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Mass measurement on the rp-process waiting point ^{72}Kr

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Abstract. With the aim of improving nucleosynthesis calculations, we performed for the first time, a direct high-precision mass measurement on the waiting point in the astrophysical rp-process ^{72}Kr. We used the ISOLTRAP Penning trap mass spectrometer located at ISOLDE/CERN. The measurement yielded a relative mass uncertainty of $\delta m/m = 1.2 \times 10^{-7}$. In addition, the masses of ^{73}Kr and ^{74}Kr were measured directly with relative mass uncertainties of 1.0×10^{-7} and 3×10^{-8}, respectively. We analyzed the role of ^{72}Kr in the rp-process during X-ray bursts using the ISOLTRAP and previous mass values of $^{72-74}$Kr.

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1 Introduction

Very precise mass values of elements formed along the rapid proton capture process (rp-process) are crucial for reliable calculations of X-ray burst light curves [1]. An X-ray burst is a thermonuclear explosion on the surface of a neutron star accreting hydrogen and helium rich matter from a companion star in a binary system. The extreme temperature and density conditions in this scenario can lead to the formation of elements up to Te ($Z = 52$) within 10–100 s. They are formed by continuous rapid proton captures, interrupted at the so-called waiting points by β^+-decays. Waiting point nuclei come on stage when (p, γ) proton capture is hindered by (γ, p) photodisintegration of weakly proton bound or unbound nuclei. This causes a delay in the X-ray burst duration and consequently, affects the X-ray burst light curve and the nucleosynthesis. This delay is the time for a certain abundance to drop to $1/e$ and is referred to as effective lifetime. The effective lifetime depends exponentially on the mass difference between the waiting point nucleus, here ^{72}Kr, and the possibly formed nucleus ^{73}Rb (or as the temperature increases ^{74}Sr). This calls for mass values of ^{72}Kr, ^{73}Rb, and ^{74}Sr with relative mass uncertainties $\delta m/m$ of the order of 10^{-7}. We measured directly the mass of ^{72}Kr at ISOLTRAP [2]. Since ^{73}Rb and ^{74}Sr are difficult to access experimentally, we determined their masses from the masses of their mirror nuclei ^{73}Kr and ^{74}Kr, also measured directly in the experiment reported here.

2 Experimental setup and method

The ISOLTRAP facility [3,4,5] is located at ISOLDE/CERN [6] in Geneva (Switzerland). The system is shown in fig. 1. It consists of three different traps: A gas-filled linear Paul trap [4], a gas-filled cylindrical Penning trap [7] and a hyperbolic Penning trap in ultra-high vacuum [3].

The 60 keV krypton beam from ISOLDE is electrostatically retarded to about 10–20 eV and thermalized in the buffer-gas-filled linear Paul trap. After an accumulation time of up to a few tens of milliseconds, the cooled ion bunch is ejected with a temporal width of less than

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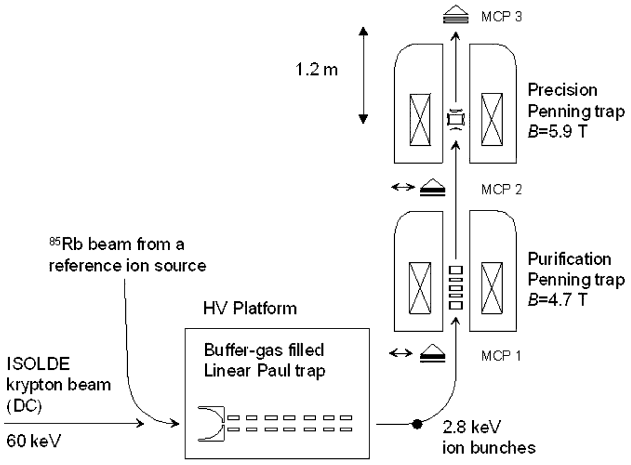

Fig. 1. Sketch of the ISOLTRAP setup.

1 μs. The ion bunches are transported with an energy of 2.8 keV and after retardation captured in the purification Penning trap for isobaric cleaning. Thereafter, the ions are ejected and transferred to the precision Penning trap where the mass measurement is carried out.

