PoS PROCEEDINGS OF SCIENCE

Decay spectroscopy for nuclear astrophysics

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Abstract. In many radiative proton capture reactions important in H-burning in novae and XRBs, the resonant parts play the major role. I will show how one can use decay spectroscopy techniques to find these resonances and study their properties. I will exemplify with techniques developed at Texas A&M University to measure β- and β-delayed proton decay, applied to *sd*-shell, proton-rich nuclei produced and separated with the MARS recoil spectrometer. The short-lived radioactive species are produced in-flight, separated, slowed down from about 30-40 MeV/u and implanted in the middle of very thin Si detectors. This allowed us to measure protons with energies as low as 200-400 keV from nuclei with lifetimes of 100 ms or less. At the same time we measured gamma-rays up to 8 MeV with high resolution HPGe detectors. We have studied the decay of ^{23}Al, ^{27}P and ^{31}Cl. The technique has shown a remarkable selectivity to beta-delayed charged-particle emission and worked even at radioactive beam rates of a few pps. The states populated are resonances for the radiative proton capture reactions ^{22}Na(p,γ)^{23}Mg (crucial for the depletion of ^{22}Na in novae), ^{26m}Al(p,γ)^{27}Si and ^{30}P(p,γ)^{31}S (bottleneck in novae and XRB burning), respectively. At the same time the decay properties were established for these 3 isotopes, which were cleanly separated here for the first time. Their lifetimes were measured; the IAS states and their decay were un-equivocally located. I will briefly show how a recent detector development allows better measurements in the critical region of proton energies 100-400 keV.

Keywords: nuclear astrophysics; explosive H-burning; beta-decay; beta-delayed proton decay
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[1] Speaker

1. Introduction

I mentioned in another lecture the reasons that are leading to the use of indirect methods in nuclear astrophysics: involvement of unstable nuclei and very low cross sections. The indirect methods described in Ref. [1] allowed to evaluate the non-resonant contributions to stellar reaction rates. However, in many cases, the reactions in stars or in stellar environments are dominated by resonances or the resonances contribute non-negligibly. Such is the case for reactions involving *sd*-shell nuclei in explosive H-burning important in classical novae or X-Ray Bursts. If the reactions are dominated by narrow, isolated resonances, to evaluate the reaction rates it is sufficient to study those resonances: to locate them and find their properties. I will present here one method that deals with the location and study resonances: decay spectroscopy. In particular I will present the use of β-delayed gamma-ray (βγ) and β-delayed proton (βp) spectroscopy. The work presented here was done in the MARS group at Texas A&M University with the useful collaboration of groups from Edinburgh, Jyvaskyla and Saclay. Some results were already published or presented at other conferences [2-6], some are new, and many are still preliminary. Two contributions by our students Ellen Simmons and Alex Spiridon, contributions present in this volume [7,8], will treat specific results of this work and I will insist less on those in this paper, as I did in the actual talk.

2. Astrophysical motivation

Classical novae outbursts are special events since they are very energetic, are relatively frequent in our Galaxy (about 30 per year) and are observed well by astrophysicists (a few per year). The current working paradigm is that they are phenomena that take place in a binary system made up of a white dwarf accreting material from its companion normal star. This material is progressively compressed at the surface of the white dwarf until the conditions for hydrogen combustion are achieved, leading to a thermonuclear runaway, which is the one observed. During this explosive burning, nucleosynthesis takes place and the newly synthesized material is ejected into the interstellar medium. Multi-wavelength observations are performed by astrophysicists in order to understand these objects and their associated nucleosynthesis. Gamma-ray astronomy studies with space-based gamma-ray telescopes and studies of presolar grains are of specific interest since they are, presumably, directly linked to this nucleosynthesis process. However, in order to interpret these observations and therefore to constrain the astrophysical modeling of classical novae it is crucial to reduce the nuclear uncertainties involved in the production of the isotopes of interest. Important reactions are ^{22}Na(p,γ)^{23}Mg, ^{26m}Al(p,γ)^{26}Si, and ^{30}P(p,γ)^{31}S. I want to make a special point here and introduce the concept of "Jordi's list" [9], as a place we experimentalists in nuclear physics for astrophysics go to get our inspiration about what to measure and what not! In particular, the latter reaction figures high on that short list as a bottleneck in the reaction chain in nova outbursts. However, the uncertainties in its reaction rates are up to 2 orders of magnitude, in spite of some recent progress. The reaction is dominated by resonant capture and the uncertainties are due to a poor spectroscopic knowledge of the corresponding states in the compound system ^{31}S (somewhat surprising given that this is a nucleus only one neutron removed from the stability valley!). Hence the spectroscopy of individual levels above proton thresholds in ^{31}S is of high interest in our understanding of the $^{30}P(p,\gamma)^{31}S$ reaction. X-Ray bursts are other explosive phenomena involving these reactions.

