Aluminum-26 Nucleosynthesis With Proton-Rich Exotic Beams

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INTRODUCTION

The origin of galactic ^{26}Al is a long-standing question in nuclear astrophysics, with important implications for galactic chemical evolution and stellar nucleosynthesis. The gamma ray line at 1.809 MeV – from the β^+ decay of the ^{26g}Al to the first excited state in ^{26}Mg – has been decidedly observed by orbiting telescopes such as COMPTEL [1], RHESSI [2], and INTEGRAL [3]. In determining the stellar source(s) of ^{26}Al, the global analyses of these gamma-emission maps has been complemented with a deeper understanding of specific nucleosynthesis sites with regard to their ^{26}Al production. The former indicate that Type II supernovae and Wolf-Rayet stars could be the dominant contributors of ^{26}Al to the measured gamma ray map [4], while present models of novae and AGB stars also suggest significant ^{26}Al production.

The present work focuses in particular on ^{26}Al nucleosynthesis in the context of explosive stellar environments. In novae, for example, the production of ^{26}Al happens in the Mg-Al (hydrogen-burning) cycles [5]. The ^{26}Al(p,γ)^{27}Si and ^{25}Al(p,γ)^{26}Si reactions are two processes in this cycle that strongly affect the ^{26}Al yield. The first has the obviously important role of depleting the yield of ^{26g}Al. The second reaction's impact is more subtle: the ^{26}Si produced in the reaction decays to ^{26}Al, but through its isomeric state (^{26m}Al) instead of its ground state, thus effectively reducing the flux of 1.8 MeV γ-rays. The impact of these reactions has been corroborated in a study that investigated the influence of rate uncertainties on nova nucleosynthesis [6]. (Another important reaction not discussed in my talk is the ^{26m}Al(p,γ)^{27}Si reaction.)

Both rates are dominated by narrow isolated resonances in the compound nuclei ^{27}Si and ^{26}Si, whose resonance energies and strengths need to be known. The ideal scenario is one in which a direct measurement of the reaction is performed. Since ^{25}Al and ^{26}Al are unstable, radioactive ion beams of high intensity are required, while lower intensities are useful in indirect approaches, such as elastic scattering or transfer reactions, to determine level parameters. In my talk, I surveyed some experiments that our McMaster group has carried out along these lines. For example, for the ^{25}Al(p,γ)^{26}Si reaction, a direct measurement remains a dream in the horizon (true also for the ^{26m}Al(p,γ)^{27}Si, and so indirect approaches have been explored [7]. In the following, in the interest of space and relevance to EURISOL, I will focus on a direct measurement of the ^{26}Al(p,γ)^{27}Si reaction with a ^{26}Al beam at TRIUMF-ISAC.

MEASUREMENT OF ^{26}Al(p,γ)^{27}Si WITH DRAGON

The dominant contribution to the ^{26}Al(p,γ)^{27}Si reaction rate at T ~ 0.1-0.4 GK is from a resonance located at excitation energy $E_x(^{27}Si)$ = 7652 keV and with resonance energy E_r = 188 keV. The uncertainty in the rate at these temperatures was determined largely by the adopted range for the resonance strength of this state: $\omega\gamma$ = 64 μeV, with upper and lower limits of 290 μeV and 0.0099 μeV, respectively [8]. This strength had been previously measured to be 55 ± 9 μeV in an experiment with a radioactive ^{26}Al target, but the results remained unpublished [9].

In view of the wide range of uncertainty in the strength of the E_r = 188 keV resonance, the goal of our experiment was to perform a measurement of this strength, taking advantage of high-intensity ^{26}Al beams from the TRIUMF-ISAC facility and the DRAGON recoil separator. The latter was built specifically for measurements of radiative capture reactions of importance to nuclear astrophysics [10].

The ^{26}Al beam was produced with the Isotope Separation On-Line (ISOL) method, by impinging 70 μA of 500 MeV protons from the TRIUMF cyclotron onto a high-power SiC target. The long-lived ^{26}Al diffuses out of the target, and a laser ionization system (TRILIS) was utilized to improve the ionization selectivity and the beam intensity. The beam was accelerated through the ISAC RFQ-LINAC accelerator. For measurements on resonance, the beam energy was 201 keV/u with intensities of about 5×10^9 particles per second. The beam energy spread was ~ 1% FWHM.

The beam ions impinged on a windowless H_2 gas target, which is the first component of the DRAGON recoil (Figure 1). The beam energy and the target pressure are selected to ensure that the resonant reactions occur at the center of the gas target. The beam intensity is monitored by a silicon detector, inside the gas of the target, which detects protons from ^{26}Al + p elastic scattering. The target is surrounded by an array of BGO detectors, which detect gamma rays from the (p,γ) reactions. The ^{27}Si recoils, along with beam ions that did not react in the gas, emerge from the target with an equilibrium distribution of charge states and enter the electromagnetic separator, whose main purpose is the separation between recoils and beam ions at the level of about one part in $10^{9\text{-}10}$.

