High-resolution α and electron spectroscopy of _{98}^{249}Cf

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High-resolution α and electron spectroscopy of $^{249}_{98}$Cf

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Abstract

α-particle spectra of ^{249}Cf have been measured with a double-focussing magnetic spectrometer and with passivated implanted planar silicon (PIPS) detectors. The conversion-electron spectra of ^{249}Cf have been measured with a cooled Si(Li) detector and with a room-temperature PIPS detector. Precise energies of α groups in the decay of ^{249}Cf have been measured with respect to the known energy of ^{250}Cf. In addition, α-electron, α-γ, and γ-γ coincidence measurements were also performed to determine the spin-parity of the previously known 643.64-keV level. From electron intensities, conversion coefficients of transitions in the daughter ^{245}Cm have been determined. The measured L_3 conversion coefficients of the 333.4- and 388.2-keV transitions are found to be in agreement with the theoretical conversion coefficients for pure E1 multipolarity. On the other hand, the K, L_1+L_2, M, and N conversion coefficients are approximately twice the theoretical values for pure E1 transitions. These measurements indicate anomalous E1 conversion coefficients for the 333.4- and 388.2-keV transitions, as has been pointed out in earlier measurements. The measured conversion coefficient of the 255.5-keV transition gives an M1 multipolarity for this transition which establishes a spin-parity of $7/2^-$ and the $7/2^-[743]$ single-particle assignment to the 643.64-keV level.

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I. INTRODUCTION

The nucleus ^{249}Cf has a half-life of 351±2 y [1] and decays by α-particle emission. Milligram quantities of ^{249}Cf are available in isotopically pure form and hence its decay has been studied by many investigators [1]. The α-particle spectrum of ^{249}Cf was first measured by Asaro *et al.* [2] with a magnetic spectrometer and the energy of the main ^{249}Cf α group was determined to be 5806 keV using the 5801-keV peak of ^{244}Cm as a standard. When we use the more accurate recommended energy of 5804.77(5) keV [3] for the ^{244}Cm α_0 group, the energy of the ^{249}Cf main α group becomes 5810 keV. The ^{249}Cf α spectrum was also measured by Ahmad [4] with a silicon detector which gave the energy of the ^{249}Cf main α group as 5808±3 keV relative to the 5805 keV of ^{244}Cm α_0 group, in agreement with the value of Asaro *et al.* [2]. Later, Baranov *et al.* measured the ^{249}Cf α spectrum with a high-resolution magnetic spectrometer and their results were published in a series of articles [5–8]. Using all published energies, Rytz [3] has recommended an energy of 5812.6±1.6 keV for the ^{249}Cf main α group. Because of changes in the absolute energies of standards with time, there is some ambiguity about the the α-particle energies of ^{249}Cf. For this reason, the energies of ^{249}Cf α groups have been measured with a magnetic spectrometer using an internal standard and also with passivated implanted planar silicon (PIPS) detectors.

Gamma-ray spectra of ^{249}Cf have been measured by many investigators; the most recent and comprehensive measurements are reported in Refs. [9, 10]. In the present study, the γ-ray spectra have been measured in coincidence with α particles and also with γ rays, and the results are presented in this paper.

The conversion-electron spectrum of ^{249}Cf was first measured by Ahmad [4] with a cooled Si(Li) detector. With an energy resolution [full width at half maximum (FWHM)] of 3.5 keV, subshell lines could not be resolved. The measured conversion coefficients of the 333.4- and 388.2-keV transitions were found to be approximately twice the theoretical values [11] for E1 multipolarity and these transitions were interpreted to have anomalous conversion coefficients. The conversion-electron spectrum of ^{249}Cf was later measured with a magnetic spectrometer by Baranov *et al.* [12], where only conversion coefficients of three strong transitions with energies of 252.8, 333.4, and 388.2 keV were reported. The enhancements in the conversion coefficients of the 333.4- and 388.2-keV transitions were attributed to the admixture of M2 multipolarity [12].

It is known [13, 14] that retarded E1 transitions in the actinide region have K, L_1, L_2, M_1, and M_2 conversion coefficients higher than the theoretical values but the L_3 and M_3 conversion coefficients are in agreement with theory. The anomalous conversion coefficients are explained due to penetration of electron wave functions in the nuclear volume [15, 16]. To distinguish whether the enhancements in K and L_1 conversion coefficients are due to M2 mixing or due to penetration effect, L_3 conversion coefficients are needed. We have therefore measured the ^{249}Cf electron spectrum with a high-resolution cooled Si(Li) spectrometer and also with a room-temperature PIPS detector and determined the L_3 conversion coefficients of the 333.4- and 388.2-keV transitions. The measured L_3 conversion coefficients are found to be in agreement with theory for E1 transitions, but K and L_1+ L_2 conversion coefficients are twice the theoretical values for the E1 multipolarity. These results indicate anomalous K and L_1 +L_2 conversion coefficients for these transitions.

II. SOURCE PREPARATION

Several sources of ^{249}Cf were prepared by an isotope separator [17] . The decelerated beams of ^{249}Cf ions were deposited on thin Al foils and these were used for the measurement of α-particle spectra in Figs. 1b, 1c, and 2, and electron spectra in Figs. 3-5. The source used for the α-particle spectrum shown in Fig. 1a was prepared by vacuum deposition and hence it has some ^{250}Cf present. The α and electron spectra of mass separated sources were measured with PIPS detectors about 40 years after the mass separation and hence they were thicker than at the time of mass separation due to radiation damage.

III. EXPERIMENTAL METHODS AND RESULTS

A. α-particle spectroscopy

The α-particle spectrum of ^{249}Cf was measured with a magnetic spectrometer at Argonne National Laboratory in the early 1970s. The performance of the spectrometer has been described in Ref. [18]; it had a resolution (FWHM) of 5 keV at a transmission of 0.1% of 4π for 6.0 MeV α particles. The Si strip detector in the focal plane of the spectrometer covered only $\sim$ 500 keV range of α-particle energy. The total spectrum of ^{249}Cf was therefore measured at three different magnetic field settings and these are displayed in Figs. 1a -1c.

