Development of an Isomeric Beam of ^{26}Al for Nuclear Reaction Studies

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Abstract

This paper describes the production and characterization of a ^{26}Al beam comprised of both, its 5^+ ground state, and its 0^+ isomeric state. The ^{26}Al beam was produced in-flight via the $p(^{26}\text{Mg}, {}^{26}\text{Al})n$ reaction. The isomer fraction of the ^{26}Al beam was maximized by choosing a bombarding energy of 158.5 MeV for the ^{26}Mg primary beam. The resulting beam had an energy of 120 MeV, a total intensity of 2×10^5 particles/sec, a purity of 98% and an isomer content of 70%. This high-quality ^{26}Al isomeric beam was used to study the $^{26}\text{Al}^m(d,p)^{27}\text{Al}$ reaction relevant for understanding the nucleosynthesis of ^{26}Al in the Galaxy.

1. Introduction

The detection of cosmic gamma-rays by space telescopes has become a very powerful tool for understanding the synthesis of elements in the Galaxy [1]. Of special interest is the detection of the 1809-keV gamma-ray line which has been observed by several gamma-ray space telescopes [2, 3], and is associated with the decay of the radioactive nucleus ^{26}Al. This gamma-ray is attributed to the β^+-decay of the 5^+ ground state of ^{26}Al ($^{26}\text{Al}^g$, $t_{1/2}$ = 717,000 yr) to the first excited 2^+ state in ^{26}Mg which then decays via the 1809-keV gamma-ray to the ground state of ^{26}Mg. Since the half-life of ^{26}Al is much shorter than the average age of the Galaxy, the detection of this gamma-ray line provides strong evidence for ongoing nucleosynthesis in the Galaxy [4]. Detailed maps of the distribution of the 1809-keV gamma-ray line provided by space telescopes suggest that massive stars are the main production sites of ^{26}Al in the Galaxy. In order to correctly interpret the observations and evaluate their impact, experiments in the laboratory need to

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be performed to understand all the reactions that produce and destroy ^{26}Al in stellar environments. The presence of a low-lying 0^+ isomeric state in ^{26}Al (^{26}Al^m, $t_{1/2} = 6.35$ s) however, strongly complicates the calibration of its nucleosynthesis. The 0^+ isomeric state in ^{26}Al decays directly to the ground state of ^{26}Mg bypassing the emission of the 1809-keV gamma-ray. This is illustrated in the partial level scheme in Fig. 1 which shows the relevant states of ^{26}Al and ^{26}Mg. It has been suggested that radiative proton captures on both, the ground and the isomeric states, are the main destruction paths of ^{26}Al in asymptotic giant branch (AGB) stars, classical novae (CN) and core collapse supernovae (CCSN) [5]. Due to its astrophysical relevance, the production and use of an isomeric ^{26}Al^m (0^+) beam has been the goal at several laboratories around the world (e.g. TRIUMF, TAMU, RIBF-RIKEN, KVI Gronengen [6–9]).

In this paper, we report on the first production of an isomeric ^{26}Al^m beam with a high isomer content, intensity and purity. The ^{26}Al^m beam was then used for a measurement of the ^{26}Al(d,p)^{27}Al reaction, where states in ^{27}Al were populated via low angular momentum transfers from ^{26}Al. Our experimental measurement puts a limit on the nucleosynthesis rate of the ^{26}Al^m(p,γ)^{27}Si reaction which is one of the main destruction paths of ^{26}Al in the Galaxy [10].

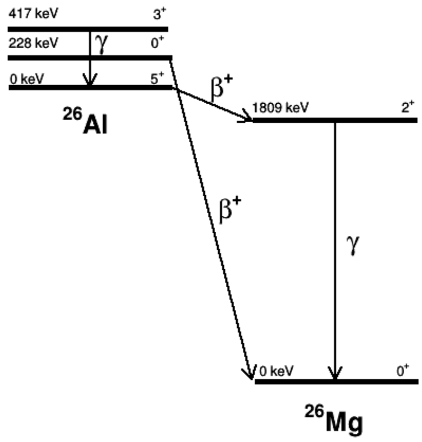

Figure 1: Partial level scheme of ^{26}Al and ^{26}Mg illustrating the β^+ transitions from ^{26}Al^m ($t_{1/2} = 6.35$ s) to the ground state of ^{26}Mg and of ^{26}Al^g ($t_{1/2} = 717000$ yr) to the 2^+ state of ^{26}Mg followed by the 1809-keV gamma-ray to the ground state of ^{26}Mg.

