Levels in ^{237}Pu populated by ^{237}Am (electron capture) and ^{241}Cm(α) decays*

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The electron capture decay scheme of ^{237}Am (73 min) has been investigated by measuring the γ-ray and conversion-electron spectra of mass-separated ^{237}Am samples. The γ-ray spectra were measured with a Ge(Li) spectrometer and the conversion-electron spectra were measured with a cooled Si(Li) detector and a magnetic β-ray spectrometer. Thirty-five γ rays were identified and the multipolarities of most of the transitions were deduced. The half-life of ^{237}Am was determined by following the decay of the 280.2 keV photopeak and was found to be 73.0 ± 1.0 min. The α-particle energy and α branching were measured to be 6.042 ± 0.005 MeV and [(2.5 ± 0.3) $\times 10^{-2}$]%, respectively. On the basis of the present investigation the following single-particle states have been identified in ^{237}Pu: $\frac{7}{2}$−[743], 0; $\frac{1}{2}$+[631], 145.5; $\frac{5}{2}$+[622], 280.2; $\frac{3}{2}$+[631], 370.4; $\frac{5}{2}$+[633], 407.8; $\frac{7}{2}$+[624], 473.5; $\frac{5}{2}$−[752], 655.3; and $\frac{7}{2}$+[613], 908.8 keV. The ground state of ^{237}Am has been deduced to be the $\frac{5}{2}$−[523] Nilsson orbital. The logft values for electron capture transitions to the observed states were derived. The α-particle spectrum of a mass-separated ^{241}Cm sample was measured with the Argonne double focusing magnetic spectrometer. Eleven α groups identified in this spectrum populate the members of the ground state, $\frac{1}{2}$+[631], and $\frac{3}{2}$+[631] bands. The α-decay hindrance factors are consistent with the Nilsson-state assignments deduced from ^{237}Am electron capture decay.

[RADIOACTIVITY ^{237}Am [from ^{237}Np(α, 4n) and ^{237}Np(^{3}He, 3n)]; measured $T_{1/2}$, E_α, E_γ, I_γ, E_{ce}, I_{ce}, $\gamma\gamma$-coin, α branching, ^{241}Cm [from ^{239}Pu(α, 2n)]; measured E_α, I_α; deduced hindrance factors. ^{237}Pu deduced levels, logft (EC), γ multipolarity, I, π, eight single-particle states. Mass-separated ^{237}Am and ^{241}Cm. Toroidal β spectrometer at 0.15% FWHM.]

I. INTRODUCTION

The α-particle spectrum of ^{241}Cm was first measured by Asaro *et al.*[1] with a magnetic spectrograph. Three α groups feeding the members of the favored band were identified. Stephens *et al.*[2] observed a 145-keV γ ray deexciting the state populated by the favored α group. They determined the multipolarity of the 145-keV transition as $E3$ and measured the half-life of the 145-keV state as 0.18 s. On the basis of these observations the ground state and 145-keV state of ^{237}Pu were given the $\frac{7}{2}$−[743] and $\frac{1}{2}$+[631] Nilsson-state[3] assignments, respectively. Recently Baranov, Aliev, and Chistyakov[4] measured the ^{241}Cm α spectrum with a magnetic spectrograph and reported 12 α groups. However, the hindrance factors for ^{241}Cm α groups feeding ^{237}Pu levels above 200 keV excitation are about an order of magnitude smaller than those for ^{239}Pu α transitions[5] involving the same initial and final states. Because of this discrepancy a remeasurement of the ^{241}Cm α spectrum was undertaken.

The nuclide ^{237}Am was first produced[6] by the irradiation of ^{239}Pu with 30–50-MeV deuterons. The α-particle spectrum of the chemically purified Am fraction contained a 6.01-MeV α group which decayed with a ~1.3-h half-life. This α group was assigned to ^{237}Am because it was not observed in α spectra of Am samples produced at deuteron bombarding energies below 30 MeV, indicating it as a (d, 4n) reaction product. The Pu K x rays associated with ^{237}Am EC (electron capture) decay could not be distinguished from those arising from ^{238}Am decay because of the closeness in their half-lives. Also no γ ray was assigned to ^{237}Am decay. The EC/α ratio, estimated on the assumption that one-half of the observed Pu K x rays belonged to ^{237}Am, was found to be $(1.1 \pm 0.4) \times 10^4$.

The ^{237}Am EC decay scheme study was started by us several years ago in order to identify single-particle states in ^{237}Pu. The preliminary results of this study have been reported[7] earlier. A few of the γ rays identified by us were later observed by Post.[8] Recently the level structure of ^{237}Pu has also been investigated by the ^{238}Pu(d, t) reaction.[9] The results of this investigation are in agreement with our present assignments. In the present paper we describe our measurements of the ^{237}Am γ-ray and conversion-electron spectra and ^{241}Cm α spectrum and discuss the single-particle orbital assignments to the observed levels.

II. SOURCE PREPARATION

The ^{237}Am samples used for the present measurements were produced by irradiating ~60 mg of ^{237}Np with 42-MeV α particles and 32-MeV ^{3}He ions in the Argonne 60-in cyclotron. The ^{237}Np target was made by evaporating a neptunium nitrate solution to dryness in a platinum crucible which was a part of the target assembly. The Np was covered with a 27-mg/cm^2 Pt foil in order to confine it to the crucible. During the irradiation the target was cooled by circulation of cold water and the Pt cover was cooled by a stream of helium gas. The irradiation time was 3 h and the average beam current density was 30 μA/cm^2.

The irradiated Np was dissolved by heating it with concentrated HNO_3 and HF. After boiling off the HF, the material was evaporated to dryness in *aqua regia*. The residue was then dissolved in ~1 ml of 9 *M* HCl and the Np was extracted four successive times with equal volumes of 0.4 *F* Aliquat-336 in xylene. To the aqueous phase, which contained Am, ~1 mg of lanthanum carrier was added and precipitated as hydroxide. The precipitate was then dissolved in a minimum amount of HCl and evaporated to dryness. The residue was dissolved in 3 *M* NH_4SCN-0.01 *M* H_2SO_4 and loaded onto a 2-mm×6-cm column containing Aliquat-336 chloride adsorbed on Celite. A solution of 1 *M* NH_4SCN-0.01 *M* H_2SO_4 was then passed through the column, which removed most of the fission products. The Am was then eluted with