The energy calibration of the spectrometer was performed [18] with the following set of standards: ^{233}U (4824 keV), ^{238}Pu (5499 keV), ^{244}Cm (5805 keV), ^{242}Cm (6113 keV), ^{211}Bi (6279 and 6623 keV), and ^{214}Po (7687 keV). This calibration provided the parameters of the equation which were used to compute energies of unknown peaks. However, energies of other standard sources measured later by this method were found to be a few keV lower than the literature values because of variations in source thickness and source location. Therefore, for high precision, spectra of mixed sources containing the unknown and the standard were measured. The energies of the ^{249}Cf main peaks were determined with respect to the energy of the ^{250}Cf α_0 peak which is known with high precision to be 6030.22±0.20 keV [3]. For this measurement, the spectrum of a source containing ^{249}Cf and ^{250}Cf, shown in Fig. 1a, was recorded with the magnetic spectrometer. The above calibration gave the energy of the ^{250}Cf α_0 group as 6025.0±0.5 keV, which is 5.0 keV lower than the literature value [3]. A correction of +5.0 keV was therefore applied to the computed energies of all peaks of this spectrum. This procedure is justified because, in the small energy range, the energy versus the spectrometer magnetic field plot is linear, and the energies of ^{249}Cf α groups obtained by this procedure agreed with the values measured with a PIPS detector. The energies of ^{249}Cf α groups were also determined with respect to the energy of the ^{250}Cf α_0 group using a linear calibration. The energy of the γ-ray transition between the 388.2-keV level and the ground state is precisely known as 388.17±0.02 keV which is also the difference between the Q_α values to the two states. After removing the α-decay recoil energies from the Q_α values we obtained the difference between the α-particle energies of 381.93±0.02 keV. Using this energy difference between the two alpha peaks we measured the dispersion in keV/channel and this was used to determine the energies of ^{249}Cf alpha groups with respect to the ^{250}Cf α_0 peak. The energies thus determined agreed with the values obtained from the spectrometer calibration within the quoted uncertainties. In addition, energies of ^{249}Cf α groups were measured with PIPS detectors with a resolution (FWHM) of 9.0 keV. The energies obtained from several spectra and the corresponding excitation energies are given in Table I. These energies are ∼2 keV lower than the recommended values by Rytz [3]. The uncertainties of ± 0.5 keV in the absolute energies of α groups are due to the uncertainty in the energy of the reference and that associated with the calibration of the spectrometer. Since the uncertainty in the energy of the ^{250}Cf α_0 group is only ±0.22 keV, the errors in the measured energies of α groups and, hence, the uncertainties in the level energies, are also ±0.5 keV.

Intensities of α groups were obtained by combining the results of the spectra measured with PIPS detectors and the results of the spectra measured with the magnetic spectrometer. The magnetic spectrometer had 224 Si strips at the focal plane, corresponding to the 224 channels in the spectrum. The areas of all the strips were not exactly the same and they were determined by calibrating them with a very thick ^{244}Cm source [18]. This calibration increased the uncertainties in the alpha intensities. Hence, for well-resolved peaks, the spectra measured with PIPS detectors were used for intensity determination. Several spectra of different mass-separated sources at different solid angles were measured in order to check α-electron summing contributions to the peak areas. Weak sources had a resolution (FWHM) of less than 9.0 keV but the stronger sources had worse resolution due to the radiation damage of the source backing. An α-particle spectrum measured with a PIPS detector at a solid angle of 0.07% of 4π is displayed in Fig. 2. The intensities listed in Table I are free from any summing contributions. The spectrum with the magnetic spectrometer was used to determine intensities of α groups which were not resolved with the PIPS detectors. The intensities of α groups obtained by combining the results of the PIPS spectra and the spectra measured with the magnetic spectrometer are included in Table I. These intensities are in excellent agreement with the values previously measured with silicon detectors [4, 19], but differ from the values measured by Baranov *et al.* as reported in Ref. [1]. The hindrance factors in Table I were calculated with the spin-independent theory of Preston [20] using a radius parameter of 9.285 fm.

B. Electron spectroscopy

The electron spectrum of a mass-separated ^{249}Cf source was measured with a cooled 80-mm$^2\times$3-mm Si(Li) detector [21] with a resolution (FWHM) of 1.2 keV for a 100-keV electron line. The spectrum measured at a solid angle of 1% of 4π is displayed in Fig. 3. The source also contained some ^{249}Bk which decays by the emission of β^- particles with an end point energy of 123.6±0.4 keV [22]. Because of the presence of β^- particles in this spectrum, weak electron lines below 100 keV could not be identified. For the measurement of the low-energy electron spectrum another mass-separated ^{249}Cf source was used which did not contain any ^{249}Bk. The spectrum of this source was measured with a room-temperature 25-mm$^2\times$0.5-mm PIPS detector with an energy resolution (FWHM) of 2.3 keV and it is displayed in Fig. 4. Electron lines below 100 keV are not shown here; they are essentially the same as in the coincidence spectrum of Fig. 5. The ^{249}Cf was mass separated about 30 years ago and, hence, the source contained some daughter ^{245}Cm nuclei. In the spectrum the 175.0 L_1 line of ^{245}Cm is present but it is absent in the spectrum of Fig. 3 because that spectrum was measured soon after the mass separation. The spectrum also contains KLL and KLM Auger electron lines of Cm. The 121.5 L_3 line is broad because it contains Cm KLM Auger lines. Its intensity was obtained after subtracting the contribution of the Auger lines from the total intensity. The 97.82 (350.66 $\rightarrow$ 252.84) L_2 line was identified in the spectrum and its intensity was determined to be 0.10$\pm$0.02% per ^{249}Cf α decay. It is not included in Table II because this γ ray has not been observed. Conversion coefficients were determined from the electron intensities measured in the present work and the γ-ray intensities given in Ref. [23]. Since the uncertainties in the γ-ray intensities are very small, fractional error in the conversion coefficients are essentially the same as the fractional error in the electron intensities. Energies (E_{CE}) and intensities (I_{CE}) of electron lines obtained from these spectra along with conversion coefficients (α) and multipolarities (Mult.) are given in Table II.

The energy calibration of the ^{249}Cf electron spectrum was made with the known energies of ^{243}Cm electron lines. The efficiency-geometry product of the spectrometer was determined with the ^{139}Ce 165.86 K electron line using a calibrated ^{139}Ce source. In Table II, the conversion coefficients of M1 transitions are in agreement with theory. For the 333.4- and 388.2-keV transitions, L3 conversion coefficients are in agreement with theory for an E1 multipolarity. However, K, L_1+L_2, M, and N conversion coefficients are twice the theoretical values for E1 multipolarity indicating anomalous conversion coefficients for these transitions.

C. α-electron, α-γ, and γ-γ spectroscopy

The ^{249}Cf electron spectrum was also measured in coincidence with selected α particles. The electrons were detected with the same cooled Si(Li) detector that was used for the spectrum in Fig. 3, and the α particles were detected with a Au-Si surface barrier detector. The spectrum measured in coincidence with α particles with energies below the α_{388} (5810.5 keV) peak is displayed in Fig. 5. Conversion-electron lines of 255.5- and 259.0-keV transitions are seen which could not be observed in the singles spectrum because of their low intensities. From the measured conversion coefficient obtained from the excess K x-ray intensity (discussed below) and K/L conversion coefficients ratios, M1 multipolarity is deduced for both transitions. Electron intensities from the coincidence data were obtained by normalizing to the intensity of the 255.5 K line calculated from its measured γ-ray intensity and its measured K conversion coefficient. The 255.5-keV transition deexcites the 643.6-keV level and 259.0-keV transition the 701.8-keV level. The intensities of the electron lines of these two transitions along with their conversion coefficients are included in Table II.

