

**This is an electronic reprint of the original article.  
This reprint *may differ* from the original in pagination and typographic detail.**

**Author(s):** Kankainen, Anu; Canete, Laetitia; Eronen, Tommi; Gorelov, Dmitry; Hakala, Jani;  
Jokinen, Ari; Kolhinen, Veli; Koponen, Jukka; Moore, Iain; Nesterenko, Dmitrii;  
Reinikainen, Juuso; Rinta-Antila, Sami; Äystö, Juha

**Title:** Mass Measurements for the rp Process

**Year:** 2017

**Version:**

**Please cite the original version:**

Kankainen, A., Canete, L., Eronen, T., Gorelov, D., Hakala, J., Jokinen, A., . . . Äystö, J.  
(2017). Mass Measurements for the rp Process. In NIC 2016 : Proceedings of the  
14th International Symposium on Nuclei in the Cosmos (pp. 011002). JPS Conference  
Proceedings, 14. Physical Society of Japan. doi:10.7566/JPSCP.14.011002

All material supplied via JYX is protected by copyright and other intellectual property rights, and duplication or sale of all or part of any of the repository collections is not permitted, except that material may be duplicated by you for your research use or educational purposes in electronic or print form. You must obtain permission for any other use. Electronic or print copies may not be offered, whether for sale or otherwise to anyone who is not an authorised user.

# Mass measurements for the $rp$ process

Anu Kankainen<sup>1</sup>, Laetitia Canete<sup>1</sup>, Tommi Eronen<sup>1</sup>, Dmitry Gorelov<sup>1</sup>, Jani Hakala<sup>1</sup>, Ari Jokinen<sup>1</sup>, Veli S. Kolhinen<sup>1</sup>, Jukka Koponen<sup>1</sup>, Iain D. Moore<sup>1</sup>, Dimitrii Nesterenko<sup>1</sup>, Juuso Reinikainen<sup>1</sup>, Sami Rinta-Antila<sup>1</sup> and Juha Äystö<sup>1</sup>

<sup>1</sup>Department of Physics, University of Jyväskylä, P.O. Box 35, FI-40014 University of Jyväskylä, Finland

E-mail: [anu.kankainen@jyu.fi](mailto:anu.kankainen@jyu.fi)

(Received August 18, 2016)

One of the key parameters for the reaction network calculations for the rapid proton capture ( $rp$ ) process, occurring e.g. in type I X-ray bursts, are the masses of the involved nuclei. Nowadays, masses of even rather exotic nuclei can be measured very precisely employing Penning-trap mass spectrometry. With the JYFLTRAP Penning trap at the IGISOL facility, masses of around 100 neutron-deficient nuclei have been determined with a typical precision of a few keV. Most recently, <sup>25</sup>Al, <sup>30</sup>P, <sup>31</sup>Cl, and <sup>52</sup>Co have been measured. Of these, the precision of the mass-excess value of <sup>31</sup>Cl was improved from 50 keV to 3.4 keV, and the mass of <sup>52</sup>Co was experimentally determined for the first time. The mass of <sup>31</sup>Cl is relevant for estimating the waiting-point conditions for <sup>30</sup>S as the <sup>31</sup>Cl( $\gamma, p$ )<sup>30</sup>S—<sup>30</sup>S( $p, \gamma$ )<sup>31</sup>Cl equilibrium ratio depends exponentially on the  $Q$  value. For <sup>52</sup>Co, located at the path towards <sup>56</sup>Ni, a deviation from the extrapolated mass value has been revealed. In this contribution, recent JYFLTRAP experiments for the  $rp$  process will be discussed.

