Author(s): Canete, Laetitia; Eronen, Tommi; Jokinen, Ari; Kankainen, Anu; Moore, Iain; Nesterenko, Dmitrii; Rinta-Antila, Sami

Title: High-precision mass measurements for the rp-process at JYFLTRAP

Year: 2017

Version:

High-precision mass measurements for the *rp*-process at JYFLTRAP

Laetitia Canete[1*], *Tommi* Eronen[1], *Ari* Jokinen[1], *Anu* Kankainen[1], *Ian D.* Moore[1], *Dimitry* Nesterenko[1], and *Sami* Rinta-Antila[1]

[1]University of Jyväskylä, P.O. Box 35 (YFL) FI-40014 University of Jyväskylä, Finland

Abstract. The double Penning trap JYFLTRAP at the University of Jyväskylä has been successfully used to achieve high-precision mass measurements of nuclei involved in the rapid proton-capture (rp) process. A precise mass measurement of ^{31}Cl is essential to estimate the waiting point condition of ^{30}S in the rp-process occurring in type I x-ray bursts (XRBs). The mass-excess of ^{31}Cl measured at JYFLTRAP, -7034.7(3.4) keV, is 15 more precise than the value given in the Atomic Mass Evaluation 2012. The proton separation energy S_p determined from the new mass-excess value confirmed that ^{30}S is a waiting point, with a lower-temperature limit of 0.44 GK. The mass of ^{52}Co effects both ^{51}Fe$(p,\gamma)^{52}$Co and ^{52}Co$(p,\gamma)^{53}$Ni reactions. The mass-excess value measured, -34 331.6(6.6) keV is 30 times more precise than the value given in AME2012. The Q values for the ^{51}Fe$(p,\gamma)^{52}$Co and ^{52}Co$(p,\gamma)^{53}$Ni reactions are now known with a high precision, 1418(11) keV and 2588(26) keV respectively. The results show that ^{52}Co is more proton bound and ^{53}Ni less proton bound than what was expected from the extrapolated value.

1 JYFLTRAP: a double Penning trap for mass measurements

Exotic nuclei are produced at the University of Jyväskylä by using a stable ion beam delivered by the K130 cyclotron to the Ion Guide Isotope Separator On-Line (IGISOL) facility. The produced ions created either by fission or fusion reactions on a thin target are extracted out from the ion guide gas cell and accelerated to 30 keV. They are then mass separated with a 55° dipole magnet and cooled in a radiofrequency cooler and buncher (RFQ). The RFQ periodically releases a bunch of ions to the double Penning trap setup JYFLTRAP [1] where a static quadrupolar electric field and an homogenous magnetic field is applied.

In a Penning trap, an ion has three eigenmotions: the axial (ν_z), the magnetron (ν_-) and the reduced cyclotron motion (ν_+). The cyclotron frequency is connected to the mass of the ion and the magnetic field of the trap by:

$$\nu_c = \nu_+ + \nu_- = qB/2\pi m \qquad (1)$$

---

[*] Corresponding author: lacanete@student.jyu.fi

The ions of interest are highly purified in the first trap (the purification trap) and sent to the second trap (the precision trap) where their cyclotron frequency is determined using the time-of-flight ion cyclotron resonance (TOF-ICR) technique [2].
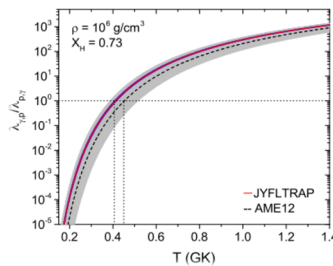
2 Mass measurements of ^{31}Cl

2.1 Astrophysical implication

In an XRB, a neutron star accretes matter from a companion star via Roche lobe overflow. The combination of high temperature and hydrogen/helium rich environment induce a nucleosynthesis flow through the rp-process. In the XRBs rp-process, the ^{30}S acts as a waiting point [3]: the half-life of ^{30}S is long (1.178(5) s) and its proton-capture Q value is low. At typical temperature range of XRBs, the proton-capture rate on ^{30}S is dominated by the resonant proton-capture to the two lowest excited states in ^{31}Cl. However, the proton-capture reaction of ^{30}S is counterbalanced by the photodisintegration ($\lambda_{\gamma p}$) of ^{31}Cl. To estimate the ratio of $\lambda_{\gamma p}$ to the proton-capture Q value on ^{30}S, a precise value of the S_p of ^{31}Cl has to be determined.

2.2 Results

A 40 MeV proton beam has been used on a 1.8 mg/cm^2-thick ZnS target to produce ^{31}Cl$^-$ ions. The mass-excess obtained, -7034.7(3.4) keV [4], is 15 times more precise than the value given in the AME2012 ($-7070(50)$ keV [5]). From the measured mass-excess value, the S_p of ^{31}Cl has been determined as 264.6(3.4) keV. The new S_p value shows that ^{31}Cl is less proton bound than previously expected. It indicates also that for temperatures higher than 0.44 GK, the ^{30}S is confirmed to be a waiting point: at least 20% of the rp-process flow must wait for the β^+ decay of ^{30}S. The update ratio of $\lambda_{\gamma p}$ to the proton-capture Q value on ^{30}S (Fig.1) shows that the photodisintegration of ^{31}Cl dominate in the rp-process of XRBs at lower temperature than expected based on AME2012.