An α-γ coincidence spectrum was measured to determine the intensities of transitions decaying the 643.6-keV level. Since the known weak transitions of 255.5 and 390.8 keV, which deexcite the 643.6-keV level, are very close in energy to the strong 252.8- and 388.2-keV γ rays, a high-resolution low-energy photon spectrometer (LEPS) was used and the spectrum was measured in coincidence with the α groups populating the 643.6-keV band. The α particles were detected with a 450-mm^2 PIPS detector and the γ rays with a 2-cm^2$\times$10-mm LEPS detector. The γ-ray spectrum measured in coincidence with the α particles with energies below α_{388} group is shown in Fig. 6 (top). Relative γ-ray and K x-ray intensities were determined from several coincidence spectra. Since the K conversion coefficients of strong transitions have been measured, as discussed in subsection B, they along with the relative γ-ray intensities were used to calculate the K x-ray intensity. This intensity accounted for only $\sim$70% of the measured K x-ray intensity; the remaining intensity coming from new weak 255.5- and 259.0-keV transitions. From the remaining K x-ray intensity and the total intensity of the 255.5- and 259.0-keV γ rays, we deduce the K conversion coefficient of 1.7$\pm$0.2, which gives an M1 multipolarity for these transitions.

A γ-γ coincidence measurement was performed with the same LEPS detector used in the α-γ coincidence experiment and with a 7.6-cm$\times$7.6-cm NaI(Tl) detector. The γ-ray spectrum in coincidence with the 388.2-keV photopeak in the NaI(Tl) crystal is shown in Fig. 6 (bottom). The presence of the 333.4- and 388.2-keV γ rays in the spectrum is due to random coincidences. Peaks at 314.0 and 347.8 keV are more clearly seen in a spectrum gated by all γ rays. The intensities obtained from both α-γ and γ-γ coincidence experiments are given in Table III and are normalized to the intensity of the 390.8-keV γ ray measured in the γ singles spectrum [23]. The relative intensities of γ rays deexciting the members of the 643.6-keV band are the same in the singles and in the α-γ coincidence spectra. The presence of the 255.5-keV γ ray in the spectrum gated by the 388.2-keV photopeak establishes that this transition deexcites the 643.6-keV level. K conversion coefficients of the 255.5- and 259.0-keV transitions were determined from the excess K x ray intensity as was done with the α-γ coincidence data.

IV. DISCUSSION

A. Level scheme

The level structure of ^{245}Cm has previously been studied by several investigators using decay techniques, involving the α decay of ^{249}Cf, β^- decay of ^{245}Am, and EC decay of ^{245}Bk, and transfer reactions which resulted in the identification of several single-particle configurations [1]. The present data confirm the previous level energies and assignments with the exception of the energies of three levels. From the α-decay energies, we derive the energies of these three levels as 199.8(5), 495.8(5), and 585.4(5) keV which are different from the literature values of 197.4, 497.6, and 587.9 keV. As the evaluators [1] pointed out, the existence of these three levels quoted in the previous measurements is questionable. The α-decay data determined in the present study and the Nilsson state assignments are shown in Fig. 7, and the level scheme of ^{245}Cm with γ-ray transitions is displayed in Fig. 8. Level energies and γ-ray transition energies in Fig. 8 are taken from Ref. [1]. The Nilsson state assignments are discussed below.

The ground-state spins and magnetic moments of ^{245}Cm and ^{249}Cf have been measured [24, 25] which establish $7/2^+$[624] and $9/2^-$[734] assignment for them. Since the 388.18-keV level in ^{245}Cm is populated by the favored alpha transition, it must have the same configuration as the ^{249}Cf ground state, i.e. $9/2^-$[734]. The spin-parity of the 252.84-keV level is established as $5/2^+$ on the basis of the measured multipolarities of transitions to the ground-state band in the EC decay of ^{245}Bk [26]. This state is given a Nilsson state assignment of $5/2^+$[622] on the basis of the low α-decay hindrance factor and the cross sections to the members of the band in (d,p) and (d,t) reactions [27].

The high-resolution α spectra measured in the present study provide directly the level energies. In the Fig. 7 more precise level energies are given when available from γ-ray spectroscopy. Although the band at 643.6 keV is well established and has been given the $7/2^-$[743] Nilsson state assignment, the transition multipolarity and coincidence relationships provide a definite assignment. The coincidence between the 388.2-keV and 255.5-keV transitions and the measured M1 multipolarity of the 255.5-keV transition establish a level at 643.6 keV with negative parity. The decay of the 643.6-keV level to the 388.2-keV (K,I^π = 9/2,9/2^-) level and to the 252.8-keV (K,I^π = 5/2,5/2^+) level with comparable intensities restricts the spin of the 643.6-keV level to 7/2. We therefore give an assignment of 7/2^-[743] Nilsson state configuration to the 643.6-keV level. This assignment is further supported by the reasonable value of the rotational constant and the cross section to this band in (d,t) and (d,p) transfer reactions [27].

The level at 554.3 keV, populated by a very weak α group, was also observed in the ^{248}Cm(d,t) reaction [27] and was interpreted as the I=11/2 member of the 1/2^+[631] band. Decay of the 971.38-keV level, populated by the 5236.2-keV alpha group, was observed in Refs. [9, 10]. This level is given a tentative spin-parity assignment of 7/2^+ on the basis of its decay pattern and the small α-decay hindrance factor. The peak at 5485.6 keV, which has an intensity of $(1.5\pm0.2)\times10^{-3}$% and corresponds to an excitation energy of 718.3 keV, has the right energy for the ^{241}Am main α group. It could therefore be due to the ^{241}Am impurity in the source and it has not been included in Table I. A very weak α peak at 5453.3 keV with an intensity $(7\pm2)\times10^{-4}$% is seen in Fig. 1c but it was not observed by Baranov *et al.* [1]. It is therefore likely that this peak does not belong to the ^{249}Cf decay.

For E1 transitions in ^{245}Cm, ^{247}Cf, and ^{251}Es, measured K and L conversion coefficients are found to be higher than the theoretical values [4, 28, 29]. To confirm that these transitions have anomalous conversion coefficients, L_3 conversion coefficients are needed. Because the transitions of interest in these nuclei have high energy and have very small L_3 conversion coefficients, these could not be measured in ^{247}Cf and ^{251}Es. In the present experiment, L_3 conversion coefficients of the 333.4- and 388.2-keV transitions in ^{245}Cm have been measured and are found to be in agreement with theory for E1 multipolarity, confirming anomalous conversion coefficients.

