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Study on ^{26m}Al(p, γ) Reaction at the SNe Temperature

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The γ-ray observatory has been detecting β-delayed γ-rays from ^{26}Al for more than two decades. The half life of ^{26}Al is 7.75×10^5 years and is sufficiently short on the scale of the galactic evolution but long enough to disperse in the interstellar medium. Hence, the abundance of this nuclide is one of the candidates to understand nucleosynthesys in massive environments such as Wolf-Rayet stars, AGB stars and supernovae. However, the abundance of ^{26}Al in the interstellar medium from the observed flux has been inconsistent with nuclear reaction network calculations. One of the clues to solve this discrepancy is its isomer, ^{26m}Al. Because its spin-parity is 0^+, it directly decays to the ground state of ^{26}Mg without emitting γ-rays. Despite the difference of the spin-parity between the ground state and the isomeric state, they could be under thermal equilibrium in high temperature environments, so that there is a possibility that the calculated flux sinks below the network calculations. To complement one of the destructive reactions of ^{26m}Al, the experiment of the resonant elastic scattering of the ^{26m}Al(p, γ) reaction with the cocktail ^{26g,m}Al RI beam was conducted.

1. Introduction

The galactic abundance of the ^{26}Al radionuclide provides a unique window to the ongoing nucleosynthesis in the Milky Way. ^{26}Al is known as the first detected specific radioactivity that decays along with its characteristic β-delayed γ-ray, and it has been directly observed by astronomical telescopes [1]. Despite a lot of effort over the past three decades, particular sites of galactic ^{26}Al are still poorly understood, and there is the discrepancy between observations and theories on estimation of its abundance.

This problem is complicated by its isomer, ^{26m}Al that has a low spin $J^\pi = 0^+$ and a short lifetime $T_{1/2} = 6.35$ s, compared with $T_{1/2} = 0.72$ Myr and $J^\pi = 5^+$ of the ground state, and thus it directly decays to a stable state of ^{26}Mg bypassing emitting γ-rays. It has been proposed that the ground state of ^{26}Al can communicate with the isomeric state through thermal excitations under high temperature environments ($T_9 > 0.3$) such as core-collapse supernovae [2].

Though the isomeric state of ^{26}Al can be a key to solve the discrepancy, only a little experimental information on the isomer has been reported and theoretical calculations based on Hauser-Feshbach theory are used in the reaction network calculations so far. For this reason, measuring nuclear properties and cross-sections of ^{26m}Al is important for inputs to calculations of stellar reaction rates.

2. Experiment of ^{26m}Al(p, γ) reaction

The experiment was conducted at the CNS Radio Isotope Beam (CRIB) separator, which is located at RIBF of the RIKEN Nishina center. CRIB is characterized by its low energy, typically less than 10 MeV/u, and high intensity of secondary beam, typically around $10^4 - 10^8$ pps. CRIB has been producing low- and medium-mass radioactive ion beams near the valley of β-stability.

2.1 RI beam production

The primary beam of ^{26}Mg^{8+} with a radio frequency of 65 MHz, a kinetic energy of 172.9 MeV (6.65 MeV/u), and an intensity of 20 − 50 pnA was supplied by an azimuthally varying field (AVF) cyclotron. A cryogenic hydrogen gas target system was used as the proton target to induce the ^{26}Mg(p, n)^{26}Al reaction in inverse kinematics. The secondary beam was bent by two dipole magnets by selecting the beams with a slit which is placed at the momentum-dispersive focal plane between the two dipole magnets, and the beam was purified according to the magnetic rigidity $B\rho$ and the slit width. The beam spot as well as the number of particles was measured by parallel plate avalanche counters (PPAC) at the dispersive-focal plane beyond the two dipole magnets.

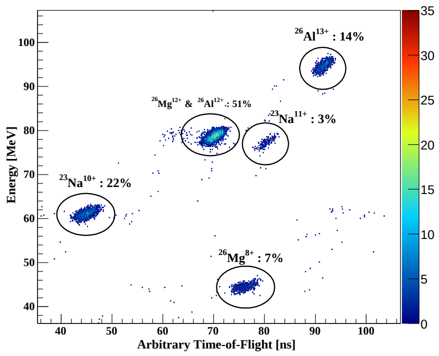

Fig. 1. RI species identified at the focal plane beyond the dipole magnets. The abscissa is the time of flight from the production focal plane with time offsets. The ordinate shows total kinetic energy of RIs.