**KEYWORDS:** atomic masses, Penning-trap mass spectrometry, novae,  $rp$  process

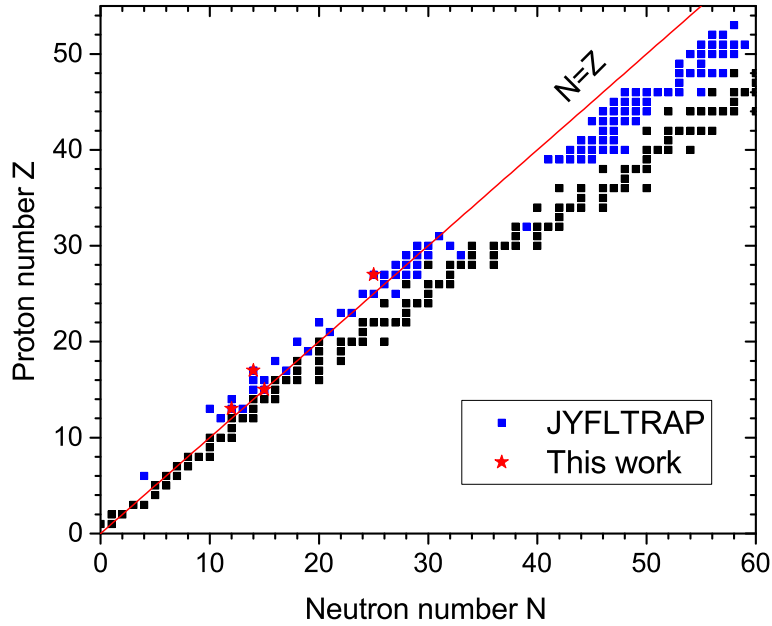
## 1. Introduction

Since the discovery of type I X-ray bursts around 40 years ago [1], nuclear reaction network calculations have been carried out to understand the observations and the underlying phenomenon, explosive hydrogen burning on the surface of an accreting neutron star, also known as the rapid proton capture ( $rp$ ) process [2, 3]. One of the key parameters for the calculations are the masses of the involved nuclei, i.e. the  $Q$  values for proton captures [4, 18]. More precise mass values enable more accurate calculations of type I X-ray burst light curves and burst ashes which can also provide essential information of the underlying neutron star crust [6].

Nowadays, masses of even rather exotic nuclei can be measured very precisely employing Penning-trap mass spectrometry. With JYFLTRAP double Penning trap mass spectrometer at the Ion Guide Isotope Separator On-Line (IGISOL) facility in the Accelerator Laboratory of the University of Jyväskylä (JYFL), masses of around 100 neutron-deficient nuclei have been measured since 2005 (see Fig. 1). In this work, we focus on the latest mass measurements performed for the  $rp$  process with JYFLTRAP. For a review on older mass measurements for the  $rp$  process at JYFLTRAP, see e.g. Ref. [7].

## 2. Experimental method

Neutron-deficient nuclei discussed in this paper, <sup>25</sup>Al, <sup>30</sup>P, <sup>31</sup>Cl and <sup>52</sup>Co, were produced via fusion-evaporation reactions using 40- or 50-MeV protons from the K130 cyclotron impinging into a thin (few mg/cm<sup>2</sup>) target of natural Si, ZnS or enriched <sup>54</sup>Fe at the Ion Guide Isotope Separator



**Fig. 1.** Neutron-deficient isotopes measured at JYFLTRAP. The isotopes discussed in this work,  $^{25}\text{Al}$ ,  $^{30}\text{P}$ ,  $^{31}\text{Cl}$  and  $^{52}\text{Co}$ , are highlighted with a star. For a review on older measurements, see Ref. [7].

On-Line (IGISOL) facility [8]. The reaction products were stopped in the helium gas cell of the ion guide and extracted out with help of a sextupole ion guide [9] and differential pumping. The beam was accelerated to 30 keV and mass-separated using a dipole magnet. The continuous beam was cooled and released as short ion bunches employing a radio-frequency quadrupole ion cooler and buncher [10] into the JYFLTRAP double Penning trap mass spectrometer [13]. There, the ions of interest were selected employing buffer-gas cooling method [11] in the first trap and injected into the second trap where high-precision mass measurements were performed using the time-of-flight ion cyclotron resonance technique (TOF-ICR) [12]. With the TOF-ICR technique, ions' cyclotron resonance frequency  $\nu_c = \frac{qB}{2\pi m}$ , where  $q$  is the charge of the ion (at IGISOL typically  $q = +e$ ), and  $m$  the mass of the ion, is measured. The magnetic field strength  $B$  is determined by doing a similar TOF-ICR measurement for a reference ion whose mass is already well known. For  $^{25}\text{Al}$ ,  $^{30}\text{P}$ ,  $^{31}\text{Cl}$  and  $^{52}\text{Co}$  measurements,  $^{25}\text{Mg}$ ,  $^{30}\text{Si}$ ,  $^{31}\text{P}$  and  $^{52}\text{Cr}$  were used as references, for which the mass values were taken from the Atomic Mass Evaluation 2012 (AME12) [16].

