Half-life measurements of Rb, Sr, Y, Cs, Ba, La and Ce isotopes with $A = 91$–98 and $A = 142$–149

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Half-lives of the extremely neutron-rich isotopes $^{91-98}$Rb, $^{94-98}$Sr, $^{96-98}$Y, $^{142-146}$Cs, $^{143-148}$Ba, $^{144-149}$La, and ^{149}Ce were determined. The isotopes ^{147,148}Ba, and ^{149}La were identified for the first time and their half-lives measured. The values obtained, in seconds, are 0.72 ± 0.07 for ^{147}Ba, 0.47 ± 0.20 for ^{148}Ba and 1.2 ± 0.4 for ^{149}La. The other measured half-lives either confirm or improve previous measurements. An extrapolation procedure based on the systematic behavior of experimental half-lives for the prediction of half-lives not yet measured was used. Similar systematic behavior is also apparent for half-lives predicted within the framework of the gross theory of β decay.

[RADIOACTIVITY $^{91-98}$Rb, $^{94-98}$Sr, $^{96-98}$Y, $^{142-146}$Cs, $^{143-148}$Ba, $^{144-149}$La, ^{149}Ce [from ^{235}U (n, fission)]; measured $T_{1/2}$. Si surface barrier detector. Mass-separated Rb, Sr, Cs, and Ba activities.]

I. INTRODUCTION

The study of the half-lives of short-lived mass separated Rb, Sr, Cs, and Ba fission products and their β decay products was conducted at the Soreq-on-line-isotope-separator (SOLIS). The isotopes studied are extremely neutron rich and cover the range of masses 91–98 and 142–149.

Earlier values of half-lives of isotopes with $A = 91$–98 and $A = 142$–149 have been published.[1-10] The present work provides a first identification and measurement of the half-lives of ^{147,148}Ba and ^{149}La. Results for the isotopes $^{96-98}$Sr, which showed a wide spread in values in different measurements, agree well with those of Wohn *et al.*[4] and may be considered acceptable.

The half-lives show near-exponential behavior, decreasing with mass, and also an odd-even effect indicating a general trend which is similar to the theoretical predictions of Takahashi *et al.*[11] By extrapolation of the experimental curves, it is possible to predict the half-lives of isotopes far from the β-stability line which have not yet been measured.

II. EXPERIMENTAL

The SOLIS facility has already been described.[12] In the present work, newly developed surface ionization integrated target-ion sources were used[13,14] with targets of ^{235}U exposed to a thermal neutron flux of about 5×10^8 $n\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$. These sources have very short nuclide hold-up times and allow measurements of half-lives down to 0.1 s.

The desired mass was focused through a circular tantalum aperture with a 4 mm opening onto either a stationary thin aluminum foil or a moving tape collector behind which a 300 μm Si surface barrier detector for counting β activity was placed.

A high mass purity was achieved. The level of contamination was checked by scanning the β activity of the masses and fitting a Gaussian function to each peak by the least-squares method. The contamination was less than 10^{-6} for the lighter masses ($A = 91$–98) and less than 10^{-4} for the heavier masses ($A = 142$–149).

The method employed for half-life measurements was multiscaling the β activity of the isotopes. The runs with short sampling times were carried out automatically, controlled by a preset programmer. The running cycle consisted of two steps. First, the beam was let through for a predetermined time to permit activity buildup. Then the beam was electrostatically deflected, and β decay was counted for a predetermined time. The time per channel and the number of channels for multiscaling the β counts were chosen according to the expected half-lives. Enough time was allowed for the activity to decay to the background level. In the case of a mass chain with several components with large differences in half-lives, runs were carried out with different buildup times in order to enhance one or the other of the components. The cycles were repeated until enough statistics were accumulated.

The use of an Si surface barrier detector for β counting ensures very low γ background, and therefore prevents distortion of the decay curves due to γ activity of neighboring mass chains. In certain cases, the activity of the longer-lived components was removed by the moving tape collector.

III. ANALYSIS

The decay curves were analyzed by a least-squares fit program DECAY. The program fits a sum of exponentials to the experimental results and provides as output the half-lives and the corresponding decay factors. The number of components used in the fit was usually known in advance for most of the chains. The maximum number of components was never greater than five, always including a background component. Dead-time corrections were not necessary except in a few cases, and these were made by including a correction factor in the program.

IV. RESULTS

The decay curve for mass 143, typical of high yield data, is given in Fig. 1. Figure 2 shows the decay curve for mass 149. This curve is a typical low yield data curve, however, it gives enough statistics to permit satisfactory analysis. Figure 3 shows the decay curve for mass 98, including ^{98}Rb which has the lowest half-life measured in the present work (0.10 s.).