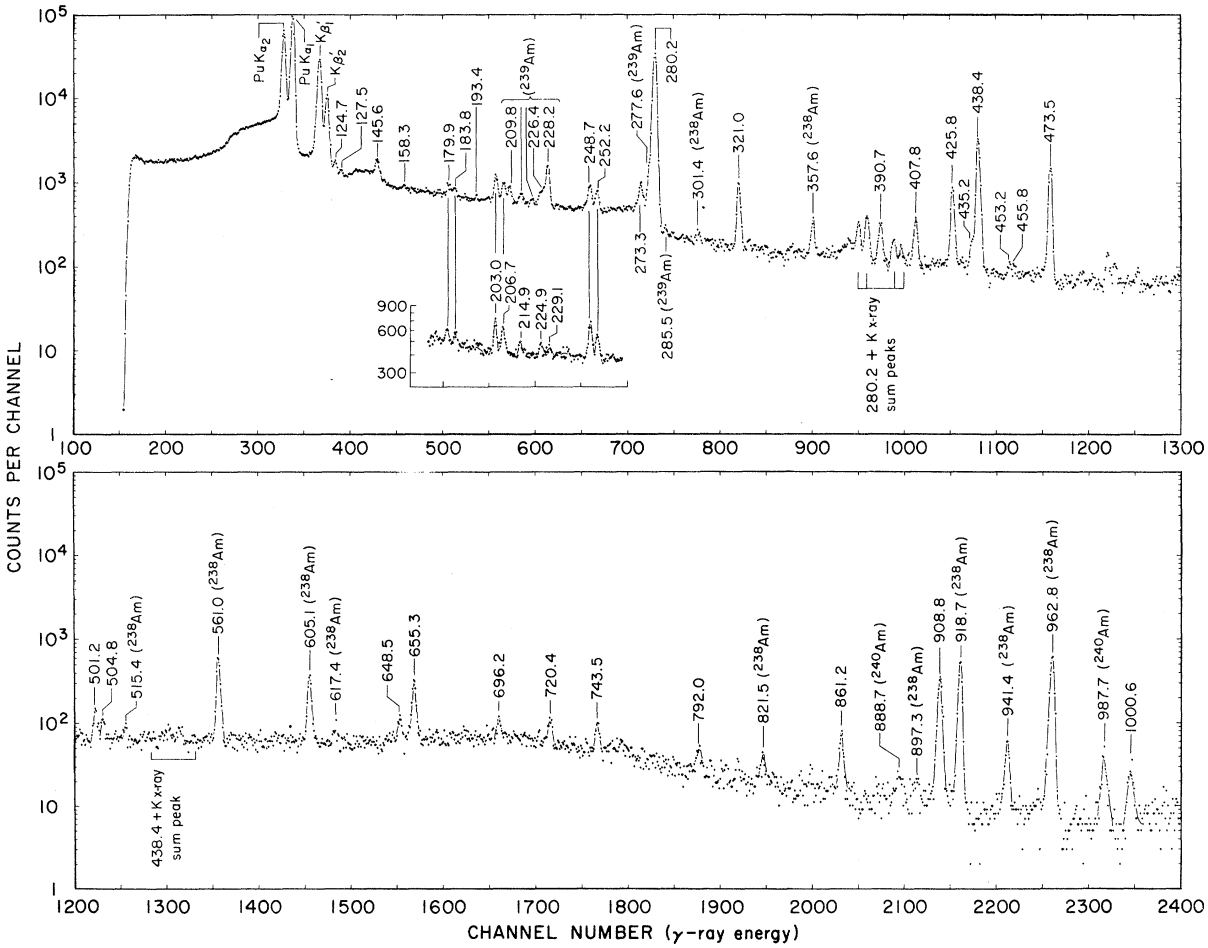

FIG. 1. γ-ray spectrum of a mass-separated ^{237}Am sample measured through a 220-mg/cm^2 Al absorber with a 25-cm^3 Ge(Li) detector. The source was placed ~3 cm from the detector end cap. The sample was produced by the ^{237}Np(α, 4*n*) reaction. The broad structure below the 145.6-keV peak is due to the backscattering of the intense 280.2-keV γ rays. The inset shows the spectrum of the mass-separated ^{237}Am sample prepared by the (^{3}He, 3*n*) reaction, measured through a set of Pb, Cd, Cu, and Al absorbers with the 25-cm^3 Ge(Li) detector. This sample had an order of magnitude less ^{238}Am and ^{239}Am and hence ^{239}Am γ rays and *K* x-ray–*K* x-ray sum peaks are absent from this spectrum.

0.02 M H_2SO_4 solution and was loaded onto another column containing di-(2-ethylhexyl) orthophosphoric acid adsorbed on Celite. The column was operated at 60°C. A 0.1 M HCl solution was passed through the column which removed most of the remaining fission products. The Am was then eluted with 0.5 M HCl solution.

The purified Am was run through the Argonne electromagnetic isotope separator[10] to obtain isotopically enriched ^{237}Am samples. It was found that the $(\alpha, 4n)$ reaction produced ~5 times more ^{237}Am activity than the $(^3\text{He}, 3n)$ reaction. However, the α-particle irradiation produced relatively larger amounts of ^{238}Am (98 min) and ^{239}Am (11.9 h) resulting in larger amounts of these isotopes contaminating the mass-separated ^{237}Am samples. Hence experiments requiring high isotopic purity were performed with ^{237}Am samples produced by the $(^3\text{He}, 3n)$ reaction.

The ^{241}Cm sample for α spectroscopy was prepared by the irradiation of a ^{239}Pu target with 40-MeV α particles. The procedure for the production and purification of ^{241}Cm activity has been described in Ref. 11.

III. EXPERIMENTAL DATA

A. γ-ray spectroscopy

The γ-ray spectrum of a mass-separated ^{237}Am sample measured with a 25-cm^3 coaxial Ge(Li) spectrometer is displayed in Fig. 1. The sample was produced by the α-particle irradiation of ^{237}Np. The energies and intensities of the ^{237}Am γ rays were determined from hand plotted graphs. In the 200–240-keV region the spectrum contains K x-ray–K x-ray sum peaks which arise mainly from ^{239}Am impurity in the sample. In this region the energies and intensities of the ^{237}Am γ rays were obtained from the spectrum of a ^{237}Am sample produced by the $(^3\text{He}, 3n)$ reaction. Also the spectra were measured at several source-to-detector geometries in order to determine the sum peak contributions. The Pu K x-ray peaks also contained small contributions from the decays of ^{238}Am (98 min), ^{239}Am (11.9 h), and ^{240}Am (50.8 h). These contributions were determined from the intensities of their prominent γ rays and by the use of the K x-ray to γ-ray intensity ratios given in Refs. 12–14.

The energies and intensities of ^{237}Am γ rays obtained from several spectra are summarized in Table I. The errors denote one standard deviation σ. γ rays were assigned to ^{237}Am on the basis of their decay with the characteristic half-life of ^{237}Am (73 min). Intensities are expressed in percent per ^{237}Am EC decay. These were obtained by equating the total γ-ray, conversion-electron, and direct EC intensities feeding the ground state to 100%. The Pu K x-ray intensity in Table I represents K x rays originating from K-shell electron capture and internal conversion in ^{237}Pu only; contributions from ^{238}Am, ^{239}Am, and ^{240}Am have been subtracted.

TABLE I. ^{237}Am γ rays and K x rays.

