FINE STRUCTURE OF THE Pa^{231} *ALPHA RADIATION AND THE ENERGY LEVEL SCHEME OF THE* Ac^{227} *NUCLEUS*

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Submitted to JETP editor June 21, 1961

J. Exptl. Theoret. Phys. (U.S.S.R.) **41**, 1475-1483 (November, 1961)

Results of an investigation of the radioactive decay of Pa^{231} are presented. The measurements were performed with magnetic α and β spectrometers and a spectrometric arrangement for γ-radiation measurements. Twenty monoenergetic α lines were detected in the α-ray spectrum. Ten of these lines have been established for the first time. From an analysis of the electron and γ spectra it has been possible to detect some new conversion lines and identify the multipolarity of the γ transitions in the Ac^{227} nucleus. A more complete energy level scheme of the Ac^{227} nucleus is constructed on the basis of all available data.

1. INTRODUCTION

THE radioactive nucleus Pa^{231} is converted via α decay into the α-active isotope Ac^{227}. The half-life of Pa^{231} is 3.4×10^4 years. Some information on the radiation emitted in the decay of this nucleus and on the levels of the Ac^{227} nucleus were presented in several papers [1-8]. These investigations did not make it possible to resolve some contradictions in the level scheme of Ac^{227}. We have therefore undertaken a further more careful investigation of the α spectrum of Pa^{231} and of the conversion-electron and γ-radiation spectra of Ac^{227}.

2. APPARATUS AND PREPARATION OF RADIOACTIVE Pa^{231} SOURCE

To study the electron and α spectrum we used magnetic α and β spectrometers with double focusing of a beam of charged particles at an angle $\pi\sqrt{2}$.[9,10] In these experiments the relative resolution of the instruments was respectively several hundredths and several tenths of one percent at solid angles on the order of $10^{-3} \times 4\pi$. The γ radiation was investigated with ordinary γ-spectrometric apparatus.

Prior to the direct preparation of the sources for the α, β, and γ spectroscopic measurements, the protactinium was thoroughly purified to remove extraneous impurities, primarily actinium.

The source for the α-spectroscopic measurements was prepared by evaporating protactinium chloride in vacuum on a glass base. The surface density of the active layer of the source was 1 $\mu g/cm^2$. The effective areas of the sources used in the series of experiments on the fine structure of the α radiation were 0.5, 1.0, and 3.0 cm^2.

For electronic and γ-spectrometric measurements, the sources were prepared by the method described in our earlier papers (see, for example,[11]).

3. EXPERIMENTAL RESULTS

A. <u>Investigation of the α spectrum of Pa^{231}</u>. In the investigation of the α spectrum we confined ourselves to the energy interval 4450—5050 kev, with intensity $I \geq 2 \times 10^{-3}$ percent. As was shown earlier,[12] the energy calibration of the spectrometer remains unchanged in this energy interval. The standard line used in these experiments was the known group of Pa^{231} 4938.0-kev α particles.[4] The accuracy in the determination of the energies of the remaining α groups was ~2 kev. The background of scattered particles in these experiments did not exceed 4×10^{-4} percent, and was therefore outside the limits of the investigated intensities. To investigate a relatively broad portion of the spectrum (600 kev), several exposures were necessary.

Figure 1 shows the apparatus spectra of the α radiation from Pa^{231}, obtained in three different exposures. The minimum half-width attained was 3 kev (T_{exp} = 12 hours). We observed 20 α-radiation fine-structure groups, of which the groups α_x, α_z (?), α_4, α_y, α_8, and α_{12}—α_{16} were found for the first time.

