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^{78}Kr fragmentation

New isotopes and β-delayed protons

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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 were sufficiently bound so that their decay is dominated by β decay, the rp process could pass through them by proton capture and proceed to higher masses.

In addition to the astrophysical interest of new isotopes, this region of the chart of nuclei offers unstable nuclei having a high β-decay Q-value so that they decay by β-delayed particle emission. The measurement of the spectrum of emitted protons allows to test level-density formulae and to determine the difference (Q_{EC} - S_p) between the β-decay Q-value and the proton separation energy. The shape of the proton spectra and the absolute proton branching ratio may give some insight in the question about the deformation of these nuclei. On the other hand, β-delayed protons are a useful tool to determine β-decay half-lives.

In an experiment performed at the SISSI/LISE facility, we searched for new proton-rich isotopes [X] by means of projectile fragmentation of a primary ^{78}Kr beam at 73 MeV/nucleon and measured for the first time β-delayed protons from ^{67}Se, ^{71}Kr, and ^{75}Sr [X].

The fragments have been identified by a TOF-ΔE-E analysis. This identification was checked by measuring the γ decay of the known isomers ^{69,71}Se with four germanium detectors surrounding the silicon-detector telescope. The measurement of γ rays from isomer decays allowed us to measure for the first time the spectrum of the isomer ^{66}As [3]. The resulting ΔE-TOF plot purified by conditions on the low-resolution TOF as well as on the energy loss in a silicon detector behind the ΔE counter is shown in Fig. 1a. The energy loss signal has been corrected for the velocity dependence of the energy loss in order to yield the nuclear charge Z. Figs. 1b,c,d show the results of the projection for the rows with isospin projections T_z = -1/2, T_z = -1, and T_z = -3/2, respectively.

The new isotopes are indicated by the arrows. We find clear evidence for ^{60}Ga, ^{64}As, ^{69,70}Kr, and ^{74}Sr. On the other hand, we have no counts which can be attributed to ^{69}Br (arrow in Fig. 1b), whereas other nuclei with the same isospin projection T_z are observed with more than 1000 counts.

The isotope ^{69}Br is expected to be proton unbound by almost all commonly used mass predictions [4]. 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 predicit proton separation energies laying inside a band of $\pm$ 260 keV around S_p=0. 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 [4]. 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

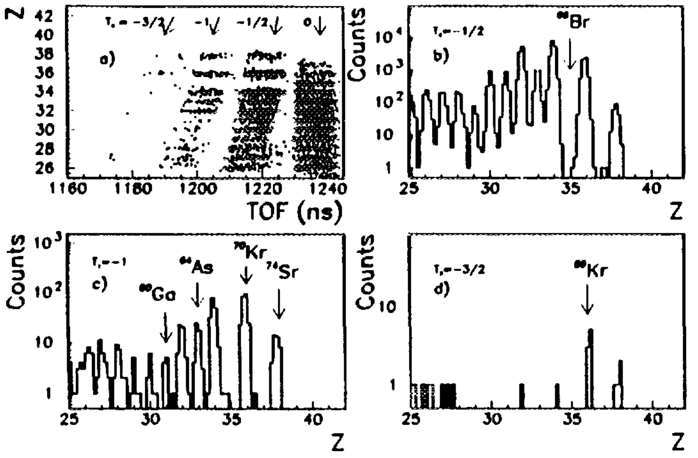

Figure 1: Two-dimensional plot of the nuclear charge Z versus the time of flight between the target and the silicon detector (a). The rows of almost constant TOF represent rows of constant isospin projection T_z. Parts b-d give the projections of the different isospin-projection rows on the nuclear charge for T_z = -1/2 (b), for T_z = -1 (c), and for T_z = -3/2 (d). The arrows indicate the new isotopes [c),d)] as well as the expected position of ^{69}Br [b)].

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 in the model of Ref. [5] due to its long half-life compared to the time scale of the rp process. 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.

In order to study the decay properties of proton-rich isotopes, nuclei of interest were stopped in the center of a silicon telescope. The range of the fragments was adjusted by using wheels with different thicknesses of aluminum. After the implantation of isotopes of interest, the primary beam was switched-off for 150 ms. During this interval, β decay of a given isotope could be observed under low-background conditions and time-correlated with the implantation event. Fig. 2 shows the energy spectra and time distributions of β-delayed particles measured for ^{67}Se, ^{71}Kr and ^{75}Sr.

