ALPHA DECAY OF CURIUM ISOTOPES

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The α spectra of the $Cm^{242-246}$ isotopes are investigated with a $\pi\sqrt{2}$ magnetic α spectrometer. The energies and intensities of the α transitions are determined precisely. A possible interpretation of some excited Pu^{239} and Pu^{241} states resulting from the α decay of Cm^{243} and Cm^{245} is discussed on the basis of the Nilsson model. Decay schemes for $Cm^{242-246}$ are presented.

THE α-decay spectra of the isotopes $Cm^{242-246}$ have been investigated often, but have not been studied with equal thoroughness. The largest amount of information has been obtained concerning the α spectra of Cm^{242} and Cm^{243}, and somewhat less knowledge in the case of Cm^{244}. Very little information has thus far been obtained regarding the α-group energies and intensities of Cm^{245} and Cm^{246}.

In 1962 we undertook an investigation of the α spectra of curium isotopes using a $\pi\sqrt{2}$ magnetic α spectrometer.[1] A portion of this work containing a more exact determination of the energies of some $Cm^{242-244}$ α transitions has already been published.[2]

In studying the curium α spectra we used samples containing a mixture of the isotopes $Cm^{242-246}$ and their plutonium daughter nuclei. The α spectra revealed no other radioactive substances in the samples. The foregoing curium isotopes, with the exception of Cm^{242}, are quite long-lived. Therefore in determining the relative intensities of the α transitions in different runs we required no corrections for decay.

The sources of the α spectra were prepared by vacuum deposition of active material on glass. In the different runs the dimensions of the sources varied from 0.1×10 to 1×15 mm, depending on the particular experiment. For this reason the half-widths of the lines shown in Figs. 1—3 differ for the various runs. The instrumental half-width of the line obtained from a source 0.5 mm wide and 10 mm long was 7 keV or 0.07% of $H\rho$. The geometric transmission of the instrument during measurements remained constant at 0.1% of 4π. The α particles were registered on A-2 photographic plates bearing a 50 μ thick emulsion. Each plate registered simultaneously a segment of the spectrum ~300 keV wide. The number of α particles was counted microscopically in a band 0.3 mm wide.

Figures 1—3 show the spectral regions from 6.12 to 5.15 MeV; the results are also given in Table I. We shall here compare our present data regarding the α decay of $Cm^{242-246}$ with earlier results, and shall discuss the decay schemes of the individual isotopes.

<u>Cm^{242}</u>. The first investigations of Cm^{242} α

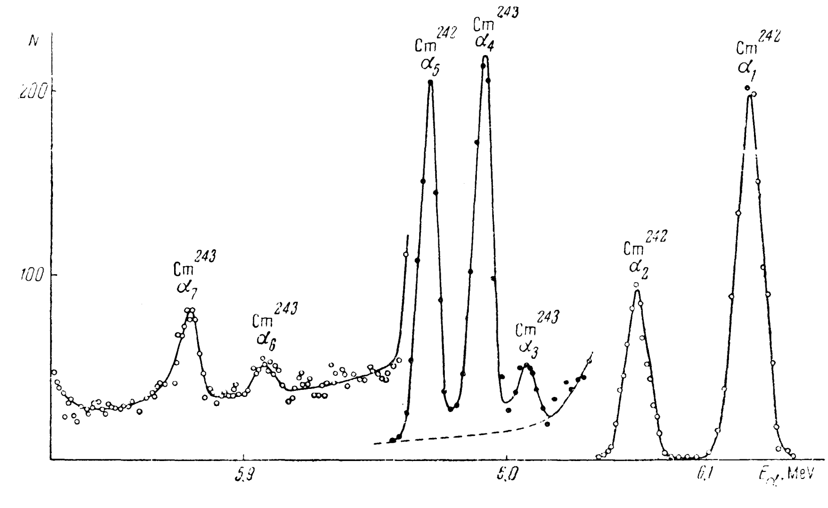

FIG. 1. α spectrum of curium isotopes in the energy region 5.8–6.12 MeV. Here, and in Figs. 2 and 3, N is the number of α tracks in a 0.3-mm wide photographic band.

