Half-lives of several states in neutron-rich nuclei from spontaneous fission of ^{252}Cf

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Half-lives ($T_{1/2}$) of several states which decay by delayed γ transitions were determined from time-gated triple γ coincidence method. We determined, for the first time, the half-life of $330.6+x$ state in ^{108}Tc and the half-life of $19/2^-$ state in ^{133}Te based on the new level schemes. Three half-lives of ^{99}Zr, ^{134}Te, and ^{137}Xe are consistent with the previously reported ones. These results indicate that this new method is useful for measuring the half-lives.

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Since the classification of delayed γ rays by Goldhaber and Sunyar [1], half-life ($T_{1/2}$) measurements of nuclear states have been a major source of information on nuclear deformations, shell structures, and validity of nuclear models. Previously, half-lives of several states in neutron-rich nuclei have been determined by single γ or γ-γ coincidence relations for the delayed γ transitions emitted from the isotopes produced in the fission of ^{235}U, ^{239}Pu, ^{248}Cm, and ^{252}Cf. Most of the previous results were obtained from the coincidence measurement between the γ transition and the fission fragment after fission. And some of them were obtained from the delayed time measurement of the γ transition following the β decay after fission.

Usually, more than 100 isotopes are produced in the fission of these heavy nuclei, with each isotope emitting many γ rays. With such complex spectra, it is very difficult to isolate a single γ ray peak. Coincidences from other transitions with energies essentially equal to that of the transition of interest can lead to significant errors in the half-life values. The triple coincidence method can reduce the error associated with complexity of the γ ray spectra in spontaneous fission. Because several new nuclei and many new levels in the known nuclei have been identified in the spontaneous fission (SF) of ^{252}Cf, the present time-gated triple γ coincidence method is very useful for the half-life measurements of nuclear states in neutron-rich nuclei. We applied this method, for the first time, to extract the half-lives of two states in ^{95,97}Sr [2]. Also, in the present work, five other cases, namely, ^{99}Zr, ^{133,134}Te, ^{137}Xe, and ^{108}Tc are investigated. Recently, the new level schemes of ^{133}Te [3,4] and ^{108}Tc [5] have been reported from the SF work of ^{252}Cf. Based on these new level schemes, the half-lives of 1610.4 keV state in ^{133}Te [3] and $330.6+x$ keV state in ^{108}Tc [5] are reported in the present work. Previously, half-lives of the delayed 125.5 keV [6,7] and 154.0 keV [7] γ rays were measured without knowing the mass number and level schemes. In the present work, we tentatively assigned the previously measured half-lives of the delayed 125.5 keV and 154.0 keV γ rays to the states in ^{133}Te and ^{108}Tc, respectively, for comparison with the present half-lives.

The γ-γ-γ coincidence measurements were done by using the Gammasphere facility with 72 Ge detectors and a ^{252}Cf SF source of strength $\sim$28 μCi at LBNL [5]. Several γ-γ-γ coincidence cubes with different time windows t_w [2] were built for the three-fold and higher-fold data by using the Radware format [8]. That is, a time-gated cube will contain all triple-coincidence events for which all these time differences are less than the specified time value.

Let us consider a downward cascade consisting of γ_3-γ_2-γ_1-γ_0 transitions, where γ_0 is the outgoing transition from a state with long half-life and γ_1 is the incoming transition into the same state. Other higher states in this cascade are assumed to have very short lifetimes. We set a double gate on E_{γ_3} and E_{γ_1} and compare the intensities of transitions, γ_0 and γ_2, $N(\gamma_0)$ and $N(\gamma_2)$ in the spectra. In the present work, γ_1, γ_2, and γ_3, are in prompt coincidence. Therefore, the delay-time between γ_1 and γ_3 will be negligible. Since γ_0 is the ending transition in this cascade, the coincidence time window (t_w) limits the TDC time difference t_{10} between the γ_1 and γ_0 transitions, and the intensity $N(\gamma_0)$ observed from the state with the long lifetime. The $N(\gamma_0)$ intensity determines the fraction of $N(\gamma_2)$ intensity observed from the state with the long half-life with decay constant λ. Therefore, $N(\gamma_0)/N(\gamma_2)=C(1-e^{-\lambda t_w})$ can be applied in this case, where C is a constant.

