Delayed-neutron activities produced in fission: Mass range 79–98

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A sensitive neutron counter has been used for a study of delayed-neutron emission from mass-separated fission products. Five new delayed-neutron precursors, ^{79}(Zn,Ga), ^{80}Ga, ^{81}Ga, ^{82}Ga, and ^{83}Ga, have been found, and the half-life determination for seven other precursors has been improved.

[RADIOACTIVITY $^{79-83}$Ga, ^{85}As, $^{87-92}$Br, ^{93}Kr, $^{92-98}$Rb; measured delayed neutrons; deduced half-lives.]

I. INTRODUCTION

The OSIRIS facility[1] has proved to be a very efficient instrument for the production of short-lived fission products. A survey of the activities obtained[2] contains half-life data for 113 fission products with half-life in the range 0.1 s–10 min. Some of these determinations were performed using delayed-neutron counting.

An extensive program involving measurements of the spectra of delayed neutrons has also been completed.[3-5] Spectra have been measured for 24 neutron emitters. The program did not involve half-life determinations, however, and some of the neutron precursors remained unidentified. The present work is a complementary study where the half-lives of delayed-neutron precursors have been determined with great accuracy using a sensitive neutron counter. Thus, all activities earlier studied spectroscopically have been examined. In addition, several new delayed-neutron activities have been detected, and statistical significance tests at mass numbers with very weak neutron emission have been performed.

II. EXPERIMENTAL

A. Sample collection

The OSIRIS isotope separator has been described in detail elsewhere.[1] In the present work two different targets have been used, containing 1.48 g and 2.36 g of ^{235}U, respectively, and prepared as described in Ref. 6. They were exposed to a neutron flux of about 2×10^{11} $n/\mathrm{cm}^2\,\mathrm{s}$ (corresponding to 500 kW of power of the reactor R2-0 at Studsvik).

The principle of the experimental arrangement is shown in Fig. 1. The spectrometer is placed at a beam extracted from the main collector chamber. The extraction system contains an electrostatic lens to refocus the beam at a distance of 80 cm from the collimator. There it impinges upon a movable aluminized mylar tape which is used for removing long-lived daughters from the detector position in repeated multiscaling studies.

The desired mass is selected by a collimator with circular openings variable from 1 to 8 mm (diam). Usually, a collimator opening of 4 mm was chosen, giving a very low degree of contamination from nearby masses. A contamination test has been carried out by comparing the neutron intensity at masses 86 and 87. The nuclide ^{87}Br is a neutron precursor which gave 3560 n/s immediately after a collection time of 60 s. At mass 86 no delayed neutrons are expected in our case because of the low separator efficiency for arsenic and selenium.[6] The neutron intensity at this mass, collected and measured at exactly the same conditions as mass 87, was 12 n/s above the background. Thus the contamination in this mass region is less than 0.4%.

A shutter in front of the collimator allows an accurate timing of the sample collection. The closing and opening time of the shutter was found to be about 15 ms.

B. Neutron counter

The neutron counter for half-life determinations consists of 30 ^{3}He detectors. They are filled with a mixture of ^{3}He and krypton of partial pressures 6 atm and 3 atm, respectively. The tubes are imbedded in paraffin and surrounded by a neutron shield consisting of a sheet of cadmium, a container filled with boric acid and blocks of borated paraffin. The counter is also shielded from the activities in the collector chamber by a layer of lead bricks.

The ^{3}He detectors are coupled in parallel and all kept at the same high tension (1910 V) by means of a common power supply. Because of different internal resistences of the individual detectors this arrangement does not give optimal resolution. This is not serious for the present measurements, however. The detectors are connected to a charge-sensitive preamplifier from which the pulses are fed into a linear amplifier and shaped to be ac-

