2 - 7 Study of Zr-Nb Cycle in Astrophysical rp-process

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We have reported the mass measurements of neutron-deficient nuclides ^{79}Y, ^{81,82}Zr, ^{83,84}Nb and the mass predictions of ^{78}Y, ^{80}Zr, ^{82}Nb and ^{84}Mo in this year's Annual Report. These nuclides have an important impact on the Zr-Nb cycle[1] in the astrophysical rp-process. This cycle can be formed via the flowing reaction sequence

$$^{83}\mathrm{Nb}(\mathrm{p},\alpha)^{80}\mathrm{Zr}(\beta^+)^{80}\mathrm{Y}(\mathrm{p},\gamma)^{81}\mathrm{Zr}\left\{\begin{array}{c}(\beta^+)^{81}\mathrm{Y}(\mathrm{p},\gamma)\\(\mathrm{p},\gamma)^{82}\mathrm{Nb}(\beta^+)\end{array}\right\}{}^{82}\mathrm{Zr}(\mathrm{p},\gamma)^{83}\mathrm{Nb}.$$

At a certain high temperature, this cycle will be dominant and end the rp-process to heavier region[2]. It provides an upper temperature limit for rp-process along the proton drip line to produce nuclides beyond $A=84$, including the light p nuclides of ^{92,94}Mo, ^{96,94}Ru. The existence of Zr-Nb cycle is an important question in rp-process[2].

α-separation energy (S_α) of ^{84}Mo plays an important role in the formation of this cycle. A strong enhancement of ^{83}Nb(p,α) reaction rate is due to a very low S_α of ^{84}Mo[1]. Noting that the ^{83}Nb(p,γ) still dominates the reaction flow, when equilibrium between ^{83}Nb and ^{84}Mo is established at high temperature, more material is transformed into ^{84}Mo. In this situation, the ^{84}Mo(γ,α) reaction turns out to be fast to compensate. Since the leakage out of this cycle is mainly determined by the β-decay of ^{84}Mo[3], its β-decay rate as well as the proton capture Q-value of ^{83}Nb which determines the ^{84}Mo equilibrium abundacne are also very important.

As we have known, the mass of ^{83}Nb has changed almost 1 MeV and the very low α separation energy island of molybdenum isotopes may not exist from smooth extrapolation. In order to explore the impact of the new mass values on Zr-Nb cycle, new reaction rate calculations[4] as well as a network calculation[5] using the new reaction rates were performed.

The left panel of Fig. 1 shows the new ^{83}Nb(p,α)^{80}Zr reaction rate using the new mass values, where the green area shows the possible upper and lower limit based on one-sigma uncertainty. Previous reaction rate based on AME12 is also shown as the black points and grey area for comparison. Owing to the new mass values, the uncertainty of the reactions rate has been largely reduced.

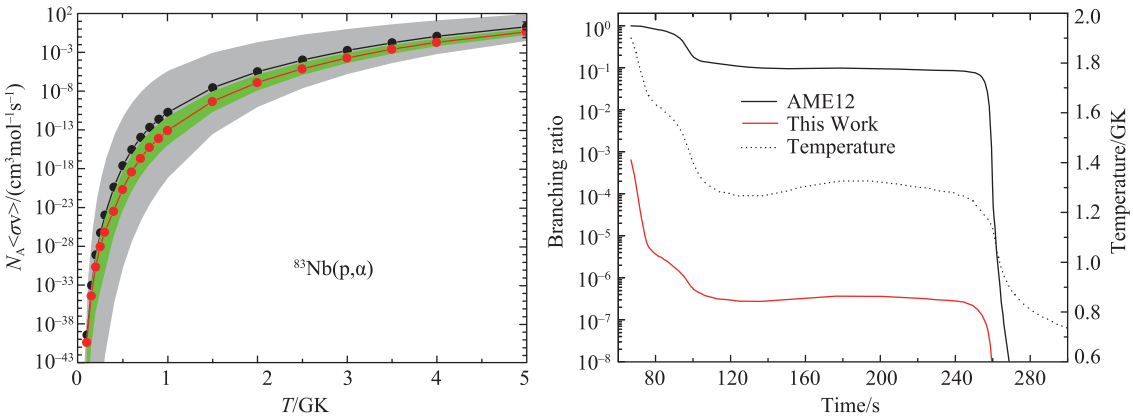

Fig. 1 (color online) Left: New ^{83}Nb(p,α)^{80}Zr reaction rate (red line) with one-sigma uncertainty indicated by the green shade area. For comparison, previous ^{83}Nb(p,α)^{80}Zr reaction rate and its one-sigma uncertainty based on AME12 are also shown as black line and grey shade area respectively. Right: Fraction of reaction flow branching into the Zr-Nb cycle under the most favourable conditions as a function of typical X-ray burst time for AME12 (red line) and this work (black line). The dashed line shows the the temperature varying with burst time. For clarity, only the cooling stage is presented.