In Fig. 1, the partial level scheme of ^{133}Te [3] is shown. In this level scheme, we set the double gate on the 933.4 and 721.1 keV transitions to extract the half-life of the

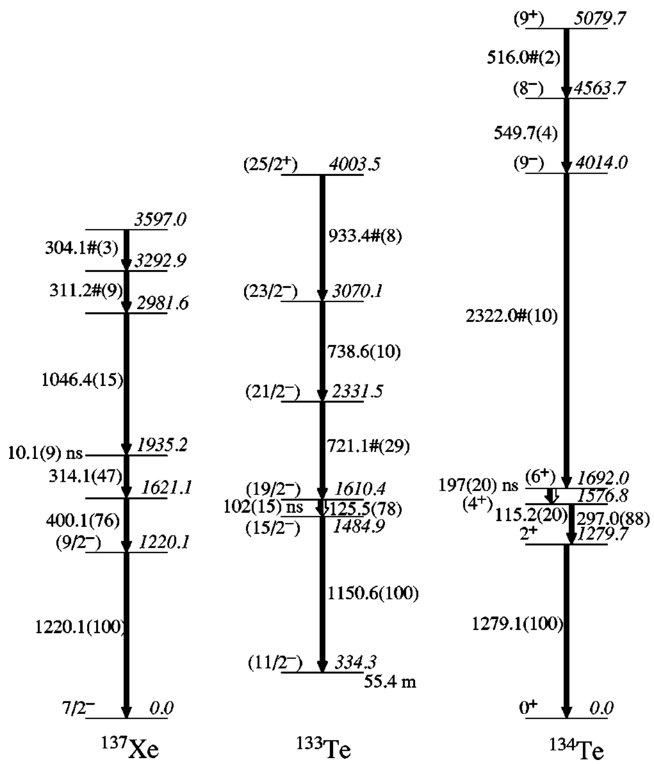

FIG. 1. Partial level schemes of ^{137}Xe [9,10], ^{133}Te [3,4], and ^{134}Te [11,12]. ♯ denotes the double gated transitions to extract the half-life. Average half-life of 102(15) ns is shown for ^{133}Te. Relative intensities of gamma rays are given in parentheses.

1610.4 keV state. In Fig. 2, coincidence spectra with double gates set on the 721.1- and 933.4-keV transitions in ^{133}Te [3] are shown. In Table I, count ratios of $R_1=N(125.5)/N(738.6)$, $R_2=N(1150.6)/N(738.6)$, and $R_3=N(1150.6)/N(125.5)$ in ^{133}Te are shown. Here, $N(E\gamma)$ means the γ ray peak area without the efficiency and internal conversion electron correction since these constant factors are included in the constant coefficient C in the fitting formula. As expected, $N(1150.6)/N(125.5)$ are nearly constant for 48, 72, 100, 300, and 500 ns time windows. This implies that the 1484.9 keV state has a negligibly small half-life. Therefore, we can use both ratios, $N(125.5)/N(738.6)$ and $N(1150.6)/N(738.6)$ to extract the half-life of 1610.4 keV

TABLE I. Count ratios of $R_1=N(125.5)/N(738.6)$, $R_2=N(1150.6)/N(738.6)$, and $R_3=N(1150.6)/N(125.5)$ in ^{133}Te.

t_w (ns)	R_1	R_2	R_3
48	0.221(7)	0.249(8)	1.02(3)
72	0.284(9)	0.304(1)	1.04(3)
100	0.333(10)	0.373(12)	1.12(3)
300	0.641(19)	0.664(22)	1.07(3)
500	0.729(22)	0.745(25)	1.13(3)

