Investigation of the ^{244}Pu(^{48}Ca,xn)$^{292-x}$Fl reaction with the LBNL SHREC detector: Investigation of decay chains of isotopes of flerovium ($Z = 114$)

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The Supplemental Material provides detailed results and statistical assessments in the analysis of events stemming from decay chains starting with the isotope ^{287}Fl. This is used to aid assignment of chain 8 in the main article. Table I summarizes the information on correlated α-decay chains, which were observed in previous and the present experiment, and which were associated with decays of the even-odd ^{287}Fl. References are provided in the Table.

Decay properties such as decay energies and lifetimes, relating to various ensembles of data associated with previous experiments in the direct or indirect production of ^{287}Fl and with the present experiment (cf. Table I), are compiled: Distributions of decay energies and correlation times along with determined E_α and $T_{1/2}$ values are presented for the different ensembles illustrated in Figs. 1, 2, and 3.

Updates for corresponding analyses for decay chains associated with ^{288}Fl (see Supplemental Material of Ref. [1] for more details) and ^{289}Fl (see Supplemental Material of Ref. [2] for more details), including data from the present data set, are provided in Tables II and III, respectively.

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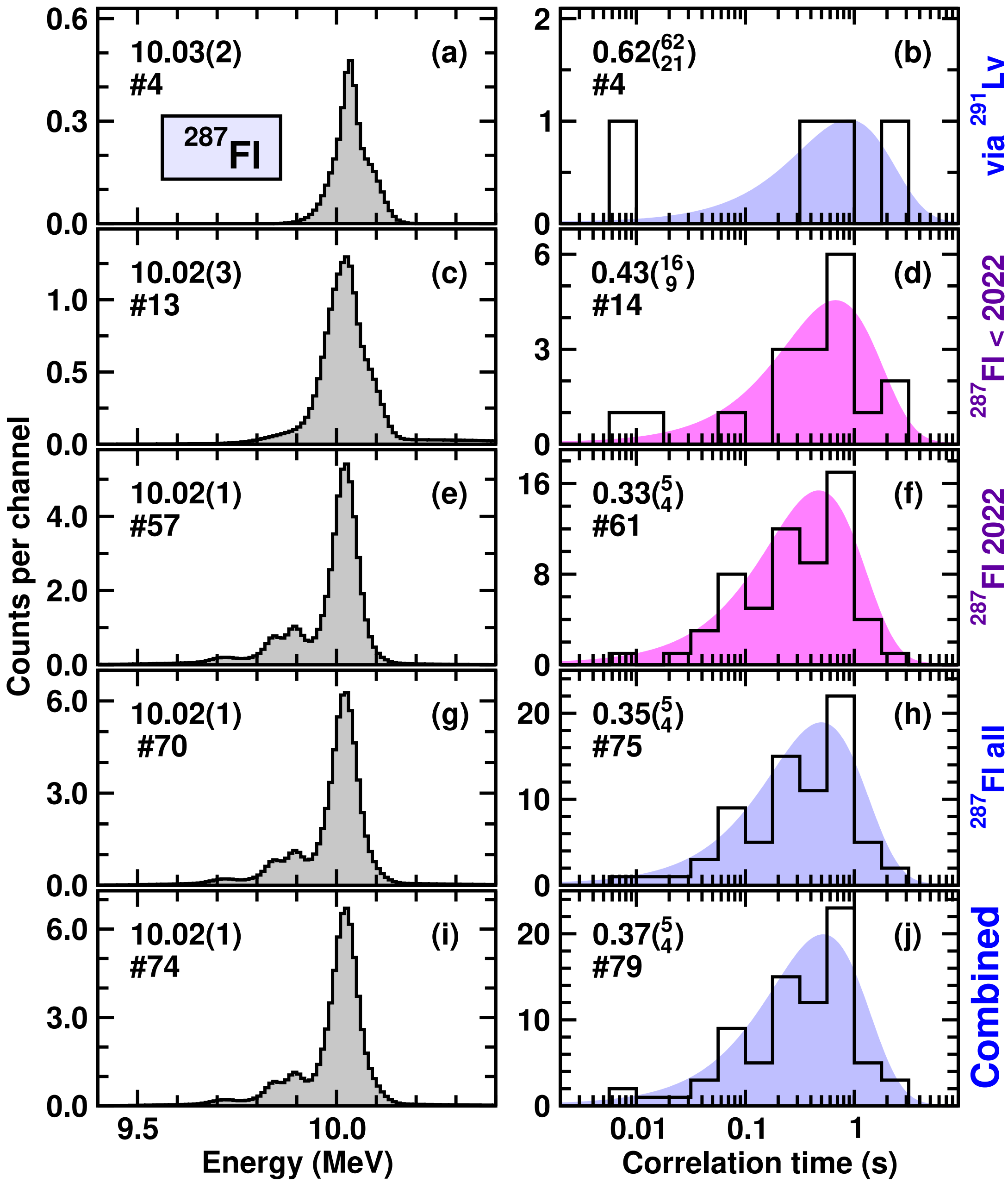

