NEW DATA ON ALPHA DECAY OF ^{253}Es *AND THE ENERGY LEVELS OF THE* ^{249}Bk *AND* ^{250}Bk *NUCLEI*

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Submitted February 13, 1972

Zh. Eksp. Teor. Fiz. **63**, 375–385 (August, 1972)

The energy states of the ^{249}Bk nucleus arising in alpha decay of ^{253}Es are studied by means of the technique of deviation of charged particles in a magnetic field. More than forty α groups with particle energies ranging from 5630 to 6650 keV are detected in the α spectrum of ^{259}Es. Some of the ^{249}Bk excited states are interpreted from the viewpoint of the unified nuclear model. It is pointed out that in the ^{249}Bk level scheme there are at least five bands with the quantum characteristics $7/2^+[533\uparrow]$, $3/2^-[521\uparrow]$, $5/2^+[642\uparrow]$, $5/2^-[523\downarrow]$ (?), and $7/2^-[514\downarrow]$ (?). Alpha decay of the odd-odd ^{254}Es nucleus is also investigated. In the spectrum of the daughter nucleus ^{250}Bk the existence of four bands is established which possess the following $J\pi K$ quantum characteristics: 2^-2, 4^+4, 7^+7 and 5^-5.

1. INTRODUCTION

ONLY a negligible number of studies[1-3] have been devoted to α decay of the isotopes ^{253,254}Es. Yet information on the energy states of the daughter nuclei ^{249}Bk and ^{250}Bk is of undisputed theoretical interest from the point of view of the validity of contemporary nuclear models in the region $Z \sim 100$. The relatively high specific activity of ^{253}Es ($T_{1/2}$ = 20.47 d) and the possibility of obtaining it in isotopically enriched form make it possible to investigate the states of ^{249}Bk up to excitation energies ~ 1 MeV with the aid of magnetic analysis. An investigation of α decay to highly excited levels can yield valuable information on the character of these states. The isotope ^{254} is of interest because it is one of the odd-odd α emitters, which are exceedingly rare in the region of heavy nuclei. A study of its decay will greatly supplement the information on the structure of excited states of odd-odd daughter states.

In an earlier paper[3] we presented data on the α decay of ^{253}Es to low-lying levels of ^{249}Bk, up to an excitation energy ~ 600 keV. We have continued this research with the isotopically enriched isotope, and this enabled us to refine our earlier data[3] and to observe a number of hitherto unknown weakly-intense α transitions. In Sec. 3 we present the corrected data on the fine structure of the α decay of ^{253}Es and on the ^{254}Es decay. The energy schemes of ^{249}Bk and ^{250}Bk are discussed in Sec. 4.

2. APPARATUS, SOURCES, ENERGY STANDARDS

The main instrument for the spectroscopic measurements was a magnetic α-spectrograph with spatial focusing of the α-particle beam into an angle $\pi\sqrt{2}$[4]. To obtain a preliminary isotopic analysis of the compounds and to verify the quality of the sources and the degree of radiochemical purification of the einsteinium we used a silicon semiconductor spectrometer. The γ spectra of the isotopes ^{253}Es and ^{254}Es in the energy interval from 0 to 1170 keV were investigated with the aid of a Ge(Li) spectrometer.

In our cited study[3], the fine structure of the ^{253}Es α decay was investigated with a sample containing the isotopes ^{253}Es, ^{254}Es, ^{255}Es, and ^{255}Fm. To separate the α lines belonging to the ^{253}Es emission from the complex spectrum we were forced to make a series of successive exposures, in which the individual groups were identified with allowance for the differences between the half-lives of the investigated isotopes ($T_{1/2\alpha}$ = 276 d and 39.3 d for ^{254}Es and ^{255}Es, respectively[1)]). To perform the present study, we separated isotopically enriched ^{253}Es from the initial compound, which contained a mixture of californium isotopes. To this end, a pure fraction of californium, containing the β emitter ^{253}Cf ($T_{1/2\beta}$ = 17 d) was set to accumulate einsteinium. The radiochemical separation of the califormium and einsteinium made it possible to obtain as a result a ^{253}Es compound in which α-active content of the other isotopes was $\sim 10^{-5}$–10^{-6}. A source measuring 3×60 mm, with surface density of the active medium $\sim 1 \times 10^{-3}$ μg/cm^2 was prepared from the enriched ^{253}Es compound by evaporation in vacuum on a glass substrate.