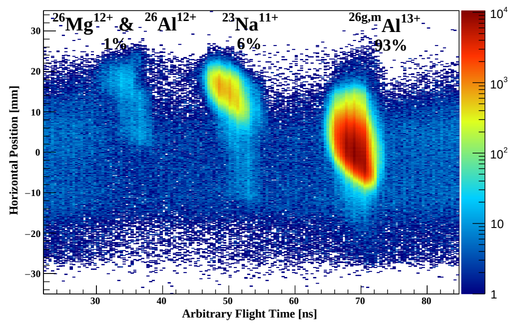

Fig. 2. RI species identified at the final focal plane. The horizontal position and the timing were detected by the PPAC.

The isotopes in the beam were identified by energy versus time-of-flight plot as shown in Figure 1. The contaminants were diverted through the Wien-Filter, and ^{26}Al^{13+} was purified to more than 90% at the experimental target position. The typical intensity was around 1.5×10^5 pps, and the energy was 114–120 MeV (Fig. 2). Since the ground state and the isomeric state of ^{26}Al have only the small mass difference (228 keV), they could not be distinguished event-by-event by the CRIB separator. By varying the pressure of the secondary beam production target, several conditions of ^{26m}Al beams were produced during the experiment. Since CRIB uses the in-flight method with a typical fight time of ^{26}Al on the order of 500 ns, the second excited state of ^{26}Al (417 keV) decays enroute to the traget, contributing to the yield of ^{26g}Al.

2.2 Measurement of scattering

In the target chamber, a CH_2 foil as the hydrogen target, and a carbon foil for background subtraction were placed. The incident RI beam was tracked by two PPACs, and the recoil particles were collected in the ΔE–E telescopes that consist of one thin position-sensitive silicon detector (75 μm) and 2–3 layers of thicker silicon detectors at 0° and 20° against the beam direction. The cross section of the elastic scattering was analyzed by Thick Target in Inverse Kinematics (TTIK) method, covering range from zero to the initial beam energy.

2.3 Isomeric purity

To obtain the absolute purity of the isomers, the beam was in a pulsing mode with a cycle of 24 s where the beam was on for 12 s for implantation, and off for 12 s independent from the main scattering measurement. The RI beam was implanted into several targets, a CH_2 film and thick blocks, and when the beam was off radiations were measured by 10 NaI scintillators placed above the center of the target to measure annihilation radiation from ^{26m}Al. The half life of the radiation at 511 ± 60 keV, where 60 keV is about 3σ of the energy resolution of the detectors, was measured to be 6.36 ± 0.15 s. Therefore it is confirmed that almost all of the decay events originated from ^{26m}Al.

As ^{26}Al decays, positrons emitted isotropically from the inside target could escape to all surroundings material and made precise counting of the annihilation radiations difficult. To estimate such complicated situation, we defined the intrinsic efficiency η of the detectors as the ratio *511 keV photons counts* per ^{26m}*Al implanted* which depends on solid angle of detectors, quantum efficiencies of the photomultiplier tubes, and the geometry of the experimental chamber. The Geant4 Monte-Carlo simulation framework was used to evaluate it. To verify the validity of the intrinsic efficiency of the simulation, we took several data with the γ- and β-ray source ^{22}Na and compared it with the simulation, and it was confirmed within an uncertainty of 5%.

By using the value of η from the simulation, the isomeric purities are tabulated in Table I under several conditions. These purities have good agreement with the previous experimental data [4, 5].

Table I. Result of the isomeric purities under the different situations labeled as #1–#5, where #3 and #5, #2 and #4 are similar conditions respectively.

RI beam label	#1	#2	#3	#4	#5
Isomeric Purity (%)	48.3 ± 2.9	43.0 ± 2.5	56.4 ± 3.4	43.9 ± 2.4	52.7 ± 2.4

3. Summary

The isomeric RI beam ^{26m}Al was produced by CRIB with a purity of at maximum 56.4% and at minimum 43.0% according to the evaluation with the Monte-Carlo simulation. The energies of RI beams can cover the region of interest of the core-collapse supernovae temperature. With these isomeric ^{26}Al beams, proton elastic scattering was measured with a thick target in inverse kinematics method to encompass the uncertainty of the recent ^{26}Al problem connected with the observation of the γ-rays and the reaction network calculations of nuclear astrophysics.

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