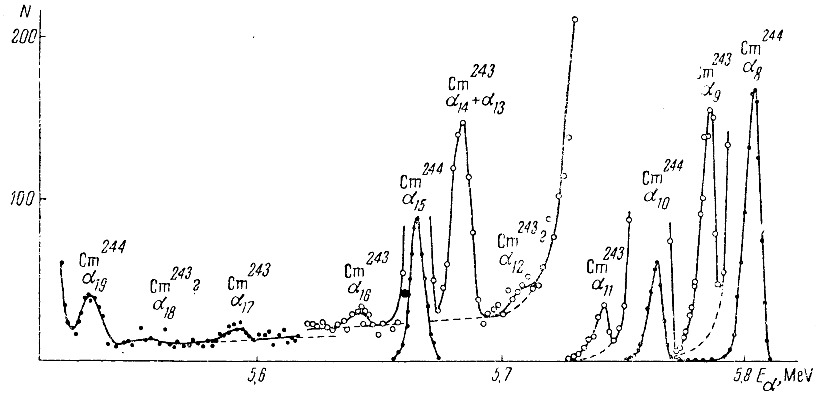

FIG. 2. α spectrum of curium isotopes in the energy region 5.5–5.8 MeV.

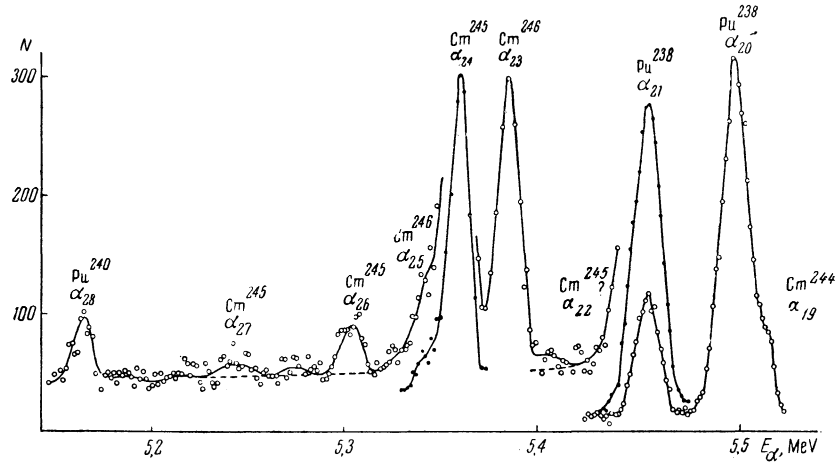

FIG. 3. α spectrum of curium isotopes in the energy range 5.15-5.5 MeV.

decay by means of α spectrometers revealed three α transitions.[3,4] The existence of two additional α transitions is indicated by the results given in [5]. All these transitions feed levels of the Pu^{238} ground-state rotational band.

The study of the Cm^{242} γ spectrum by several investigators [6,7] has shown the existence of hard γ rays from the de-excitation of daughter-nucleus states at ~0.6–1.1 MeV. Including these γ transitions in the Cm^{242} decay scheme, the energies of other excited Pu^{238} states were determined and the intensities of α transitions to the corresponding levels were evaluated.

In Fig. 1 the lines α_1, α_2, and α_5 belong to the Cm^{242} spectrum and arise through α transitions to the Pu^{238} ground-state rotational-band levels having spins and parities 0^+, 2^+, and 4^+. The intensities of these α transitions are in good agreement with earlier data (Table I). The α transitions to higher excited Pu^{238} levels were not observed by us, since these transitions were masked by the tails of intense α transitions of other curium isotopes.