state in ^{133}Te. In Fig. 3, $N(1150.6)/N(738.6)$ versus coincidence time window (t_w) for ^{133}Te is plotted. The measured half-life value ($T_{1/2}$) is 107(14) ns from the ratios of $N(125.5)/N(738.6)$ and 97(7) ns from the ratios of $N(1150.6)/N(738.6)$. The average value of 107(14) and 97(7) ns is 102(15) ns. Actually, the new level scheme of ^{133}Te was published [3], recently. Previously, the delayed 125.5 keV ray was observed without identifying the mass number in the fission. Because the present half-lives of 107(14) and 97(7) ns are consistent with the previous half-lives of 115[6] ns and 81.6(14) ns [7] [the delayed 125.5 keV transition time measurement from the ^{252}Cf(SF) [6] and the ^{235}U(n,f) and ^{239}Pu(n,f) neutron induced fissions [7]], the previously measured delayed 125.5 transition is thought to belong to ^{133}Te. The time difference between the delayed γ-ray and its fission fragment was measured for the half-life determination with time delay method in these previous experiments. The long half-life of the $19/2^-$ state is explained by the difference in configuration between the $19/2^-$ $[\pi(1g_{7/2})^2\nu(1h_{11/2})^{-1}]$ and $21/2^-$ $[\pi(1g_{7/2})(2d_{5/2})\nu(1h_{11/2})^{-1}]$ states as predicted in terms of the shell model calculations [3].

For ^{134}Te, we set the double gate on the 2322.0 and 516.0 keV transitions above the 1692.0 keV isomeric state with the coincidence time windows of 72, 100, 300, and 500 ns. The partial level scheme of ^{134}Te [11,12] is shown in Fig. 1. By comparing the 549.7 and 115.2 keV transition intensities, we obtained the half-life of 197(20) ns. The half-life of 175(6) ns was determined from the time measurement of the delayed 115.2 keV transition emitted from the ^{235}U(n,f) and ^{239}Pu(n,f) neutron induced fissions [6]. The

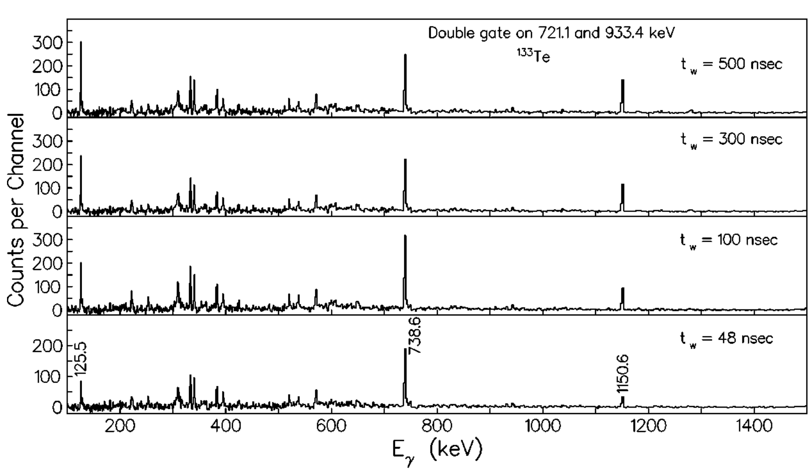

FIG. 2. Coincidence spectra with double gates set on 721.1- and 933.4-keV transitions in ^{133}Te with coincidence time windows (t_w) of 48, 100, 300, and 500 ns. See figures of Ref. [2] for ^{95,97}Sr.

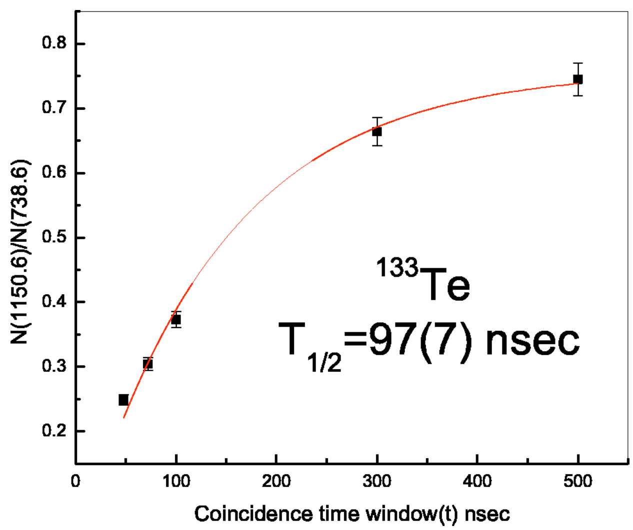

FIG. 3. (Color online) $N(1150.6)/N(738.6)$ vs coincidence time window (t_w) plot for ^{133}Te. The fitted half-life $(T_{1/2})$ value (solid curve) is 97(7) ns. See figures of Ref. [2] for ^{95,97}Sr.

half-life of 196(7) ns was obtained from the 10.22 *s* ^{134}Sb β_- decay [13]. Also, another half-life value of 161(4) was reported from the time measurement of the delayed 115.2 keV transition emitted from ^{252}Cf(SF) [14]. Our present half-life value of 197(20) ns is consistent with one [196(7) ns] of them.

