Study of astrophysically important states in ^{26}Si with the p(^{27}Si,d)^{26}Si* reaction and the p(^{25}Al,p)^{25}Al elastic scattering

J. Chen[∗a], **A. A. Chen**[a], **G. Amadio**[b], **D. Bazin**[c,l], **A. Becerril**[c,l], **A. M. Amthor**[c,l], **S. Cherubini**[i], **M. La .Cognata**[i], **D. Galaviz**[c,l], **A. Gade**[c,l], **T. Glasmacher**[c,l], **H. Fujikawa**[b], **S. Hayakawa**[b], **N. Iwasa**[k], **J. J. He**[b], **D. Kahl**[a], **L. H. Khiem**[b], **S. Kubono**[b], **Y. Kurihawa**[b], **Y. K. Kwon**[d], **J. LeNestour**[a], **G. Lorusso**[c,l], **M. Matos**[c,l], **J Y. Moon**[d], **M. Niikura**[b], **S. Nishimura**[g], **A. Odahara**[f], **C. V. Ouellet**[a], **J. Pearson**[a], **J. Pereira**[c,l], **R. Pizzone**[i], **A. Saito**[b], **H. Schatz**[c,l], **A. Signoracci**[c,l], **C. Signorini**[j], **A. Smith**[a], **K. Smith**[c,l], **T. Teranishi**[e], **Y. Togano**[h], **B. Wales**[a], **Y. Wakabayashi**[b], **D. Weisshaar**[c,l], **H. Yamaguchi**[b], **R. Zegers**[c,l]

[a]*Department of Physics and Astronomy, McMaster University, Canada*
[b]*Center for Nuclear Study, Graduate School of Science, University of Tokyo, Japan*
[c]*National Superconducting Cyclotron Laboratory, Michigan State University, USA*
[d]*Department of Physics, Chung-Ang University, South Korea*
[e]*Department of Physics, Kyushu University, Japan*
[f]*Department of Physics, Nishinippon Institute of Technology, Japan*
[g]*RIKEN (The Institute of Physical and Chemical Research)*
[h]*Department of Physics, Rikkyo University, Japan*
[i]*Department of Physics, University of Catania and INFN, Italy*
[j]*Department of Physics, University of Padova and INFN, Italy*
[k]*Department of Physics, Tohoku University, Japan*
[l]*Department of Physics, Michigan State University, USA*

E-mail: `chenj26@mcmaster.ca`

The radioisotope ^{26}Al is an important probe of the interstellar medium of our galaxy, but its production is now still not well determined partially due to the lack of knowledge of the important states in ^{26}Si, which dominate the large uncertainty in the ^{25}Al$(p,\gamma)^{26}$Si reaction rate at nova temperatures. We give an update on two experiments that were performed to study these states. One is a measurement of the ^{27}Si(p,d)^{26}Si* reaction at the NSCL, and the other one is a measurement of the ^{25}Al+p elastic scattering with the CRIB facility at RIKEN.

10th Symposium on Nuclei in the Cosmos
July 27 - August 1, 2008
Mackinac Island, Michigan, USA

[∗]Speaker.

1. Introduction

Galactic ^{26}Al is observed through the emission of 1.8 MeV gamma rays from the decay of ^{26g}Al produced by the proton capture on ^{25}Mg. In nova explosions, the proton capture of ^{25}Al competes with its β decay and bypasses the production of ^{26g}Al, since the capture product ^{26}Si decays quickly to ^{26m}Al instead of its ground state, without the emission of the 1.8 MeV gamma ray. But at even higher temperatures, such as in supernova explosions, ^{26m}Al can be excited to the higher excited states by thermal excitation and then quickly de-excite to the ground state, thereby enhancing the production of ^{26g}Al [1]. The energy levels in ^{26}Si in the Gamow window corresponding to these temperatures therefore need to be well understood in order to determine the ^{25}Al(p,γ)^{26}Si reaction rate, and thus the production rate of ^{26}Al in these explosive environments.

