New Isotopes from ^{78}Kr Fragmentation and the Ending Point of the Astrophysical Rapid-Proton-Capture Process

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In an experiment at the SISSI/LISE facility of GANIL, we used the projectile fragmentation of a ^{78}Kr primary beam at 73 MeV/nucleon to produce new isotopes of astrophysical interest. We obtained clear evidence for the existence of the five new isotopes ^{60}Ga, ^{64}As, ^{69,70}Kr, and ^{74}Sr. However, we did not find any evidence for ^{69}Br, whereas comparable nuclei were observed with more than 1000 counts. The isotope ^{69}Br is thus deduced to be a proton-unbound nucleus with a half-life shorter than about 100 ns. The influence of these results on our understanding of the astrophysical RP process is discussed.

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The cold as well as the hot CNO cycles are well-known processes to produce light proton-rich nuclei in stellar environments (see, e.g., [1]). Most of the input parameters defining the path of these processes are experimentally known with sufficient precision. Under certain conditions, i.e., high density and high temperatures, the rapid-proton-capture (RP) process is an extension of the CNO cycle. This process has been proposed by Wallace and Woosley [2] to be able to synthesize proton-rich isotopes up to masses as large as $A = 100$. It consists of a chain of proton captures and β^+ decays. The conditions for the RP process are believed to be present in various stellar scenarios like supernova shock waves, novas, or x-ray bursts [1]. However, parts of the reactions in the transition phase between the hot CNO cycle and the RP process are still under study.

As the path of the RP process is very close to the proton drip line, the knowledge of the limits of stability is of particular interest and determines most key points of the RP-process path such as waiting points and the ending point. Nuclei like ^{65}As, ^{69}Br, and ^{73}Rb have been considered as key nuclei for the RP-process path. If these nuclei are sufficiently bound so that their decay is dominated by β decay, the RP process can pass through them by proton capture and proceed to higher masses. Therefore, if one of the nuclei is proton unbound, the RP process ends or is at least significantly slowed down at ^{64}Ge, ^{68}Se, or ^{72}Kr, respectively, due to their rather long β-decay half-life as compared to the time scale of the RP process.

The predictions for the limits of stability depend strongly on the mass models used [3,4]. For example, the isotopes ^{65}As and ^{69}Br are predicted to be particle stable by some models, whereas others predict them to be proton unbound. Therefore an experimental verification of their stability is highly desirable. The time scale for the different steps of the RP process is determined by the β-decay half-life of even-Z nuclei, the binding energies of the nuclei involved, and the capture cross sections of the relevant nuclear reactions. This time scale is of the order of 10 s [1].

These facts triggered searches for the ground-state proton decay of ^{65}As and ^{69}Br [5,6]. However, both papers reported on the nonobservation of protons in the expected energy range. Therefore they concluded that either the decay of these nuclei is dominated by β decay or the ground-state proton-decay half-life is shorter than the respective experimental limits of 100 [6] and 10 μs [5].

Mohar *et al.* [7] identified six new isotopes, among them ^{65}As and ^{69}Br, in the fragmentation of a ^{78}Kr beam impinging on a nickel target, an experiment recently performed at the A1200 separator of MSU. On the other hand, they reported the absence of ^{73}Rb and concluded that the RP process is at least significantly slowed down at ^{72}Kr, since its β-decay half-life is comparable to the time scale of the RP process. In following experiments, the half-lives of ^{61}Ga, ^{63}Ge, and ^{65}As have been measured, showing that their decay is dominated by β decay so that the RP process can pass through these nuclei [8]. However, the half-life of ^{69}Br could not be determined [9].

In an experiment performed at the SISSI/LISE facility of GANIL, we searched for new proton-rich isotopes in this mass region by means of projectile fragmentation of a primary ^{78}Kr beam at 73 MeV/nucleon. We took advantage of the much higher primary-beam intensities available at GANIL (1 μA of $^{78}\mathrm{Kr}^{34+}$), the high transmission of the SISSI+ALPHA+LISE device [10–12] (momentum acceptance $\Delta p/p \approx 1\%$, angular acceptance $\Delta\Theta \approx 80$ mrad horizontally and vertically), and the high selectivity of the LISE3 spectrometer combining magnetic-rigidity, energy-loss, and velocity analyses [12]. The beam spot on the SISSI target has a typical diameter of about 0.4 mm yielding a good isotope resolution.

We used a nickel target of a thickness of about 110 mg/cm^2 in the SISSI device, combined with a thin degrader (12 mg/cm^2 of aluminum) at the LISE dispersive focal plane. The main fragment selection has been performed by means of the velocity filter of LISE3 [12]. The new isotopes were identified by a time of flight (TOF) ΔE-E technique. The time of flight was measured twice, (i) between a parallel-plate avalanche counter (PPAC) at the exit of LISE (about 28 m upstream of the detection setup at the final focus) and a silicon detector at the final focus of LISE3 as well as (ii) between the cyclotron radio frequency (RF) and the silicon detector. The energy-loss measurements were performed by a silicon-detector telescope. All detectors as well as the TOF's have been calibrated by means of the primary beam. Details of the detection setup are schematically shown in Fig. 1.