The right panel of Fig. 1 shows the branching ratio into Zr-Nb cycle as well as the temperature as a function of typical burst time (For clarity, only the cooling stage is presented). The definition of branching ratio is the fraction of the flow ending in ^{80}Zr via ^{83}Nb(p,α) or ^{84}Mo(γ,α) and not escape the cycle via β^+ decay into N=43 isotones. To explore the possible contribution of Zr-Nb cycle for rp-process, the calculation was performed under the favourable condition, which means a set of nuclides masses changed by 1 standard deviation for the advantage of the formation of this cycle. From the right panel of Fig. 1, one can see that under the favourable condition, rp-process ends up at Zr-Nb cycle at the temperature of $\sim$ 2 GK. Then, the importance of this cycle reduced quickly as the temperature decreased dramatically in tens of seconds. By this work, similar tendency can be found if AME12 values are used. But the important difference of the branching ratio into Zr-Nb cycle is much smaller in this work than AME12 and even at the temperature of $\sim$ 2 GK, the contribution of this cycle still can be ignored.

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2 - 8 Direct Mass Measurements of Short-Lived A=2Z+3 Nuclides at CSRe

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Nuclear mass is one of the fundamental quantity of atomic nucleus. The total binding energy of a nucleus derived from the related mass values reflects all the interactions among the constituting nucleons. Masses of short-lived A=2Z+3 nuclei of ^{112}Sn projectile fragments have been measured at the experimental cooler storage ring CSRe, employing the Isochronous mass spectrometry (IMS). The experiment was conducted at the Heavy Ion Research Facility in Lanzhou at the beginning of 2016. The primary beam of ^{112}Sn^{35+} was accumulated in the synchrotron CSRm and accelerated to 467.91 MeV/u. Secondary beam were produced by impinging the high intensity ^{112}Sn^{35+} beam onto a 10 mm beryllium target which was located at the entrance of the radioactive beam line RIBLL2. The projectile fragments of ^{112}Sn emerged from the target were then transmitted, separated in flight through RIBLL2 and finally injected into CSRe. The RIBLL2-CSRe system was set to a fixed magnetic rigidity of $B\rho$= 5.337 4 Tm to guarantee best transmission efficiency for ^{101}In. The mass of this nucleus is unknown up to date[1]. In the present experiment, the transition point of CSRe was tuned to be γ_t= 1.302 in order to fulfill the isochronous condition of γ_t=γ for ^{101}In where γ is the Lorentz factor of the stored ions. The revolution times of the stored ions were measured by a Time-Of-Flight detector which is installed inside the vacuum pipe of CSRe. The secondary beam was injected and stored in CSRe every 25 s, and the measurement last for 200 μs after each injection. The standard deviations of the measured revolution times for different nuclei are shown on the left panel of Fig. 1. The best isochronous condition was fulfilled for ^{110}In as it can be seen in Fig. 1 where the minimum standard deviation was achieve for ^{101}In. A metal slit was used at CSRe during the experiment in order to reduce the momentum acceptance of the ring and therefore higher mass resolving power for all nuclides were achieved ($R \leq 3.8\times 10^5$). As a result, the ground state and isomeric state of ^{101}In were clearly separated in the revolution time spectrum, as was shown on the on right panel of Fig. 1.

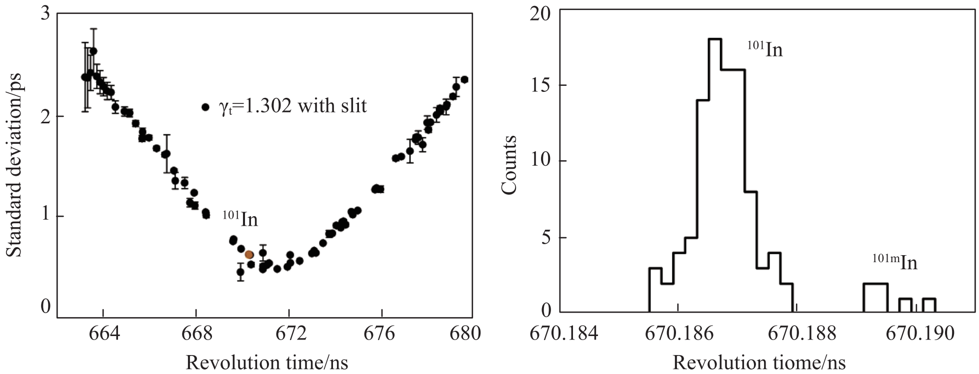

Fig. 1 Left: The standard deviation of the measured revolution time for different nuclei. The data were taken under condition γ_t = 1.302 and the slit in CSRe was positioned at ±30 mm. Right: The revolution time spectrum for ^{101}In and ^{101m}In.