For ^{137}Xe, we double gated on the γ transitions of 311.3 and 304.1 keV to compare the 314.1 and 1046.4 keV transition intensities in the coincidence time windows (t_w) of t_w =20, 48, and 72 ns. The partial level scheme of ^{137}Xe [9,10] is shown in Fig. 1. The measured half-life of 1935.2 keV state is 10.1(9) ns which is consistent with the previous value of 8.1(4) [15] from the time measurement of delayed 314.1 keV transition in the ^{252}Cf (SF).

For ^{108}Tc, we double gated on the γ transitions of 123.4 keV and 341.6 keV to compare the 154.0 and 125.7 keV transition intensities with the coincidence time windows (t_w) of t_w=48, 100, 300, and 500 ns. The partial level scheme of ^{108}Tc [5] is shown in Fig. 4. Previously, the delayed 154.0 keV transition was observed without identifying the mass number in the fission. Because the present half-life of 94(10) ns is consistent with the previous value of 100(10) ns [6] obtained from the delayed 154.0 keV transition time measurement from the ^{252}Cf (SF), the previously measured delayed 125.5 transition is thought to belong to ^{108}Tc.

For ^{95}Sr, we double gated on the γ transitions of 682.4 and 678.6 keV to compare the 427.1 and 204.0 keV transition intensities in the coincidence time windows (t_w) of t_w =8, 20, 48, and 100 ns. The partial level scheme of ^{95}Sr [2,16] is shown in Fig. 4. The measured half-life of 556.1 keV state is 23.6(24) ns [2] which is consistent with the previously measured value of 24 ns for the delayed 204.0 keV transition time measurement from the ^{235}U(n,f) and ^{239}Pu(n,f) neutron induced fission studies [6], and 21[12] ns for the delayed 352.0 keV transition measured in the ^{252}Cf(SF) [7] and 21.8(11) ns for the delayed 352.0 keV transition measurement from the ^{235}U(n,f) and ^{239}Pu(n,f) neutron induced fission [16].

For ^{97}Sr, we double gated on the γ transitions of 239.6 and 272.5 keV to compare the 205.9 and 522.7 keV transition intensities with the coincidence time windows (t_w) of t_w=100, 300, and 500 ns. The partial level scheme of ^{97}Sr [2,17] is shown in Fig. 4. The measured half-life of 830.8 keV state is 265(27) ns [2] which is much less than the values of 382(11) ns [the delayed 522.7 keV transition measurement in the ^{235}U(n,f) and ^{239}Pu(n,f) neutron induced fission] [6] and 515(15) ns [the delayed 522.7 keV transition measurement from the ^{252}Cf(SF)] [17]. But recently, Pfeiffer (a co-author of Ref. [17]) corrected their value of 515(15) ns to 255(10) ns [2,20] because of calibration error in data analysis. This corrected half-life is consistent with our value.

For ^{99}Zr, we double gated on the γ transitions of 426.4 and 415.2 keV and compare the intensities of 142.5 and 130.2 keV transitions in the coincidence time windows (t_w) of t_w=100, 300, and 500 ns. The partial level scheme of ^{99}Zr [18,19] is shown in Fig. 4. The measured half-life of 252.0 keV state is 316(48) ns. The previous value of 375(11) ns (the delayed 130.4 keV transition measurement in ^{235}U(n,f) and ^{239}Pu(n,f) neutron induced fission) [6] and 294(10) ns from γ-γ coincidence measurement from the β^- decay ^{99}Y [18]. The measured half-lives are shown in Table

