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Short note

Proton instability of ^{73}Rb

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Abstract. The study of the stability of an astrophysically interesting nucleus ^{73}Rb was performed by searching its β^+ and proton decay at the ISOLDE facility at CERN. Light rubidium isotopes were produced in a spallation reaction of a niobium target induced by a pulsed 1 GeV proton beam. The previously reported proton-unbound character of ^{73}Rb was confirmed and the upper limit for its production cross-section was reduced by more than one order of magnitude.

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Information on the position of the proton drip-line is of utmost interest for nuclear structure effects as well as for the astrophysical rp-process. In this connection we have studied light Rb-isotopes with a special focus on the possible existence and the decay modes of the yet unknown ^{73}Rb isotope. The mass models and the 1995 Atomic Mass Table predict ^{73}Rb to be proton unbound. However, very large deformations and their changes with Z and N are predicted in this region, which could lead to additional hindrance of the proton decay and hence to increased decay half-life. In an earlier measurement employing β-spectroscopy at the previous ISOLDE/SC facility, ^{74}Rb was identified and an upper limit of the production rate of about 1 at/s was determined for ^{73}Rb [1]. The experiment at the A1200 facility at MSU utilizing projectile fragmentation of $E/A = 65\,\mathrm{MeV}$ ^{78}Kr beam on a ^{58}Ni target [2] suggested also, that ^{74}Rb is the lightest bound Rb-isotope. In this experiment ^{74}Rb isotope was observed, but not ^{73}Rb. However, in the same work, a drop of a factor of more than 100 in the production was obtained between similar isotope pairs ^{66}As-^{65}As and ^{70}Br-^{69}Br. It could not be excluded that the non-observation of ^{73}Rb could be related to a similar lowering of the production cross section from ^{74}Rb to ^{73}Rb, since the number of observed ^{74}Rb isotopes was rather low. In a recent experiment performed at GANIL [3] similar results were obtained supporting the instability of ^{69}Br and ^{73}Rb. These experiments set an upper limit of the order of 100 ns or less for the proton decay half-lives of these two nuclei with an upper limit of their cross sections being roughly 10^{-2} and 10^{-1} times the expected cross sections for ^{69}Br and ^{73}Rb, respectively.

The binding energy and the decay modes of ^{73}Rb are crucial for the rapid proton capture (rp)-process in the vicinity of the proton drip-line [4]. If temperature and density are constant, then the rp-process path is defined by the half-lives and binding energies of nuclei close to the proton drip-line. Among the heavier nuclei, ^{65}As, ^{69}Br and ^{73}Rb are particularly important since they can largely retard the rp-process flow or even terminate it. The first one of these, ^{65}As, was identified as a beta-emitter [2] with a half-life of 190(11) ms [5] suggesting that the rp-process can proceed towards heavier nuclei. However, as stated earlier, recent work at GANIL found ^{69}Br to be unbound by at least 450 keV resulting in a partial half-life for proton decay to be below 100 ns [3]. This would suggest that the rp-process terminates at this point as the rp-process can proceed from ^{68}Se only via its beta decay, which has a half-life of 35.5 s, much longer than a typical time scale for the explosive hydrogen burning [4]. However, the process involves more than only a pure competition between the (p,γ) and the β-decay rates, if the boundary conditions for the rp-process flow calculations are allowed to vary. This might open a possibility for two proton (2p) capture reactions, which are known to be relevant among the light waiting point nuclei [6]. Then ^{69}Br can be bypassed via the 2p-capture of ^{68}Se to ^{70}Kr, after which the rp-process can proceed towards the next crucial nuclide, ^{73}Rb.

In the present experiment, a spallation reaction of Nb induced by the pulsed 1 GeV proton beam of the CERN PS-Booster was used to produce nuclides of interest. The pulse width and intensity of the proton beam were 2.4 μs and