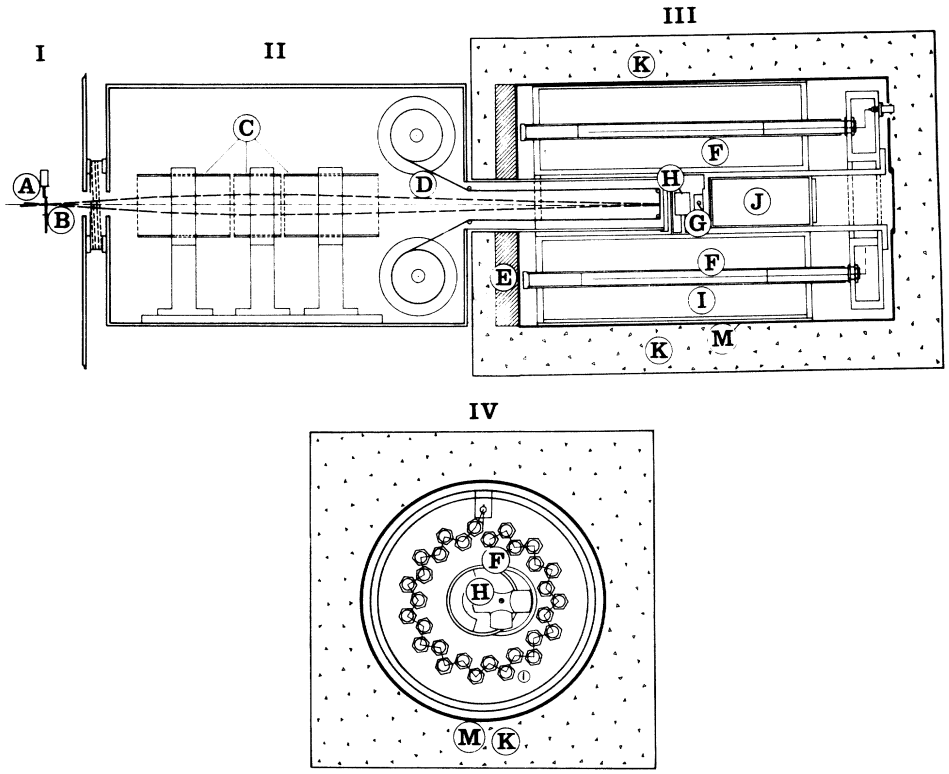

FIG. 1. Experimental arrangement seen from the side (I, II, III) and the back (IV). I: collector chamber; (A) shutter, (B) wheel with different openings for the beam. II: electrostatic lens system; (C) lens elements, (D) ion beam. III and IV: neutron detector; (E) lead shielding, (F) neutron counters, (G) β detector (foreseen for P_n studies), (H) β filter (foreseen for P_n studies), (I) paraffin, (J) exchangeable plug (paraffin or heavy water), (K) boric acid, (M) cadmium sheet.

cepted by a multichannel analyzer.

The efficiency of detecting neutrons is about 13%.

C. Neutron multiscaling

In all runs the pulse spectrum was first checked, and a discriminator level high enough to completely remove the γ effect was set. This may result in removing some of the true neutron pulses also, a negligible drawback in view of the strong samples normally obtained. The runs with short sampling times were carried out in an automatic mode with all phases controlled by a clock unit. First, the shutter was opened and kept open for a predetermined time (selectable from 0.5 to 5 s). The shutter was then closed, and the neutron counts were multiscaled by means of a 2048-channel analyzer. After finishing this cycle the Mylar tape was moved in order to remove all activities, and a new cycle was started. The procedure was recycled until enough statistics had built up.

In order to keep track of the photoneutron production by high energy γ rays interacting with the deuterium in the paraffin, runs were always carried out with a paraffin plug exchanged for a container with 370 g of heavy water. This means an increase of the deuterium content in the counter by a factor of 150. Any photoneutron production should then increase by a large factor. In no case were significant increases of the counting rates found when adding the heavy water. Consequently, it must be concluded that all neutron activities registered correspond to neutron emission in the sample and not to photoproduced neutrons.

The neutron background was usually low, varying from 80 to 200 cps depending on the running conditions (most of the background neutrons originate from activities in the collector chamber).

D. Dead-time correction

Although all counts are to be considered as true neutron counts, the γ effect must be taken into account when correcting for dead-time losses. The dead time is attributed to the ^{3}He tubes and not to the electronics, and thus the small γ pulses will also cause dead-time losses. Therefore, in all experi-

TABLE I. Experimental results on delayed-neutron precursors.

