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Study of the $^7\mathrm{Be}(\alpha,\gamma)^{11}\mathrm{C}$ reaction with DRAGON for νp–process nucleosynthesis

Athanasios Psaltis, A. A. Chen, L. Kroll, J. Liang

Department of Physics and Astronomy, McMaster University, Hamilton, ON L8S 4M1, Canada

E-mail: `psaltisa@mcmaster.ca`

D. S. Connolly, B. Davids, D. A. Hutcheon, A. Lennarz, C. Ruiz, M. Williams

TRIUMF, 4004 Wesbrook Mall, Vancouver, British Columbia V6T 2A3, Canada

U. Greife, J. Karpesky, M. Lovely

Department of Physics, Colorado School of Mines, Golden, CO 80401, USA

C. Brune, S. N. Paneru, R. Giri

Department of Physics and Astronomy, Ohio University, Athens, OH 45701, USA

M. Luo, G. Tenkila

Department of Physics and Astronomy, University of British Columbia, Vancouver, British Columbia V6T 1Z4, Canada

J. Fallis

North Island College, 2300 Ryan Rd, Courtenay, BC V9N 8N6, Canada

C. Marshall

North Carolina State University, Department of Physics, Raleigh, NC 27695, U.S.A.
Triangle Universities Nuclear Laboratory, Duke University, Durham, NC 27708, U.S.A.

A. C. Shotter

School of Physics & Astronomy, University of Edinburgh, Edinburgh, UK

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Abstract. The production of the p–nuclei is one of the unsolved puzzles in nuclear astrophysics. A possible mechanism is the nucleosynthesis in the neutrino–driven winds of core–collapse supernovae (νp–process), but it carries uncertainties, mostly in the supernova dynamics and the nuclear physics input. The pp-chain breakout

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reaction ^{7}Be$(\alpha, \gamma)^{11}$C, which occurs prior to the supernova explosion, was identified as an important link which can influence the nuclear flow of the νp–process and the final abundances of the p-nuclei. Nevertheless, its reaction rate is poorly known over the relevant energy range (T= 1.5-3 GK). To improve the ^{7}Be$(\alpha, \gamma)^{11}$C rate for νp–process nucleosynthesis temperatures, the first measurement of the strengths of two important resonances with unknown strength was recently performed at TRIUMF. A radioactive ^{7}Be beam ($t_{1/2} = 53.24$ d) beam and the DRAGON recoil separator were used. The experimental details and preliminary results for the resonance strengths will be discussed.

1. Introduction

In astrophysical environments where ejected hot, proton rich matter interacts with a strong neutrino flux, such as the neutrino–driven winds in core–collapse supernovae, the νp-process operates synthesizing heavy elements with $A > 64$ [1, 2, 3].

The aforementioned nucleosynthesis scenario exhibits many uncertainties that arise mainly from the hydrodynamic models (*e.g.*, neutrino luminosity, L_ν, and electron fraction Y_e) and the nuclear physics input (*e.g.*, reaction rates and nuclear masses) [2, 3]. Wanajo *et al.* identified the ^{7}Be$(\alpha, \gamma)^{11}$C reaction, which acts as a breakout from the hot pp-chains prior to the onset of the νp–process, as an important reaction that affects the final abundances in the $90 < A < 110$ region [2].

In the relevant temperature region, $T_9 = 1.5 - 3$, there are five resonances that can affect the reaction rate, but only two of them have experimentally determined strengths (E_r= 561 & 876 keV) [4, 5, 6]. To improve our knowledge of the ^{7}Be$(\alpha, \gamma)^{11}$C reaction and its impact on the νp–process, a study of the resonances with unknown strengths in the relevant energy region is imperative.

2. Experimental details

The ^{7}Be$(\alpha, \gamma)^{11}$C reaction was studied in inverse kinematics at TRIUMF using the DRAGON recoil separator [7]. DRAGON has four main components, (a) a windowless, differentially pumped, recirculating gas target that was filled with helium gas, (b) a γ ray detection system with 30 BGO detectors that surround the gas target, (c) the main separator which comprises two magnetic (charge selection) and two electrostatic (mass selection) dipoles and (c) the focal plane detection system, which consists of a pair of MCP detectors and a Double–Sided Silicon Strip Detector (DSSSD)‡.

Studying the ^{7}Be$(\alpha, \gamma)^{11}$C reaction in inverse kinematics using a recoil separator is a challenging measurement, since the maximum momentum cone of the recoils ($\theta_{max} \sim$ 43 mrad) far exceeds its geometric acceptance ($\theta_{DRAGON} \sim 21$ mrad). Therefore, we performed a complete simulation of the BGO array and the separator using `GEANT3`

‡ Depending on the reaction studied, an Ionization Chamber or a hybrid DSSSD/Ionization Chamber detector can also be used as the focal plane detector.

