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Mass measurements at JYFLTRAP for explosive hydrogen burning below A=60

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This contribution gives an overview of the mass measurement programme at the JYFLTRAP Penning trap mass spectrometer for explosive hydrogen burning below $A = 60$. The proton-capture Q-values of ^{22}Na(p,γ)^{23}Mg, ^{22}Mg(p,γ)^{23}Al, ^{25}Al(p,γ)^{26}Si, and ^{30}P(p,γ)^{31}S important for modeling nucleosynthesis in ONe novae have been determined with sub-keV precision. In addition, the $Q_{p,\gamma}$ value for ^{56}Ni(p,γ)^{57}Cu essential for the modeling of the rp process has been measured directly. The new precise $Q_{p,\gamma}$ values have an effect on the calculated reaction rates and decrease the uncertainties significantly.

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1. Introduction

Novae are binary systems consisting of a white dwarf accreting hydrogen-rich matter from a main-sequence companion. Explosive hydrogen burning can proceed up to $A = 40$ in oxygen-neon (ONe) novae reaching peak temperatures up to 4×10^8 K. After breakout from the hot CNO cycle, the hydrogen burning in ONe novae proceeds as a sequence of proton captures and β^+ decays (and some (p,α) reactions) up to ^{40}Ca (see e.g. Ref. [1]). Hydrogen burning occurring e.g. in type I X-ray bursts, where hydrogen is accreted in a binary system onto the surface of a neutron star, is typically called the rapid proton capture (rp) process [2]. Compared to the nucleosynthesis in ONe novae, the rp process reaches considerably higher peak temperatures of about 3×10^9 K. Accurate modeling of both astrophysical processes requires a precise knowledge of the proton capture Q-values or proton separation energies $S_p(Z+1,A+1) = ME(Z,A) + ME(^1H) - ME(Z+1,A+1) = Q_{p,\gamma}(Z,A)$ where ME stands for mass excess. The calculated reaction rate for a resonant proton capture depends exponentially on the resonance energy $E_r = E_x - S_p$ where E_x is the excitation energy of the final state and S_p is the proton separation energy of the product nucleus. Therefore, already a small change in the proton separation energy will have an effect on the calculated resonant capture rate:

$$N_A \langle \sigma v \rangle_r = N_A \left(\frac{2\pi}{\mu kT} \right)^{3/2} \hbar^2 \sum_i (\omega\gamma)_i \exp\left[-E_{r,i}/(kT)\right] \tag{1.1}$$

where N_A is the Avogadro number, k is the Boltzmann constant, μ is the reduced mass, E_r, i is the resonance energy of a state i in the center-of-mass frame and $(\omega\gamma)_i$ is the corresponding resonance strength.

2. Experimental method

The ions of interest discussed in this paper have been produced at the Ion Guide Isotope Separator On-Line (IGISOL) facility [3] employing an approximately 40-MeV proton beam on ^{nat}Mg, ^{27}Al, ZnS, or ^{58}Ni targets. After acceleration to 30 keV and mass-separation, the ions are sent to a radiofrequency quadrupole (RFQ) [4] for bunching and cooling. After the RFQ, the ion bunches are injected to the purification trap of the JYFLTRAP [5] double Penning trap mass spectrometer for isobaric purification, and then to the precision trap for mass measurements. The mass measurements are based on the time-of-flight ion cyclotron resonance method [6, 7] where the cyclotron frequency $\nu_c = qB/(2\pi m)$ of an ion with a charge q and mass m is determined. The magnetic field B is calibrated with ions whose masses are already well-known. See Refs. [8, 9, 10, 11] for the details of the experimental method.