Two experiments were performed to study the important states in ^{26}Si : one is the p(^{27}Si,d)^{26}Si* reaction at the NSCL, aiming to construct the level scheme of low lying states around the proton threshold; the other experiment is a measurement of the elastic scattering of ^{25}Al+p with CRIB [2] at RIKEN in order to obtain information on states in a broad range above the proton threshold [3]. The thick target method with inverse kinematics [4, 5] was used in the latter experiment, with the advantage that a wide range of energy levels can be scanned simultaneously with only one beam energy, and the scattered protons are detected at forward angles in the laboratory system.

2. Experimental Details

The radioactive ^{27}Si ($T_{1/2}$=4.16s) beam used in the NSCL experiment was produced by fragmenting 150 MeV/nucleon ^{36}Ar primary beam ions on a 940 mg/cm^2 ^{9}Be target, resulting in a ^{27}Si beam energy of 89 MeV/nucleon, with an intensity of about 1×10^7 pps and purity of about 36%. A 250 mg/cm^2 polypropylene foil (CH_2) was used as the secondary target, which is surrounded by a highly segmented germanium detector array (SeGA) for detecting the gamma rays from the decay of the ^{26}Si* recoils. These gamma rays were detected in coincidence with the detection of the ^{26}Si recoils at the S800 focal plane [6, 7]. The SeGA detectors were arranged in two rings at 37° and at 90°. Each detector consists of 32 segments, providing accurate 3-dimensional position for the Doppler broadening correction of the measured gamma ray energies. The detector system on the S800 focal plane consists of a pair of cathode readout drift chambers (CRDC) for beam tracking information, followed by a multi-segmented ion chamber for energy loss measurement, and three large plastic scintillators for timing and total energy measurements. The ^{26}Si recoils were identified by the time of flight (TOF) from the scintillators together with the energy loss in the ion chamber.

The CRIB elastic scattering experiment was performed using a 7.5 MeV/A ^{24}Mg primary beam. The reaction ^{2}H(^{24}Mg,n)^{25}Al was used to produce the secondary ^{25}Al beam with energy of about 3.4 MeV/A, a purity of about 50% and intensity of up to 10^6 pps. The secondary beam was identified by two PPACs (Parallel Plate Avalanche Counters), which were also used for beam tracking to determine the beam position on target, and the scattering angle when combined with the proton position measured on a PSD (Position-Sensitive silicon Detector). The secondary target was a 6.58 mg/cm^2 CH_2 target, which was thick enough to stop the ^{25}Al beam ions. The elastically scattered protons were measured with 3 sets of ΔE-E telescopes at 0°, 17° and 27°, respectively. Each telescope consists of one 75μm double-sided 16ch$\times$16ch PSD and two 1500μm single channel SSDs (Silicon Strip Detectors). Directly above the target, 10 NaI detectors were used to detect γ-rays from the decay of the first excited state of the ^{25}Al produced in the inelastic proton scattering.

The scattered protons that punch through the PSD were identified by using the ΔE versus E spectrum, while the spectrum of PSD energy versus TOF (between the PSD and the second PPAC) was used to identify both protons punching through the PSD and the ones stopped in the PSD.

3. Data Analysis

I. For the p(^{27}Si,d)^{26}Si* experiment:

To select only the gamma rays coincident with the ^{26}Si recoils, a gate was applied on the histogram of TOF vs ΔE measured by the detector system at the focal plane. Due to the high velocity of the beam particles, the Doppler broadening is significant for the gamma ray measurement, and is corrected as follows:

$$E_{\gamma,dop} = \frac{1-\beta cos\theta}{\sqrt{1-\beta^2}} E_{\gamma,measured}$$

