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ODD-PARITY ROTATIONAL BANDS IN Cm^{246}

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In the present note we will report briefly our experimental study of the sequence, $Pu^{246} \xrightarrow[11d]{\beta-} Am^{246} \xrightarrow[25min]{\beta-} Cm^{246}$, and then discuss in somewhat greater detail the interpretation of the levels observed. While most of these levels agree surprisingly well with the expectations of the existing theory, the K=2- band observed in Cm^{246} at 842 keV, seems to be somewhat lower in energy and more collective in nature than might have been expected.

The Pu^{246} was produced in a thermonuclear explosion, and was subjected to extensive chemical purification. The purification procedure involved co-precipitation first with $BiPO_4$ and then with LaF_3 to separate the actinides from the bulk of the fission products. Absorption and elution from both anion and cation resin columns under varying conditions of oxidation and reduction served to separate the plutonium fraction from the other actinides. A final extraction step using the reagent TTA (essentially specific for Pu under our conditions) yielded carrier free material. The resulting Pu^{246} solution was evaporated to dryness on a small area of a film of Teflon about 3 mils thick. The Teflon film served as the source for these determinations. The only radioactive impurity detected in the final samples was 40-day Pu^{237}, and the low-energy radiations from this isotope caused a minimum of interference with the present study. The availability of high-resolution Ge (Li-drifted) gamma-ray detectors makes the present work on this sequence considerably easier and less ambiguous than previous studies.[1,2,3]

Portions of the gamma-ray spectrum of the equilibrium mixture taken on a Ge detector 0.8-cm deep by ~ 6 cm^2 in area are shown in Fig. 1. The transitions observed are listed in Table I together with their relative intensities. Also in Table I are the results of the following coincidence runs: (1) L x-rays (NaI) vs 600-1200 keV region (Ge); (2) 1050 ± 50 keV (NaI) vs 100-500 keV region (Ge); (3) 800 ± 50 keV (NaI) vs 100-500 keV region (Ge); and (4) 44 keV (NaI) vs 15-400 keV region (NaI). These results, taken together with a variety of supporting measurements and the rather precise gamma-ray energies, establish the decay scheme shown in Fig. 2. Parts of this scheme were known previously; in particular, the beta groups have all been directly seen[2,3] except for the weak lowest-energy one from Am^{246}. We have, however, adjusted their intensities to agree with the present gamma-ray data.

Two additional measurements require special comment. A delay was found between the 44 keV transition and both K x-rays and 180 keV photons. Using two NaI detectors and a time-to-height converter, we measured this delay to be $(4.3 \pm 0.3) \times 10^{-9}$ sec. The $\sim$40 keV photon was shown[3] to belong to the decay of Pu^{246}. The second measurement was of the conversion coefficients of the 799 and 1079 keV transitions. This measurement was made by Hollander and Haverfield[4] using simultaneously a Ge (Li-drifted) detector for gamma rays and a Si (Li-drifted) detector for electrons. The electron lines were not observed, but a sufficiently low limit was set to exclude all multipolarities except E1.

In the following few paragraphs, we will assign spins, parities, K-values, and configurations (in terms of the Nilsson states)[5] to the levels observed. Although a highly consistent picture can be established, it must be pointed out that, particularly in Am^{246}, direct proof of the assignments is largely absent.

In Am^{246} (Pu^{246} decay), the observed levels must have spins no larger than 2 or 3, since beta transitions from Pu^{246} (I=0+) are reasonably fast. The lowest Nilsson state for the 151-st neutron is almost surely 9/2- [734] (cf. Cf^{249}),[6] and for the 95-th proton should be 5/2- [523] with 5/2+ [642] lying rather close. Considering only low-spin components $K=|\Omega_n - \Omega_p|$, we have levels of 2+ and 2- expected to lie lowest in Am^{246}. We propose that these are the ground and 44 keV levels, respectively, observed in Am^{246}, because then: (1) the 4.3 nsec half-life of the E1 transition is in agreement with the range of half-lives observed for the analogous E1 transitions in odd-A neptunium and americium nuclei; (2) the lack of observed beta population to the ground state is explained ($\Delta I=2$, no); (3) the log ft for beta decay to the 2- state (as observed by Hoffman and Brown)[2] is 7.9 according to our intensities, which is reasonable for $\Delta I=2$, yes (no odd-A analogous transitions known); and (4) the beta decay of Am^{246} to Cm^{246} can be understood (as will be described later). It is perhaps worth pointing out that there is very likely a 7- (or possibly 7+) isomer of Am^{246} corresponding to the opposite coupling of the 9/2- neutron and the 5/2± proton. Indeed, the 7- state could be at slightly lower energy than the 2+ state, indicated as the ground state.