Table I summarizes the data of three experiments. We give here the values of the energy (in kev) and the intensity (percent) of individual groups of α particles, along with the calculated values of

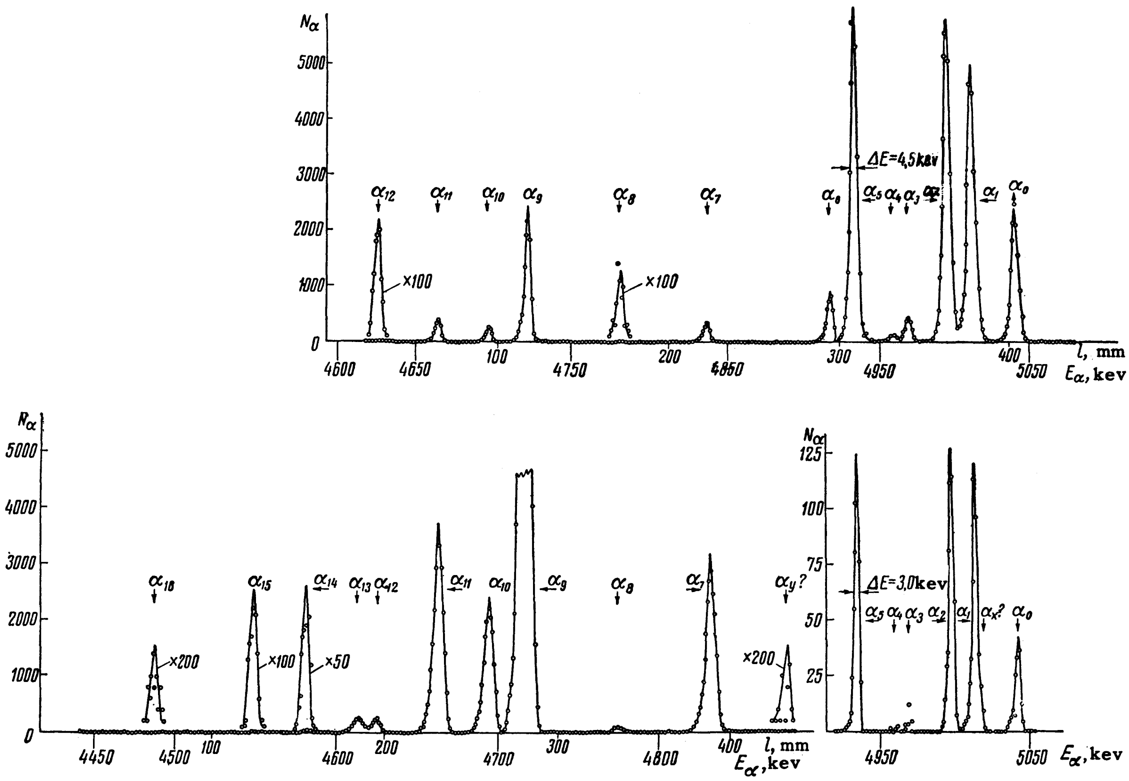

FIG. 1. Apparatus spectrum of the fine structure of the α radiation of Pa^{231}.

Table I. Fine structure of α spectrum of Pa^{231}

α group	Energy* of α particles, kev	Intensity**, percent	Hindrance coefficient, m	Level energy, kev	α group	Energy* of α particles, kev	Intensity**, percent	Hindrance coefficient, m	Level energy, kev
α_0	5045,3	11.0	205	0	α_7	4839,4	1.4	75	209.5
α_x	5018,5	~2.5	640	27.4	α_8	4781,7	$4\cdot10^{-2}$	1050	268.2
α_1	5016,4	⩽20.0	70	29.4	α_9	4724,0	8.4	2	327.0
α_z ?	5012 5010			~34?	α_{10}	4699,7	~1	12	351.7
					α_{11}	4667,5	1.5	5	384,5
α_2	4999,3	25.4	45	45.9	α_{12}	4630,2	$\sim10^{-1}$	~40	422.4
α_3	4972,2	1.4	525	73.1	α_{13}	4618,7	$\sim10^{-1}$	30	434.0
α_4	4961,5	0.4	1600	84.4	α_{14}	4586,0	$1.5\cdot10^{-2}$	120	467.4
α_5	4938,0	22.8	20	107.1	α_{15}	4553,3	$8\cdot10^{-3}$	120	501.0
α_6	4920,7	3.0	120	126.8	α_{16}	4494,8	$3\cdot10^{-3}$	135	560.0
α_y	4887,0	$2\cdot10^{-3}$	$\sim10^5$	~160					

*The standard line used was the 4938.0-kev α_5 group.