On the basis of the fraction of the number of implanted nuclei as counted in the TOF-ΔE-E analysis and of the number of observed protons the branching ratios for proton emission has been deduced to be P_p = (6.5±3.3)% for ^{75}Sr, P_p = (5.2±0.6)% for ^{71}Kr, and P_p = (0.5±0.1)% for ^{67}Se. The factor of ten between the branching ratios for ^{75}Sr and ^{71}Kr on the one hand and of ^{67}Se on the other hand is most likely due to nuclear-structure effects like deformation. A similar effect has been observed by Hardy et al. [6] for the T_z=1/2 nuclei ^{69}Se, ^{73}Kr, and ^{77}Sr.

In order to calculate the energy spectra of β-delayed protons, we used a statistical model [7]. In the calculations, we assumed a constant β-strength function and (Q_{ec}-S_p) values of 7.84 MeV, 8.55 MeV, and 8.23 MeV for ^{67}Se, ^{71}Kr, and ^{75}Sr, respectively [8]. The spin of the decaying nuclei was assumed to be $I^\pi = 5/2^-$ and only transitions to the ground state of the final nucleus were considered. The probability of a proton emission from a given state, expressed in terms of angular-momentum dependent transmission coefficients through the Coulomb barrier and level densities, was calculated using different sets of spherical optical-model parameters and the level-density formula of Gilbert and Cameron [9]. The dashed lines in Figs. 2a-c show the predicted shapes of the proton spectra. The calculated curves were normalized to get the best agreement with the measured spectra.

Figs. 2d-f show the time distributions of protons emitted after β decay of ^{67}Se, ^{71}Kr, and ^{75}Sr,

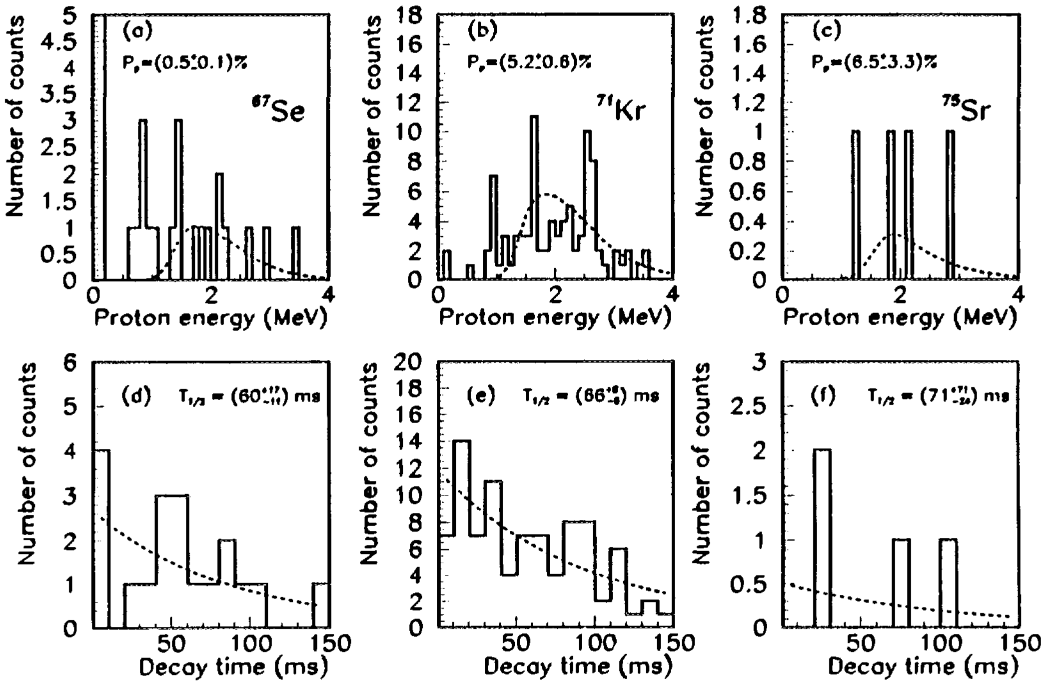

Figure 2: Upper panel: Energy spectra of particles emitted in the β decay of ^{67}Se (a), ^{71}Kr (b), and ^{75}Sr (c). The events with energy lower than 500 keV correspond to the detection of β particles, signals with energies higher than 500 keV are due to the registration of protons. The dashed line shows the results of statistical-model calculations (see text for details). Lower panel: Time distributions of protons emitted after β decay of the studied nuclei. The dashed line represents a maximum likelihood fit to the data using a single decay component.

respectively. To select protons, only signals with energies higher than 500 keV were accumulated in these spectra. The half-lives of the nuclei studied were deduced by fitting a single-component decay curve (dashed line in Figs. 2 d-f) to the measured time distribution. The half-lives of $T_{1/2} =$ (60^{+17}_{-11})ms, (64^{+8}_{-5})ms, and (71^{+71}_{-24})ms for ^{67}Se, ^{71}Kr, and ^{75}Sr, respectively, were obtained.

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