Cm^{243}. The Cm^{243} α spectrum has been studied very thoroughly and twelve α groups are now known. It has been possible to identify reliably the majority of excited Pu^{239} levels from the results obtained in investigating the α spectrum of Cm^{243},[3,5,8,11] the β decay of Np^{239},[9,12,13] K capture in Am^{239},[10] and the γ spectrum of Cm^{243}.[14] The decay scheme of Cm^{243} has been constructed using extensive information regarding the Pu^{239} levels.[16,18]

The ground state of Cm^{243} has the Nilsson assignment $5/2^+$ [622], and the ground state of Pu^{239} has $1/2^+$ [631]. Alpha transitions to levels of the Pu^{239} ground-state rotational band have been observed up to a transition to the $11/2^+$ level. All these transitions are forbidden ($F \geq 300$, see Table I). A favored transition ($F = 1.6$) goes to a 286-keV level of the daughter nucleus, which thus is of the same quantum character as that of the parent nucleus ($5/2^+$ [622]). Two additional members of the rotational band based at this level are known ($7/2^+$ and $9/2^+$).

In addition to the α transitions to levels of these two rotational bands, two α groups are known which lead to 392- and 432-keV levels of Pu^{239}. In [9] the assignment $7/2^-$ [743] has been proposed for the 392-keV level (the first "hole" level in the Nilsson model). The known Pu^{239} levels also include one at 512 keV which was not observed in the α decay of Cm^{243}, but was detected in investigations of Np^{239} β decay and K

TABLE I

Lines in figures	Data of different authors: Transition energy, keV		Data of different authors: Transition intensity, %	Our data in [2,8,22] and the present work: Transition energy, keV	Energy level, keV	Transition intensity, %	Hindrance factor, F
				Cm^{242} ($T_{1/2}$ = 162.5 days [17])			
	[3,6]	[5]	[3,6]				
α_1	6110	6115.0	73.7	6115±1	0	74.0±2.0	
α_2	6066	6071.4	26.3	6071±1	44	26.0±0.9	
α_5	5965	5971.4	0.035	5971±3	146	0.035±0.002	
—	—	5816		—	—	—	
—	—	5614		—	—	—	
				Cm^{243} ($T_{1/2}$ = 35 years [17])			
	[3,11]	[5]	[3,11]				
—	6061	—	1.0	6066*	0	1.0**	3500
—	6054	—	5.0	6058*	8	5.0**	700
α_3	6005	—	0.9	6009±3	57	0.91±0.09	2000
α_4	5987	5993	6.0	5992±3	76	5.4±0.2	320
α_6	5900	5907	0.1	5902±3	164	0.14±0.03	3700
α_7	5872	5877	0.5	5875±3	193	0.54±0.07	850
α_9	5780	5786	73.0	5785±3	286	73±4	1.6
α_{11}	5736	5742	11.5	5740±3	330	12.3±0.6	4.5
α_{12}	—	—	—	5713±5?	358	⩽0.04	⩾1300
α_{13}	5680	5686	1.6	5684±3	388	1.65±0.2	23***
α_{14}	5676	5682	0.2				170**
α_{16}	5634	5640	0.15	5640±3	432	0.12±0.04	150
α_{17}	—	5590	—	5593±4	480	0.03±0.01	350
α_{18}	—	—	—	5558±5?	516	⩽0.005	⩾1000
				Cm^{244} ($T_{1/2}$ = 18 years [17])			
	[3,17]	[5]	[3,17]				
α_8	5801	5806	76.7	5806±3	0	76.2±2.0	
α_{10}	5759	5765	23.3	5763±3	43	23.8±0.9	
α_{15}	5661	—	0.017	5666±3	142	0.021±0.002	
α_{19}	—	—	—	5515±4	292	0.003±0.001	
				Cm^{245} ($T_{1/2}$ = 10 000 years [17])			
	[17,24]		[17,24]				
—	—		—	5532+	0	⩽2	⩾700
—	5450		15	5461++	72	⩽8	⩾55
α_{22}	—		—	5409?	125	⩽1.2	⩾270
α_{24}	5360		77	5362±4	173	80±5	1.9
α_{26}	5310		8	5306±4	230	7±1	8.5
α_{27}	—		—	5246±5	291	2±0.8	11
				Cm^{246} ($T_{1/2}$ = 6000 years [17])			
	[28]						
α_{23}	5370		—	5387±4	0	78±5	
α_{25}	—		—	5345±5	43	22±5	

*The transition energies were calculated from the energies of the γ rays and other α groups; transitions were not observed in the present work.

