PROCEEDINGS OF SCIENCE

The Beta-Delayed Proton and Gamma Decay of ^{27}P For Nuclear Astrophysics

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Abstract. The creation site of ^{26}Al is still under debate. It is thought to be produced in hydrogen burning and in explosive helium burning in novae and supernovae, and possibly also in the H-burning in outer shells of red giant stars. Also, the reactions for its creation or destruction are not completely known. When ^{26}Al is created in novae, the reaction chain is: ^{24}Mg(p,γ)^{25}Al(β^{+})^{25}Mg(p,γ)^{26}Al, but this chain can be by-passed by another chain: ^{25}Al(p,γ)^{26}Si(p,γ)^{27}P and it can also be destroyed directly. The reaction ^{26m}Al(p,γ)^{27}Si* is another avenue to bypass the production of ^{26}Al and it is dominated by resonant capture. We study these resonances by an indirect method, through the β-decay of ^{27}P. We use ^{27}P produced and separated with MARS and a setup which allows increased efficiency for low energy protons and for high-energy gamma-rays. We measure gamma-rays and β-delayed protons emitted from states above the proton threshold in the daughter nucleus ^{27}Si to identify and characterize the resonances. Its lifetime was also measured with accuracy under 1%.

Keywords: nuclear astrophysics, decay spectroscopy, beta-delayed proton decay
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1. Introduction

Energetically speaking, stars are too cold to study their reaction rates directly, that is, the actual cross sections are too low to allow us to measure them easily in the lab. So, we apply an indirect method to gain the information we require. In the case of interest here $^{26}\mathrm{Al}^{m}(p,\gamma)^{27}\mathrm{Si}$, the indirect method we use is the study of beta-delayed gamma (βγ) and proton (βp) decay. As shown in Figure 1, the direct reaction would involve a proton tunneling through the Coulomb barrier of ^{26m}Al to form excited states in ^{27}Si, which then decay through gamma emission. Instead, we start with ^{27}P, which may β-decay to the same excited states in ^{27}Si (due to selection rules). The states that are populated above the proton threshold ($E^{*} > S_p + E(0^+) = 7.463 + 0.228 = 7.691$ MeV) can then decay by proton emission to ^{26m}Al. These are the states we are seeking. They represent resonance states in the time-reversed proton capture reaction. To evaluate their contribution to the astrophysical reaction rate, we need to determine the position of the resonances and their partial gamma and proton widths. That is, we obtain information on the energy of these resonances, the spin and parity of the states involved, and the resonance strength.

The difficulty is that the low energy protons we want to study (typically less than 400 keV) must compete with the β-background in the detector used to study the process. In silicon detectors, the beta energy loss signal is usually the dominant feature at this energy range. So, all experiments involving this type of decay study must minimize the beta contribution as much as possible (discussed below) in order to obtain a clear proton spectrum.

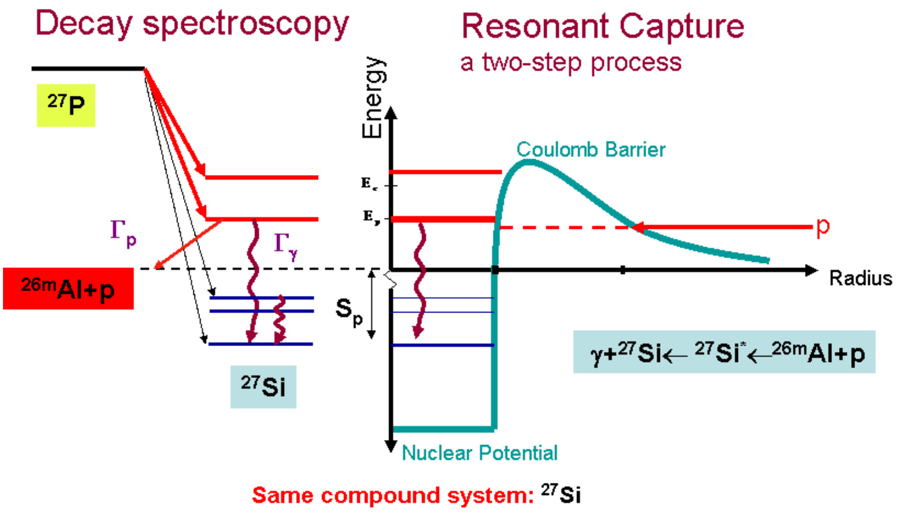

Figure 1. Indirect method used to study resonances in the $^{26m}\mathrm{Al}(p,\gamma)$ reaction. Note that they have the same compound system ^{27}Si.

