PROCEEDINGS OF SCIENCE

Measurement of the Beta Decay of ^{26}P to Determine Classical Nova ^{26}Al Production in the Milky Way Galaxy

M.B. Bennett, [1,2] * **C. Wrede,** [1,2,3] **K.A.Chipps,** [4] **J.José,** [5] **S.N.Liddick,** [6,2] **M.Santia,** [1,2] **A.Bowe,** [1,2,7] **A.A. Chen,** [8] **N. Cooper,** [9] **D. Irvine,** [2,10] **E. McNeice,** [8] **F. Montes,** [2,10] **F. Naqvi,** [9] **R. Ortez,** [1,2,3] **S.D. Pain,** [11] **J. Pereira**[2,10]**, C. Prokop**[6,2]**, J. Quaglia**[12,10,2]**, S.J. Quinn**[1,2,10]**, S.B. Schwartz**[1,2,13]**, S. Shanab,**[1,2] **A. Simon,**[2,10] **A. Spyrou,**[1,2,10] **and E. Thiagalingam**[8]

Observation across the Milky Way of a 1809-keV γ-ray characteristic of ^{26}Al decay provides direct evidence for ongoing nucleosynthetic production of ^{26}Al. Although massive stars and supernovae are likely to be the primary sites for ^{26}Al production, classical novae may also contribute a significant portion of the total amount of Galactic ^{26}Al. At peak nova temperatures of approximately 0.4 GK, the rate of the ^{25}Al(p,γ)^{26}Si reaction, which bypasses ^{26}Al production and therefore places an upper limit on the amount of ^{26}Al contributed by novae to Galactic abundances, is likely dominated by a single 3^+ resonance. Constraining the energy and strength of this resonance is therefore critical to determining the ^{25}Al(p,γ)^{26}Si reaction rate. We have used a radioactive ^{26}P beam produced at the National Superconducting Cyclotron Laboratory to populate the 3^+ state via beta decay, and have observed first evidence for its γ decay branch, the last piece of information needed to calculate the resonance strength. We find the 3^+ state to have a resonance energy of E_r = 414.9 ± 0.6 (stat) ± 0.3 (syst) ± 0.6 (lit.) keV and a resonance strength of $\omega\gamma$ = 23 ± 6 (stat) $^{+11}_{-10}$ (lit.) meV. We have also used hydrodynamic nova simulations to model ^{26}Al production and we find that novae may contribute up to 0.6 solar masses of the Galactic ^{26}Al – 38% of the total Galactic ^{26}Al abundance.

XIII Nuclei in the Cosmos
7-11 July, 2014
Debrecen, Hungary

* Speaker
[1] Department of Physics and Astronomy, Michigan State University, East Lansing, Michigan 48824, USA
[2] National Superconducting Cyclotron Laboratory, Michigan State University, East Lansing, Michigan 48824, USA
[3] Department of Physics, University of Washington, Seattle, Washington 98195, USA
[4] Department of Physics, Colorado School of Mines, Golden, Colorado 08401, USA
[5] Departament Fı´sica i Enginyeria Nuclear (UPC) and Institut d'Estudis Espacials de Catalunya (IEEC), E-08034 Barcelona, Spain
[6] Department of Chemistry, Michigan State University, East Lansing, Michigan 48824, USA
[7] Physics Department, Kalamazoo College, Kalamazoo, Michigan 49006, USA
[8] Department of Physics and Astronomy, McMaster University, Hamilton, Ontario L8S 4M1, Canada
[9] Department of Physics and Wright Nuclear Structure Laboratory, Yale University, New Haven, Connecticut 06520, USA
[10] Joint Institute for Nuclear Astrophysics, Michigan State University, East Lansing, Michigan 48824, USA
[11] Oak Ridge National Laboratory, Oak Ridge, Tennessee 37831, USA
[12] Department of Electrical Engineering, Michigan State University, East Lansing, Michigan 48824, USA
[13] Geology and Physics Department, University of Southern Indiana, Evansville, Indiana 47712, USA

