PHYSICAL REVIEW C VOLUME 47, NUMBER 1 JANUARY 1993

^{223}Ra levels fed in the ^{223}Fr β decay

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(Received 27 February 1992)

The ^{223}Fr β decay was reinvestigated using high-resolution single γ spectrometry as well as γ-γ coincidence techniques. For single γ-spectra measurements, radiochemically pure ^{223}Fr sources were obtained by chromatographic separation from a 75 MBq activity ^{227}Ac parent source and continuously purified of ^{223}Ra and daughters. The analysis of the γ spectra of 30 sources showed the existence of 131 γ lines, of which 87 are reported for the first time in the ^{223}Fr β decay although many of them are observed following the ^{227}Th α decay. The ^{223}Fr half-life was remeasured and found to be $T_{1/2}=22.00\pm0.07$ min. γ-γ-t coincidence measurements were also carried out with ^{223}Fr purified sources. The ^{223}Ra level scheme was built on the basis of our γ data, as well as ^{227}Th α-decay data. Among the 32 excited ^{223}Ra levels, of which 22 were also known from ^{227}Th α decay, 13 are newly reported from ^{223}Fr β decay. Low energy levels ($E<400$ keV) may be classified as parity doublet bands according to the predictions of the reflection asymmetric rotor model. Above a 700 keV gap, a coexistence of symmetric and asymmetric shapes including both static and dynamic octupole correlations is suggested.

PACS number(s): 23.40.−s, 23.20.Lv, 27.90.+b

I. INTRODUCTION

The study of light actinides has found a renewed interest since the prediction of a static octupole nuclear deformation [1] in the mass range $220<A<230$. In particular, Leander and Chen [2] and Sheline, Chen, and Leander [3] reinterpreted the state properties of the ^{223}Ra nucleus from previous decay data of both ^{227}Th and ^{223}Fr nuclei. However, the main study of the ^{223}Fr β decay, carried out by Maria *et al.* [4] with a low-efficiency Ge(Li) detector, did not allow the observation of γ lines in the 300–700 keV energy range. We therefore thought it useful to reinvestigate this decay for higher-energy ^{223}Ra low-spin levels unreachable by nuclear reactions. As such, we used an improved radiochemical separation, using an intense ^{227}Ac source, in which the ^{223}Ra in growth from the ^{223}Fr parent was continuously discarded during counting time; the gamma spectra were mainly measured with a 40% relative efficiency HPGe detector. Moreover, γ-γ coincidence measurements were performed to help in the placement of the γ transitions in the ^{223}Ra level scheme.

II. EXPERIMENTAL PROCEDURES

A. Radiochemical procedure

A 75-MBq-activity ^{227}Ac mother source was prepared by chromatographic separation from a 200-mg-weighted stock of $^{231}Pa_2O_5$ having undergone no chemical treatment for 20 years [5]. This source was first brought to 8M HNO_3 and poured through a Dowex 1X-8 anionic exchanger column ($l=10$ cm, $\Phi=2$ mm), to fix ^{227}Th as nitrato complexes. The eluate, containing ^{227}Ac as well as ^{223}Ra and the short-lived ^{223}Fr, ^{211}Pb, ^{211}Bi, and ^{207}Tl activities, was evaporated to dryness and then dissolved in 0.02M HNO_3. The purification of ^{227}Ac was achieved by adsorption on a column of bis(2-ethylhexyl)phosphoric acid (HDEHP) adsorbed on Voltalef; ^{223}Fr was eluted afterwards with 1.5 cm^3 of 0.001M HNO_3, after first having washed the column with 2.5 cm^3 of 0.02M HNO_3 to elute ^{223}Ra and let ^{223}Fr grow in for 40 min. However, preliminary spectra of separated ^{223}Fr sources showed that the ^{223}Ra growth during counting times of 10 min, i.e., half the ^{223}Fr half-life ($T_{1/2}=22$ min), contributed about 0.2% of the total activity (measured on its 269.4 keV γ line). So we decided to perform a further purification by eluting the ^{223}Ra continuously from the ^{223}Fr sources prepared as described above. The ^{223}Fr sources were dissolved in 0.01M sodium ethylenediamine tetracetate salt (NaEDTA), at pH=9, and fixed on a column of composite NCF ion exchange (nickel composite ferrocyanide) [6] continuously washed with the EDTA solution by means of a peristaltic pump (Fig. 1). Under these conditions, ^{223}Fr is selectively adsorbed on the NCF exchanger while ^{223}Ra and other divalent cations are eluted [7].

B. Counting equipment

The γ spectrometer consisted of a 40%-relative-efficiency HPGe detector (Canberra), with an energy resolution [full width at half maximum (FWHM)] of 1.80 keV at the 1.333 MeV γ photopeak of ^{60}Co. Pulses, amplified by a 672 (EG&G Ortec) amplifier, were ana-

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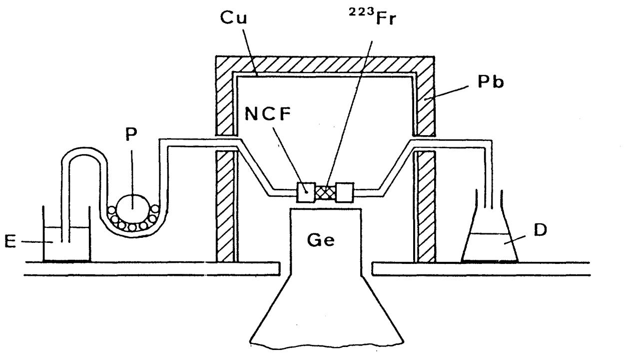

FIG. 1. Experimental setup used to count ^{223}Fr γ-ray spectra in continuous elution of ^{223}Ra and its daughters. *P*, peristaltic pump; NCF, nickel ferrocyanide composite exchanger column; Ge, 40% HPGe coaxial detector; *E*, 0.01M NaEDTA elutriant; *D*, daughter products (Ra,Bi,Rn,Pb,...).

lyzed with a 4096-channel analog-to-digital converter card plugged in an IBM PC microcomputer. For low-energy γ- and x-ray measurements, we also used an HPGe LEPS planar detector of 2000 mm^2 active area, with a resolution (FWHM) of 0.50 keV at the 122 keV γ line of ^{57}Co. All single γ ray measurements were carried out in a 5-cm-thick lead castle internally covered with a 1.5-mm-thick copper sheet.

III. MEASUREMENTS

A. Single γ-ray spectra measurements

The γ spectrometers described above were calibrated in energy and efficiency using counting runs with standard multigamma sources such as ^{152}Eu and ^{133}Ba, as well as ^{241}Am for low-energy γ and x rays.

The ^{223}Fr sources were poured through the NCF column placed in front of the HPGe coaxial detector. At the beginning the counting rate was about 2000 counts/s, and each source could be measured for 30–40 min. Thirteen ^{223}Fr sources were recorded separately to check their purity and summed afterward. A fraction of the total spectrum thus obtained is shown in Fig. 2. Other measurements of ^{223}Fr spectra have been performed by inserting a 1.5-mm-thick copper foil between source and detector to decrease the low-energy γ-ray counting rate, mainly due to the intense 50.1 keV γ transition and to stop the hard β component ($E_\beta = 1.10$ MeV) to the ^{223}Ra second excited state.

Low-energy γ spectra were measured without absorbent using the LEPS detector. The spectrum displayed in Fig. 3 was obtained by addition of nine sources, each counted for 10 min. The energies and relative intensities of the γ lines assigned to ^{223}Fr decay were deduced using the GAMANAL computer code [8] running on a VAX 8530 computer. Table I summarizes the results obtained in the present work and compares them, on the one hand,

