Direct mass measurements of ^{58}Ni projectile fragments at CSRe

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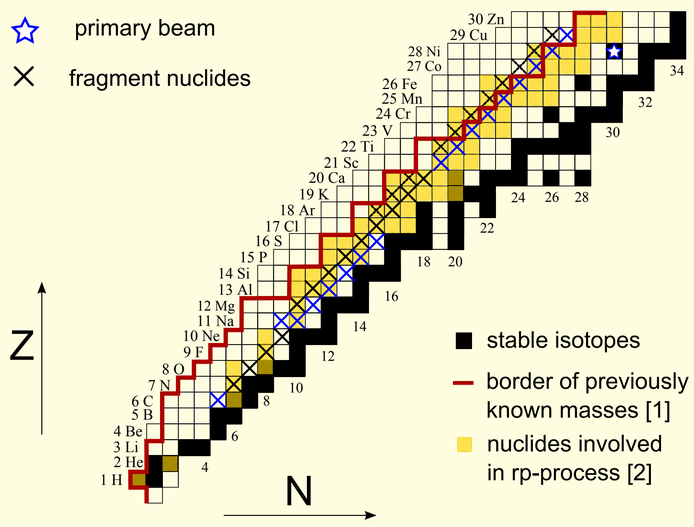
Motivation for the experiment

Unknown masses [1] of neutron-deficient T_z= -3/2 nuclides near the proton drip-line (c.f. Fig. 1) and their impacts on the rapid proton-capture process (rp-process) which occurs during the thermonuclear explosions in X-ray bursts [2].