FIG. 1. (Color online) The left column provides experimental decay-energy spectra from events associated with the decay step ^{287}Fl$\rightarrow$ ^{283}Cn. For a single entry, a Gaussian with integral one and a width compliant with its measured uncertainty was added into the respective spectrum. The numbers at the top left of each panel in the left column are the (α-decay) energies extracted by either computing the histogram mean in the interval [9.5,10.5] MeV for panels (a) and (c), or by least-squares fitting a Gaussian function to the main peak at $E = 10.02$ MeV. The right column provides the correlation-time analysis for decays associated with ^{287}Fl. Experimental data points are comprised in the histograms (black lines). The shaded areas (blue or pink) provide correlation-time distributions expected for the corresponding half lives, $T_{1/2}$, which are given in the top left corner of each panel. For all panels, the number after the hashtag, #, indicates the number of available data points. The first row, panels (a) and (b), refers to indirect production of ^{287}Fl [3–5]. The second row, panels (c) and (d), refers to direct production of ^{287}Fl prior to the year 2022 [3, 6, 7]. Panels (e) and (f) summarize more recent results [8]. The spectra in the fourth row, panels (g) and(h), are the sums of the spectra in the second and third row. The spectra in the fifth row, panels (i) and (j), are the sums of the spectra in the first and fourth row. See also Table I.

