Studies of astrophysically interesting nucleus $^{23}$Al

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Abstract. We have studied the $\beta$-delayed proton decay of $^{23}$Al with a novel detector setup at the focal plane of the MARS separator at the Texas A&M University to resolve existing controversies about the proton branching of the IAS in $^{23}$Mg and to determine the absolute proton branchings by combining our results to the latest $\beta\gamma$-decay data. We have made also a high precision mass measurement of the ground state of $^{23}$Al to establish more accurate proton separation energy of $^{23}$Al. Here the description of the used techniques along with preliminary results of the experiments are given.

1. Introduction

Classical novae are relatively common events in our galaxy with a rate of a few per year detected. The present understanding is that novae occur in interacting binary systems where hydrogen-rich material accretes on a white dwarf from its low-mass main-sequence companion. At some point in the accretion the hydrogen-rich matter compresses leading to a thermonuclear runaway [1]. Understanding the dynamics of the nova outbursts and the nucleosynthesis fueling it is crucial in understanding the chemical evolution of the galaxy.

The key parameters in determining the astrophysical reaction rates dominated by resonant proton capture, as is the case with many sd-shell nuclei, are the energies and decay widths of the associated nuclear states. Accurate determination of these energies can be achieved through traditional decay spectroscopy, accompanied with high-precision mass measurements of the ground states by using Penning trap mass spectrometry. One of the key reactions that possibly deplete $^{22}$Na produced in the so called NeNa-cycle and for which the reaction rates are known only with large uncertainties is the radiative proton capture $^{22}$Na(p,$\gamma$)$^{23}$Mg [2, 3]. This reaction rate is dominated by the capture through low-energy proton resonances which correspond to excited states in $^{23}$Mg nucleus above the proton separation threshold.

The relevant states in $^{23}$Mg can be studied via $\beta$-decay of $^{23}$Al, populating the excited states of $^{23}$Mg that are decaying by both proton and $\gamma$-emission. Earlier works on the $\beta$-decay of $^{23}$Al show contradicting results for the lowest states above the $^{22}$Na+p threshold [4, 5] The scope of
the present work is to solve this controversy and to deduce the absolute proton branchings from the excited states of $^{23}\text{Mg}$ by combining our data to existing decay data [3].

2. $\beta$-decay of $^{23}\text{Al}$

The $\beta$-decay of $^{23}\text{Al}$ was studied at the Cyclotron Institute of the Texas A&M University. In this experiment the $^{23}\text{Al}$ beam was produced in inverse-kinematics reaction $^1\text{H}(^{24}\text{Mg},^{23}\text{Al})2n$ by bombarding a hydrogen gas target with $^{24}\text{Mg}$ beam at 48 MeV/u. The recoil products were separated with the Momentum Achromat Recoil Separator (MARS) [6], resulting a beam of $^{23}\text{Al}$ with typical intensity of 4000 pps and purity of better than 95%.

The beam was taken into the detector setup, illustrated in Fig 1, consisting of a 65$\mu$m thick Double-Sided Silicon Strip Detector (DSSSD) with $16+16 \times 50$ mm$^2$ strips, a 1 mm thick Si-pad detector and a high-purity germanium detector (HPGe). The beam implantation depth was controlled by using a rotatable 300 $\mu$m Al degrader, allowing us to tune the beam into the center of the DSSSD. The beam was pulsed with an implantation period of 1 second and a decay period of 1 second. The data was collected only during the decay part of the cycle.

The particle detectors were calibrated online with beams of $^{20}\text{Na}$, $^{21}\text{Mg}$, $^{22}\text{Mg}$ and the germanium detector with $^{24}\text{Al}$. Both, the DSSSD and the HPGe were gated with the $\beta$-spectrum from the Si-pad detector. As the DSSSD used had fairly large pixel size, the $\beta$-response extends up to several hundred keV even with a pure source. One way to extract out the meaningful data is to measure the actual $\beta$-response from the detector by using an implanted source that does not emit any other charged particles and try to deduct this contribution from the interesting data. In this case the $\beta$-response was measured with $^{22}\text{Mg}$. The measured $\beta$-spectrum was smoothed to get rid of statistical fluctuations and then scaled so that it matched the $^{23}\text{Al}$ spectrum at 150 keV. The resulting spectrum is illustrated in figure 2.

