}He was produced via the reaction ^{7}Li(^{2}H,^{3}He)^{6}He. A 2.5-cm-long gas cell with ^{2}H at ∼ 950 Torr was used as production target while a primary beam of ^{7}Li at a total kinetic energy of 29.48 MeV was produced by the Notre Dame FN tandem accelerator. The intensity of the produced secondary ^{6}He beam was $< 10^4$ pps. The ^{6}He secondary beam was collected and transported via the TriSol solenoid system to a 1.5 mg/cm^2 -thick ^{208}Pb secondary target with a total kinetic energy of 19.3 MeV. The enriched ^{208}Pb target was produced by members of the collaboration in the target laboratory of the University of Lisbon-LIP and it was analysed in the C2TN-Lisbon facility, with particular detail after the experiment in the microprobe line.

The beam had ^{4}He contaminants, appart from ^{3}He (production reaction), originated in different reactions: i) ^{7}Li(^{2}H,^{4}He)^{5}He (and those resulting from the decay of ^{5}He); ii) breakup of ^{7}Li in the tantalum window of the gas cell. During the preparation of the beam, the elements of the beam optics were adjusted in order to reduce as much as possible the ^{4}He contamination, as it is the goal of the experiment to detect alpha particles resulting from the break up of ^{6}He. Additional key issues were to reduce the size of the beam spot on the reaction target and avoid the beam to impinge in the frame of the ^{208}Pb self sustained target, which is not trivial due to the characteristics of the beam line and the kinematics of the reactions taking place in the production target. A monitor particle telescope was placed in the moveable ladder where the reaction target was fixed (see Fig. 3). It was used with the purpose of analysing the beam, identifying the different species and registering its energy.

It can be observed a "blank frame" in Fig. 3, which was used for background subtraction purposes, as will be explained below.

The DAQ, electronics, and detectors used in the experiment were provided by the laboratory. The detection system consists of six particle telescopes arranged as shown in Fig. 4, each of them composed of a 70 μm and a 1000 μm thick YY1 type silicon detector manufactured by the

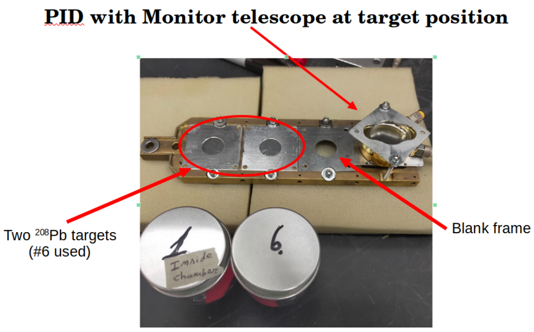

Figure 3. Movable structure hosting different ^{208}Pb targets and the particle telescope on top.

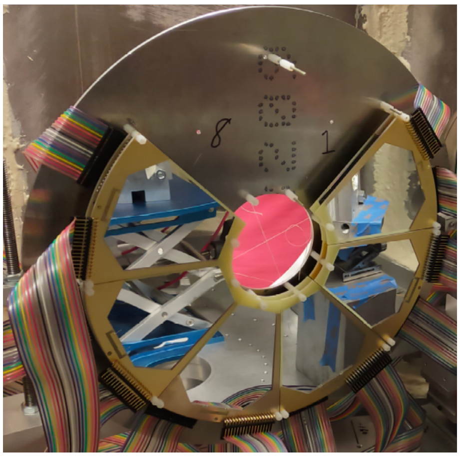

Figure 4. Arrangement of particle telescopes. Every sector is divided in 16 rings centered in the nominal beam axis, covering laboratory angles from 10 to 26 degrees.

Micron company, radially divided into 16 strips, which allows measurements at 16 observation angles.

3 Analysis

Systematic measurements of six hours every night with the blank target were made in order to subtract beam-induced scattering in the frame. In the subtraction procedure, the dead time of the DAQ and the intensity of the beam will be taken into account. A representative example of frame scattering is shown in Fig. 5 The observed two contours correspond to ^{4}He and ^{6}He scattering.

The energy calibration of the detectors was made after the experiment using two radioactive sources of ^{228}Th. The use of such isotope allows for a robust energy calibration of every detector in the range of ~ 5 to ~ 9 MeV. As it will be explained in the text later on, according to our calculations the expected energy range of the breakup alpha fragments will be around 13 MeV. In what follows we will try to address the problems encountered in this analysis where the goals are: The unambiguous identification of the alpha fragments resulting from the breakup of ^{6}He but also the ^{6}He elastic scattering to be used for normalization purposes.