where $E_{\gamma,dop}$, $E_{\gamma,measured}$, β, θ represent the corrected gamma ray energy, the measured gamma ray energy, the ^{27}Si beam velocity and the gamma ray emission angle, respectively. Figure 1 shows the spectrum of corrected gamma rays. Since a cascade of gamma rays can be emitted from an excited state in a single reaction, the γ-γ coincidence analysis technique is usually used to construct the level scheme. Figure 2 (black histogram) shows an example of a coincidence spectrum of the gamma ray of 1400 keV from the transition from the excited state of ^{26}Si at 4184 keV to the excited state at 2783 keV [8]. The energy of the 4184 keV state can then be confirmed by adding the energies of the cascade γ-rays (1400 keV, 993 keV and 1796 keV). Also shown in red is the corresponding background spectrum, which is obtained by placing gates on the tails around the gated peak, since it is not practical to separate the background gamma rays from the actual transition γ-rays inside the gated peak energy range. After all cascades are extracted from the γ-γ coincidence analysis, they will be compared to the equivalent ones from the well known states in ^{26}Mg, the mirror nucleus of ^{26}Si, to determine spin-parity assignments of the ^{26}Si states.

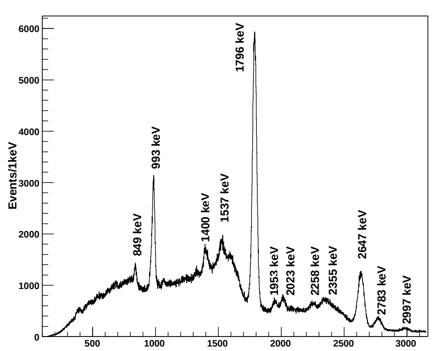

Figure 1: Doppler corrected gamma-ray spectrum. The energies indicated are from skewed Gaussian fits to the peaks.

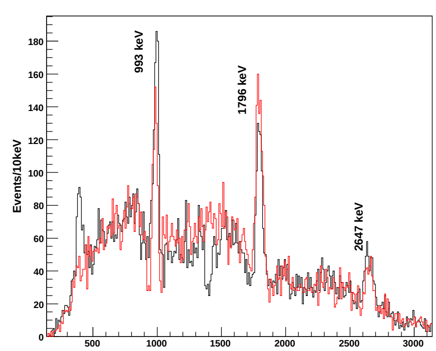

Figure 2: An example of a coincidence gamma-ray spectrum for the gamma ray of 1400 keV (in black), with its background shown in red.

II. For the p(^{25}Al,p)^{25}Al experiment:

When using the thick target method, the energy loss of the scattered proton traveling through the remaining part of the target must be taken into account. The following steps were performed to account for this energy loss event by event. First, the range of the ^{25}Al beam in the CH_2 target is determined and then divided into 5000 equal parts. The residual energy of the ^{25}Al beam is calculated after each part using Ziegler's energy-loss routines [9]. The proton energy at the scattering location is also calculated. Knowing the length of the path the proton takes through the target, its energy after the target is obtained and compared with the measured proton energy for a given event. The original proton energy of this event, i.e., the energy of the proton with energy loss correction included, is then deduced from the comparison.

The total yields of background protons of different energies from a carbon target were normalized by the inverse ratio of the energy-dependent stopping power of the proton in the CH_2 and C targets, as well as the ratio of the total number of beam events for each target times the number density of carbon in the target. The yield Y is given by the equation:

$$Y = I\sigma n\Delta x = I\sigma n\Delta E/\frac{dE}{dx}(E).$$

where I represents the accumulated number of events, n is the number density of the target material and Δx is the target thickness per energy bin ΔE in the spectrum, which is inversely proportional to the stopping power of the proton at the corresponding energy. From the above formula,the excitation function can be obtained from the yield spectrum by multiplying Y by the energy-dependent stopping power dE/dx since $\sigma \propto Y \times \frac{dE}{dx}$.

Figure 3 shows a proton spectrum after correcting for the energy loss in the target.