Mass number	Element assignment	Collection time (s)	Half-life (s) Experimental values, this work	Average value, this work	From β decay [a]	From literature
79	Zn, Ga	4	2.65 ± 0.05			
		4	2.81 ± 0.14			
		0.5	2.26 ± 0.17	2.63 ± 0.09	3.00 ± 0.09	
80	Ga	2	1.66 ± 0.01			
		0.5	1.63 ± 0.06	1.66 ± 0.02	1.7 ± 0.2	
81	Ga	4	1.228 ± 0.005	1.23 ± 0.01		1.2 ± 0.2 [b]
82	Ga	1	0.599 ± 0.009	0.60 ± 0.01		
83	Ga	1	0.321 ± 0.015			
		3	0.299 ± 0.017	0.31 ± 0.01		
85	As	4	2.08 ± 0.05	2.08 ± 0.05		2.028 ± 0.012 [c]
						2.05 ± 0.05 [d]
87	Br	60	55.5 ± 0.1	55.5 ± 0.3	56.3 ± 0.5	55.67 ± 0.11 [e]
88	Br	20	16.9 ± 0.1			15.5 ± 0.3 [f]
			16.55 ± 0.07	16.7 ± 0.2	16.5 ± 0.5	15.5 ± 0.4 [g]
						15.9 ± 0.1 [h]
89	Br	5	4.41 ± 0.01			
		5	4.347 ± 0.008			4.4 ± 0.5 [i]
		5	4.31 ± 0.02	4.37 ± 0.03	4.55 ± 0.10	4.5 ± 0.4 [h]
90	Br	3	2.06 ± 0.01			
		2	1.930 ± 0.006			1.6 ± 0.6 [i]
		2	1.944 ± 0.013	1.96 ± 0.05		1.63 ± 0.14 [k]
91	Br	1	0.544 ± 0.002			
		1	0.533 ± 0.003	0.541 ± 0.005		0.64 ± 0.08 [k]
92	Br	0.5	0.38 ± 0.05			
		1	0.365 ± 0.007	0.365 ± 0.007		0.25 ± 0.10 [k]
92	Rb	1	4.26 ± 0.18			4.43 ± 0.05 [l]
		1	4.35 ± 0.06 [m]	4.34 ± 0.06	4.50 ± 0.04	4.50 ± 0.03 [n]
						4.48 ± 0.02 [o]
93	Kr	5	1.52 ± 0.23			
		4	1.37 ± 0.22			
		1	1.39 ± 0.07			1.289 ± 0.012 [n]
		1	1.25 ± 0.07	1.33 ± 0.05		1.30 ± 0.01 [o]
93	Rb	5	5.86 ± 0.03			5.89 ± 0.04 [l]
		4	5.82 ± 0.04			5.86 ± 0.13 [n]
		4	5.85 ± 0.05	5.85 ± 0.03	5.80 ± 0.05	6.18 ± 0.06 [o]
						5.8 ± 0.1 [p]
94	Rb	4	2.681 ± 0.006			2.67 ± 0.04 [l]
		4	2.705 ± 0.008	2.69 ± 0.02	2.78 ± 0.05	2.8 ± 0.1 [p]
						2.76 ± 0.08 [j]
95	Rb	1	0.400 ± 0.002	0.400 ± 0.004		0.36 ± 0.02 [l]
						0.3832 ± 0.0060 [j]
96	Rb	1	0.199 ± 0.002			0.23 ± 0.02 [l]
		1	0.204 ± 0.001	0.203 ± 0.003		0.207 ± 0.003 [q]
						0.1990 ± 0.0035 [j]

TABLE I *(Continued)*

Mass number	Element assignment	Collection time (s)	Half-life (s) Experimental values, this work	Average value, this work	From β decay [a]	From literature
97	Rb	1	0.172 ± 0.003	0.172 ± 0.003		0.135 ± 0.010 [l] 0.176 ± 0.005 [q] 0.1722 ± 0.0050 [j]
98	Rb	1	0.141 ± 0.010	0.14 ± 0.01		0.136 ± 0.008 [q] 0.1061 ± 0.0056 [j]

[a] Reference 2.
[b] Reference 14.
[c] Reference 16.
[d] Reference 17.
[e] Reference 18.
[f] Reference 19.
[g] Reference 20.
[h] Reference 21.
[i] Reference 30.
[j] Reference 29.
[k] Reference 22.
[l] Reference 23.
[m] From experiments enhancing Rb.
[n] Reference 24.
[o] Reference 25.
[p] Reference 27.
[q] Reference 28.

ments certain runs were carried out with the discriminator set just above the noise level. Both γ rays and neutrons are then recorded, and the pulse rate can be used for calculating the dead-time correction.

The dead time of the counter arrangement was determined by multiscaling two samples of mass 137 (with low discriminator setting) obtained under identical conditions except for the reactor power which was 10 times higher in one run as compared to the other. The strength of the sample in the different channels in the high-power run was assumed to be proportional to the intensity obtained in the corresponding channels in the low-power run, and the dead time was determined as described in Ref. 7. This first approximation of the dead time was used to correct the counting rates in the different channels of the low-power run, and the dead time was again determined assuming the high-power strengths to be proportional to the corrected low-power counting rates. After a few iterations the dead time did not change significantly. A value of 5.0 μs was obtained for the arrangement.

E. Half-life determination

The multiscale data were punched on paper tape and then analyzed by means of the computer code HALFLIFE.[2] This code was first modified so as to compute dead-time corrections from a second decay curve read in after the proper neutron decay curve. As described in Sec. II D, this second curve should be taken with low discriminator setting. All decay curves shown in Sec. III have been corrected for dead-time losses.

At several mass numbers there are more than one neutron precursors among the isobars. In such cases the runs were carried out with different timing in order to enhance one or the other of the components. It may still occur that the parent activity does not show up in the complex decay curve. It is easily verified (see Appendix) that