3. Method: beta and beta-delayed proton decay studies

Among the indirect methods, a large class is the spectroscopy of resonances, in general (transfer reactions, gamma-ray in-beam spectroscopy, decay spectroscopy, etc...). 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_r) and their resonance strengths ($\omega\gamma$):

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

These may be obtained by studying the spectroscopic properties of the corresponding metastable states, populated through another, more convenient method. The decay spectroscopy is one such method: instead of measuring radiative proton capture (p,γ) one can study the inverse of its first step, the proton decay of the same state. The states populated by beta-delayed proton decay: in the same compound nucleus, states above the proton threshold are populated by β-decay, and then they decay emitting a proton. This happens provided, of course, the selection rules for (p,γ) and βp allow for the population of the same states (energy and spin-parity selection rules). One can determine that way the energy of the resonance, restrict the spins and parity (may be even determine them) and determine the branching ratios. This simple connection is schematically presented in figure 1 for the case of the $^{22}Na(p,\gamma)^{23}Mg$ radiative proton capture: we aim at populating and study states in the ^{23}Mg daughter nucleus following the β-decay of ^{23}Al. The selection rules allow that: s-wave radiative capture involves $J^{\pi}=5/2^+$ and $7/2^+$ states; beta-decay populates predominantly positive parity states with spins 3/2, 5/2 and 7/2. Figure 1, a slide from the actual lecture, underlines that we need to locate the resonances and determine their properties (spin and parity and partial widths). Similar situations for the other two proton capture in our list, which we study through the decay of ^{27}P and ^{31}Cl, respectively.

4. Experiments

One important point here is that, on the nuclear scale, the stars are cold! Even for explosive burning processes, like novae and X-ray bursts (XRB) that are our particular focus here, at temperatures T=0.1-0.3 GK for novae and T≥ 1 GK for X-ray bursts, the energies in the Gamow peak are of the order of a few hundred keV, therefore we need to measure proton energies E_p~100-800 keV.

A major experimental problem is that these proton energies are very small, close to the limits of our current detection techniques. We made recently progress at Texas A&M University by using a method consisting in the implantation of radioactive sources in very thin Si double sided strip detectors (DSSD), which allows, up to a point, measuring

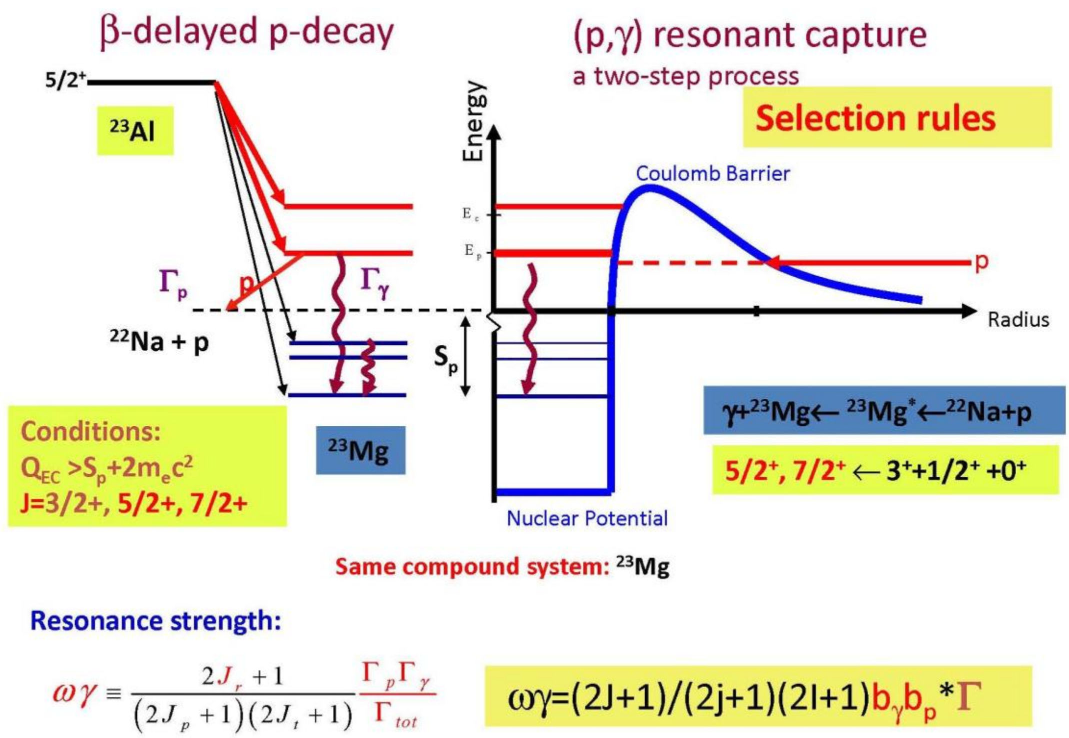

FIGURE 1. (Color online) Schematic presentation of the use of β-delayed proton decay to study resonant H-burning in nuclear astrophysics.