2. ^{26}Al Beam Production

The ^{26}Al beam was produced via the ^{26}Mg(p,n)^{26}Al reaction, in inverse kinematics, at the ATLAS in-flight facility at Argonne National Laboratory. Previous cross section measurements of the ^{26}Mg(p,n)^{26}Al reaction were fundamental for the beam production and enhancement of the isomeric content of the beam [11, 12]. The excitation function as measured by Doukellis et al. [11] using a proton beam to bombard a ^{26}Mg target and to produce ^{26}Al, is shown in Fig. 2. Neutrons from the 5^+, 0^+, and 3^+ states in ^{26}Al populated via the (p,n)

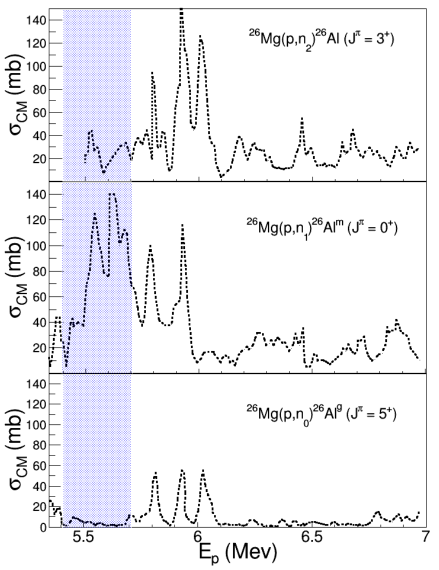

Figure 2: Cross section of the ^{26}Mg(p,n)^{26}Al reaction measured by Doukellis et al. [11]. The shaded region indicates the chosen energy range for the present experiment to maximize production of the isomer. Adapted from Ref. [11]

reaction were measured and their relative cross sections were extracted. As can be seen from the highlighted area in Fig. 2, a high percentage of the isomeric ^{26}Al^m beam can be obtained if the proton energy is chosen to be between E$_p$ = 5.4 - 5.7 MeV. For an inverse kinematic reaction this corresponds to ^{26}Mg energies between E$_{lab}$ (^{26}Mg) = 140.3 - 148.1 MeV.

A ^{26}Mg primary beam with an energy of 158.5 MeV was used to bombard a H_2 filled gas cell in order to produce ^{26}Al via the $p(^{26}$Mg,^{26}Al$)n$ reaction. The gas cell [13] was 3.7 cm long and enclosed by two HAVAR^{TM} windows of 1.9 mg/cm^2 thickness each, resulting in an energy loss of 9.5 MeV of the ^{26}Mg beam before reaching the hydrogen gas at about 149 MeV. The gas was pressurized to 1000 Torr and kept at room temperature (293 K) achieving an effective target thickness of 0.41 mg/cm^2. Under these conditions, the primary beam loses about 8.5 MeV through the gas. This results in an energy of the ^{26}Mg primary beam in the range of 5.7 - 5.4 MeV/u at which it will interact with the hydrogen gas. The corresponding proton energy in normal kinematics is indicated by the shaded energy range shown in Fig. 2. A secondary 120 MeV beam of ^{26}Al was produced along with unreacted ^{26}Mg from the primary source material in their various charge states. The contaminants were filtered out primarily by a 22° bending magnet located downstream from the production gas cell [13]. A schematic of the beam production is shown in Fig. 3.

3. Beam Characterization

The profile of the beam was measured with a silicon detector located in the characterization station depicted in Fig. 3. To reduce the primary and thus the secondary beam intensities, a 1/1000 attenuator was inserted after the ion source to insure good working condition of the silicon detector used for characterization. After the 22° bending magnet shown in Fig.