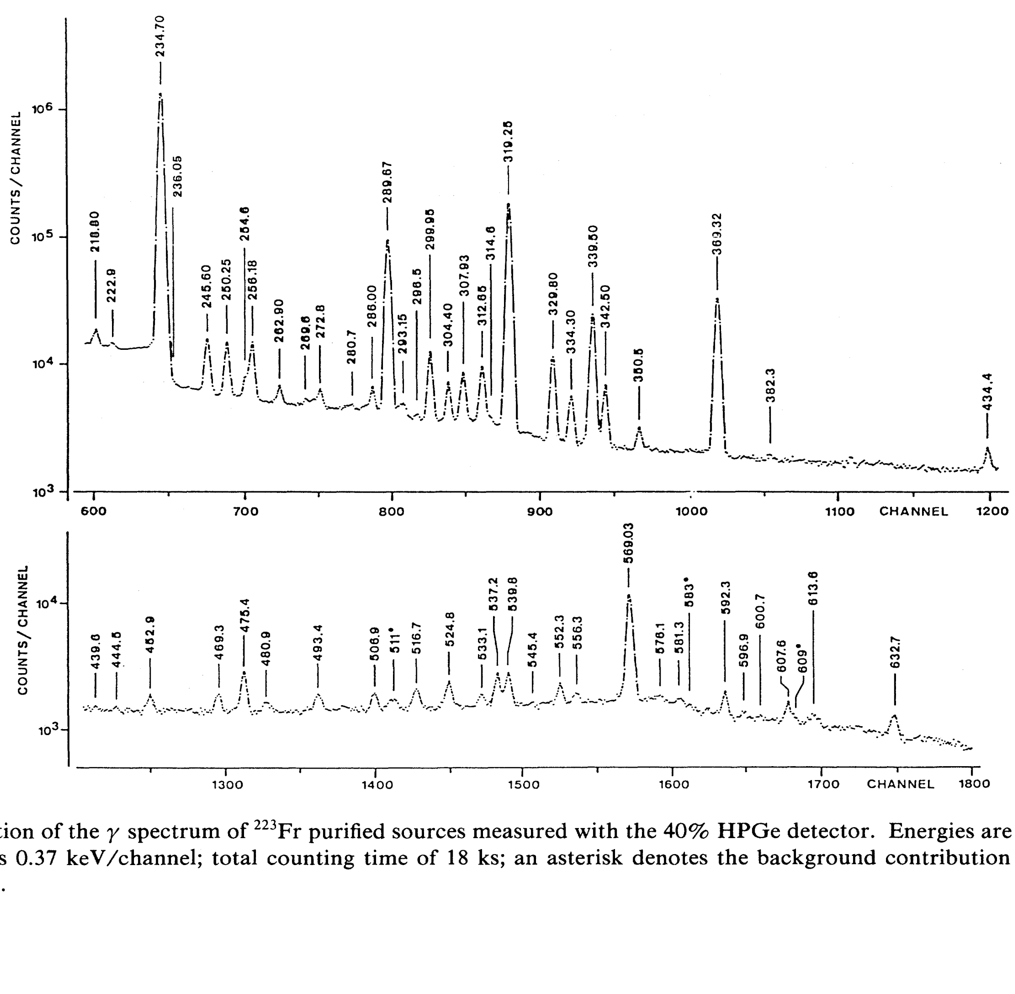

FIG. 2. Portion of the γ spectrum of ^{223}Fr purified sources measured with the 40% HPGe detector. Energies are in keV; the energy dispersion is 0.37 keV/channel; total counting time of 18 ks; an asterisk denotes the background contribution from natural radioactive series.

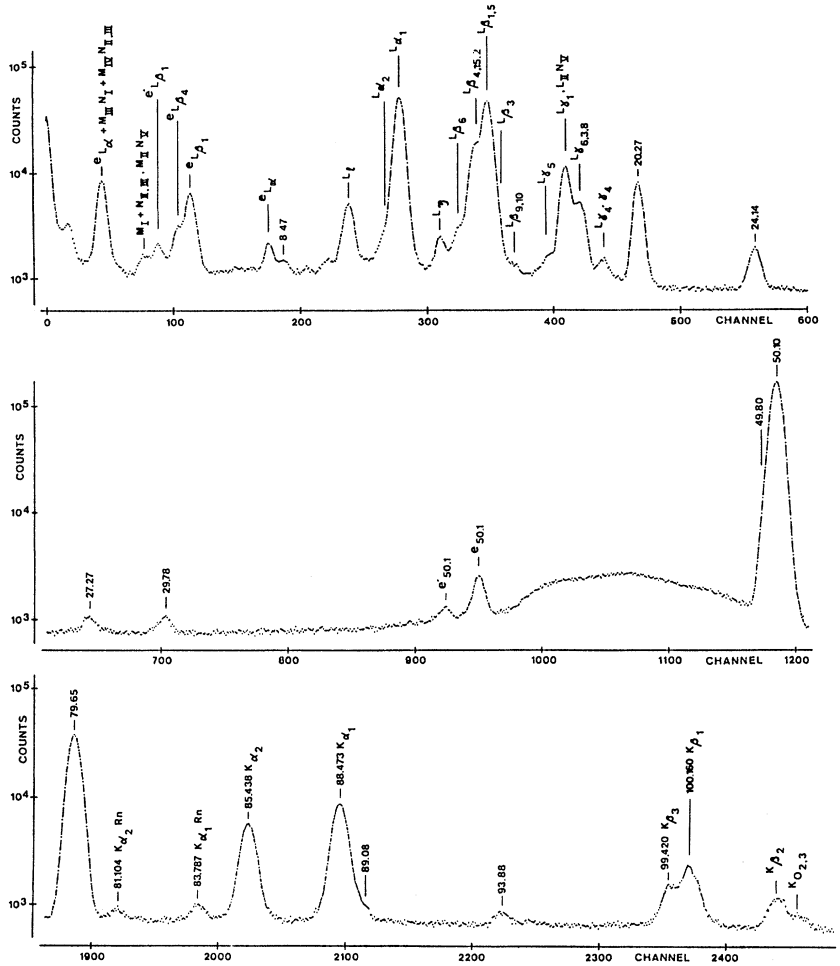

FIG. 3. Low-energy spectrum of ^{223}Fr measured with the 20 cm^3 HPGe LEPS detector. Energies are in keV; the energy dispersion is 0.042 keV/channel. Ra X_L lines are labeled. *e* and *e'* denote, respectively, the K_α and K_β escape in the Ge detector.

TABLE I. Energy, intensity, and placement of the γ rays following the ^{223}Fr β decay and ^{227}Th α decay. The 1σ uncertainties, in parentheses, are given as the last digit(s) of the values.

^{223}Fr β decay: Present work				Maria *et al.* [4]		^{227}Th α decay Ref. [9]	
E_γ (keV)	I_γ (rel)	Initial level (keV)	Final level (keV)	E_γ (keV)	I_γ (rel)	E_γ (keV)	I_γ (rel)
						6.5(3)	0.7(2)
						8.3(2)	0.06(2)
20.27(5)	53(5)	50.09	29.78			20.19(5)	1.9(2)
						20.8(2)	0.05(2)
						22.0(2)	0.07(7)
24.14(3)	9.5(7)	a				24.13(5)	0.68(5)
27.27(3)	2.3(4)	a				27.32(5)	0.23(4)
29.78(4)	2.6(4)	29.78	0.0			29.86(5)	0.56(8)
31.69(5)[b]	0.05[c]	61.45	29.78			31.56(5)	0.51(8)
						33.3(2)	0.06(2)
						40.20(3)	0.12(3)
						41.91(5)	0.12(3)
43.5(2)[b]	0.08[c]	329.80	286.06			43.75(5)	1.6(1)

TABLE I. (*Continued*).

^{223}Fr β decay: Present work E_γ (keV)	I_γ (rel)	Initial level (keV)	Final level (keV)	Maria *et al.* [4] E_γ (keV)	I_γ (rel)	^{227}Th α decay Ref. [9] E_γ (keV)	I_γ (rel)
44.0(1)[b]	0.05[c]	123.75	79.62			44.33(5)	0.4(1)
						48.1(2)	0.12(3)
49.80(5)	93(8)	79.62	29.78			49.75(5)	3.3(5)
50.10(2)	1224(50)	50.09	0.0	50.8(5)	1000	50.11(2)	63(2)
						50.8(2)	0.11(5)
						54.1(1)	0.05(1)
						56.3(2)	0.12(2)
61.43(5)[b]	0.13[c]	61.45	0.0	61.0(15)	< 8	61.42(5)	0.70(8)
62.31(6)	0.6(2)	123.75	61.45			62.33(5)	1.5(2)
						62.7(2)	0.05(2)
						64.5(2)	0.19(3)
						65.2(1)	0.13(3)
						68.72(5)	0.53(4)
						69.8(3)	0.08(3)
						72.85(5)	0.32(4)
73.5(1)	0.05(3)					73.8(2)	0.07(2)
						75.00(5)	0.29(3)
79.65(2)	335(20)	79.62	0.0	80.0(4)	240(24)	79.66(3)	15.1(5)
89.08(10)	2.0(1)	369.33	280.2			89.17(8)	0.03(1)
93.88(5)	2.2(3)	123.75	29.78			93.86(5)	11.9(5)
						94.9(1)	0.30(4)
						96.02(5)	0.6(1)
						99.5(2)	0.20(5)
						100.2(2)	0.7(2)
						106.1(2)	0.03(1)
						107.9(2)	0.05(2)
						108.9(3)	0.03(1)
111.05(3)	0.18(4)	234.73	123.75			110.7(2)	0.04(1)
						113.06(2)	6.6(3)
						117.20(5)	1.7(1)
						123.6(1)	0.14(2)
						124.4(2)	0.04(2)
						128.02(2)	0.025(4)
						129.4(2)	0.010(5)
134.60(2)	18.5(5)	369.33	234.73	134.4(4)	16.0(16)	134.6(1)	0.30(5)
						138.4(1)	0.11(2)
						140.5(3)	0.05(2)
						141.34(5)	1.1(1)
150.6(4)	0.10(3)	a				150.1(2)	0.07(3)
155.5(5)[b]	0.1[c]	234.73	79.62				
						162.2(1)	0.07(2)
						164.5(1)	0.11(2)
						168.4(1)	0.11(2)
						169.7(2)	0.06(2)
						171.5(2)	0.03(1)
173.35(5)	4.26(5)	234.73	61.45	173.1(5)	4.0(4)	173.45(5)	0.16(2)
						181.1(3)	0.02(1)
						182.3(2)	0.03(1)
184.65(5)	8.27(5)	234.73	50.09	184.5(5)	9.0(9)	184.65(5)	0.29(3)
						197.5(1)	0.07(2)
200.7(2)	0.10(3)	280.2	79.62			200.5(1)	0.17(2)
						201.7(1)	0.16(2)
						204.2(1)	1.7(2)
204.85(5)	33.7(3)	234.73	29.78	204.8(4)	34.0(34)	204.9(1)	1.2(2)

TABLE I. (*Continued*).