In the investigation of the α decay of ^{254}Es we used an einsteinium compound stored for a time sufficient to permit decay of practically all the isotopes with half-lives shorter than ^{254}Es. Additional radiochemical separation of ^{249}Cf (the daughter product of ^{253}Es) and ^{250}Cf (the daughter product of ^{254}Es) has yielded a compound in which only microscopic impurities of the other isotopes could be present. In this case, two sources measuring 3×60 mm with active-layer density $\sim 2 \times 10^{-5}$ and 3×10^{-6} μg/cm^2 were prepared for the measurements. Naturally, the real source density was somewhat higher, owing to the extraneous inactive impurities that settled on the substrate at the einsteinium sublimation temperature.

We used as a standard the energy of the α_0 group of ^{253}Es (E_{α_0}(^{253}Es) = 6632.73 ± 0.05 keV), which was obtained from absolute measurements[6]. The accuracy with which the energies of individual α groups were determined (with the exception of cases when a graphic

[1)]The α branch of ^{255}Es amounts to ~8.5% of the number of β decays [5].

TABLE I

Present work					Preliminary data of A. M. Fridman** and data of [7] (in parentheses)		
α_i line, i	E_α, keV	I_α, %	HF	E_{lev}, keV	E_{lev}, keV	Proposed $J\pi K[Nn_z\Lambda]$	W ***
0	6632.7	90.2	2.1	0	0	3/2−3/2[521]	A
9	6624.0	0.8	210	8.8	—		
40	6593.1	0.7	180	40.3	—		
42	6590.8	6.5	18	42.6	42±2	9/2+7/2[633]	A
82	6552.5	0.6	140	81.9	79±3	7/2−3/2[521]	A
94	6541.5	0.8	90	94.0	—		
137	6498.0	0.25	190	136.9	132±5	9/2−3/2[521]	A
155	6480.5	0.075	500	154.7	154±2	13/2+7/2[633]	A
176?	6460	$4.4\cdot10^{-4}$	$7\cdot10^4$	176	—		
203	6433	$5.9\cdot10^{-2}$	390	203	198±5	11/2−3/2[521]	A
221?	6415	$4.6\cdot10^{-4}$	$4.2\cdot10^4$	221	—		
228	6408	$1.2\cdot10^{-2}$	1450	228	—		
270?	6367	$3.6\cdot10^{-4}$	$3.3\cdot10^4$	270	—		
282	6355	$7.4\cdot10^{-3}$	1400	282	—		
299?	~6338	$\sim4\cdot10^{-4}$	$\sim2\cdot10^4$	299	—		
334?	6304	$\sim2\cdot10^{-4}$	$\sim3\cdot10^4$	334	—		
370?	6268	$9\cdot10^{-4}$	4400	370	350±5	15/2−3/2[521]	B
377?	6262	$\sim2\cdot10^{-4}$	$\sim2\cdot10^4$	377	(377.8)	(1/2+1/2[400])	
390	6249	$4.3\cdot10^{-3}$	75	390	—		
421? *	6218	$\leqslant10^{-4}$	$\geqslant2\cdot10^4$	421	(421.4)	(3/2+1/2[400])	
428	6211	$3.9\cdot10^{-3}$	50	428	—		
473	6168	$1.5\cdot10^{-2}$	85	473	—		
496 *	6145	—	—	496	—		
516?	~6125	$8.3\cdot10^{-4}$	960	~516	—		
535?	~6106	$4.4\cdot10^{-4}$	1450	~535	—		
539	~6102	$3.2\cdot10^{-3}$	190	~539	—		
554	~6083	$\sim8.6\cdot10^{-5}$	$\sim2.9\cdot10^4$	~554	(558.3)	(3/2−)	
569	6072	—	—	569	577±10 (569.3)	(1/2−1/2[530]), 7/2−5/2[523] or: 5/2+5/2[642]	C B

*Not shown in Fig. 1.

**Private communication from A. M. Fridman, Dubna, Conference on Heavy Ions, February, 1971.

***The reliability of W is classified as follows: A—reliable, B—less reliable, C—not reliable.

resolution of the spectral lines was necessary) was not worse than 1–2 keV.