Fig. 1: Neutron-deficient side of the chart of the nuclides

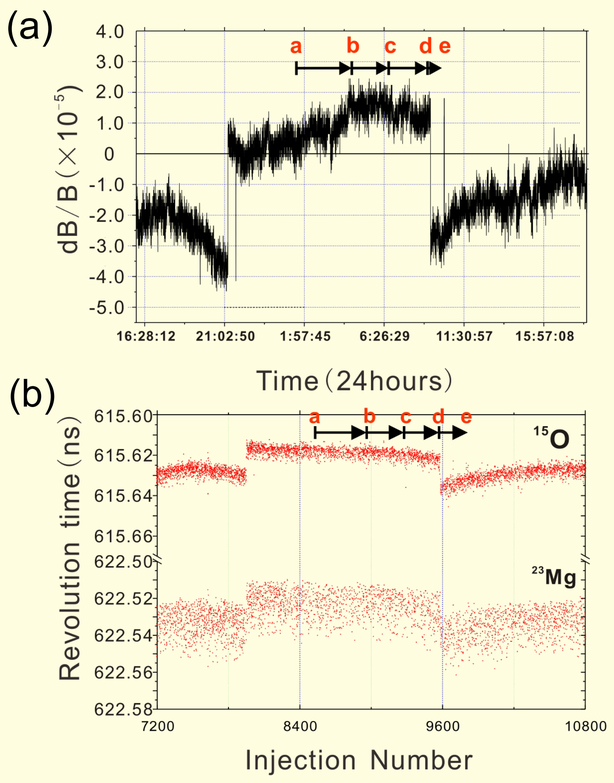


Experimental conditions

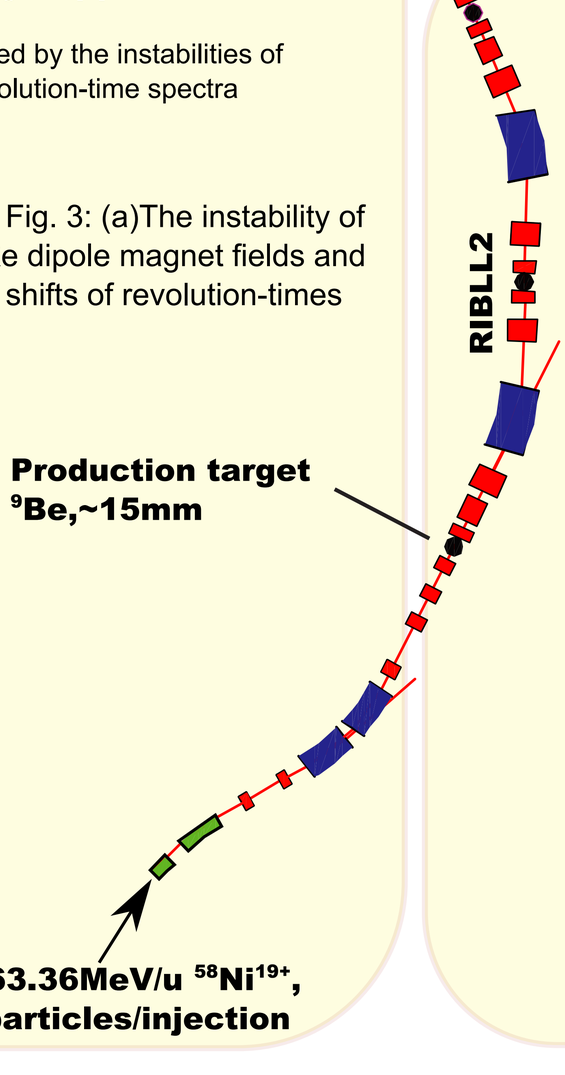
Nuclides of interest were produced in the projectile fragmentation reaction of ^{58}Ni. They were separated in-flight with the RIBLL2 separator and finally injected into CSRe (c.f. Fig. 2). The magnetic rigidity of RIBLL2-CSRe was set to Bρ=5.677 Tm for the optimum transmission of Z=N-3 nuclides centered around ^{47}Mn (c.f. Fig. 1).

The revolution-times of stored ions were measured with a dedicated time of flight detector [5], which is installed inside the CSRe aperture. Revolution times of each individual ion were obtained from the respective timing signals [6].

The resolving power of CSRe mass spectrometry is limited by the instabilities of magnetic fields which cause small shifts of the entire revolution-time spectra measured for different injections (c.f. Fig. 3a,b).



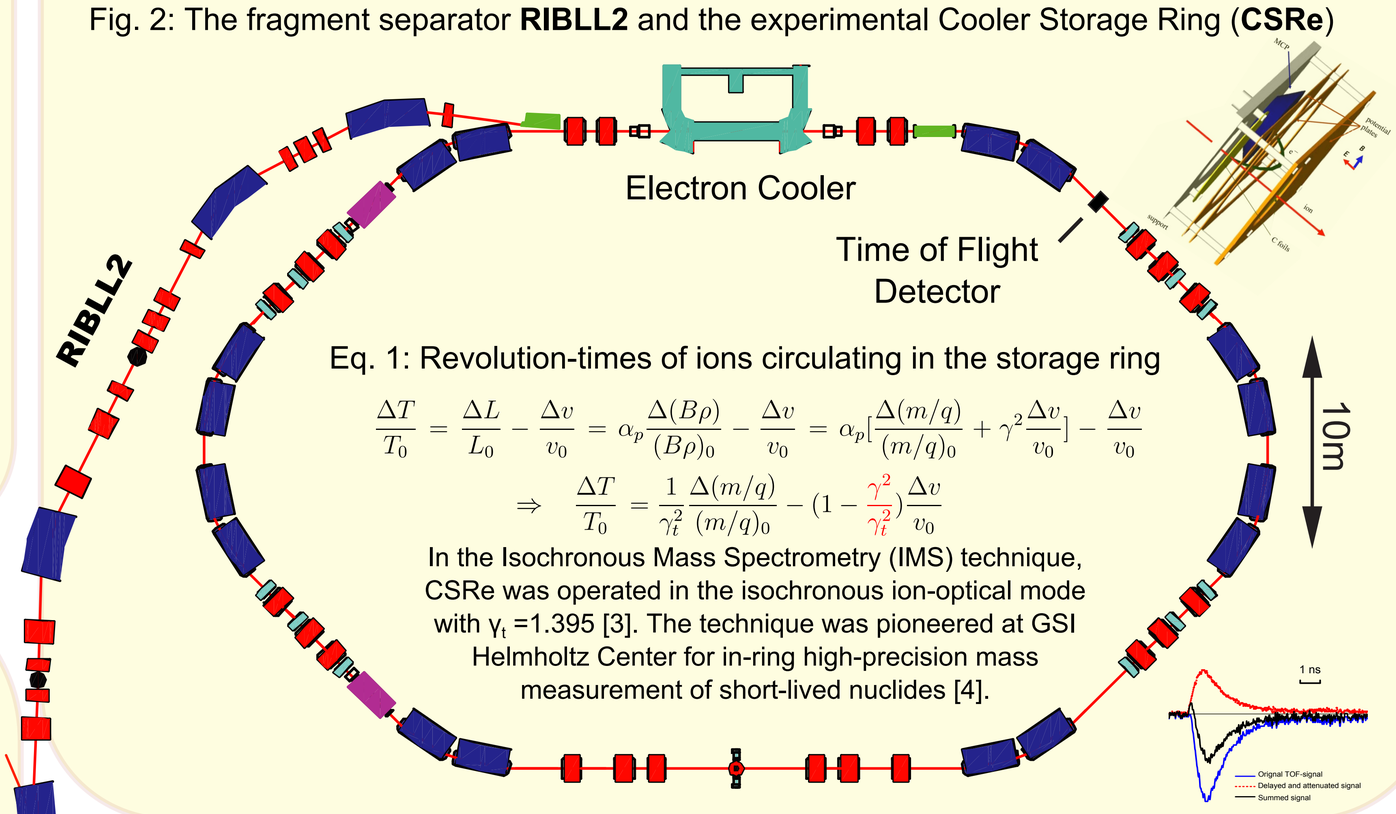
Left: Fig. 3: (a)The instability of CSRe dipole magnet fields and (b) shifts of revolution-times



