Impact of the ^{26m}Al(p, γ) reaction to galactic ^{26}Al yield

D. Kahl, H. Shimizu, H. Yamaguchi, K. Abe, O. Beliuskina, S. M. Cha, K. Y. Chae, A. A. Chen, Z. Ge, S. Hayakawa, N. Imai, N. Iwasa, A. Kim, D. H. Kim, M. J. Kim, S. Kubono, M. S. Kwag, J. Liang, J. Y. Moon, S. Nishimura, S. Oka, S. Y. Park, A. Psaltis, T. Teranishi, Y. Ueno, and L. Yang

Citation: AIP Conference Proceedings **1947**, 020003 (2018); doi: 10.1063/1.5030807

View online: https://doi.org/10.1063/1.5030807

View Table of Contents: http://aip.scitation.org/toc/apc/1947/1

Published by the American Institute of Physics

Impact of the $^{26\mathrm{m}}$Al(p, γ) Reaction to Galactic ^{26}Al Yield

D. Kahl[1,a)], H. Shimizu[2], H. Yamaguchi[2], K. Abe[2], O. Beliuskina[2], S. M. Cha[3], K. Y. Chae[3], A. A. Chen[4], Z. Ge[5], S. Hayakawa[2], N. Imai[2], N. Iwasa[6], A. Kim[7], D. H. Kim[7], M. J. Kim[3], S. Kubono[5], M. S. Kwag[3], J. Liang[4], J. Y. Moon[8,9], S. Nishimura[5], S. Oka[10], S. Y. Park[7], A. Psaltis[4], T. Teranishi[10], Y. Ueno[10] and L. Yang[2]

[1]*School of Physics & Astronomy, the University of Edinburgh, James Clerk Maxwell Building, Peter Guthrie Tait Road, Edinburgh EH9 3FD, United Kingdom*
[2]*Center for Nuclear Study, the University of Tokyo, Wako Branch at RIKEN, 2-1 Hirosawa, Wako, Saitama 351-0198, Japan*
[3]*Department of Physics, Sungkyunkwan University, 300 Chunchun-dong, Jangan-gu, Suwon, Korea*
[4]*Department of Physics & Astronomy, McMaster University, 1280 Main St. W, Hamilton, Ontario L8S 4M1, Canada*
[5]*RIKEN Nishina Center, RIKEN, 2-1 Hirosawa, Saitama 351-0198, Japan*
[6]*Department of Physics, Tohoku University, Sendai, Miyagi 980-8578, Japan*
[7]*Department of Physics, Ewha Womans University, Dae-Hyun-Dong, Seoul 120-750, Korea*
[8]*Institute of Particle and Nuclear Studies, KEK, Japan*
[9]*Wako Nuclear Science Center, KEK (The High Energy Accelerator Research Organization), 2-1 Hirosawa, Wako, Saitama 351-0198, Japan*
[10]*Department of Physics, Kyushu University, Fukuoka 812-8581, Japan*

[a)]Corresponding author: daid.kahl@ed.ac.uk

Abstract. Astrophysical observables that are directly linked to nuclear physics inputs provide critical and stringent constraints on nucleosynthetic models. As ^{26}Al was the first specific radioactivity observed in the Galaxy, its origin has fascinated the nuclear astrophysics community for nearly forty years. Despite extensive research, the precise origins of ^{26}Al remain elusive. At present, the sum of all putative stellar contributions generally overestimates the ^{26}Al mass in the interstellar medium. Among the many reactions that influence the yield of ^{26}Al, radiative proton capture on its isomer $^{26\mathrm{m}}$Al is one of the least constrained reactions by experimental data. To this end, we developed a ^{26}Al isomeric beam and performed proton elastic scattering to search for low-spin states in ^{27}Si. The experimental method and the preliminary results of this on-going study will be presented.

