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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: $^{24}\text{Mg}(p, \gamma)^{25}\text{Al}(\beta^+ \nu)^{25}\text{Mg}(p, \gamma)^{26}\text{Al}$, but this chain can be by-passed by another chain, $^{25}\text{Al}(p, \gamma)^{26}\text{Si}(p, \gamma)^{27}\text{P}$ and it can also be destroyed directly. The reaction $^{26m}\text{Al}(p, \gamma)^{27}\text{Si}^*$ is another avenue to bypass the production of ^{26}Al and it is dominated by resonant capture. We find and study these resonances by an indirect method, through the beta-decay of ^{27}P . A clean and abundant source of ^{27}P was produced for the first time and separated with MARS. A new implantation-decay station which allows increased efficiency for low energy protons and for high-energy gamma-rays was used. We measured gamma-rays and beta-delayed protons emitted from states above the proton threshold in the daughter nucleus ^{27}Si to identify and characterize the resonances. The lifetime of ^{27}P was also measured with accuracy under 2%.

1. Introduction

Our group at TAMU has had a recent interest in H-burning reactions involving proton rich nuclei in the sd-shell. In order to better understand astrophysical reactions relating to novae and x-ray bursts we have used decay-spectroscopy in order to obtain the information we seek on important reaction rates. So far ^{23}Al , ^{31}Cl and ^{20}Mg have been studied in this fashion [1-3]. In the work reported here, these studies have been extended to include ^{27}P , another $T_z = -\frac{3}{2}$ nuclei in this region.

1.1. Astrophysical Motivation

One of the first and most well observed gamma-ray lines in the interstellar medium is that of 1.809 MeV. It originates from the β -decay of the ground state of ^{26}Al to an excited state in ($^{26}\text{Mg}^*$), which then undergoes γ -decay. Since the half-life of ^{26}Al ($T_{1/2} = 7.2 \times 10^5$ yr) is much less than age of our solar system (4.57×10^9 yr), its presence is a clear indication of ongoing nucleosynthesis in the Milky Way, and by extension, the universe. Also pointing to the recent

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synthesis of ^{26}Al are excess amounts of ^{26}Mg found in pre-solar grains contained in carbonaceous meteorites which were formed in the early days of the solar system. However, the main creation site of ^{26}Al is still under debate. Recent studies have suggested that Wolf-Rayet stars could be the main producers of ^{26}Al , but there could also be some contribution from AGB stars, classical novae and core collapse supernovae [4].

An interesting detail about ^{26}Al is that while its ground state has a large spin ($J^\pi = 5^+$), an isomeric state only 228 keV above it has a spin of $J^\pi = 0^+$. Due to the large spin difference transitions from one to the other are highly forbidden. Thus, in most environments we can basically treat these two states as two different species. However, at higher temperatures ($T > 1\text{ GK}$), they are correlated through higher lying excited states. So, to fully understand the role ^{26}Al plays in nuclear astrophysics, all reactions involving both the ground state and the isomeric state must be considered. The destruction reaction of interest here is $^{26m}\text{Al}(p, \gamma)^{27}\text{Si}^*$ which is dominated by resonant capture.

1.2. Indirect Method

Energetically speaking, stars are too cold to study directly, that is, the reaction cross sections are too low for easy measurement in the lab. So, an indirect method is applied in order to gain the information required. In the case of interest here ($^{26m}\text{Al}(p, \gamma)$), the indirect method chosen was the beta-delayed gamma and proton decay of ^{27}P . As shown below in Fig. 1, the direct method involves a proton tunneling through the Coulomb barrier of ^{26m}Al in order to form excited states in ^{27}Si which then decay through gamma emission. Instead, we start with ^{27}P , which may then β -decay to the same excited states in ^{27}Si (due to selection rules). The states that are populated above the proton threshold ($E^* > S_p + E(0^+) = 7.463 + 0.228 = 7.691\text{ MeV}$) can then decay by proton emission to ^{26m}Al . These are the states of interest. They represent the resonance states in the time-reversed proton capture reaction. To evaluate their contribution to the astrophysical reaction rate, the position of the resonances and their partial gamma and proton widths must be determined. That is, information on the energy of these resonances, the spin and parity of the states involved, and the resonance strength are required.

The difficulty encountered here is that the low energy protons (typically those 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 in this energy range. So, a major requirement of this type of experiment is to minimize the beta contribution as much as possible in order to obtain a clear proton spectrum.