**The transition intensities were taken from [11].

***In calculating the hindrance factor the intensity of the transition to 388 keV was taken to be 1.45%.

+The error limits are not shown; the transition energy was determined from data in [2] and from the transition energy to the 173-keV level.[22]

++The transition was not observed, and its energy was calculated from data in [16,17].

capture in Am^{239}. From the data in [9,10,13] we have the assignment $7/2^+$ [624] for this level.

As already mentioned, the Cm^{243} spectrum has revealed six α transitions to levels of the Pu^{239} ground-state rotational band, four of which (α_3, α_4, α_6, and α_7) are seen in Fig. 1. We were unable to observe transitions to levels having spins $1/2$ and $3/2$, since these are located close to the intense line α_2 of Cm^{242} and are concealed by the tail of this line. For this reason the intensities of these transitions given in Table I have been borrowed from [6], and their energies have been calculated using our present data and earlier results appearing in [2,12].

Figure 2 shows the spectrum of Cm^{243} from 5.8 to ~5.5 MeV. The lines α_9, α_{11}, and α_{13} correspond to transitions to levels of the K = $5/2$ rotational band (favored transitions). We were unable to resolve the close α_{13} and α_{14} transitions (5686 and 5682 keV), although the half-width of the combined line was somewhat greater than the half-widths of other lines; we have designated it in Fig. 2 as a double line. In computing the hindrance factor of the α_{13} transition its intensity was taken to be 1.45%, which is the difference between the combined intensities of α_{13} and α_{14} in the present work and the intensity of the 5682-keV transition observed in [5,11].

The α_{16} and α_{17} lines in Fig. 2 also belong to the Cm^{243} spectrum. An elevation above the background at 5710 keV has been denoted as the line α_{12}. The existence of a transition with this energy can still not be regarded as completely proven, because of the large statistical error. Similarly, the existence of a 5558-keV transition (α_{18} in Fig. 2) cannot be asserted. For both cases Table I contains the estimated upper intensity limit of these possible transitions. In Fig. 4 both levels are designated by dashed lines.

It follows from Table I that our present data on the energies and intensities of Cm^{243} α transitions are in good agreement with the results obtained by other investigators.[5,11] Our results do not require a revision of the spin and parity assignments of most Pu^{239} levels based on earlier work. A hypothesis can be advanced regarding the nature of the 432-keV level because a transition to the 480-keV level has been observed. The energy difference of these levels makes it possible to regard them as members of a single rotational band. The hindrance factors of these transitions (Table I) are consistent with this hypothesis. We can still not assign unique spins and parities to these levels; it will be shown that data regarding the γ spectrum of Cm^{243} will be required for this purpose.

According to the Nilsson model the relatively low-lying single-particle excited states of Pu^{239} have the following assignments: $^5/_2^+$ [622], $^7/_2^-$ [743], $^7/_2^+$ [624], $^5/_2^+$ [633], and $^9/_2^-$ [734]. The first three assignments correspond to levels at 286, 392, and 512 keV. The transition to the $^9/_2^-$ [734] level is associated with a change of spin ($\Delta K = 2$) and parity and must therefore be highly forbidden. The relatively large hindrance factors of the 432- and 480-keV α transitions indicate that there is only a small difference between the parent and daughter states involved in these transitions. This condition is fulfilled if we assign $^5/_2^+$ [633] and $^7/_2^+$ [624] to the 432- and 480-keV levels, or if we assume that they are members of the rotational band based at the 392-keV level with $K = {^7/_2^-}$ [743]. The possible interpretations of these levels are summarized in Table II.