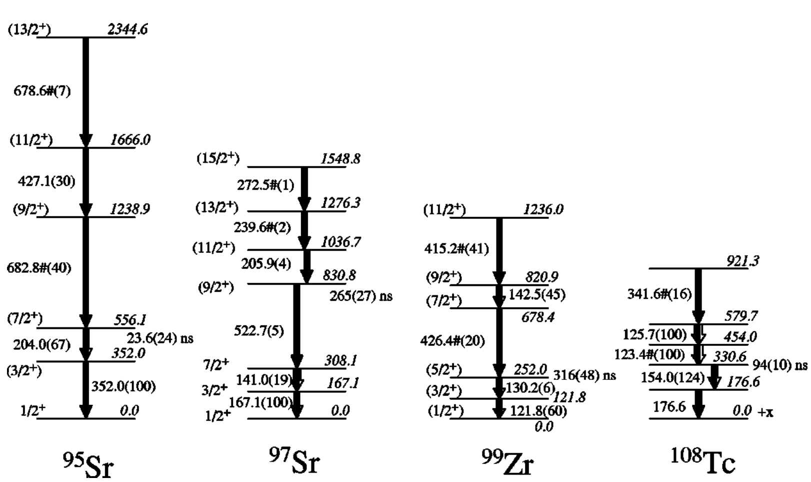

FIG. 4. Partial level schemes of ^{95}Sr [2,16], ^{97}Sr [2,17], ^{99}Zr [18,19], and ^{108}Tc [5]. "♯" denotes the double gated transitions to extract the half-life.

TABLE II. Half-lives ($T_{1/2}$ ns) of several states (E_{IS},keV). $E(\gamma_1)/E(\gamma_3)$ are the double-gated transition energies. For ^{97}Sr, $E(\gamma_2)/E(\gamma_3)$ and $E(\gamma_1)$ are used instead. Half-lives of delayed γ rays without the mass identification were reported to be 110 ns for 154.0 keV γ ray [7] and 115 ns [6] and 81.6(114) ns [7] for 125.5 keV γ ray. The half-life of the 1610.4 keV state in ^{133}Te is the average value extracted from 125.5 and 1150.6 delayed transitions.

Nuclei	E_{IS}	$E(\gamma_1)/E(\gamma_3)$	$E(\gamma_2)$	$E(\gamma_0)$	Present $T_{1/2}$	Reference's $T_{1/2}$	ENSDF [21]
^{95}Sr	556.1	682.4/678.6	427.1	204.0	23.6(24) [2]	24 [6], 21 [7], 21.8(11) [16]	21.7(5)
^{97}Sr	830.8	239.6/272.5	205.9	522.0	265(27) [2]	382(11) [6], 255(10) [20], 515(15) [17]	515(15)
^{99}Zr	252.0	426.4/415.2	142.5	130.2	316(48)	294(10) [18], 375(11) [6]	293(10)
^{108}Tc	330.6+x	123.4/341.6	125.7	154.0	94(10)		
^{133}Te	1610.4	721.1/933.4	738.6	125.5	102(15)		
^{134}Te	1692.0	2322.0/516.0	549.7	115.2	197(20)	161(4) [14], 196(7) [7], 175(6) [6]	164(1)
^{137}Xe	1935.2	311.3/304.1	1046.4	314.1	10.1(9)	8.1(4) [15]	8.1(4)

II. Also, in Table II, we show some previous measurements to give a sampling of the scatter of those values along with the ENSDF values [21].

In the present work, we report half-lives of five states in ^{99}Zr, ^{108}Tc, ^{133}Te, ^{134}Te, and ^{137}Xe by using the new time-gated triple coincidence method. Yields (% per SF; average value of A_p' and Z_p models) [22] for ^{95}Sr, ^{97}Sr, ^{99}Zr, ^{108}Tc, ^{133}Te, ^{134}Te, and ^{137}Xe, are 0.82, 0.48, 1.50, 3.74, 1.79, 1.96, and 2.39, respectively. We determined, for the first time, half-lives of ^{108}Tc and ^{133}Te based on the new level schemes. The half-lives of states in ^{99}Zr, ^{134}Te, and ^{137}Xe are compared with the previously reported ones. The measured half-lives are consistent with the previously reported ones. These results indicate that this new method is useful for the half-life measurements.

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