	^{223}Fr β decay Present work			Maria *et al.* [4]		^{227}Th α decay Ref. [9]	
E_γ (keV)	I_γ (rel)	Initial level (keV)	Final level (keV)	E_γ (keV)	I_γ (rel)	E_γ (keV)	I_γ (rel)
205.6(2)[b]	0.22[c]	329.80	123.75			206.05(6)	1.9(2)
210.60(5)	0.36(2)	334.27	123.75			210.58(5)	9.4(3)
						212.76(5)	0.63(5)
						216.0(1)	0.002(1)
218.80(5)	0.32(2)	280.2	61.45			218.89(5)	0.83(8)
222.9(3)	0.08(2)	a				222.8(2)	0.04(1)
						225.9(1)	0.07(2)
						229.4(2)	0.03(1)
234.70(5)	100[d]	234.73	0.0	234.6(4)	100[d]	234.7(1)	3.4(3)
236.05(5)	1.0(2)	286.06	50.09			235.94(3)	100[d]
245.60(5)	0.71(3)	369.33	123.75	246(1)	1.3(4)	246.1(1)	0.10(3)
						248.1(1)	0.19(4)
250.25(5)	0.11[c]	329.80	79.62	250.6(10)	1.3(4)	250.19(3)	4.0(3)
	0.58[c]	280.2	29.78			250.1(2)	0.08(2)
						252.50(5)	0.9(2)
254.6(2)	0.21(2)	334.27	79.62			254.62(3)	5.6(3)
256.18(5)	0.75(3)	286.06	29.78	256(1)	1.3(4)	256.22(2)	54(1)
						260.6(2)	0.04(1)
262.9(2)	0.13(3)	342.46	79.62			262.85(5)	0.9(1)
						265.3(2)	0.04(1)
						267.0(2)	0.08(2)
						267.7(2)	0.06(2)
269.6(3)	0.03(1)	a					
						270.6(2)	0.16(3)
272.8(2)	0.15(2)	334.27	61.45			272.90(5)	3.9(2)
						279.7(5)	0.35(5)
280.7(5)	0.02[c]	280.2	0.0			280.4(2)	0.02(1)
	0.02[c]	342.46	61.45			281.42(5)	1.4(1)
						284.2(1)	0.4(1)
						285.6(2)	0.25(5)
286.0(2)	0.17(2)	286.06	0.0	286.0(15)	0.52(15)	286.06(2)	15(1)
289.67(5)	1.0[c]	369.33	79.62	289.6(15)	7.2(7)	289.6(1)	15(3)
	6.7[c]	a				289.8(1)	0.15(3)
293.2(2)	0.14(3)	a				292.41(5)	0.52(6)
296.5(2)	0.05(1)	376.1	79.62			296.50(5)	3.3(3)
299.95(5)	0.75(4)	329.80	29.78	300.0(15)	1.3(4)	299.95(3)	17.3(5)
						300.8(2)	0.11(2)
304.40(5)	0.32(2)	334.27	29.78	304.2(15)	0.67(20)	304.47(3)	8.6(5)
						306.1(3)	0.08(3)
307.93(5)	g	369.33	61.45	307.3(15)[e]	0.90(27)	308.40(5)	0.14(2)
	0.45(5)	593.9	286.06				
312.65(5)	0.60(5)	342.46	29.78	313.3(15)[e]	0.75(22)	312.69(3)	4.0(3)
314.6(2)	0.08(2)	376.1	61.45			314.85(4)	3.7(3)
319.25(5)	17.0(5)	369.33	50.09	319.0(5)	16.2(16)	319.24(5)	0.30(3)
						324.8(2)	0.08(2)
						325.7(3)	0.07(3)
						326.7	
329.80(5)	0.90(5)	329.80	0.0	330.0(15)	1.0(3)	329.85(2)	21.7(5)
						332.2(2)	0.013(4)
334.30(6)	0.31(2)	334.27	0.0	333.1(15)[e]	0.45(13)	334.36(2)	8.2(3)
339.50(5)	2.3(2)	369.33	29.78	338.7(10)	2.0(4)	339.6(2)	0.03(1)
342.50(7)	0.43(4)	342.46	0.0	343.0(15)	0.90(27)	342.56(4)	3.4(1)
						346.48(5)	0.10(1)
350.5(2)	0.10(5)	350.5	0.0			350.66(2)	0.9(2)

TABLE I. (*Continued*).

	Present work	^{223}Fr β decay		Maria *et al.* [4]		^{227}Th α decay Ref. [9]	
E_γ (keV)	I_γ (rel)	Initial level (keV)	Final level (keV)	E_γ (keV)	I_γ (rel)	E_γ (keV)	I_γ (rel)
						362.7(1)	0.04(1)
369.32(5)	3.3(2)	369.33	0.0	369.0(5)	3.2(3)	369.5(5)	0.05(1)
						371.0(1)	0.06(2)
						376.0(3)	0.04(1)
						379.4(1)	0.08(2)
382.3(2)	0.03(1)	a				381.9(1)	0.05(1)
						383.51(4)	0.37(5)
						398.2(2)	0.011(3)
						401.9(1)	0.10(3)
						415.1(1)	0.016(3)
						432.4(5)	0.030(4)
434.4(1)	0.08(2)	803.8	369.33				
439.6(3)	0.011(3)	782.5	342.46				
444.5(3)	0.04(1)	787.2	342.46				
452.9(2)	0.03[c]	787.2	334.27			452.9(3)	0.002(5)
	0.03[c]	782.5	329.80				
457.5(2)[b]	0.03[c]	787.2	329.80				
						466.8(2)	0.004(2)
469.3(2)	0.04[c]	593.9	123.75				
	0.04[c]	803.8	334.27			469.0(2)	0.007(2)
475.4(1)	0.11[c]	825.9	350.5				
	0.10[c]	805.4	329.80				
480.9(3)	0.05(1)	823.2	342.46				
493.4(2)	0.09(2)	823.2	329.80				
506.9(2)	0.08(2)	787.2	280.2			507.5(1)	0.007(2)
516.7(2)	0.12(2)	846.3	329.80			516.7(3)	0.003(1)
						521.8(3)	0.003(1)
524.8(2)	0.16(3)	867.3	342.46			524.7(4)	0.0018(4)
533.1(3)	0.07(2)	867.3	334.27				
						534.5(4)	0.001
537.2(2)	0.07[c]	867.3	329.80				
	0.12[c]	823.2	286.06			536.9(1)	0.013(2)
539.8(2)	0.22(5)	825.9	286.06			540.2(3)	0.002(1)
545.4(4)	0.011(3)	825.9	280.2				
552.3(2)	0.10(2)	787.2	234.73				
556.3(3)	0.04(1)	842.2	286.06			556.0(2)	0.004(1)
						565.4(1)	0.011(2)
569.03(8)	1.8(2)	803.8	234.73			569.4(5)	0.010(2)
576.1(4)	0.04(1)	905.9	329.80			576.0(2)	0.004(1)
						579.0(2)	0.006(2)
581.3(4)	0.05(1)	867.3	286.06				
						585.8(1)	0.007(2)
592.3(2)	0.12(3)	926.5	334.27				
596.9(4)	0.03(1)	926.5	329.80				
						598.9(2)	0.005(1)
600.7(4)	0.020(5)	943.3	342.46				
607.6(3)	0.08(2)	842.2	234.73			607.8(3)	0.002(1)
613.6(4)	0.04(1)	943.3	329.80				
						623.8(5)	0.002(1)
632.7(3)	0.08(2)	867.3	234.73				
						644.3(3)	0.0010(3)
						662.5(3)	0.003(1)
663.7(3)	0.04(1)	787.2	123.75				
671.9(4)	0.020(5)	957.7	286.06				
682.3(3)	0.03(1)	a					

TABLE I. (*Continued*).