such low energy protons from βp-decays [2,3]. The simple technique allows to measure β- and β-delayed proton-decay of proton-rich nuclei produced and separated with the MARS recoil spectrometer [10] at the K500 superconducting cyclotron. The short-lived radioactive species are produced in-flight with X(p,2n)Y reactions (where X is the projectile and Y is the nucleus to decay) in inverse kinematics on a cryogenic H_2 gas target, separated in MARS, then slowed down (from about 30-40 MeV/u) and implanted in the middle of a very thin Si detector. Then the beam is turned off and the decay of Y 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}Mg at 48 MeV/u, ^{28}Si and ^{32}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 μm 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.

5. Results

We carried βγ and βp-decay studies of Y=^{23}Al, ^{27}P and ^{31}Cl, aiming at determining the properties of resonances that contribute to the ^{22}Na(p,γ)^{23}Mg, ^{26m}Al(p,γ)^{27}Si and ^{30}P(p,γ)^{31}S reactions, respectively. A sequence of experiments has been devoted to measuring the beta delayed protons from ^{23}Al. Recent work on this nucleus was most extensive [2-5] and will be used as best example. Stronger protons peaks with energies down to about 200 keV from the decay of some levels were observed. The best results obtained at using a DSSD are given in [4] and shown below in Figure 2.

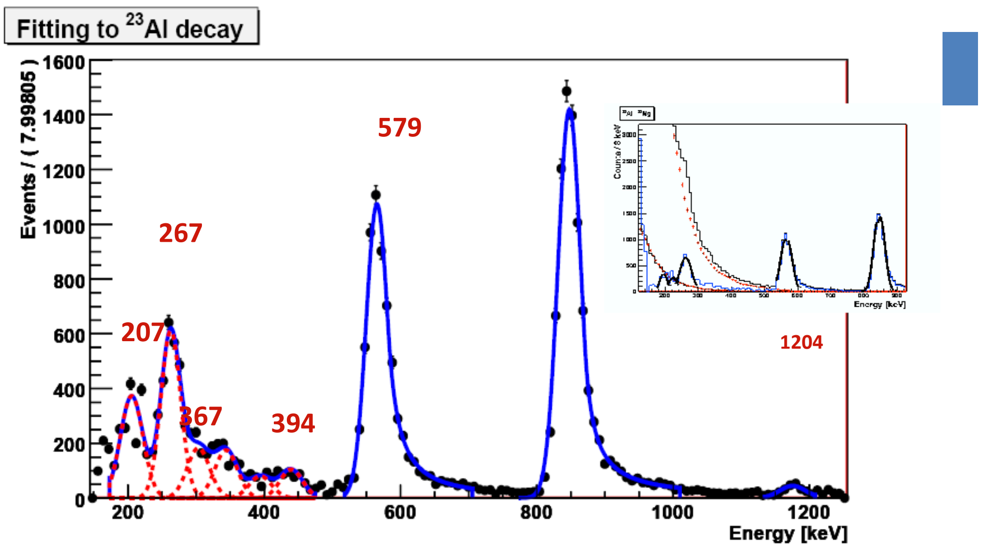

Figure 2. Proton spectrum following the β-decay of ^{23}Al measured with a 65 μm DSSD (from Ref. [4]). Note in the insert the high background which is attributed to the betas, as are the tails of the proton peaks.

However, it must be stressed that the proton spectrum in the main body of the figure is obtained from the real spectrum shown in the insert on right after subtracting a considerable background. The proton decay spectra are described in [4] and obtained by implanting ^{23}Al in DSSD and allowed to decay. The principal difficulty here was to reduce the high β^+ background, because Si detectors are sensitive to positrons. Each proton is accompanied by β^+, but most betas are not followed by proton emission and they produce a very large, continuous background in the low part of the energy spectra. The ratio β^+-p versus β^+ branch is like 1:100 in this case (not so bad actually; see later!).