Energy (keV)	Photon intensity (% per ^{237}Am EC decay)	Transition (initial → final level)
99.5 ± 0.1	27.9 ± 1.4	Pu K_{α_2}
103.8 ± 0.1	43.5 ± 2.3	Pu K_{α_1}
117.1 ± 0.1	15.7 ± 1.0	Pu $K_{\beta_1'}$
120.7 ± 0.1	5.1 ± 0.4	Pu $K_{\beta_2'}$
123.8 ± 0.3	~0.04	404.2 → 280.2
124.7 ± 0.2	0.28 ± 0.05	280.2 → 155.4
127.5 ± 0.2	0.11 ± 0.02	407.8 → 280.2
145.6 ± 0.1	0.48 ± 0.04	145.5 → 0
158.3 ± 0.3	0.07 ± 0.02	438.4 → 280.2
179.9 ± 0.2	0.24 ± 0.05	404.2 → 224.2
183.8 ± 0.2	0.19 ± 0.05	407.8 → 224.2
193.4 ± 0.3	0.09 ± 0.03	473.5 → 280.2
203.0 ± 0.1	0.42 ± 0.05	404.2 → 201.2
206.7 ± 0.1	0.33 ± 0.04	407.8 → 201.2
214.9 ± 0.2	0.24 ± 0.05	370.4 → 155.4
224.9 ± 0.2	0.24 ± 0.05	370.4 → 145.5
229.1 ± 0.3	0.15 ± 0.05	453.2 → 224.2
248.7 ± 0.2	0.59 ± 0.06	404.2 → 155.4
252.2 ± 0.2	0.42 ± 0.05	407.8 → 155.4
273.3 ± 0.1	0.76 ± 0.05	321.0 → 47.7
280.2 ± 0.1	47.3 ± 2.0	280.2 → 0
321.0 ± 0.1	1.4 ± 0.1	321.0 → 0
390.7 ± 0.1	0.55 ± 0.04	438.4 → 47.7
407.8 ± 0.1	0.63 ± 0.05	407.8 → 0
425.8 ± 0.1	1.94 ± 0.12	473.5 → 47.7
435.2 ± 0.3	0.25 ± 0.04	908.8 → 473.5
438.4 ± 0.1	8.3 ± 0.4	438.4 → 0
453.2 ± 0.3	0.10 ± 0.02	453.2 → 0
455.8 ± 0.3	0.09 ± 0.02	908.8 → 453.2
473.5 ± 0.1	4.3 ± 0.3	473.5 → 0
501.2 ± 0.3	0.28 ± 0.04	908.8 → 407.8
504.8 ± 0.3	0.19 ± 0.04	908.8 → 404.2
648.5 ± 0.3	0.26 ± 0.04	696.2 → 47.7
655.3 ± 0.2	1.30 ± 0.13	655.3 → 0
696.2 ± 0.3	0.20 ± 0.04	696.2 → 0
720.4 ± 0.5	0.24 ± 0.05	1000.6 → 280.2
743.5 ± 0.5 [a]	0.27 ± 0.05	
792.0 ± 0.5 [a]	0.16 ± 0.04	
861.2 ± 0.3	0.37 ± 0.04	908.8 → 47.7
908.8 ± 0.2	2.60 ± 0.15	908.8 → 0
1000.6 ± 0.3	0.19 ± 0.05	1000.6 → 0

[a] We are not certain whether these γ rays belong to ^{237}Am decay. These are definitely not associated with ^{238}Am, ^{239}Am, or ^{240}Am EC decay.

The Compton background in the γ-ray spectrum

was such that γ rays with intensities <0.07% per EC decay would not have been identified. Hence γ rays expected from postulated levels and not listed in Table I have intensities of <0.07% per EC decay.

B. Conversion-electron spectroscopy

The conversion-electron spectra of several ^{237}Am samples were measured with a cooled Si(Li) spectrometer[15] and with a magnetic spectrometer. The Si(Li) spectrometer consists of an 80-mm^2×3-mm lithium-drifted silicon detector coupled to a low-noise preamplifier, with the detector and the input stage field-effect transistor cooled to liquid nitrogen temperature. The spectrometer had a resolution [full width at half-maximum (FWHM)] of 1.0 keV at 100-keV and 1.6 keV at 600 keV electron energy. We found that the electron lines appeared lowered with respect to the photon energies measured with the same Si(Li) detector by 0.7 keV at 100 keV and 1.0 keV at 20 keV. The different response of the detector to electrons and γ rays could be accounted for by an electron energy loss in the detector "window."

The electron spectrum of a mass-separated ^{237}Am sample measured with the cooled Si(Li) spectrometer is shown in Fig. 2. This sample was produced by ^{3}He-ion irradiation and the efficiency-geometry product of the detector was 4.2%. The spectrum of a ^{237}Am sample produced by the $(\alpha, 4n)$ reaction was also measured at 1.0% efficiency-geometry product. This latter spectrum contained ^{238}Am and ^{239}Am electron lines which were used for energy calibration. Absolute conversion coefficients of the internal transitions in ^{237}Pu were determined with respect to the K conversion coefficient[16] of the 279.2-keV transition in ^{203}Tl (0.163 ± 0.002). The γ-ray (and the conversion-electron) spectra of ^{237}Am and ^{203}Hg samples were measured at identical geometries. Since γ and e^- spectra were measured at different times, relative decay corrections were applied to the spectra. The electron energies and intensities obtained from the present measurements are given in Table II. The electron binding energies used to obtain transition energies in Table II were determined in our transuranic element decay studies.[13] Transition multipolarities were determined by comparing the observed conversion coefficients and ratios with the theoretical values.[17]

Because of the short half-life (73 min) and the weak intensities of the ^{237}Am sources the information obtained from magnetic electron spectroscopy was limited to the more intense transitions of $\leq$280 keV. The Argonne toroidal-field spectrometers,[18] operated in tandem with a source diameter of <3 mm and exit aperture of 3 mm diam, gave momentum resolutions (FWHM) of 0.11 to 0.18% at a transmission of ~10% of 4π. Seven sources prepared by the deposition of 200-eV

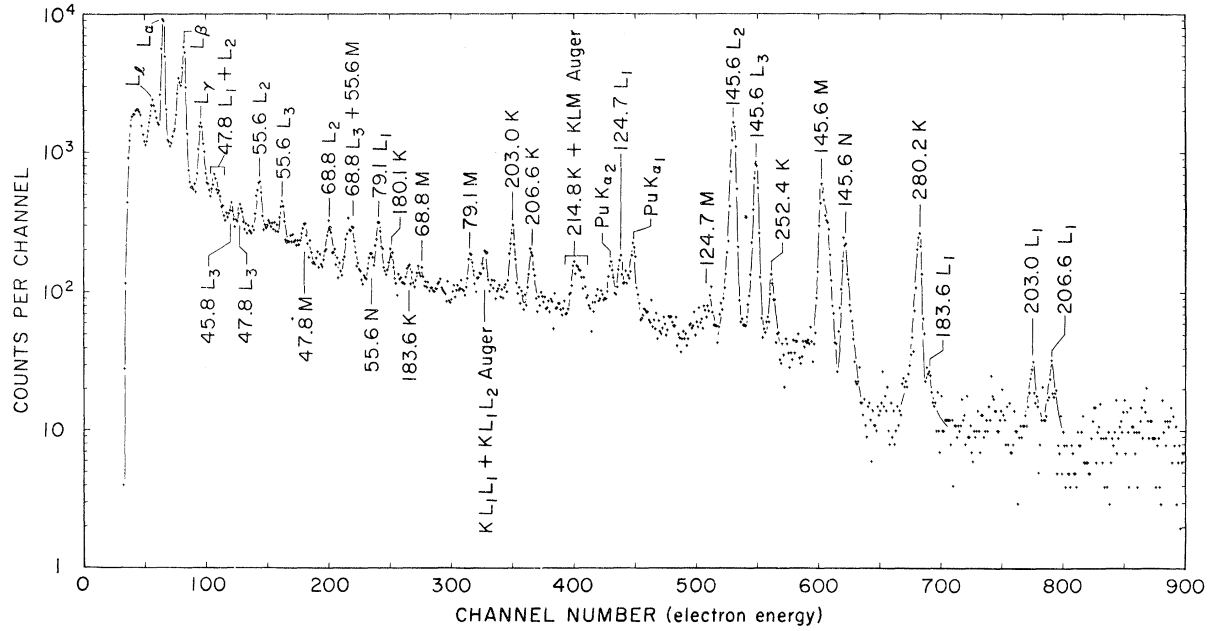

FIG. 2. Conversion-electron spectrum of a mass-separated ^{237}Am sample measured with a cooled Si(Li) detector. The efficiency-geometry product is 4.2%. The sample was produced by the (^{3}He, $3n$) reaction. The energy scale is 0.23 keV per channel.

