PROCEEDINGS OF SCIENCE

PoS(NIC XI)211

β-delayed proton decay of ^{23}Al and nova nucleosynthesis

A. Saastamoinen[*a], **L. Trache**[b], **A. Banu**[b†], **M. A. Bentley**[c], **T. Davinson**[d], **J. C. Hardy**[b], **V. E. Iacob**[b], **M. McCleskey**[b], **B. Roeder**[b], **E. Simmons**[b], **G. Tabacaru**[b], **R. E. Tribble**[b], **P. J. Woods**[d], **J. Äystö**[a]

[a] *Department of Physics, University of Jyväskylä, P.O.Box 35 (YFL), FI-40014, Finland*
[b] *Cyclotron Institute, Texas A&M University, College Station, TX 77843, USA*
[c] *Department of Physics, University of York, Heslington, York, YO10 5DD, UK*
[d] *School of Physics and Astronomy, University of Edinburgh, Edinburgh, EH9 3JZ, UK*

E-mail: `antti.j.saastamoinen@jyu.fi`

We have studied β-decay of ^{23}Al with a novel detector setup at the focal plane of the MARS separator at the Texas A&M University. Absolute proton-decay branching ratios from excited states of ^{23}Mg are determined by combining our results to the latest γ-decay data. Contrary to previous β-decay studies, no strong proton intensity from the isobaric analogue state (IAS) in ^{23}Mg ($E_x = 7803$ keV) was observed. Instead, we assign the lowest observed proton group at $E_{cm} = 206$ keV to the state 16 keV below the IAS. In this contribution, a description of the used technique along with results of the experiment are given and their relevance for astrophysics discussed.

11th Symposium on Nuclei in the Cosmos, NIC XI
July 19-23, 2010
Heidelberg, Germany

---

[*] Speaker.

[†] Present address: James Madison University, Harrisonburg, VA 22807, USA

1. Introduction

Classical novae are relatively common events in our galaxy with a rate of a few per year detected. 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 of the hydrogen-rich matter compresses leading to a thermonuclear runaway [1]. An understanding of the dynamics of nova outbursts and of the nucleosynthesis fueling them is crucial in testing our understanding of the dynamics of stellar phenomena in general. Novae are relatively frequent phenomenon and they are observed throughout the whole electromagnetic spectrum and therefore the models can be compared more easily with the observations. If nova ejecta have short-lived nucleus ^{22}Na ($T_{1/2} = 2.6$ y) in large enough quantities, it can be observed by space-based telescopes through its characteristic γ-ray following β decay. Non-observation of this γ-line constrains the amount of ^{22}Na produced in the novae, setting also limits for key reactions that take place in this mass region.

Many H-burning reactions important here are dominated by resonant capture. The key parameters in understanding the astrophysical reaction rates are the energies and decay widths of the associated nuclear states near the particle separation threshold of the compound nucleus formed in the capture reaction. One of the key reactions that possibly deplete the so called NeNa-cycle (and thus ^{22}Na) and for which the reaction rates are known with large uncertainties is the radiative proton capture ^{22}Na(p,γ)^{23}Mg. The rate of this reaction is dominated by the radiative proton capture through low-energy resonances which correspond to the excited states in ^{23}Mg nucleus. This reaction has been studied in challenging direct measurements [2 – 4] as well as in indirect measurements, including β decay studies [5, 6].

The relevant excited states in ^{23}Mg are populated in the β-decay of ^{23}Al. , following a decay by both proton or γ-emission. Earlier works on the β-decay of ^{23}Al show contradicting results for the lowest states above the ^{22}Na+p threshold [5, 6] The scope of the present work is to solve this controversy and to deduce the absolute proton-decay branching ratios from the excited states of ^{23}Mg by combining our data to existing decay data [7, 8].

2. Experimental technique

The β-decay of ^{23}Al was studied at Cyclotron Institute of the Texas A&M University. In this experiment the ^{23}Al beam was produced in inverse-kinematics reaction ^{1}H(^{24}Mg,^{23}Al)2n by bombarding a hydrogen gas target with ^{24}Mg beam at 48 MeV/u. The recoil products were separated and with the Momentum Achromat Recoil Separator (MARS) [9], resulting a beam of ^{23}Al with typical intensity of 4000 pps and purity of better than 95%.

Ions of interest were implanted int a detector setup consisting of a 69μm Double-Sided Silicon Strip Detector (DSSSD), a 1 mm thick Si-pad detector and a high-purity germanium (HPGe) detector. The beam implantation depth was controlled by using a rotatable 300 μm Al degrader, allowing us to tune the beam into the middle of the DSSSD. Overview of the setup is illustrated in Fig. 1. The beam was pulsed with implantation period of 1 second and decay period of 1 second and the data was collected only during the decay part.