3. FINE STRUCTURE OF α RADIATION OF THE ISOTOPES ^{253}Es AND ^{254}Es

Several exposures with total duration ~ 300 h were made with a source prepared from the isotopically enriched ^{253}Es compound. The exposures covered the energy range 5600–6650 keV. The solid angle of the instrument varied from 10^{-4} to 8×10^{-4}, depending on the requirements imposed on the concrete experiment. The energy resolution of the instrument was 2.4 keV (the width of the spectral line at half height) for the intense groups of particles, and 3.7 and 5.5 keV for the low-energy part of the spectrum. In the 6100–6650 keV range we obtained an α spectrum which was practically analogous to that published in[3], but the absence of noticeable admixtures of other isotopes has enabled us to observe several new α groups and to refine the energies and relative intensities of individual lines. The corrected values of the α-group energies, intensities, hindrance factors HF, and level energies of the daughter nucleus ^{249}Bk are listed in Table I together with the data for the energy levels E_{lev} with assumed values $J\pi K[Nn_z\Lambda]$, obtained by A. M. Fridman in an investigation of the reactions ^{248}Cm(α, t)^{249}Bk and ^{248}Cm(^{3}He, d)^{249}Bk (private communication, Symposium on Heavy Ions, Dubna, February 1971) and by Hoff et al.[7] in a study of the β decay of ^{249}Cm.

The noticeable discrepancy between the α-particle energies listed in the table and the data of[3] are explained also by the following circumstance. The energy standard used in[3] was the energy of the α_0 group of ^{242}Cm (E_α = 6111.30 ± 0.25 keV), as indicated by Grennberg and Rytz[8]. They have subsequently informed us that this value is incorrect and should be increased by ~ 1.6 keV. As indicated above, in the present research we used as the standard the recently determined absolute value of the energy of the ^{253}Es α_0 group. The α spectrograms in the energy range 5600–6650 KeV for this isotope are shown in Fig. 1. Each line is marked by a letter α_i whose subscript denotes the corresponding value of the level energy of the daughter nucleus.

In the upper part of Fig. 1 is shown the low-energy part of the ^{253}Es α spectrum, concerning which some remarks are in order. As shown by an analysis of this part of the spectrum, the source contains microscopic impurities of californium (^{249,252}Cf) and apparently also ^{242,244}Cm. Particularly disturbing is the ^{249}Cf impurity, the α spectrum of which masks part of the α lines belonging to ^{253}Es. However, using the data from a study[9] of the α spectrum of ^{249}Cf it is easy to obtain the simple corrections and to indicate the existence of several new α lines in the spectrum of ^{253}Es. Lederer[10] has observed in the α spectrum of ^{253}Es an α_{921} line with intensity $I(\alpha_{921}) = (8 \pm 9) \times 10^{-7}$, i.e., comparable in intensity with the sum $I(\alpha_{664}) + I(\alpha_{673})$. In the present experiments we did not observe this α group. If it does exist, then its intensity is less than 10^{-7}.

Table II lists information on the fine structure of the α radiation of ^{253}Es in the α-particle energy range 5600–6050 keV. We registered a total of 20 α groups. The accuracy in the determination of the energies and intensities of the α groups listed in the table is somewhat lower than in the high-energy part of the spectrum, because the line intensity is exceedingly low (~ 10^{-5}%) and is comparable in some cases with the background in the indicated range. Table II lists also the results of Lederer[10], the data of A. M. Fridman, and the data of Hoff, Evans, et al.[7].

The ^{254}Es sources were used to make several exposures of different durations at spectrograph solid angles 1×10^{-4}, 5×10^{-4} and 8×10^{-4} of 4π. The resolution of the instrument was several hundredth of a per