According to Ref. [16], the anomalous conversion coefficients in E1 transitions arise due to the penetration of the electron wave functions in the nuclear volume. Thus the measured internal conversion coefficient contains two terms - the normal conversion coefficient and the anomalous conversion coefficient. When the γ-ray transition is retarded, the normal conversion coefficient is also reduced making the anomalous contribution measurable. Asaro *et. al* [13] have shown that a plot of the anomaly against the retardation for the available data on a log-log paper gives a straight line with a slope of 1.0. The anomaly is defined as the relative increase over the theoretical L_1+L_2 conversion coefficient and the retardation is defined as the ratio of the experimental partial γ-ray half-life and the theoretical single-particle half-life. We have plotted the data from Ref. [13] on a log-log scale in Fig. 9. In the figure we have omitted the data on ^{223}Ra, ^{225}Ac, and ^{239}Np because the measured conversion coefficients are in agreement with the more accurate values of theoretical conversion coefficients [11]. The half-life of the 388.2-keV level has been measured from delayed coincidence technique as 0.45$\pm$0.02 ns in Ref. [30] and 0.47$\pm$0.01 ns in Ref. [31]. Using a half-life of 0.46 ns and the measured γ-ray branching ratios we have calculated the partial half-lives of the 388.2- and 333.4-keV transitions. The single-particle γ-ray half-life was calculated with the same formula as was used in Ref. [13]. The ratio of the two half-lives gave a retardation of 3.3×10^5 for the 388.2-keV γ ray and 9.7×10^5 for the 333.4-keV transition. These retardations are plotted against the anomalies of 1.7$\pm$0.15 (388.2-keV γ ray) and 1.04$\pm$0.10 (333.4-keV γ ray) in Fig. 9. The data fit reasonably well on the straight line which suggests that this straight line could be used to estimate the γ-ray half-life when the anomaly is known. The 480.4-keV γ ray in ^{247}Cf and the 453.1-keV γ ray in ^{251}Es have anomalies similar to that in ^{245}Cm, and hence these γ rays should have half-lives similar to that of the 388.2-keV γ ray in ^{245}Cm.

B. Summary

α-particle spectra, presented here, were measured with the Argonne double-focussing magnetic alpha spectrometer. Precise energies and intensities of ^{249}Cf α groups and conversion electron lines in ^{245}Cm have been measured. The α-particle energy of the main α group measured in this work is $\sim$2 keV lower than the recommended literature value. For the 333.4- and 388.2-keV transitions, L_3 conversion coefficients are found to be in agreement with theory but K and L_1+L_2 conversion coefficients are found to be approximately twice the theoretical values. These results demonstrate anomalous E1 conversion coefficients for the 333.4- and 388.2-keV transitions in ^{245}Cm. The present measurements indicate anomalous conversion coefficients for E1 transitions in actinide nuclei and this effect is expected to be more pronounced in superheavy elements because of their higher Z values.

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TABLE I: ^{249}Cf α-decay data obtained in the present work. Hindrance factors were calculated with the spin-independent theory of Preston [20] using a radius parameter of 9.285 fm.

α energy (keV)	Level energy (keV)	α intensity (%)	Hindrance factor
6192.4±0.5	0	2.44±0.05	6.03×10^3
6138.5±0.5	54.8	1.32±0.03	5.97×10^3
6072.8±0.5	121.6	0.34±0.01	1.07×10^4
5995.8±0.5	199.8	0.040±0.002	3.7×10^4
5943.8±0.5	252.7	3.29±0.05	233
5901.5±0.5	295.6	3.17±0.05	144
5847.5±0.5	350.5	1.44±0.03	161
5810.5±0.5	388.1	82.4±0.3	1.77
5782.4±0.5	416.7	0.35±0.01	290
5756.9±0.5	442.6	4.68±0.07	15.6
5704.6±1.0	495.8	0.048±0.003	760
5692.3±0.5	508.3	0.29±0.01	108
5647.0±1.0	554.3	$(2.6\pm0.4)\times10^{-3}$	6.7×10^3
5616.4±0.5	585.4	0.022±0.001	510
5559.3±0.5	643.4	0.115±0.005	46.5
5529.0±1.0	674.2	$(2.2\pm0.3)\times10^{-3}$	1.7×10^3
5502.0±0.5	701.7	0.044±0.002	55
5432.8±0.5	772.0	0.0103±0.0007	91
5353.3±1.0	852.8	$(2.0\pm0.3)\times10^{-3}$	150
5236.2±1.0	971.8	$(1.5\pm0.3)\times10^{-3}$	36

TABLE II: ^{249}Cf conversion-electron lines.

E_T (keV)	Shell	E_{CE} (keV)	I_{CE} (%)	α(exp.)	α(theory) E1	E2	M1	Mult.
54.8	L_1+L_2	30.3(3)	12.3(9)	60(4)	0.33	134	30	M1-E2
	L_3	35.8(3)	5.7(4)	28(2)	0.17	101	0.14	
	M	48.6(5)	5.1(4)	25(2)	0.13	66	7.4	
	N+O	53.3(3)	1.6(2)	7.8(10)	0.04	23	2.5	
66.8	L_1+L_2	42.5(3)	0.68(8)	22(3)	0.20	53	16.8	M1-E2
	M	60.6(3)	0.24(3)	7.7(10)	0.075	26	4.1	
	N+O	65.3(3)	~0.08	~2.6	0.025	8.9	1.4	
121.5	L_2	97.9(3)	0.22(2)	3.0(4)	0.018	3.4	0.34	E2
	L_3	~102.0	0.14(2)	1.9(3)	0.014	1.9	0.012	
240.9	K	112.6(2)	0.44(3)	2.10(17)	0.055	0.113	2.06	M1
	L_1+L_2	216.4(2)	0.090(7)	0.43(4)	0.010	0.21	0.42	
252.8	K	124.6(2)	4.25(12)	1.70(7)	0.049	0.11	1.80	M1
	L_1+L_2	228.3(2)	0.90(7)	0.35(3)	9.0×10^{-3}	0.17	0.367	
	M	246.6(2)	0.23(2)	0.091(8)	2.6×10^{-3}	0.064	0.090	
	N+O	251.3(2)	0.08(1)	0.032(4)	8.7×10^{-4}	0.022	0.031	
255.5	K	127.5(3)	0.060(6)	1.7(2)	0.048	0.10	1.75	M1
	L_1+L_2	231.0(3)	0.012(3)	0.34(9)	8.8×10^{-3}	0.17	0.36	
259.0	K	130.9(3)	0.015(3)	1.8(4)	0.047	0.10	1.69	M1
	L_1+L_2	235.0(3)	$\sim4\times10^{-3}$	~0.5	8.5×10^{-3}	0.16	0.34	
266.6	K	138.5(2)	0.045(3)	0.068(5)	0.044	0.097	1.56	E1
	L_1+L_2	242.1(5)	0.014(3)	0.020(5)	8.0×10^{-3}	0.14	0.32	
295.7	K	167.5(2)	0.14(1)	1.03(9)	0.035	0.082	1.17	M1
	L_1+L_2	271.3(2)	0.028(3)	0.21(3)	6.4×10^{-3}	0.096	0.24	
	M	289.5(3)	$8(2)\times10^{-3}$	0.059(15)	1.8×10^{-3}	0.034	0.058	
333.4	K	205.1(2)	0.73(5)	0.050(4)	0.027	0.067	0.84	E1
	L_1+L_2	309.0(2)	0.15(1)	0.010(1)	4.9×10^{-3}	0.062	0.17	
	L_3	314.4(2)	0.009(1)	$6.4(7)\times10^{-4}$	6.3×10^{-4}	0.015	6.3×10^{-4}	
	M	327.2(3)	0.045(4)	$3.1(3)\times10^{-3}$	1.35×10^{-3}	0.021	0.042	
	N+O	331.8(3)	0.014(1)	$1.00(9)\times10^{-3}$	4.6×10^{-4}	7.4×10^{-3}	0.015	
388.2	K	259.9(2)	2.95(10)	0.042(2)	0.0201	0.051	0.55	E1
	L_1+L_2	363.8(2)	0.64(5)	$9.7(8)\times10^{-3}$	3.6×10^{-3}	0.037	0.12	
	L_3	369.2(2)	0.025(3)	$3.60(45)\times10^{-4}$	4.0×10^{-4}	7.6×10^{-3}	4.1×10^{-4}	
	M	381.9(2)	0.17(2)	$2.6(3)\times10^{-3}$	9.6×10^{-4}	0.012	0.027	
	N+O	386.6(3)	0.065(8)	$1.00(13)\times10^{-3}$	3.3×10^{-4}	4.2×10^{-3}	9.4×10^{-3}	