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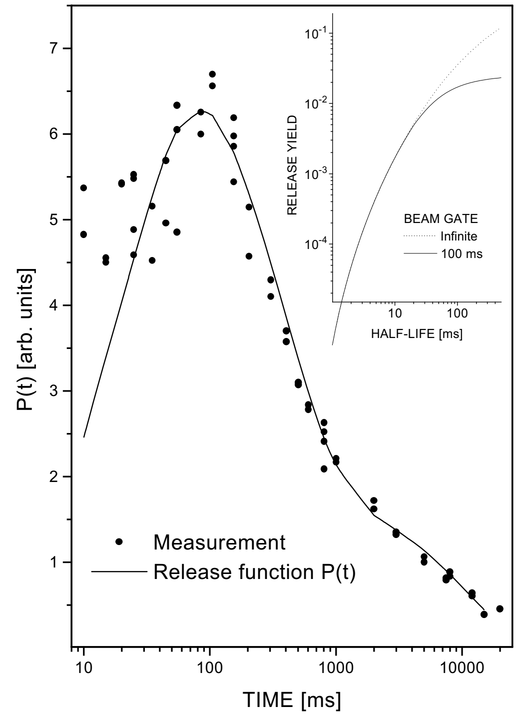

Fig. 1. Release function P(t) of the Rb-isotopes from Nb-foil target with a tungsten surface ionization source. *Inset* presents release yield of the Rb-isotopes as a function of the half-life with 100 ms and an infinite opening of the beam gate

2.3×10^{13} protons/pulse. Beam pulses were separated by a multiple of 1.2 seconds and typically 58% of the pulses were used leading to an average proton beam intensity of 1.8 μA. A Nb-foil target of 39 g/cm^2 was used together with a positive surface ionization source. The mass purified ion beam from the General Purpose Separator (GPS) [7] was implanted into an aluminized mylar tape tilted to 45° with respect to the beam axis. In addition to the differences in the time structure of the primary proton beam (pulsed versus continuous) and the energy of the primary proton beam (1 versus 0.6 GeV), the experimental setup differed also considerably from the one used in a previous attempt at ISOLDE [1], where only beta-particles were observed. The present detector setup included a Si particle telescope (20 μm ΔE, 500 μm E), a thin plastic detector for betas, a large volume (70%) HP Ge-detector for gamma-rays and a planar Ge-detector for low energy photons and high-energy betas, all in close geometry around the implantation position. Altogether ten parameters were collected and simultaneous singles spectra in multiscaling mode and list mode data were recorded. In the list mode data, all events were tagged with the time elapsed since the last proton impact and with the real time. The ion beam could be interrupted by electrostatic deflection and it was possible to vary the duration of this "beam gate" as well as the delay between the proton pulse and the "beam gate".

The yields of the heavier isotopes, namely $^{76-74}$Rb, were checked to ensure the satisfactory performance of the separator. An important part of the experiment was to determine the release behavior of the Rb-isotopes from the Nb-foil target-ion source system. This was done by measuring the amount of ^{76}Rb isotopes after mass separation with a fixed beam gate width of 10 ms and with a varying delay. Figure 1 shows the results of this measurement together with a fit to the data using the expression [8] for the release function:

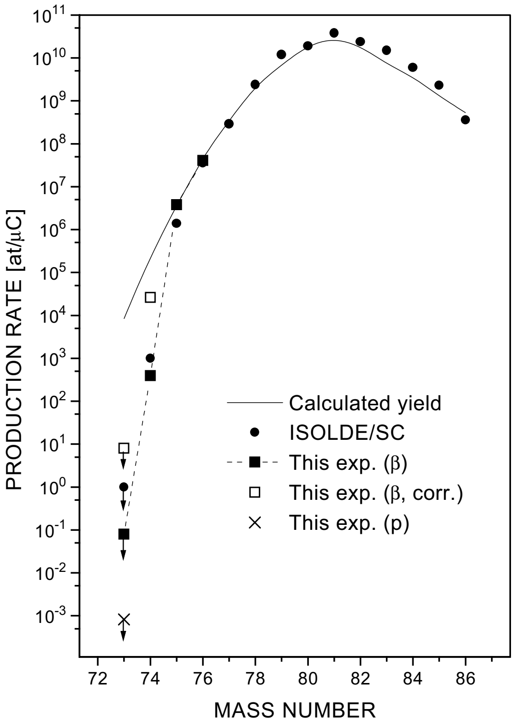

Fig. 2. Yields of the neutron-deficient Rb-isotopes. Experimental yields as obtained in this work are presented with filled squares. The *solid line* represents the calculated yield based on the semiempirical formula of Silberberg and Tsao [10]. The calculated curve is normalized to the ^{76}Rb yield as obtained in this work. *Open squares* present the release and decay-loss-corrected yields of ^{74}Rb and ^{73}Rb. In addition the experimental limit of the production rate based on the non-observation of protons is printed by the cross

$$P(t) \propto (1 - e^{-t/\tau_r})\big(\alpha e^{-t/\tau_f} + (1-\alpha) e^{-t/\tau_s}\big) ,$$

where α stands for the fast fraction of the release function and τ_r, τ_f and τ_s to the rise, fast-, and slow-fall time constants. The fit resulted in the following parameters: τ_r = 20 ms, τ_f = 270 ms, τ_s = 9 s, α = 0.83. Based on the measured release properties it was decided to keep the separator beam gate open for 100 ms after each proton-impact. With this choice of the beam gate width and assuming the same half-life for ^{73}Rb and ^{74}Rb, about 97% of the ^{73}Rb activity in the focal plane of the GPS separator, should be observed, minimizing the effective background contribution.