PoS(NIC XIII)040

1.Introduction

Classical novae are cataclysmic thermonuclear explosions occurring on the surface of hydrogen-accreting white-dwarf stars in binary systems [1]. In these violent events, a peak temperature of 0.4 GK may be achieved, providing opportunity for so-called nova nucleosynthesis. Here, ground-state ^{26}Al is produced via the proton capture reaction ^{25}Mg(p,γ)^{26}Al and bypassed by a reaction chain involving the ^{25}Al(p,γ)^{26}Si reaction. While the primary location of galactic ^{26}Al production is thought to be massive stars, previous work on the classical nova contribution has suggested that up to 0.4 $M_\odot$ may be produced in O-Ne novae as a secondary source [2]. In order to determine the overall quantity of ^{26}Al produced in classical novae, it is necessary to determine the ^{25}Al(p,γ)^{26}Si reaction rate.

At nova temperatures, proton capture on ^{25}Al is dominated by the strengths of resonance states above the proton emission threshold in ^{26}Si. While there are three known resonances (spins and parities 0^+, 1^+, and 3^+) that could contribute to the ^{25}Al(p,γ)^{26}Si reaction rate, only the 3^+ resonance at 5.93 MeV is expected to contribute significantly to the total rate at peak nova temperatures [3,4]. This 3^+ state decays primarily by proton emission, and its proton decay partial width has been measured to be Γ_p = 2.9 ± 1.0 eV [6]. Unfortunately, however, the gamma decay branch from this state, which has not been observed, sets the resonance strength. This radiative exit channel is expected to proceed primarily via emission of a gamma-ray of approximately 1740 keV [7-9] from the 3^+ resonance state to the second 3^+ state in ^{26}Si at 4187 keV [10]. Conveniently, even though direct measurements of proton capture to this ^{26}Si state are not yet possible, it is possible to exploit the relatively strong beta-decay population of the state from ^{26}P in order to study its properties [11].

In the execution of this experiment, we utilized a fast ^{26}P rare isotope beam to measure the 1.74-MeV gamma-ray de-excitation of the 3^+ resonance in order to determine an experimental value for its gamma decay partial width and hence the resonance strength.

2.Experimental Setup

^{26}P ions were produced at the National Superconducting Cyclotron Laboratory (NSCL) via fragmentation of a primary ^{36}Ar beam of energy 150 MeV/u and current 75 pnA upon a 1.55 g/cm^2 Be target. In order to filter out unwanted fragments, the A1900 fragment separator was used along with an achromatic Al wedge [12]. This secondary beam was further purified using the Radio Frequency Fragment Separator [13], resulting in a final ^{26}P beam of approximately 75% purity. To accomplish particle identification, a pair of 60-μm Si PIN detectors located approximately one meter upstream of the experimental setup was used. These detectors recorded energy deposition and served as one end of a time-of-flight measurement between a scintillator at the focal plane of the A1900 and the PIN detectors.

The experimental setup included a planar double-sided strip detector (GeDSSD) [14]. The GeDSSD was electrically segmented in orthogonal directions on the front and back sides respectively, creating a pixelation that allowed for determinations of accurate implantation and decay locations. In addition to this pixelation, the GeDSSD electronics output both at a high-gain and a low-gain setting, enabling discrimination between implants and decays on an event-by-event basis.

To detect the gamma de-excitation of the 3^+ resonance state, the GeDSSD was surrounded by the Segmented Germanium Array (SeGA) in a barrel configuration [15] of two concentric rings of eight detectors each. Each detector was a coaxial germanium crystal which could be used not only for gamma-ray detection but for γ-γ coincidence measurements. The electrical signals from both SeGA and the GeDSSD, as well as the PIN detectors, were collected using the NSCL Digital Data Acquisition System [16].

3. Analysis and Discussion

During offline analysis [17], the gamma-ray signals from the 16 SeGA detectors were gain-matched and added together in an energy spectrum. In order to reduce the data, a series of cuts were employed. First, only gamma-ray events happening within a coincidence time window of approximately 1.2 μs with a beta-decay event in the GeDSSD were accepted. These cuts reduced room background in the SeGA detectors. Figure 1 shows the resulting gamma-ray spectrum in the region of interest. A previously-unidentified peak was observed at 1741.6 ± 0.6(stat) ± 0.3(sys) keV, consistent with expected values for the gamma-ray de-exciting the 3^+ resonance state.