**Data from three experiments were included in the estimate of the α-group intensity.

the hindrance coefficients m and the level energies.

The experimental values of the energy and intensity which we have obtained for the ten known α groups differ somewhat from the corresponding values quoted in the literature.[4-8] This discrepancy lies apparently within the limits of experimental error.

It is highly interesting to consider separately the α-spectrum shown in the lower right of Fig. 1. It is easily seen that the form of the α_1 line, and particularly the width of its base and the fall-off on the high-energy side differ from the forms of the groups α_2 and α_5, which have almost the same intensity. This gives grounds for assuming the α_1 line to have a complex structure. The groups α_X, α_1, and α_Z in Table I are the components of this complex α line. Naturally, the intensities of these groups cannot be determined with sufficient accuracy.

B. Investigation of the electron and γ spectra. These spectra were studied in several investigations, but not the low-energy region of the electron spectrum of Ac^{227}. Using very thin organic films for the window of the Geiger-counter (the electron indicator in the β spectrometer), we could study the electron spectrum, starting with low energies (1.5—2.0 kev).

Table II. Interpretation of electron lines produced in the decay of Pa^{231}

Number of electron line	Observed electron energy, kev	Conversion shell	Transition energy, kev	Intensity of conversion lines (relative units)
3	5.9	M	~11.0	70. L_I (25)+M(11)
11	11.5	M_I	16.5	130
14	15.1	N_I	16.3	40
		average	16.4	
2	3.8	L_{III}	19.6	~10
1	2	L_I	22.7	~25
10	2.7	L_{II}	22.7	~25
4	6.9	L_{III}	22.7	~25
		average	22.7	
3	5.6	L_I	25.4	70 L_I(25)+M(11)
19	20.2	M_I	25.2	25
20	20.8	M_{II}	25.4	2
21	21.5	M_{III}	25.4	1
		average	25.4	
6	8.1	L_{II}	27.2	
10	10.8	L_{III}	26.7	
15	21.9	M_I	26.9	
	23.0	M_{II}	26.9	
		average	27.0	
5	7.6	L_I	27.4	70
7	8.4	L_{II}	27.5	100
12	11.5	L_{III}	27.4	120
23	22.4	M_I	27.4	30
24	22.7	M_{II}	27.3	15
26	23.4	M_{III}	27.3	30
27	24.0	$M_{IV,V}$	27.3	5
30	26.2	N	27.4	16
31	27.2	O	27.4	
		average	27.4	
8	9.5	L_I	29.5	90
9	10.2	L_{II}	29.3	90
13a	13.7	L_{III}	29.5	~40
28	24.2	$M_{I,II}$	29.8	~35
29	25.2	$M_{III,IV}$	29.2	~35
32	28.5	N	29.7	
		average	29.4	
13	14.1	L_I	34.1	~100
33	29.0	M_I	34.0	
		average	34.0	

Table II (continued)