TABLE II. ^{237}Am conversion-electron lines.

Transition energy [keV(±eV)][a] (initial→final state)	Shell	Electron energy [keV(±eV)][b]	Intensity (% per EC decay) Magnetic spec.	Si(Li) spec.	Multipolarity: Mixing derived from:
9.903(16)	N_1	8.340(16)	1.6 ±0.3		99.5% $M1$ + (0.5 ± 0.3)% $E2$
(155.4→145.5)	N_2	8.517(16)	1.4 ±0.3		
	N_3	8.776(16)	1.1 ±0.4		N_1/N_2, N_1/N_3
40.748(6)	L_1	17.637 (9)	1.5 ±0.2		96% $M1$ + (4 ± 1)% $E2$
(321.0→280.2)	L_2	18.480 (9)	0.6 ±0.2		
	L_3	22.699 (9)	0.41 ± 0.06		L_1/L_2, L_1/L_3
45.724(8)	L_1	22.618 (9)	0.29 ± 0.07		82% $M1$ + (18 ± 4)% $E2$
(201.2→155.4)	L_2	23.462(13)	0.43 ± 0.07		
	L_3			0.4 ±0.1	L_1/L_2
47.71(40)	L_1	24.61 (40)	2.0 ±0.5	2.5 ±0.5	
(47.71→0)	L_2				$M1$
	L_3			0.6 ±0.15	L_1/L_3
	M			0.8 ±0.2	
55.638(11)	L_2	33.369(15)	1.9 ±0.3	2.2 ±0.3	$E2$, L_2/L_3
(201.2→145.5)	L_3	37.580(17)	1.5 ±0.3	1.4 ±0.2	
	M			~1.2	
	N			~0.5	
68.8(100)[S]	L_2	46.5 (100)[S]		1.2 ±0.2	$E2$
(224.2→155.4)	L_3			~1.0	L_2/L_3
	M			~0.6	
	N			~0.2	
79.05(20)	L_1	55.946(20)	1.6 ±0.3	1.8 ±0.2	$M1$, Scheme
(280.2→201.2)	L_2				
	M			0.61 ± 0.15	
124.72(30)					
(280.2→155.4)	L_1	101.632(27)	0.76 ± 0.13	0.8 ±0.2	$M1$, α_{L_1}
145.552(12)	L_1+L_2			11.9 ±0.8	
(145.5→0)	L_2	123.287(13)	10.6 ±0.5		$E3$
	L_3	127.474(30)	4.8 ±0.6	5.0 ±0.4[c]	α_L
	M			6.1 ±0.6	
	N			2.2 ±0.2	
179.94(20)	K	58.141(15)	0.69 ± 0.07	0.7 ±0.1	$M1$, α_K
(404.2→224.2)					
183.6(200)[S]	K	61.8 (200)[S]		0.5 ±0.1	$M1$
(407.8→224.2)	L			0.12 ± 0.03	α_K
203.03(43)	K	81.230(43)	1.0 ±0.2	1.2 ±0.15	$M1$
(404.2→201.2)	L			0.21 ± 0.03	α_K, α_L
206.6(100)[S]	K	84.8 (100)[S]		0.85 ± 0.12	$M1$
(407.8→201.2)	L			0.16 ± 0.03	α_K, α_L
214.8(200)[S]	K	93.0 (200)[S]		0.61 ± 0.15	$M1$, α_K
(370.4→155.4)					
224.86(40)	K	103.053(40)	0.56 ± 0.12		$M1$, α_K
(370.4→145.5)					
248.7	L			0.18 ± 0.03	$M1$, α_L
(404.2→155.4)					
252.4(200)[S]	K	130.6 (200)[S]		0.6 ±0.1	$M1$, α_K, α_L
(407.8→155.4)	L			0.12 ± 0.03	
280.23(20)	K	158.430(20)	1.92 ± 0.2	1.92 ± 0.15	$E1$, α_K, α_L
(280.2→0)	L_1+L_2			0.32 ± 0.03	

TABLE II *(Continued)*

Transition energy [keV(±eV)] [a] (initial → final state)	Shell	Electron energy [keV(±eV)] [b]	Intensity (% per EC decay) Magnetic spec.	Si(Li) spec.	Multipolarity: Mixing derived from:
	L_3			0.06 ± 0.02	
321.0 (321.0 → 0)	K			<0.07	$E1$, α_K
390.7 (438.4 → 47.7)	K			<0.02	$E1$, α_K
407.8 (407.8 → 0)	K			~0.02	$E1$, α_K
425.8 (473.5 → 47.7)	K			0.04 ± 0.01	$E1$, α_K
435.2 (908.8 → 473.5)	K			0.10 ± 0.02	$M1$, α_K
438.4 (438.4 → 0)	K			0.13 ± 0.03	$E1$, α_K
455.8 (908.8 → 453.2)	K			~0.03	$M1$, α_K
473.5 (473.5 → 0)	K			0.07 ± 0.02	$E1$, α_K
501.2 (908.8 → 407.8)	K			0.06 ± 0.02	$M1$, α_K
504.8 (908.8 → 404.2)	K			0.05 ± 0.02	$M1$, α_K
648.5 (696.2 → 47.7)	K			~0.03	$M1$, α_K
655.3 (655.3 → 0)	K			0.13 ± 0.02	$M1$, α_K
696.2 (696.2 → 0)	K			~0.02	$M1$, α_K

[a] Letter S denotes transition energies obtained from the Si(Li) spectrometer. Energies with no errors represent γ-ray energies measured with the Ge(Li) diode.

[b] Letter S denotes electron energy measured with the Si(Li) spectrometer. Energies with errors of >0.5 keV are not given in this table.

[c] This intensity was obtained by subtracting the expected intensity (0.8%) of the 248.7 K line from the measured intensity.

^{237}Am ions on 5-mg/cm^2 Al foils from the decelerated beam of the isotope separator were used for these measurements. The intensity of these sources varied from 4×10^4 to 20×10^4 EC disintegrations per min; only the strongest lines were comfortably above the background. In spite of this, most of the 19 electron lines were identified in more than one run; intensities obtained from various runs were related to each other via the L_3 line of the 145.5-keV transition which was measured in each run. The energies and intensities of the ^{237}Am electron lines measured by magnetic spectrometer are separately identified in Table II. Electron intensities are expressed in percent per EC decay. The e^- and the γ-ray intensities are related to each other via the experimental K conversion coefficient of the 280.2-keV transition which was measured with the cooled Si(Li) detector.