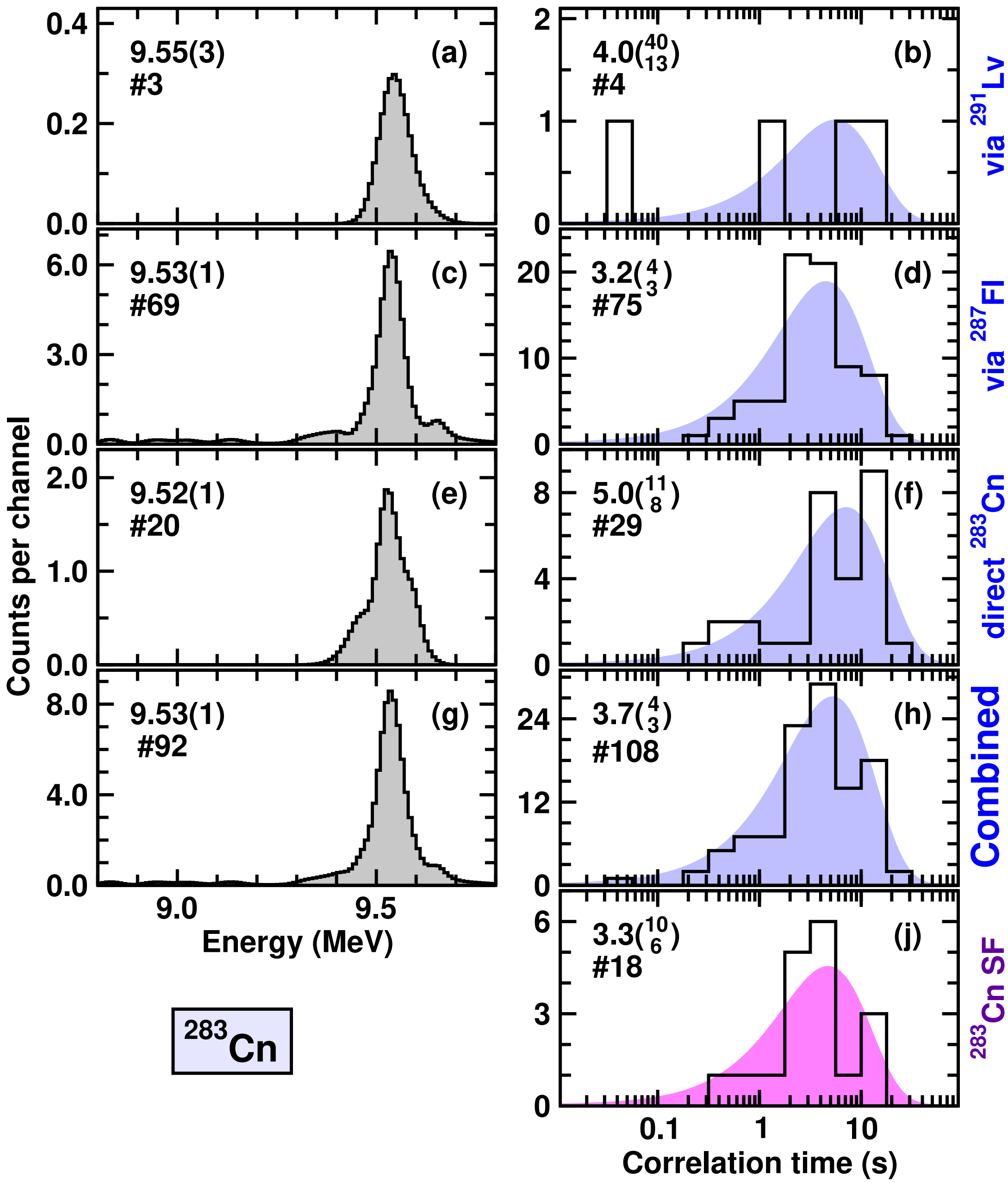

FIG. 2. (Color online) The left column provides experimental decay-energy spectra from events associated with the decay step ^{283}Cn $\rightarrow$ ^{279}Ds. For a single entry, a Gaussian with integral one and a width compliant with its measured uncertainty was added into the respective spectrum. The numbers at the top left of each panel in the left column are the (α-decay) energies extracted by either computing the histogram mean in the interval [9.2,9.8] MeV for panels (a) and (e), or by least-squares fitting a Gaussian function to the main peak at $E = 9.53$ MeV for panels (c) and (g). The right column provides the correlation-time analysis for decays associated with ^{283}Cn. Experimental data points are comprised in the histograms (black lines). The shaded areas (blue or pink) provide correlation-time distributions expected for the corresponding half lives, $T_{1/2}$, which are given in the top left corner of each panel. For all panels, the number after the hashtag, #, indicates the number of available data points. The first row, panels (a) and (b), refers to indirect production of ^{283}Cn via ^{291}Lv [3–5]. The second row, panels (c) and (d), refers to indirect production of ^{283}Cn via ^{287}Fl [3, 6–8]. The third row, panels (e) and (f), refers to direct production of ^{283}Cn [6, 8–10]. The spectra in the fourth row, panels (g) and(h), are the sums of the spectra in the first, second, and third row. The time distribution of panel (j) corresponds to 18 events interpreted as SF of ^{283}Cn in line with assessments in Ref. [9]. Note that these 18 SF events are included in panels (d), (f), and (h). See also Table I.