INTRODUCTION

Exothermic nuclear processes are one of the main sources of energy generation during stellar evolution, while nuclear transmutations are simultaneously responsible for the production of most chemical elements and their various isotopes found in the Universe. However, there are many steps between a given nuclear reaction occurring in a stellar interior and the incorporation of enriched material into a given galaxy, often with competing types and scales of the physics involved. Thus, it is critically important to pinpoint those astrophysical observables which are most closely linked with the input nuclear physics, as these allow for the direct testing of models which in turn suggest which nuclear uncertainties should be reduced by experimental investigation. Owing to energy dependent reaction rates that typically vary by many orders of magnitude among the myriad of interacting species found in a stellar plasma, it is often the case that only a small number of thermonuclear reactions are of significant importance in a given domain.

In this context, 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 four decades since its discovery [1, 2]. The ground state of the neutron-deficient isotope ^{26}Al, which we denote $^{26\mathrm{g}}$Al, has an exceptional spin-parity $J^{\pi} = 5^{+}$. As

14th International Symposium on Origin of Matter and Evolution of Galaxies (OMEG 2017)
AIP Conf. Proc. 1947, 020003-1–020003-7; https://doi.org/10.1063/1.5030807
Published by AIP Publishing. 978-0-7354-1642-0/$30.00

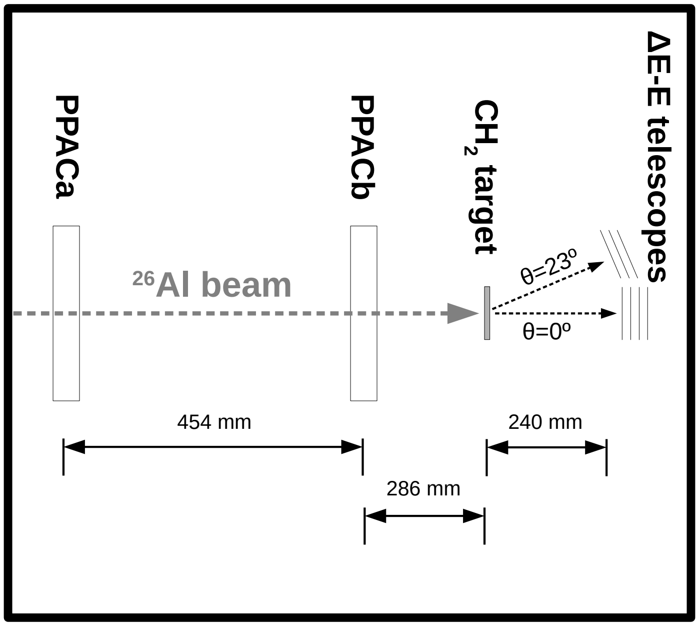

FIGURE 1. Beam is tracked by PPACs before impinging on and stopping in one of the targets. Scattered protons were detected by ΔE-E Si telescopes, the first layer is 75 μm with 16×16 strips and the other detectors 1.5 mm. An array of 10 NaI detectors was placed above the target to measure γ-rays (not depicted).

^{26}Mg is an even-even nucleus, then its ground state has $J^{\pi} = 0^{+}$, and the large ΔJ strongly inhibits the ground-state-to-ground-state decay of ^{26}Al. Thus, ^{26g}Al decays predominately through the first excited state in ^{26}Mg ($J^{\pi} = 2^{+}$) located at 1.809 MeV, which then de-excites by emission of characteristic electromagnetic radiation. The halflife of ^{26g}Al is 0.72 Myr, representing a reasonable timescale for stellar production, ejection, and mixing into an optically-thin region of the interstellar medium.

All-sky imaging in the ^{26g}Al decay band shows its spatial distribution to be inhomogeneous [3], with the main concentrations clumped along the galactic plane in the direction of star-forming regions [4]. Precise spectral measurements show that the 1.809-MeV photons are Doppler shifted in a manner consistent with an origin in spiral arm sources [5]. As stellar mass correlates inversely with stellar lifetime, these observations point to massive stars as the main producers of the observed ^{26}Al [6], although it is unclear at present whether this production occurs predominately in the Wolf-Rayet phase or during subsequent core collapse. However, possible contributions to the galactic ^{26g}Al inventory from novae [7, 8], asymptotic giant branch (AGB) stars [9], and super-AGB stars [10] cannot be ruled out, yet summing the maximum yield from all available stellar models overestimates the mass of ^{26}Al [11]. We hypothesize that one or more of the destruction pathways of ^{26}Al in stellar models may presently be underestimated, which can be tested by laboratory investigation of specific channels.