On the basis of the above assignments, the 224 keV level probably has spin and parity 1- due to its low log ft value and the observed E1 and M1 transitions to the 2+ and 2- levels respectively. The only two likely candidates for this state are: (1) proton 5/2- [523] and neutron

7/2+ [624] or (2) proton 7/2+ [633] and neutron 9/2- [734]. These have predicted log ft values of 6.1 (cf. $Pu^{243} \rightarrow Am^{243}$ and $Am^{239} \rightarrow Pu^{239}$) and 7.0 (cf. $Bk^{249} \rightarrow Cf^{249}$) respectively, and the observed log ft value of 5.9 strongly suggests the former assignment. With assignment (2) above, the 180 keV M1 transition ought to be much ($\sim 10^2 - 10^4$) faster than the 224 keV E1 transition with no apparent way to speed up the E1; whereas, with assignment (1), the M1 transition is forbidden, but could be introduced in sufficient strength by only a few percent admixture (in the amplitude) of state (2) above. Thus we prefer assignment (1). A survey of the expected levels in Am^{246} shows that it is entirely reasonable that no other levels should be populated in the beta decay of Pu^{246} to Am^{246} ($Q_{\beta-} \simeq 400$ keV).

In Cm^{246} the K=2- and K=1- bands at 842 and 1080 keV, respectively, are well established. The assignments of K=1- to the band at 1351 keV, however, must be considered tentative; the evidence for it being only the spacing of the two levels and the pattern of transitions (shown to be largely M1) to the lower K=1- band. In assigning configurations to these bands we will use as a guide the calculation of Soloviev and Siklos,[7] which give the energies of the two-quasi-particle excited states of even-even nuclei, based on the Nilsson states and the superfluid model. These calculations are quite useful, even though they are not necessarily expected to be accurate to better than a few hundred keV.

There are only three K=1- configurations expected to lie at reasonably low energy in Cm^{246}. These are: (1) n-n, 7/2+ [624] + 9/2- [734], E_{calc} = 1.1 MeV; (2) p-p, 5/2- [523] + 7/2+ [633], E_{calc} = 1.3 MeV; and

(3) p-p, 5/2+ [642] + 3/2- [521], E_{calc} = 1.5 MeV. The log ft values expected to these configurations from Am^{246} (as previously assigned) are: (1) 6.1 (cf. $Pu^{243} \rightarrow Am^{243}$ and $Am^{239} \rightarrow Pu^{239}$); (2) 7.0 (cf. $Bk^{249} \rightarrow Cf^{249}$); and (3) no population (change of two quasi-particles). The 1080 keV band is in excellent agreement with the energy of configuration (1) above, and the observed log ft of 6.3 is quite consistent with the expected one for this assignment. Similarly the 1351 keV band, with an observed log ft of 6.8, agrees very well with configuration (2) above. Configuration (3) should not be populated, in agreement with our observation of only two K=1- bands.

The E1 transitions between the 1080 keV band and the ground band have relative transition probabilities in agreement with the vector addition coefficients for K=1: i.e., B(E1; 1- → 0+)/B(E1; 1- → 2+) = 1.94 ± 0.08 cf. 2.00 for K=1; and B(E1; 3- → 2+)/B(E1; 3- → 4+) = 1.13 ± 0.25 cf. 1.33 for K=1. We estimate that these E1 transitions compete more or less equally with the rotational transitions within the 1080 keV band, making the E1 lifetimes $\sim 10^5$ longer than the single particle estimate. This is typical for E1 transitions between Nilsson states in this region of the periodic table. The M1 transitions between the K=1- bands are forbidden if the configurations are pure, but could be introduced by very small mixing of these two bands (cf. the two k=8- bands[8] in Hf^{178}).

The spacings in the 1080 keV band are interesting. If we neglect terms in $I^2(I+1)^2$, and use the formula:[9]

$$E_I = E_0 + [A+(-)^{I+1}A_2]I(I+1),$$

then we find A=5.5 keV, and A_2= -0.51 keV. This value of A_2 is somewhat larger than might have been expected, although it falls in a reasonable range: $A > A_2 > 10^{-3}A$. The fact that the relative E1 transition probabilities agree with K=1, suggests that the above A_2 energy term results mainly from diagonal rather than nondiagonal matrix elements (see Ref. 10), as the latter type of coupling would normally be expected to affect the transitions.