If $^5/_2^+$ [633] is assigned to the 432-keV level and it is assumed that this level and the 480-keV

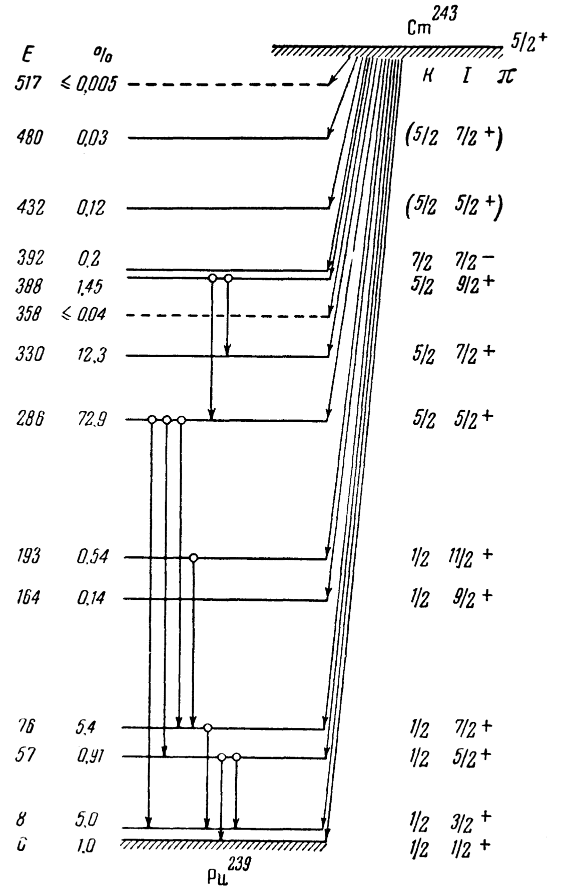

FIG. 4. Cm^{243} decay scheme. Spin and parity assignments based on our present work are given in parentheses.

level form a rotational band, the nuclear moment of inertia for this band is 6.85 keV (Table II). This value does not differ much from the moments of inertia determined for other Pu^{239} bands, which are 6.25 keV for the $K = {^1/_2}$ band and 6.39 keV for the $K = {^5/_2}$ band.[16] The similarity of the moments of inertia for the different rotational bands is, of course, not a final criterion of the correctness with which the levels have been labeled, but it can serve as an argument favoring the proposed assignments. The intensity ratio of α transitions to the 432- and 480-keV levels and the hindrance factors of the transitions are also consistent with the given assignments.

If the 432- and 480-keV levels are members of a rotational band based at 392 keV, the nuclear moment of inertia is 4.5 keV. In this case the 480-keV level agrees well with the value obtained from the formula for determining the energies of rotational band members.[16] However, the intensity ratio of the 392- and 432-keV transitions and their hindrance factors engender some doubt that these transitions belong to a single rotational band.

We have already discussed the reasons for considering the assignment $^9/_2^-$ [734] unacceptable for

TABLE II

Energy level E, keV	Transition intensity, %	Hindrance factor F_-	K	I^π	$[Nn_Z\Lambda]$	Moment of inertia $\hbar^2/2J$, keV	ΔK	Parity change
432	0.12	150	$5/2$	$5/2+$	[633]	6.85	0	No
480	0.03	350	$5/2$	$7/2+$				
392	0.2	170	$7/2$	$7/2-$	[743]	4.5	1	Yes
432	0.12	150	$7/2$	$9/2-$				
480	0.03	350	$7/2$	$11/2-$				
432	0.12	150	$9/2$	$9/2-$	[734]	4.4	2	Yes
480	0.03	350	$9/2$	$11/2-$				
432	0.12	150	$7/2$	$7/2+$	[624]	5.3	1	No
480	0.03	350	$7/2$	$9/2+$				

the 432- and 480-keV transitions. In addition, the following objection can be raised against the assignment $7/2^+$ [624] for these levels. According to [9] the 512-keV state has even parity, and can therefore be either $5/2^+$ [633] or $7/2^+$ [624] (in the Nilsson model there are no other low-lying states with even parity). If we should assign $5/2^+$ [633] to 512 keV and $7/2^+$ [624] to 432 keV, it would be found that appreciable α decay goes to the $7/2^+$ level ($\Delta K = 1$) and not to the $5/2^+$ level ($\Delta K = 0$). (It has already been mentioned that the α spectrum of Cm^{243} did not reveal the 512-keV level.) Nevertheless, the probability of a transition with $\Delta K = 0$ apparently should be larger than with $\Delta K \neq 0$. It follows that if there is no reason for removing the hindrance of a change of K in this case, we should assign $7/2^+$ [624] to the 512-keV level rather than $5/2^+$ [633]. This excludes the possibility of assigning $7/2^+$ [624] to the 432-keV level.

