Decay spectroscopy for nuclear astrophysics: $\beta$- and $\beta$-delayed proton decay

L Trache, A Banu, JC Hardy, VE Iacob, M McCleskey, BT Roeder, E Simmons, A Spiridon and RE Tribble - Texas A&M University, College Station, TX, USA
A Saastamoinen, A Jokinen and J Äysto - University of Jyvaskyla, Finland
T Davinson, G Lotay and PJ Woods - University of Edinburgh, UK
E Pollacco - CEA Saclay, France

Abstract. In several radiative proton capture reactions important in novae and XRBs, the resonant parts play the capital role. We use decay spectroscopy techniques to find these resonances and study their properties. We have developed techniques to measure beta- and beta-delayed proton decay of sd-shell, proton-rich nuclei produced and separated with the MARS recoil spectrometer of Texas A&M University. The short-lived radioactive species are produced in-flight, separated, then slowed down (from about 40 MeV/u) and implanted in the middle of very thin Si detectors. This allows us to measure protons with energies as low as 200 keV from nuclei with lifetimes of 100 ms or less. At the same time we measure gamma-rays up to 8 MeV with high resolution HPGe detectors. We have studied the decay of $^{23}$Al, $^{27}$P, $^{31}$Cl, all important for understanding explosive H-burning in novae. The technique has shown a remarkable selectivity to beta-delayed charged-particle emission and works even at radioactive beam rates of a few pps. The states populated are resonances for the radiative proton capture reactions $^{22}$Na$(p,\gamma)^{23}$Mg (crucial for the depletion of $^{22}$Na in novae), $^{26m}$Al$(p,\gamma)^{27}$Si and $^{30}$P$(p,\gamma)^{31}$S (bottleneck in novae and XRB burning), respectively. Lastly, results with a new detector that allowed us to measure down to about 80 keV proton energy are announced.

1. Introduction
The difficulties encountered in doing direct measurements in nuclear astrophysics (very low cross sections and/or involvement of unstable nuclei) lead to the use of indirect methods. Among the indirect methods, a large class is the spectroscopy of resonances. In many cases, the resonant parts are important or dominant to reactions that are important in stars. These resonances are metastable states in the compound system produced in reaction as an intermediate step. To evaluate the corresponding contributions to the reaction rates (for narrow, isolated resonances) it is sufficient to determine the location of the resonances ($E_{\text{res}}$) and their resonance strengths ($\omega \gamma$). These may be obtained by studying the spectroscopic properties of the corresponding metastable states, populated through a convenient method. The decay spectroscopy is one such method: instead of measuring proton capture we study its inverse, the proton decay of the same state. We study here states populated by beta decay. Of course the condition of populating exactly those states is crucial: selection rules of energy, spin and parity must be met. In this contribution we present the use of $\beta$- and $\beta$-delayed proton-decay ($\beta p$)
studies to populate and characterize resonances in a few proton capture reactions on sd-shell nuclei; reactions important in H-burning in novae and X-ray bursters (XRB). A major problem is that the energies of the protons to be measured are very small, below 300-400 keV, close to the limits of our current detection techniques. We describe a method consisting in the implantation of radioactive sources in very thin Si detectors, which allows, up to a point, measuring such low energy protons from $\beta^p$-decays. We did $\beta^-$ and $\beta^p$-decay studies of $^{23}\text{Al}$, $^{27}\text{P}$ and $^{31}\text{Cl}$, aiming at determining the properties of resonances that contribute to the $^{22}\text{Na}(p,\gamma)^{23}\text{Mg}$, $^{26m}\text{Al}(p,\gamma)^{26}\text{Si}$ and $^{30}\text{P}(p,\gamma)^{31}\text{S}$ reactions, respectively. These reactions are important in the description of thermonuclear runaways in novae and XRB [1]. Part of the results were published elsewhere [2-4], but most were not, and the full analysis is still on-going. Only the first and the third isotopes in the list are going to be briefly treated here, with emphasis on the case of $^{23}\text{Al}$, which is the most complete to date.

2. Experimental methods
We have developed a simple technique to measure $\beta^-$ and $\beta^p$-delayed proton-decay of proton-rich nuclei produced and separated with the MARS recoil spectrometer at the K500 superconducting cyclotron of Texas A&M University. The short-lived radioactive species are produced in-flight with $(p,2n)$ reactions in inverse kinematics on a cryogenic $\text{H}_2$ gas target, separated in MARS, then slowed down (from about 40 MeV/u) and implanted in the middle of a very thin Si detector. Then the beam is stopped and the decay is measured for times equal to about 2 half-lives of the isotope. The cycle is repeated until a convenient statistics is reached. The primary beams used were $^{24}\text{Mg}$ at 48 MeV/u, $^{28}\text{Si}$ and $^{32}\text{S}$ @ 40 MeV/u, respectively. The implantation of sources directly in the active part of the detector avoids the problems with detector windows or dead layers and allows us to measure protons with energies as low as 200 keV from nuclei with lifetimes of 100 ms or less. Two different double sided strip Si detectors (DSSSD), 65 or 45 $\mu$m thick (W1-65 and BB2-45, respectively), were used as proton detectors. A 1 mm thick Si detector was placed behind the proton detector to measure betas in coincidence. One or two HpGe detectors were put outside the implantation chamber, as close as possible to the implantation site, to measure gamma-rays. Protons and gamma-rays in coincidence with the beta-detector were measured simultaneously. The technique provides a valuable tool for the study of states that are resonances important in the radiative proton capture on nuclei close to the proton drip line.