Nucleosynthesis of ^{26}Al is complicated by a low-lying isomeric state ^{26m}Al at 228 keV with $J^{\pi} = 0^{+}$. Unlike ^{26g}Al, there is no angular momentum barrier for the decay of this state to the ground state of ^{26}Mg, and it does so with a halflife of just $T_{1/2} = 6.3$ 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. Processes that produce ^{26}Al do not necessarily produce ^{26g,m}Al equitably; for example, while ^{25}Mg(p, γ) produces both species, the β^{+}-decay of ^{26}Si ($J^{\pi} = 0^{+}$) preferentially populates ^{26m}Al. Moreover, in a hot photon bath such as found in an astrophysical plasma, the tail-end of the Planck distribution may be energetic enough to link the species through thermally-induced transitions regardless of which one is produced by nuclear processes [12, 13, 14, 15]; these studies highlighted the complexity of these physics, yet there can be no doubt the states ^{26g,m}Al are thermally coupled and almost certainly in statistical equilibrium at temperatures > 1 GK.

The ^{26m}Al(p, γ) stellar reaction rate is highly uncertain at present owing to sparse experimental information. Conversely, the ^{26g}Al(p, γ) rate has been relatively much more well understood, and in consequence estimates of the

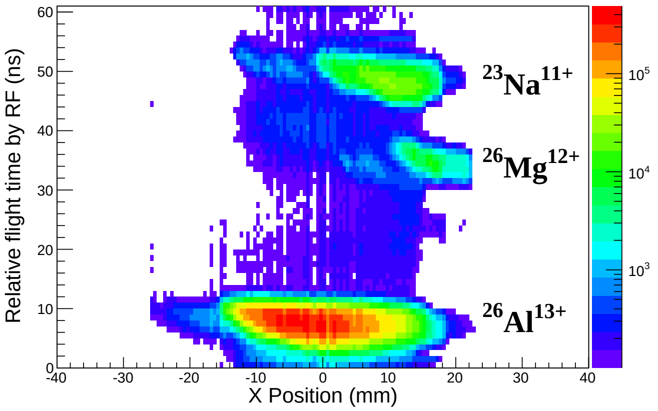

FIGURE 2. (Color online) Cocktail beam profile as measured at the experimental focal plane by the PPACs. The abscissa is the beam *X* position (the Wien filter dispersive axis) and the ordinate is the relative time-of-flight between the cyclotron RF and the PPAC. ^{26}Al is clearly separated. The only contaminants are *stable isotopes*.

radiative proton capture on $^{26\mathrm{m}}$Al have been based on the $^{26\mathrm{g}}$Al rate [16]. However, resonant radiative capture on $^{26\mathrm{g,m}}$Al would proceed through states with significantly different structure in the compound nucleus ^{27}Si; for example, an $\ell = 0$ proton capture on $^{26\mathrm{g}}$Al proceeds through $J^\pi = \frac{9}{2}^+, \frac{11}{2}^+$ states whereas in the case of $^{26\mathrm{m}}$Al $\frac{1}{2}^+$ states would instead be relevant. At present, $^{26\mathrm{m}}$Al states in ^{27}Si have been studied via charged-particle spectroscopy [17] and in-beam γ spectroscopy [18], while mirror states in ^{27}Al were recently studied by a neutron-transfer reaction on $^{26\mathrm{m}}$Al [19]. Although important progress has been made in the last decade, still 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. Proton resonant elastic scattering has long been known as an experimental probe sensitive to states with large proton partial widths and low ℓ transfer somewhat above the proton separation energy. As such, a measurement of $^{26\mathrm{m}}$Al(p, p) was performed as the method nicely complements the existing studies.