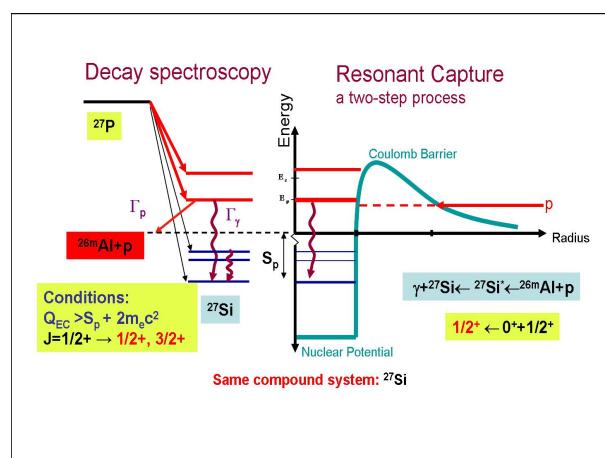


Figure 1. Indirect method used to study the resonances in the $^{26m}\text{Al}(p, \gamma)$ reaction.

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 these resonances, which can then dominate the reaction rates. For radiative proton capture reactions dominated by narrow, isolated resonances, the rate can be written as:

$$\langle\sigma v\rangle = \sum_{Res} (\omega\gamma)_i e^{-E_r^i/kT}$$

where E_r are the energies of the resonances and $\omega\gamma$ are the resonance strengths. The resonance strength of a state i is defined as:

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

where Γ_p is the proton width and Γ_γ is the gamma width of that given state [5]. This equation shows that if the proton were to tunnel through the top of the barrier in Fig. 1, Γ_p is large, and thus $\Gamma_p \gg \Gamma_\gamma$, the resonance strength will be dominated by the gamma width. However, at the lower energies of interest, where the proton has difficulties tunneling through the bottom of the barrier in Fig. 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 can both decay branches be detected.

1.3. Previous work on ^{27}P

The most recent work done on the β -delayed proton decay of ^{27}P , prior to this experiment, was done by a group at Berkley [6]. Though there were some problems with beam intensity and purity, a total proton branching ratio of 0.07% and a lifetime value of 260(80)ms was obtained. The proton spectrum had several protons from the β -delayed proton decay of ^{28}P , an impurity that could not be gotten rid of but one which was known. Thus, the remaining protons were identified as coming from ^{27}P . Up till now no one has been able to produce a clean and abundant source of ^{27}P in order to study, in detail, both it's βp and $\beta\gamma$ decays.

2. The Measurement

Study of the resonances of interest require the detection of very low energy protons (around a few hundred keV). Innovative methods and modifications have been developed through the experience of several similar experiments. One of the biggest improvements was to change the configuration of the silicon detector used to measure the protons. It was found that changing to a thinner detector with more strips (and thus a smaller detector pixel volume) greatly reduced the β -background in the low energy region.

2.1. The Production, Separation and Implantation of ^{27}P

A preliminary beam of ^{28}Si at 40 MeV/u was obtained from the K500 superconducting cyclotron. A primary target of hydrogen gas kept at LN₂ temperature and 2 atm pressure was used to create ^{27}P in a (p,2n) fusion evaporation reaction. After tuning and optimizing the secondary beam through MARS, ^{27}P was obtained with an energy around 34 MeV/u and with about 11% total impurities, most of which was ^{24}Al . The final production is shown below in Fig. 2. Actually, this ^{24}Al impurity was an important advantage during the experiment. It allowed extended energy and efficiency calibrations (up to 8 MeV) to be obtained for the high purity germanium detectors. Due to the different ranges in silicon (compared to ^{27}P) this and other impurities did not cause a problem in the proton spectrum.

The basic experimental setup consists of three silicon detectors in a telescope configuration and two HpGe gamma-ray detectors placed on either side of the chamber around the location

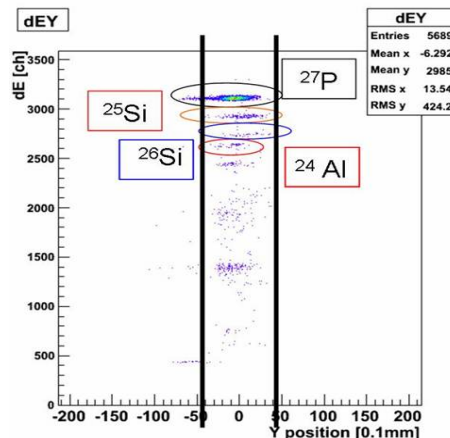


Figure 2. The final tuning results for the production of ^{27}P .

of the silicon detectors. The silicon detectors were kept at a 45 degree angle to the beam in order to increase the amount of silicon material the beam encounters. The parent nucleus (^{27}P) was implanted into a thin (45 and later a 104 μm) double sided strip detector (DSSD), referred to as the proton-detector, where the decay occurred. This thin silicon detector was sandwiched between two thicker (300 μm and 1 mm) silicon detectors (the β_1 and β_2 detectors), which were used for background reduction. 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, as shown below in Fig. 3. By monitoring the two-dimensional histograms β_1 vs Proton and the Proton vs β_2 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.