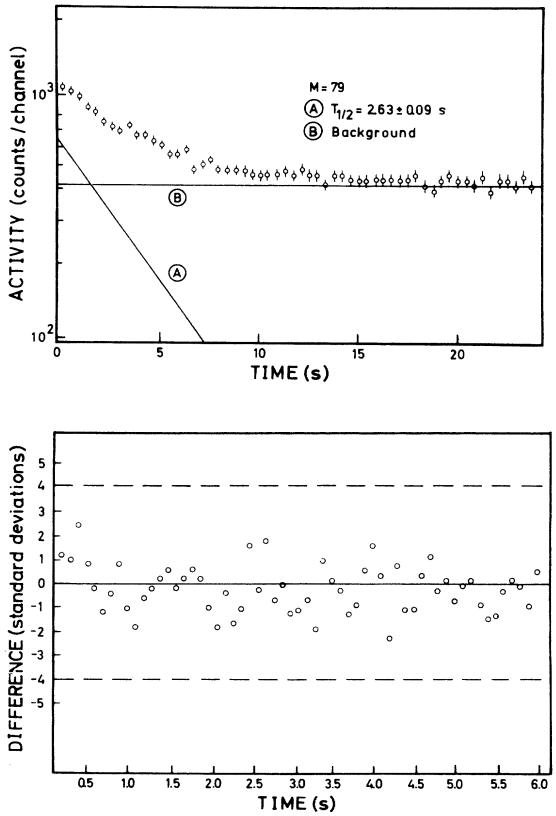

FIG. 2. Decay curve of mass 79, the lower part showing the difference between measured and calculated activities under the assumption of only one component.

TABLE II. Relative "neutron window" estimated from various mass formulas.

Nuclide	$(Q_\beta - B_n)/Q_\beta$ Garvey *et al.* [a]	Myers and Swiatecki [b]	Seeger [c]	Zeldes [d]	Wapstra and Gove [e]
^{74}Zn	−1.67	−3.04	−2.78	−1.57	
^{75}Zn	−0.48	−0.76	−0.73	−0.38	
^{76}Zn	−0.55	−0.80	−0.72	−0.33	
^{77}Zn	−0.08	−0.23	−0.22	−0.04	
^{78}Zn	−0.02	−0.09	−0.10	0.07	
^{78}Ga	−0.09	−0.13	−0.16	−0.04	
^{79}Zn	0.12	0.07	0.09		
^{79}Ga	0.07	0.02	−0.03	0.17	
^{79}Ge	−1.37	−1.35	−1.32	−0.91	
^{80}Zn	0.46	0.26	0.19		
^{80}Ga	0.11	0.13	0.09	0.14	
^{80}Ge	−1.86	−1.85	−1.83	−1.37	
^{81}Zn	0.39	0.41	0.34		
^{81}Ga	0.32	0.29	0.20	0.35	
^{81}Ge	−0.82	−0.57	−0.60	−0.39	
^{82}Zn	0.72	0.84	0.72		
^{82}Ga	0.34	0.42	0.34	0.37	
^{82}Ge	−0.69	−0.53	−0.74	−0.42	
^{83}Zn	0.67	0.68	0.61		
^{83}Ga	0.72	0.77	0.70		
^{83}Ge	0.05	0.13	−0.03	0.08	
^{85}Ge	0.50	0.50	0.22	0.50	
^{85}As	0.55	0.58	0.48	0.51	
^{87}Se	0.12	0.23	0.07	0.20	
^{87}Br	0.18	0.24	0.04	0.18	0.15
^{88}Se	0.24	0.43	0.28	0.30	
^{88}Br	0.20	0.26	0.11	0.22	
^{89}Br	0.35	0.43	0.30	0.40	
^{90}Br	0.41	0.37	0.33	0.37	
^{90}Kr	−0.23	−0.23	−0.46	−0.33	−0.30
^{90}Rb	−0.19	−0.16	−0.31	−0.21	−0.18
^{91}Br	0.50	0.52	0.50	0.55	
^{91}Kr	−0.05	−0.04	−0.07	0.01	−0.03
^{91}Rb	−0.07	−0.06	−0.18	−0.04	−0.04
^{92}Br	0.48	0.46	0.46	0.48	
^{92}Kr	0.06	0.09	0.08	0.09	
^{92}Rb	0.05	0.03	0.04	0.06	0.08
^{93}Br	0.77	0.62	0.67	0.46	
^{93}Kr	0.23	0.17	0.21	0.23	
^{93}Rb	0.23	0.16	0.19	0.27	0.26
^{94}Kr	0.37	0.35	0.43	0.35	
^{94}Rb	0.23	0.21	0.26	0.25	
^{95}Kr	0.34	0.34	0.37	0.38	
^{95}Rb	0.42	0.37	0.48	0.44	
^{96}Rb	0.38	0.36	0.38	0.38	
^{97}Rb	0.56	0.52	0.54	0.58	
^{97}Sr	0.04	−0.03	−0.01	0.07	
^{98}Rb	0.49	0.47	0.50	0.48	
^{98}Sr	0.13	0.14	0.15	0.18	

[a] Reference 9.
[b] Reference 10.
[c] Reference 11.
[d] Reference 12.
[e] Reference 13.

this will happen for the following relation between half-lives and neutron branching ratios (P_n values). Component 1 is then assumed to decay with a half-life T_1 and a P_n value P_{n1} to the β decay daughter 2 with half-life T_2 and P_n value P_{n2}. No component with half-life T_1 is seen in the decay curve