EXPERIMENT

We conducted a measurement of proton resonant elastic scattering with a mixed $^{26\mathrm{g,m}}$Al beam at the Center for Nuclear Study (CNS) low-energy radioactive ion beam (RIB) separator [20, 21], called CRIB. To produce the beam, we used the inflight method with a ^{26}Mg primary beam and a H_2-filled production target, producing the isotope of interest via the ^{1}H(^{26}Mg, ^{26}Al)n reaction. The ^{26}Mg beam was extracted from an ion source loaded with $^{\mathrm{nat}}$Mg (abundance of ^{26}Mg is 11%) and accelerated with the RIKEN AVF cyclotron 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 [22] 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 for effective target thicknesses ranging from 0.4 to 0.8 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.

The experimental setup, shown in Fig. 1, consisted of two parallel plate avalanche counters (PPACs) [23] to track the beam, a target slider, two ΔE–E silicon telescopes to measure protons, and an array of ten NaI detectors to measure γ-rays. The PPACs enabled us to track the beam ions event-by-event, to determine their trajectory and nuclear species as shown in Fig. 2. 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 isotope ^{23}Na and leaky primary beam ^{26}Mg [24]. 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

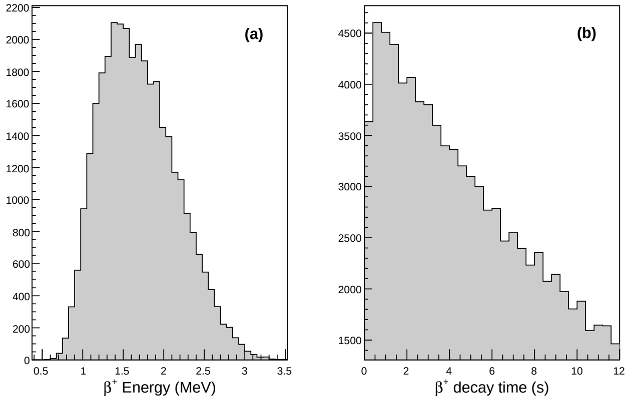

FIGURE 3. β^{+} decay measurements: (a) Energy spectrum and (b) Decay timing. Both are consistent with $^{26\mathrm{m}}$Al, which has a β^{+} Q-value of 3.2 MeV and a halflife of 6.3 s.

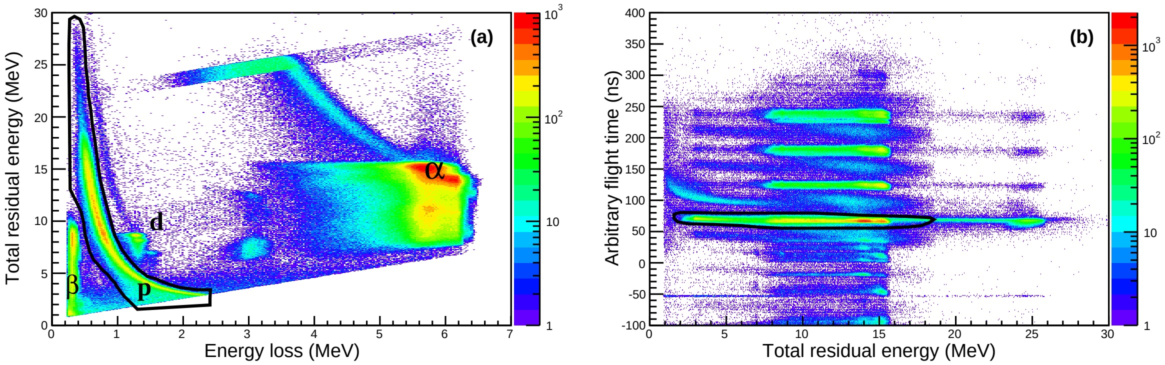

FIGURE 4. (Color online) Proton identification: (a) Energy loss from the 75 μm PSD and the sum of the residual light ion energy from the Si telescope. Several particle groups are seen and separated. A graphical cut for protons is shown. (b) Residual light ion energy from the Si telescope against time of flight between PPACa and the Si telescope. The depicted gate shows the scattered protons.