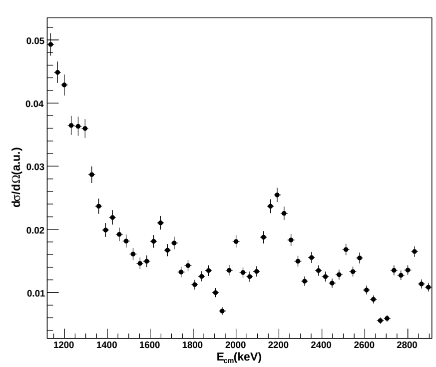

Figure 3: Excitation function in the center of mass frame with energy loss correction and background subtraction.

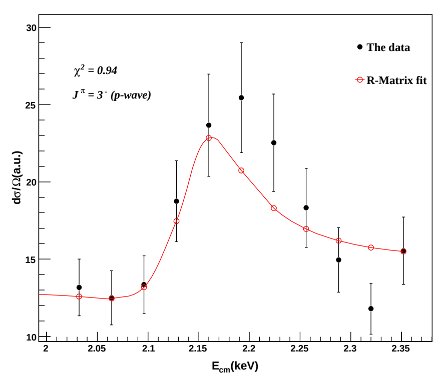

Figure 4: A sample R-Matrix fit for the resonance at E_R=2.186 MeV.

An R-Matrix [10] fit for the excitation function will be used to extract physical parameters such as energy levels and proton widths. Assuming only one open channel (elastic scattering) and only one level per J^{π}, then the single-channel single-level R-Matrix formula will be used:

$$\frac{d\sigma}{d\Omega} = \frac{\pi}{k^2}[(2I_1+1)(2I_2+1)]\sum_{ss'}(CT+RT+IT).$$

where I_1, I_2 are the spins of the nuclei in the entrance channel; s, $s^{'}$ are the channel spins of the entrance and the exit channels; and CT, RT, and IT are the Coulomb term, resonant term and interference term, respectively. All terms depend on the single-channel single-level R function:

$$R = \frac{\gamma^2}{E_\lambda - E}$$

where γ and E_λ are the reduced level width and resonance energy respectively, the two physical parameters to be extracted from the fitting. Figure 4 shows a sample fit for the resonance at E_R=2.186 MeV.

4. Ongoing and Future Work

The analysis towards getting the final outcome is ongoing. It includes, for the p(^{27}Si,d)^{26}Si* experiment, constructing level schemes from the coincidence analysis of gamma rays to determine the energies and spin-parity assignments of the levels; and for the elastic scattering experiment, extracting the energies and J^π for the resonances in the excitation function by a least-squares fit using the R-Matrix theory for compound nuclear reactions. Results from both analyses will be used as input for calculating the new ^{25}Al(p,γ)^{26}Si reaction rate.

References

[1] R. C. Runkle ,A. E. Champagne, and J. Engel, *Thermal Equilibration of ^{26}Al*, APJ **556** (2001) 970-978

[2] S. Kubono *et al.*, *New low-energy RIB separator CRIB for nuclear astrophysics*, EPJ A **13** (2002) 217-220

[3] J. Chen *et al.*, *Study of Astrophysically Important States in ^{26}Si through Elastic Scattering with CRIB*, CNS Annual Report **2006** (2007) 5

[4] S. Kubono, *Experimental determination of astrophysical reaction rates with radioactive nuclear beams*, NPA **693** (2001) 221-248.

[5] A. H. Hernández *et al.*, *Proton resonance reactions using thick targets in inverse kinematics* , NIM B **143** (1998) 569-574

[6] D. Bazin *et al.*, *The S800 spectrograph*, NIM B **204** (2003) 629-633

[7] J. Yurkon *et al.*, *Focal plane detector for the S800 high-resolution spectrometer*, NIM A **422** (1999) 291-295

[8] J. C. Thomas *et al.*, *Beta-decay properties of ^{25}Si and ^{26}P*, EPJ A **21** (2004) 419-435

[9] J.F. Ziegler, The Stopping and Ranges of Ions in Matter,vols. 3 and 5, Pergamon Press, Oxford, 1980.

[10] A. M. Lane, and R. G. Thomas, *R-Matrix Theory of Nuclear Reactions*, Rev. Mod. Phys. **30** (1958) 257