Number of electron line	Observed electron energy, kev	Conversion shell	Transition energy, kev	Intensity of conversion lines (relative units)
17	18.4	L_I	38,2	60
18	19.1	L_{II}	38.2	15
23	22.4	(L_{III})	38.2	~15
35	33.0	M_I	38.0	
36	33.3	M_{II}	38.1	$\Sigma M=30$
37	33.6	M_{III}	38.0	
38	36.8	$N_{I,II}$	~38.0	$\Sigma N=16$
39	37.1	N_{III-V}	~38.0	
40	37.5	O	~38.0	
		average	38.2	
41	37.9	L_{II}	57.0	26
43	41.2	L_{III}	57.1	23
47	52.4	$M_{II,\ III}$	57.0	$\Sigma M=14$
48	56.2	$N,\ O$	~57.0	
		average	57.0	
44	43.4	L_I	63.2	3
45	44.2	L_{II}	63.3	22
46	47.5	L_{III}	63.5	21
51	58.4	M_{II}	63.4	$\Sigma M=12$
52	59.0	M_{III}	~63.1	
		average	63.3	
55	77.0	L_{II}	~96.0	
57	80.0	L_{III}	96.0	
		average	96.0	
56	78.0	L_{II}	97.1	5,5
58	81.2	L_{III}	97.0	4
62	92.0	M	97.0	$\Sigma M=3$
63	96.0	$N,\ O$	~97	
		average	97,0	
59	83.6	L_{II}	102.7	2
60	86.6	L_{III}	102.5	1.5
64	98.1	M	102,7	
65	101.2	$N,\ O$	102.5	
		average	102.5	
19	20.0	K	126.8	
66	107.1	L	126.8	
		average	126.8	
67	153.8	K	260.5	
75	240.0	L	260.5	
		average	260.5	
68	178.3	K	285.0	1
77	265.2	L	285.1	~0,2
79	280	M	~285.0	
		average	285,0	

Table II shows the calculated energies of the conversion electrons, the intensities, and the values of the γ-transition energies. The data of Table II show that the observed conversion lines are due to at least twenty γ transitions in the Ac^{227} nucleus.

Figure 2 shows the apparatus spectra of the x-ray and γ radiation of Ac^{227}. The ordinates represent the number of pulses per channel of the pulse-height analyzer, while the abscissas represent the energies of the x rays and γ rays.

The experimental data obtained in the investigation of the e_K and γ spectra of Ac^{227} made it possible to determine the multipolarity class for twelve γ transitions in this nucleus (see Table III).

Table II (continued)

Number of electron line	Observed electron energy, kev	Conversion shell	Transition energy, kev	Intensity of conversion lines (relative units)
71	193.5	*K*	300	12.5
80	279.3	*L*	300	2.8
81	295.1	*M*	300	0.6
		average	300	
72	196.0	*K*	303	
		average	303	
74	223.2	*K*	330	5.0
83	310	*L*	330	1.3
	325	*M*	330	~0.3
		average	330	
76	248.7	*K*	354.5	0.4
		average	354.5	
78	274	*K*	380	
		average	380	

Table III

Number	E_γ, kev	Multipolarity	Reduced intensity of γ transitions, %
1	11.0		11 $(\Sigma\gamma_1, \gamma_5)$
2	16.5	*M*1	~20
3	19.6		~ 2
4	22.7		~ 2
5	25.4	*M*1	11 $(\Sigma\gamma_1, \gamma_5)$
6	27.0		< 2
7	27.4	*E*1	~50
8	29.4	*M*1+*E*2	} 40 $\Sigma(\gamma_8, \gamma_9)$
9	34.0	*M*1	
10	38.2	*E*1+*M*2?	~15
11	57.0	*E*2	} 13 $\Sigma(\gamma_{11}, \gamma_{12})$
12	63.3	*E*1	
13	96.0	*E*2?	weak
14	97.1		~1.5
15	102.5	*E*2	~0.5
16	126.8		weak
17	260.5		weak
18	285		weak
19	300	*M*2	2.2
20	303		weak
21	330	*M*2	1
22	354		weak
23	~380		weak

