EPJ Web of Conferences **165**, 01030 (2017) DOI: 10.1051/epjconf/201716501030
NPA8 2017

Isomer beam elastic scattering: ^{26m}Al(p, p) for astrophysics

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Abstract. The advent of radioactive *ground-state* beams some three decades ago ultimately sparked a revolution in our understanding of nuclear physics. However, studies with radioactive *isomer* beams are sparse and have often required sophisticated apparatuses coupled with the technologies of ground-state beams due to typical mass differences on the order of hundreds of keV and vastly different lifetimes for isomers. We present an application of a isomeric beam of ^{26m}Al to one of the most famous observables in nuclear astrophysics: galactic ^{26}Al. The characteristic decay of ^{26}Al in the Galaxy was the first such specific radioactivity to be observed originating from outside the Earth some four decades ago. We present a newly-developed, novel technique to probe the structure of low-spin states in ^{27}Si. Using the Center for Nuclear Study low-energy radioisotope beam separator (CRIB), we report on the measurement of ^{26m}Al proton resonant elastic scattering conducted with a thick target in inverse kinematics. The preliminary results of this on-going study are presented.

1 Motivation

The observation of 1.809-MeV γ-rays associated with the decay of ^{26}Al across the Milky Way has attracted much attention in various subfields of nuclear astrophysics in the years since its discovery [1]. Observations point to massive stars as the main producers of the observed ^{26}Al [2], although it is unclear whether its production occurs mainly in the Wolf-Rayet phase or during subsequent supernova. The ground state of ^{26}Al, which we denote ^{26g}Al, has a spin-parity $J^\pi = 5^+$, a halflife of 0.72 Myr, and decays predominately through the first excited state in ^{26}Mg located at 1.809 MeV,

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which then de-excites by emission of characteristic electromagnetic radiation. Nucleosynthesis of ^{26}Al is complicated by a low-laying isomeric state $^{26\text{m}}$Al at 228 keV with $J^{\pi} = 0^{+}$ and a halflife of $T_{1/2} = 6.3$ s. The isomeric decay not only tends to bypass the production of the characteristic 1.809-MeV γ-ray, given its short lifetime it is unlikely to be transported intact from its site of production to a transparent region of space for observation. In an astrophysical plasma, the tail-end of the Planck distribution may be energetic enough to link the two species through thermally-induced transitions [3, 4]; these studies highlighted the complexity of these physics, yet there can be no doubt the states $^{26\text{g,m}}$Al are almost certainly in statistical equilibrium at temperatures > 1 GK.

The $^{26\text{m}}$Al(p, γ) stellar reaction rate is highly uncertain owing to sparse experimental information. At present, $^{26\text{m}}$Al states in ^{27}Si have been studied via charged-particle spectroscopy [5] and in-beam γ spectroscopy [6], while mirror states in ^{27}Al were recently studied by a neutron-transfer reaction on $^{26\text{m}}$Al [7]. No proton partial widths Γ_{p} are known, and only limited information is known about the nature of higher energy resonances which might be important for temperatures > 1 GK corresponding to those typically found in core collapse supernovae. We performed a measurement of $^{26\text{m}}$Al(p, p) which should reveal any states with large proton partial widths and low ℓ transfer somewhat above the proton separation energy.

2 Experiment

We conducted a measurement of proton resonant elastic scattering with a mixed $^{26\text{g,m}}$Al beam at the Center for Nuclear Study (CNS) low-energy radioactive ion beam (RIB) separator [8], called CRIB. To produce the beam, we used the inflight method and the ^{1}H(^{26}Mg, ^{26}Al)n reaction. The ^{26}Mg beam was accelerated to 6.65 MeV/u with typical intensities of 25–50 pnA. The beam then impinged on a Havar-windowed, 8 cm long gas cell [9] filled with H_2 gas and cooled to an effective temperature of 90 K with LN_2. To change the ^{26}Al isomeric purity, we produced the cocktail beam at different center-of-mass energies which turned out to be effective. We accomplished this with an energy-degrader foil upstream of the production target as well as by varying the H_2 gas pressure over 130–290 Torr (0.5 to 1.0 mg cm^{-2}). The cocktail beam was selected by its magnetic rigidity at the dispersive focal plane between two magnetic dipoles, and further purified by a Wien (velocity) filter before arriving at the experimental scattering chamber.