3. Proton separation energies

3.1 ^{23}Mg, ^{23}Al, and ^{26}Si

^{22}Na ($T_{1/2} = 2.6019(4)$ y [12]) decays into a short-lived excited state of ^{22}Ne which de-excites to its ground state by emitting a 1.275 MeV γ-ray. Although several attempts to observe these γ-rays from nearby novae have been made, only an upper limit of the ejected ^{22}Na has been obtained

[1]. ^{22}Na is produced in a so-called NeNa cycle where ^{20}Ne(p,γ)^{21}Na is followed either by proton capture ^{21}Na(p,γ)^{22}Mg(β^+)^{22}Na or beta decay ^{21}Na(β^+)^{21}Ne(p,γ) ^{22}Na(β^+)^{22}Ne(p,γ)^{23}Na(p,α) ^{20}Ne. In order to model the production of ^{22}Na, the destruction channels, such as ^{22}Mg(p,γ)^{23}Al and ^{22}Na(p,γ)^{23}Mg have to be known precisely. The new S_p value for ^{23}Al (see Table 1) is higher than the Atomic Mass Evaluation 2003 (AME03) value [13]. Thus, ^{23}Al is more proton-bound and the resonant contribution for the rate of ^{22}Mg(p,γ)^{23}Al is little higher than previously. It also indicates ^{23}Al to be more resilient to destruction through photodissociation. In addition to the mass of ^{23}Al, the mass of ^{23}Mg has been measured at JYFLTRAP [8]. For the ^{22}Na(p,γ)^{23}Mg reaction, the improvement in the precision of the proton separation energy is not so striking and has not yet been investigated in detail.

^{26}Al ground state ($T_{1/2} = 7.17(24) \times 10^5$ y [12]) decays to an excited state of ^{26}Mg at 1.809 MeV. The γ-rays following the de-excitation of this state have been observed with γ-ray telescopes. ^{26}Al is produced in a so-called MgAl cycle where ^{24}Mg(p,γ)^{25}Al(β^+)^{25}Mg(p,γ)^{26}Al$_{g.s.}$(β^+)^{26}Mg(p,γ) ^{27}Al(p,α)^{24}Mg. The production of ^{26}Al$_{g.s.}$ can be bypassed via ^{25}Al(p,γ)^{26}Si(β^+)^{26}Al^m(β^+)^{26}Mg. Therefore, the reaction rate for the proton capture ^{25}Al(p,γ)^{26}Si is extremely important to constrain the model [1]. The JYFLTRAP mass value of ^{26}Si changes the calculated stellar reaction rates of ^{25}Al(p,γ)^{26}Si by about 10 % [9] compared to the rates calculated with the values from Ref. [15].

3.2 ^{31}S

The reaction ^{30}P(p,γ)^{31}S plays a major role governing the flow towards ^{32}S and heavier species in nova nucleosynthesis [1, 16]. At ^{30}P, the reaction flow has to proceed either via ^{30}P$(p,\gamma)^{31}$S(p,γ) ^{32}Cl$(\beta^+)^{32}$S or via ^{30}P$(p,\gamma)^{31}$S$(\beta^+)^{31}$P$(p,\gamma)^{32}$S. The ^{30}P$(p,\gamma)^{31}$S rate also has an effect on the ^{30}Si abundance [16]: the lower the proton capture rate, more favorable is the β^+ decay of ^{30}P and more ^{30}Si is produced. A more accurate reaction rate and ^{30}Si abundance (or ^{30}Si/^{28}Si abundance ratio) helps in the identification of presolar grains with a possible nova origin [17].

The reaction rate of ^{30}P$(p,\gamma)^{31}$S has been studied for example in Refs. [18, 19, 20, 21]. At $0.08 < T < 0.25$ GK the captures populate dominantly the states at $6327.0(20)$ and $6399.4(22)$ keV [20]. At lower temperatures ($0.02 < T < 0.08$ GK), captures to the state at $6259.9(17)$ keV are dominant [20], and at higher temperatures ($0.25 < T < 0.4$ GK), to the states at $6543.1(20)$ and $6585.1(20)$ keV [20].