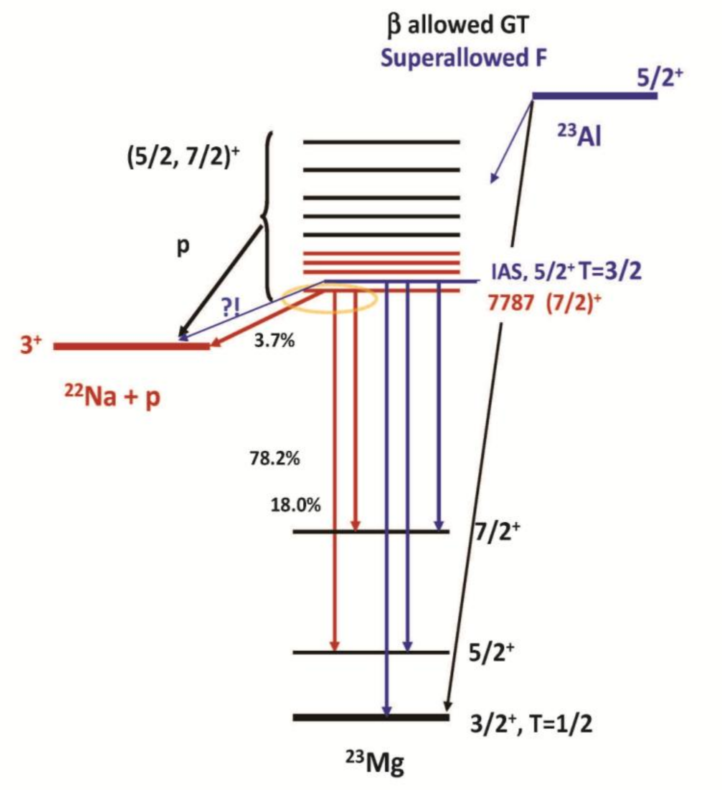

Figure 3. Partial decay scheme of ^{23}Al. Only the transitions to the first 3 levels of daughter nucleus ^{23}Mg are shown in the lower part to justify the spin and parity assignment of its ground state. The decay of the doublet around E*=7.8 MeV (the IAS and the E=7787 keV state), including a 3.7% proton branch is also shown. It is very rare that the decay of a state by both gamma-ray and proton emission is observed.

The continuous background was subtracted here based on a measurement for a case where betas-only (^{22}Mg) were implanted and detected.

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 β–γ 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 β-delayed proton emission. The lifetimes of all 3 isotopes could also be determined with <1% uncertainties, improving considerably the previous data (uncertainties were ~25%).

Time limitations during lecture did not allow discussing there in detail the results for all cases; I will not go beyond that here. In brief, the most important results from the study of the decay of ^{23}Al are:

- first clean and intense ^{23}Al source was produced
- the decay scheme was established
- established unambiguously the g.s. spin and parity $J^{\pi}=5/2^{+}$ (not $1/2^{+}$) [2], which allowed to evaluate that the reaction ^{22}Mg(p,g)^{23}Al is not important for depletion of ^{22}Na in novae
- absolute beta-decay 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 *logft=3.31(2) – measured, not assumed!*
- used IMME to get new ^{23}Al mass [2] $\Rightarrow$ $S_p(^{23}Al)$=143(3) keV
- after ^{23}Al mass was 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 Ep=207 keV from the E*=7787 keV state (see figure 2). This state is an important resonance in ^{22}Na(p,γ)^{23}Mg reaction. From the gamma and proton branchings measured here, and the lifetime from Ref. [11] we could determine its resonance strength: ωγ=1.4(5) meV
- Determined the total proton branching =1.26(5)%.

At least one burning question did remain – namely does the IAS at 7.803 MeV ($J^{\pi}=5/2^{+}$, T=3/2) in ^{23}Mg proton-decays to the ground state of ^{22}Na? (see Figure 3). We could not answer this question with this method.

Studies of the ^{31}Cl and ^{27}P βp-decays in the proton energy region below 400 keV were expected to be of great importance for astrophysics and the decay of ^{31}Cl is expected to complete the scarce spectroscopic data in ^{31}S immediately above the proton threshold line. A list of similar results were obtained for the decay of ^{31}Cl [3,4,5]. The decay of ^{27}P will provide unique data on the resonances governing the radiative proton capture on the ^{26m}Al $J^{\pi}=0^{+}$ isomer, part of the reactions leading to the production and destruction of astrophysically important ^{26}Al. It is presented in more detail elsewhere in this Proceedings [6], I will refer the reader to that contribution. A remarkable result here is that the proton branching was found to be of the order of 10^{-4}.