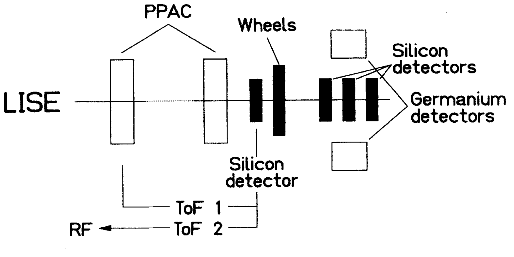

FIG. 1. Experimental setup as used for the identification of the new isotopes and for the measurement of the γ rays of the isomers. It consisted of two parallel-plate avalanche counters (PPAC) for the position determination and the TOF measurement, four silicon detectors (600 mm^2 each, 300 μm thickness for the first silicon detector, and 150 μm for the others), wheels with different thicknesses of aluminum in order to adjust the implantation depth, and four germanium detectors for the detection of the γ rays.

The TOF ΔE-E identification was checked by measuring the γ decay of the known isomers ^{69,71}Se with four germanium detectors surrounding the silicon-detector telescope. By setting the coincidence gate to about 100 μs, the implantation signal of the heavy ions and the γ rays from the decay of the short-lived isomers could be recorded in the same event of the data acquisition. Therefore they can be correlated directly with the isotopes in the ΔE vs TOF plot. This technique has been used for the first time in connection with high-energy radioactive beams by Grzywacz *et al.* [13].

A first selection of the events of interest has been performed by a software gate on the absolute TOF between the PPAC and the silicon detector. Because of the limited resolution of the PPAC and the short flight path of only 28 m, the resolution of this TOF is not sufficient to separate neighboring nuclei by their TOF. However, it is good enough to give a first selection for the TOF between the radio frequency of the cyclotron and the silicon detector, which has, in turn, the problem of periodicity with a RF period of about 80 ns.

In order to reject events where the heavy ions interacted in the first silicon detector which may yield a wrong identification, conditions have been imposed on the ΔE-E plot of the first and the second silicon detectors. This procedure rejects almost all contaminant reactions in the detectors used for the identification.

The resulting ΔE vs TOF plot purified by conditions on the low-resolution TOF as well as on the energy loss of the second silicon detector is shown in Fig. 2. For the projection of the different rows on the isospin projection T_z, the energy-loss signal has been corrected for the velocity dependence of the energy loss in order to yield the nuclear charge Z. Figure 3 shows the result of this projection for the rows with $T_z = -1/2$, -1, and $-3/2$ [Figs. 3(a), 3(b), and 3(c), respectively].

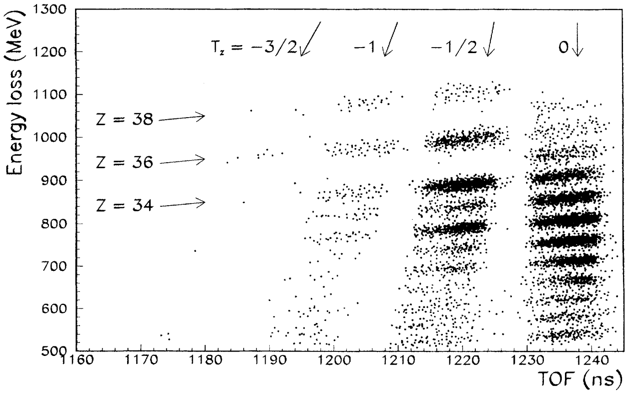

FIG. 2. Two-dimensional plot of the energy loss in the first silicon detector vs the time of flight between the target and the silicon detector. The rows of almost constant TOF represent rows of constant isospin projection T_z.

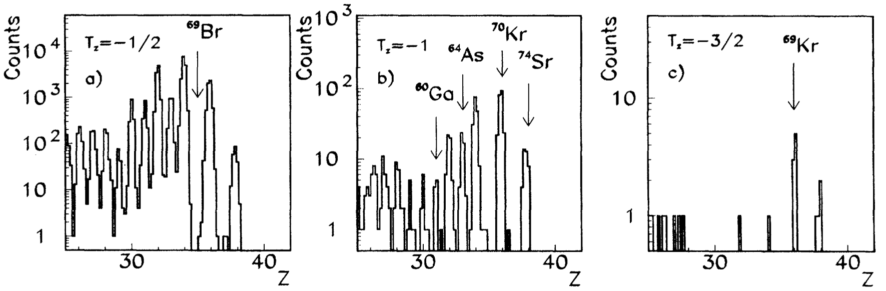

FIG. 3. Projections of the different isospin-projection rows (see Fig. 2) on the nuclear charge for (a) $T_z = -1/2$, (b) $T_z = -1$, and (c) $T_z = -3/2$. The arrows indicate the new isotopes [(b), (c)] as well as the expected position of ^{69}Br [(a)].