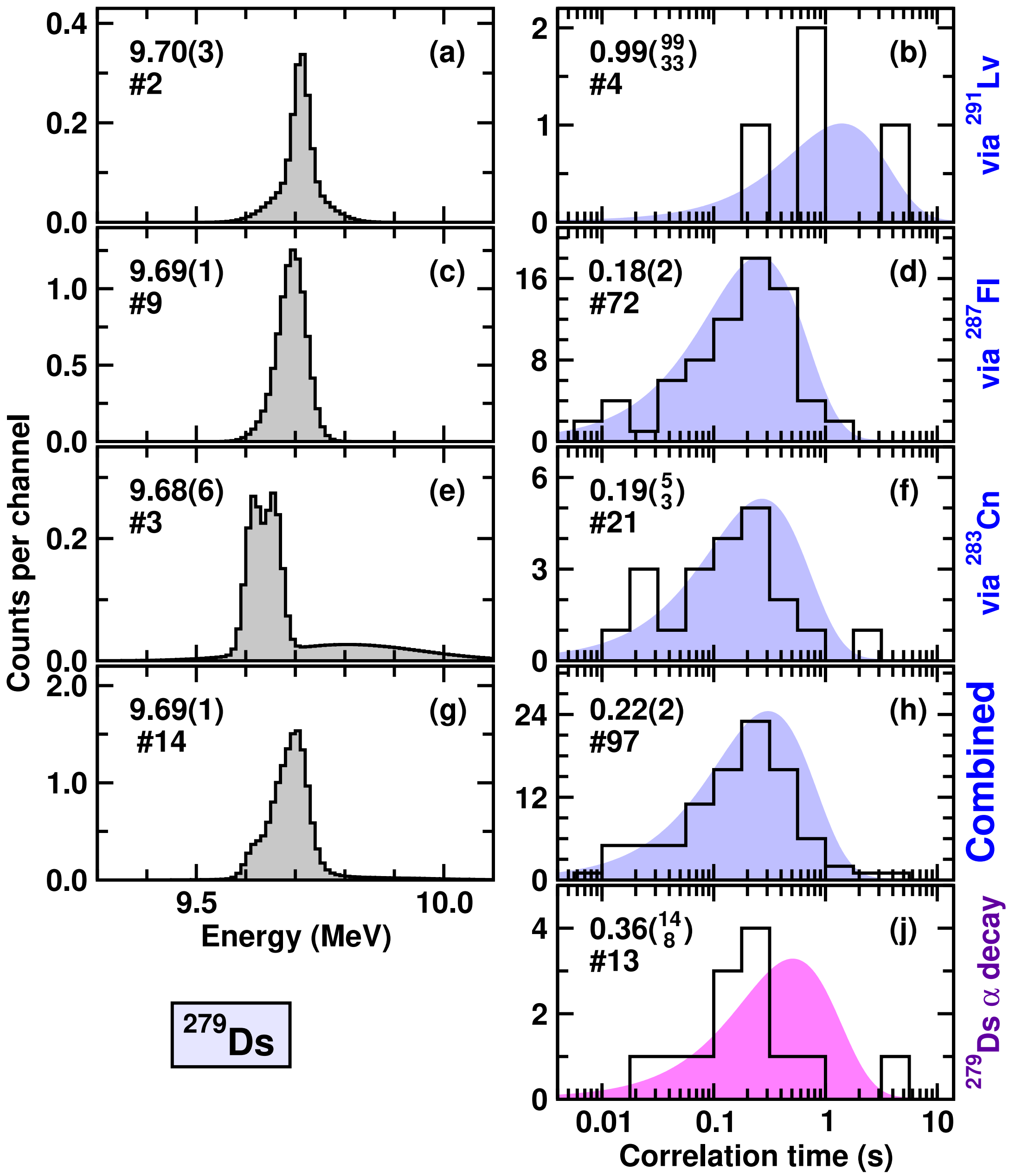

FIG. 3. (Color online) The left column provides experimental decay-energy spectra from events associated with the decay step ^{279}Ds$\rightarrow$ ^{275}Hs. For a single entry, a Gaussian with integral one and a width compliant with its measured uncertainty was added into the respective spectrum. The numbers at the top left of each panel in the left column are the (α-decay) energies extracted by either computing the histogram mean in the interval [9.3,10.0] MeV. The right column provides the correlation-time analysis for decays associated with ^{279}Ds. Experimental data points are comprised in the histograms (black lines). The shaded areas (blue or pink) provide correlation-time distributions expected for the corresponding half lives, $T_{1/2}$, which are given in the top left corner of each panel. For all panels, the number after the hashtag, #, indicates the number of available data points. The first row, panels (a) and (b), refers to indirect production of ^{279}Ds via ^{291}Lv [3–5]. The second row, panels (c) and (d), refers to indirect production of ^{279}Ds via ^{287}Fl [3, 6–8]. The third row, panels (e) and (f), refers to indirect production of ^{279}Ds via ^{283}Cn [6, 8–10]. The spectra in the fourth row, panels (g) and(h), are the sums of the spectra in the first, second, and third row. The time distribution of panel (j) corresponds to 13 available data points of hitherto observed α decay of ^{279}Cn. Note that these 13 events are included in panels (d), (f), and (h). See also Table I.

TABLE I. Overview of correlation time analyses of single decay steps according to Ref. [11] of various ensembles of decay chains associated with previous direct and indirect and present direct production of ^{287}Fl. These are the same ensembles as displayed in the corresponding rows of Figs. 1, 2, and 3.