TABLE III: ^{249}Cf γ-ray energies and intensities obtained in α-γ and γ-γ coincidence experiments.

Energy (keV)	Absolute intensity (% per ^{249}Cf α decay)	Transition (initial level $\rightarrow$ final level)
109.3±0.1	0.034±0.003	Cm $K_{\alpha 1}$
255.54±0.07	0.035±0.003	643.64→388.18
259.15±0.07	$(8.5\pm0.9)\times10^{-3}$	701.82→442.92
314.0±0.3	$(2.0\pm0.6)\times10^{-3}$	701.82→388.18
347.8±0.3	$(3.5\pm0.5)\times10^{-3}$	643.64→295.71
390.8±0.1	0.016±0.002	643.64→252.84
405.8±0.2	$(5.1\pm0.5)\times10^{-3}$	701.82→295.71

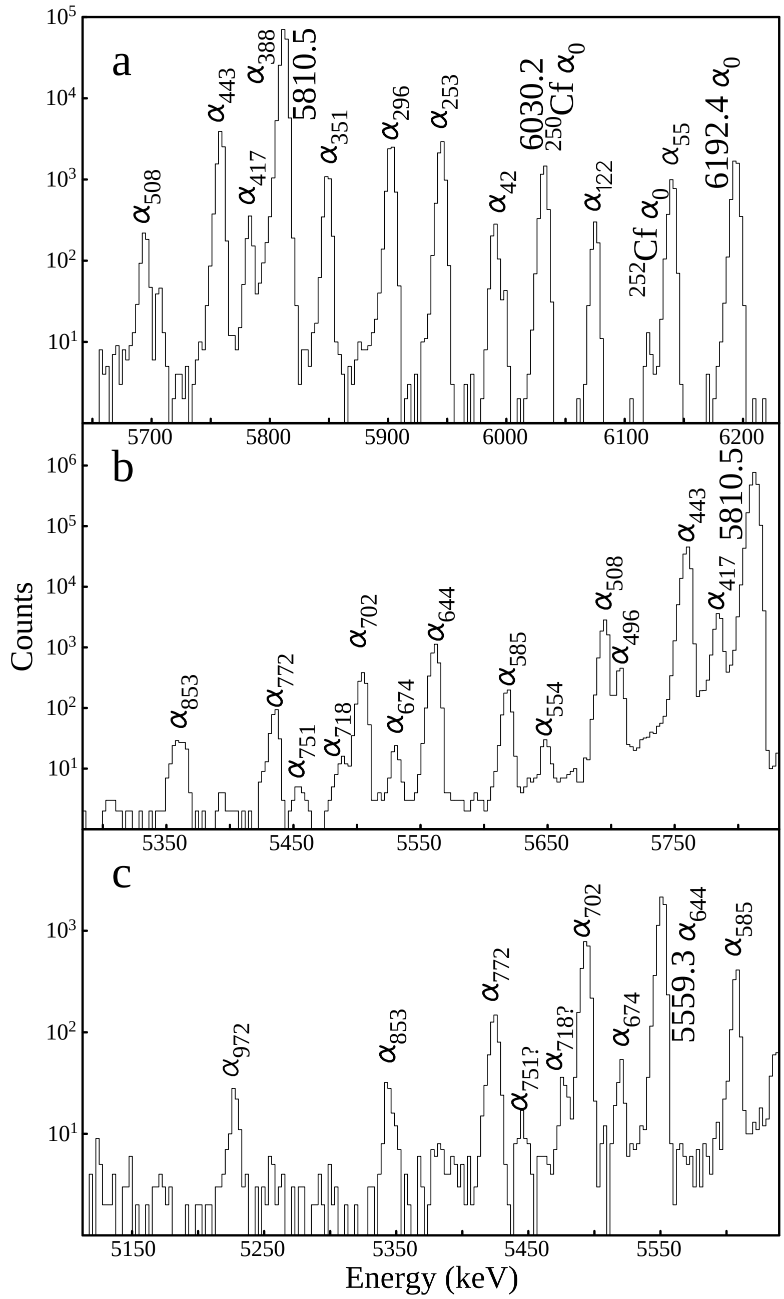

FIG. 1: ^{249}Cf α-particle spectra measured with the Argonne double-focussing magnetic spectrometer. The three spectra show different energy ranges. The spectrometer had a resolution (FWHM) of 5 keV. Energy scales for the three spectra are 2.804 keV per channel (top), 2.610 keV per channel (middle), and 2.511 keV per channel (bottom). The α_{853} peak in Fig. 1b is wide because it contains the 5360.5-keV peak of ^{245}Cm.