The new isotopes are indicated by the arrows. We find clear evidence for ^{60}Ga, ^{64}As, ^{69,70}Kr, and ^{74}Sr. The projection in Fig. 3(a) shows that the few counts located in between the two neighboring distributions which might be attributed to ^{69}Br clearly belong to the tails of ^{67}Se and ^{71}Kr. Therefore we have no counts which can be attributed to ^{69}Br [arrow in Fig. 3(a)], whereas other nuclei with the same isospin projection T_z are observed with more than 1000 counts. This allows us to give an upper limit of 100 ns for the half-life of ^{69}Br. It should be noted that our results do not necessarily contradict the results reported by Mohar *et al.* [7] on the observation of ^{69}Br, since the flight path in our study was about 6 times longer than the one of the MSU experiment.

The isotope ^{69}Br is expected proton unbound by almost all commonly used mass predictions [3]. However, e.g., the 1993 Atomic Mass Tables [4] predict it unbound by only 180 ± 300 keV, which would yield a rather long partial half-life for proton ground-state emission of about 10^6 s according to barrier-penetration calculations. From this point of view, the decay of ^{69}Br would be expected to be dominated by β decay with a half-life of the order of 100 ms [14]. The present results demonstrate that ^{69}Br is proton unbound by at least 450 keV to yield a barrier-penetration half-life of less than 100 ns.

In the case of ^{60}Ga, the mass models differ in predicting its stability. However, all mass models predict proton separation energies laying inside a band of ±260 keV around $S_p = 0$. The 1993 Atomic Mass Tables [4] predict that this nucleus is bound by 30 ± 118 keV. Therefore ^{60}Ga is expected to decay mainly by β decay.

The nucleus ^{64}As is predicted to be unbound by about 100–400 keV according to commonly used mass models [3]. Only the 1993 Atomic Mass Tables [4] predict it to be bound by 33 keV, however, with an error bar of 540 keV. This yields barrier-penetration half-lives for proton emission which are longer than 10 ns. The observation of ^{64}As in our experiment and the comparison of the counting rate to neighboring nuclei excludes half-lives much shorter than about 1 μs. From different barrier-penetration calculations, we conclude that ^{64}As is unbound by less than about 400 keV or bound. The even-Z new isotopes ^{69,70}Kr and ^{74}Sr are predicted by all mass models to be stable against particle emission from their ground state.

The upper limit deduced from our data for the half-life of ^{69}Br shows that this nucleus is proton unbound. This finding together with the observation of ^{60}Ga and ^{64}As changes our understanding of the astrophysical RP process in this region, ^{68}Se being now the ending point for rapid proton capture [1]. The presence of ^{60}Ga and ^{64}As could open new branches for the RP process around these nuclei. However, it has to be shown that ^{60}Ga and ^{64}As are stable enough, i.e., that their decay is dominated by β decay. Using the new results of the present experiment, the possible paths of the astrophysical RP process near its ending point are shown in Fig. 4. Beyond ^{68}Se, slow proton capture may continue to proceed to higher masses.

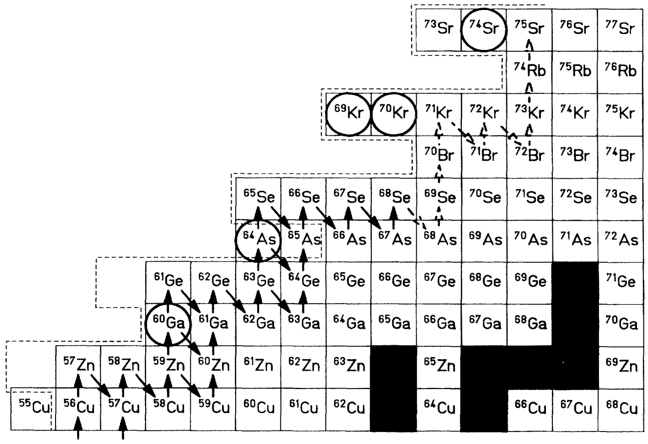

FIG. 4. RP-process path in the region between copper and strontium. Stable nuclei are indicated by full squares. Nuclei to the left of the dashed line are predicted to be unstable by the mass model of Jänecke and Mason [3]. The circles indicate the nuclei which have been identified for the first time in the present experiment. The RP-process path (arrows) has been taken from the calculations of Champagne and Wiescher [1], however, modified according to the results reported here. Thus the dashed arrows indicate the RP-process path after its slowing down at ^{68}Se.

A study of properties in this region of the nuclear chart with higher statistical significance is still highly desirable. In particular, half-life measurements going beyond the measurement reported in Ref. [8] could fix details of the RP-process path in this mass region. A determination of the proton-decay half-life of ^{69}Br is of particular interest.

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