Label	previous ^{283}Cn	previous ^{287}Fl	previous via ^{291}Lv	previous combined	all combined
No. of chains	7+4+2+16=29	1+15+1+67[h]=84	2+1+1=4	117	118
References	[6, 8–10]	[3, 6–8]	[3–5]		
$T_{1/2}(^{287}\mathrm{Fl})$ (s)		$0.35\binom{5}{4}$	$0.62\binom{62}{21}$	$0.37\binom{5}{4}$	$0.37\binom{5}{4}$
data points; $\sigma_{\Theta,\mathrm{exp}}$		75 ; 1.17	4 ; 2.08[e]	79 ; 1.23	80 ; 1.23
$[\sigma_{\Theta,\mathrm{low}}, \sigma_{\Theta,\mathrm{high}}]$ [11]		[1.03,1.53]	[0.31,1.92]	[1.04,1.52]	[1.04,1.52]
data points; E_{decay} (MeV)[a]		70; 10.02(1)	4; 10.03(2)	74 ; 10.02(1)	75 ; 10.02(1)
number α ; SF[b]	21 ; 8	74 ; 10	4 ; 0	99 ; 18	100 ; 18
$T_{1/2}(^{283}\mathrm{Cn})$ (s)	$5.0\binom{11}{8}$	$3.2\binom{4}{3}$	$4.0\binom{40}{13}$	$3.7\binom{4}{3}$	$3.7\binom{4}{3}$
data points; $\sigma_{\Theta\,\mathrm{exp}}$	29 ; 1.15	75 ; 0.88[e]	4 ; 2.33[e]	108 ; 1.07	109 ; 1.07
$[\sigma_{\Theta,\mathrm{low}}, \sigma_{\Theta,\mathrm{high}}]$ [11]	[0.88,1.68]	[1.03,1.53]	[0.31,1.92]	[1.07,1.49]	[1.07,1.49]
data points; E_{decay} (MeV)[c]	20; 9.52(1)	69; 9.53(1)	3; 9.55(3)	92 ; 9.53(1)	93 ; 9.53(1)
number α ; SF	3 ; 18	10 ; 64	2 ; 2	15 ; 84	15 ; 85
$T_{1/2}(^{279}\mathrm{Ds})$ (s)	$0.19\binom{5}{3}$	0.18(2)	$0.99\binom{99}{33}$	0.22(2)	0.21(2)
data points; $\sigma_{\Theta,\mathrm{exp}}$	21 ; 1.21	72 ; 1.18	4 ; 0.99	97 ; 1.23	98 ; 1.25
$[\sigma_{\Theta,\mathrm{low}}, \sigma_{\Theta,\mathrm{high}}]$ [11]	[0.81,1.75]	[1.03,1.53]	[0.31,1.92]	[1.05,1.51]	[1.06,1.50]
data points; E_{decay} (MeV)[d]	3 ; 9.68(6)	9 ; 9.69(1)	2 ; 9.70(3)	14 ; 9.69(1)	14 ; 9.69(1)
number α ; SF	3 ; 0	9 ; 1	2 ; 0	14 ; 1	see column to the left
$T_{1/2}(^{275}\mathrm{Hs})$ (s)	$0.48\binom{65}{17}$	$0.73\binom{40}{19}$	$0.34\binom{83}{14}$	$0.60\binom{23}{13}$	
data points; $\sigma_{\Theta,\mathrm{exp}}$	3 ; 2.08[e]	8 ; 1.28	2 ; 0.02[e]	13 ; 1.48	
$[\sigma_{\Theta,\mathrm{low}}, \sigma_{\Theta,\mathrm{high}}]$ [11]	[0.19,1.91]	[0.58,1.58]	[0.04,1.83]	[0.70,1.79]	
data points; E_{decay} (MeV)[f]	3 ; 9.31(2)	7 ; 9.29(3)	2 ; 9.33(8)	12 ; 9.30(2)	
number α ; SF	2 ; 1	6 ; 3	1 ; 1	9 ; 5	see column to the left
$T_{1/2}(^{271}\mathrm{Sg})$ (s)	$9.3\binom{127}{34}$	$68\binom{41}{19}$	$56\binom{135}{23}$	$50\binom{20}{11}$	
data points; $\sigma_{\Theta,\mathrm{exp}}$	3 ; 0.97	7 ; 2.14[e]	2 ; 0.32	12 ; 1.84[e]	
$[\sigma_{\Theta,\mathrm{low}}, \sigma_{\Theta,\mathrm{high}}]$ [11]	[0.19,1.91]	[0.52,1.87]	[0.04,1.83]	[0.70,1.79]	
data points; E_{decay} (MeV)[g]	2 ; 8.31(2)	5 ; 8.30(2)	1 ; n/a	7 ; 8.31(2)	
	8.53(3)	8.50(1)		8.51(2)	
$T_{1/2}(^{267}\mathrm{Rf})$ (h)	$1.2\binom{30}{5}$	$0.75\binom{52}{22}$	$0.24\binom{115}{11}$	$0.80\binom{40}{20}$	see column to the left
data points; $\sigma_{\Theta,\mathrm{exp}}$	2 ; 1.53	6 ; 1.90[e]	1 ; n/a	9 ; 1.73	
$[\sigma_{\Theta,\mathrm{low}}, \sigma_{\Theta,\mathrm{high}}]$ [11]	[0.04,1.83]	[0.48,1.89]	n/a	[0.62,1.84]	