### 3. Results and discussion

#### 3.1 $^{25}\text{Al}$

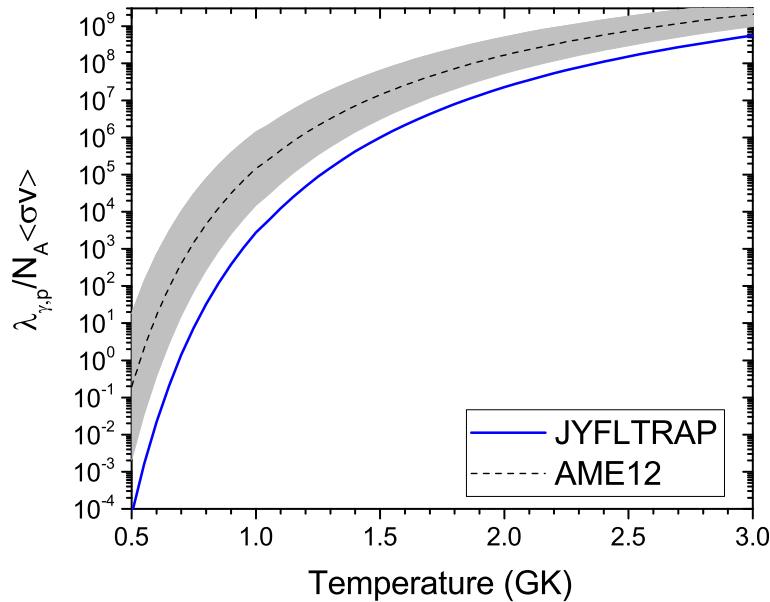
Mass of  $^{25}\text{Al}$  is relevant for understanding the production of cosmic 1809-keV  $\gamma$ -rays following the beta decay of  $^{26}\text{Al}$ . Namely,  $^{25}\text{Al}(p, \gamma)^{26}\text{Si}(\beta^+)^{26}\text{Al}^m$  provides a bypass for  $^{26}\text{Al}$  ground state, and hence the more favorable it is, the fewer 1809-keV  $\gamma$ -rays are produced. Therefore, for quantifying the amount of produced 1809-keV  $\gamma$ -rays, it is essential to know the proton-capture rate for  $^{25}\text{Al}(p, \gamma)^{26}\text{Si}$ . For that purpose, a precise  $Q$  value is required as the resonant proton captures to states depend exponentially on the resonance energies. The  $Q$  value determined at JYFLTRAP, 5513.99(13) keV, is in agreement with the AME12 value but about four times more precise [15].

### 3.2 $^{30}\text{P}$

$^{30}\text{P}(p, \gamma)^{31}\text{S}$  is one of the key reactions to understand nucleosynthesis in ONe novae, as it controls the production of elements heavier than sulphur and thus affects e.g. on the abundance of  $^{30}\text{Si}$  [14]. The  $Q$  value determined at JYFLTRAP for the  $^{30}\text{P}(p, \gamma)^{31}\text{S}$  reaction is 6130.64(24) keV [15], which reduces the uncertainty in the  $Q$  value by about 40 %. Further details on the experiment and results can be found from Ref. [15] and from a separate proceedings article in this volume.

### 3.3 $^{31}\text{Cl}$

$^{30}\text{S}$  ( $T_{1/2} = 1.178(5)$  s) can act as a waiting point in the  $rp$  process. It has been suggested that  $^{30}\text{S}$  and  $^{34}\text{Ar}$  waiting points could be possible explanations for the double-peaked type I X-ray burst curves observed e.g. in Ref. [17]. The temperature and density regime where  $^{30}\text{S}$  can act as a waiting point depends sensitively on the ratio between the rates of the proton-captures  $^{30}\text{S}(p, \gamma)^{31}\text{Cl}$  and the inverse photodisintegration reactions  $^{31}\text{Cl}(\gamma, p)^{30}\text{S}$ . This ratio depends exponentially on the proton-capture  $Q$  value, and its uncertainty has been shown to affect the final  $^{30}\text{Si}$  abundance significantly in high temperature ( $T=2.50$  GK,  $\Delta t \approx 100$  s) and short duration ( $T=1.36$  GK,  $\Delta t \approx 10$  s) type I X-ray burst scenarios [18]. The proton-capture  $Q$  value determined at JYFLTRAP,  $Q_{p,\gamma} = 264.6(34)$  keV [19] is about 35 keV lower than in the AME12 ( $Q_{p,\gamma} = 300(50)$  keV [16]). Thus with the new  $Q$  value, photodisintegration takes over at lower temperatures than previously, and the uncertainties related to the reaction  $Q$  value have been significantly reduced. In typical type I X-ray burst conditions ( $\rho = 10^6$  g/cm $^3$  and hydrogen mass fraction of  $X_H = 0.73$ ),  $^{30}\text{S}$  becomes a waiting point at around 0.44(1) GK, after which at least 20% of the reaction and decay flow has to wait for the beta decay of  $^{30}\text{S}$ . The upper-temperature limit for the  $^{30}\text{S}$  waiting point, 1.0(3) GK, comes from the rate of the unmeasured  $^{30}\text{S}(\alpha, p)^{33}\text{Cl}$  reaction [20].



