ENERGY LEVELS OF U^{232}

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Radioactive decay of Pa^{232} was studied with a double-focusing magnetic β-spectrometer and a scintillation γ-spectrometer. An energy level scheme for the U^{232} nucleus is derived by analyzing the β spectrum, conversion-electron spectrum, and γ-ray spectrum. The scheme agrees with the level schemes of other even-even deformed nuclei. The existence of E0 transitions between the levels $0_2^+ \rightarrow 0_1^+$ and $2_2^+ \rightarrow 2_1^+$ is established. The experimental data are compared with the predictions of the Bohr-Mottelson theory and the theory of nonaxial deformed even-even nuclei developed by Davydov, Filippov, Rostovskii, and Chaban.

INTRODUCTION

A study of the levels of deformed even-even nuclei is of interest from the point of view of checking the theories that have recently been used to describe these levels. The prevalent notions are that a developed band of rotational levels ($I = 0^+$, 2^+, 4^+), connected with the collective motion of the nucleons in the nucleus, exists near the ground state of these nuclei, with octupole oscillation bands ($I = 1^-$, 3^-) and β and γ vibrational nuclear levels located above the rotational band. These notions are confirmed by the experimental data obtained in investigations of radioactive decay of the nuclei (see, for example, [1]).

The experimental data hitherto obtained on the levels of U^{232} have been contradictory [2] and did not fit the framework of the above scheme. We have continued our investigation of the decay of Pa^{232} in order to construct a more complete level scheme for U^{232}.

1. PREPARATION OF SOURCE AND EXPERIMENTAL PROCEDURE

The Pa^{232} was obtained by bombarding Pa^{231} with slow neutrons. The bombarded substance was a mixture of 0.5 mg protactinium oxide and 15 mg magnesium oxide. The initial Pa^{231} sample had practically no extraneous α and β active impurities, as checked by high-transmission spectrometers. After the irradiation, the mixture of oxides was dissolved in an 8N solution of hydrochloric acid with addition of a few drops of hydrogen fluoride. After the mixture was completely dissolved, 5 mg of aluminum chloride was added to bind the fluorine ions. The resultant solution was passed through a column with Dowex-1 x-8 anion-exchange resin, on which the protactinium was gathered. After passing the entire solution, the compound was washed out to eliminate the extraneous activity of the hydrochloric acid. The protactinium was then selectively washed out of the resin with a mixture of 8N HCl + 0.1 N HF. The cleaning operation was then repeated. The result was 5 ml of pure solution of protactinium, which was evaporated in a platinum crucible to 0.5 ml. The sources for the β and γ spectrometric measurements were prepared of this solution.

To investigate the electron spectrum, the Pa^{232} specimens were made by evaporating the solution on a thin organic film, on which a semi-transparent strip of Aquadag was deposited beforehand. The sources for the β spectrometer had dimensions ranging from 1×30 to 5×40 mm.

The window of the electron counter had dimensions corresponding to those of the source and was covered with a celluloid film, which transmitted all electrons with energies above 2 kev.

The electron and γ spectra were measured with the apparatus described in our earlier papers. [3,4]

2. EXPERIMENTAL RESULTS

The electron spectrum produced in the β decay of Pa^{232} is shown in Figs. 1—3, while the γ spectrum is shown in Fig. 4. Conversion-electron lines are interpreted in Table I.

The electron spectrum in the energy range from 1 to 110 kev was measured with a source measuring 1×30 mm. In addition to the conversion lines of the known 47.5- and 109-kev γ transitions, the spectrum shows the electron lines 45, 9, 16, and 19, which are respectively interpreted

