The beta delayed proton and gamma decay of ^{27}P for nuclear astrophysics

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In 1982 a high-resolution gamma-ray detector was placed on a NASA spacecraft and it recorded, for the first time, a gamma ray peak at 1.809 MeV. These gamma rays result from the de-excitation of an excited state in ^{26}Mg, which itself is created by the β^+ decay of ^{26}Al ($T_{1/2}$=0.7 My). The discovery of this gamma line was a clear indication of ongoing nucleosynthesis. 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 [1]. When ^{26}Al is created in novae, the reaction chain is: ^{24}Mg(p, γ)^{25}Al(β+v)^{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. Having a better understanding of the reactions involved in the creation and destruction of ^{26}Al will lead us to a better understanding of how much and where ^{26}Al is created, and thus, to a greater understanding of the evolution of stars. The study of ^{27}P adds to other proton-rich nuclei in the sd-shell (^{23}Al, ^{31}Cl and ^{20}Mg), which have already been studied by our group. The study of ^{27}P decay (also a T_z=-3/2 nucleus) could add significant knowledge to our understanding of creation and destruction of ^{26}Al.

The reaction ^{26m}Al(p,γ)^{27}Si* is dominated by two-step resonant captures. Due to the low cross sections in the lab at astrophysical energies we can study this process only by an indirect method,

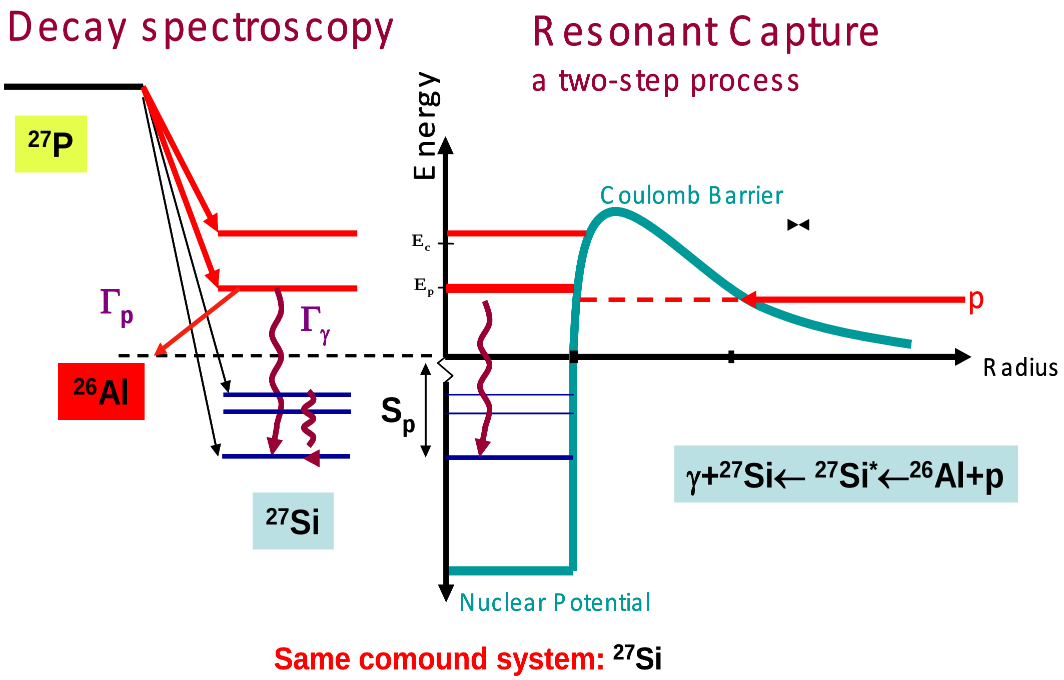

FIG. 1. Indirect method used to study resonances in the ^{26m}Al(p,γ) reaction. Note that they populate states in the same compound system ^{27}Si.

through the β-delayed proton emission of ^{27}P, which has a half-life of 260(80) ms. This indirect method involves ^{27}P β^+ decaying to ^{27}Si*, which was originally cited as having a 0.07% beta-delayed proton-decay branching. States that are populated above the proton threshold in ^{27}Si (S_p = 7.463 MeV) can then decay by proton emission to ^{26}Al; see Fig. 1. The difficulty in these types of experiments is that the low energy protons of greatest interest must compete with the beta-background, which is usually the dominant feature in the Si detectors at this energy range (0 - 400 keV).