The separator comprises two stages, each consisting of a magnetic dipole and an electrostatic dipole. One charge state (4^+) of the Si recoils and beam ions is selected after the first magnetic dipole. Most of this remaining beam is stopped at a set of slits immediately after the first electrostatic dipole. The second stage serves to remove additional beam ions that passed through the first stage. At the final focus of the separator, a double-sided silicon strip detector was used to measure the energies of the ^{27}Si recoils and of any remaining "leaky" beam ions. The latter are further suppressed by a coincidence requirement between gamma-ray and recoil detections. The time-of-flight through the separator (21m in length) for the recoils is also measured.

The right panel in Fig. 1 shows a two-dimensional histogram of time-of-flight versus energy for coincident events, in which a locus corresponding to the ^{27}Si recoils is seen. More than 100 recoil-gamma coincidence events for the E_r = 188 keV resonance were observed in the experiment. The main results of this study [11] are: (1) a resonance energy E_r = 184 ± 1 keV, which represents a small change, but is still

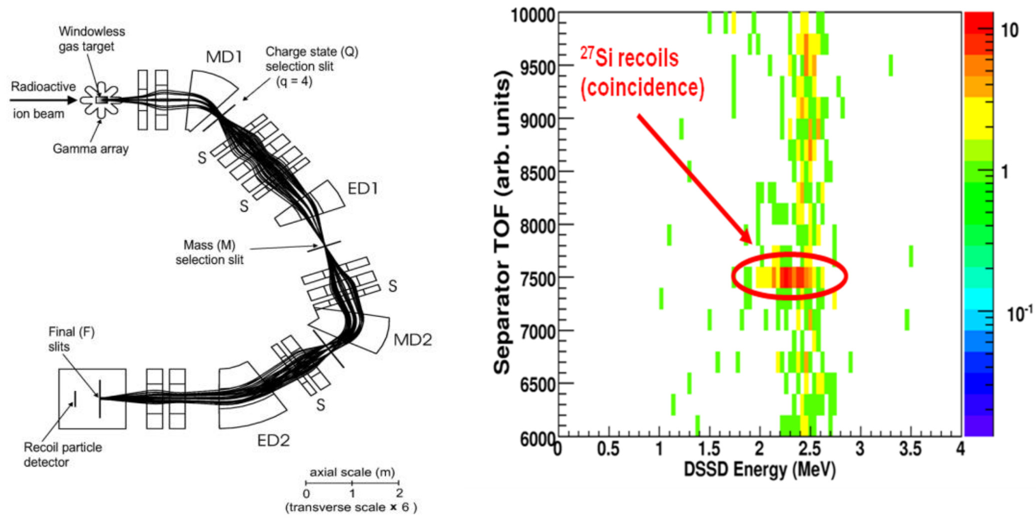

FIGURE 1. Left panel: Schematic of the DRAGON recoil separator. Right panel: Two-dimensional histogram of time-of-flight (TOF) vs. energy. The highlighted region circumscribes ^{27}Si events.

significant for the reaction rate; (2) a (p,γ) strength $\omega\gamma = 35 \pm 7$ μeV, which is only 64% of the unpublished value of Ref. [9] and demonstrates DRAGON's ability to measure weak strengths to 20%; and (3) a re-evaluated thermonuclear ^{26}Al(p,γ)^{27}Si reaction rate, resulting in more reliable estimates for ^{26}Al synthesis in classical novae.

CONNECTION TO EURISOL

The ^{26}Al(p,γ)^{27}Si reaction is the easiest to study, given the long half-life of ground-state ^{26}Al. For the ^{25}Al(p,γ)^{26}Si and ^{26m}Al(p,γ)^{27}Si reactions, however, achieving the required beam intensities of ^{25}Al and ^{26m}Al has presented significant challenges. EURISOL can contribute by (1) creating a dedicated program for the development of intense beams of these short-lived Aluminum isotopes, drawing on past experience at ISAC REX-ISOLDE; and by (2) including a recoil mass separator, similar to DRAGON (ISAC), in its suite of experimental facilities.

REFERENCES

1. R. Diehl et al., *Astron. and Astrophys*. **97** 181 (1993).
2. D. M. Smith, *New Ast. Rev*. **48** 87 (2004).
3. R. Diehl et al., *Nature* **439** 45 (2006).
4. J. Knödlseder, *Astrophys. J*. **510** 915 (1999).
5. J. José, A. Coc, and M. Hernanz, *Ap. J*. **520** 347 (1999).
6. C. Iliadis et al., *Ap. J. Suppl*. **142** 105 (2002).
7. J. Chen et al., *Nucl. Phys*. A **834** 667c (2010).
8. C. Angulo et al., *Nucl. Phys*. A **656** 3 (1999).
9. R. B. Vogelaar, Ph.D. Thesis, California Institute of Technology (1989).
10. D. A. Hutcheon et al., *Nucl. Inst. Meth*. A **498** 190 (2003).
11. C. Ruiz et al., *Phys. Rev. Lett*. **96** 252501 (2006).