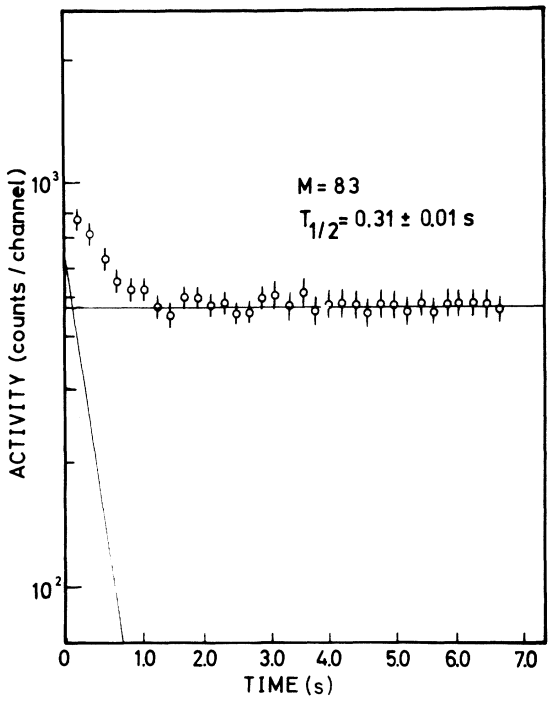

FIG. 3. Decay curve of ^{83}Ga.

if the following relation is fulfilled:

$$\frac{P_{n1}}{(1-P_{n1})P_{n2}} = \frac{T_1}{T_2 - T_1} . \quad (1)$$

III. EXPERIMENTAL RESULTS

The experimental data are collected in Table I, the average weighted mean values evaluated from half-life data obtained with different collection times and different statistics. The collection time indicates which isobar has been favored in cases with several isobaric neutron precursors.

Use has been made of the relative "neutron window" $(Q_\beta - B_n)/Q_\beta$ (Q_β = total β disintegration energy; B_n = neutron separation energy) evaluated from four current mass formulas[9-12] and from the 1971 Mass Table[13] for the interpretation of the experimental results (Table II).

The errors given for the individual determinations are standard deviations as calculated by the HALFLIFE program. The errors (standard deviations) of the weighted mean values are based on the reproducibility of several determinations with due regard to the internal consistencies. When the internal and external consistencies have indicated an error below 0.5%, this error has somewhat arbitrarily been increased to about 0.5%.

Results obtained with D_2O present in the detector arrangement have not been included in the calculation of the average values. They generally agree well with the half-lives obtained without the heavy water.

Some typical decay curves are shown in Figs. 2–6. The decay has normally been followed longer than indicated in the figures. The errors (± one standard deviation) are shown unless they are smaller than the size of the circles. It should be noted that only part of the measured points has been plotted.

A. Mass number 79

According to various mass formulas ^{79}Zn should be a delayed-neutron precursor. As for ^{79}Ga, three of the mass formulas in Table II predict it to be a precursor. In the present work only one neutron activity has been found. The half-life obtained, 2.63 ± 0.09 s, agrees fairly well with the value of 3.00 ± 0.09 s found at the same mass number using β counting.[2]

Experiments with a rapid chemical separation apparatus attached to the collector chamber of the isotope separator[8] have indicated the presence of a zinc activity at mass 79 (no half-life determination was carried out, however). A decay curve from the present work is shown in Fig. 2. In the lower part of the figure the differences (in units of standard deviation) between the measured points and the values calculated under the assumption of only one neutron activity are plotted. No systematic deviation of the measured points is seen. Furthermore, an experiment with very short collection time enhancing any short-lived component failed to yield more than one activity.

The experimental results can be explained by concluding that ^{79}Ga is not a precursor and that we see only ^{79}Zn. We cannot exclude the possibility that the half-life obtained is representative for ^{79}Ga, however, and that the half-life of ^{79}Zn happens to be such that the corresponding activity cannot be detected [i.e., relation (1) is nearly fulfilled]. Thus, the element assignment of the activity found must be left open.

B. Mass number 80

Table II shows that both ^{80}Zn and ^{80}Ga should be neutron precursors, but not ^{80}Ge. We have found only one activity with half-life 1.66 ± 0.02 s in agreement with the value 1.7 ± 0.2 s obtained at this laboratory by β counting.[2]

In this case the activity found can with reasonable confidence be assigned to gallium which, according to estimates based on fission yields and P_n values[3] should dominate over ^{80}Zn.