Thus only the first assignment of the 432- and 480-keV levels given in Table II encounters no serious objections based on the presently available data. For this reason we consider it most probably correct to assign $5/2^+$ [633] to the 432- and 480-keV levels. A final answer will be reached only after a more detailed study of the γ rays accompanying the α decay of Cm^{243}. Fig. 4 shows the Cm^{243} decay scheme taking into account the data given in [5,8] and earlier investigations.

Cm^{244}. The investigations of the Cm^{244} α spectrum have revealed three α transitions[3,17] to levels of the Pu^{244} ground-state rotational band with spins and parities 0^+, 2^+, and 4^+. The study of the Cm^{244} γ spectrum has led to the determination of the energy and intensity of an α transition to the next level (6^+) of this band.[17,18] From the β decay of Np^{240}[19,21] and K capture in Am^{240}[10,20] information has been obtained concerning other, higher-lying, excited Pu^{240} states.

Our results for the α spectrum of Cm^{244} have already been published.[8] The intensities of transitions to ground-state rotational-band levels of the daughter nucleus (0^+ and 2^+; lines α_8 and α_{10} in Fig. 2) are in full agreement with earlier data. The intensity of the transition to the 4^+ level of this band (α_{15} in Fig. 2) was found to be somewhat greater than the previously accepted value (Table I). A transition to the 6^+ rotational level of the Pu^{240} ground-state band was also observed (α_{20} in Fig. 2). The energy and intensity of this transition (Table I) agree well with the values given in [17]. We observed no transitions to higher-lying excited Pu^{240} states.

Cm^{245}. Only two α groups had previously been found in the α spectrum of Cm^{245}.[24] The energies of these transitions were measured with an ionization chamber; therefore their accuracy was not greater than ± 10 keV. The γ spectrum of Cm^{245} revealed three γ transitions with energies of 101, 130, and 173 keV.[17,25] The combined α and γ data for Cm^{245} suggested[16,23] the existence of an excited daughter-nucleus state at 230 keV and enabled the evaluation of the energy and intensity of α decay to this level.

The lack of sufficient data regarding the excited states of Pu^{241} makes it extremely difficult to construct the Cm^{245} decay scheme.

Direct measurements showed that the spin of Pu^{241} is $5/2$;[27] this agrees with the Nilsson assignment $5/2^+$ [622] of the Pu^{241} ground state. The Cm^{245} ground state can have the Nilsson assignment $7/2^+$ [624]; this assignment was considered most probable in [26], where the α decay of Cf^{249} was investigated. Since the spin of Cm^{245} has still not been measured directly, in discussing the decay scheme of Cm^{245} we shall assume that the assignment $7/2^+$ [624] is correct. Thus a favored Cm^{245} α transition must go to an excited $7/2^+$ [624] level of Pu^{241}; the energy of this level can be determined from data regarding the Cm^{245} γ spectrum.

It is reasonable to assume that the most intense γ transitions of Cm^{245} (101 and 173 keV) represent the deexcitation of the most highly populated level of the daughter nucleus, i.e., of a level which is fed by a favored α transition. The multipolarity of a γ transition between a $7/2^+$ level and the $5/2^+$ ground state of Pu^{241} should be E2 or M1. Indeed, as a rule these transition types possess appreciable intensity in the γ spectra. If both the 101- and 173-keV γ transitions originate in the excited level fed by the favored transition the 173-keV transition obviously goes to the Pu^{241} ground state. This conclusion does not conflict with the conversion coefficient for M1 transitions with this energy or with the intensity of the 173-keV transition given in [17]. We assume from the foregoing considerations that the favored transition in Cm^{245} α decay goes to the 173-keV level.

In [22] we presented data on the energies and intensities of three α transitions which we attribute to Cm^{245} decay; these are designated in Fig. 3 as α_{24}, α_{26}, and α_{27}. The first two undoubtedly belong to Cm^{245}; their energies and intensities are in good agreement with previously known data. The third transition probably also arises through Cm^{245} decay, although we have no rigorous proof; this question will be discussed below.