3. Results
For all three cases announced, the isotopes were for the first time abundantly produced (2-4000 pps) and well separated from their isobars (purities >85% at the focal plane and close to 100% at implantation). These have allowed good $\beta^-\gamma$ measurements and to establish their decay scheme for the first time. For example, we obtained information on the location and decay of Isobaric Analog States (IAS) and possible isospin mixing. Before our measurements, most of the decay data for these isotopes were based solely on the observation of their $\beta^p$-delayed proton emission. The lifetimes of all 3 isotopes could also be determined with <1% uncertainties, improving considerably the previous data (uncertainties were ~25%).

Space limitations do not allow discussing here in detail the results for all cases. In brief, the most important results from the study of the decay of $^{23}\text{Al}$ are:

- first clean and intense $^{23}\text{Al}$ source was produced
- the decay scheme was established
- established unambiguously the g.s. spin and parity $J^p=5/2^+$ (not $1/2^+$) [2], which allowed to evaluate that the reaction $^{22}\text{Mg}(p,\gamma)^{23}\text{Al}$ is not important for depletion of $^{22}\text{Na}$ in novae
- absolute branching ratios were measured (not easy or common!)
- measured $T_{1/2}=446(4)$ ms (<1% accuracy) - w. gamma-ray multiscaling
- and from these absolute log $ft$ were determined
- the IAS was identified at $E^*=7802.9(5)$ keV by its log$ft=3.31(2)$ – measured, not assumed!
• used IMME to get new $^{23}$Al mass \[2\] ⇒ $S_p(^{23}Al)=143(3)$ keV
• after $^{23}$Al mass measured in Jyvaskyla, the A=23 isobar multiplet became best IMME check
• observed for the first time in the same experiment the IAS and a state at E*=$7787$ keV with $J^\pi=(7/2)^+$ (only 16 keV apart)
• measured proton transitions with energies as low as $E_p=207$ keV from the E*=$7787$ keV state (see figure 1). This state is an important resonance in $^{22}$Na(p,\gamma)$^{23}$Mg reaction. From the gamma and proton branchings measured here, and the lifetime from Ref. [5] we could determine its resonance strength: $\omega\gamma=1.4(5) \text{ meV}$ [4].
• Determined the total proton branching =1.26(5)%.

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{figure1.png}
\caption{Partial decay scheme of $^{23}$Al. Only the transitions to the first 3 levels of daughter nucleus $^{23}$Mg are shown in the lower part to justify the spin and parity assignment of its ground state. The decay of the doublet around $E^*=7.8$ MeV (the IAS and the $E=7787$ keV state), including a 3.7% proton branch is also shown. It is very rare that the decay of a state by both gamma-ray and proton emission is observed. More recently a weak proton decay branch was observed from the IAS (the ?! on figure; in first order this transition is isospin forbidden).}
\end{figure}

Very similar results were obtained from the study of $^{31}$Cl, separated as in figure 2 below. The position and four gamma-ray decay branches of the IAS were found, a new mass excess could be determined using IMME, new resonances were found and resonance energies could be determined with +/-1.5 keV uncertainties (reducing the uncertainties of the astrophysical reaction rates). No proton-decay branch was observed from the IAS at this time.

While our technique of using very thin Si strip detectors allowed a very good sensitivity to protons, at energies below 400 keV there is a large background arising from the energy loss of the positrons in the Si detector, which peaks at \sim{12 – 20} keV but extends down in the region of interest. This is particularly important in the cases, as those described here, where the proton branchings are very small. We succeeded to reduce this background by selecting the events to occur in a single detector pixel, rather than in a full strip. Later, a considerable reduction was obtained when the volume
of a pixel was reduced from $3 \text{ mm} \times 3 \text{ mm} \times 65 \, \mu\text{m}$ in the W1-65 detector to $1 \text{ mm} \times 1 \text{ mm} \times 45 \, \mu\text{m}$ in the BB2-45 detector. However, the proton spectra around 200 keV could only be obtained with a careful background subtraction; background measured with the decay of a beta-only emitter implanted in the same detector.

![Image](image_url)

**Figure 2.** Representation of the isotope separation in the focal plane of MARS for the case of $^{31}\text{Cl}$. After this position vs energy spectrum is taken, a couple of slits are moved to allow only $^{31}\text{Cl}$ through (red lines).

In a very recent experiment (only two weeks ago), using a new type of detector developed with E. Pollacco of CEA-Saclay, we could reduce drastically the beta background that has hindered the measurement of low energy proton branches while improving the resolution. The beta background was restricted to energies lower than about 80 keV. This will be reported elsewhere.

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