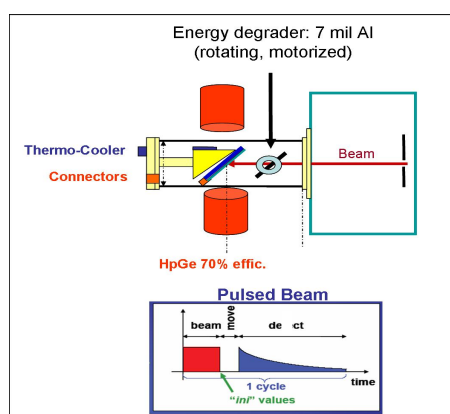


Figure 3. Top view of the experimental setup at the end of MARS.

Using the two β detectors, the proton detector and the two HpGe detectors, the βp and $\beta\gamma$ coincidences were measured simultaneously. In order to do this the beam from the K500 cyclotron had to be pulsed. That is, the ^{27}P was implanted for a period of time, then the beam was switched off and the decay was measured before switching the beam back on and repeating the process.

2.2. The Implantation-Decay Station

Several improvements were made to the design of the implantation-decay station to help reduce background and improve efficiency. Namely, it was desired to move the HpGe detectors in even closer to the silicon detectors where the actual implantation and decay occurs. The first implantation station was a cylinder 6" in diameter, whereas the new design 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, as shown below at the back end of MARS in Fig. 4.

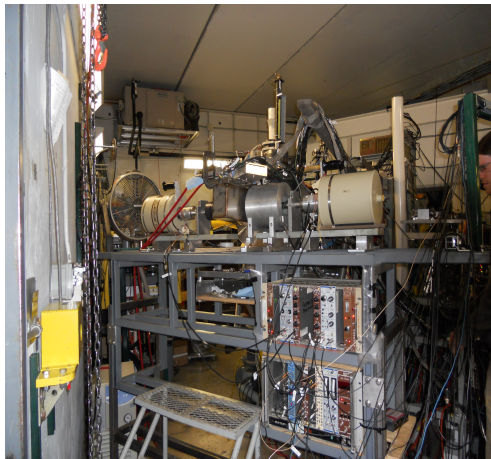


Figure 4. New implantation-decay station at the back end of MARS.

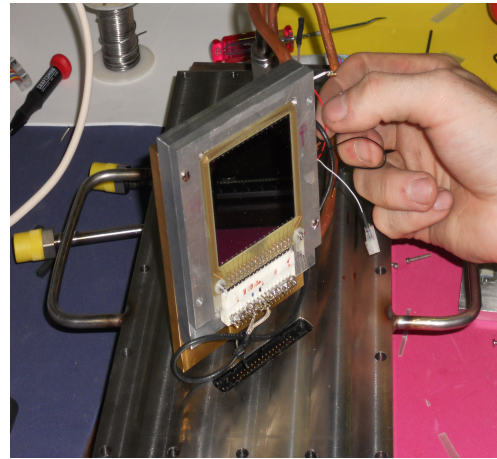


Figure 5. Silicon detector setup for the new rectangular chamber.

Changing from a 6" diameter cylindrical chamber to a 4" wide and 6" tall rectangular one 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 would cause the gamma-rays to be blocked or scattered. The inclusion of the rotating degrader motor (taken from the old implantation station) made this a complete, self-contained chamber. The silicon detectors were again placed at a 45 degree angle to the path of the beam, as shown above in Fig. 5.

This chamber design allowed for either the BB2 or the W1 type DSSD detectors to be used as the proton detector (both made by Micron Semiconductor, but of different sizes). Enough room was left for a beta detector to be placed on either side of the proton detector without coming into contact with the sides of the chamber. All silicon detectors, as before, were attached to a brass stand that was cooled by flowing chilled water through brass pipes welded to the back of this stand. The brass stand was placed on a simple plastic component that was then secured to the top flange of the chamber in order to try and maintain some electrical isolation (even though the detector cables went through the BNC feed through connection).