In order to test the hypothesis that the new peak indeed corresponded to the radiative exit channel for the 3^+ resonance state, we produced a spectrum of beta-delayed gamma-ray events which where also in coincidence with the 1401-keV gamma-ray de-exciting the second 3^+ state [10], to which the 3^+ resonance decays. Given the observed background of random coincidences in the region of interest, a total of 3.4 ± 0.9(stat) ± 0.4(sys) coincidences were expected. However, a total of 9 counts were actually observed, which for a Poisson distribution has only a 0.4% chance of happening. Given the significance of the peak in the singles spectrum (3.9σ) and the low probability of observing so many γ-γ coincidences by accident, along with the consistency of the energy measurement with expected values for this peak, the peak was assigned to the transition from the 3^+ resonance state.

Using the observed intensity of the peak, the total β-γ intensity of primary gamma-rays from the 1742-keV level was calculated. With this number, the known proton decay intensity through the level, and the known proton decay partial width, the gamma decay partial width was then calculated to be $\Gamma_\gamma = 40 \pm 11(\text{stat})^{+19}_{-18}(\text{lit.})$ meV. With this value, a resonance strength of $23 \pm 6(\text{stat})\ ^{+11}_{-10}(\text{lit.})$ meV was then calculated. This value of the resonance strength is the first value based on actual measurement of the ^{26}Si partial widths and branching ratios; previous estimates have been based on shell model calculations [18] or measurements of the ^{26}Mg mirror level [5,19,20].

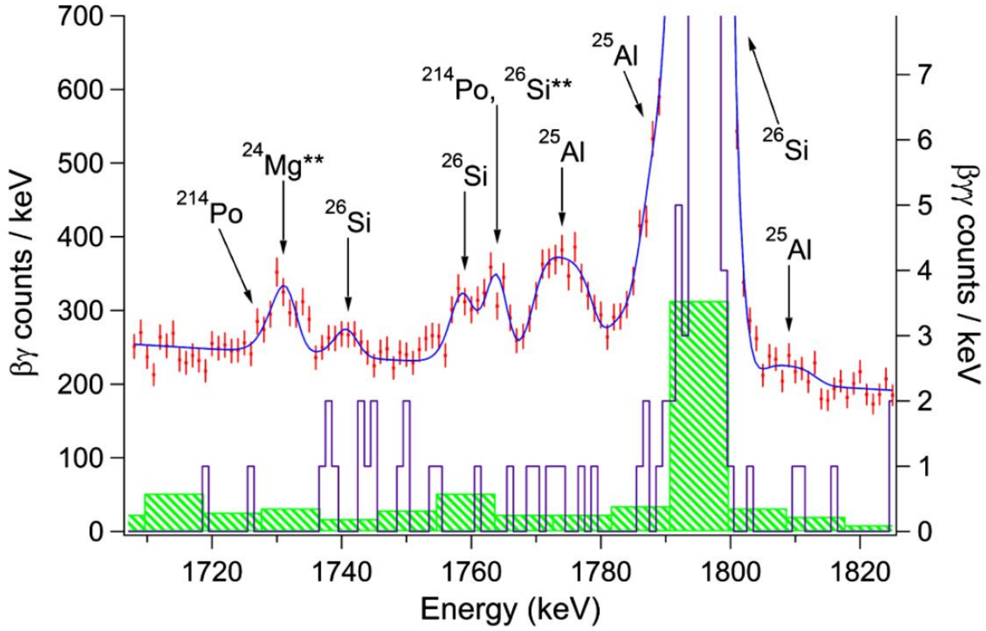

Figure 1: Beta-delayed gamma spectrum (left axis, red points) and β-γ-γ coincidences (right axis). Error bars are 1 standard deviation. All peaks corresponding to radiation-producing nuclides have been labeled, and the solid curve is a fit to the data including these transitions. The open histogram represents events coincident with the 1401-keV gamma ray, while the hatched histogram represents coincidences with continuum background in an energy region just above 1401 keV.