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. As mentioned above, we varied the isomeric purity by changing the RIB production conditions, and with the decay measurements we found the purity $^{26\mathrm{m}}$Al/$^{26\mathrm{g,m}}$Al did not change in a given run and preliminary results suggest it covered a range of roughly 50 ± 20% depending on the beam production conditions; for further information on the precise determination of the isomeric purity by the NaI experimental data and a GEANT4 simulation, please see the contribution of Shimizu *et al.* in these proceedings.

The physics data of astrophysical interest were obtained by measuring the protons elastically scattered by the ^{26}Al beam ions in inverse kinematics. The CH_2 target was thick enough to fully stop the heavy beam ions, but only induced a small energy loss to the scattered protons. The protons were measured with two silicon telescopes placed at forward angles in the laboratory (corresponding to backwards proton angles in the center-of-mass frame). 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. 4(a), and protons scattered by the ^{26}Al beam were further distinguished from other protons by the timing between PPACa and the Si telescope as shown in Fig. 4(b).

The proton spectra from the 0° telescope are shown in Fig. 5, where the spectra obtained with the C target are

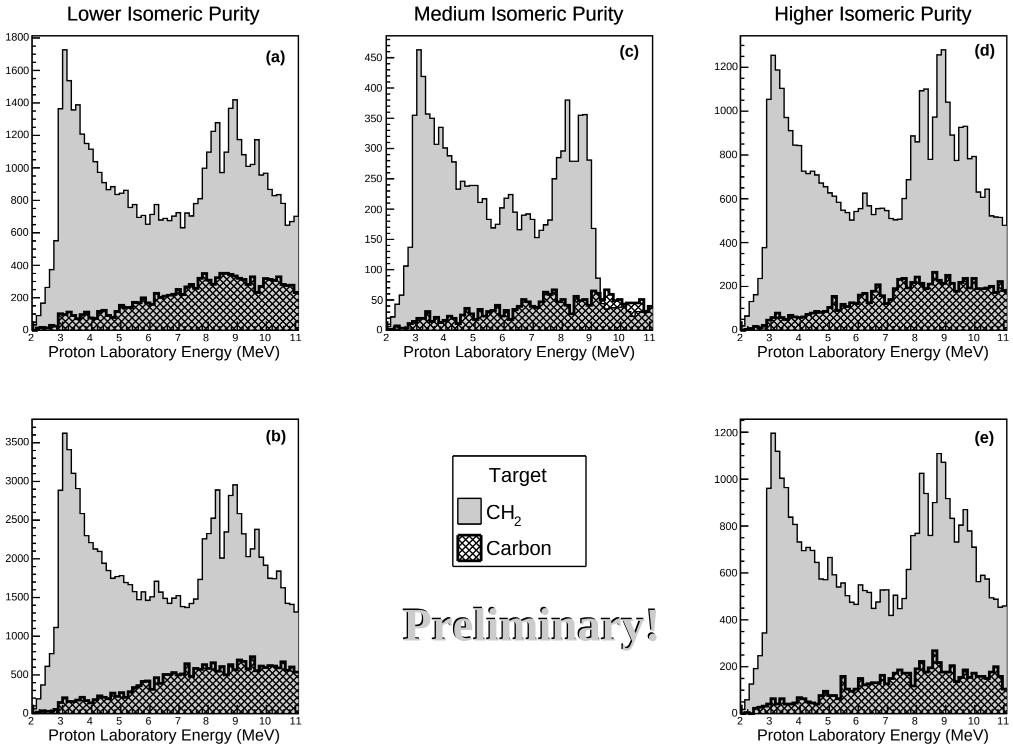

FIGURE 5. Residual *laboratory* energy histograms for protons scattered by ^{26}Al. Several peak structures which might be attributed to $^{26\mathrm{m}}$Al emerge as the isomeric purity increases left to right under different beam conditions. See the text