[a] Result from the integration of the energy spectra in the interval [9.5,10.5] MeV (column 3) or least-squares Gaussian fit of the main peak (columns 2, 4, and 5).

[b] In line with assessments in Refs. [5, 9] ^{283}Cn was set to always decay by spontaneous fission in case of a "missing α" in Refs. [6, 8]. Handling all 18 SF events as "missing α" yields $T_{1/2} = 3.8(4)$ s for ^{283}Cn.

[c] Result from the integration of the energy spectra in the interval [9.2,9.8] MeV (columns 1 and 3) or least-squares Gaussian fit of the main peak (columns 2, 4, and 5).

[d] Result from the integration of the energy spectra in the interval [9.3,10.0] MeV.

[e] The experimental value for $\sigma_{\Theta_{\mathrm{exp}}}$ falls outside the confidence limit.

[f] Result from the integration of the energy spectra in the interval [9.0,9.6] MeV.

[g] Result from the integration of the energy spectra in the intervals [8.2,8.4] and [8.4,8.7] MeV.

[h] Chain 26 in Table III of Ref. [8] is assigned to ^{288}Fl and chain 22 is omitted due to an unusual combination of decay energies and correlation times.

TABLE II. Overview of correlation time analyses of single decay steps according to Ref. [11] of various ensembles of decay chains associated with previous indirect and direct and present direct production of ^{288}Fl, respectively. This is an update of Table II of the Supplemental Material of Ref. [1].

Label	previous	this work	combined
No. of chains	47	7	54
References	see Ref. [1]		
$T_{1/2}(^{288}\mathrm{Fl})$ (s)	$0.65(^{12}_{8})$	$0.43(^{26}_{12})$	$0.62(^{10}_{8})$
data points; $\sigma_{\Theta_{\mathrm{exp}}}$	43 ; 1.04	7 ; 1.37	50 ; 1.13
$[\sigma_{\Theta,\mathrm{low}}, \sigma_{\Theta,\mathrm{high}}]$ [43]	[0.95,1.61]	[0.52,1.87]	[0.98,1.58]
data points; E_{decay} (MeV)[a]	43 ; 9.92(1)	6 ; 9.92(1)	49 ; 9.92(1)
number α ; SF	1 ; 50	0 ; 7	1 ; 57
$T_{1/2}(^{284}\mathrm{Cn})$ (ms)[b]	$121(^{20}_{15})$	$36(^{22}_{10})$	$110(^{17}_{13})$
data points; $\sigma_{\Theta_{\mathrm{exp}}}$	49 ; 1.20	7 ; 0.96	56 ; 1.22
$[\sigma_{\Theta,\mathrm{low}}, \sigma_{\Theta,\mathrm{high}}]$ [43]	[0.97,1.59]	[0.52,1.87]	[0.99,1.57]
data points; E_{decay} (MeV)	1 ; 9.33(1)		1 ; 9.33(1)

[a] Result from the integration of the energy spectra in the interval [9.5,10.3] MeV.