A resonance occurs when the energy of the reaction is close to that of a metastable state in the compound system. Reaction cross sections can become very large and quickly vary in narrow energy regions due to resonances, which usually dominate the rates when they are available. For radiative proton capture reactions dominated by narrow, isolated resonances, the rate can be written as [1]:

$$\langle \sigma \upsilon \rangle_{res} = \left(\frac{2\pi}{\mu kT} \right)^{3/2} \hbar^2 \omega\gamma \exp\left(-\frac{E_r}{kT} \right)$$

where E_r are the energies of the resonances and ωγ are the resonance strengths. The resonance strength of a state *i* is defined as:

$$(\omega\gamma)_i = \frac{2J_i + 1}{(2J_p + 1)(2J_t + 1)} \left[\frac{\Gamma_p \Gamma_\gamma}{(\Gamma_p + \Gamma_\gamma)} \right]_i$$

where Γ_p is the proton width and Γ_γ is the gamma width of that given state. A closer look at this equation shows that if the proton were to tunnel through the top of the barrier in Figure1, Γ_p is large, $\Gamma_p \gg \Gamma_\gamma$ and the resonance strength would be dominated by the gamma width. At the lower energies that we are interested in, however, the proton has difficulties tunneling through the bottom of the barrier in Figure 1, $\Gamma_p \ll \Gamma_\gamma$, and the resonance strength depends only on the width of the proton. The energy dependence of the barrier penetrability is exponential and only in very rare cases both decay branches can be detected.

2. The Measurement

A βp & βγ experiment was run in November 2010. A primary beam of ^{28}Si at 40 MeV/u was obtained from the K500 superconducting cyclotron and a target of hydrogen gas kept at LN$_2$ temperature and 2 atm pressure was used to create the desired ^{27}P by a (p, 2n) fusion evaporation reaction. After tuning and optimizing the secondary beam we ended up with ^{27}P at about 34 MeV/u and with about 11% total impurities, most of which was ^{24}Al. However, this ^{24}Al impurity was actually to our advantage during experiment. We were able to use it for extended energy and efficiency calibrations (up to 8 MeV) for the high purity germanium detectors and due to the different range in silicon (compared to ^{27}P) it did not cause a problem in the proton spectrum (discussed below). The setup is shown below in Figure 2. It consisted of one 3 Si-detectors telescope and two HpGe gamma-ray detectors.

The parent nucleus (^{27}P) was implanted in the center of a thin detector where the decay occurred. We used a telescope combination of silicon detectors. A thin (45 and later a 104 μm) double sided strip detector (DSSD), the p-detector, was sandwiched between two thick (300 μm and 1 mm) silicon detectors (the β1 and β2 detectors). The implantation was possible due to the inherent high kinetic energy (30-40 MeV/u) of the exotic secondary beams produced in MARS using the in-flight technique. The precise implantation in the middle of the very thin proton detector was possible due to the good momentum control in MARS and was realized by changing the angle of a rotating Al degrader foil, placed in front of the silicon detectors. By monitoring the two-dimensional histograms β1 vs Proton detector and the Proton detector vs β2 as the angle of the Al foil was changed, it was possible to determine when the ^{27}P nuclei were truly implanted in the center (proton) detector.

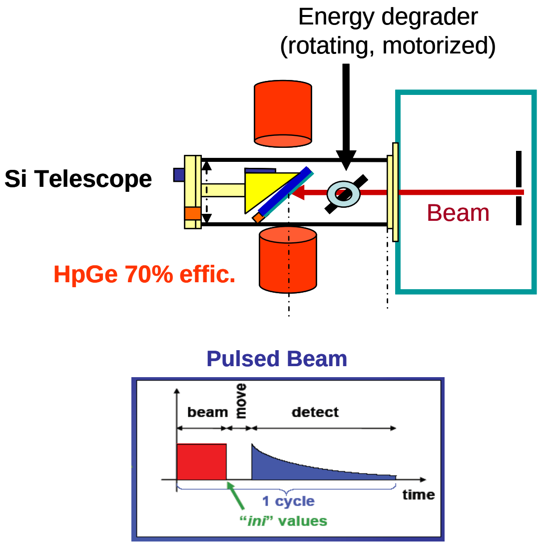

Figure 2. Implantation and Decay Station Setup.