C. Coincidence measurements

A two-parameter γ-γ coincidence experiment was performed to determine which levels deexcite via the 280.2-keV state. The γ rays were detected with a 4-cm^3 Ge(Li) diode and a 7.6-×7.6-cm NaI(Tl) crystal and the resolving time (2τ) was 300 ns. The single-channel analyzer on the NaI(Tl) spectrum was set to exclude Pu K x rays from the gate in order to reduce the chance coincidence rate. Coincidence events were recorded on a magnetic tape and were later read back into the analyzer memory through a digital-gate system, with which any desired γ-ray gate could be selected. The γ-ray spectrum measured with the 4-cm^3 Ge(Li) detector and gated by the 280.2-keV photopeak contained only two γ rays with energies 123.8 and 127.5 keV. Spectra obtained in coinci-

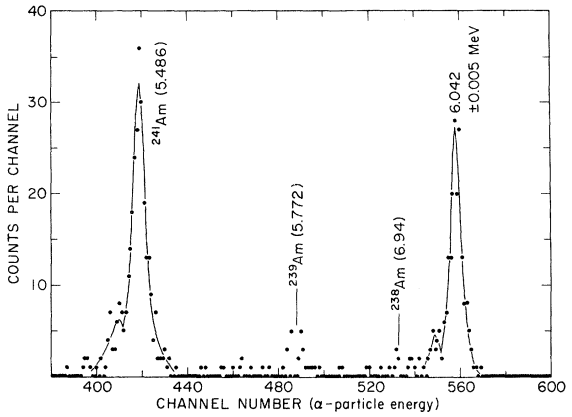

FIG. 3. α-particle spectrum of a mass-separated ^{237}Am sample measured with a 2-cm^2 Au-Si surface-barrier detector at a source-to-detector geometry of 8.0%. The sample was produced by the $(\alpha, 4n)$ reaction. The energy scale is 3.96 keV per channel. The ^{241}Am contaminant was present in the isotope separator. α-particle energies in parentheses are literature values.

dence with other gates did not show any true coincidence peak; intensities of the expected transitions were too low to be observed in the coincidence spectra. The results of the γ-γ coincidence experiment give support to the existence of two levels at 404.0 and 407.8 keV in ^{237}Pu.

D. Half-life and α branching

The half-life of ^{237}Am was determined by following the decay of the 280.2-keV γ ray measured with a 25-cm^3 Ge(Li) detector at a fixed geometry. The counts in the photopeaks were determined from hand plotted graphs. A least-squares fit to the observed peak areas gave a half-life of 73.0 ± 1.0 min for ^{237}Am decay.

The α-particle spectrum of a mass-separated ^{237}Am sample was measured with a 2-cm^2 Au-Si surface-barrier detector. A spectrum measured at a source-to-detector geometry of 8% is shown in Fig. 3. The energy of the only observed ^{237}Am α group determined with respect to the ^{249}Cf α_{388} group (5.812 MeV[19]) is 6.042 ± 0.005 MeV. The decay of the α spectrum was followed for several hours and α groups were assigned to individual isotopes on the basis of their observed decay rates. α branching was determined by measuring the α and γ spectra of the same sample at known geometries. Using the intensity of the 280.2-keV γ ray as 47.3% per EC decay we found the $\alpha/(\alpha + \mathrm{EC})$ ratio as $(2.5 \pm 0.3) \times 10^{-4}$. The hindrance factor for the 6.042-MeV α group calculated with Preston's equations[20] is 1.2, using a radius parameter of 9.30 fm and assuming the intensity of the α group as 100%. This hindrance factor indicates that the 6.042-MeV α groups is a favored α transition.

E. α spectroscopy of ^{241}Cm

The α spectrum of ^{241}Cm was measured with the Argonne double-focusing magnetic spectrometer.[21] The spectrometer had a resolution (FWHM) of 5 keV at a transmission of 0.1% of 4π for 6.0-MeV α particles. Two sources were used for these measurements. One was an available poorly focused isotope separator spot collected at 50-keV

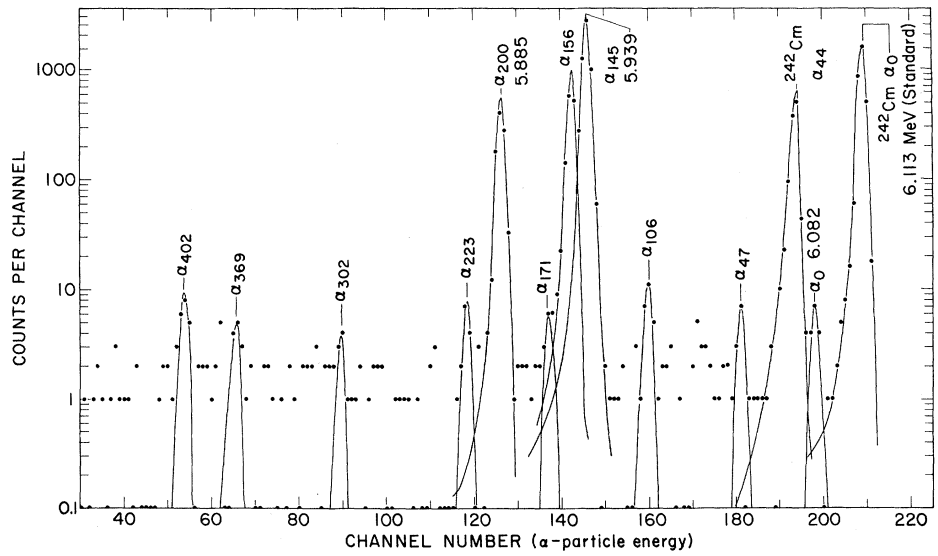

FIG. 4. α-particle spectrum of a mass-separated ^{241}Cm sample measured with the Argonne double-focusing magnetic spectrometer. The α-particle energy scale is 2.76 keV per channel; channels correspond to elements (1 mm) of a multielement focal plane detector array. Subscripts on α peaks are level energies. Zero events are plotted at 0.1.

TABLE III. ^{241}Cm α groups.

Energy (MeV)	Excited state energy (keV)	Intensity (%)	Hindrance factor
6.082 ± 0.003	0	0.15 ± 0.05	6.3×10^3
6.036 ± 0.003	47	0.12 ± 0.04	4.6×10^3
5.978 ± 0.003	106	0.28 ± 0.07	1.0×10^3
5.939 ± 0.002	145	68.9 ± 1.0	2.6
5.929 ± 0.002	156	18.1 ± 0.5	8.6
5.914 ± 0.004	171	0.12 ± 0.05	1.1×10^3
5.885 ± 0.002	200	11.8 ± 0.4	7.8
5.863 ± 0.003	223	0.14 ± 0.05	5.0×10^2
5.785 ± 0.003	302	~0.07	~4 $\times 10^2$
5.719 ± 0.003	369	0.08 ± 0.04	1.5×10^2
5.687 ± 0.003	402	0.22 ± 0.05	35

ion energy, with ~4×10^3 ^{241}Cm α dis/min. The spectrum measured with this source had a resolution (FWHM) of 9.0 keV; the poor resolution was caused by the penetration of the ^{241}Cm ions into the source backing. The other source was the 1-mm-diam source (made from the retarded beam of the separator) used for electron spectroscopy.[11] This source was available for α-spectrum measurement after the electron spectroscopy experiments were finished (five half-lives). The α spectrum of this source (source strength ~1×10^3 α dis/min) measured with the magnetic spectrometer is displayed in Fig. 4. The energies of ^{241}Cm α groups were measured with respect to that of the ^{242}Cm α_0 group (6.113 MeV[22]). Energies, intensities, and hindrance factors of the ^{241}Cm α groups are given in Table III. The hindrance factors were calculated from the spin-independent theory of Preston[20]; the half-life, α branching, and the radius parameter used were 32.8 day, 1.0%, and 9.28 fm, respectively. The errors denote one standard deviation σ.