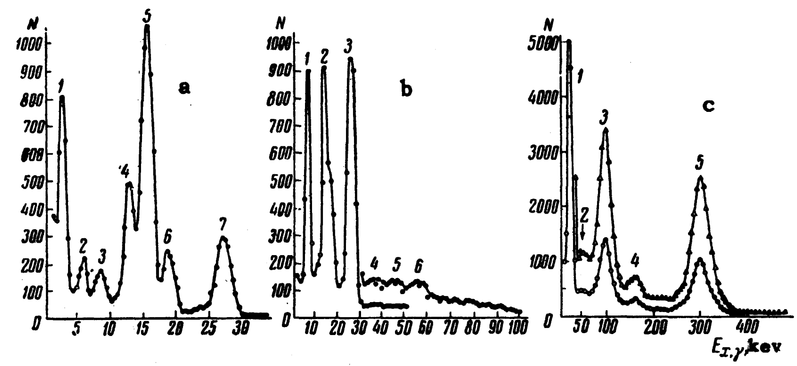

FIG. 2. X-ray and soft γ-ray spectrum of Ac^{227}, obtained with the aid of a proportional counter: a) counter filled with mixture of Kr and CH_4, b) counter filled with mixture of Xe and CH_4, c) x-ray and γ-ray spectrum of Ac^{227}, obtained with scintillation spectrometer.

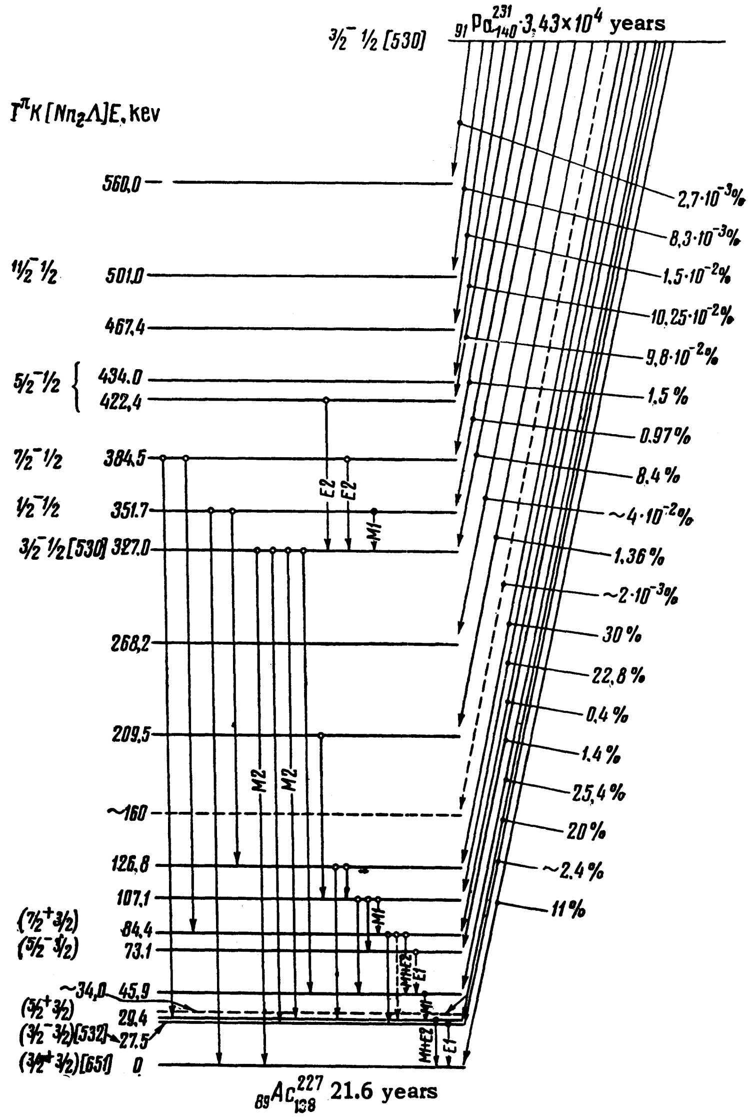

FIG. 3. Level scheme of Ac[227].

With the aid of a calibrated proportional counter it was also established that the γ-ray yield of 27.4-kev γ rays is $(10 \pm 2)\%$ of the total α decay. This is in good agreement with the value given in[6].

Taking account of this result and of the data Tables II and III, we calculated the intensities of the strongest γ transitions between the levels, referred to the total number of α decays. The results of the calculations are listed in the last column of Table III.