The experimental half-lives measured in the present work are reported in Table I. The values are the average weighted means evaluated from half-life measurements obtained with different collection times and different statistics. The errors are weighted means of the standard deviations (calculated by the program DECAY).

Owing to improvement in the ion source assembly, it was possible to obtain much higher statistics for the final results, published in Table I, than in the first stages of the present work. This helped to remove uncertainties in the half-lives of isotopes with very low fission yields, especially for ^{97}Sr, ^{97}Y, and ^{98}Sr for which the preliminary

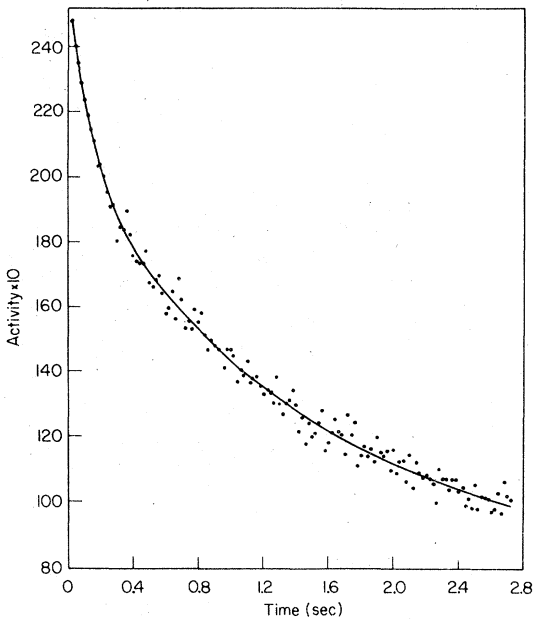

FIG. 2. Decay curve of mass 98 obtained by β multiscaled data. (Experimental conditions: irradiation time = 2 s, decay time = 3 s, 2000 cycles, 0.02 s /channel, Re ionizer).

results[9,10,14] deviate appreciably from the present values.

The most recently reported results of others are cited in Table I for comparison. The agreement of the present results with those of others is, in general, good and the present results either confirm or improve previous measurements. The agreement for $^{96-98}$Sr with the results of Wohn *et al.*[4] is good and removes the uncertainties in the half-lives of these isotopes where a large spread in values existed previously.

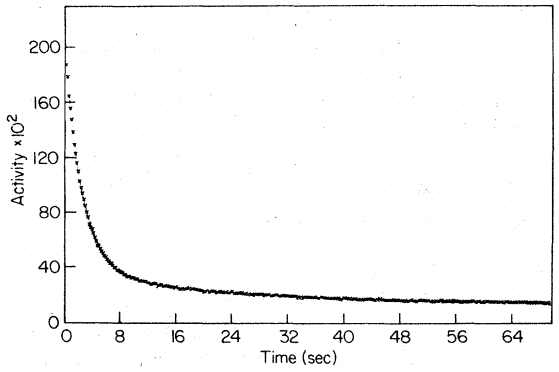

FIG. 1. Decay curve of mass 143 obtained by β multiscaled data. (Experimental conditions: irradiation time = 0.3 s, decay time = 70 s, 60 cycle run, 0.2 s /channel, Re ionizer).

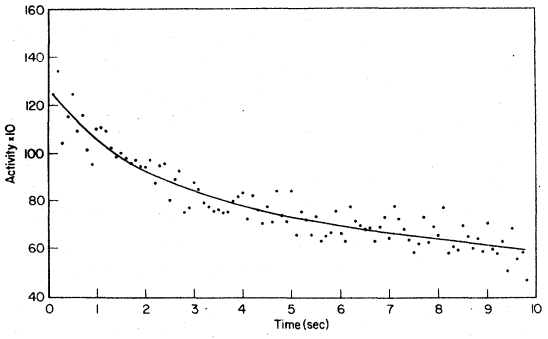

FIG. 3. Decay curve of mass 149 obtained by β multiscaled data. (Experimental conditions: irradiation time = 4 s, decay time = 10 s, 220 cycles, 0.1 s /channel, Re ionizer).

TABLE I. Measured half-lives of neutron-rich Rb, Sr, Y, Cs, Ba, La, and Ce nuclides.