The measured value for the resonance strength was used to calculate a thermonuclear reaction rate. This rate and its upper and lower limits were then used as input to the state-of-the-art hydrodynamic nova modeling code SHIVA [21] to simulate ^{26}Al production in classical novae. It is worth noting that even treating the above calculated 3^+ resonance strength as an upper limit and varying it between 0 and its above value in the simulation input, the amount of ^{26}Al produced in the nova simulations was unchanged for novae on all but the most massive, and therefore rarest, white dwarf stars. The results of the simulations and rough estimates of the galactic nova rate therefore show that the nova contribution to galactic ^{26}Al production may be as high as 0.6 $M_\odot$, an increase from the previously-estimated value of 0.4 $M_\odot$. Considering the recently-updated estimate on the amount of galactic ^{26}Al of 2.25 ± 0.65 $M_\odot$ [22], it is possible that classical novae may contribute as much as 38% of observed galactic ^{26}Al.

4. Outlook

The ^{25}Al(p,γ)^{26}Si reaction rate was the last nuclear physics uncertainty affecting galactic ^{26}Al production in models of classical novae. Uncertainties in this value are now astrophysical or astronomical in nature, and in the near future could be reduced by improving both the estimation of the ONe nova occurrence rate and the amount of ^{26}Al in the galaxy. In addition, incorporating multiple-dimensionality and mixing into nova models will greatly help in the calculation and prediction of nova production of ^{26}Al.

This work was supported by the U.S. National Science Foundation under Grants No. PHY-1102511 and No. PHY 08-22648, the U.S. Department of Energy under Contract No. DE-FG02-97ER41020, the U.S. National Nuclear Security Agency under Contract No. DE-NA0000979, MEC Grant No. AYA2010-15685, and the ESF EUROCORES Program EuroGENESIS through Grant No. EUI2009-04167. We gratefully acknowledge A. García for advice during the preparation of our experimental proposal and the NSCL Operations staff for delivering the beam.

References

[1] J. José, M. Hernanz, and A. Coc, *Astrophys. J. Lett. 469* (1997) L55

[2] N. Prantzos and R. Diehl, *Phys Rep 267* (1996) 1

[3] A. Parikh and J. José, *Phys. Rev. C 88* (2013) 048801

[4] D.W. Bardayan *et al., Phys. Rev. C 74* (2006) 045804

[5] C. Wrede, *Phys. Rev. C 79* (2009) 035803

[6] P.N. Peplowski *et al., Phys. Rev. C 79* (2009) 0.32801(R)

[7] G. Audi *et al., Chin. Phys. C 36* (2012) 1157

[8] J.-C. Thomas *et al., Eur. Phys. J. A 21* (2004) 419

[9] K.A. Chipps *et al., Phys. Rev. C 82* (2010) 045803

[10] D. Seweryniak *et al., Phys. Rev. C 75* (2007) 0.62801(R)

[11] C. Wrede, *Proc. Sci., NIC XII* (2012) 242

[12] D. Morrissey *et al., Nucl. Instrum. Methods Phys. Res., Sect. B 204* (2003) 90

[13] D. Bazin *et al., Nucl. Instrum. Methods Phys. Res., Sect. A 606* (2009) 314

[14] N. Larson *et al., Nucl. Instrum. Methods Phys. Res., Sect. A 727* (2013) 59

[15] W.F. Mueller *et al., Nucl. Instrum. Methods PHys. Res., Sect. A 466* (2001) 492

[16] K. Starosta *et al., Nucl. Instrum. Methods Phys. Res., Sect. A 610* (2009) 700

[17] M. B. Bennett *et al., Phys. Rev. Lett. 111* (2013) 232503

[18] W.A. Richter *et al., Phys. Rev. C 83* (2011) 065803

[19] D.W. Bardayan *et al., Phys. Rev. C 65* (2002) 032801(R)

[20] F Glatz *et al., Z. Phys. A 324* (1986) 324

[21] J. José and M. Hernanz, *Astrophys. J. 494* (1986) 187

[22] R. Diehl, "Introduction to Gamma-Ray Astronomy," 2014 Russbach School, Rußbach am Paß Gschütt, Austria