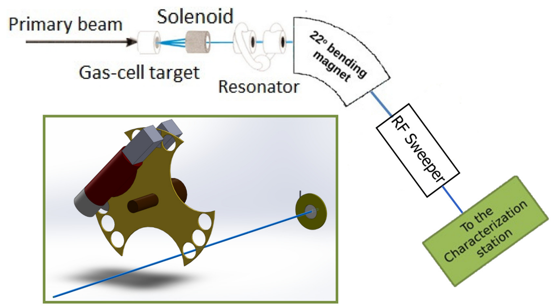

Figure 3: Schematics of the beam production setup. After the primary beam interacts with the gas cell, a solenoid, a 22° magnet, and an radio frequency (RF) sweeper are used to select, focus and reduce contaminants of the radioactive beam. The insert in the lower left part of the figure is a 3D-model of the characterization station composed of a rotating wheel, two NaI detectors, and a silicon detector which are described in Section 3. Adapted from Ref. [14].

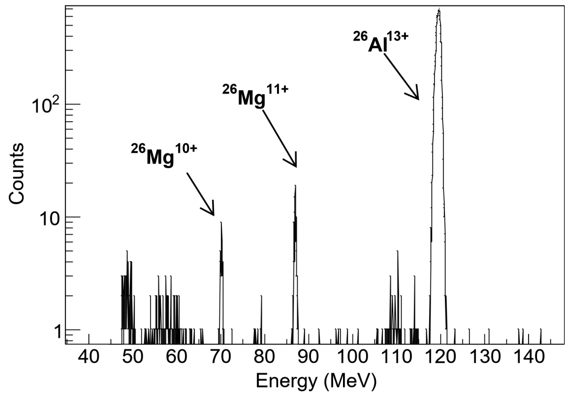

Figure 4: Beam profile after the magnetic rigidity was set for ^{26}Al (q=13^+) and the RF sweeper was optimized. The 12^+ charged state of the primary ^{26}Mg beam was completely removed. The remaining contaminants ($\leq$ 2%) are mainly lower charge states of ^{26}Mg.

3, the secondary beam still contains contaminants with magnetic rigidities similar to the one of the ^{26}Al (q = 13^+) beam. These contaminants were removed through the use of a radio frequency (RF) sweeper [15]. Optimization of the RF sweeper resulted in a 120 MeV ^{26}Al beam with about 98% purity and 1% energy resolution (FWHM). The optimized beam as measured by the silicon detector placed in the characterization station with an attenuated primary beam is shown in Fig. 4, where the final contaminants are mainly lower charge states of the primary beam. From the count rate obtained in this measurement and the attenuation factor of 1/1000, the intensity of the total ^{26}Al beam (g.s. and isomer) was determined, with a typical value of about 2×10^5 particles/sec per 20-30 pnA of primary ^{26}Mg beam incident on the production target.

The isomeric content of the beam (^{26}Al^m) was measured through its β^+-decay radiation, which was followed by positron-electron annihilation that resulted in two 511-keV gamma-rays. The measurement of the 511-keV gamma-ray was performed by using the rotating wheel setup shown in Fig. 5 which was located about 50 cm upstream of the Si detector. A 100 mg/cm^2 thick Au foil was mounted at the bottom of the rotating wheel as shown in Fig. 5(a). The Au foil was chosen because its high Z and therefore a high Coulomb barrier prevented nuclear reactions with the 120 MeV ^{26}Al beam. The Au foil was bombarded by

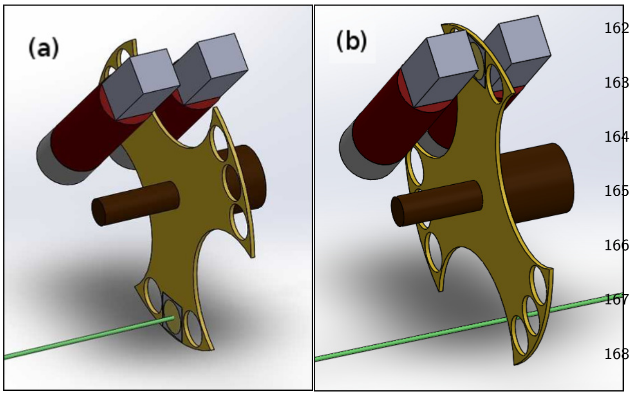

Figure 5: Schematics of the rotating wheel setup used to measure the isomer content of the beam. (a) A Au foil was irradiated by the beam for 15 s. (b) The Au foil was then rotated by 180° and placed in between two NaI detectors where the gamma-rays are measured for another 15 s.