normalized to the number of incident ^{26}Al ions on CH_2 for comparison. Several important points must be emphasized regarding Fig. 5. Firstly, 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, and decreases with increasing angle. No correction has been applied for the energy loss of protons in the target, which has two important consequences: 1) The actual proton energy is somewhat higher than the measured one; 2) The energy scales of the CH_2 and C targets do not map identically to the center-of-mass frame owing to minor differences in the energy loss induced by the differing target number densities of carbon. Nevertheless, the background contribution from carbon appears to be quite smooth. In the future, we will add all the kinematic conditions including all energy losses 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 [25]. Thus, to obtain a given $^{26\mathrm{m}}$Al proton spectrum at low energy, 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 might arise from scatterings on either $^{26\mathrm{g,m}}$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 function 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 can be seen, and moreover they may become more prominent when the isomeric purity of the beam is higher. Although we already know there are no strong proton resonances from $^{26\mathrm{g}}$Al in this energy region, our data alone also indicate that these peaks arise from $^{26\mathrm{m}}$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 [19], 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 $E_{\mathrm{c.m.}}$.

CONCLUSIONS

We reported the first experimental work to produce an RIB of $^{26\mathrm{m}}$Al and control its isomeric purity. Using this beam, we measured $^{26\mathrm{m}}$Al proton resonant elastic scattering for the first time. We observed several peak-like structures around 1–2 MeV in $E_{\mathrm{c.m.}}$ in the $^{26\mathrm{m}}$Al+p system. Curiously, there are no strong $^{26\mathrm{g}}$Al proton resonances over the same energy region in ^{27}Si, possibly suggesting that $^{26\mathrm{m}}$Al is more efficiently destroyed by radiative proton capture than $^{26\mathrm{g}}$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 $^{26\mathrm{g,m}}$Al will be in thermal equilibrium for $T > 1$ GK, $^{26\mathrm{m}}$Al(p, γ) could be an efficient pathway to destroy $^{26\mathrm{g}}$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 experiment was performed at RI Beam Factory operated by RIKEN Nishina Center and CNS, University of Tokyo. This work was partly supported by grants from the Science and Technology Facilities Council (STFC) in the United Kingdom, the JSPS KAKENHI (Grants No. 25800125 and 16K05369) in Japan, grants from the National Research Foundation (NRF) funded by the Korea government (MEST) (No. NRF-2014S1A2A2028636, NRF-2015R1D1A1A01056918, NRF-2016K1A3A7A09005579, and NRF-2016R1A5A1013277), and the Natural Sciences and Engineering Council of Canada. We also sincerely thank both the CNS and RIKEN staff for operation of the ion source and accelerator during the machine time.

REFERENCES

[1] W. A. Mahoney, J. C. Ling, A. S. Jacobson, and R. E. Lingenfelter, Astrophysical Journal **262**, p. 742 (1982).

[2] G. H. Share, R. L. Kinzer, J. D. Kurfess, D. J. Forrest, E. L. Chupp, and E. Rieger, Astrophysical Journal **292**, p. L61 (1985).

[3] R. Diehl, C. Dupraz, K. Bennett, H. Bloemen, W. Hermsen, J. Knoedlseder, G. Lichti, D. Morris, J. Ryan, V. Schoenfelder, H. Steinle, A. Strong, B. Swanenburg, M. Varendorff, and C. Winkler, Astronomy and Astrophysics **298**, p. 445 (1995).

[4] R. Diehl, H. Halloin, K. Kretschmer, G. G. Lichti, V. Schönfelder, A. W. Strong, A. von Kienlin, W. Wang, P. Jean, J. Knödlseder, J.-P. Roques, G. Weidenspointner, S. Schanne, D. H. Hartmann, C. Winkler, and C. Wunderer, Nature **439**, p. 45 (2006).

[5] K. Kretschmer, R. Diehl, M. Krause, A. Burkert, K. Fierlinger, O. Gerhard, J. Greiner, and W. Wang, Astronomy and Astrophysics **559**, p. A99 (2013).

[6] M. Limongi and A. Chieffi, Astrophysical Journal **647**, p. 483 (2006).

[7] J. José, M. Hernanz, and A. Coc, Astrophysical Journal **479**, p. L55 (1997).