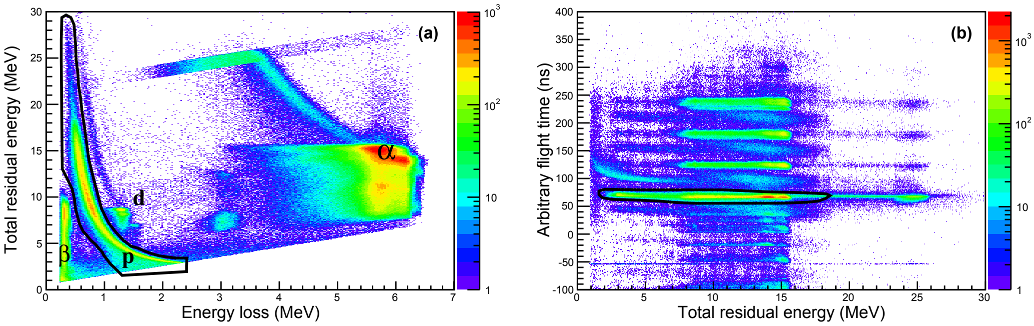

Figure 1. (Color online) Proton identification: (a) Energy loss versus residual energy from the Si telescope. (b) Residual energy from the Si telescope against time of flight between PPACa and the Si telescope. The depicted gates show the scattered protons.

The experimental setup consisted of two parallel plate avalanche counters (PPACs) [10] to track the beam, a target slider, two ΔE–E silicon telescopes to measure protons, and an array of ten NaI de-

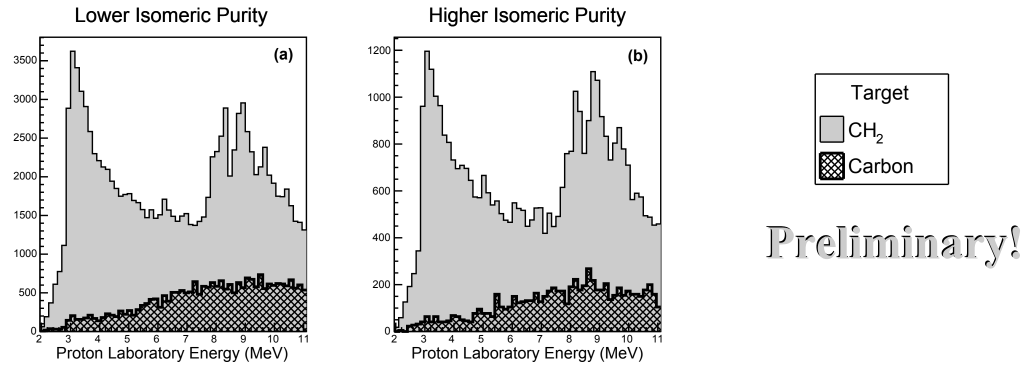

Figure 2. Residual *laboratory* energy histograms for protons scattered by ^{26}Al from two of the runs. Isomeric purity of the beam is lower in (a) than in (b).

tectors to measure γ-rays. The PPACs enabled us to track the beam ions event-by-event, to determine their trajectory and nuclear species. The ^{26}Al cocktail beam had an average intensity of 1.5×10^5 pps, 93% purity, and on-target energies of 68, 83, and 93 MeV; the main contaminants were the stable isotopes ^{23}Na and leaky primary beam ^{26}Mg [11]. The target slider held the secondary targets, which were a 7.5 mg cm^{-2} CH$_2$ foil as a proton target, a 10.6 mg cm^{-2} $^{\mathrm{nat}}$C foil for background subtraction, and 1 cm blocks of Al and plastic which are thick enough to completely stop the β^+-rays from the decay of $^{26\mathrm{m}}$Al. We made regular measurements of the isomeric purity by both directly measuring the positrons with the Si telescopes as well as measuring the annihilation γ-rays at 511 keV with the NaI array. During these decay measurements, we pulsed the primary beam in an on/off mode with a duty cycle of 24 s. The β^+ energy distribution and the derived halflife was completely consistent with $^{26\mathrm{m}}$Al, as shown in Fig. 3 of [11]. With the decay measurements we found the purity $^{26\mathrm{m}}$Al/$^{26\mathrm{g,m}}$Al covered a range of roughly 50 ± 20% depending on the beam production conditions.