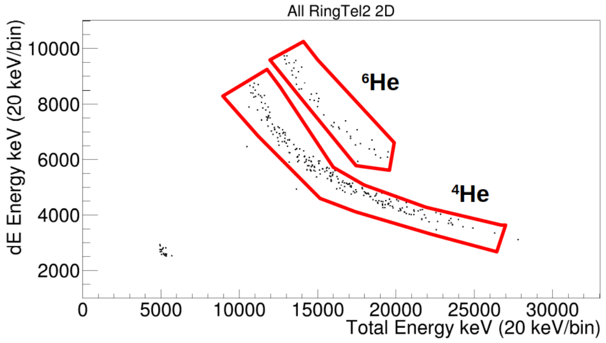

Figure 5. Representative spectra of ring at observation angle of 13.2 degrees for the measurement with the "blank target".

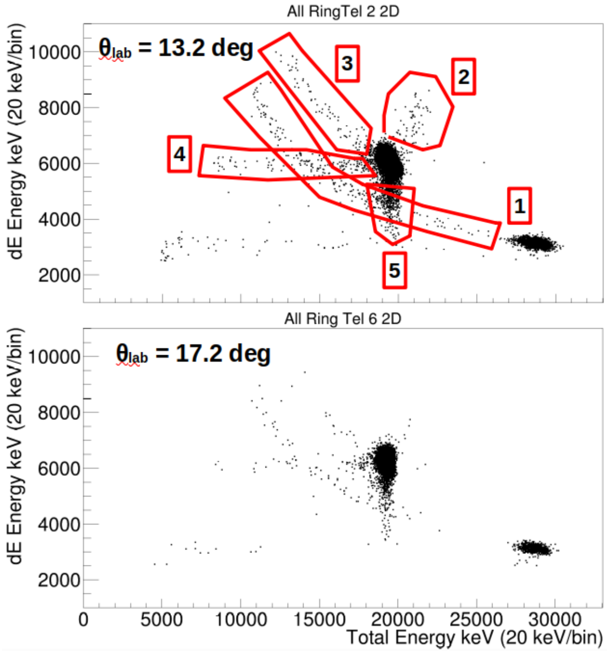

Figure 6. Representative spectra of rings at observation angles of 13.2 and 17.2 degrees for the measurement with the ^{208}Pb target. The two intense spots are due to elastically scattered ^{6}He (~ 19 MeV) and ^{4}He (~ 29 MeV). See text for explanations of the various contours.

In Fig. 6 we show two illustrative spectra of the particle telescopes, at different laboratory angles. In the spectrum on top, five windows are depicted, each of them enclosing events of different characteristics. Window 1 encloses the band of alpha particles both due to ^{6}He breakup but also due to target frame scattering. The black intense spot at ~ 29 MeV is due to spurious alpha particles in the beam, elastically scattered by ^{208}Pb. The same effect relative to ^{6}He is reflected in events enclosed by window 3. In Fig. 5 those effects can be seen in the spectrum corresponding to the ring at 13.2 degrees for the measurement with the blank target. Window 2 includes signals of elastically scattered ^{6}He affected by pile-up. The pile-up effect becomes less important as the laboratory angle associated with the telescope increases, as can be seen in the spectrum at the bottom. The window 5 includes elastically scattered

^{6}He events affected by channeling. The horizontal band located at ∼ 6 MeV, window 4, corresponds to elastically scattered ^{6}He which produced partial charge collection in the thick detector of the telescope. This set of events represents an additional difficulty in our analysis. Since the total kinetic energy of the ^{6}He is 19.2 MeV, according to our calculations the alpha particles produced in a quasi-elastic breakup process due to Coulomb breakup are expected to carry 4/6 of the energy of ^{6}He, that is, the energy range of those alpha particles is ∼ 13 MeV.

4 Summary and future work

In this work, a first report of a measurement of ^{6}He+^{208}Pb collisions has been presented, using the ^{6}He beam produced by the NSL laboratory at the University of Notre Dame. The measurement was proposed by an international collaboration, in view of the interest of the reaction within the framework of the stellar nucleosynthesis and the r-process. Prior to carrying out the measurement, intense work was done to mainly minimize alpha particle impurities, and reduce the beam size in the reaction target. Despite this, during the measurement a non-negligible presence of alpha particles in the beam was verified. Once all the data files have been converted and energy calibrations have been performed, we are studying the charged particle telescope spectra. We are analysing aspects that will have to be addressed in order to unambiguously identify the events of interest. These events are those related to the alpha particles generated as consequence of Coulomb breakup processes suffered by ^{6}He and those related to elastic scattering of ^{6}He on ^{208}Pb.

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