[b] Half-life analysis of ^{284}Cn includes four decay chains from element 114 chemistry experiments behind TASCA [12, 13].

TABLE III. Overview of correlation time analyses of single decay steps according to Ref. [11] of various ensembles of decay chains associated with previous indirect and direct and present direct production of ^{289}Fl. This is an update of Tables II and III of the Supplemental Material of Ref. [2].

Label	previous	this work	combined	previous set (H&)M	combined set (H&)M
No. of chains	33	2	35	(29) 25	(31) 27
References	see Ref.[2]				
$T_{1/2}(^{289}\mathrm{Fl})$ (s)	$2.3(^{6}_{4})$	$0.80(^{385}_{36})$	$2.3(^{6}_{4})$	$2.5(^{8}_{5})$	$2.4(^{7}_{5})$
data points; $\sigma_{\Theta,\mathrm{exp}}$	25 ; 1.31	1	26 ; 1.29	18 ; 1.37	19 ; 1.34
$[\sigma_{\Theta,\mathrm{low}}, \sigma_{\Theta,\mathrm{high}}]$ [11]	[0.85,1.71]	n/a	[0.86,1.70]	[0.79,1.73]	[0.80,1.72]
data points; E_{decay} (MeV)[a]	30 ; 9.80(2)	n/a	9.80(2)	9.80(4)	9.80(4)
$T_{1/2}(^{285}\mathrm{Cn})$ (s)[b]	$40(^{8}_{6})$	$110(^{523}_{49})$	$42(^{8}_{6})$	$42(^{10}_{7})$	$45(^{11}_{7})$
data points; $\sigma_{\Theta\ \mathrm{exp}}$	34 ; 0.99	1	35 ; 1.01	26 ; 0.93	27 ; 0.95
$[\sigma_{\Theta,\mathrm{low}}, \sigma_{\Theta,\mathrm{high}}]$ [11]	[0.91,1.65]	n/a	[0.92,1.64]	[0.86,1.70]	[0.87,1.69]
data points; E_{decay} (MeV)[c]	29 ; 9.14(2)	2 ; 9.19(2)	31 ; 9.15(2)	26 ; 9.14(2)	28 ; 9.15(2)
number α ; SF[a]	3 ; 34	1 ; 1	4 ; 35	3 ; 33	4 ; 34
$T_{1/2}(^{281}\mathrm{Ds})$ (s)[b]	$18(^{4}_{3})$	$186(^{449}_{77})$	$26(^{5}_{4})$	$19(^{4}_{3})$	$29(^{6}_{4})$
data points; $\sigma_{\Theta,\mathrm{exp}}$	37 ; 0.97	2 ; 1.31	39 ; 1.10	29 ; 0.95	31 ; 1.11
$[\sigma_{\Theta,\mathrm{low}}, \sigma_{\Theta,\mathrm{high}}]$ [11]	[0.93,1.63]	[0.04,1.83]	[0.94,1.62]	[0.88,1.68]	[0.89,1.67]
data points; E_{decay} (MeV)[d]	3 ; 8.67(2)	1 ; 7.99(1)[e]	3 ; 8.67(2)	3 ; 8.67(2)	3 ; 8.67(2)
$T_{1/2}(^{277}\mathrm{Hs})$ (ms)	$18(^{25}_{7})$	$83(^{397}_{37})$	$35(^{35}_{12})$	$18(^{25}_{7})$	$35(^{35}_{12})$
data points; $\sigma_{\Theta,\mathrm{exp}}$	3 ; 1.67	1	4 ; 1.88	3 ; 1.67	4 ; 1.88
$[\sigma_{\Theta,\mathrm{low}}, \sigma_{\Theta,\mathrm{high}}]$ [11]	[0.19,1.91]	n/a	[0.31,1.92]	[0.19,1.91]	[0.31,1.92]

[a] Result from the integration of the energy spectra in the interval [9.2,10.2] MeV.

[b] Half-life analyses of ^{285}Cn and ^{281}Ds include four decay chains from Fl-chemistry experiments behind TASCA [12, 13].

[c] Result from the integration of the energy spectra in the interval [8.6,9.6] MeV.

[d] Result from the integration of the energy spectra in the interval [8.4,9.0] MeV.

[e] The data point is interpreted as decay into a higher-lying excited state of ^{277}Hs or an incomplete decay energy measurement.