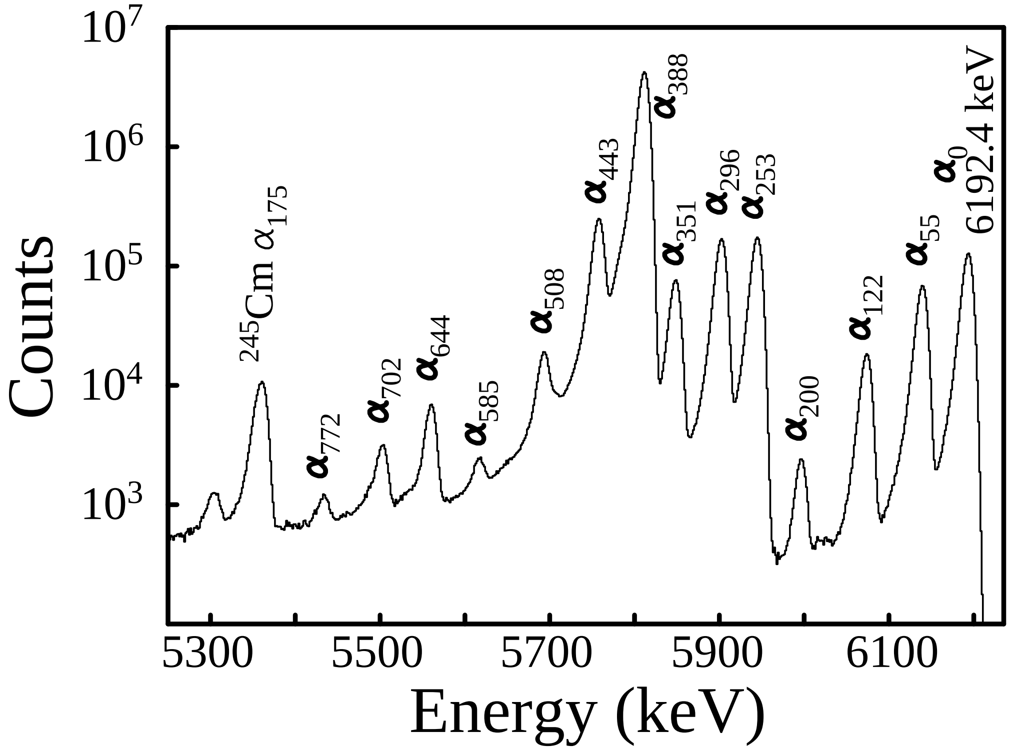

FIG. 2: α-particle spectrum of a 30-year old mass-separated ^{249}Cf source measured with a 25-mm$^2\times$0.3-mm passivated implanted planar silicon (PIPS) detector at a solid angle of 0.07% of 4π. The energy scale is 1.449 keV per channel and the energy resolution (FWHM) is 13.0 keV. The subscript after α denotes the energy of the level populated by that α group.

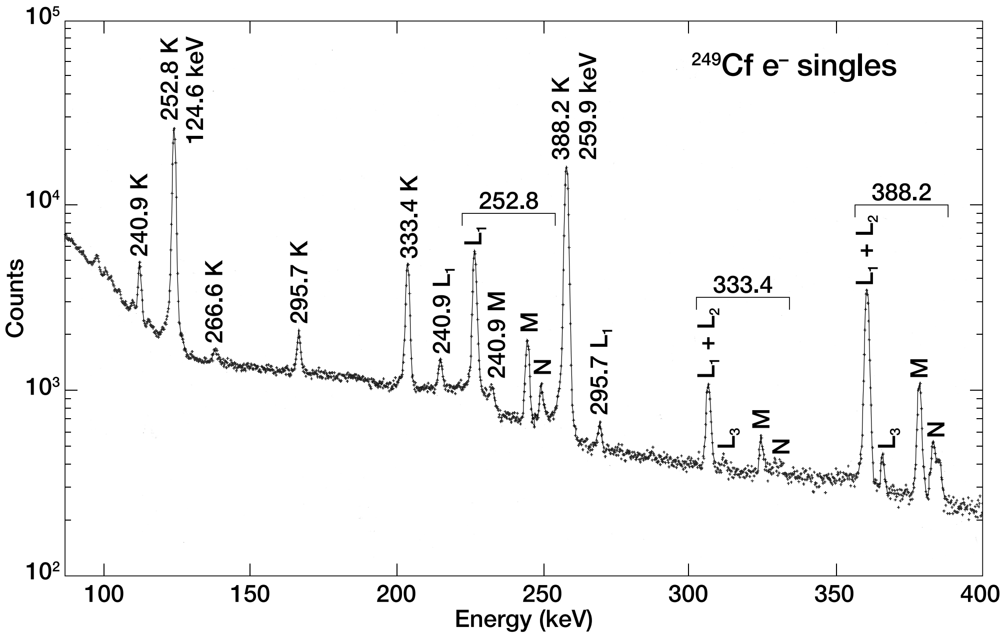

FIG. 3: Electron spectrum of a mass-separated ^{249}Cf source measured with a cooled Si(Li) spectrometer. The spectrometer had a resolution (FWHM) of 1.2 keV for a 100-keV electron line. The spectrum was measured soon after the source preparation and hence it does not contain the ^{245}Cm L_1 line, present in Fig. 4.

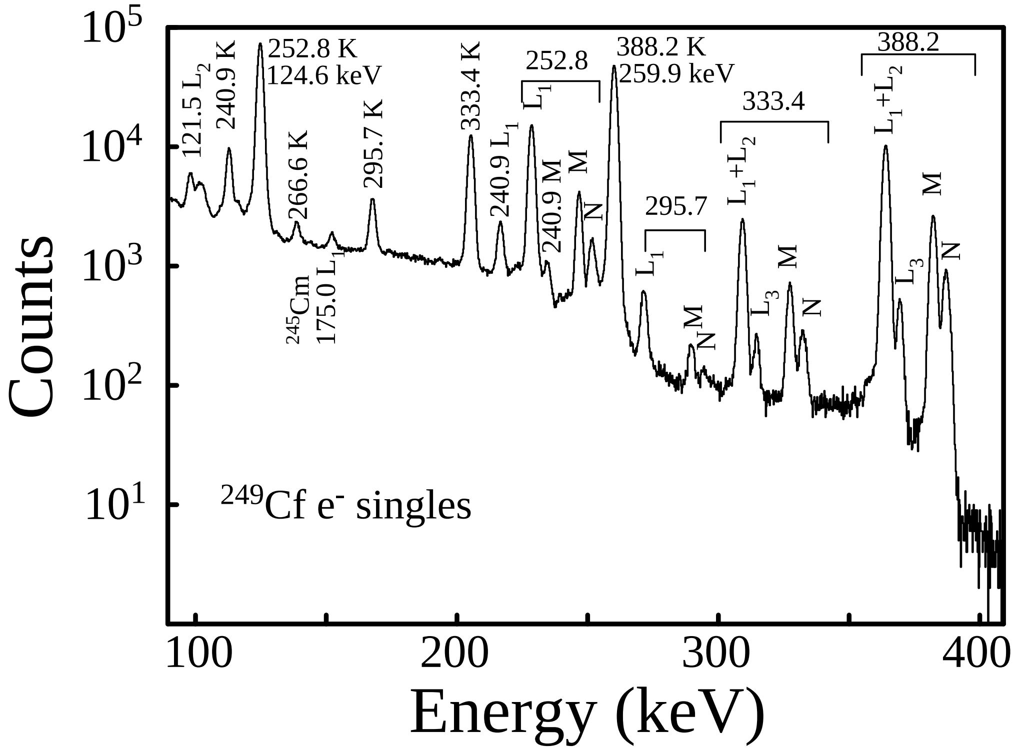

FIG. 4: Electron spectrum of a 30-year old mass-separated ^{249}Cf source measured with a room-temperature 25-mm^2×0.5-mm PIPS detector. The detector has a resolution (FWHM) of 2.3 keV for a 100-keV electron line. The energy scale is 0.213 keV per channel.