The most intense transition (α_{24}) having the energy 5362 keV obviously is favored ($F = 1.9$; Table I). The hindrance factors for two other transitions with 5306 and 5246 keV ($F = 8.5$ and ~ 11) suggest that all three transitions go to levels of the $K = 7/2$ rotational band. The moment of inertia of Pu^{241} for this band was determined from the first two levels to be 6.33 keV. Using this value, we calculated the energy of the next level of the same rotational band to be 299 keV, which agrees sufficiently well with the level to which the third of the observed α transitions goes (Table I). This good agreement between the calculations and experiment further confirms the hypothesis that the third α transition also goes to a level of the $K = 7/2$ rotational band.

Although the arguments favoring the foregoing identification of this transition seem very convincing, we do not regard this interpretation as unique. It can be argued that the 5246-keV transition is not associated with the decay of even-even curium isotopes in our sources. The transition intensity is too high to go to any high-lying level of a daughter nucleus derived from one of these isotopes. However, we cannot exclude the possibility that the transition arises through Cm^{243} decay. The arguments supporting the assignment of the transition to the Cm^{245} spectrum in Table I and in Fig. 5 are that the excited Pu^{239} states have been very thoroughly investigated, as we have seen, so that it is unlikely that a level with the given population would not have been observed previously. The origin of this transition can obviously be decided only by investigating the pure Cm^{245} isotope or a mixture with different Cm^{243} and Cm^{245} contents than in our case.

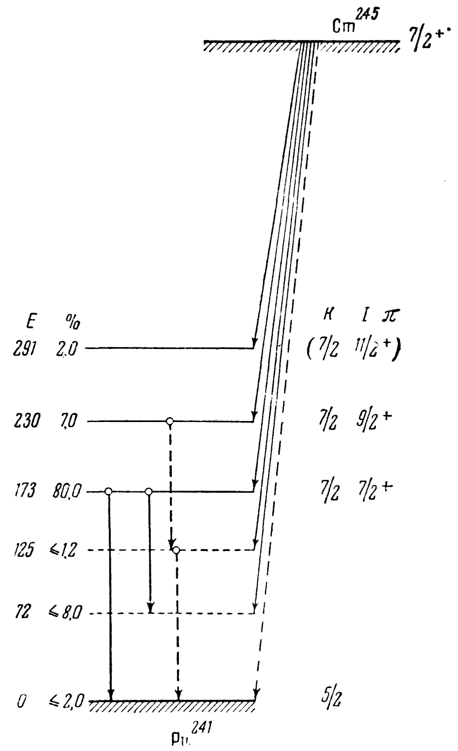

FIG. 5. Cm^{245} decay scheme. Spin and parity assignments based on our present work are given in parentheses. The γ transitions designated by dashed lines represent a possible interpretation of the γ-γ coincidences used in [17] to establish the existence of a 230-keV level.

We are, of course, also not obliged to relate the 5246-keV transition to the rotational band. Alpha transitions to single-particle levels of Pu^{241} are also possible; the character of the α spectrum does not enable us to determine definitely the excited state of the daughter nucleus that is associated with the transition. For this reason the character of the 5246-keV transition is not entirely certain.

We have hitherto discussed α transitions to excited levels of Pu^{241}. The energy of a α transition to the ground state can be established from the previously presented data on the γ spectrum of Cm^{245} and from our data on the energy of the favored transition.[22] Adding to the latter the energy of the 173-keV transition, which, as we have seen, obviously terminates in the Pu^{241} ground state, we determined the energy of the α transition to this ground state (Table I). In investigating the α spectrum in this energy region we observed a rise above the background, but the large statistical error does not permit an affirmation that the α transition having this energy is actually observed. Table I gives the upper intensity limit of this transition, which is denoted by a dashed line in the Cm^{245} decay scheme (Fig. 5).