the ^{26}Al beam for 15 seconds ($\sim$ 2 half-lives of ^{26}Al^m). After this irradiation time, the Au foil was rotated by 180° to a position in between two NaI detectors, shown in Fig. 5(b) where a measurement of the 511-keV annihilation radiation was performed for another 15 seconds. A 48-bit latching scalar was added to the electronics to obtain the timing information from the events measured in the NaI detectors.

Fig. 6 shows a coincidence spectrum of the two NaI detectors. The ^{26}Al^g (5^+) g.s. also undergoes a β^+-decay, but, since the half-life of the ground state is much longer ($t_{g,1/2}$ = 717,000 years) than that of the isomeric state, the contribution of β^+-decays from ^{26}Al^g in the time of the measurement is negligible. The timing of the 511-keV gamma-rays measured with the NaI detectors was extracted and a decay curve was fitted. Since the decay was taken in cycles lasting 15 second each, the intervals were later summed to improve the statistics. A typical summed run is shown in Fig. 7. The fit to the decay curve gives a half-life of 6.2 $\pm$ 0.2 seconds, in good agreement with the accepted half-life of 6.35 seconds of the ^{26}Al^m [16], confirming the existence and positive identification of the isomer. The detection efficiency of the NaI detectors for 511-keV photons was calculated using a GEANT4 simulation which was validated with a calibrated ^{22}Na source placed at the Au foil position. The measurement of the 511-keV photons from the source was compared with the counts from the simulation and were found to agree within 10%. For the configuration used in this experiment, the simulated single-photon efficiencies for 511-keV photons were found to be 1.82% $\pm$ 0.02% and 1.90% $\pm$ 0.02% for each NaI detector while for the coincidence efficiency a value of 0.07% $\pm$ 0.01% was obtained [14]. The yield from the coincident 511-keV gamma radiation was then integrated, adjusted for efficiency as calculated by the GEANT4 simulation, and divided by the total ^{26}Al yield measured in the silicon detector. This resulted in a 70 $\pm$ 10% isomeric-to-ground-state ratio. This result is shown by the solid point in Fig. 8.

The present experimental value extracted for the isomeric-to-ground-state ratio is in good agreement with the ratio extracted from the cross section measurements by Doukellis et al. [11] shown in Fig. 2 when the data is averaged to take into account the extended geometry and the energy loss of the production target. This agreement is shown in Fig. 8 where the present experimental value is indicated by the solid point and the solid line is obtained by averaging the experimental data in Fig. 2 over the energy loss of the ^{26}Mg beam in the production target. It can also be noted that by increasing the bombarding energy to 6.1 MeV/u one can invert the isomer-to-ground-state ratio to 0.2. Included also in Fig. 8 is the isomer-to-ground state ratio that would be expected if the energy loss in the gas target is reduced from 325 keV to 100 keV (dashed line). As can be seen in the figure, an increase in the ratio to about 0.9 could be obtained by using a thinner target with an incident energy of about 5.7 MeV/u. The higher isomeric ratio, however, would come at the expense of a lower radioactive beam intensity due to the lower effective target thickness. At the moment, the main limitation in the production of this isomeric beam is the amount of primary beam that the windows in the gas cell can tolerate without risking breakage (∼ 20 - 30 pnA). Next generation hydrogen targets, e.g. using thin films of hydrogen-containing oils [17] should be able to tolerate higher primary beam intensities in order to enhance the secondary beam yields.