[8] M. B. Bennett, C. Wrede, K. A. Chipps, J. José, S. N. Liddick, M. Santia, A. Bowe, A. A. Chen, N. Cooper, D. Irvine, E. McNeice, F. Montes, F. Naqvi, R. Ortez, S. D. Pain, J. Pereira, C. Prokop, J. Quaglia, S. J. Quinn, S. B. Schwartz, S. Shanab, A. Simon, A. Spyrou, and E. Thiagalingam, Physical Review Letters **111**, p. 232503 (2013).

[9] N. Mowlavi and G. Meynet, Astronomy and Astrophysics **361**, p. 959 (2000).

[10] L. Siess and M. Arnould, Astronomy and Astrophysics **489**, p. 395 (2008).

[11] R. Diehl, *Journal of Physics Conference Series*, Journal of Physics Conference Series, **703**, p. 012001 (2016).

[12] R. A. Ward and W. A. Fowler, Astrophysical Journal **238**, p. 266 (1980).

[13] A. Coc, M. Porquet, and F. Nowacki, Physical Review C **61**, p. 015801 (2000).

[14] R. C. Runkle, A. E. Champagne, and J. Engel, Astrophysical Journal **556**, p. 970 (2001).

[15] S. S. Gupta and B. S. Meyer, Physical Review C **64**, p. 025805 (2001).

[16] C. Iliadis, A. Champagne, A. Chieffi, and M. Limongi, ApJS **193**, p. 16 (2011).

[17] C. M. Deibel, J. A. Clark, R. Lewis, A. Parikh, P. D. Parker, and C. Wrede, Physical Review C **80**, p. 035806 (2009).

[18] G. Lotay, P. J. Woods, D. Seweryniak, M. P. Carpenter, R. V. F. Janssens, and S. Zhu, Physical Review C **80**, p. 055802 (2009).

[19] S. Almaraz-Calderon, K. E. Rehm, N. Gerken, M. L. Avila, B. P. Kay, R. Talwar, A. D. Ayangeakaa, S. Bottoni, A. A. Chen, C. M. Deibel, C. Dickerson, K. Hanselman, C. R. Hoffman, C. L. Jiang, S. A. Kuvin, O. Nusair, R. C. Pardo, D. Santiago-Gonzalez, J. Sethi, and C. Ugalde, Phys. Rev. Lett. **119**, p. 072701 (2017).

[20] S. Kubono, Y. Yanagisawa, T. Teranishi, S. Kato, Y. Kishida, S. Michimasa, Y. Ohshiro, S. Shimoura, K. Ue, S. Watanabe, and N. Yamazaki, European Physical Journal A **13**, p. 217 (2002).

[21] Y. Yanagisawa, S. Kubono, T. Teranishi, K. Ue, S. Michimasa, M. Notani, J. J. He, Y. Ohshiro, S. Shimoura, S. Watanabe, N. Yamazaki, H. Iwasaki, S. Kato, T. Kishida, T. Morikawa, and Y. Mizoi, Nuclear Instruments and Methods in Physics Research A **539**, p. 74 (2005).

[22] H. Yamaguchi, Y. Wakabayashi, G. Amadio, S. Hayakawa, H. Fujikawa, S. Kubono, J. J. He, A. Kim, and D. N. Binh, Nuclear Instruments and Methods in Physics Research A **589**, p. 150 (2008).

[23] H. Kumagai, A. Ozawa, N. Fukuda, K. Sümmerer, and I. Tanihata, Nuclear Instruments and Methods in Physics Research A **470**, p. 562 (2001).

[24] D. Kahl, H. Yamaguchi, H. Shimizu, K. Abe, O. Beliuskina, S. M. Cha, K. Y. Chae, Z. Ge, S. Hayakawa, M. S. Kwag, D. H. Kim, J. Y. Moon, S. Y. Park, and L. Yang, Nuovo Cimento C **39**, p. 362 (2016).

[25] S. T. Pittman, D. W. Bardayan, K. Y. Chae, K. A. Chipps, K. L. Jones, R. L. Kozub, C. Matei, M. Matos, B. H. Moazen, C. D. Nesaraja, P. D. O'Malley, S. D. Pain, P. D. Parker, W. A. Peters, J. F. Shriner, Jr., and M. S. Smith, Physical Review C **85**, p. 065804 (2012).