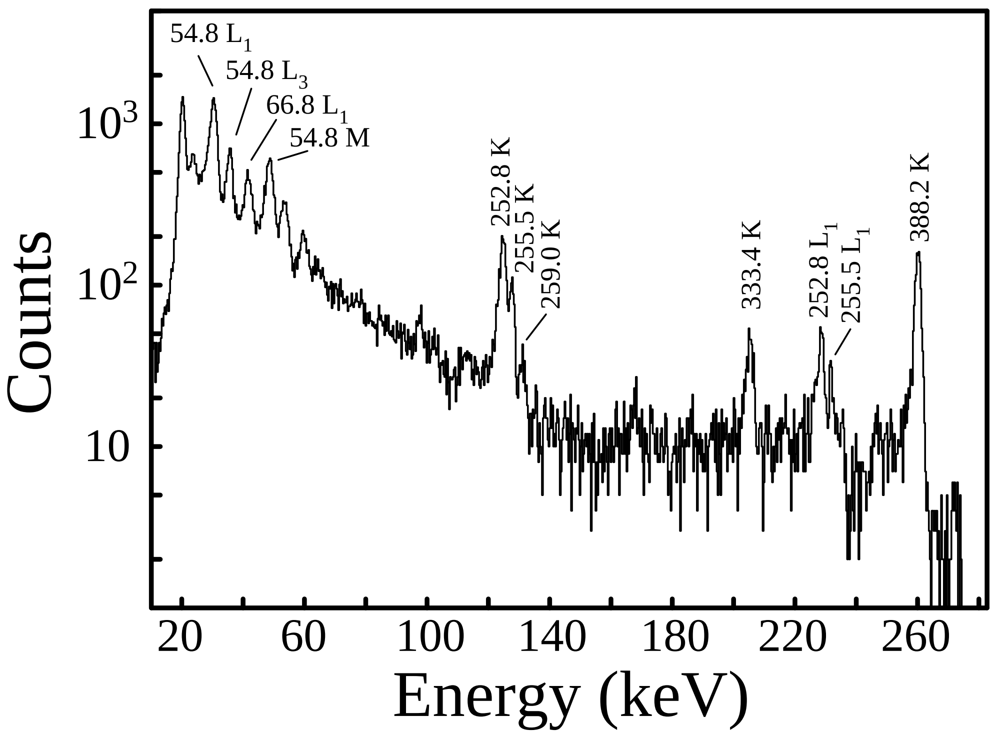

FIG. 5: Electron spectrum of a mass-separated ^{249}Cf source measured with a cooled Si(Li) detector in coincidence with α particles with energies less than the ^{249}Cf α_{388} group. The electron detector had a resolution (FWHM) of 1.2 keV for a 100-keV electron line. The energy scale is 0.306 keV per channel.

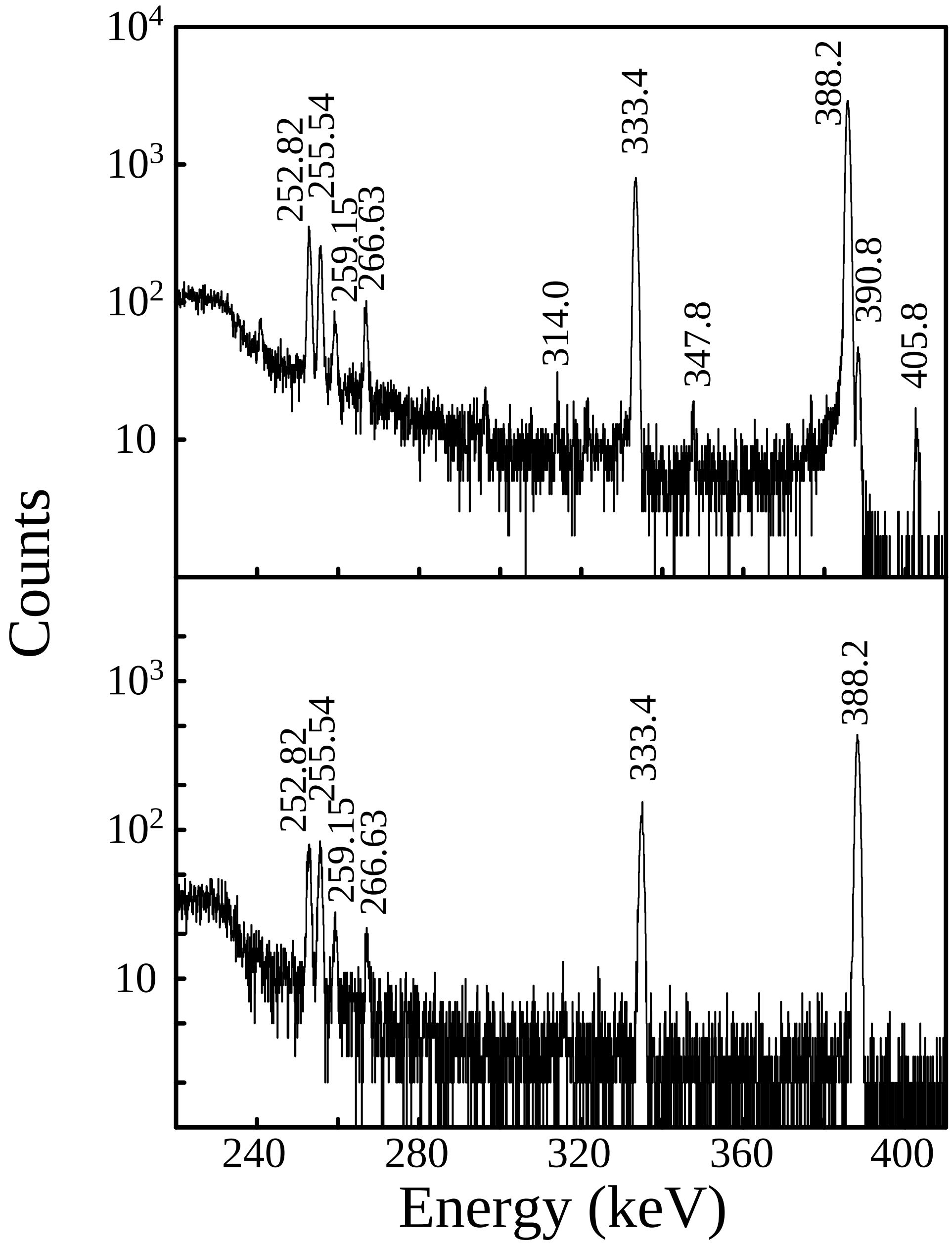

FIG. 6: γ-ray spectra of a mass-separated ^{249}Cf source measured with a 2-cm$^2\times$10-mm LEPS detector in coincidence with α particles with energies less than the ^{249}Cf α_{388} group (top) and in coincidence with the 388.2-keV γ ray measured with a NaI(Tl) detector (bottom). The energy scale is 0.085 keV per channel. The resolving time was 0.5 μs.