The Experiment

The primary beam from the K500 superconducting cyclotron, ^{28}Si at 40 MeV/u, struck a hydrogen gas target (kept at a pressure of 2 atm and liquid nitrogen temperatures), and several residual nuclei were thus created. The nuclei of interest in this experiment are created by a (p,2n) fusion-evaporation reaction. The exotic secondary beam was then taken through the rest of MARS in order to separate out our desired ^{27}P nuclei with as few impurities as possible. By the time it reached the target detector used to fine tune the beam, it had an energy of about 34 MeV/u. With the coffin slits closed to ±0.4 cm we ended up with a production rate of about 2.9 events/nC and total impurities of about 10.4%, most of which were ^{25}Si and ^{24}Al, but since they have different ranges in Si than ^{27}P, we could implant them in different locations.

A technique that we have had great success with in past experiments involves implanting the desired parent nucleus (^{27}P) in the center of a thin Si detector where the resulting β+ decay will then occur at rest. Two HpGe gamma-ray detectors were also utilized for this experiment, one on either side of a newly designed implantation station that would allow us to move them in even closer to the Si detectors than what was previously achievable; see Fig 2. We used a telescope design for the Si detector arrangement; a thin (45 μm and later a 104 μm) double sided strip detector (DSSD), the p-detector, which was sandwiched between two thick (300 μm and 1 mm) Si detectors (referred to here as the β-detectors).

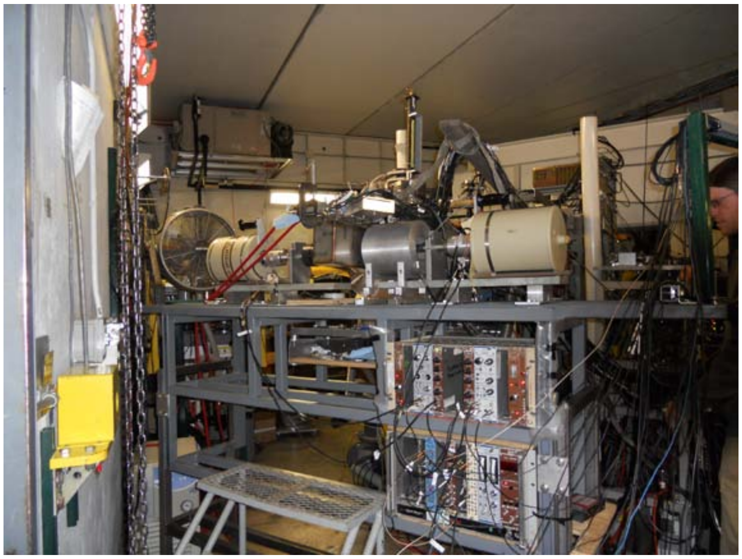

FIG. 2. The experimental Setup: two HpGe Detectors were used, one on either side of the Si detectors located inside the chamber.

These beta-detectors were used to reduce the background. The precise implantation in the middle of a very thin detector is obtainable because of the combination of good momentum control in MARS, and by the ability to change the angle of a rotating Al degrader foil that was placed in the implantation station, right in front of the Si detectors. Using the β-detectors, p-detector and HpGe detectors, and pulsing of the beam from the cyclotron, we were able to measure, simultaneously, the β-p and β-γ coincidences.

