Chapter 81
Radiative Alpha Capture on ^{7}Be with DRAGON at Energies Relevant to the νp-Process

A. Psaltis, A. A. Chen, D. S. Connolly, B. Davids, N. Esker, G. Gilardy, Uwe Greife, W. Huang, D. A. Hutcheon, J. Karpesky, A. Lennarz, J. Liang, M. Lovely, S. N. Paneru, R. Giri, C. Ruiz, G. Tenkila, A. Wen and M. Williams

Abstract The origin of the p-nuclei, has been a long-standing puzzle in nuclear astrophysics. The νp-process is a candidate for the production of the light p-nuclei, but it presents high sensitivity to both supernova dynamics and nuclear physics. It has been recently shown that the breakout from pp-chains through the ^{7}Be$(\alpha, \gamma)^{11}$C reaction, which occurs prior to νp-process, can significantly influence the reaction flow, and subsequently the production of p-nuclei in the $90 < A < 110$ region.

A. Psaltis (✉) · A. A. Chen · J. Liang
Department of Physics and Astronomy, McMaster University,
Hamilton, Ontario L8S 4M1, Canada
e-mail: psaltisa@mcmaster.ca

D. S. Connolly · B. Davids · N. Esker · W. Huang ·
D. A. Hutcheon · A. Lennarz · C. Ruiz · M. Williams
TRIUMF, 4004 Wesbrook Mall, Vancouver, British Columbia V6T 2A3, Canada

G. Gilardy
Department of Physics, Joint Institute for Nuclear Astrophysics,
University of Notre Dame, Notre Dame, IN 46556, USA

Centre d'Études Nucléaires de Bordeaux Gradignan,
UMR 5797 CNRS/IN2P3 - Université de Bordeaux, 19 Chemin du Solarium,
CS 10120, Gradignan 33175, France

U. Greife · J. Karpesky · M. Lovely
Department of Physics, Colorado School of Mines, Golden, CO 80401, USA

W. Huang
Department of Physics, University of Northern British Columbia,
Prince George, BC V2N 4Z9, Canada

G. Tenkila · A. Wen
Department of Physics and Astronomy, University of British Columbia,
Vancouver, British Columbia V6T 1Z4, Canada

S. N. Paneru · R. Giri
Department of Physics and Astronomy, Ohio University, Athens, OH 45701, USA

M. Williams
Department of Physics, University of York, Heslington, York YO10 5DD, UK

A. Formicola et al. (eds.), *Nuclei in the Cosmos XV*, Springer
Proceedings in Physics 219, https://doi.org/10.1007/978-3-030-13876-9_81

Nevertheless, this reaction has not been studied well yet in the relevant temperature range - T = 1.5–3 GK. To that end, the first direct study of important resonances of the $^{7}\mathrm{Be}(\alpha,\gamma)^{11}\mathrm{C}$ reaction with unknown strengths using DRAGON was recently performed at TRIUMF. The reaction was studied in inverse kinematics using a radioactive ^{7}Be ($t_{1/2}$ = 53.24 d) beam provided by ISAC-I and two resonances above the ^{11}C α-separation energy - $Q_\alpha = 7543.62$ keV - were measured. The experimental details, in particular how the recoil transmission and BGO efficiencies were accounted for considering the large cone angle for this reaction, will be presented and discussed alongside some preliminary results.

81.1 Introduction

The nucleosynthesis of heavy elements in the neutrino-driven wind of core-collapse supernovae has gained a lot of attention in recent years. Assuming that the ejecta of the supernova are proton-rich, as has been shown in simulations [1], the νp-process operates synthesizing the nuclei with A $>$ 64 [2].

However, the particular scenario appears to be very sensitive to both supernova dynamics and nuclear physics input. In a recent study of the uncertainties of the aforementioned factors, Wanajo et al. [3] found that the breakout from the hot *pp*-chains through the $^{7}\mathrm{Be}(\alpha,\gamma)^{11}\mathrm{C}$, which occurs prior to the onset of the νp-process, influences the reaction flow and eventually the final abundances of nuclei in the $90 < \mathrm{A} < 110$ region.

Nevertheless, most of the reactions related to breakout processes have not yet been studied well, since they involve unstable nuclei. More specifically, for $^{7}\mathrm{Be}(\alpha,\gamma)^{11}\mathrm{C}$, there are five known resonances in the relevant energy window for T = 1.5–3 GK that regulate the astrophysical reaction rate but only two of them have known strengths [4–6]. In order to improve the reaction rate at energies relevant to the νp-process, a new direct measurement of $^{7}\mathrm{Be}(\alpha,\gamma)^{11}\mathrm{C}$, focusing on resonances with unknown strengths was recently performed at TRIUMF using the DRAGON recoil separator.

81.2 Experimental Details

The DRAGON recoil separator [7] has four main components: (a) the windowless, differentially pumped, recirculated gas target, (b) the γ-ray detector array consisting of 30 BGO detectors, (c) the electromagnetic separator and (d) the recoil detection system.