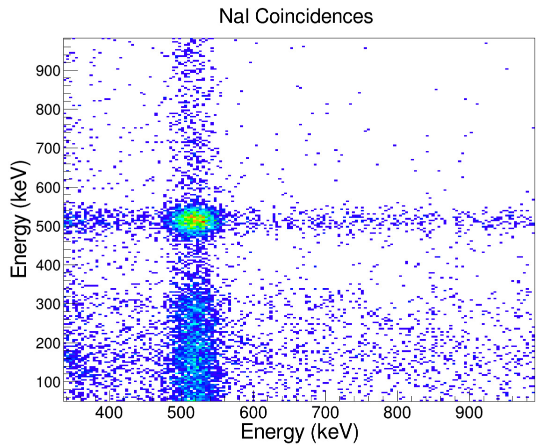

Figure 6: Energy spectra from the two NaI detectors used to measure the gamma radiation implanted in an Au foil plotted against each other. Here, the coincident 511-keV gamma-rays are clearly visible. A 48-bit latching scalar was 'latched' to the NaI detectors to get the timing information of the events. Gating on these coincidences allowed the measurement of the half-life of the decay radiation and confirm the presence of ^{26}Al^{m}.

4. Conclusions

An isomeric ^{26}Al (0^+) beam was successfully produced at the ATLAS accelerator facility at Argonne National Laboratory using the in-flight production method with a ^{26}Mg beam bombarding a hydrogen gas target. A silicon detector, a rotating wheel, and NaI detectors were used to characterize the beam. By choos-

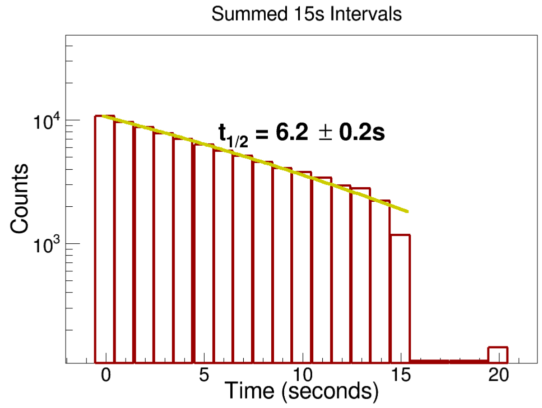

Figure 7: Timing spectrum associated with coincidences of 511-keV gamma radiation measured in the two NaI detectors summed over 15 second time intervals. The exponential decay fit yields a 6.2 ± 0.2 s half-life in agreement with the accepted 6.35 s half-life of $^{26}\text{Al}^m$.

ing the appropriate energy of the primary ^{26}Mg beam and the pressure and temperature of the production gas cell filled with H_2, we have successfully produced a beam of $^{26}\text{Al}^m$ with 1% energy resolution, 98% purity, a total intensity of 2×10^5 particles/sec, and a 70% isomer content.

This technique opened the possibility for using isomeric beams as probes to explore reactions that previously could not be studied, thus, making the technique a very powerful tool in nuclear reactions, nuclear structure and nuclear astrophysics studies. A study of the $^{26}\text{Al}^m(d,p)^{27}\text{Al}$ reaction which was the motivation for this development has already been performed [10]. Studies of similar reactions using e.g. ^{34}Cl, ^{38}K [18], and ^{18}F [19] beams are already ongoing or planned in the near future.

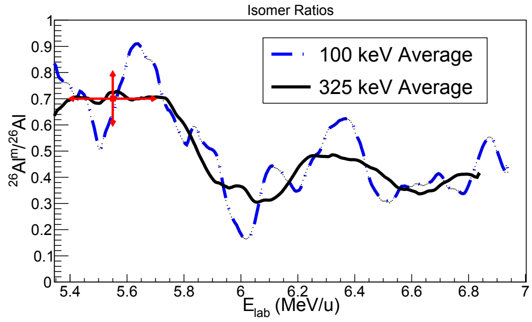

Figure 8: Ratio of isomer to ground state components of the ^{26}Al beam as function of the energy of the primary beam. The solid and dashed lines were extracted from the measurement of Ref. [11] by averaging the cross sections using the different effective target thicknesses indicated in the figure. The solid point is the value of the ratio measured in this experiment.

Acknowledgements

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