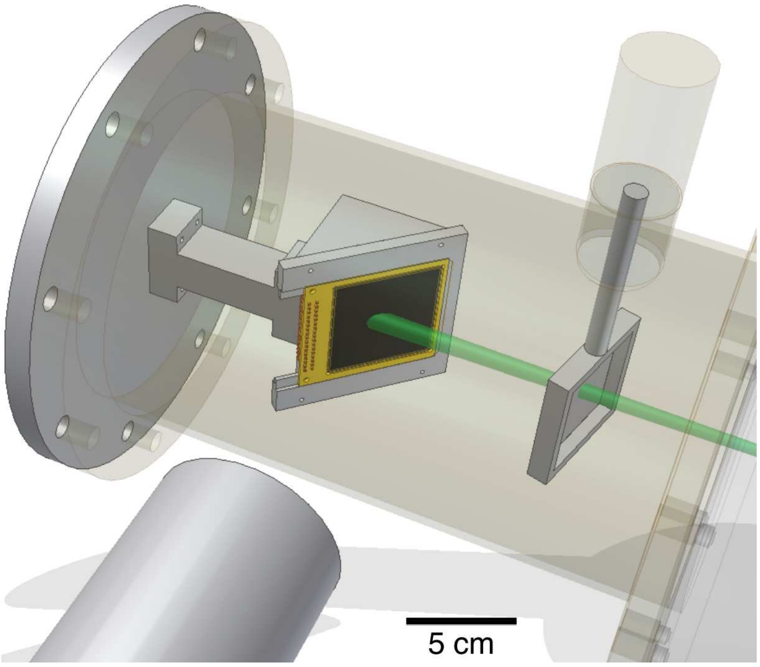

Figure 1: Experimental setup at the focal plane of MARS. Beam enters the chamber from right, through the tunable aluminum degrader and finally into the detector setup consisting of a DSSSD backed with a thick Si-pad detector. The HPGe detector was installed outside the measurement chamber.

The particle detectors were calibrated online with secondary beams of ^{20}Na, ^{21}Mg, ^{22}Mg that were available from same primary beam and target combination. The germanium detector was calibrated with standard calibration sources and checked online with ^{24}Al beam. Both, the DSSSD and the HPGe were gated with the β-spectrum from the Si-pad detector. As the DSSSD used had fairly large pixel size, the β-response extends up to about 500 keV even with a pure source. The meaningful low energy protons are on top of this background (e.g. the height of the continuum at 300 keV was comparable to the major proton groups shown in Fig. 2) and thus background subtraction has to be used. This can be done by measuring the actual β-response from the detector by using an implanted source that does not emit any other charged particles and then reducing this contribution from the actual data set. In this case the β-response was measured with ^{22}Mg available in the same cocktail of produced ions. The measured β-spectrum was smoothed to get rid of statistical fluctuations and then scaled so that it matched the ^{23}Al spectrum around 150 keV. The resulting background reduced spectrum with a comparison to spectrum from Ref. [6] is illustrated in figure 2.

3. Results

The measured energy of the spectrum is sum of the energies of the emitted proton, the recoil and average energy deposited by the preceding β-particle:

$$E_{\mathrm{meas.}} = \left(1 + k \cdot \frac{M_{\mathrm{p}}}{M_{\mathrm{rec.}}}\right) \cdot E_{\mathrm{p}} + E_{\langle\beta\rangle}, \tag{3.1}$$

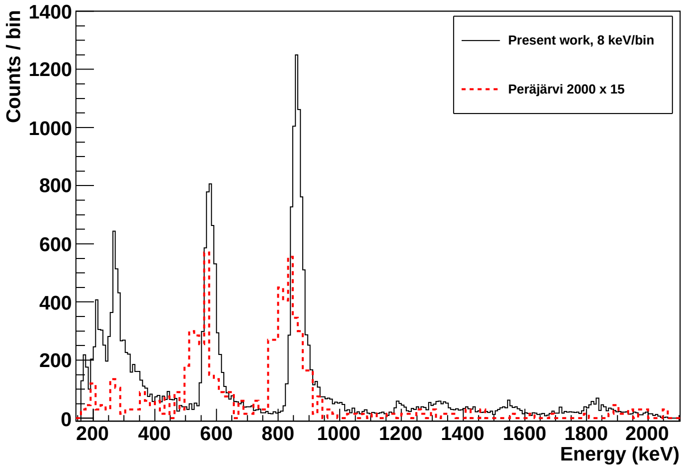

Figure 2: The background reduced β-delayed proton spectrum from this work compared against the spectrum from Ref. [6]. The data published in Ref. [6] is multiplied by factor of 15 to bring it up to same scale with our data.

where k denotes the fraction of the recoil energy that is actually deposited to the detector due to ionization and M_p and $M_{rec.}$ are masses of proton and the recoil, respectively. The intensities of the acquired proton peaks is normalized to the simultaneously measured intensity of 451 keV γ-transition. These relative proton intensities are converted to absolute proton intensities with known absolute γ-intensity for the 451 keV transition [8]. Figure 2 shows that our result agree closer to the results from Ref. [6], but still with somewhat larger intensities for the lower energy protons.