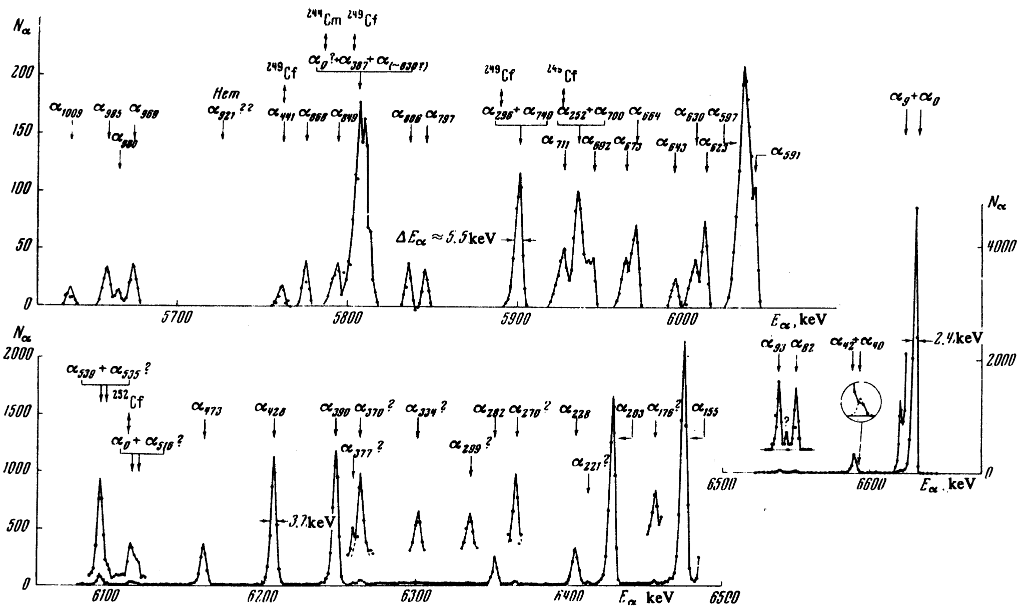

FIG. 1. Instrumental α spectrum of ^{253}Es (E_α is the α-particle energy and N_α is the number of α particles).

TABLE II

Present work					Lederer's data [10]				Preliminary data of A. M. Fridman** and data of Hoff et al. [7] – in parentheses		
α_i line, i	E_α, keV	$10^3 I_\alpha$, %	HF	E_{lev}, keV	$10^3 I_\alpha$, %	HF	E_{lev}, keV	W*	E_{lev}, keV	Proposed $J\pi K[Nn_z\Lambda]$	W**
591	6051	10	3400	591							
597	6045	24	1300	597	6±3	4000±2000	600±10	B			
623	6020	5.6	4100	623	24±10	550±250	617±10	A	616±2	$9/2^{-}\,5/2[523]$	B
630	6013	3.5	6200	630							
643	5999	∼2	9000	643	2±1	7000±3500	642±10	B	646±8(643.1)	{ ($1/2^{-}\,1/2[521]$), $7/2^{-}\,7/2[514]$	C
664	5979	8	1800	664					(661.5)	($3/2^{-}\,1/2[521]$)	
673	5970	2.6	4900	673							
692	5951	5.4	1900	692	3.0±1.5	2800±1400	687±10	B			
700	5943	∼10	960	700							
711	5933	5.6	1500	711	2±1	3000±1500	712±10	B	710±2	$11/2^{-}\,5/2[523]$	C
740	5904	—	—	740	2.7±0.8	1400±400	748±10	B	745±2	$9/2^{-}\,7/2[514]$	B
797?	5849	2	1500	797	0.4	6000	790	C			
806?	5839	2.4	1100	806							
830?	5815	—	—	830					825±5	$11/2^{-}\,7/2[514]$	C
849	5797	4.3	360	849							
868	5779	4.2	290	868							
921	—	<1	—	—	8±3	60±20	921±10	A			
969	5679	3	110	969	1	240	966	C			
980	5668	∼1	300	980							
985?	5663	3	100	985							
1009	5640	1	210	1009	1	120	1010	C			
					0.4	180	1060	C			
					0.8	50	1110	C			
									1196±5	$1/2^{-}\,1/2[521]$	B
									1221±2	$9/2^{+}\,13/2[624]$	B
									1247±5	$3/2^{-}\,1/2[521]$	C
									1291±5	$5/2^{-}\,1/2[521]$	C

*Reliability: A—reliably established α transition, B—position of peak not determined, C—doubtful α transition.
**Private communication, Conference on Heavy ions, Dubna, February, 1971.
***Reliability: A—reliable, B—less reliable, C—not reliable.

cent. These experiments have made it possible to observe 17 α groups in the ^{254}Es spectrum in the energy interval 6550–6050 keV. The data pertaining to the α decay of ^{254}Es are summarized in Table III, which gives also the results of McHarris et al.[2].