**Fig. 2.** The ratio between the photodisintegration rate  $\lambda_{\gamma,p}$  to the proton-capture rate  $N_A \langle \sigma v \rangle$  for the  $^{51}\text{Fe}(p, \gamma)^{52}\text{Co}$  reaction. The gray-shaded region shows the  $Q$ -value related uncertainties for the extrapolated  $Q$  value from the AME12 [16], and the blue curve shows the ratio calculated with the experimental  $Q$  value from the JYFLTRAP measurement. The uncertainties related to the JYFLTRAP  $Q$  value are so small that they are invisible in this figure.

### 3.4 $^{52}\text{Co}$

Most recently, the mass for  $^{52}\text{Co}$  ( $T_{1/2} = 104(7)$  ms) has been experimentally determined for the first time employing the JYFLTRAP Penning trap [21]. As a consequence, also the  $Q$  values for the reactions  $^{51}\text{Fe}(p, \gamma)^{52}\text{Co}$  and  $^{52}\text{Co}(p, \gamma)^{53}\text{Ni}$  could be experimentally determined for the first time, and the  $Q$ -value related uncertainties for these reactions have now been reduced considerably as compared to the AME12. Figure 2 demonstrates the effect of the new  $Q$  value on the photodisintegration versus proton-capture rate ratio for  $^{51}\text{Fe}(p, \gamma)^{52}\text{Co}$ . A significant change in the ratio is seen when the new, experimental  $Q$  is adopted. Photodisintegration on  $^{52}\text{Co}$  is not so likely than predicted by the AME12  $Q$  value.

## 4. Conclusions

Masses of nuclei involved in the  $rp$  process are pivotal for modeling the process, and thus for understanding type I X-ray bursts occurring on the surface of neutron stars. Around 100 neutron-deficient nuclei have been measured with the JYFLTRAP double Penning trap at the IGISOL facility. Most recently, the measurements of  $^{25}\text{Al}$ ,  $^{30}\text{P}$ , and  $^{31}\text{Cl}$  have improved the precisions of the related proton-capture  $Q$  values significantly. The mass of  $^{52}\text{Co}$  has been experimentally determined for the first time and found to deviate from the extrapolated value in the AME12. In future, new techniques in ion trapping (see e.g. Ref. [22]), such as phase-imaging ion cyclotron resonance technique or multi-reflection time-of-flight separators, will help in the quest for measuring more exotic nuclei for the astrophysical  $rp$  and  $r$  processes.

## Acknowledgments

This work has been supported by the Academy of Finland under the Finnish Centre of Excellence Programme 20122017 (Nuclear and Accelerator Based Physics Research at JYFL). A.K., D.N., and L.C. acknowledge support from the Academy of Finland under grant No. 275389.

## References

- [1] J. Grindlay *et al.*: *Astrophys. J.* **205** (1976) L127.
- [2] R.K. Wallace and S.E. Woosley: *Astrophys. J. Suppl. Ser.* **45** (1981) 389.
- [3] H. Schatz *et al.*: *Phys. Rep.* **294** (1998) 167.
- [4] H. Schatz: *Int.J. Mass Spectrom.* **349** (2013) 181.
- [5] A. Parikh *et al.*: *Phys. Rev. C* **79** (2009) 045802.
- [6] H. Schatz: *J. Phys. G: Nucl. Part. Phys.* **43** (2016) 064001.
- [7] A. Kankainen *et al.*: *Eur. Phys. J. A* **48** (2012) 50.
- [8] I.D. Moore *et al.*: *Nucl. Instrum. Meth. Phys. Res. B* **317** (2013) 208.
- [9] P. Karvonen *et al.*: *Nucl. Instrum. Meth. Phys. Res. B* **266** (2008) 4794.
- [10] A. Nieminen *et al.*: *Nucl. Instrum. Meth. Phys. Res. A* **469** (2001) 244.
- [11] G. Savard *et al.*: *Phys. Lett. A* **158** (1991) 247.
- [12] M. König *et al.*: *Int. J. Mass Spectrom. Ion Processes* **142** (1995) 95.
- [13] T. Eronen *et al.*: *Eur. Phys. J. A* **48** (2012) 46.
- [14] J. José *et al.*: *Astrophys. J.* **560** (2001) 897.
- [15] L. Canete *et al.*: *Eur. Phys. J. A* **52** (2016) 124.
- [16] M. Wang *et al.*: *Chin. Phys. C* **36** (2012) 1603.
- [17] M. Sztjano *et al.*: *Astrophys. J.* **299** (1985) 487.
- [18] A. Parikh *et al.*: *Phys. Rev. C* **79** (2009) 045802.
- [19] A. Kankainen *et al.*: *Phys. Rev. C* **93** (2016) 041304(R).
- [20] C. Wrede *et al.*: *Phys. Rev. C* **79** (2009) 045808.
- [21] D.A. Nesterenko *et al.*, to be submitted.
- [22] T. Eronen, A. Kankainen and J. Äystö, *Progr. Part. Nucl. Phys.* (2016).