4. LEVEL SCHEME OF Ac^{227}

An analysis of all the experimental data obtained indicates that the level scheme of Ac^{227} contains at least 4–5 rotational bands. (see Fig. 3). The most clearly distinguishable is the rotational band located in the upper part of the scheme, in the energy interval 327–501 kev. Actually, as can be seen from Table I, the smallest hindrance coefficient is possessed by the group α_9. This favored transition is to a single-particle level with energy ~327 kev, which should have the same characteristics as the ground state of the decaying nucleus $^3/_2$–$^1/_2$ [530]* (see[13,3]). In view of their hindrance coefficients, the α_{10}, α_{11}, and α_{15} transitions can go to the next levels of this rotational band (U_{lev} = 352, 385, 434 kev).** The experimentally obtained ratio of the reduced intensi-

*The quantum numbers $I\pi K[Nn_z\Lambda]$, which characterize the state of the deformed nucleus, are defined as follows: I – spin, π – parity, K – projection of spin on the symmetry axis of the nucleus, $Nn_z\Lambda$ – asymptotic quantum numbers introduced by Nilsson, N – principal quantum number of the oscillator, n_z – quantum number of the oscillations along the symmetry axis, Λ – projection of orbital angular momentum on the symmetry axis of the nucleus.

**It must be noted that, like the rotational band of Pa^{231}, which belongs to the ground state, the spin sequence should apparently be reversed here, too ("inverted doublets"), i.e., $^3/_2^-$, $^1/_2^-$, $^7/_2^-$, $^5/_2^-$ etc.

ties of these α transitions to the levels 327, 352, 385 and 434 kev is 100: 17.1, 44.8: 6.8, which is in good agreement with the theoretical estimate for the intensity of the transitions to the levels with characteristics $I = 3/2, 1/2, 7/2$, and $5/2$, namely 100, 17.2, 44.4, and 7.4. Nor is assignment of the 501-kev level to this rotational band excluded ($I = 11/2$).

The most reliably established levels in this band are 327, 352, and 385 kev. Taking into consideration the spins and spacings of these levels, we obtained $\hbar^2/2J = 7.5$ kev and $a = -2.1$. Thus, the moment of inertia in this case differs insignificantly from the moments of inertia of the neighboring even-even nuclei.

An analysis of the lower part of the level scheme, located in the narrow energy interval 0—100 kev, shows that it is very difficult to identify these levels from the point of view of the existing theories. In this narrow interval are concentrated almost half the observed levels, and it is therefore natural to assume that several rotational bands are present here. Although some of these levels belong to different rotational bands, they probably have identical spins and parities. This results in an "interaction between levels",[14] which leads to violation of O. Bohr's known interval rule for rotational bands and can distort the expected distribution of the intensities of the α transitions [15] to levels of the same band. Consequently, a reliable interpretation of these levels cannot be made without taking these singularities into account. However, allowing a certain leeway, we can draw the following rough conclusions from the experimental facts. The ground state of Ac^{227} is $3/2^+$ [651]. The rotational band of this state apparently contains the levels 0 kev ($3/2^+$), 34 kev ($5/2^+$), and 84 kev ($7/2^+$).

The level with energy ~ 34 kev must be introduced to conserve the balance of the intensities in the proposed scheme, and is also due to the probable existence of the α_Z group in the α-particle spectrum of Pa^{231}.

The 27.4-kev level, the existence of which is not subject to doubt according to our data (see Tables I and III), has also been proposed by others (see [16]). Apparently an orbit $3/2^-$ [532] must be ascribed to it. It is possible that the next term in this new rotational band is the 73-kev level.

Nor is it excluded, finally, that the levels with energy 29 and 46 kev are terms of a different rotational band, the start of which is the hole level (from the point of view of the Nilsson diagram) with characteristics $1/2^+$ [660] and an energy 29.4 kev.

We shall not stop to explain the other levels of the scheme, since their interpretation cannot be made unambiguous as yet.

In conclusion we thank S. N. Belen'kii, A. A. Arutyunov, K. I. Merkulova, Yu. N. Dmitriev, and G. V. Shishkin for help with the measurements.

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Translated by J. G. Adashko
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