4. ENERGY LEVEL SCHEMES OF ^{249}Bk AND ^{250}Bk

As indicated in Sec. 3, we have refined the energies and intensities of the α transitions to the ^{249}Bk states lying in the excitation-energy interval 0–600 keV. This, however, does not influence the energy positions of the levels and the interpretation given for them in the earlier paper[3]. Using the data of Tables I and II, we constructed for the ^{249}Bk nucleus an energy level scheme more complete than before[1,3], as shown in Fig. 2. It is seen from the figure that more than 40 levels exist in the excitation energy interval 0–1 MeV. Many of them have been observed for the first time with the aid of a magnetic α spectrograph. We note that an analysis of the data does not make it possible to interpret unambiguously all the experimentally observed levels. We have therefore confined ourselves to indicating only five bands in the level scheme of this nucleus, with characteristics $7/2^{+}[633\uparrow]$, $3/2^{-}[521\uparrow]$, $5/2^{+}[642\uparrow]$, $5/2^{-}[523\downarrow]$ and $7/2^{-}[514\downarrow]$. However, even in the case of these bands the interpretation of the levels with energies 299, 270, 692, and 830 keV remains unreliable to a certain degree (see Tables I and II).

According to the theoretical predictions presented,

TABLE III

α_i line, i	Our data				Data of McHarris et al. [2]			
	E_α, кэв	I_α, %	HF	E_{lev}, keV	E_α, MeV	I_α, %	HF	E_{lev}, keV
0	~6512	~4,6·10⁻³	~1,6·10⁵	0	6,520	⩽0.005	>1.3·10⁵	0
34	6478	⪅0.05	⪆10⁴	34				
36	~6476	⪆0.18	⪅3·10³	~36	6,486±0.005	0.27	1.7·10³	35.5 *
78	~6435	~0.03	~10⁴	~78				
85	6428,8	93.2	3,1	85	6.437±0.005	93.0	2.9	85.5 *
98	6415,6	1.9	140	98	6.424±0.005	1.7	140	99
131	6383	<0.1	>1,8·10³	131	6.392±0.005	0.13	1.3·10³	131
136	~6378	<0.01	>1,7·10⁴	~136				
156	6358,6	2.4	60	156	6.367±0,005	2.9	43	155.9 *
169	6347	0.75	170	169	6.355±0,005	0.74	150	169
191	6324	0.035	2.8·10³	191	6.331±0,005	0.05	1.7·10³	193
241	6275	~0.11	~520	241	6,284±0,005	0.16	310	241
250	6266	0.22	230	250	6.276±0,005	0.22	210	249
258	6258	⪅0.02	⪆2.4·10³	258				
323	6194	0.04	590	323	6.200±0,010	~0.05	~340	~326
333	6184	~0.08	~260	333	6,193±0.010	~0.05	~380	~333
341	6177	~0.02	90	341				
414	6105	0,36	24	414	6,113±0.005	0,33	23	414
					6.056±0.005	0.16	25	472

*The level positions were determined from the γ rays.

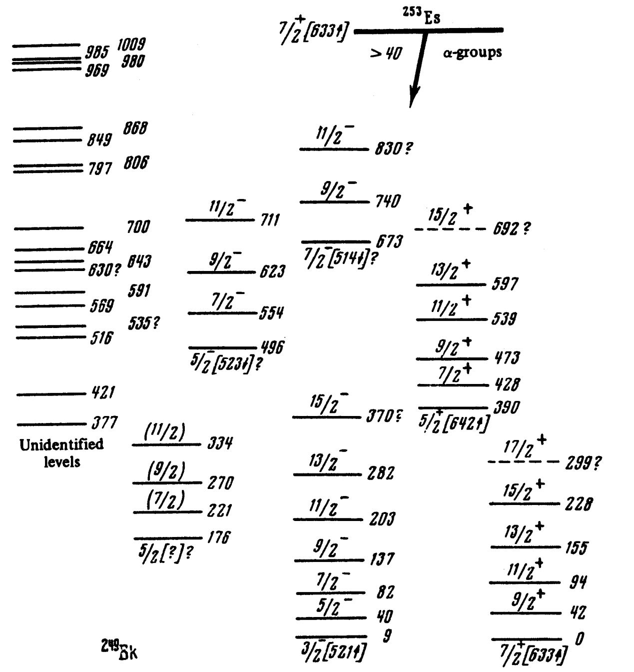

FIG. 2. Energy level scheme of ^{249}Bk.