Several improvements were made to the design of the implantation-decay station to help reduce background and improve efficiency. First and foremost we wanted to be able to move the HpGe detectors in even closer to the silicon detectors where the implantation and decay occurred. The first implantation station was a cylinder 6” in diameter. The new one is rectangular and only 4” across. This decrease in distance alone (3” to 2”) results in an approximate 50% increase in solid angle (when using two HpGe’s). Changing from a cylindrical chamber to a rectangular one also allows the HpGe’s to be placed flush with the chamber side.

The change from 6” diameter chamber to a rectangular chamber 4” wide and 6” tall required a complete rearrangement of water pipes and electric feed-through locations. Careful attention was paid so that no cables or pipes would be in the path of the beam or of the gamma-rays either as a hindrance or as a potential source for scattering. The inclusion of the rotating degrader motor (taken from the old implantation station) made this a complete, self contained chamber. As before, the silicon detectors are placed at a 45 degree angle to the path of the beam in order to increase the amount of silicon the beam encounters. This chamber design also allows for either the BB2 or the W1 type DSSD detectors to be used for the proton detector (both made by Micron Semiconductor, but of different designs). Also, a beta detector can be placed on either side of the proton detector without coming into contact with the side of the chamber. All silicon detectors, as before, are attached to a brass stand that is cooled by flowing cool water through pipes that are welded to the back of this stand. This brass stand is placed on a plastic part that is then secured to the top plate of the chamber in order to try to maintain electrical isolation.

Using the β-detectors, p-detector and HpGe detectors, we measured simultaneously the β-p & β-γ coincidences. In order to do this the beam from the K500 cyclotron had to be pulsed, that is, ^{27}P was implanted for a time, then the beam was switched off and the decay was measured before switching the beam back on and repeating the process.

At the same rigidity, ^{24}Al has a longer range in silicon, with about 60 μm, which put it out of our p-detector and stopped in the back β2-detector. It did give impurity peaks (identifiable though!) in the gamma-ray spectra, which we used to our advantage, for energy and efficiency calibrations at very high energies E_γ=3-8 MeV.

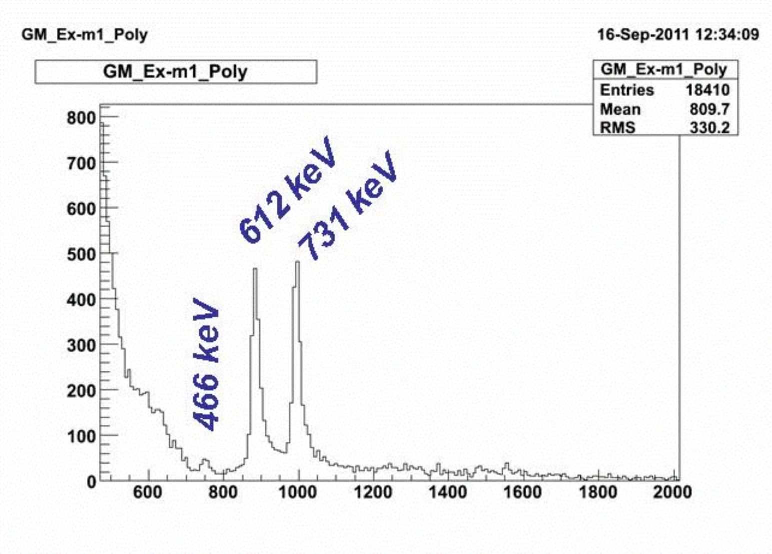

Figure 3. Preliminary proton spectrum from the βp & βγ experiment.