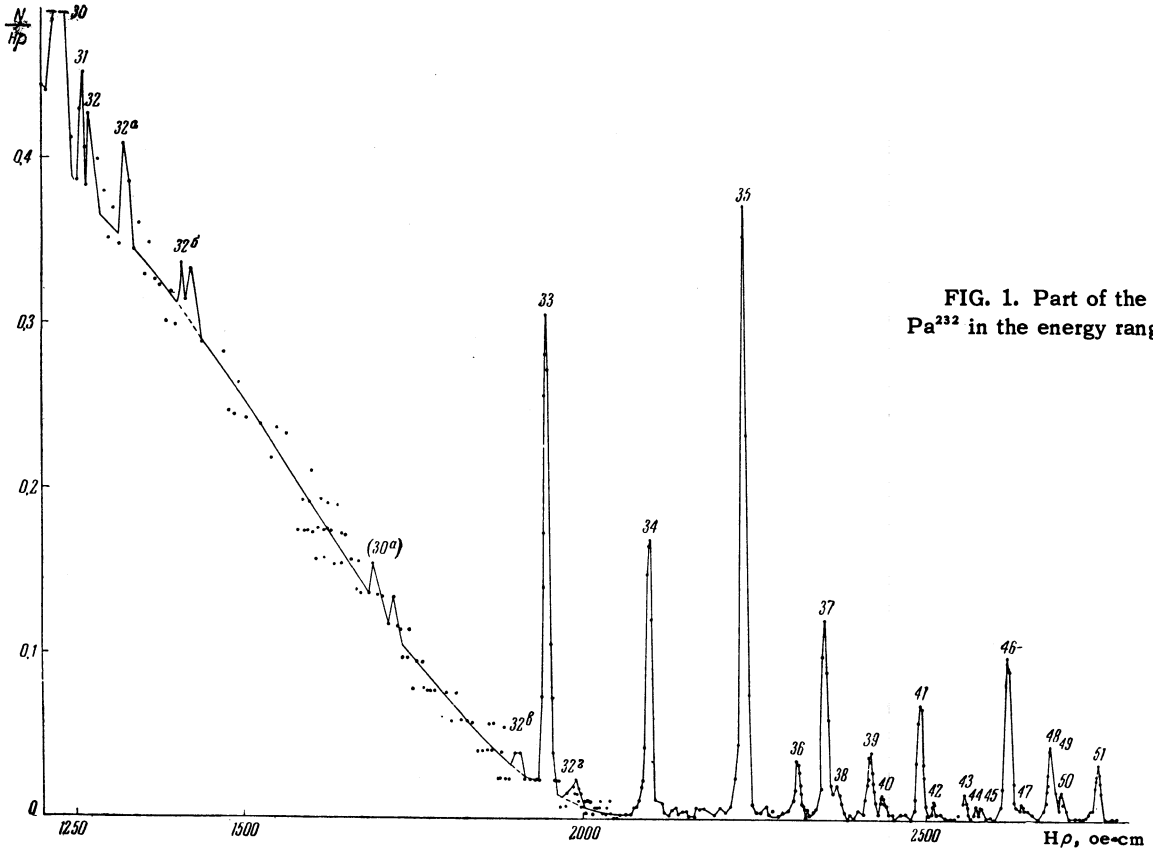


FIG. 1. Part of the electron spectrum of Pa^{232} in the energy range from 1 to 120 kev.

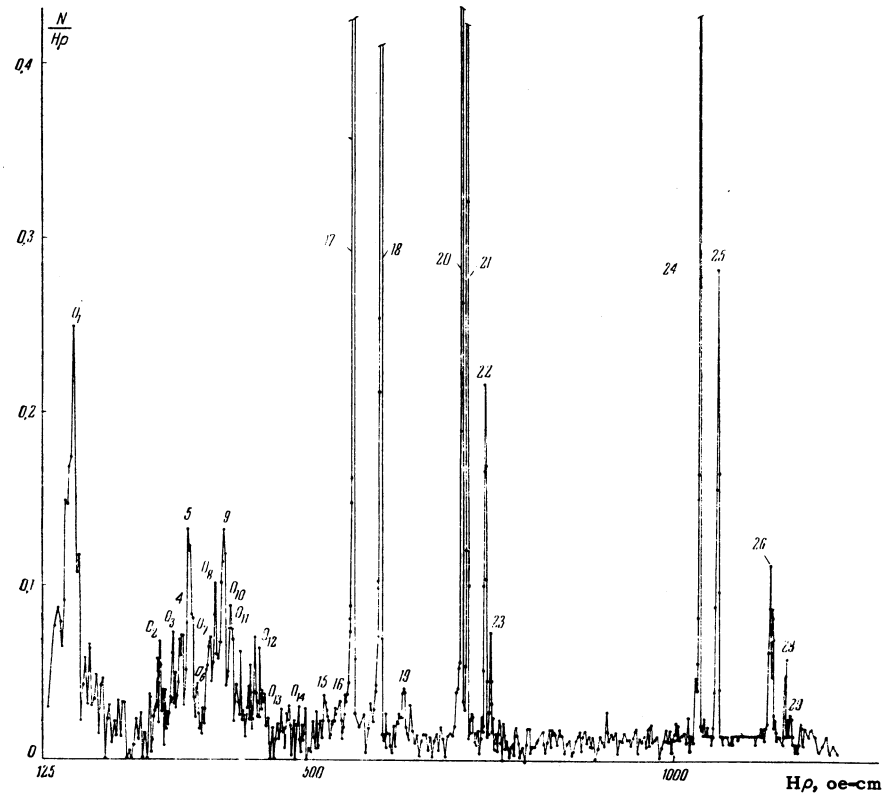


FIG. 2. Part of electron spectrum of Pa^{232} in the energy range from 120 to 500 kev.