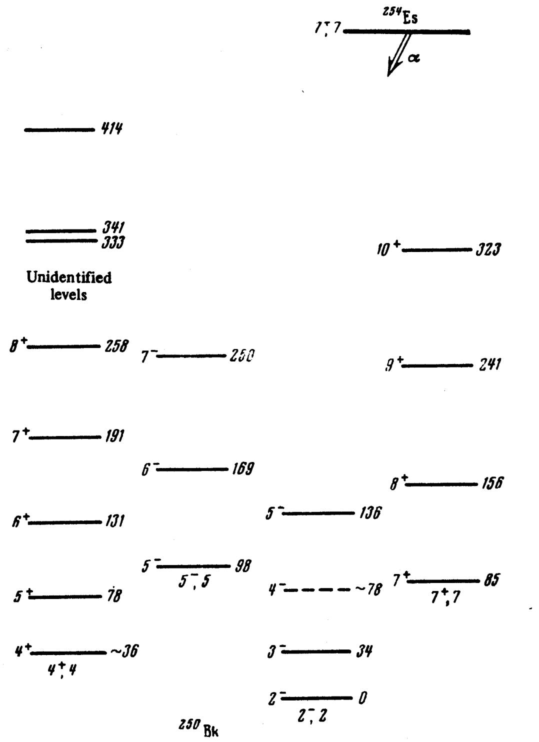

FIG. 3. Energy level scheme of ^{250}Bk.

e.g., in a recent paper by Gareev et al.[11], at least 12 different energy states, arranged in a definite sequence in the scheme, should exist for ^{249}Bk in the excitation-energy interval 0–1 MeV. In the case of the first four bands there is indeed a qualitative agreement between the first four bands there is indeed a qualitative agreement between the predictions of the theory and experiment. It is not excluded, apparently, that the remaining states indicated in[11] are contained among the levels that were not interpreted (see the left-hand side of the scheme). We note that we consider it too early to require that the experimental data for the state energies agree quantitatively with the theoretical predictions. Furthermore, if we agree with the fact that the sequence of energy states in the ^{249}Bk scheme, which was predicted by the theory, agrees qualitatively with experiment, then it becomes difficult to understand the appearance of several levels with energies, e.g., E_{lev} = 176, 221, 270, and 334 keV, for which it is possible to make up a band with $J\pi K = \frac{5}{2}^{\pm}\frac{5}{2}$ ($\hbar^2/2J \approx 6.4$ keV). Is it correct to combine these levels into one band? Are not the experimentally observed α groups corresponding to α transitions to these levels an unpredicted experimental error, in spite of all the precautions? These are questions to be answered by further studies of the energy level scheme of ^{249}Bk.

Before we proceed to discuss the ^{254}Es levels, we make a few remarks concerning the data given in Table III. From a comparison of our data with the results of[2] we see that there is a discrepancy between the energies of identical α-particle groups. This is apparently due to the fact that a less accurate standard was used in[2] to determine the energies for the α groups of the ^{254}Es spectrum. Some discrepancy between the hindrance factors of the α transitions (principally transitions with intensity $<0.2\%$) can be attributed to disparities in the experimentally determined values of the relative intensities.

We constructed the level scheme of the odd-odd nucleus ^{250}Bk in accordance with our data. We shall not dwell in detail on the method of using the known characteristics of the rotational bands ($J\pi K[Nn_Z\Lambda]$, E_{lev}, $\hbar^2/2J$) of the neighboring nuclei (^{249}Bk and ^{251}Cf) to predict similar characteristics of the ground and excited states of ^{250}Bk, since it was already described in the cited paper of McHarris et al.[2]. We confine ourselves therefore only to an illustration of the level scheme of ^{250}Bk (Fig. 3). For the four rotational bands indicated in the scheme, the respective values of $\hbar^2/2J$ and B[2)] are

$J\pi K$:	2−2	4+4	7+7	5−5
$\hbar^2/2J$, keV:	5.9	4.2	4.6	5.9
B:	−0.01	+0.009	+0.008	−0.002

The upper right part of the scheme in Fig. 3 shows three unidentified levels with energies 333, 341, and 414 keV. The first two levels might be assigned spins 9^+ and 8^- levels and attributed to the bands 4^+4 and 5^-5. However, the accessibly low hindrance factors for the transitions to these levels (see Table III) do not allow us to regard them as members of the indicated bands.

The authors thank N. I. Aleshin, Yu. N. Dmitriev, and K. I. Merkulov for help with the laborious measurements, and also É. G. Chudinov, I. K. Shvetsov, and L. V. Chistyakov for supplying the einsteinium compounds.

2) Here $\hbar^2/2J$ and B are quantities that enter in the well known Bohr-Mottelson formula for the nuclear level energies.

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Translated by J. G. Adashko
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