Mass	Element	Half-life (s) Present work	Half-life (s) Latest measurements by others	Mass	Element	Half-life (s) Present work	Half-life (s) Latest measurements by others
91	Rb	59.6 ±0.2	58.42 ±0.07 [a]	142	Cs	1.78 ±0.02	1.70 ±0.02 [b]
92	Rb	4.57 ±0.07	4.54 ±0.02 [b]	143	Cs	1.78 ±0.01	1.79 ±0.02 [b]
93	Rb	6.01 ±0.02	6.12 ±0.08 [b]		Ba	15.2 ±0.2	14.5 ±0.5 [g]
94	Rb	2.80 ±0.04	2.83 ±0.03 [b]	144	Cs	1.03 ±0.01	1.02 ±0.04 [d]
	Sr	76.7 ±0.9	75.7 ±0.2 [c]		Ba	12.0 ±0.4	12.3 ±0.4 [d]
95	Rb	0.402±0.008	0.377±0.004 [b]		La	40 ±4	42.1 ±0.7 [h]
	Sr	25.1 ±0.2	26.8 ±1.5 [c]	145	Cs	0.605±0.03	0.590±0.020 [d]
96	Rb	0.217±0.009	0.203±0.004 [d]		Ba	3.85 ±0.12	4.31 ±0.16 [d]
	Sr	1.10 ±0.02	1.015±0.019 [d]		La	21 ±5	25.2 ±2.6 [h]
	Y	6.3 ±0.2	6.0 ±0.3 [c]	146	Cs	0.31 ±0.06	0.305±0.010 [d]
97	Rb	0.187±0.019	0.170±0.002 [d]		Ba	2.2 ±0.2	2.18 ±0.11 [d]
	Sr	0.43 ±0.03	0.441±0.015 [d]		La	9.0 ±0.6	8.5 ±1.0 [h]
	Y	3.3 ±0.2	3.7 ±0.1 [f]	147	Ba	0.72 ±0.07	0.70 ±0.06 [d]
98	Rb	0.10 ±0.02	0.108±0.005 [d]		La	4.4 ±0.5	2.2 ±0.4 [h]
	Sr	0.6 ±0.1	0.66 ±0.07 [d]	148	Ba	0.47 ±0.20	•••
	Y	2.1 ±0.3	2.0 ±0.3 [c]		La	2.6 ±0.6	~1 [h]
				149	La	1.2 ±0.4	•••
					Ce	4.7 ±0.8	5.7 ±0.5 [h]

[a–h] Refer respectively to Refs. 1–8.

In their analysis, Wohn *et al.*[4] included the delayed neutron branching for Rb and Cs precursors in their multicomponent fitting function. In the present work, this was not necessary for the following two reasons. First, there is no interference due to delayed neutron branching with the precursor isotope even for the highest P_n values, because in all cases the differences in the half-lives of the precursor and the isotope created by the delayed neutron branching are large. Second, in the present experiments the Sr and Ba isotopes are not only created by β decay at the collector, as in the experiment of Wohn *et al.*, but also arrive with high efficiency directly from the source and, therefore, the contribution of the activity of the isotopes created by the delayed neutron branching may be neglected. This is also reflected in the half-lives which compare well in both works, as may be seen from Table I.

Masses 147, 148, *and* 149. The first identification and half-life measurements of ^{147,148}Ba and ^{149}La are reported in this work. The half-lives of ^{147,148}Cs could not be measured due to the low yields of these isotopes. They were, however, identified and their fission yields measured.[15] The Ba isotopes are directly deposited, while the La isotopes appear as decay products of Ba.

The assignment of a measured half-life to a certain isotope was based on mass identification of the isobaric decay chain and on the systematics of the half-lives which show a monotonous decrease with mass as discussed below.

V. DISCUSSION

Figures 4 and 5 show the half-lives of isotopes of Rb, Sr, Y, and Cs, Ba, La, respectively, as a function of mass on a semilog scale. The experimental half-lives are plotted on the left-hand side and the half-lives calculated from theory are on the right. The theoretical values were calculated within the framework of the gross theory of β decay by Takahashi *et al.*[11] using a modified Lorentzian form for the single particle strength function and with Q values taken from Myers and Swiatecki.[16]

The experimentally determined half-lives of the higher isotopes of a certain element exhibit a regularity which is characterized by the nearly exponential decline with mass, with slopes which are nearly equal for neighboring elements. In addition, a small odd-even effect is apparent as a saw-tooth structure. These features are also apparent in the theoretical values, but with two major differences. First, the experimental values decline more steeply with mass than the theoretical ones, and for the higher masses the ratio of experimental to theoretical values is as high as ~5; second, the odd-even effect is less prominent in the experimental values. It should be noted,