As can be seen in the spectrum, there is no α group below 5.88 MeV with intensity >0.3%. This clearly indicates that the α_{256}, α_{263}, α_{278}, α_{300},

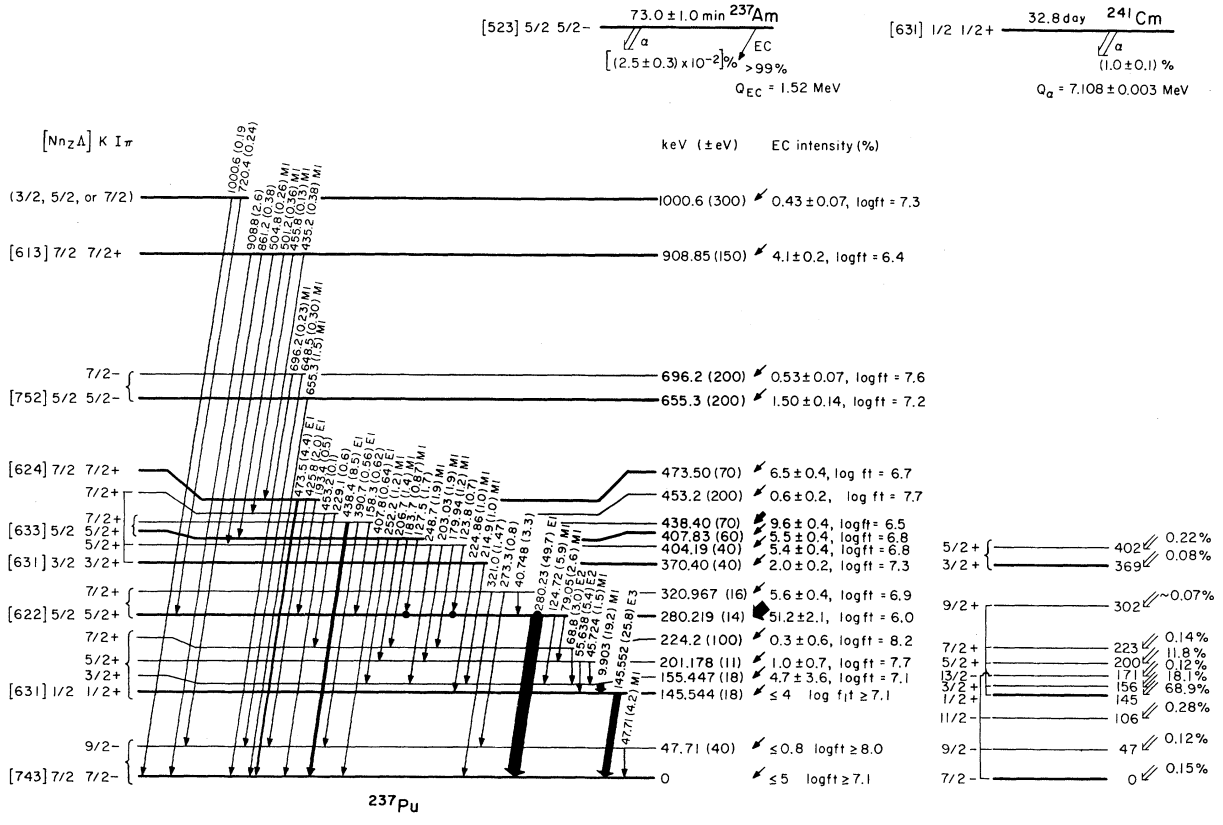

FIG. 5. Level diagram of ^{237}Pu populated by EC decay of ^{237}Am and α-decay of ^{241}Cm. Transition intensities in percent per ^{237}Am EC decay are given in parentheses following transition energies in keV. Intraband transitions are shown by vertical arrows; the interband by slanted arrows. The EC intensities at 0-, 47.7-, and 145.5-keV levels are 0.6 ± 5%, 0.2 ± 0.8%, and 0.2 ± 4%, respectively. γ-γ coincidences are shown by dots. For first forbidden unique transition at 145.5 keV logf_1t is given.

α_{307}, and α_{357} groups reported in Ref. 4 were due to contaminants.

IV. DISCUSSION

The energy levels of ^{237}Pu deduced from the results of the present investigation are shown in Fig. 5. For the ^{237}Am EC decay, all energy balances for stopover sums versus crossover transitions lie within a maximum disparity of 0.2 keV. These balances, combined with the γ-γ coincidence and ^{241}Cm α-decay data, unambiguously imply the indicated levels and transition ordering. All observed transitions except for the two weak γ rays of 743.5 and 792.0 keV are incorporated in this scheme.

A. Electron capture transition probabilities

Experimental γ-ray and conversion-electron intensities were obtained in relative units normalized at the 280.2-keV γ intensity as 100. Transition intensities were then obtained by summing the γ-ray and electron intensities; for transitions whose electron intensities were not measured theoretical[17] values for assumed pure multipolarities were used. The EC population to each ^{237}Pu level was determined from the difference between its γ and conversion-electron outfeed and infeed. Using the EC intensity and the theoretical[23] K/total capture ratio the number of K- shell holes created at each level was obtained. The K-shell vacancies created by internal conversion were determined by summing the intensities of all K-electron lines. The total K-shell holes created by internal conversion and electron capture to ^{237}Pu excited states were then subtracted from the K-shell vacancies obtained from the experimental K x-ray intensity (fluorescence yield[24] $\omega_K = 0.976$). This difference gave the K capture to the ^{237}Pu ground state, which after correction for capture from other shells gave the EC population to this state.

The γ-ray, conversion-electron, and EC intensities in percent per ^{237}Am EC decay were obtained by normalizing the total γ, conversion-electron, and direct EC intensities to the ground state to 100%. The EC intensities to the ground state, 47.7-, and 145.5-keV levels were found to be $0.6 \pm 5\%$, $0.2 \pm 0.8\%$, and $0.2 \pm 4\%$, respectively. The logft values were determined by the method of Major and Biedenharn,[25] using a value of the available EC decay energy[26] of 1.52 MeV between the two ground states. The EC intensities to the ^{237}Pu levels and the logft values deduced from them are given in Fig. 5. For the first forbidden unique transition to the 145.5-keV level f_1t was determined from $f_1t = (q_K^2/12)f_0t$, where q_K is the neutrino energy in K-shell capture.

B. Single-particle orbital assignments

1. $\frac{1}{2}+[631]$ band

The ground state spin of ^{241}Cm has been established as $\frac{1}{2}$ from the study[11] of its EC decay scheme, with a single-particle orbital assignment of $\frac{1}{2}+[631]$. Since the 145.5-keV level of ^{237}Pu is populated by the favored α transition of ^{241}Cm (hindrance factor = 2.6) we assign it to the same single-particle configuration as the ^{241}Cm ground state, namely $\frac{1}{2}+[631]$. Four members of this band have been identified in the ^{237}Am EC decay. From the measured energies of these levels we calculate the rotational constant $\hbar^2/2\mathcal{I}$, and the decoupling parameter a as 6.224 keV and -0.4696, respectively. Five members of this band have been observed in the ^{241}Cm α spectrum.