The mass m of singly charged ions is determined by a measurement of the cyclotron frequency ν_c employing the relationship

$$\nu_c = \frac{1}{2\pi} \cdot \frac{e}{m} \cdot B, \tag{1}$$

where B is the strength of the homogeneous magnetic field in the center of the precision Penning trap (~ 5.9 T), and e is the atomic unit of charge. The cyclotron frequency is determined using a resonant time-of-flight technique [8]. The magnetic field B in eq. (1) is deduced from the measurement of the cyclotron frequency of ions with well-known mass, here $^{85}Rb^+$ ($\delta m/m = 2 \times 10^{-10}$ [9]). This is performed before and after the measurement of the cyclotron frequency of each ion of interest. The value adopted for B is the result of the linear interpolation of both measurements to the center of the time interval during which the cyclotron frequency of the ion of interest was measured. In that way, possible drifts of the magnetic field are accounted for. The final relative mass uncertainty includes effects like the long term drifts of the magnetic field and the presence of contaminating ions, among the mass dependant uncertainty and the systematics uncertainty of the apparatus ($\delta m/m = 8 \times 10^{-9}$) [10].

3 Results and discussion

The mass excess D of a nucleus is given by

$$D = m - A \cdot \mathrm{u}, \tag{2}$$

where m is the atomic mass, A the atomic mass number, and u the atomic mass unit [11]. Table 1 shows the mass excess values of ^{72,73,74}Kr, ^{73}Rb, and ^{74}Sr from ISOLTRAP [2] compared to those given in the literature prior to our measurements [12].

Table 1. Mass excess values for ^{72,73,74}Kr, ^{73}Rb, and ^{74}Sr from ISOLTRAP [2] compared to previous results [12]. Note that the mass values of ^{73}Rb and ^{74}Sr are obtained through the mass values of their mirror nuclei ^{73}Kr and ^{74}Kr using the calculated Coulomb shifts from Brown *et al.* [13].

Nuclide	$T_{1/2}$	D_{pre} /keV	D_{ISOLTRAP} /keV
^{72}Kr	17.2 s	−54110(270)	−53940.6(8.0)
^{73}Kr	27.0(1.2) s	−56890(140)	−56551.7(6.6)
^{74}Kr	11.5(1) min	−62170(60)	−62332.0(2.1)
^{73}Rb	< 24 ns	−46270(170)	−45940(100)
^{74}Sr	50 ms	−40670(120)	−40830(100)

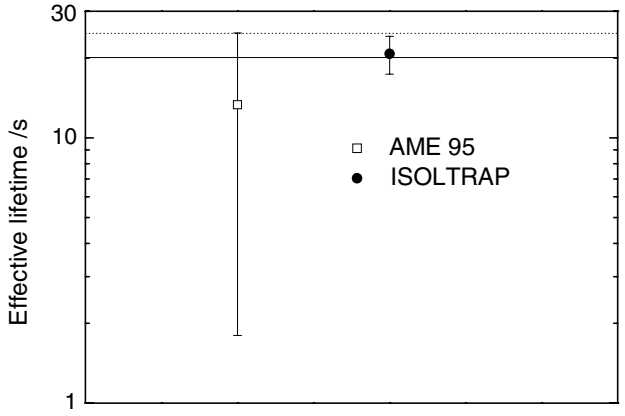

Fig. 2. Effective lifetime for ^{72}Kr at 1.3 GK. The solid line marks the lowest limit due to the non-observation of ^{73}Rb, and the dotted line gives the β-decay lifetime.

With the mass excess values given in table 1 we calculated the effective lifetime for ^{72}Kr. We took into account proton capture on ^{72}Kr and ^{73}Rb, photodisintegration on ^{73}Rb, and ^{74}Sr, and β^+-decay of ^{72}Kr, ^{73}Rb, and ^{74}Sr. Proton capture rates are as in Schatz *et al.* [14]. Figure 2 shows the minimum effective lifetime ($T = 1.3$ GK, $\rho = 10^6$ g/cm^3, $Y_{\mathrm{p}} = 0.88$) using the ISOLTRAP mass values and the previous results. Our result shows that ^{72}Kr is a strong waiting point in the rp-process [2]. It delays the X-ray burst by at least 20.8(3.4) s. This reduces considerably the uncertainty in the delay obtained using the previous mass values (2–24.8 s). However, the effective lifetime depends linearly on the ^{73}Rb$(p,\gamma)^{74}$Sr reaction rate and for this reaction rate, uncertainties of a few orders of magnitude cannot be excluded. This implies the necessity to measure this rate experimentally.

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