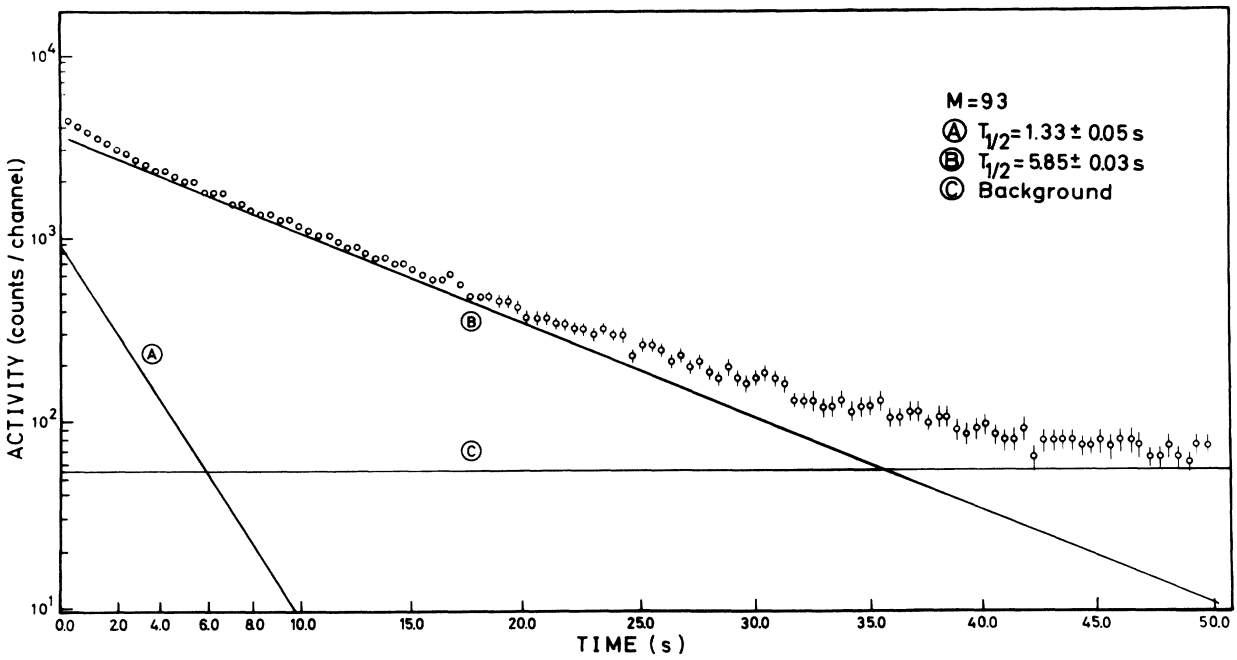

FIG. 4. Decay curve of mass number 93 showing ^{93}Kr and ^{93}Rb. The long-lived component has been determined in another experiment with suitable collection time and with the decay followed for more than 10 half-lives.

C. Mass number 81

The only neutron activity at this mass number can be assigned to gallium for the same reasons as in the case of mass 80. The half-life 1.23 ± 0.01 s agrees with the result 1.2 ± 0.2 s obtained by multiscaling γ rays of energy 217 keV.[14]

D. Mass number 82

One activity has been found, and again gallium seems to be the most probable element assignment. This is another new delayed-neutron precursor.

E. Mass number 83

In this case ^{83}Ga very likely is a delayed-neutron precursor (cf. Table II). For ^{83}Ge, on the other hand, the mass formulas disagree. We have found only one activity of half-life 0.31 ± 0.01 s. This activity can be assigned to gallium, as ^{83}Ge is reported to be a precursor with half-life 1.9 ± 0.4 s.[15] Gallium is much more efficiently separated at OSIRIS than germanium.[6] Consequently, ^{83}Ge should be formed mainly by decay of ^{83}Ga. If the P_n value of ^{83}Ge is very low such a daughter activity might have escaped detection. A decay of this new delayed-neutron precursor is shown in Fig. 3.

F. Mass number 85

The half-life 2.08 ± 0.05 s found at this mass number agrees well with the values 2.028 ± 0.012 s determined by Tomlinson and Hurdus[16] and 2.05 ± 0.05 s given by Kratz, Franz, and Herrmann.[17] In those articles the half-life is attributed to ^{85}As. The present work confirms the mass of this arsen-

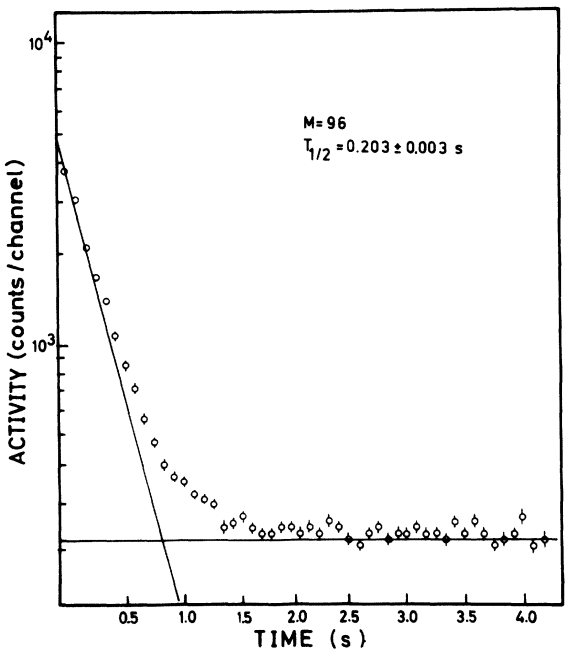

FIG. 5. Decay curve of ^{96}Rb.