The determined emitted proton energy (in CMS) for the lowest proton group 206(11) keV, combined with the $S_p(^{23}\mathrm{Mg})$ = 7580.9(7) keV [10 – 12] indicates that these protons are coming from 7788(11) keV state in ^{23}Mg. This corresponds to a known $(7/2)^+$ state at 7785.7(11) keV [7, 13] that is located 16 keV below the IAS. This is also more plausible as it is not isospin forbidden as the decay/capture through the IAS.

The typical peak temperature of ONe nova is 0.1-0.4 GK and the ^{22}Na(p,γ) reaction rate depends on narrow isolated resonances in this region. The observed 7785.7(11) keV state is located in this energy window (e.g. at 0.3 GK the Gamov window is 170–360 keV) and the determined proton decay branching ratio (0.32(6) per 100 451 keV γ rays) can be used in combination with the γ-decay branching ratios [8] and the level life-time [14] to determine the resonance strength $\omega\gamma$ for this resonance. Our result $\omega\gamma = 1.4(5)$ meV agrees to the old value 1.8(7) meV from a direct measurement [3], but disagrees with the recent value of $5.7^{+1.6}_{-0.9}$ meV [4]. Our value does not make significant change in the reaction rate presented in the compilation [16], but confirms and reduces the uncertainties. If the Also, to our knowledge, this state is only the second case known in literature for which both the gamma and proton decay branches are observed following β decay, the other case being in a state in ^{32}Cl [15].

4. Conclusions and outlook

We have measured β-delayed protons from decay of ^{23}Al and determined absolute proton branches of excited states above $S_p(^{23}\text{Mg})$. From the our decay data, it is clear that there is no exceptionally large proton branching from the IAS in ^{23}Mg and the lowest energy proton group from the β-decay is actually from a state below the IAS. Our decay data completes the required indirect data to evaluate the resonance strength of the 7787 keV resonance in ^{22}Na(p,γ) reaction taking place in ONe novae. Our result for the resonance strength agrees to old value from direct measurement, but disagrees with the newer value reported in this conference. The setup described here has been used already in studies of β-decay of ^{31}Cl and ^{20}Mg and more experiments are being planned.

References

[1] J. Jose *et al.*, *Nucleosynthesis in classical novae*, *Nucl. Phys A* **777** (2006) 550

[2] S. Seuthe *et al.*, *Resonances in the* ^{22}*Na(p,*γ*)*^{23}*Mg reaction*, *Nucl. Phys A* **514** (1990) 471

[3] F. Stegmüller *et al.*, ^{22}*Na(p,*γ*)*^{23}*Mg resonant reaction at low energies*, *Nucl. Phys A* **601** (1996) 168

[4] A. Sallaska *et al.*, *Destruction of 22Na in Novae: Surprising Results from an Absolute Measurement of* ^{22}*Na(p,*γ*) Resonance Strengths*, in proceedings of *11th Symposium on Nuclei in the Cosmos, NIC XI*, PoS(NIC XI)051

[5] R. J. Tighe *et al.*, *Observation of strong isospin mixing in proton emission from the astrophysically interesting isobaric analog state in* ^{23}*Mg*, *Phys. Rev. C* **52**(1995) R2298

[6] K. Peräjärvi *et al.*, *Measurement of the IAS resonance strength in* ^{23}*Mg*, *Phys. Lett. B* **492** (2000) 1

[7] V. E. Iacob *et al.*, β *decay of proton-rich nucleus* ^{23}*Al and astrophysical consequences*, *Phys. Rev. C* **74** (2006) 045810

[8] Y. Zhai , *Ph. D. Thesis*, Texas A&M University 2007

[9] R. E. Tribble *et al.*, *Radioactive beams at Texas A&M University*, *Nucl. Phys. A* **701** (2002) 278c

[10] G. Audi, A. H. Wapstra, and C. Thibault, *The AME2003 atomic mass evaluation (II). Tables, graphs and references*, *Nucl. Phys. A* **729** (2003) 337

[11] M. Mukherjee *et al.*, *Mass measurements and evaluation around A = 22*, *Eur. Phys. J. A* **35** (2008) 31

[12] A. Saastamoinen *et al.*, *Mass of* ^{23}*Al for testing the isobaric multiplet mass equation*, *Phys. Rev. C* **80** (2009) 044330

[13] R. B. Firestone, *Nuclear Data Sheets for A = 23*, *Nucl. Data Sheets* **108** (2007) 1

[14] D. G. Jenkins *et al.*, *Reevaluation of the* ^{22}*Na(p,*γ*) Reaction Rate: Implications for the Detection of* ^{22}*Na Gamma Rays from Novae*, *Phys. Rev. Lett.* **92** (2004) 031101

[15] M. Bhattacharaya *et al.*, *ft value of the* $0^+ \to 0^+\beta^+$ *decay of* 32*Ar: A measurement of isospin symmetry breaking in a superallowed decay*, *Phys. Rev. C* **77** (2008) 065503

[16] C. Angulo *et al.*, *A compilation of charged-particle induced thermonuclear reaction rates*, *Nucl. Phys A* **656** (1999) 3