3. Preliminary Results

The preliminary proton results from this experiment are shown below in Fig. 6. The higher energy protons identified by the Berkley group [6] are clearly seen but, in the low energy region a β -background larger than expected was obtained. It has been determined that this was not due to technical difficulties, but due to the fact that the proton branching ratio was much lower than in the previously studied cases of ^{23}Al and ^{31}Cl (about 10 – 100 times lower) [1-3]. So, it was not that the β -background overwhelmed the protons in this region, it was just that there were

so *few* protons to detect. However, it can be seen below in Fig. 6, that there is structure above a continuous background in the low-energy region 2-400 keV. This suggests there is valuable information yet to be obtained by a careful background subtraction, or a background reduction using a different type of detector. Analysis on these data is ongoing and nearly finished.

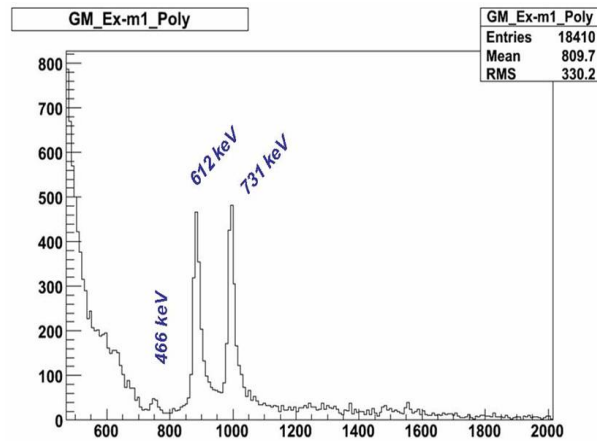


Figure 6. Preliminary proton spectrum obtained in the βp & $\beta \gamma$ experiment.

The gamma spectra came out very nicely, as shown below in Fig. 7, especially in the high energy region due to the good efficiency of the re-designed implantation-decay station. The only impurities that were visible, due to our $\beta \gamma$ coincidence setup, were 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 β -delayed decay of ^{27}P has been measured before this experiment.

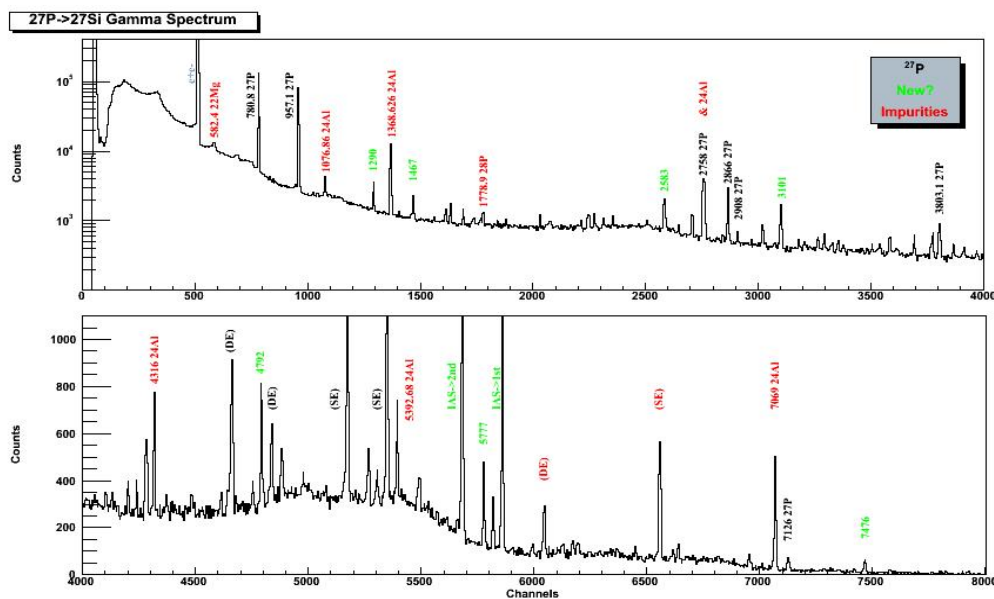


Figure 7. Preliminary gamma spectrum obtained in the βp & $\beta \gamma$ experiment.

4. Conclusions and Future Plans

A very clean and rather intense secondary beam of ^{27}P was obtained for the first time using the MARS beam line at Texas A & M University. The β -delayed gamma-rays from its decay were studied for the first time and β -delayed protons were observed with energies down to 400 keV. Proton peaks with branchings as low as about 10^{-4} were observed. A precise determination (within 2%) of the ^{27}P lifetime was also made at Texas A & M (not reported here). Future plans include finishing the analysis for the ^{27}P βp and $\beta\gamma$ experiment to finalize the determination of the branching ratios and the log ft values, and possibly extending the observation to include protons with even lower energies.

5. Acknowledgments

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