Table I

Number of electron line in spectrum	Observed electron energy, kev	Interpretation	γ-transition energy, kev	Intensity, relative units
4	8.3	L_I	30	10
5	9	L_{II}	29.9	27
9	12.5	L_{III}	29.7	26
16	25.2	$M_{II, III}$	≈30	7
		Average:	29.9	
17	26.5	L_{II}	47.5	330
18	30.33	L_{III}	47.5	275
20	42.5	M_{II}	47.6	91
21	43.4	M_{III}	47.7	73
22	46.3	N_I	47.6	54
23	47.2	O	47.4	14
		Average:	47.55	
24	88.2	L_{II}	108.8	75
25	91.6	L_{III}	108.8	46
26	103.9	M_{II}	109.0	19
27	104.5	M_{III}	108.8	13
28	106.8	N	108.8	
29	108.2	O	108.6	
		Average:	108.8	
19	32	K	147.6	6
31	126.6	$L_{I, II}$	147	≈2
32	130	L_{III}	147	≈2
32a	140	M	≈147	≈2
		Average:	147	
30	121	K	236.6	≈8
30a	215	L	236	≈1.5
		Average:	≈236	
32b	163	K	≈280	
32b	267	L	≈280	
32c	274	M	≈280	
		Average:	≈280	
33	266.9	K	382.5	8.3
37	361.8	$L_{I, II}$	382.8	3.7
38	365.7	L_{III}	382.8	0.7
39	378	M	≈383	1.3
40	382	N	≈383	0.6
		Average:	382.8	
34	301.2	K	416.8	5.2
41	396.0	$L_{I, II}$	416.9	2.2
42	399.8	L_{III}	417	0.2
43	411.2	M	416.7	0.4
44	415.2	N	116.7	0.15
45	417.0	O	417	0.13
		Average:	416.8	
35	334.3	K	449.9	10
46	429.3	$L_{I, II}$	450	2.7
47	432.6	L_{III}	449.8	0.35
48	444	M	449.5	(1.1)
50	448.2	N	449.6	0.2
		Average:	449.9	
36	351	K	466.6	1
(49)	444.6	L	≈466.4	(0.35)
		Average:	466.5	
51	463.7	K	579.2	1
53	558.4	$L_{I, II}$	579.4	0.5
54	562.5	L_{III}	579.7	
56	574.7	M	579.8	0.5
57	577.5	N	≈579	
		Average:	579.5	
55	567.5	K	683	1
58	661.5	$L_{I, II}$	682.5	0.17
59	665.2	L_{III}	682.4	
		Average:	682.6	
60	700.8	K	816.4	0.9
65	794.5	L	816.3	0.5
66	812	M	≈817	
		Average:	816.6	
61	702	K	817.6	0.9
		Average:	817.6	
62	747.5	K	863	1.5*
67	841	L	863	0.6**
		Average:	863	
63	750	K	866	
68	845	L	866	
		Average:	866	
64	876.8	K	892.5	1.1
72	870.7	L	892.4	0.35
73	887.0	M	~892	0.16
		Average:	892.3	
69	848	K	963.5	12.6
74	945.7	L	963.7	0.4
75	960	M	964	0.15
		Average:	963.7	
76	1035	K	1150	0.2

* Σ (K 863 + K 866).
** Σ (L 863 + L 866).

as L_I, L_{II}, L_{III}, M_{II} and M_{III} conversion lines of the 30-kev γ transition and the K line of the 147-kev γ transition. The spectrum shows a large number of Auger-electron lines, O_1—O_{14}, which are not interpreted in this paper.

The electron spectrum from 110 kev to 1 Mev was measured with a 3 × 35 mm source of activity 15 times greater than that of the preceding source. Multipole measurements and checks of the period of fall-off of the conversion-electron line intensities have established that lines 34, 41, 42, and 43 belong to the 416.8-kev γ transition, while line 36 corresponds to the 466.5-kev γ transition in U^{232}. Ong Ping Hok and Sizoo,[2] who worked with a mixture of Pa^{230}, Pa^{232}, and Pa^{233}, were apparently in error in assuming that the 416.8- and 466.5-kev γ transitions belonged to Pa^{233} and Pa^{230} respectively. They observed in the same