	^{223}Fr β decay Present work			Maria *et al.* [4]		^{227}Th α decay Ref. [9]	
E_γ (keV)	I_γ (rel)	Initial level (keV)	Final level (keV)	E_γ (keV)	I_γ (rel)	E_γ (keV)	I_γ (rel)
694.6(3)	0.03(1)	a					
708.3(3)	0.05(1)	787.2	79.62				
722.65(5)	1.4(2)	846.3	123.75	723(1)	1.5(3)		
						723.5(1)	0.008(2)
724.15(5)	0.52(8)	803.8	79.62				
						735.4(2)	0.002(1)
737.4(3)	0.033(8)	787.2	50.09				
742.4(3)	0.04(1)	803.8	61.45				
746.30(5)	0.74(8)	825.9	79.62	746.5(15)	0.70(15)		
						749.2(1)	0.004(1)
753.65(5)	0.35(5)	803.8	50.09			754.1(2)	0.003(1)
757.20(5)	0.28(5)	787.2	29.78	756(2)	0.40(8)	757.7(1)	0.010(2)
762.6(2)	0.09(2)	842.2	79.62			763.1(2)	0.003(1)
766.64(5)	0.83(8)	846.30	79.62	766.5(20)	0.80(16)		
						773.5(4)	0.0013(3)
775.83(5)	16.8(5)	825.9	50.09	776.0(6)	12.3(12)	776.3(1)	0.013(2)
780.8(1)	0.11(3)	842.2	61.45			781.5(2)	0.0025(8)
784.93(5)	0.32(5)	846.3	61.45	784(2)	0.70(15)		
787.6(2)	0.10(2)	867.3	79.62			787.7(5)	0.0011(3)
	g	787.20	0.0				
792.2(3)	0.020(5)	842.2	50.09	793.(2)	0.40(6)		
796.22(5)	0.40(5)	846.3	50.09	797.5(20)	0.30(6)		
						797.7(1)	0.008(1)
803.77(5)	2.2(3)	803.8	0.0	804(1)	1.70(25)	804.2(1)	0.009(1)
806.0(2)	0.05(1)	805.4	0.0				
						808.6(4)	0.0006(2)
812.40(6)	0.78(8)	842.2	29.78	813(2)	0.60(9)	813.0(1)	0.024(5)
816.5(2)	0.05(1)	940.8	123.75				
						818.1(2)	0.0019(5)
823.20(7)	0.26(3)	823.2	0.0	821.5(25)	0.30(9)	823.8(1)	0.024(5)
825.95(7)	2.0(3)	825.9	0.0	826(1)	1.4(2)	826.9(5)	0.0012(4)
						829.0(2)	0.006(2)
833.9(2)	0.05(1)	957.7	123.75				
837.5(1)	0.36(4)	867.3	29.78	835(2)	0.20(6)	838.2(2)	0.005(1)
842.2(1)	0.18(2)	842.2	0.0	840.5(20)	0.20(6)	842.8(1)	0.007(1)
846.85(10)	2.0(3)	926.5	79.62	847(1)	1.4(2)	847.8(3)	0.003(1)
	g	846.3	0.0				
				860(2)	0.10(3)	858.9(2)	0.003(1)
863.6(1)	0.14(2)	943.3	79.62	864.(2)	0.10(3)		
867.4(1)	0.06(1)	867.3	0.0			867.1(5)	0.004(1)
876.5(1)	1.4(2)	926.5	50.09	876.5(10)	1.3(2)	876.5(5)	0.0023(6)
878.1(2)	0.12(2)	957.7	79.62			878.2(4)	0.0015(5)
893.1(2)	0.09(2)	943.3	50.09	892(3)	0.10(3)		
896.7(2)	0.50(5)	926.5	29.78	897.5(20)	0.50(8)		
907.6(2)	0.53(5)	957.7	50.09	908(2)	0.40(7)		
						908.9(1)	0.021(2)
911.3(2)	0.03(1)[f]	940.8	29.78				
913.6(3)	0.015(5)	943.3	29.78				
926.5(3)	0.06(1)	926.5	0.0				
941.2(3)	0.11(2)	940.8	0.0				
949.3(4)	0.012(3)	1028.9	79.62				
958.0(7)	0.013(3)	957.7	0.0				
969.2(4)	0.012(3)[f]	1019.2	50.09				
						970.3(2)	0.0020(5)
975.2(5)	0.006(2)	1024.6	50.09				

TABLE I. (*Continued*).

	^{223}Fr β decay Present work			Maria *et al.* [4]		^{227}Th α decay Ref. [9]	
E_γ (keV)	I_γ (rel)	Initial level (keV)	Final level (keV)	E_γ (keV)	I_γ (rel)	E_γ (keV)	I_γ (rel)
978.7(4)	0.025(5)	1028.9	50.09				
989.4(5)	0.005(1)	1019.2	29.78				
994.3(3)	0.004(1)	1024.6	29.78				
999.3(5)	0.007(2)	1028.9	29.78				
1025.1(5)	0.005(1)	1024.6	0.0				

[a]γline unplaced in the ^{223}Ra level scheme.
[b]Only seen in coincidence experiments.
[c]Relative intensity deduced from γ-γ coincidence measurements.
[d]Intensity used for the normalization.
[e]γ uncertain from Ref. [4].
[f]Intensity corrected for a weak background contribution.
[g]The intensity of this component is less than 10% of the total transition intensity.

with those of Maria *et al.* [4], who used a 2 cm^3 Ge(Li) detector having a 4 keV energy resolution at 280 keV, and, on the other hand, with those measured in our study of the ^{227}Th α decay [9]. It can be noted that among 131 γ lines reported in Table I, 87 are new with respect to the most extensive study of ^{223}Fr decay published by Maria *et al.* [4], but many of them have been observed following the ^{227}Th alpha decay. Their energy and intensity values are in fair agreement with those reported by these authors, except for the two intense low-energy γ rays of 50.0 and 79.6 keV, for which our intensities are 30% higher, but remain in good agreement with those published by Mitsugashira, Yamana, and Suzuki [10], who used a 20%-efficiency Ge detector. Some γ rays, considered as questionable in Ref [4], were confirmed in this study, and their energy and intensity values were improved.

The presence of the new 569.03 keV γ line to the ^{223} Fr β decay was carefully checked, since very-close-lying γ rays of 569.15 keV are also found in both ^{207}Ti and ^{211}Po decays [11] associated with the ^{223}Ra decay chain; this γ line decays with the 22 min ^{223}Fr half-life.

B. γ-γ coincidence measurements

The system consisted of three *n*-type HPGe coaxial detectors of 18% relative efficiency, placed at respective angles of 90°, 180°, and 270° from the 2000 mm^2-area HPGe planar detector described above. Each detector was covered with a graded lead-copper collimator with a 4-cm-diam hole to reduce coincidence from higher-energy photons which could be Compton scattered from one detector into the others. The NCF column, on which ^{223}Fr activity was fixed, was placed at the center of the setup. The distance of the column from each detector was 4.5 cm. Three parameters were recorded on magnetic tapes using the acquisition system MIPRE. For every γ-γ-t coincidence, the width of the prompt time distribution was about 30 ns FWHM. About 1.7×10^7 events were stored in a 2 day experiment needing the preparation of 35 ^{223}Fr sources fixed on the NCF column and continuously eluted as described above. The counting rate on each detector was held between 8000 and 15 000 s^{-1} by splitting up each source.

The analysis of the different coincidence spectra was performed off line on a VAX 8530 computer. The sorting routine allowed the subtraction of random events as well as coincidence events due to the underlying Compton distribution. About 80 γ-γ coincidence matrices 4096×4096 were obtained by sorting these γ-γ-t data with various energy and time gates. Typical spectra obtained from prompt coincidences with selected gates are shown in Fig. 4. Compton-scattered (CS) peaks are easily detected in coincidence spectra, since they appear as positive-negative peak pairs in the coincidence spectra by subtraction of the Compton contribution, with half-widths depending on the width of the coincidence gate.

Table II summarizes the energy of the γ lines in prompt coincidence with various gates taken with coaxial as well as planar HPGe detectors.

IV. ^{223}Fr HALF-LIFE MEASUREMENT

Since the most recent value of the ^{223}Fr half-life, $T_{1/2}=21.8\pm0.4$ min, was measured by Lieser and Kluge [12] in 1967, from β and γ counting with scintillation and Geiger-Muller counters, we decided to remeasure this half-life with a HPGe detector whose energy resolution allows us to clearly distinguish possible impurities in the sources. A ^{223}Fr source, separated by HDEHP elution as described above (Sec. II A), was fixed in front of the 40% HPGe detector and counted for 60 s at fixed intervals of 120 s. The counting rate was followed for ten half-lives, and the analysis was performed either on the total γ spectra or on the 236.1 keV γ line. The improved half-life value $T_{1/2}=22.00\pm0.07$ min was obtained as the weighted value of the two half-life values deduced for the 236.1 keV γ line and total ^{223}Fr activities using a standard least-squares fitting program.