2. Ground state, $\frac{7}{2}-[743]$ band

The multipolarity of the 145.5-keV transition which deexcites the 145.5-keV level has been determined to be $E3$. Thus the spin-parity of the ^{237}Pu ground state can only be $\frac{7}{2}-$. We make the $\frac{7}{2}-[743]$ orbital assignment to the ^{237}Pu ground state because this is the only $\frac{7}{2}-$ single-particle state available in this energy region. This assignment was also deduced[27] from the EC decay properties of ^{237}Pu. Since the 47.7-keV level decays to the $\frac{7}{2}-$ ground state by an $M1$ transition it can have spin-parity of $\frac{5}{2}-$, $\frac{7}{2}-$, or $\frac{9}{2}-$ only. The fact that we do not observe any $145.5 \rightarrow 47.7$ transition favors a $\frac{9}{2}-$ assignment. We interpret it as the $\frac{9}{2}-$ member of the ground state band and calculate a rotational constant of 5.3 keV for this band.

3. $\frac{5}{2}+[622]$ band

The 280.2-keV level decays to the $\frac{7}{2}-$ ground state by an $E1$ transition, with no detectable branching (<1/600 of 280.2-keV γ intensity) to the $\frac{9}{2}-$ member of the ground state band. Thus the most likely spin-parity assignment for the 280.2-keV state is $\frac{5}{2}+$. The 321.0-keV level deexcites to the 280.2-keV state by an $M1$ transition and also to the $\frac{7}{2}-$ and $\frac{9}{2}-$ members of the ground state band by $E1$ transitions (the multipolarity of the 321.0-keV γ ray has been deduced from the upper limit on its K conversion coefficient). We therefore make an $I^\pi = \frac{7}{2}+$ assignment to the 321.0-keV state and interpret it as the $\frac{7}{2}+$ member of the $K^\pi = \frac{5}{2}+$ band at 280.2 keV.

Only two $K^\pi = \frac{5}{2}+$ Nilsson states are expected in the low energy (<1-MeV) spectrum of ^{237}Pu: the $\frac{5}{2}+[622]$ particle state and the $\frac{5}{2}+[633]$ hole state. Both these states occur[5,28,29] in ^{235}U; the $\frac{5}{2}+[622]$ band at 129.3 keV with a rotational constant of 6.0 keV and the $\frac{5}{2}+[633]$ band at 332.9 keV with a rota-

tional constant of 4.9 keV. Our value of the rotational constant (5.83 keV) for the 280.2-keV band in ^{237}Pu clearly suggests the $\frac{5}{2}+[622]$ assignment. This assignment was also deduced from the results of the ^{238}Pu(d,t) reaction studies.[9]

4. ^{237}Am ground state

The ground state of ^{237}Am is expected to be either the $\frac{5}{2}-[523]$ or the $\frac{5}{2}+[642]$ proton orbital. The logft value of the $\frac{5}{2}-[523]\rightarrow\frac{5}{2}+[622]$ transition in ^{239}Am EC decay[13] is known to be 6.0 whereas the logft for the $\frac{5}{2}+[642]\rightarrow\frac{5}{2}+[622]$ transition in ^{239}Np β^- decay[30] is 6.8. In the present work the logft value of the EC transition to the $\frac{5}{2}+[622]$ state has been deduced to be 6.0. This suggest that the ^{237}Am ground state is the $\frac{5}{2}-[523]$ orbital.

In ^{239}Am decay[13] the $\frac{5}{2}-[523]\rightarrow\frac{7}{2}-[743]$ EC transition occurs with a logft of 8.6. This allowed transition is theoretically predicted to be very retarded[31] owing to the large mismatch between the angular momenta of the predominant components in each state, 90% $J=\frac{15}{2}$ in the $\frac{7}{2}-[743]$ state and 90% $J=\frac{9}{2}$ in the $\frac{5}{2}-[523]$ state. The logft of 8.6 corresponds to an EC intensity of 0.2% to the ^{237}Pu ground state. Thus our experimental intensity of $0.6\pm5\%$ is consistent with the $\frac{7}{2}-[743]$ assignment to the ^{237}Pu ground state. The upper limit of 6% EC intensity corresponds to a lower limit of 7.1 for the logft value.

The EC transition to the $\frac{1}{2}+$ state at 145.5 keV is first forbidden unique ($\Delta I=2$, yes). Such transitions have logf_1t values of ~8.5, which in the ^{237}Am case corresponds to an EC intensity of 0.1% for the 145.5-keV state. The observed intensity of $0.2\pm4\%$ is consistent with the spin-parity assignment of $\frac{1}{2}+$ to the 145.5-keV level.

5. $\frac{3}{2}+[631]$, $\frac{5}{2}+[633]$, and $\frac{7}{2}+[624]$ bands

From the systematics of logft values in the actinide region it is known that β transitions with logft values of ≤ 8.0 are either allowed or first forbidden with $|\Delta I|=0,1$. Hence the states in ^{237}Pu which are populated by EC transitions with logft values of <8.0 can have spins of $\frac{3}{2}$, $\frac{5}{2}$, or $\frac{7}{2}$ only. We have shown in the decay scheme (Fig. 5) that all levels of the three bands under discussion receive EC feeds with logft of <8.0. Since the 370.4-keV state decays to the $\frac{1}{2}$ and $\frac{3}{2}$ members of the $\frac{1}{2}+[631]$ band by $M1$ transitions it must be an $I^\pi=\frac{3}{2}+$ state. Because it is the lowest spin state unassigned it is most likely a single-particle bandhead. The levels at 404.2 and 407.8 keV deexcite to the $\frac{3}{2}$, $\frac{5}{2}$, and $\frac{7}{2}$ members of the 145.5-keV band by $M1$ transitions. Hence the spin-parity of these states must be $\frac{5}{2}+$. The multipolarities of the 438.4 → 0 and 473.5 → 0 transitions have been deduced to be $E1$. The upper limits on the K conversion coefficients of the 438.4 → 47.7 and 473.5 → 47.7 transitions are consistent with an $E1$ multipolarity only. These facts establish the spin-parity of the 438.4- and 473.5-keV states as $\frac{7}{2}+$.

Since the intensity of the 407.8 → 0 $E1$ γ ray is comparable to that of the K-allowed 407.8 → 280.2 $M1$ transition, the former should be a K-allowed transition. Hence the K quantum number of the 407.8-keV state is $\frac{5}{2}+$ and it is a bandhead. On the other hand we did not find any intensity (<0.06%) for the 404.2 → 0 transition indicating that this transition is K forbidden. We therefore assign the 404.2-keV state to the $\frac{5}{2}+$ member of the $K^\pi=\frac{3}{2}+$ band at 370.4 keV. The 438.4-keV level is interpreted as the $\frac{7}{2}$ member of the $K^\pi=\frac{5}{2}+$ band at 407.8 keV because this assignment gives a more reasonable value for the rotational constant (4.37) than the assignment of the 473.5-keV level as its $\frac{7}{2}$ member (9.4). Since no lower spin states are left unassigned the 473.5-keV state must have K^π of $\frac{7}{2}+$ (states with spin $\frac{3}{2}$ or $\frac{5}{2}$ would have been populated in EC decay). We give an assignment of $\frac{7}{2}+[624]$ to the 473.5-keV state because this is the only $\frac{7}{2}+$ orbital available in this energy region. The 370.4- and 407.8-keV bands are assigned to the $\frac{3}{2}+[631]$ and $\frac{5}{2}+[633]$ orbitals, respectively, because they are the lowest $\frac{3}{2}$ and $\frac{5}{2}$ states available in the Nilsson diagram.[3] The rotational constants for these bands are determined to be 6.76 and 4.37 keV and are very similar to the corresponding values[5] in ^{235}U(6.68 and 4.91 keV). The single-particle assignments of $\frac{3}{2}+[631]$ and $\frac{5}{2}+[633]$ to the 370.4- and 407.8-keV states were also deduced from the ^{238}Pu(d,t) reaction studies.[9] The 453-keV level was assigned to the $\frac{7}{2}$ member of the $\frac{3}{2}+[631]$ band. Our results are consistent with this assignment.