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to perform the data analysis. In addition, we measured a known resonance of the ^{6}Li$(\alpha, \gamma)^{10}$B reaction whose momentum cone also exceeds DRAGON's acceptance. Our result is in very good agreement with the literature value, demonstrating that DRAGON can measure resonance strengths of astrophysically important reactions with momentum cones that exceed its geometric acceptance [8].

The radioactive ^{7}Be ion beam ($t_{1/2} = 53.4$ d) was produced using the ISOL technique, with 55 μA protons from TRIUMF's cyclotron impinging on a thick ZrC target. The A = 7 isobars (mainly ^{7}Be and ^{7}Li) were extracted from the target using TRIUMF's Resonant Ionization Laser Ion Source (TRILIS) [9]. The beam was accelerated through the ISAC-I linear accelerators (RFQ & DTL) to average energies of 442 and 462 keV/u, corresponding to the $E_r = 1110$ keV and $E_r = 1155$ keV resonance respectively. The aforementioned energies were selected to account for the energy loss in the gas target (the measured stopping power was $\epsilon = (4.07 \pm 0.15) \times 10^{-14}$ eV/cm^2 atom) and place the resonance in its center. A carbon foil upstream of the DTL stripped the beam to the 4^+ charge state to completely eliminate the isobaric contaminant (^{7}Li). Finally, ^{7}Be^{4+} was delivered to the DRAGON windowless gas target (P= 8 T, $n = 3.85 \times 10^{18}$ cm^{-2}) at a mean intensity of $I \sim 2 \times 10^8$ pps.

The most intense recoil charge state (q = 2^+) was tuned through DRAGON and the recoils were detected using the DSSSD. To better identify the recoils of interest, we employed two time–of–flight signals using 1) a signal in the BGO array (separator) and 2) a signal in one of the Micro-Channel Plate (MCP) detectors (local) as the start and a trigger at the DSSSD as the end signal (see Section 3).

3. Preliminary Results

Two resonances, $E_r = 1110$ keV and $E_r = 1155$ keV, with unknown strengths were studied in the latest measurement. Given the much more intense radioactive ion beam current and purity compared to the ones reported in Ref. [10], we observed clear recoil signals for the aforementioned resonances. Figure 1a shows a separator time–of–flight spectrum and Figure 1b shows a composite separator/local time–of–flight 2D–spectrum. We can identify a clean locus of recoil events, without background, due to the high beam suppression of DRAGON for (α, γ) reactions.

4. Conclusions and Future Goals

In the framework of the present work, we report preliminary results of the most recent measurement of the ^{7}Be$(\alpha, \gamma)^{11}$C reaction, at energies relevant to νp–process nucleosynthesis using the DRAGON recoil separator. Clear recoil signals were observed for two resonances, $E_r = 1110$ and 1155 keV.

In the near future, with the remaining ^{7}Be beamtime, we will attempt to probe the existence of the $E_r = 1356$ keV resonance [6] and re–visit the important $E_r = 876$ keV resonance [4].
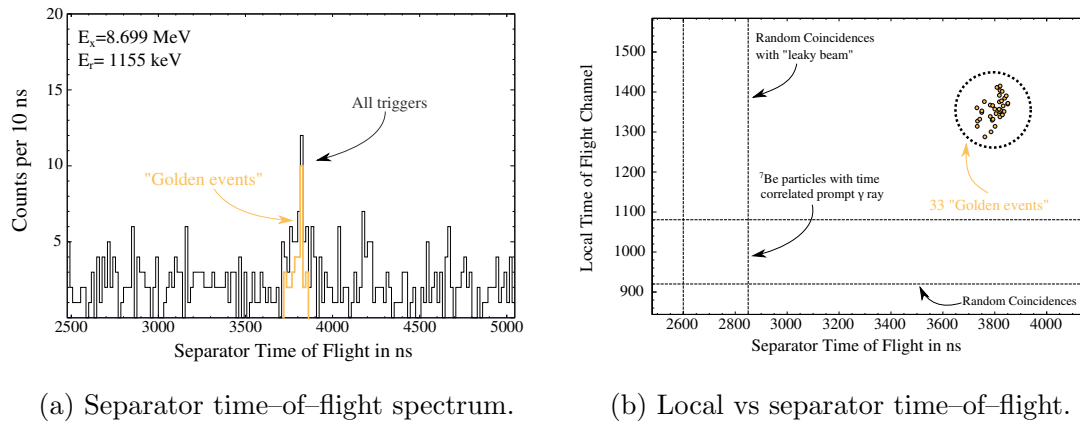
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(a) Separator time–of–flight spectrum.   (b) Local vs separator time–of–flight.

Figure 1: Preliminary particle identification plots for the E_r = 1155 keV resonance. The "golden events" represent the recoils that satisfy software cuts on the separator and local time–of–flight, the energy deposited on the DSSSD and the energy deposited by the associated γ ray in the BGO array.

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