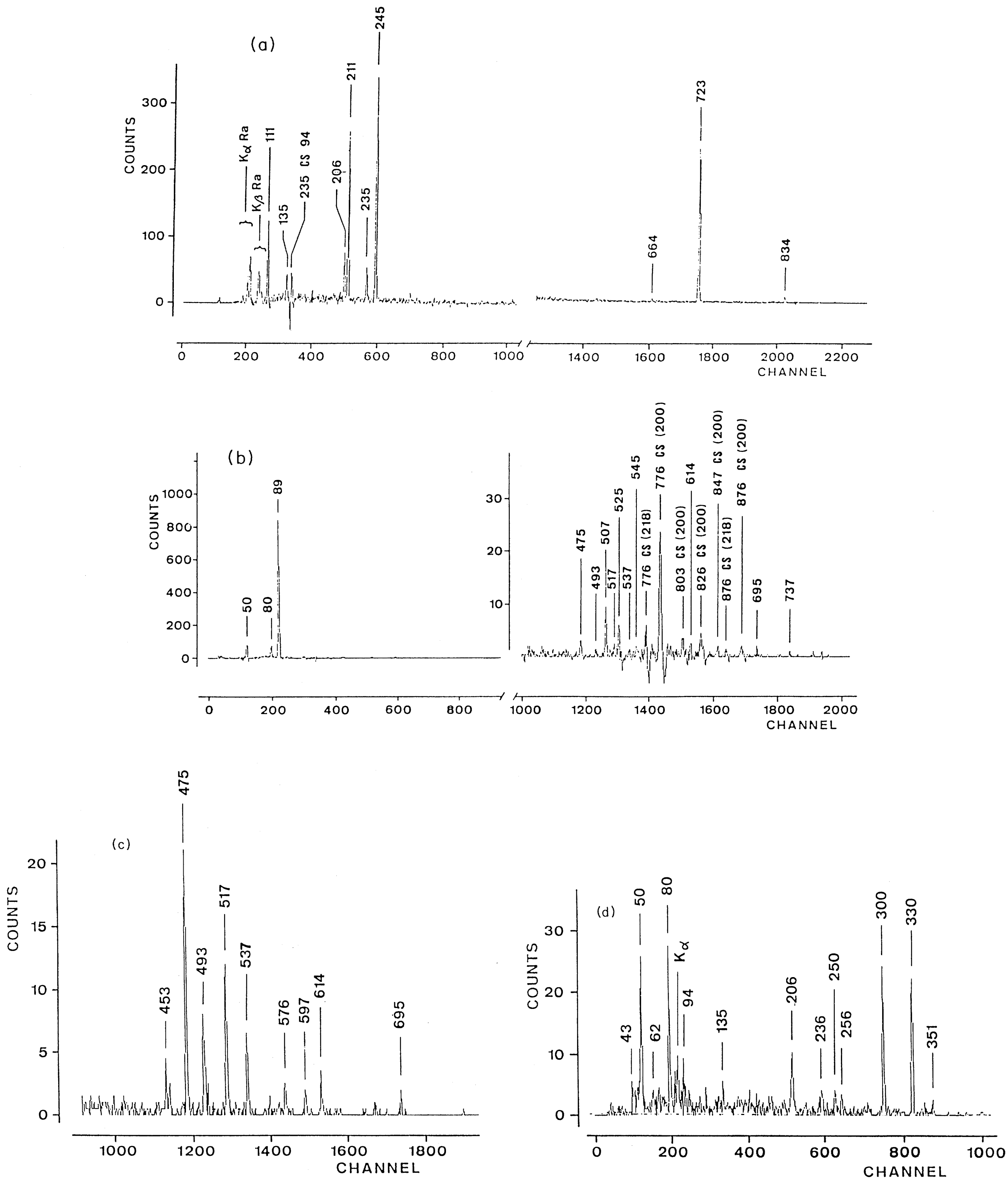

FIG. 4. Typical ^{223}Fr γ-γ coincidence spectra sorted with different gates: (a) sum of 62+94 keV gates, (b) sum of 200+218 keV gates, (c) sum of 300+330 keV gates, and (d) sum of 475+495 keV gates. Energies are in keV. Bipolar peaks appears at locations labeled C.S., in the subtraction process of the Compton contribution when a γ line of energy E_γ is Compton scattered from one detector to another with a gate of energy E_g. The energy E_g is left in the gated detector and the complementary energy $(E_\gamma - E_g)$ in the other detector.

TABLE II. Summary of the γ-γ coincidence data obtained with the three coaxial HPGe detectors and the HPGe planar detector. Energies are in keV; parentheses indicate weak evidence; X means ^{223}Ra K_α X lines.

Gate energy (keV)	Coincident γ lines (keV)
20.27	134.6, 184.65, 319.25, 775.83, 876.5, 907.6
24.14	X_L, (44.0), 50.1, 79.65, 134.6, 173.35, 184.65, 204.85, 234.7, 289.67, 319.25, (775.83)
29.78	X_L, 49.80, (73.5), 79.65, (134.6), 173.35, 204.85, 289.67, 319.25, 339.50
43.5+44.0	79.65, 134.6, 173.35, 184.65, 204.85, 234.7, 236, 256.18, (269.6), 289.67, 319.25, 475.4, (576.1), 775.8
50.10	X_L, 20.27, 29.78, 134.6, (173.35), 184.65, 236.0, 289.67, 319.25, (339.5), (369.3), 537.15, 539.8, 569.05, 724.15, 737.4, 746.3, 753.65, 766.64, 775.85, 796.22, (812.4), 846.85, 876.5, 893.1, (896.7), 907.6
61.4	173.35, 272.8 (722.65)
62.31	111.05, (205.60), 210.6, 245.6, 289.67, 722.65, 833.9
79.65	X_L, 173.35, 184.65, 200.7, 210.6, 245.6, 250.25, 254.6, 262.9, 289.67, 434.4, 469.3, (569.03), 708.3, 724.15, 746.3, 762.6, 766.64, 787.6, 846.85, 863.6, (878.1)
89.08	(150.6), 200.7, 218.8, 250.25, 280.7
93.88	111.05, (205.6), 210.6, 245.6, 663.7, 722.65, 833.9
134.6	X_L, 20.27, 24.14, 29.78, 50.1, 79.65, 111.05, (155.5), 173.35, 184.65, 204.85, 234.7, 434.4
173.35	X_L, 24.14, 29.78, (31.69), 61.4, 134.6, 569.03
184.65	X_L, 20.27, 50.1, 134.6, 569.03
200.7	X_L, 49.80, 79.65, 89.08, 506.9, 545.4
204.85+205.6	X_L, 29.78, 62.31, 93.68, 134.6, 569.03, 607.6, 632.7
210.6	X_L, 29.78, (44.0), 50.1, 62.31, (73.5), 79.65, 93.88, 452.9, 469.3, 533.1, 592.3
218.8	X_L, 89.08, 506.9
245.6	X_L, (44.0), 50.1, 62.31, (73.5), 79.65, 93.88, (124)
250.25	X_L, 49.8, 79.65, 89.08, 475.4, 506.9, (516.7), 576.1, (613.6)
254.6	49.8, 79.65
256.18	X_L, (434.4), 537.2, 539.8, (581.3)
289.67	X_L, 29.78, 49.8, 79.65, (434.4)
299.95	X_L, 452.9, 475.4, 493.4, 516.7, 537.2, 576.1, 596.9, 613.6, (694.6)
304.4	X_L, 29.78, (43.5), 452.9, 469.3, 533.1, 592.3
307.93	X_L, 236, 256.18, 286.0
312.65	X_L, 29.78, 439.6, 480.9, 524.8
319.25	X_L, 20.27, 24.14, 29.78, 50.1, (319.25), 434.4
329.80	X_L, 452.9, 475.4, 493.4, 516.7, 537.2, 576.1, 596.9, 613.6
334.3	X_L, 469.3, 533.1, 592.3
342.50	480.9, 524.8, 600.7
350.5	475.4
434.4	89.08, 134.6, (234.7), 319.25, 339.50
452.9	X_L, (44.0), (93.88), 210.60, (304.4), (329.8), (334.3)
469.3	X_L, (44.0), 50.1, (62.3), 93.88
475.4	X_L, (43.5), 50.1, 62.3, 79.65, 93.88, (205.6), 250.25, 299.95, 329.8, 350.5
493.4	299.95, 329.8, 93.88
506.9	X_L, 50.1, 62.31, 79.65, 93.88, 218.8, 250.25
516.7	X_L, (43.5), (236.0), 256.18, 262.9, 286.0, 304.4, 312.65, 342.5
537.2	X_L, 50.1, (236.0), 256.18, 286.0, 299.95, 329.8
539.8	X_L, 50.1, (205.6), (236.0), 256.18, 286.0
569.03	50.1, 173.35, 184.65, 204.85, 234.7
576.1	(299.95), (329.8)
663.7	62.31, 93.88
722.65	X_L, 62.31, 93.88
724.15	X_L, 49.8, 79.65
737.4	50.1

TABLE II. (Continued).

Gate energy (keV)	Coincident γ lines (keV)
746.3	X_L, 49.8, 79.65
753.65	X_L, 50.1
762.6	X_L, 49.8, 79.65
766.64	X_L, 49.8, 79.65
787.6	X_L, 49.8, 79.65
796.22	X_L, 50.1
816.5	X_L, 62.31, 93.88
846.85	X_L, 49.8, 79.65
863.6	X_L, 49.8, 79.65
876.5	X_L, 50.1
893.1	50.1
907.6	50.1
949.3	X_L, 49.8, 79.65
969.2	X_L, 50.1
975.2	X_L, 50.1

V. ^{223}Fr DECAY SCHEME

A revised ^{223}Ra level scheme fed in the ^{223}Fr β decay was built (Fig. 5), taking into account the data deduced from γ-γ coincidence measurements and the existence of good sum energy relationships. Additional information was gained from a detailed analysis of the ^{227}Th α decay [9,13–15].

The β feedings of the ^{223}Ra levels were calculated from the (γ+c.e.) (c.e. is the conversion electron) intensity balance, using relative γ-ray intensities measured in this work (Table I). For the internal conversion coefficient (ICC) of the most intense low-energy transitions, the experimental values deduced from the ^{227}Th α decay study [15] were used; for other cases, ICC values were deduced by interpolation from the theoretical values of Rösel *et al.* [16].

In the absence of experimental data concerning the β feeding of ^{223}Ra (g.s.), the total β intensity was normalized supposing, as in earlier works, that the ^{223}Ra (g.s.) has no β feeding. The logft values were computed from our measured half-life value (Sec. IV) and the decay energy $Q_{\beta^-}=1147.6\pm2.8$ keV [17]. This assumption results in a 9.5% β feeding [Fig. 5(a)] to the first excited state ($I^\pi=\frac{5}{2}^+$). A more reasonable hypothesis would allow a similar β feeding (i.e., $\approx10\%$) to the $I^\pi=\frac{3}{2}^+$ ground state. This hypothesis would increase logft values reported in Fig. 5 by an amount of 0.05–0.1.

VI. DISCUSSION

The ^{223}Fr ground-state spin $I=\frac{3}{2}$ was well established using optical pumping and magnetic selection of thermal atomic beams [18]. The $\frac{3}{2}^-[532]_p$ main configuration was assigned to the odd proton state [19].

A. $K^\pi=\frac{3}{2}^\pm$ parity doublet

The ^{223}Ra ground-state band $K^\pi=\frac{3}{2}^+$ [20] and the first excited band $K^\pi=\frac{3}{2}^-$ were described as octupole mixed bands $\frac{3}{2}[761]\otimes\frac{3}{2}[631]$, in the framework of the reflexion asymmetric rotor model (ARM), by Sheline, Chen, and Leander [3]. The first excited level $I^\pi=\frac{5}{2}^+$ of the g.s. band is found to decay by the newly measured γ transition of 29.78 keV. The 61.45 keV ($I^\pi=\frac{7}{2}^+$) energy state, considered as uncertain in Ref. [4], is confirmed by the observation of its deexciting γ transitions of 61.43 and 31.69 keV in γ-γ coincidence spectra; the level intensity balance, calculated assuming a pure $E2$ multipolarity for the 61.43 keV transition, means no β feeding according to the selection rules for this ($\Delta I=2,\Delta\pi=$yes) unique first forbidden β transition.