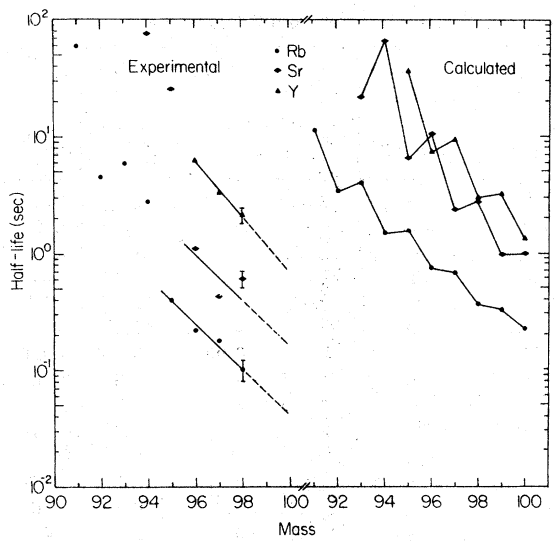

FIG. 4. Comparison of the systematic behavior of experimentally determined half-lives of neutron-rich isotopes of Rb, Sr, and Y with calculated half-lives of Takahashi *et al.* (Ref. 11). The solid lines of the experimental curves represent a least-squares fit of the data and the broken lines are extrapolations.

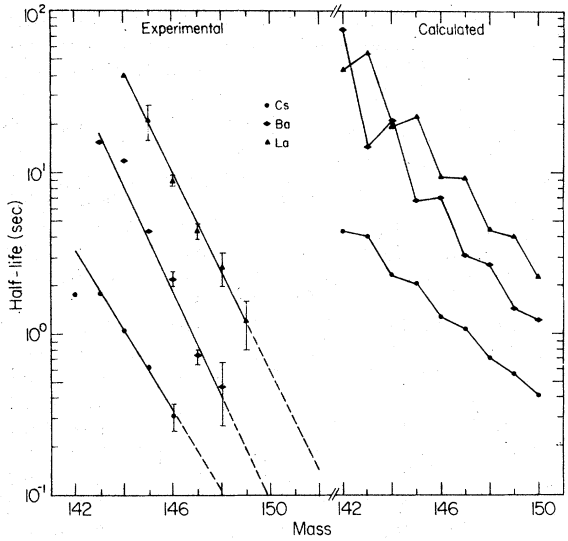

FIG. 5. Comparison of the systematic behavior of experimentally determined half-lives of neutron-rich isotopes of Cs, Ba, and La with calculated half-lives of Takahashi *et al.* (Ref. 11). The solid lines of the experimental curves represent a least-squares fit of the data and the broken lines are extrapolations.

however, that the odd-even structure in the theoretical values washes out considerably for the higher masses. Thus, even though the theory does not predict the experimental half-lives, there is a striking similarity in the systematic features between experimental and theoretical values with regard to the slope and smoothness for the higher masses, as may be seen from Figs. 4 and 5.

The smooth behavior of the experimentally determined half-lives for the higher masses permits the prediction of half-lives not yet measured. This is done for a certain isotope by extrapolating the measured half-lives of the neighboring isotopes of the same element. The solid lines in Figs. 4 and 5 represent a least-squares fit of the experimental points of the higher masses and the broken lines are the extrapolated portions. As may be seen in Fig. 5, the heavy elements present a smooth behavior and the extrapolation is rather straightforward. For the light elements Rb and Sr (Fig. 4), this is not the case. An abrupt change in the half-lives occurs near $N=58$ (^{95}Rb and ^{96}Sr) which may be due to a neutron shell effect.[4] Therefore, the lines for Rb and Sr were fitted to the experimental values beginning with ^{95}Rb and ^{96}Sr.

Half-lives of several isotopes predicted by the extrapolation method, which were used for determination of fission yields,[15] are given in Table II. Also cited are results of available measured half-lives. They seem to be in good agreement with the predicted values.

TABLE II. Predicted half-lives of neutron-rich Rb, Sr, Y, Cs, and Ba nuclides compared with measured half-lives.

Mass	Element	Half-life (*s*) Predicted	Measured	Mass	Element	Half-life (*s*) Predicted	Measured
99	Rb	0.066	0.059 ± 0.004 [a]	147	Cs	0.19	0.218 ± 0.009 [c]
	Sr	0.25	0.25 ± 0.04 [a]	148	Cs	0.11	•••
	Y	1.2	1.45 ± 0.22 [b]	149	Ba	0.20	•••
100	Rb	0.043	0.046 ± 0.015 [a]				
	Sr	0.26	0.15 ± 0.04 [a]				
	Y	0.68	•••				

[a] Reference 17.
[b] Reference 18.
[c] Reference 4.

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