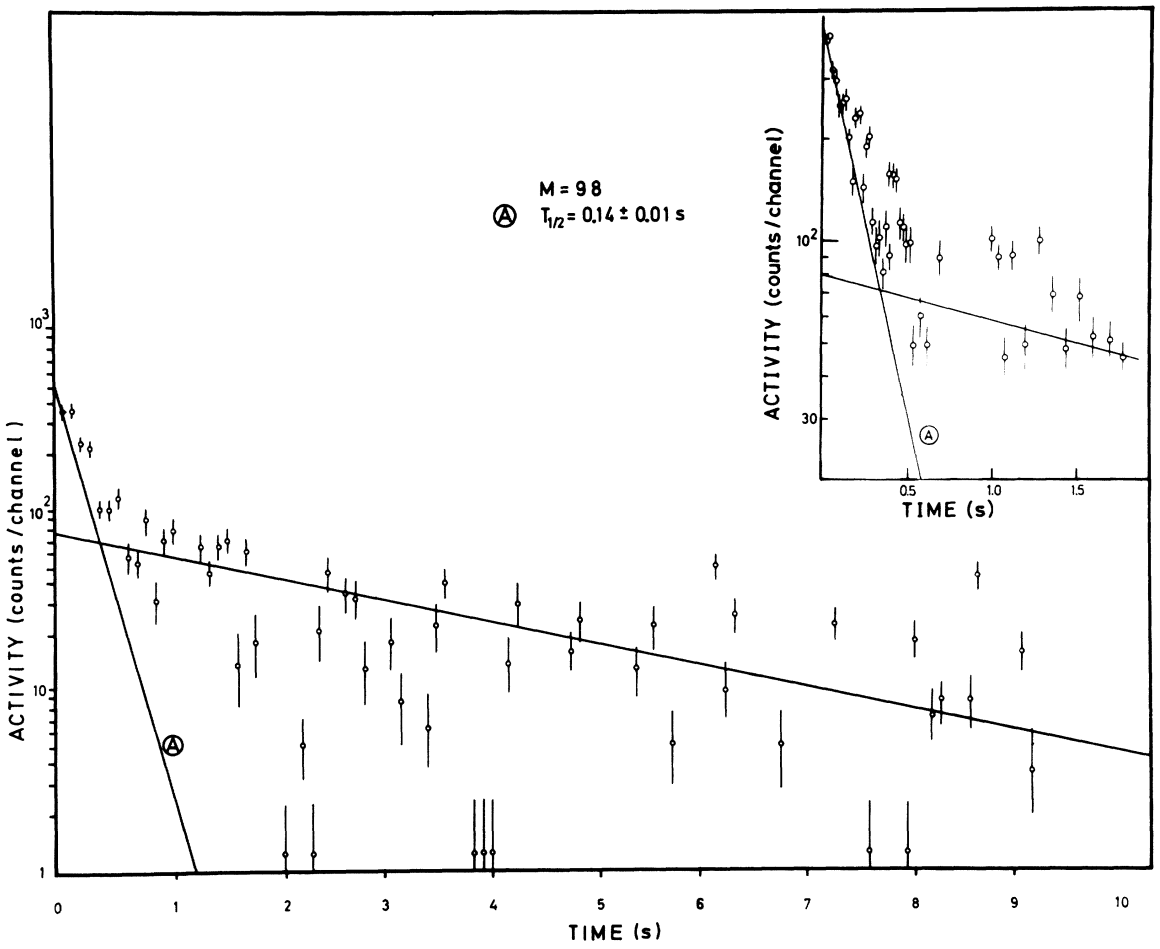

FIG. 6. Decay curve of ^{98}Rb. The background has been subtracted but trace of a weak long-lived activity is seen. The first part of the decay with all the measured points plotted is inserted.

ic isotope (the earlier experiments were not run with mass-separated samples).

G. Mass numbers 87, 88, and 89

At each of these mass numbers only one neutron activity has been found, and the half-lives correspond to the known bromine delayed-neutron precursors. No selenium activities have been seen,[18] apparently because the separator efficiency for selenium is known to be very low.[6]

The half-life of ^{87}Br agrees with earlier measurements.[18] That of ^{88}Br is significantly higher than a number of older measurements.[19-21] Since those measurements were done without mass separation and by resolving decay curves containing several bromine activities, we consider our new result to be the more accurate, however. Thus, the half-life of ^{88}Br should be 16.7 ± 0.2 s. Also, for ^{89}Br our half-life determination means a considerable improvement compared to earlier measurements.

H. Mass numbers 90 and 91

Herrmann *et al.*[22] have found the half-lives 1.63 ± 0.14 s and 0.64 ± 0.08 s for ^{90}Br and ^{91}Br, respectively. We obtain one activity at each of these mass numbers with half-lives accurately determined to be 1.96 ± 0.05 s at mass 90 and 0.541 ± 0.005 s at mass 91. The former result is at variance with that given in Ref. 22, while the latter agrees. In spite of the disagreement of mass 90 the element assignment should be bromine for both activities.