Protons elastically scattered from the CH$_2$ target were measured with two silicon telescopes placed at forward angles in the laboratory. Each silicon detector was 50×50 mm^2. We measured the position and energy loss of each proton with the first layer, which was nominally 75 μm thick and had 16 orthogonal strips on each side. The other telescope layers were 1.5 mm thick which we summed to get the proton residual energy. Protons were distinguished from other light ions by the ΔE–E method as shown in Fig. 2(a), and protons scattered by the ^{26}Al beam were further distinguished from other protons by their timing between PPACa and the Si telescope as shown in Fig. 2(b).

Selected proton spectra from the 0° telescope are shown in Fig. 2, where the spectra obtained with the C target are normalized to the number of incident ^{26}Al ions on CH$_2$ for comparison. These spectra are *preliminary* and taken in the *laboratory* frame. To obtain the center-of-mass energy of the protons from the laboratory energy for small θ, the kinematic compression is about a factor of four. No correction has been applied for the energy loss of protons in the target yet. Next, we will solve the kinematic equation with energy loss and angle for each event to construct the excitation function.

At present, despite the above limitations of the laboratory proton spectra, the basic features are quite informative. Firstly, we note that pure $^{26\mathrm{g}}$Al proton elastic scattering was previously measured up to 1.5 MeV in the center-of-mass frame, and no strong resonances were observed [12]. Thus, to obtain a given $^{26\mathrm{m}}$Al proton spectrum, we simply need to perform a background subtraction of the well-known Rutherford scattering cross-section scaled to the intensity of $^{26\mathrm{g}}$Al. The strong features that emerge in our spectra at proton energies higher than 8 MeV could be from either state of ^{26}Al, although these energies are likely to be too high to have an astrophysical impact; in the future, their origin may be clarified by a more careful analysis of their strength as a fuction of isomeric purity. Below proton energies of 3 MeV, the protons do not have enough energy to reach the second layer of the Si telescope. However, between these two energies, hints of peak-like structures may be present. Although we already know there are no strong proton resonances from ^{26g}Al in this energy region, further analysis of our proton scattering data as a function of isomeric purity would help confirm that any peaks arise from ^{26m}Al. In order to be resolved, these states must have large proton partial widths Γ_p, yet no strong states were observed in this region of the mirror nucleus via the (d, p) reaction [7], suggesting the states we observe may have $\ell > 0$. In the future, we will perform an R-Matrix fit on the proton scattering excitation function to extract the resonant properties of Γ_p, ℓ, and $E_{\mathrm{c.m.}}$.

3 Summary

We reported the first experimental work to produce an RIB of ^{26m}Al and control its isomeric purity. Using this beam, we measured ^{26m}Al proton resonant elastic scattering for the first time. We observed hints of resonant-like structure with large Γ_p around 1–2 MeV in $E_{\mathrm{c.m.}}$ in the ^{26m}Al+p system. Curiously, there are no strong ^{26g}Al proton resonances over the same energy region in ^{27}Si, possibly suggesting that ^{26m}Al is more efficiently destroyed by radiative proton capture than ^{26g}Al in high temperature astrophysical environments. The nuclear structure which gives rise to this behavior of unbound proton states in ^{27}Si will be interesting to investigate. As ^{26g,m}Al will be in thermal equilibrium for $T > 1$ GK, ^{26m}Al(p, γ) could be an efficient pathway to destroy ^{26g}Al in core collapse supernovae, which may impact the contribution of massive stars to galactic ^{26}Al. More definite conclusions will be possible in the near future after we complete our analysis.

Acknowledgments

This work was partly supported by grants from the STFC in the UK, the JSPS KAKENHI (Grants No. 25800125 and 16K05369) in Japan, NRF funded by the Korea government (MEST) (No. NRF-2014S1A2A2028636, NRF-2015R1D1A1A01056918, NRF-2016K1A3A7A09005579, and NRF-2016R1A5A1013277), and NSERC of Canada. We thank the CNS and RIKEN staff for operation of the ion source and accelerator during the machine time.

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