The preliminary proton results from this experiment are shown above in Figure 3. We see the higher energy protons that were identified by a Berkeley group [2] but, in the low energy region we saw a background larger than expected. We have determined that it was not due to technical difficulties, but we were being relatively overwhelmed by β's, because the proton branching ratio was being much lower than in the cases of ^{23}Al and ^{31}Cl studied before (about 10-100 times lower) [3-5]. However, it can be seen in Figure 3, that there is a clear structure above a continuous background in the low energy region 2-400 keV. That suggests there is valuable information yet to be obtained through a careful background subtraction, or a background reduction in a different detector**.** Analysis on these data is ongoing.

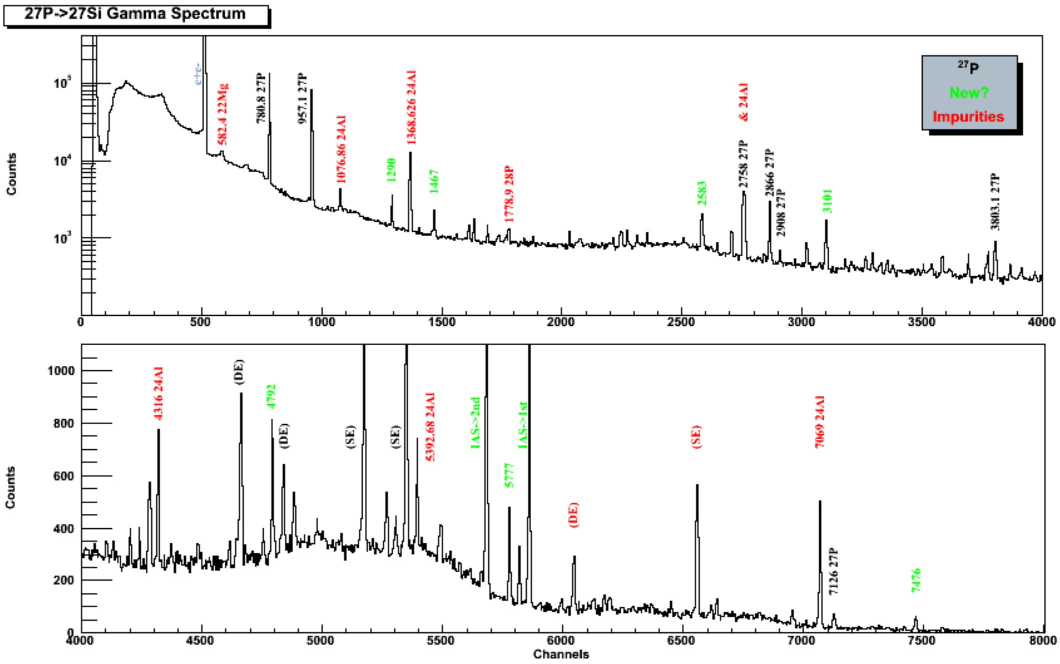

Figure 4. Preliminary gamma-ray spectrum from the βp & βγ experiment.

The gamma spectrum came out very nicely, as shown above in Figure 4, especially in the high energy region, showing the payoff of having re-designed the implantation-decay station to allow the HpGe's to be moved in as close as possible to the silicon detectors where ^{27}P was implanted. The only impurities that were visible, due to our β–γ coincidence setup, are from impurities in the beam (^{22}Mg and ^{24}Al). The ^{24}Al gammas, as mentioned before, were used to create extended energy and efficiency calibrations, up to 8 MeV. No gamma-rays from the decay of ^{27}P could be measured before. A decay scheme for these gammas is still being developed.

3. Conclusions and Future Plans

A clean and rather intense secondary beam of ^{27}P was obtained for the first time (2-3000 pps, 89% purity). Beta-delayed gamma-rays from its decay were for the first time observed and beta-delayed protons were observed with energies down to 400 keV, possibly lower. Proton peaks with branchings as low as ~10^{-4} were observed. A precise determination (within 2%) of the ^{27}P lifetime was made (not reported here). Future plans include finishing the analysis for the ^{27}P βp & βγ experiment and extending the observation to proton energies further down. This includes working to resolve more information from the proton spectrum in the low energy region, finalizing the decay scheme for the gammas and finalizing the determination of the branching ratios and logft values.

Acknowledgments

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