I. Mass number 92

Three isobars of mass 92 are known to be delayed-neutron precursors,[18] i.e., ^{92}Br, ^{92}Kr, and ^{92}Rb. In the present work a short-lived activity, presumably ^{92}Br, was found and, in addition, one component with half-life in between those of ^{92}Kr and ^{92}Rb, apparently a mixture of those precursors. No serious attempt was made to separate these two activities except for running the ion source of the isotope separator in a nonoscillating mode, thereby enhancing rubidium. The half-life then obtained was 4.34 ± 0.06 s, in fair agreement with various published values for ^{92}Rb. For ^{92}Br an accurate half-life determination of 0.365 ± 0.007 s was obtained to be compared to the value 0.25 ± 0.10 s reported for this precursor.[22]

J. Mass number 93

Two activities with half-lives 1.33 ± 0.05 s and 5.85 ± 0.03 s have been found. The half-lives agree well with published results for ^{93}Kr and ^{93}Rb.[23-27] A decay curve is given in Fig. 4.

K. Mass numbers 94, 95, and 96

At each of these mass numbers we have found only one activity. The half-lives are, 2.69 ± 0.02 s for mass 94, 0.400 ± 0.004 s for mass 95, and 0.203 ± 0.003 s for mass 96, all of which agree well with half-lives reported for rubidium isotopes.[23,27-29] The nuclide ^{94}Kr is known to be a neutron precursor.[28] It has not been found in the present work, obviously because the ^{94}Rb activity would completely dominate (cf. estimates in Ref. 3). A decay curve of mass 96 is given in Fig. 5.

L. Mass numbers 97 and 98

According to Table II ^{97}Rb should be a precursor whereas ^{97}Sr is more doubtful. We have found only one activity at this mass. The half-life 0.172 ± 0.003 s is in agreement with the recent determinations 0.176 ± 0.005 s[28] and 0.1722 ± 0.0050 s.[29]

At mass 98 both rubidium and strontium are predicted to be delayed-neutron precursors (Table II). We find one component of half-life 0.141 ± 0.010 s and traces of a more long-lived one. The half-life agrees with the value 0.136 ± 0.008 s given in Ref. 28 but disagrees with the more recent value 0.1061 ± 0.0056 s of Ref. 29. A decay curve of mass 98 is shown in Fig. 6.

M. Mass numbers 74, 75, 76, 77, 78, 84, and 99

Multiscale results obtained for the above-mentioned mass numbers were analyzed in order to disclose any excess of neutrons in the first part of the experiment when compared to the last part. A weak positive effect was found for mass numbers 76 and 99, indicating the existence of delayed-neutron precursors at these masses.

IV. SUMMARY

The results of the present study might be summarized as follows. The nuclides ^{79}(Zn, Ga), ^{80}Ga, ^{81}Ga, ^{82}Ga, and ^{83}Ga have been found to be new delayed-neutron precursors. Accurate half-life values are given for these precursors. The mass assignment of the precursor ^{85}As has been confirmed. Improved half-life determinations have been given for ^{88}Br, ^{89}Br, ^{90}Br, ^{91}Br, ^{92}Br, ^{95}Rb, and ^{97}Rb.

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APPENDIX: CONDITION FOR DISAPPEARANCE OF THE COMPONENT OF PARENT HALF-LIFE IN DECAY CURVES OBTAINED BY NEUTRON COUNTING

We assume that the parent of decay constant λ_1 and neutron branching ration P_{n_1} decays by β decay to a daughter nuclide of decay constant λ_2 and neutron branching ration P_{n_2}. The number of atoms of the parent and the daughter are given by $N_1(t)$ and $N_2(t)$. These quantities are related by the equation system

$$\frac{dN_1}{dt} = -\lambda_1 N_1 \ ,$$
$$\frac{dN_2}{dt} = \lambda_1(1 - P_{n_1})N_1 - \lambda_2 N_2 \ . \tag{2}$$

The neutrons from the parent are detected with an efficiency η_1 and those from the daughter with an efficiency η_2. The resulting decay curve can then be expressed by the formula

$$D(t) = Ae^{-\lambda_1 t} + Be^{-\lambda_2 t} \ , \tag{3}$$

with

$$A = \eta_1 \lambda_1 N_1(0) + \frac{\eta_2 \lambda_2 (1 - P_{n_1}) \lambda_1 N_1(0)}{\lambda_2 - \lambda_1} \ ,$$

and

$$B = \eta_2\lambda_2 N_2(0) - \frac{\eta_2\lambda_2(1-P_{n_1})\lambda_1 N_1(0)}{\lambda_2 - \lambda_1} .$$

Only one component is seen if $A = 0$. The condition for this is found to be

$$\eta_1 = \frac{\eta_2\lambda_2(1-P_{n_1})}{\lambda_2 - \lambda_1} . \quad (4)$$

If we assume that the efficiency for detecting neutrons is proportional to the neutron branching ratios, Eq. (4) gives

$$\frac{P_{n_1}}{(1-P_{n_1})P_{n_2}} = \frac{\lambda_2}{\lambda_2 - \lambda_1} , \quad (5)$$

which is equivalent to relation (1) in the main article.

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