The bandhead of the $K^\pi=\frac{3}{2}^-$ band at 50.09±0.02 keV depopulates by two γ transitions of 50.10 and 20.27 keV, also observed in the ^{227}Th α-decay study [15]. The reduced probability ratio value

$$B(E1;\tfrac{3}{2}^-\to\tfrac{5}{2}^+)/B(E1;\tfrac{3}{2}^-\to\tfrac{3}{2}^+)=0.72\pm0.08\ ,$$

is in agreement with the Alaga ratio value, i.e., 0.665. The 79.66±0.02 keV level ($I^\pi=\frac{5}{2}^-$) depopulates by a 79.65 and a 49.8 keV γ transition which was resolved from the more intense 50.10 keV γ line only by coincidence experiments, but owing to angular correlation effects the intensity balance was obtained from deconvolution in the single γ-ray spectrum rather than in γ-γ coincidence spectra.

The 123.75±0.06 keV ($I^\pi=\frac{7}{2}^-$) state, not reported in the earlier ^{223}Fr decay study [4], was inferred from its deexcitation by four transitions of 93.88, 73.5, 62.31, and 44.0 keV energy, to the respective $I^\pi=\frac{5}{2}^+$, $\frac{3}{2}^-$, $\frac{7}{2}^+$, and $\frac{5}{2}^-$ lower levels. The β-feeding value <0.2%, deduced for this level (log$ft>8$), is consistent with the charac-

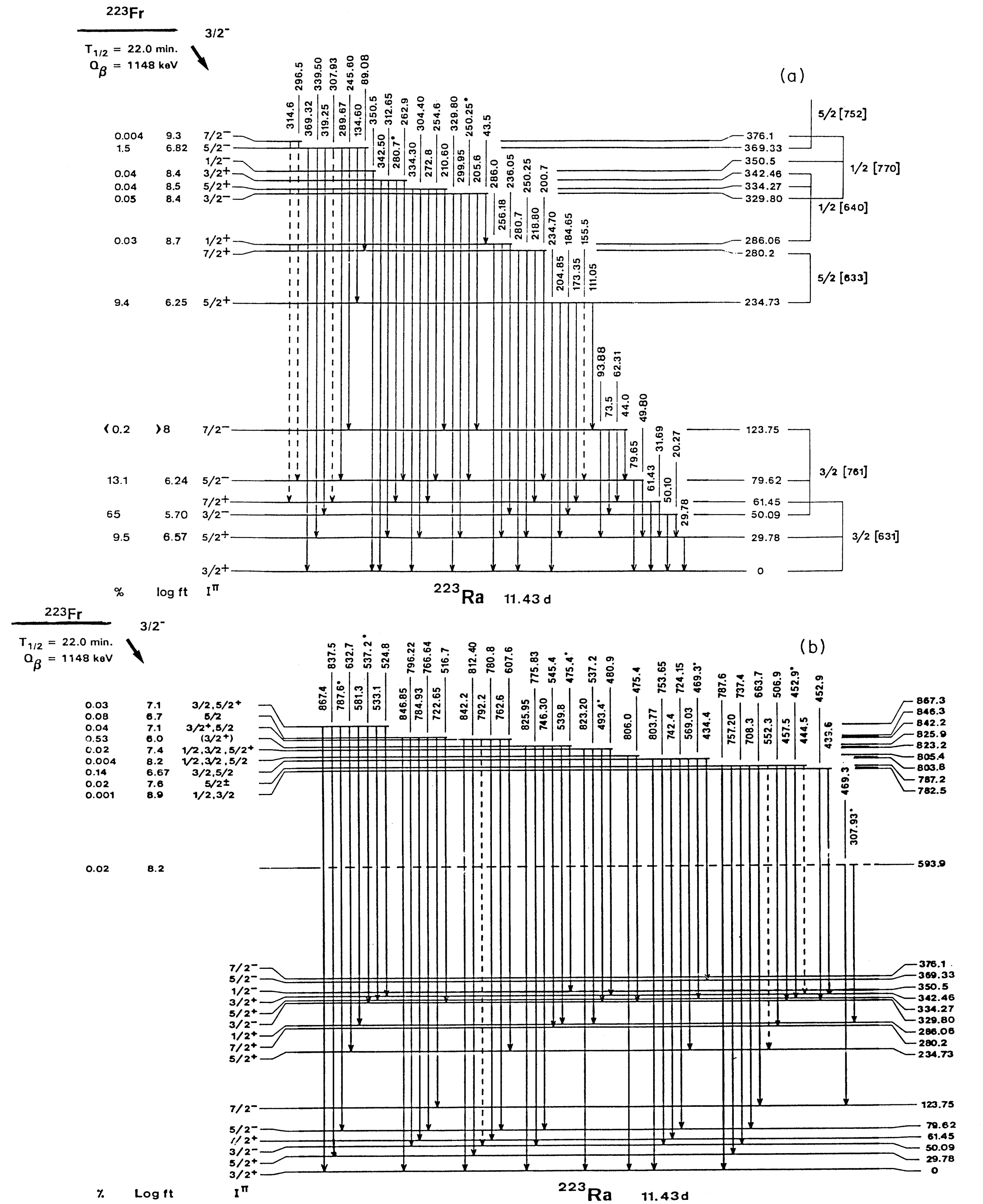

FIG. 5. (a) Level scheme of ^{223}Ra (0–400 keV) fed in the ^{223}Fr β decay. Energies are in keV; spins and parities of energy levels with $E<400$ keV are taken from Ref. [15]. Low-lying parity mixed bands are labeled according to their dominant Nilsson components. Asterisk denotes a γ line placed twice; γ transitions drawn as dashed lines are only placed on the basis of good energy sum relationships. (b) Level scheme of ^{223}Ra (500–870 keV) fed in the ^{223}Fr β decay. Levels drawn in dashed line are uncertain. (c) Level scheme of ^{223}Ra (900–1030 keV) fed in the ^{223}Fr β decay.

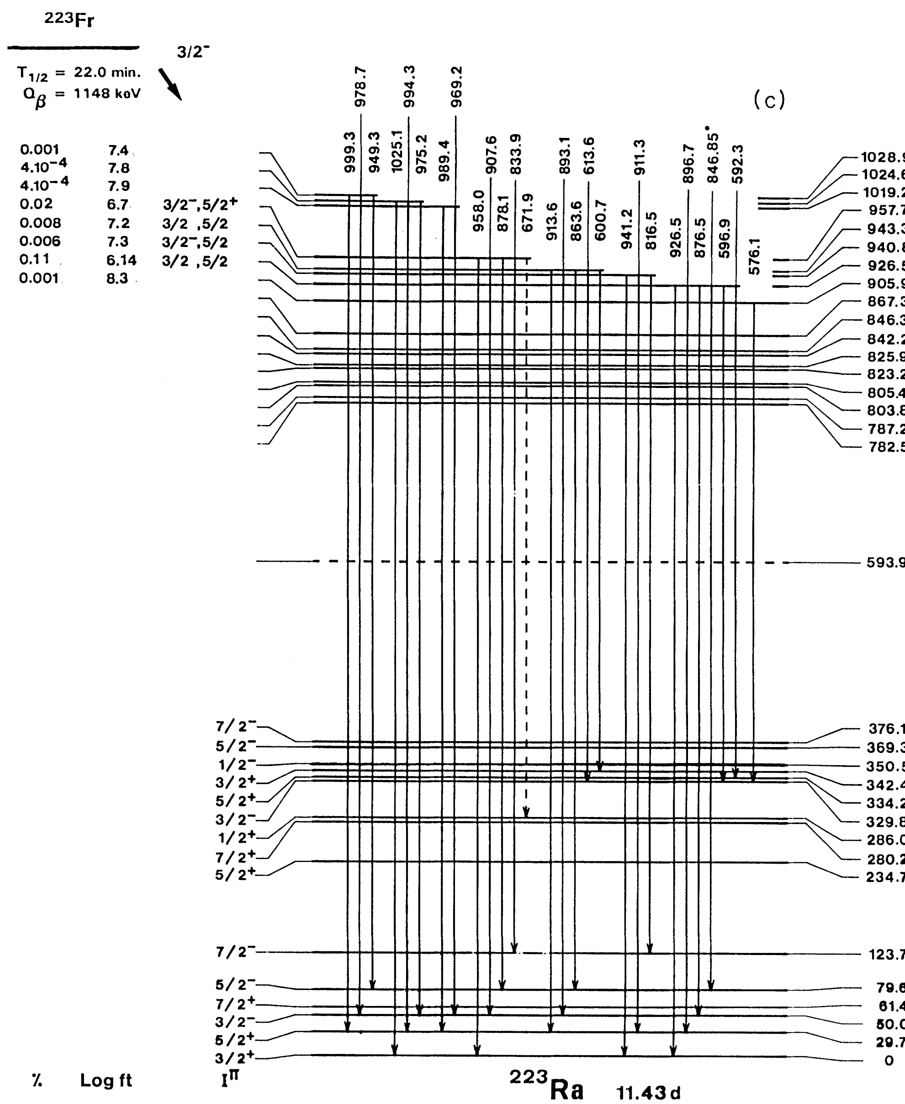

FIG. 5. (*Continued*).

teristics ($\Delta I=2$, $\Delta\pi=$no) of the corresponding β transition.