Isochronous Mass Spectrometry technique at CSRe

The revolution-times of ions circulating in a storage ring are related to their mass-over-charge ratio and their velocity spread (c.f. Eq. 1). γ is the relativistic Lorentz factor. γ_t is the transition point of the ring. The energy of the stored ions has to fulfill the condition that $\gamma=\gamma_t$, so that the second term on RHS of Eq. 1 vanishes. As a result, the revolution-time of the ion becomes a direct measure of its m/q value.

Fig. 2: The fragment separator **RIBLL2** and the experimental Cooler Storage Ring (**CSRe**)



Eq. 1: Revolution-times of ions circulating in the storage ring

$$\frac{\Delta T}{T_0} = \frac{\Delta L}{L_0} - \frac{\Delta v}{v_0} = \alpha_p \frac{\Delta(B\rho)}{(B\rho)_0} - \frac{\Delta v}{v_0} = \alpha_p[\frac{\Delta(m/q)}{(m/q)_0} + \gamma^2\frac{\Delta v}{v_0}] - \frac{\Delta v}{v_0}$$

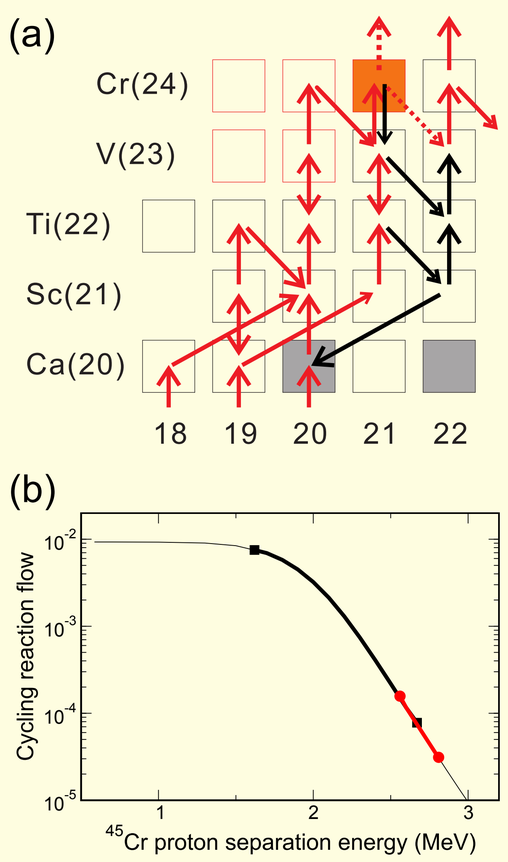
$$\Rightarrow \quad \frac{\Delta T}{T_0} = \frac{1}{\gamma_t^2}\frac{\Delta(m/q)}{(m/q)_0} - (1-\frac{\gamma^2}{\gamma_t^2})\frac{\Delta v}{v_0}$$

In the Isochronous Mass Spectrometry (IMS) technique, CSRe was operated in the isochronous ion-optical mode with γ_t =1.395 [3]. The technique was pioneered at GSI Helmholtz Center for in-ring high-precision mass measurement of short-lived nuclides [4].