The $^{7}\mathrm{Be}(\alpha,\gamma)^{11}\mathrm{C}$ reaction also poses a great challenge for DRAGON as far as its acceptance in the light mass regime is concerned. The maximum momentum cone of the recoils far exceeds its acceptance and for this reason, simulations using `GEANT3` were performed to investigate the transmission of the recoils as well as the BGO array efficiency. Since DRAGON measures reaction yields, resonance strengths are extracted by:

$$\omega\gamma = \frac{2Y\epsilon}{\lambda_{cm}^2}\frac{m_{^4\mathrm{He}}}{m_{^4\mathrm{He}} + m_{^7\mathrm{Be}}} \;\&\; Y = \frac{N_{recoils}}{N_{beam} \times \eta_{BGO} \times \eta_{sep} \times \eta_{DSSSD} \times f_q} \tag{81.1}$$

Where ϵ is the target stopping power and f_q is the charge state distribution of the recoils The aforementioned simulations provide the efficiencies of the separator and the BGO array (η_{sep} & η_{BGO}).

The reaction was studied in inverse kinematics using a radioactive ^{7}Be beam ($t_{1/2}$ = 53.24 d) provided by ISAC impinging on the ^{4}He filled gas target. The most intense charge state of ^{11}C (q = 2^+) was tuned through the separator and the recoils were detected using a double-sided silicon strip detector (DSSSD). To further increase the beam suppression, identification of real events was carried out using the BGO array signals in coincidence with the DSSSD.

81.3 Preliminary Results

Two resonances corresponding to states of ^{11}C were studied (E_x = 8.654 MeV & E_x = 8.699 MeV). Unfortunately, the radioactive ion beam was contaminated by the isobar ^{7}Li, nevertheless some encouraging results were obtained. Figure 81.1 Left shows a clean separator time-of-fight spectrum, which however suffers from low statistics. The ^{7}Be content in the beam was extracted using TRIUMF's Resonant Ionization Laser Ion Source (TRILIS) [8] and was around 10^7 pps during the experiment.

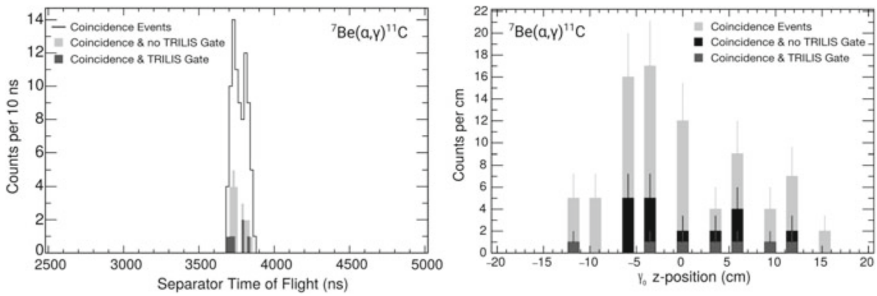

Fig. 81.1 Preliminary results from the resonance at E_x = 8.699 MeV. (Left) Separator time-of-flight, time a recoil takes to travel through DRAGON which starts by a γ-ray signal in the BGO array and stops by a hit in the DSSSD & (Right) BGO γ-ray hit pattern, γ-ray signals in the BGO array versus their position along the beam axis with respect to the target center. Coincidence events are gated only on the Separator time-of-flight and include all DSSSD triggers, while the other two include DSSSD, BGO energy and TRILIS signal cuts

81.4 Conclusion and Future Goals

A first attempt to study the astrophysically important $^{7}Be(\alpha, \gamma)^{11}C$ reaction was recently performed using the DRAGON recoil separator. Given the challenging nature of the reaction, detailed simulations are necessary to obtain reliable resonance strengths and this first measurement can be used as a benchmark to further improve them. A new measurement of the reaction with a more intense and pure radioactive ^{7}Be beam is expected in the near future.

References

1. S. Wanajo et al., Astrophys. J. **852**, 40 (2018). http://iopscience.iop.org/article/10.3847/1538-4357/aa9d97/meta
2. C. Fröhlich et al., Phys. Rev. Lett. **96**, 142502 (2006). https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.96.142502
3. S. Wanajo, H.-T. Janka, S. Kubono, Astrophys. J. **729**, 46 (2011). http://iopscience.iop.org/article/10.1088/0004-637X/729/1/46/meta
4. G. Hardie et al., Phys. Rev. C **29**, 1199 (1984). https://journals.aps.org/prc/abstract/10.1103/PhysRevC.29.1199
5. M. Wiescher et al., Phys. Rev. C **28**, 1431 (1983). https://journals.aps.org/prc/abstract/10.1103/PhysRevC.28.1431
6. H. Yamaguchi et al., Phys. Rev. C **87**, 034303 (2013). https://journals.aps.org/prc/abstract/10.1103/PhysRevC.87.034303
7. D.A. Hutcheon et al., Nucl. Instrum. Meth. Phys. Res. A **498**, 190 (2003). https://www.sciencedirect.com/science/article/pii/S0168900202019903
8. J. Lassen et al., Hyperfine Interactions **162**, 69 (2005). https://link.springer.com/article/10.1007/s10751-005-9212-2