The behavior of the yield for various Rb isotopes is shown in Fig. 2. The yields obtained at the previous ISOLDE/SC are also presented here for comparison. The experimental yields of ^{76}Rb and ^{75}Rb were obtained from beta-activity observed in the monitoring tape station of the ISOLDE-separator [8]. The yield of ^{74}Rb was determined from the TDC-spectrum of beta-events assuming that all short-lived activity comes from ^{74}Rb, see inset of Fig. 3. The obtained yield of ^{74}Rb was 390 at/μC. Non-observation of the decay events at A = 73, which could be associated

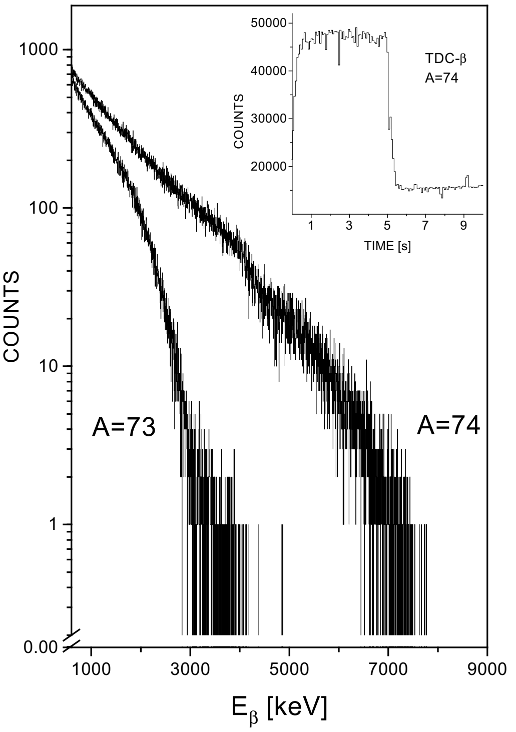

Fig. 3. The beta spectra obtained with the planar Ge counter at mass A = 73 and A = 74. Measurement times of β-spectra are 16 h and 4.8 h at A = 73 and A = 74, respectively. The *inset* shows the beta-gated TDC-spectrum at A = 74, which exhibits the fast decaying component after a 5 s beam on period and a flat background during the beam off period. The timing was chosen to uncover the decay of a possible long-lived isomeric state in ^{74}Rb. The area above the background level was used to determine the number of beta-decays of ^{74}Rb

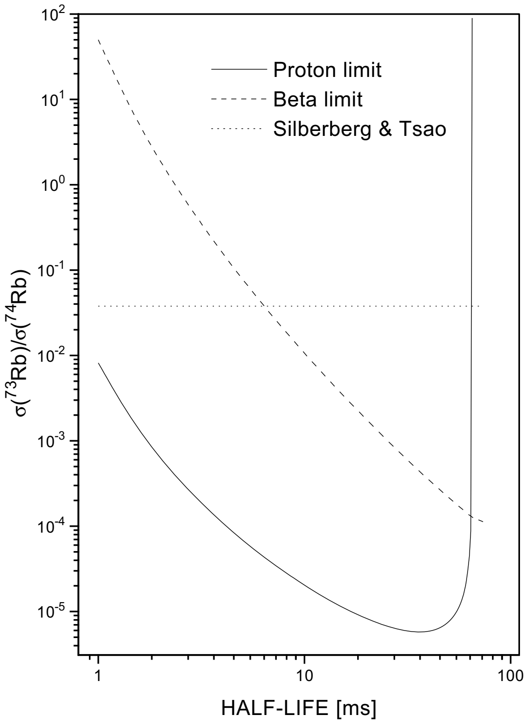

Fig. 4. Relation between the half-life of ^{73}Rb and the upper limit of the cross section of ^{73}Rb relative to ^{74}Rb. The *solid* and *dashed lines* give a limit from the proton- and beta-decay measurements, respectively. The *dotted line* illustrates the calculated cross section ratio according to [10]