Fig. 1. Ratio of the photodisintegration to the proton-capture rates for typical XRB conditions. The uncertainties related to the JYFLTRAP Q value are shown by the blue lines and to the AME12 value by the gray-shaded area.

3 Mass measurement of ^{52}Co

In the XRBs, the rp-process flow toward heavier elements is affected by the proton-capture Q value of ^{55}Fe and ^{56}Co. The proton-capture reactions, ^{55}Fe$(p,\gamma)^{56}$Co and ^{56}Co$(p,\gamma)^{57}$Ni are in competition with their inverse photodisintegration reactions, ^{56}Co$(\gamma,p)^{55}$Fe and ^{57}Ni$(\gamma,p)^{56}$Co. To estimate the ratio of the inverse photodisintegration to the total proton-capture rate, a precise Q value of these reactions has to be determined. The ^{56}Co$^+$ has been produced using a 50 MeV proton beam on a 1.8 mg/cm^2 thick ^{56}Fe target. The TOF-ICR technique has been applied with a 100 ms long quadrupolar radiofrequency (RF) excitation. A new mass-excess value for ^{56}Co was measured: -34 331.6(6.6) keV [6]. The proton-capture Q values for ^{55}Fe$(p,\gamma)^{56}$Co and ^{56}Co$(p,\gamma)^{57}$Ni are 1418(11) keV and 2588(26) keV, respectively. The precision were highly improved in comparison to the extrapolated Q values given in AME2012 (1077(196)# keV and 2930(197)# keV respectively [5]). ^{56}Co is around 340 keV more proton-bound than expected based on the AME2012 value: the photodisintegration of ^{56}Co is less probable to occur in XRBs (Fig.2a). ^{57}Ni is less proton bound, and thus, the photodisintegration of ^{57}Ni is more dominant in the XRBs rp-process than previously expected (Fig.2b).
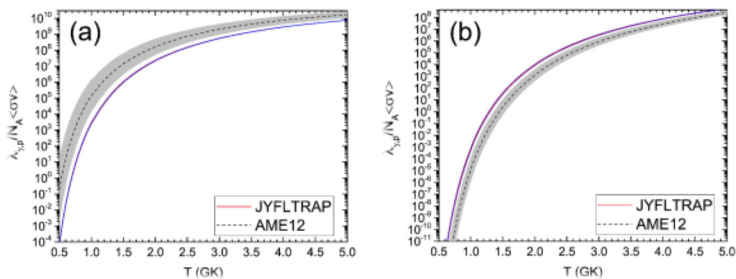
Fig.2. Ratio of the photodisintegration to the proton-capture rates for (a) ^{55}Fe$(p,\gamma)^{56}$Co–^{56}Co$(\gamma,p)^{55}$Fe and (b) ^{56}Co$(p,\gamma)^{57}$Ni –^{57}Ni$(\gamma,p)^{56}$Co reactions.

References

1. T. Eronen, V.S. Kolhinen, V.-V. Elomaa, D. Gorelov, U. Hager, J. Hakala, A. Jokinen, A. Kankainen, P. Karvonen, S. Kopecky, I.D. Moore, H. Penttilä, S. Rahaman, S. Rinta-Antila, J. Rissanen, A. Saastamoinen, J. Szerypo, C. Weber, J. Äystö, Eur. Phys. J. A **48,** 46 (2012)
2. M. König, G. Bollen, H.-J. Kluge, T. Otto, J. Szerypo, Int. J. Mass Spec. Ion Proc. **142**, 95 (1995)
3. J. L. Fisker, F.-K. Thielemann, M. Wiescher, Astrophys. J. **608**, L61 (2004)
4. A. Kankainen, L. Canete T. Eronen, J. Hakala, A. Jokinen, J. Koponen, I. D. Moore, D. Nesterenko, J. Reinikainen, S. Rinta-Antila, A. Voss, J. Äystö, Phys. Rev. C **93**, 041304 (R) (2016)
5. M. Wang, G. Audi, A. Wapstra, F. Kondev, M. MacCormick, X. Xu, B. Pfeiffer, Chin. Phys. C **36**, 1603 (2012)
6. D.A. Nesterenko, A. Kankainen, L. Canete, M. Block, D. Cox, T. Eronen, C. Fahlander, U. Forsberg, J. Gerl, P. Golubev, J. Hakala, A. Jokinen, V.S. Kolhinen, J. Koponen, N. Lalović, C. Lorenz, I. D. Moore, P. Papadakis, J. Reinikainen, S.

Rinta-Antila, D. Rudolph, L. G. Sarmiento, A. Voss, J. Äystö, J. Phys. G: Nucl. Part. Phys. **44**, 065103 (2017)