The rotational formula for a $K=\frac{3}{2}$ band [21],

$$E(I)_{3/2}=E_0+AI(I+1)+BI^2(I+1)^2 +(-1)^{(I+3/2)}(I-\tfrac{1}{2})(I+\tfrac{1}{2})(I+\tfrac{3}{2}) \times[A_3+B_3I(I+1)+\cdots], \quad (1)$$

was used, assuming $B_3=0$, to calculate the parameters $E_0=41.0$ keV, $A=5.96$ keV, $B=4.46$ eV, and $A_3=-23.8$ eV, from the energy values of the $I^\pi=(\frac{3}{2}\text{-}\frac{7}{2})^-$ members fed in ^{223}Fr β decay, as well as the value $E_{9/2^-}=174.6$ keV, measured in the ^{227}Th α decay [9]. The calculated values $E_{11/2^-}=250.8$ keV and $E_{13/2^-}=319.9$ keV agree well with the experimental values 247.3 and 315.0 keV measured in the ^{227}Th decay [9,15].

B. $K^\pi=\frac{1}{2}^\pm$ coupled bands

Two $\Omega=\frac{1}{2}$ bands, described by Sheline, Chen, and Leander [3] as parity mixed, contain an important admixture of the $\frac{1}{2}^+[640]$ and $\frac{1}{2}^-[770]$ Nilsson orbitals [Fig. 5(a)]. For these two coupled bands, we can note that the logft values to the $I=\frac{3}{2}$ and $\frac{5}{2}$ levels are $8.5^{+0.2}_{-0.1}$; this constancy correlates well with a ^{223}Ra static octupole deformation, since the logft values are expected to have rather close values for transition to different members of a spin-parity doublet (PD).

1. $K^\pi=\frac{1}{2}^+$ band

The bandhead is the 286.06±0.06 keV level, which depopulates by three transitions of 286.0, 256.18, and 236.05 keV with a branching ratio $I_{286}/I_{256}=0.2$, in good agreement with that obtained in the ^{227}Th α-decay study [15]. The 334.27±0.06 keV ($I^\pi=\frac{5}{2}^+$) level was previously known from the ^{223}Fr decay study [4]. Three new γ transitions of 272.8, 254.6, and 210.6 keV are found to deexcite this level to the $I^\pi=\frac{7}{2}^+$ $\frac{5}{2}^-$, and $\frac{7}{2}^-$ lower levels. The 342.46±0.09 keV state ($I^\pi=\frac{3}{2}^+$) is confirmed on the basis of three γ transitions depopulating it, as observed in γ-γ coincidence experiments. The logft value of 8.4, obtained here, is in accordance with related values for such $\Delta K=1$, $\Delta\Lambda=1$, β transitions.

2. $K^\pi=\frac{1}{2}^-$ band

The lower state is the $I^\pi=\frac{3}{2}^-$ level at 329.80±0.05 keV; the $I^\pi=\frac{1}{2}^-$ bandhead state, identified at 350.48 keV, in ^{227}Th α decay [3,15], is tentatively suggested to be fed by ^{223}Fr β decay to account for the 350.50 keV γ line seen in single γ-ray spectra, for which a careful analysis allowed its differentiation from the ^{214}Pb background line; the 299.95 keV γ transition, supposed to depopulate it to the 50.1 keV level, was mainly placed between the 329.8 and 29.78 keV states. The 376.1±0.1 keV level ($I^\pi=\frac{7}{2}^-$), newly found in ^{223}Fr decay, is suggested to account for the 314.6 and 296.5 keV γ transitions to the $I^\pi=\frac{5}{2}^-$ and $\frac{7}{2}^-$ states of the $K=\frac{3}{2}$ band. It appears then that γ feeding from higher-lying energy levels is plausible owing to the β-decay forbiddenness to this level.

The inverse moment of inertia $A=\hbar^2/2\mathcal{J}$, the decoupling parameter a, and the bandhead energy E_0 were calculated from the formula

$$E(I)_K=E_0+A[I(I+1)-K^2+(-1)^{(I+1/2)}\delta_{K,1/2}a(I+\tfrac{1}{2})] \quad (2)$$

and the experimental energy values of the $I=\frac{3}{2}$, $\frac{1}{2}$, and $\frac{7}{2}$ members of this band; they are, respectively, 6.00, -2.15, and 333.02 keV, in good agreement with those calculated by Sheline, Chen, and Leander [3] and Briançon *et al.* [15]. The value $E=424.3$ keV, predicted for the energy of the $I=\frac{5}{2}$ member of this band, agrees moderately well with the experimental value of 432.2 keV measured in the ^{227}Th α decay [9].

C. $K^\pi=\frac{5}{2}^\pm$ coupled bands

The bandhead of the $K^\pi=\frac{5}{2}^+$ band at 234.73±0.03 keV, observed in the previous ^{223}Fr study [4], is one of the most strongly fed levels in this β decay; we added two new γ transitions of 155.5 and 111.05 keV, respectively feeding the $I^\pi=\frac{5}{2}^-$ and $\frac{7}{2}^-$ states. The logft value 6.25 associated with $I_\beta=9.4\%$ is characteristic of an allowed β transition ($\Delta N=1$, $\Delta n_z=0$, $\Delta\Lambda=1$), if we assume for this parity-mixed state a dominant component of the reflection symmetric $\frac{5}{2}^+[633]$ state. The $I^\pi=\frac{7}{2}^+$ member at 280.2±0.2 keV, not evidenced earlier [4], is established here from the good agreement between the energy fits involving the four new γ lines of 280.7, 250.25, 218.80, and 200.7 keV assumed to feed the g.s. and the $I^\pi=\frac{5}{2}^+$, $\frac{7}{2}^+$, and $\frac{5}{2}^-$ states, as well as from coincidence relationships with the 79 and 507 keV gates (Table II). The branching ratios $I_{250}/I_{218}/I_{200}$, i.e., 2.1:1:0.56, are in good agreement with those observed (2:1:0.3) in ^{227}Th α decay [13,15].

Both these energies and the energy value of the $I^\pi=\frac{9}{2}^+$ member of this band observed in ^{227}Th decay [9], i.e., 342.7 keV, were used in the rotational energy formula and gave $A=6.155$ keV, $B=28.4$ eV, and $E_0=219.16$ keV. The calculated energy of the $I^\pi=\frac{11}{2}^+$ member of this band (425.4 keV) agrees well with the experimental one [9,15], i.e., 424.0 keV.

The 369.33±0.02 keV level was interpreted by Sheline, Chen, and Leander [3] and Briançon *et al.* [15] as being the bandhead of the $K^\pi=\frac{5}{2}^-$ band. Eight γ transitions deexcite this state to the g.s. and to the $I^\pi=(\frac{3}{2}\text{-}\frac{7}{2})^\pm$ lower excited states. The logft value of 6.82 deduced for this level is quite different from the corresponding value for the opposite-parity level of this PD (above-mentioned 234.73 keV level); this discrepancy could be related to a lesser degeneracy of these $\Omega=\frac{5}{2}$ coupled bands arising from their energy separation or to the Coriolis coupling of this band and the $\Omega=\frac{3}{2}$, lower band; the reduced parity splitting $\Delta\bar{E}=0.61$, defined as [2]

$$\Delta\bar{E}=\frac{E(I=K,p=-1)-E(I=K,p=+1)}{E_{\text{core}}(1^-)-\hbar^2/\mathcal{J}}\ , \quad (3)$$

is quite different from the values 0.23 and 0.29 for the respective $\Omega=\frac{3}{2}$ and $\frac{1}{2}$ bands, discussed above.

The reduced transition probability ratio

$$B(E1;\tfrac{5}{2}\tfrac{5}{2}^-\rightarrow\tfrac{5}{2}\tfrac{5}{2}^+)/B(E1;\tfrac{5}{2}\tfrac{5}{2}^-\rightarrow\tfrac{3}{2}\tfrac{3}{2}^+)=116\pm8\ ,$$

calculated assuming pure $E1$ multipolarity for the respective 369.32 and 134.60 keV transitions, compared to the Clebsh-Gordan ratio 1.07, shows an enhancement of 10^2 for the $\Delta K=0,E1$ transitions between members of the PD band relative to the $\Delta K=1,E1$ transition; again, a quite similar enhancement is deduced from the reduced transition probability ratio

$$B(E1;\tfrac{5}{2}\tfrac{5}{2}^-\rightarrow\tfrac{5}{2}\tfrac{5}{2}^+)/B(E1;\tfrac{5}{2}\tfrac{5}{2}^-\rightarrow\tfrac{5}{2}\tfrac{3}{2}^+)=129\pm12\ .$$

D. Higher-energy levels

If we exclude the new 593.9 keV level, proved by the existence of coincidence relations with the 79, 94, and 307 keV gates, no ^{223}Ra level was found to be fed in the ^{223}Fr β decay between 376.1 and 782.5 keV energies. This gap may be interpreted in the framework of single-particle excitations as the lack of low-K orbitals available in this energy range. Indeed, from a detailed calculation of the neutron single-particle levels performed [22] using a Woods-Saxon mean field and deformation parameters β_λ up to $\lambda=7$, the lower-lying $\Omega=\frac{1}{2}$ state of the $K^\pi=\frac{1}{2}^\pm$ PD band is expected at 398 keV. The corresponding experimental bandheads were found at 286 and 329 keV. The next $\Omega=\frac{1}{2}$, $\frac{3}{2}$, and $\frac{5}{2}$ bands which may be fed by ^{223}Fr decay, allowed by β-decay selection rules, are expected at 1124, 1217, and 1148 keV, respectively [15,22]. Unfortunately, owing to the high experimental level density (at least 17 levels with $I=\frac{1}{2}\text{-}\frac{5}{2}$) in the energy range