![Figure 1](image1.png)

**Figure 1.** A sketch of the setup used in this experiment. The beam enters the setup from right through the rotatable aluminum degrader (A) and is implanted into the DSSSD backed with a Si-pad detector (C). The HPGe detector (B) was located outside the chamber at 90° to the beam.

![Figure 2](image2.png)

**Figure 2.** The background-reduced total decay energy spectrum from this work (black) compared with the proton spectrum from Ref. [5]. The old Jyväskylä data is multiplied by factor of 20 to make it more visible (red).
Even from the raw spectrum, it is clear that there is no anomalously large proton branch from the IAS in $^{23}\text{Mg}$, as reported in Ref. [4]. From the background reduced spectrum, illustrated in Fig. 2, it is clear that our result agree with Ref. [5]. From these proton and $\gamma$-data one can extract the relative proton intensities and then by using the existing absolute $\gamma$-branchings [3] one can assign the absolute proton branchings from the states studied.

3. Mass of $^{23}\text{Al}$
A high-precision mass measurement of $^{23}\text{Al}$ was conducted by using the JYFLTRAP setup at the IGISOL facility in the Accelerator Laboratory of the University of Jyväskylä. The $^{23}\text{Al}$ beam was produced by using Ion Guide Isotope Separator On Line (IGISOL) method [7]. From the IGISOL facility, ions having the same $A/q = 23$ were sent into a gas-filled radiofrequency quadrupole (RFQ) cooler-buncher [8] to prepare the samples for injection into the JYFLTRAP Penning trap setup consisting of two identical, cylindrical traps inside the same superconducting 7 T magnet [9]. The first trap is filled with low-pressure helium gas and works as a purification trap with a mass resolving power of a few $\times 10^5$. The second trap is a precision trap where the mass of the ion is determined by using the time-of-flight ion cyclotron resonance (TOF-ICR) method [10, 11]. The absolute mass of the ion of interest is determined from the ratio of the measured cyclotron frequencies of the sample and a well known reference case: $m = (\nu_{c,\text{ref}}/\nu_c) \cdot (m_{\text{ref}} - m_e) + m_e$. Figure 3 illustrates typical TOF resonance curves from this experiment.

![Figure 3. Typical cyclotron resonance curves of $^{23}\text{Al}^+$ and $^{23}\text{Na}^+$. The RF-excitation time was 100 ms.](image)

In this experiment $^{23}\text{Na}$ was used as reference for determining the masses of $^{23}\text{Al}$ and $^{23}\text{Mg}$. The full analysis and the implication for the Isobaric Multiplet Mass Equation are discussed in a separate article [17]. One can calculate a new value for the $^{23}\text{Al}$ proton separation energy, $S_p(^{23}\text{Al}) = 141.11(43) \text{ keV}$, by combining our result for the mass excess of $^{23}\text{Al}$, 6748.07(34) keV, and the mass excesses of $^{22}\text{Mg}$, -399.79(25) keV, [18] and $^1\text{H}$, 7288.97050(11) keV, [12].

4. Conclusions and outlook
From the $\beta$-decay data, it is clear that there is no exceptionally large proton branching from the IAS in $^{23}\text{Mg}$ and thus strong isospin mixing as proposed by Tighe et al. in Ref. [4]. Our decay data allows us to extract the proton branchings from the excited states of $^{23}\text{Mg}$ that are close to $^{22}\text{Na}+p$ threshold and thus crucial to the $^{22}\text{Na}(p,\gamma)^{23}\text{Mg}$ reaction rate. The detailed analysis is to be finished and published in near future. The same setup has been improved and optimized for further experiments, which include $\beta$-decay of $^{31}\text{Cl}$ and similar studies under planning.
The $S_p$ value resulting from our mass measurement is higher than the previous value indicating a reduced halo nature. This new value has influence on the calculated astrophysical S-factor for the proton capture reaction $^{22}\text{Mg}(p,\gamma)^{23}\text{Al}$ and its corresponding reaction rate in the stellar environments. It also shows $^{23}\text{Al}$ to be more resilient to destruction through photodissociation, making this isotope a more important player in the reaction networks in the explosive H-burning processes, like novae and X-ray bursts.

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