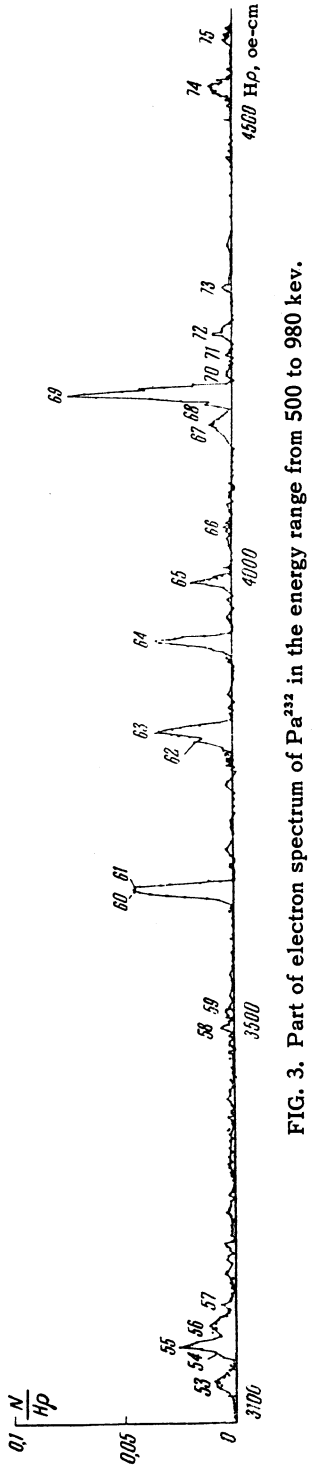


FIG. 3. Part of electron spectrum of Pa^{232} in the energy range from 500 to 980 kev.

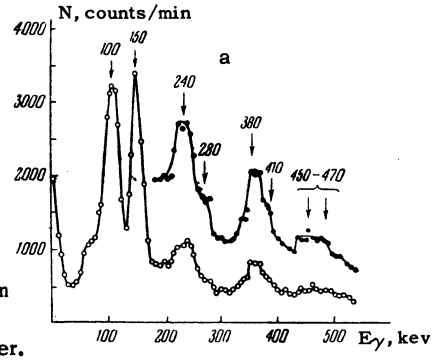
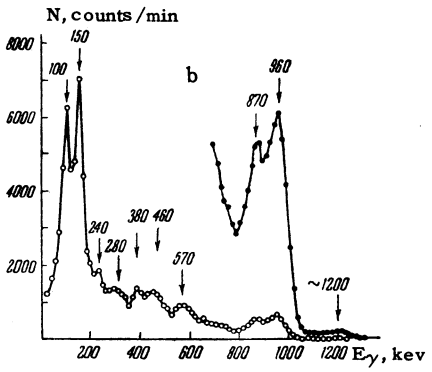


FIG. 4. γ-ray spectrum of Pa^{232} measured with scintillation γ spectrometer.



energy region intense conversion lines which they ascribed to a 517-kev γ transition in U^{232}. We observed no 517-kev γ transition in our measurements.

In addition to the indicated conversion lines, we observed the lines 30, 32b, 32c, and 32d, assigned to the 236- and 280-kev γ transitions. The very weak conversion line No. 78 (see Table I) is assigned to the 1150-kev γ transition.

The existence of the newly-observed γ transitions with energies 147, 236, 280, and 1150 kev is confirmed by measurement of the spectrum of the γ rays produced in the decay of Pa^{232} (Fig. 4). The γ-ray spectra were measured with a scintillation γ spectrometer with resolution 8—9% for Cs^{137} (E_γ = 667 kev) when a 30 × 20 mm NaI(Tl) crystal is used.

Analysis of the β spectrum of Pa^{232} with the aid of a Fermi-Kurie plot[5] has shown that this spectrum consists of at least four partial spectra (see Table II). We note that the low-energy partial β spectrum (E_{max} = 260 kev, J = 51%) is

Table II

Component	E_{max}, kev	Intensity, %	$\log_{10} ft$
I	260 ± 30	51	5.7
II	330 ± 30	34	6.1
III	640 ± 50	6	7.9
IV	1220 ± 100	9	8.6

apparently the sum of two or three components with end-point energies less than 260 kev.

3. DISCUSSION OF RESULTS

By comparing the experimental and theoretical values of the relative conversion coefficients on the K and L subshells, we established the multipolarity class for several γ transitions in U^{232} (Table III). However, our experimental data do not yield an unambiguous level scheme for U^{232}. We can therefore make only the following assumptions concerning the series of levels of this nucleus (see also [8,9]).