We were unfortunately unable to investigate with sufficient thoroughness the 5.55 — 5.40-MeV region of the spectrum. In constructing the Cm^{245} decay scheme we are greatly interested in a 5.45-MeV α transition, which has 10—15% intensity according to different investigators.[16,17] The energy of this transition can be determined with greater accuracy than previously by the same means that were used in determining the energy of the α transition to the Pu^{241} ground state. An intense 101-keV γ line in the Cm^{245} spectrum appears to result from deexcitation of the 173-keV level and to terminate in a lower-lying level at 72 keV; the energy of the α transition to this level is 5461 keV. However, we were unable to observe this transition.

Figure 3 shows that this energy region contains two intense α transitions (α_{21} and α_{22}) belonging to the spectrum of Pu^{238}, which is the product of Cm^{242} decay. The energies of these transitions are 5498 and 5453 keV,[17] thus one of them differs by 8 keV from the energy of the discussed Cm^{245} transition.

Since the line half-width in this spectral region was ~13 keV because of the very thick source, and it was thus impossible to resolve lines separated by 8 keV, we attempted an indirect intensity evaluation of the transition to the 72-keV level, using the known ratio between the intensities of the Pu^{238} α groups. After comparing the intensities of these lines we concluded that[17] probably gives too high a value for the intensity of Cm^{245} decay to the 72-keV level, since if the intensity were 15% it would contribute appreciably to the intensity of the 5453-keV transition of Pu^{238}. However, the measured intensities of both Pu^{238} transitions showed no appreciable departure from the ratio in the tables of [17]. For this reason we assume an upper limit of 8% for the intensity of the 5461-keV transition.

The existence of a 5409-keV transition cannot be regarded as fully proven. In Fig. 3 this transition is denoted as α_{22}, and in Table I it is assigned to the Cm^{245} spectrum. However, further investigation is required, and in the decay scheme of Cm^{245} in Fig. 5 the transition is represented by a dashed line.

The absence of precise data regarding the intensities of Cm^{245} α transitions to low-lying excited levels prevents us from determining the hindrance factors of these transitions. Table I gives the lower limits of the hindrance factors, calculated from the intensity estimates presented here.

$\underline{Cm^{246}}$. The energy of the single α transition observed in the Cm^{246} spectrum was determined with an ionization chamber.[28] According to [29], the γ spectrum of Cm^{246} contains a 44.5-keV transition, which can be assumed to go from a 2^+ daughter level to the ground state. There is no other information available regarding Cm^{246} decay.

We attribute the α_{23} line in Fig. 3 to a Cm^{246} transition to the ground state of the daughter nucleus. The energy measurements show that the previously assumed value for this transition (Table I) is somewhat lower than that given in [22]. A transition to a 2^+ level of the ground-state rotational band of Pu^{242} should have about one-third the intensity of a transition to the ground state; the excitation energy of this level, as already mentioned, is 44.5 keV. Fig. 3 shows an α group (α_{25}) corresponding to this transition. Poor resolution prevented us from separating the lines α_{24}(Cm^{245}) and α_{25} and from determining reliably the relative intensities of Cm^{246} α groups. Table I gives the values of these quantities obtained by resolving the α_{24} and α_{25} lines. Fig. 6 shows the decay schemes of the even-even curium isotopes Cm^{242}, Cm^{244}, and Cm^{246}, based on the α decay data for these isotopes.[5,8,22]

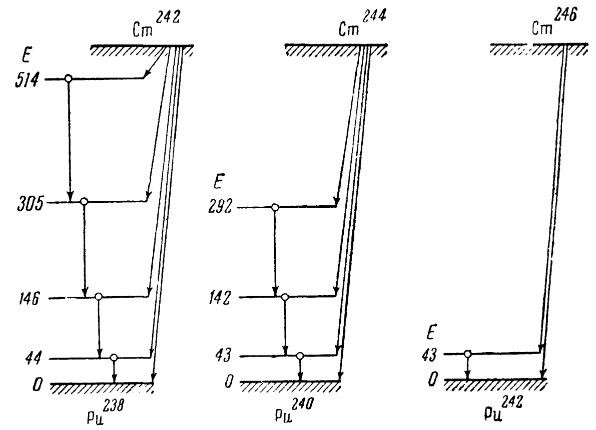

FIG. 6. Decay schemes of even-even curium isotopes.

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