6. AstroBox

I said before that with the setup using Si detectors, even very thin ones, we could not lower sufficiently the background in the low energy part of the spectra measured. The question here is: can we develop an instrument that reduces further the β^+ background and yet retains semi-conductor energy resolutions and uniform efficiency?! The desirable proton resolution would be approximately 10-15 keV (FWHM) at 200 keV. An efficiency known with accuracy ~10-20% is required to obtain astrophysics information. A mustering of this well studied nucleus will open possibilities to study further the nuclei we studied here at much lower proton energies, getting into the Gamow region for the H-burning in novae.

In a very recent development, this spring of 2011, we have replaced the Si detector with a gas based detector, part of a small project that we call AstroBox. It was developed with people from CEA-Saclay, CERN and IKP Koln. Using a P5 gas we could reduce drastically the beta background that has hindered the measurement of low energy proton branches, while improving the resolution. The charge produced by protons in gas is further amplified by micromegas detectors. The beta background was pushed down to energies lower than about 150 keV (figure 4), opening an important window for further studies.

Figure 4 shows quasi-online beam-off proton spectrum resulting principally from the decay of ^{23}Al. Comparing figure 4 with figure 2, we note a very strong beta reduction thus making it possible to obtain clean spectra down to 100 keV or lower. The linearity in the rage 150 to 700 keV is good and the resolutions are typically ~10% (FWHM) and consistent with the source data. We plan to continue on this path, improving the conditions further and extending the measurements to ^{27}P and ^{31}Cl.

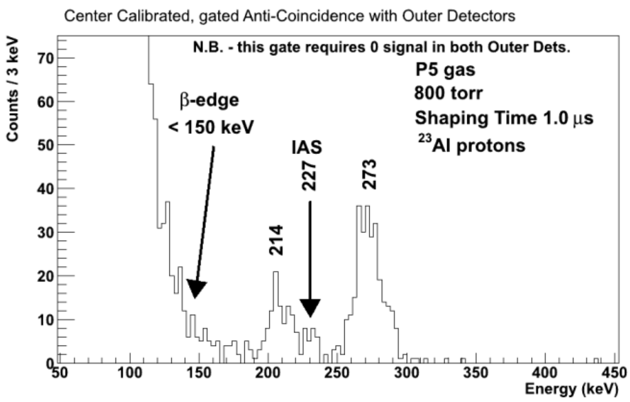

Figure 4. Zoom of calibrated spectrum for the low energy p spectrum of ^{23}Al measured with AstroBox. The energies marked are c.m. energies (preliminary calibration and analysis).

7. Conclusions

Our studies showed that:

- the technique of implanting radioactive species in very thin Si detectors works very well. We could measure protons with energies as low as 200 keV.
- The technique can be applied to nuclei with lifetimes as short as 100 ms or less.
- It is very selective and sensitive, we could work with rates of 1-10 pps
- or with proton branchings ~10^{-4}.

The strengths of the method arise from:

- the good isotope separation offered by the recoil spectrometer MARS
- the in-flight production that allows implantation

We have shown that with AstroBox type detectors we can aim down to Ep~100 keV with little or no background from accompanying beta particles.

Acknowledgments

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References

[1] L. Trache, *in these Proceedings,* **PoS (ENAS 6)030**.
[2] V.E. Iacob *et al.*, *Phys.Rev. C* **74**, 045810 (2006).
[3] L. Trache *et al.*, in *Proc. 10th Symposium on Nuclei in the Cosmos, July 27-Aug 1, 2008, Mackinac Island, MI,* **PoS (NIC X) 163.**
[4] A. Saastamoinen *et al.*, *Phys. Rev. C* **83**, 045808 (2011).
[5] L. Trache et al., in *Proc. Intern. Conf. Nuclear Physics for Astrophysics V, Apr. 3-8, 2011, Eilat, Israel.*
[6] L. Trache *et al.*, in Proc. Fourth International Conference on Proton-emitting Nuclei (PROCON2011), Bordeaux, France, 6-10 June 2011, ed. B. Blank, AIP Conf. Series, vol. 1409, Melville, NY, 2011; A. Saastamoinen et al., *ibidem*.
[7] Ellen Simmons et al. *in these Proceeding,* **PoS (ENAS 6)037**.
[8] Alexandra Spiridon et al. *in these Proceedings,* **PoS (ENAS 6)038.**
[9] Jordi Jose, *in these Proceedings,* **PoS (ENAS 6)008.**
[10] R.E. Tribble et al., *Nucl. Instr. Meth. A* **285**, 441 (1991).
[11] D.G. Jenkins *et al.*, *Phys.Rev. Lett.* **92**, 031101 (2004).