Preliminary Results

The gamma ray spectra turned out very well. The design of the new implantation station with improved efficiency, the good beam and low noise conditions gave very clean spectra. Extended energy calibrations were done using the well known gamma lines form ^{24}Al as well as a couple lines from the other beams impurities (^{26}Si and ^{22}Mg). Natural background peaks are not present due to the coincidences included in the electronics trigger. The spectra were further improved by gating on the beta-gamma TAC signal; see Fig 3(b). The measured gamma-ray decay spectrum allows us the build for the first time the decay scheme of ^{27}P. So far, analysis has also shown several ^{27}Si gamma lines not previously reported.

For the proton side of the experiment, the major problems we encountered were the large background from the betas below 400 keV and the lower than expected branching ratios of the protons. We now determine that this branching is more like 0.03 - 0.04% instead of the 0.07% previously reported. For once, noise was not our main problem. With both sides of the silicon BB2 detector (proton detector) calibrated, gain matched and summed we could clearly see the 731(2) keV and 612(2) keV protons

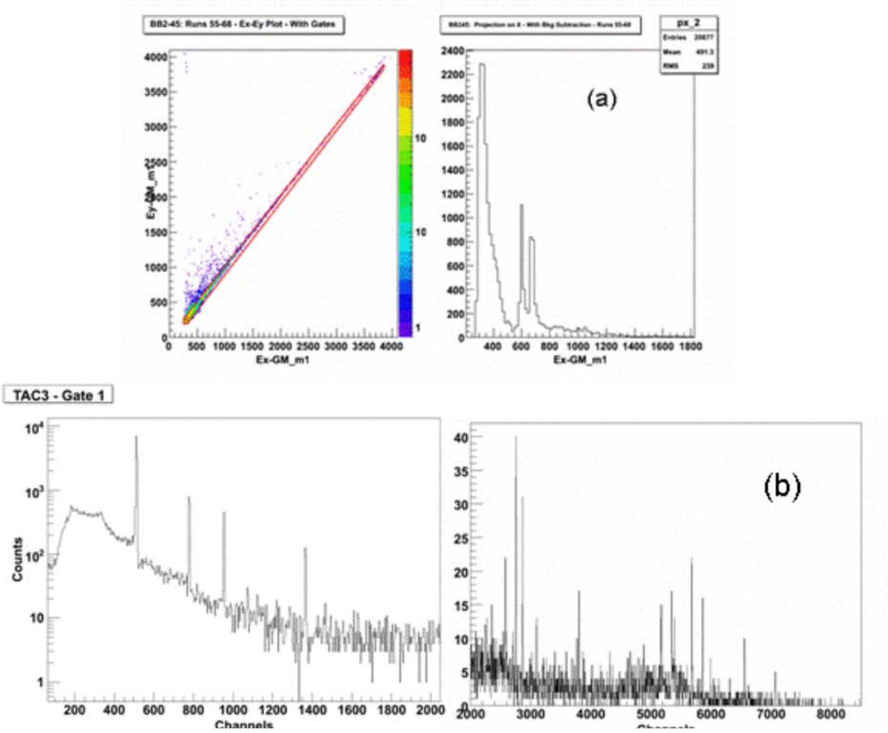

FIG. 3. Preliminary Spectra Results from the experiment, the top shows the BB2-45 p-detector preliminary results and the bottom (b) shows the results of ^{27}Si gamma spectrum.

peaks, and even what looks to be the 466 (3) keV peak [2] when some of the background was removed. Below about 400 keV, all we see so far are betas. Analysis is ongoing; see Fig 3(a).

In April-May 2011 a lifetime measurement was undertaken with the tape transport system, with expectations of greatly improving upon the uncertainty (to under 1%) – analysis of that data is now underway.

[1] N. Prantzos and R. Diehl, Phys. Rep. **267**, 1 (1996).
[2] T.J. Ognibene *et al.*, Phys. Rev C **54**, 1098 (1996).