with ^{73}Rb leads to a well defined upper limit for the yield based on the following arguments. If ^{73}Rb were a pure beta-emitter, it should have a similar β-decay characteristics as ^{74}Rb since their estimated QEC values are 10.62(50) and 10.44(44) MeV [9], respectively and both of them are super-allowed beta emitters. Figure 3 presents the beta-spectrum as observed at mass A = 74 and A = 73. In the case of ^{74}Rb we can clearly observe high-energy betas related to the decay of ^{74}Rb. Other sources of high energy betas can be excluded both in the A = 74 and A = 73 mass chains as Sr was not released from the ion source which was deduced at heavier masses, and the properties of Kr and Br inhibits the ionization of these elements in the ion source used. In case of the A = 73 beta-spectrum, there is no high energy component present. For A = 73, the observed activity below 4 MeV can be assigned to neutron-rich isobars near stability (^{73}Ga, ^{73}Zn).

By taking into account the measurement time and the observed integral of the high energy beta-events, we can determine an upper limit for the ratio of the yields Y(^{73}Rb)/Y(^{74}Rb) to be 2×10^{-4}. By combining this number and the obtained yield of ^{74}Rb we can give an upper limit of 0.08 at/mC for the yield of ^{73}Rb, which is ten times lower than observed in the previous study. Figure 2 includes also the calculated yield normalized to the experimental yield of ^{76}Rb. Calculation is based on the semiempirical formula of Silberberg and Tsao [10]. For ^{75}Rb and the heavier isotopes, the calculated and the experimental values agree. A slight deviation in the experimental yield is observed for ^{74}Rb. These observations can be partly explained by decay and release losses. However, the correction for these effects does not bring the experimental values to the calculated production rates, as illustrated in Fig. 2. This implies that ^{73}Rb is indeed unbound. The discrepancy between the decay corrected yield of ^{74}Rb and the normalized Silberberg and Tsao might be due to the fact that ^{74}Rb is already so weakly bound that the lack of bound excited states lowers the production rate of ^{74}Rb in the spallation reaction.

An additional production limit comes from the non-observation of the ground state proton decay. Protons were searched in the energy region above 300 keV. The energy threshold is determined by the continuum in the low energy part of the ΔE-detector spectrum. The non-observation of proton groups gives an upper limit of 8×10^{-4} protons/μC for A = 73. Since proton decay can occur with a half-life much shorter than the partial half-life of the super-allowed beta decay, the limit obtained from the non-observation of protons has to be analyzed as a function of half-life. Due to the super allowed character of their β-decay it is reasonable to assume that the partial beta decay half-lives of ^{73}Rb and ^{74}Rb are very similar. The ground state proton decay would shorten the total half-life of ^{73}Rb and increases the decay losses according to Fig. 1. These effects have been taken into account in Fig. 4, where the upper limit of the cross section ratio, $\sigma(^{73}$Rb$)/\sigma(^{74}$Rb$)$, is given as a function of the partial half-life of the proton decay both for the beta-measurement and the proton measurement. In the latter case, for partial proton half-life equal or greater than the beta half-life, the mere existence of proton emission increases the sensitivity; on the contrary, larger proton branches imply a decrease of total half-life leading to large decay losses lowering the sensitivity.

We have given strong evidence for the proton unbound character of ^{73}Rb with one to three orders of magnitude better limits than obtained in the earlier studies. If the non-observation of ^{73}Rb in the GANIL work was not related to the low cross section, but to the short half-life, then one can restrict the half-life of ^{73}Rb to be about 100 ns or less [3]. This means that the corresponding proton separation energy is relatively high, of the order of 500 keV, which provides a stringent test for the existing mass predictions. For example, the recent macroscopic-microscopic model by [11] predicts the proton separation energy of 310 keV, the atomic mass relation by [12] predicts 820 keV, but the recent Atomic Mass Table gives 590 keV [9]. If the proton separation energy is as high as suggested, the proton decay of ^{69}Br and ^{73}Rb could only be measured in a delayed coincidence experiment following the β^+-decay of the even Z-precursors ^{69}Kr and ^{73}Sr, respectively. These measurements would be important, since they provide crucial information for the rp-process modeling as well as for the barrier penetrability calculations in the region of rapid changes of nuclear shapes.

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