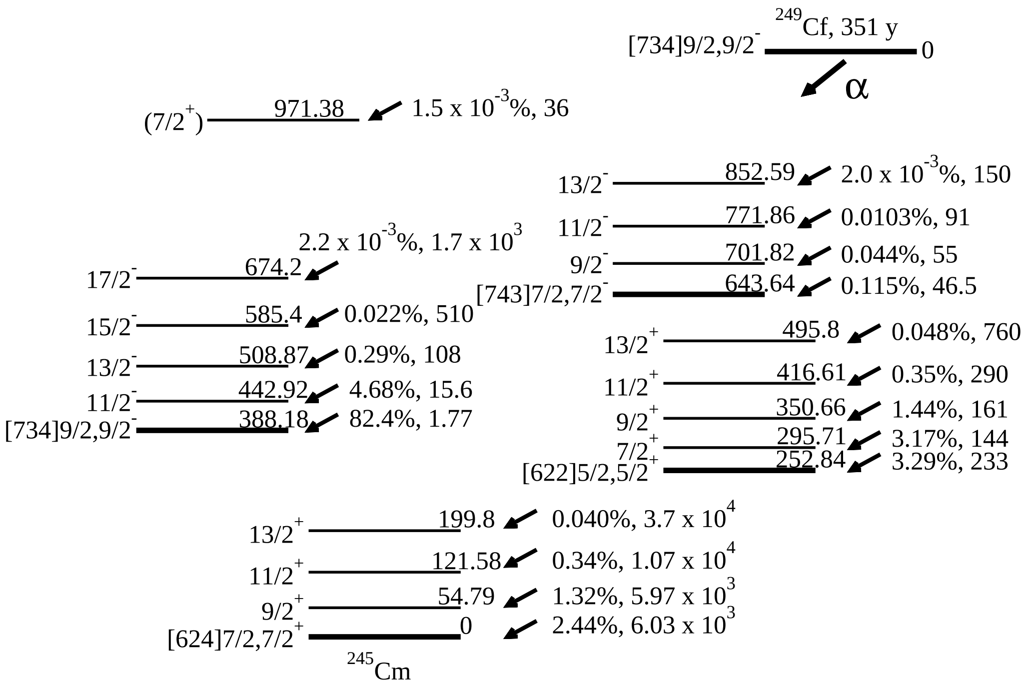

FIG. 7: A partial α-decay scheme of ^{249}Cf deduced in the present work. On the left side of the levels, the single-particle state quantum numbers [N$n_z\Lambda$]K,I$^\pi$ are given. On the right side, level energies in keV, α intensities in %, and hindrance factors are given.

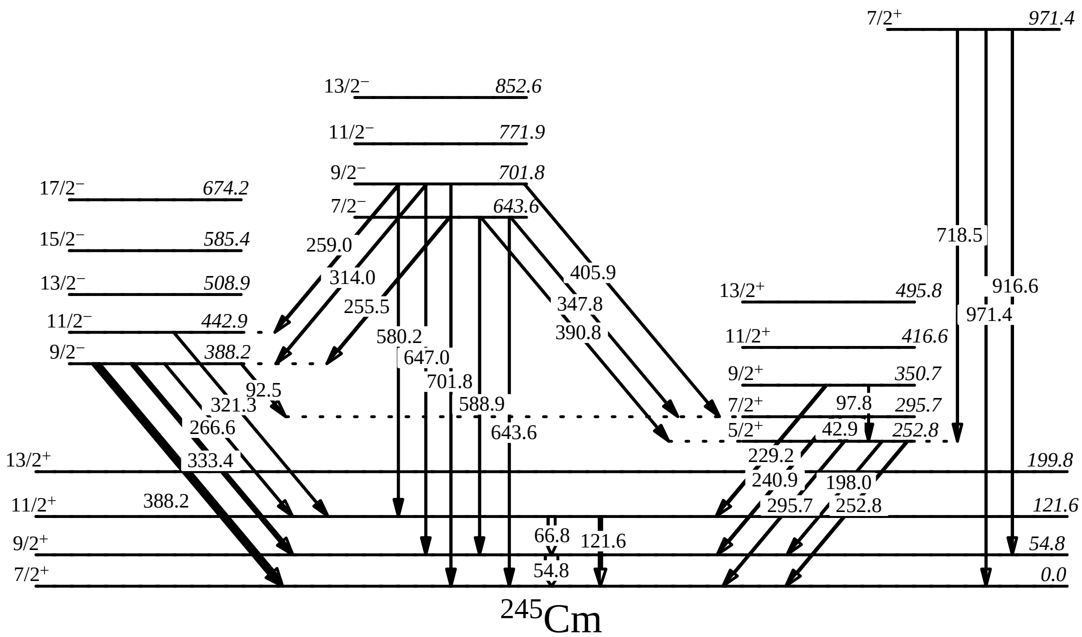

FIG. 8: Level scheme of ^{245}Cm from Ref. 1. Level energies and γ-ray energies are given in keV.

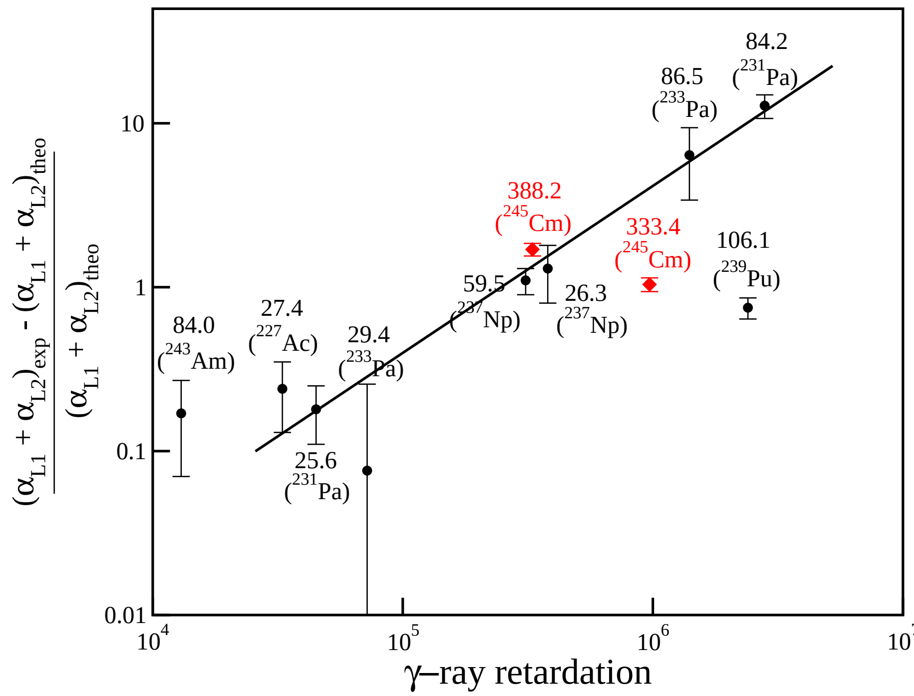

FIG. 9: A plot of the E1 conversion coefficient anomaly against the γ-ray retardation using data from Ref. 13. The anomaly is defined as $[(\alpha_{L1+L2})_{exp}$ - $(\alpha_{L1+L2})_{theo}]$ / $(\alpha_{L1+L2})_{theo}$ and the retardation is defined as the ratio of the experimental partial γ-ray half-life and the theoretical single-particle half-life. Our data in ^{245}Cm are shown as filled diamonds.