The levels with energies 0, 47.5, 108.8, and ~ 321 kev are members of the main rotational band. Their energies, spins, and parities are in good agreement, like in all other even-even nuclei, with the predictions of the theory of O. Bohr and B. Mottelson [10] and also with earlier data by others. [2,8]

Unfortunately, no such definite conclusion can be drawn concerning the remaining levels of this nucleus. This can be illustrated by the following example. The recently published short communication by Bjornholm, Knutsen, and Nielsen, [11] devoted to the rotational and vibrational levels of U^{232}, points to the existence of a 564-kev γ transition in this nucleus. We did not observe this γ transition in our measurements. We therefore cannot regard it as established that the 564-kev level is due to octupole oscillations of the nucleus and that its characteristics K, I, and π are 0 and 1^- as indicated in [11].

Let us consider the existence of β and γ vibrational levels in U^{232}. The conversion lines of the 816.4- and 817.5-kev γ transitions could not be separated. But the shape of their summary line indicates that this is a complex electron line (Fig. 3). The γ-ray spectrum shows no 817-kev line. It is established from this spectrum that the contribution of the 960- and 870-kev γ lines to a possible 817-kev line cannot be more than 10%. Consequently, the internal-conversion coefficients of the 816.4- and 817.5-kev γ transitions exceed the internal conversion coefficient of the 866- and 863-kev γ transitions by more than tenfold. This indicates that if the 816.4- and 817.5-kev γ transitions are not pure E0 transitions, they at least contain a large admixture of E0 transition. Thus, we can assume that the 816.4-kev level has spin and parity 0^+, while the characteristic of the 863-kev level is 2^+, i.e., they apparently form a band of β-vibrational levels. In accordance with the observed class E2 of γ transitions with energies 833 and 30 kev, we assign spin and parity 2^+ to the 893-kev level, which may be a γ-vibrational one. We were unable to draw from our data any conclusions concerning the character of the remaining levels.

Let us see how the values of the energies and spins of the identified levels agree with the predictions of the existing theories.

Table III

γ-transition energy, kev	K/L				$(L_I+L_{II})/L_{III}$				M_{II}/M_{III}		Multipolarity of γ-transition
	Experiment	Theory* for			Experiment	Theory* for			Experiment	Theory**	
		$E1$	$E2$	$M1$		E_1	E_2	M_3			
30					1.42						$M1+E2$
47.5					1.2±0.05		1.2		1.3 ± 0.1	1.2	$E2$
108.8					1.6±0.05		1.6		1.5 ± 0.2	1.5	$E2$
147	1.5	0.5	0.12								$E1$
236	6	5	0.5								$E1$
(280)?											
383	1.8	5	1.5	4.9	5.3	8.4	4	200			$M1+E2$
416.8	2.2	5.1	1.5	5	10	9	4.5	200			$M1+E2$
450	3.3	5.2	2	5	8	10	5.5	220			$M1+E2$
466.5	(4)	5.3	2.1	5.1		12	6.5	230			$(E1)$
580	2										?
683	5										$(E1)$
816.4	3.5										$E0$
817.5											$E0\,(+E2)$
863	2.5	~6	~3								$(E2)$
866											$(E2)$
893	3.8	~6	~3								$E2$
963	6.8	6	4	6							$(E1)$?

*The theoretical values of the coefficient of internal conversion on the K and L subshells were taken from Sliv and Band [6].

**The theoretical values of the coefficient of internal conversion on the M subshells were taken from Rose [7].

The lower band of rotational levels is well described both by the theory of O. Bohr and Mottelson for axial deformed nuclei, and by the theory developed in the adiabatic approximation by Davydov and Filippov [12] for non-axial deformed nuclei. The theory of non-axial nuclei was further developed to account for the connection between the rotation of nuclei with β oscillations, [13] which, depending on the values of the non-axiality and non-adiabaticity parameters γ and μ and on the position of the 2_1^+ and 2_2^+ levels makes it possible to establish the values of other levels of even-even deformed nuclei. For U^{232}, in terms of the indicated theory, we have $\mu = 0.212$ and $\gamma = 8.8°$.

Using the Mallmann tables obtained on the basis of the Davydov and Chaban formulas, [13] we can establish the following level-energy ratios: $E(6_1^+)$: $E(2_1^+) = 6.75$ and $E(0_2^+)$: $E(2_1^+) = 19.6$. The first value coincides with the experimental one, while the second differs from the experimental one (~ 17.1) by 15%. The energy determined for the β-vibrational level 0^+ is thus in satisfactory agreement with the predictions of the theory. [13]

In conclusion, we are grateful to G. V. Shishkin, A. A. Arutyunov, and Yu. A. Dmitriev for help in the measurement of the electron spectra.

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