780–1030 keV [Figs. 5(b) and 5(c)], it is difficult to clearly identify the states without additional information. In both the strong- and intermediate-coupling version of the ARM of Leander and Sheline [23], a "sister" configuration counterpart of the low-state PD is predicted at higher energy with inverted parities. The gap is still of the same order of magnitude. In the multiphonon model (MPM) applied to odd light actinium isotopes, Piepenbring [24] showed that the existence of PD's and their properties, i.e., the enhancement of $\Delta K=0, E1$ strength between opposite-parity members, the "anomalous" values of decoupling parameters for $K^{\pi}=\frac{1}{2}^{\pm}$ bands as well as the appearance of a second PD with inverted parities for each low-energy PD with a gap of about 1 MeV separating them, were well reproduced without the need of static octupole deformation. Therefore he claims that these properties cannot be used as a criterion for the existence of octupole deformed orbitals ($\beta_3 \neq 0$). In ^{223}Ra such a gap is of the same order as the energy differences between the $E_{0_2^+}$ and $E_{0_1^-}$, levels in the neighboring doubly even cores ^{222}Ra and ^{224}Ra i.e., 671.87 and 700.3 keV, respectively. The existence in ^{223}Ra of such reflection symmetric bands does not seem incompatible with reflection asymmetric ones if we refer to the ^{225}Ra nucleus in which the coexistence of symmetric and asymmetric shapes was assumed at low energy, where, e.g., the 237 keV, $I^{\pi}=\frac{5}{2}^{+}$ level is associated with the reflection-symmetric $\frac{5}{2}[633]$ Nilsson state [25].

A 787.2±0.2 keV state, not seen in the previous ^{223}Fr decay study [4], but observed in ^{227}Th α decay [13], was inferred from numerous coincidence relationships (Table II). Since it deexcites by ten γ transitions to lower $I^{\pi}=\frac{3}{2}^{\pm}$, $\frac{5}{2}^{\pm}$, and $\frac{7}{2}^{\pm}$ states, but not to $\frac{1}{2}^{\pm}$ states, its spin may be limited to $I=\frac{5}{2}$. It may be the $\frac{5}{2}^{+}$ member of a $K^{\pi}=\frac{1}{2}^{+}$ band expected by Sheline, Chen, and Leander [3], rather than the $I^{\pi}=\frac{3}{2}^{+}$ assumed by these authors [3]. Besides, this state, fed in ^{227}Th α decay [9] with a low hindrance factor ($F_{\alpha}=8$), should have an intrinsic structure similar to the parent one, as well to the $K^{\pi}=\frac{1}{2}^{+}$ band beginning at 286.16 keV in ^{233}Ra ($F_{\alpha}=5.6$, 7.9, and 16 for the respective $\frac{1}{2}^{+}$, $\frac{3}{2}^{+}$, and $\frac{5}{2}^{+}$ members). The assumption of Leander and Chen [2], who proposed a reflection-asymmetric $K^{\pi}=\frac{1}{2}^{+}$ ^{227}Th ground state, should be preferred to the assumption of Cwiok and Nazarewicz [26], who suggested a $\Omega=\frac{3}{2}$ reflection-symmetric ground state (i.e., a $\frac{3}{2}[631]$-like orbital).

The 803.8±0.1 keV state, previously known from the ^{223}Fr decay [4], was confirmed here on the basis of its deexcitation by seven γ transitions, among which four are reported for the first time. However, we did not retain the previous placement [4] of the 776 keV γ line as a stopover transition to the 29.8 keV state, which seems better interpreted as deexciting the 825.9 keV level (see below).

A 805.4±0.4 keV level is newly proposed to account for the coincidence of the 475.4 keV γ transition with the 300 and 330 keV gates and the existence of the 806.0 keV crossover γ transition.

A 823.2±0.2 keV level, previously identified by Maria et al. [4] was confirmed here from coincidence relations concerning four γ transitions, different from those placed by these authors, but identical with those observed in ^{227}Th α decay [9,13] in which the transition is found to be favored with $F_{\alpha}=13$ [9].

A new level at 825.9±0.2 keV, proposed to interpret coincidence as well as good energy sum relationships, is also fed in ^{227}Th α decay [13]; the deexcitation pattern implies that the spin and parity are $I^{\pi}=\frac{3}{2}^{+}$. The low logft value of 6.0 seems to denote a configuration similar to the parent one. The only configuration available at this energy (for $\beta_3=0$) is the reflection-symmetric state $\frac{1}{2}^{-}[501]$ observed at 898 keV in ^{225}Ra [27].

The 842.2±0.1 keV state was previously found in both ^{223}Fr [4] and ^{227}Th decays [13]; four new γ transitions are added to the pattern proposed earlier [4]. Taking into account the low hindrance factor ($F_{\alpha}=19$) deduced for the feeding of this level from ^{227}Th α decay [9], spin values are restricted to $I=\frac{3}{2},\frac{5}{2}$.

A 846.3±0.1 keV state not observed in earlier studies [4,13] is suggested to be fed in ^{223}Fr decay; from its deexcitation pattern and logft value of 6.7, a spin $I=\frac{5}{2}$ can be suggested. If we assume, on the one hand, that this level is the $I^{\pi}=\frac{5}{2}^{+}$ member of the rotational band built on the $K^{\pi}=\frac{3}{2}^{+}$ state at 825.9 keV and, on the other hand, that the 879.0 keV level, fed in the ^{227}Th α decay [9,13], has a spin $I=\frac{7}{2}$ (due to its decay to the $\frac{5}{2}^{+}$, $\frac{7}{2}^{+}$, and $\frac{9}{2}^{+}$ states), we can fit these energy values into the rotational formula and deduce $A=\hbar^2/2\mathcal{I}=3.463$ keV, $B=49.3$ eV, and $E_0=812.2$ keV. The calculated 928.1 keV energy value for the $I=\frac{9}{2}$ member of this band agrees well with the experimental 927.3±0.2 keV level reported in ^{227}Th decay [9,13].

The 867.3±0.1keV level, earlier observed in the ^{227}Th α decay [13] on the basis of two γ transitions, is newly reported in the ^{223}Fr decay. It allows the interpretation of eight γ transitions of which five are new with respect to the previous study [4].

The 926.5±0.3 keV state, only suggested [4] by a 896 keV γ transition, is confirmed here by coincidence relations (Table II); it deexcites by six γ transitions to $I=\frac{3}{2}$ and $\frac{5}{2}$ states of the $K^{\pi}=\frac{3}{2}^{\pm}$ PD. This $I=\frac{3}{2},\frac{5}{2}$ level, characterized by a low logft value of 6.1, might have a configuration like the ^{223}Fr g.s. Besides, from the deexcitation pattern, showing a strong correlation between these states, it may be proposed as the high-lying $K=\frac{3}{2}$ partner of the low-energy PD expected either in the four-level model of Leander and Sheline [23] or in the MPM of Piepenbring [24].

A 940.8±0.3 keV level is proposed from coincidence relations (Table II); from its γ decay and β-feeding characteristics, its spin and parity are limited to $I^{\pi}=\frac{3}{2}^{-}, \frac{5}{2}^{\pm}$.

A 957.7±0.2 keV state, not reported in neither ^{223}Fr nor ^{227}Th decay, is based on the existence of firm coincidence (Table II) and sum-difference relations. From its deexcitation pattern, spin and parity of this level are restricted to $I^{\pi}=\frac{3}{2}^{-}$ or $\frac{5}{2}^{+}$

A 1024.6±0.4 keV level, only observed in ^{227}Th α decay [13], is proposed here by the existence of three γ transitions.

A 1028.9±0.3 keV level, not observed in earlier studies [4,13], is proposed to account for coincidence relations involving three γ transitions.

VII. CONCLUSION

We have presented a new investigation of the ^{223}Ra low-spin levels fed in ^{223}Fr β decay with improved resolution γ spectroscopy. Here 87 new γ transitions have been reported in this decay and 32 levels were found to be fed: 13 are reported for the first time in ^{223}Fr decay. Although no detailed calculation was performed, comparison with previous known theoretical studies shows that the asymmetric rotor model [2,3] seems to give a rather satisfactory description of the lower-energy part ($E < 400$ keV) of the spectrum, but other models, such as the multiphonon model [24] may be applied. For higher-lying levels situated above the gap, the coexistence of symmetric shapes may be assumed; however, the high density of experimental levels prevents a clear identification.

ACKNOWLEDGMENTS

Thanks are due to Z. Szeglowsky (Joint Institute for Nuclear Reactions, Dubna) and L. Brillard (Institut de Physique Nucléaire, Orsay) for their help during the preparation of francium sources. We also acknowledge C. F. Liang (C.S.N.S.M., Orsay) for the loan of a HPGe planar detector and J. Sauvage (I.P.N., Orsay), who kindly put to our disposal the γ-γ coincidence acquisition system. One of us (G.A.) specially thanks Ch. Briançon for providing unpublished calculations and helpful discussion.

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