The proton separation energy obtained at JYFLTRAP, $S_p = 6130.95(39)$ keV [10], deviates from the adopted value [13] by $-2.1(16)$ keV. Here, we have compared the resonant reaction rate to eleven states between $6160.2(7)$ and $6636.8(13)$ keV with the new S_p value for ^{31}S to the rate obtained with the adopted S_p value [13]. The proton widths Γ_p have been scaled from Table II of Ref. [20] according to $\Gamma_p \propto \exp\left(-31.29 Z_1 Z_2 \sqrt{(\mu/E_r)}\right)$ [22], where Z_1 and Z_2 are proton numbers for the incoming particles, μ is the reduced mass in u, and E_r is the resonance energy in keV. The gamma widths have been taken from Ref. [20]. As seen from Fig. 1, the calculated reaction rate agrees with the rate calculated with the old S_p value [13]. The new resonance energy reduces the uncertainty of the calculated reaction rate by about 20 % at relevant peak temperatures of $0.1 < T < 0.4$ GK in ONe novae.

3.3 ^{57}Cu

Previously ^{56}Ni was considered to be the end-point of the rp process [23] because it has a beta-

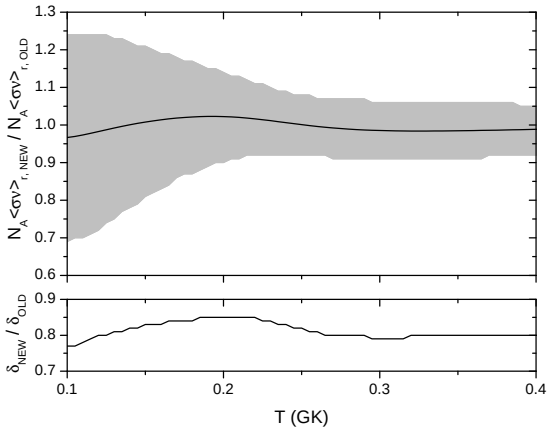

Figure 1: The ratio of the sum of the resonant capture rates of ^{30}P(p,γ)^{31}S with the new S_p value from this work to the one with the old S_p value [13]. Eleven states between 6160.2(7) keV and 6636.8(13) keV in ^{31}S were taken into account. The gray-shaded area shows the error band based on the uncertainties of the resonance energies. The lower panel shows the ratio of the corresponding uncertainties. The uncertainties in the resonance strengths have not been taken into account.

Table 1: Proton separation energies of ^{23}Mg, ^{23}Al, ^{26}Si, ^{31}S, and ^{57}Cu determined at JYFLTRAP.

Nuclide	S_p (keV)	S_p(AME03) [13] (keV)	JYFL-AME03 (keV)
^{23}Mg	7580.8(8) [8, 14]	7580.3(14)	0.5(16)
^{23}Al	141.11(43) [8]	122(19)	19(19)
^{26}Si	5513.7(5) [9]	5517(3)	−3.7(31)
^{31}S	6130.95(39) [10]	6133.0(15)	−2.1(16)
^{57}Cu	689.69(51) [11]	695(19)	−5(19)

decay half-life of 6.075(10) days [24] exceeding all normal time scales of X-ray bursts and other places where the *rp* process could occur. However, later it was shown to proceed until the SnSbTe-region [25, 26]. The proton separation energy of ^{57}Cu has been determined at JYFLTRAP via a frequency ratio measurement between ^{57}Cu and ^{56}Ni [11]. The obtained value, $S_p = 689.69(51)$ keV, agrees with the AME03 value but is 37 times more precise. With the new S_p value, the calculated reaction rates from Ref. [27] have been revised. The new rate is a little higher than calculated with the old S_p value [13]. The precise $Q_{p,\gamma}$ value removes a factor of 4 in the uncertainty of the reaction rate at temperatures around 1 GK shown in Ref. [27]. The JYFLTRAP $Q_{p,\gamma}$-value supports the conclusions of Ref. [27] that the proton captures are more likely which reduces the temperature required for the *rp* process to proceed beyond ^{56}Ni.

4. Summary and conclusions

The IGISOL method coupled to the JYFLTRAP mass spectrometer offers a possibility to measure masses of various nuclides independent of their chemistry. Proton separation energies of many nuclides important for nova nucleosynthesis and the *rp* process have been determined with JYFLTRAP. In some cases it has been possible to measure the frequency ratio between the proton-capture mother and daughter, which yields directly the mass difference between these nuclides and

thus also the $Q_{p,\gamma}$ value. The improved precisions of $Q_{p,\gamma}$ values reduce the uncertainties of the calculated reaction rates.

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