Discussion

Ca-Sc Cycle in rp-processes

Fig. 5: Time integrated reaction flow during an X-ray burst



The rp-process reaction flow in the Ca-Cr region is shown in Fig. 5a. ^{44}V and ^{43}Ti are in (p,γ)-(γ,p) equilibrium.The net proton capture flow at ^{43}Ti is determined by the leakage out of this equilibrium at ^{44}V via the 2p-capture process on ^{43}Ti.

For a low ^{45}Cr proton seperate energy, ^{45}Cr(γ,p) becomes effective, hampering the proton capture flow at ^{43}Ti. As a result, a significant β-decay branch develops at ^{43}Ti driving the reaction flow into ^{43}Sc, which has a particularly high Q-value for (p,α) reactions.

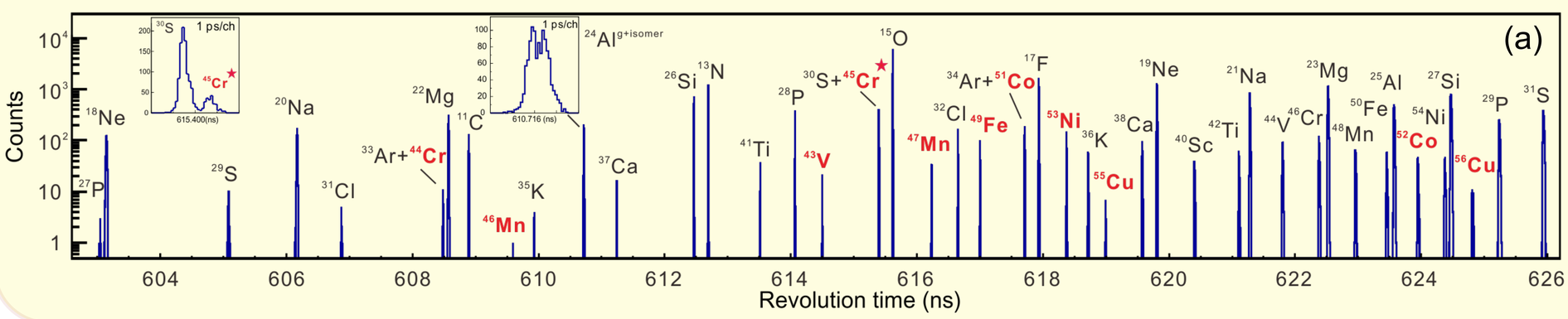
The resulting large ^{43}Sc(p,α)^{40}Ca reaction leads to the formation of a Ca-Sc cycle (black arrows in Fig. 5a) that strongly limits the reaction flow towards heavier elements, leading to a significant increase in the burst rise time, a broader main burst, and, due to increased helium production, which accelerates hydrogen consumption, a more rapid end of nuclear burning [9].

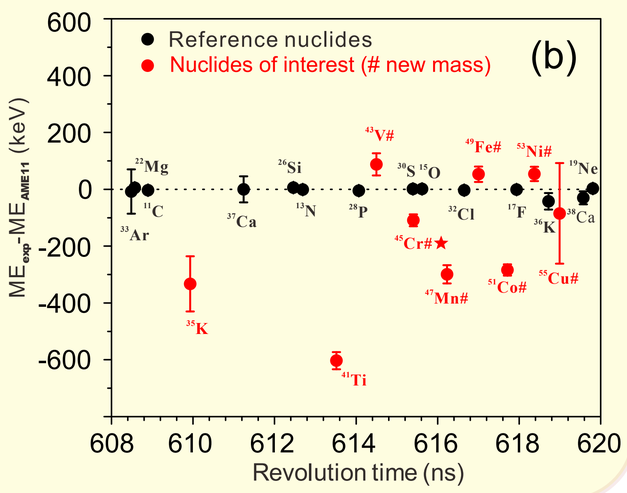
With our new measurement of the ^{45}Cr mass (c.f. Fig. 4b), the formation of a significiant Ca-Sc cycle in X-ray bursts is basically excluded (red line in Fig. 5b) [10].

Results

A mass resolving power of 1.8 x 10^5 had been achevied in this experiment [7] (c.f. Fig. 4a,b). The final mass uncertainty of ^{45}Cr was increased to 35 keV, after taking into account of the possible contamination by an isomeric state [8] (c.f. inset in Fig. 4a)

Fig. 4: (a) Revolution-time spectrum and (b) masses determined in this experiment





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