6. $\frac{5}{2}-[752]$ band

The level at 655.3 keV deexcites to the ground state by an $M1$ transition, with no detectable branching ($<\frac{1}{18}$ of the 655.3-keV γ intensity) to the $\frac{9}{2}-$ member of the ground state band. The level at 696.2 keV decays to the $\frac{7}{2}-$ and $\frac{9}{2}-$ members of the ground state band by $M1$ transitions. Hence the 655.3- and 696.2-keV levels should have spin-parity of $\frac{5}{2}-$ and $\frac{7}{2}-$, respectively. These states are interpreted as the rotational members of the $\frac{5}{2}-[752]$ band because this is the only $K^\pi=\frac{5}{2}-$ Nilsson state[3] available in the low-energy spectrum of ^{237}Pu. This state has also been identified[32] in ^{235}U and its energy (633.1 keV) and rotational constant (5.4) are very similar to the corresponding values (655.3 and 5.8 keV) in ^{237}Pu.

7. $\frac{7}{2}$+[613] single-particle state

Since the 908.8-keV level decays to four of the $I^\pi = \frac{5}{2}$+ and $\frac{7}{2}$+ states by $M1$ transitions it can have spin-parity of $\frac{5}{2}$+ or $\frac{7}{2}$+ only. This level also decays to the $\frac{7}{2}$− and $\frac{9}{2}$− members of the ground state band. Since the intensities of the parity-changing 908.8 → 0 and 908.8 → 47.7 transitions are comparable to those of the deexciting $M1$ transitions, these γ rays must have $E1$ multipolarity. Hence the 908.8-keV state must have spin-parity of $\frac{7}{2}$+. This state is given a single-particle assignment of $\frac{7}{2}$+[613]. One would expect that because of the high excitation energy this state might have substantial phonon admixture. In general logft values of β transitions to vibrational states are larger than the values for transitions feeding single-particle states. Thus the low logft value of 6.4 for the EC transition to the 908.8-keV state indicates that this state is of predominantly single-particle character.

C. Coriolis interaction calculation

The logft value for the $\frac{5}{2}$−[523] → $\frac{7}{2}$+[624] transition in the ^{239}Am EC decay was found to be 5.8. In ^{237}Am decay the logft for this transition is 6.7. On the other hand the $\frac{7}{2}$+ state at 438.4 keV receives an order of magnitude more EC population than expected for an $I = \frac{7}{2}$ member of the $\frac{5}{2}$+[633] band. This suggests that because of the Coriolis mixing[33] between the two $I^\pi = \frac{7}{2}$+ states part of the EC intensity is transferred from the upper to the lower state. Similarly the Coriolis interaction between the two $\frac{5}{2}$+ states at 404.2 and 407.8 keV can explain the enhancement of the EC feed to the 404.2-keV level.

A Coriolis interaction calculation was carried out to determine the extent of mixing between various positive-parity states. These calculations were performed with a computer code BANDMIX.[34] Five bands, $\frac{1}{2}$+[631], $\frac{3}{2}$+[631], $\frac{5}{2}$+[622], $\frac{5}{2}$+[633], and $\frac{7}{2}$+[624] were used in this calculation. The input energies of the unperturbed bandheads were chosen so as to reproduce the observed level energies from the BANDMIX calculation. The value of the rotational constant used was 6.25 keV and the decoupling parameter a was −0.47. The Coriolis matrix elements between various states needed for the BANDMIX program were calculated with Nilsson[3] wave functions for the deformation parameter $\eta = 5.0$ and these were: $A_{1/2,3/2} = 0.12$; $A_{3/2,5/2(622)} = 4.66$; $A_{3/2,5/2(633)} = 1.24$; $A_{5/2(622),7/2} = 1.03$; and $A_{5/2(633),7/2} = 4.77$. However, in order to obtain even approximate agreement between the observed and calculated level energies, the matrix elements had to be reduced considerably. The matrix elements which gave the best fit are: $A_{1/2,3/2} = 0.1$; $A_{3/2,5/2(622)} = 1.2$; $A_{3/2,5/2(633)} = 0.3$; $A_{5/2(622),7/2} = 0.3$; and $A_{5/2(633),7/2} = 0.8$. The large and variable reduction of the matrix elements might be due to large collective admixtures in these states; the reduction factors due to pair correlation effects were calculated to be between 1.0 and 0.6. The perturbed wave functions obtained from these calculations are given below.

$$\psi^{5/2}_{404} = -0.007\psi_{1/2} + 0.79\psi_{3/2} - 0.11\psi_{5/2(622)} + 0.60\psi_{5/2(633)},$$

$$\psi^{5/2}_{408} = 0.005\psi_{1/2} - 0.59\psi_{3/2} + 0.08\ \psi_{5/2(622)} + 0.80\psi_{5/2(633)},$$

$$\psi^{7/2}_{438} = -0.005\psi_{1/2} + 0.42\psi_{3/2} - 0.12\psi_{5/2(622)} + 0.81\psi_{5/2(633)} + 0.4\psi_{7/2},$$

$$\psi^{7/2}_{473} = -0.002\psi_{1/2} + 0.17\psi_{3/2} - 0.06\psi_{5/2(622)} - 0.51\psi_{5/2(633)} + 0.84\psi_{7/2},$$

where subscripts to the ψ on the left sides of the equations are the level energies (keV).

In spite of the *ad hoc* matrix elements used in the calculation the above wave functions suggest that there probably is a considerable amount of mixing between various positive-parity states. Since the β-decay matrix elements are not available, it is not possible to make a detailed calculation of logft values. However, from the admixture coefficients one can infer the effects on the EC population. The amplitudes of the $\frac{5}{2}$+[633] states in the 404.2- and 407.8-keV levels are 0.6 and 0.8, respectively, indicating that these two states should be populated with almost equal intensity, in agreement with our observation. The amplitudes of the $\frac{7}{2}$+[624] state in 438.4- and 473.5-keV levels are 0.4 and 0.84, respectively. Thus the $\frac{5}{2}$−[523] → $\frac{7}{2}$+[624] transition strength, which gives the dominant contribution to EC to these levels, will divide between these two states in the ratio of $(0.4)^2/(0.84)^2 = 1/4.4$, causing an increase in the EC population at the 438.4-keV level. Further the negative sign of the $\frac{5}{2}$+[633] amplitude in the 473.5-keV state might cause interference between the $\frac{5}{2}$− → $\frac{7}{2}$+[624] and $\frac{5}{2}$− → $\frac{5}{2}$+[633] components, thus reducing its EC intensity. On the other hand the two transition components will reinforce each other causing an increase in the EC population at the 438.4-keV state. Thus these effects can perhaps reproduce the observed EC intensities to the 438.4- and 473.5-keV levels.

The Coriolis interaction between the two $\frac{3}{2}$+ levels is too weak to have any effect on the EC population.

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