The most interesting band in Cm^{246} is probably the K=2- one. Only two configurations are available for this band: (1) n-n, 5/2+ [622] + 9/2- [734], E_{calc} = 1.4 MeV; and (2) p-p, 3/2- [521] + 7/2+ [633], E_{calc} = 1.7 MeV. Thus while Soloviev and Siklos are in excellent agreement with the energies of the K=1- bands, the lowest calculated two-quasi-particle K=2- state lies about 600 keV too high. This immediately suggests a collective nature for the 842 keV band; and, in fact, Soloviev and Siklos construct a collective state, mainly from the above two K=2- configurations, and predict its energy to be 1.1 MeV. It would appear that the state may be somewhat more collective than their estimate. Additional evidence for the collective nature comes from the log ft value for the beta decay to this band. One would predict a value of 5.8 for configuration (1) above (cf. $Pu^{241} \rightarrow Am^{241}$, $Am^{239} \rightarrow Pu^{239}$, and $U^{239} \rightarrow Np^{239}$), and no decay to configuration (2). The observed log ft of 7.0 is consistent with neither of these, and requires either the collective explanation or a different ground state for Am^{246}. The latter alternative leads to difficulties elsewhere in the scheme. Sizeable two-quasi-particle components in the collective band (e.g., configuration (1) above) could account for the observed log ft of 7.0. (The admixed amplitudes required here are at least an order of magnitude larger than those required to introduce the M1 transition from the 224 keV level of Am^{246}.)

The E1 transitions from the 877 keV, 3- level appear to compete roughly equally with the rotational transition to the 842 keV level. This implies E1 transitions about 10^5 times slower than the single particle estimate, similar to those previously found for the 1080 keV band. This time, however, the E1 transitions are K-forbidden, and under such circumstances they are surprisingly fast if we are dealing with Nilsson states. This would seem to be still more evidence for the collective nature of this band.

A survey of the expected levels in Cm^{246} shows no others (Q_β=2.4 MeV) that might be expected to receive more than a few percent population in the beta decay of Am^{246}, as assigned above. Thus the scheme proposed (see Fig. 2) can account for the lack of appreciable beta transitions elsewhere in Cm^{246} as well as describing reasonably well the levels observed.

Perhaps the strongest evidence for the collective nature of the 2- band in Cm^{246} would be the systematic occurrence of such levels at comparable energies in neighboring nuclei. Some evidence on this point exists. A characteristic feature of the lowest member (2-) of this band is a <u>single</u> transition to the ground band. No other collective band thus far known in deformed nuclei decays in this manner, and not many two-quasi-particle states would be expected to do so. Thus the occurrence of <u>single</u> transitions at energies around one MeV in even-even nuclei might serve to indicate such bands. Transitions fitting these requirements are known to occur in Cm^{244} (Bk^{244} decay)[11] and Cf^{250} (Es^{250} decay),[12] suggesting 2- levels in these nuclei at about 950 and 850 keV, respectively. Thus, collective 2- levels lying around 900 keV may be a systematic feature of nuclei in this region.

These K=2- bands presumably correspond to octupole vibrations, similar to the well-known K=0- bands in the Ra-Th-U region. In this regard it would be important to try to Coulomb excite the 2- bands and show the enhanced B(E3) values (as has been done for the K=0- bands)[13]. It is not likely that a K=0- band lies below the K=2- band in Cm^{246}, and thus the lowest octupole band has probably changed between plutonium and curium from K=0- to K=2-. It is interesting that in just this same region the lowest quadrupole vibration changes from K=0+ (beta) to K=2+ (gamma). This must have to do with the general type of orbitals filling in these regions, and the calculations of Soloviev and Siklos bear out both of these cross-overs in a general way; although they have probably underestimated the collective nature of the K=2- bands.

This work would not have been possible without the help of the staff of the Lawrence Radiation Laboratory at Livermore, who produced the Pu^{246}. We are particularly grateful to Dr. Richard W. Hoff. The initial chemical processing on one of the Pu samples was done at Argonne National Laboratory. We appreciate the help of their chemistry staff, especially that of Dr. Herbert Diamond. The initial chemical processing for the other Pu^{246} sample was done by the Berkeley Heavy Element Production Staff. Special thanks are due to Mr. Thomas C. Parsons.

Table I. Gamma ray and coincidence data.

E_γ	Rel. inten.[a]	Coinc. w.L x ray	Coinc. w. 44 keV transition	Coinc. w. 1050	Coinc. w. 800
44	c				
K x rays			~50	3.7	(0.6)[d]
171				0.1	
180.4	10.2		(10.2)[e]		
224.0	25.3				
228					0.08
238	0.3			~0.08	0.2
244.6	1.5	b		0.6	d
245.4					
256	0.2				
262	0.1_4			0.2	(0.04)[d]
270.3	1.0			(1.0)[e]	d
288	0.1			0.1	
402	0.3			0.3	
734	1.2	2.5			
752	1	1.7			
759	0.8				
799.0	28.6	30.3			
834	2.2	2.5			
			b	b	b
987	1.1	2.1			
1037	14.4	13.9			
1063	19.3	(19.3)[e]			
1079	31.5	5.6			
1086	1.7	1.9			

[a] In percent of beta disintegrations provided there is no beta population to the ground band of Cm^{246}.

[b] Region not observed in this experiment.

[c] An intensity for the 44 keV photons of ~30% was determined from coincidence measurements.

[d] Corrected for a contribution due to gates from Compton scattered ~1 MeV photons.

[e] Normalized.

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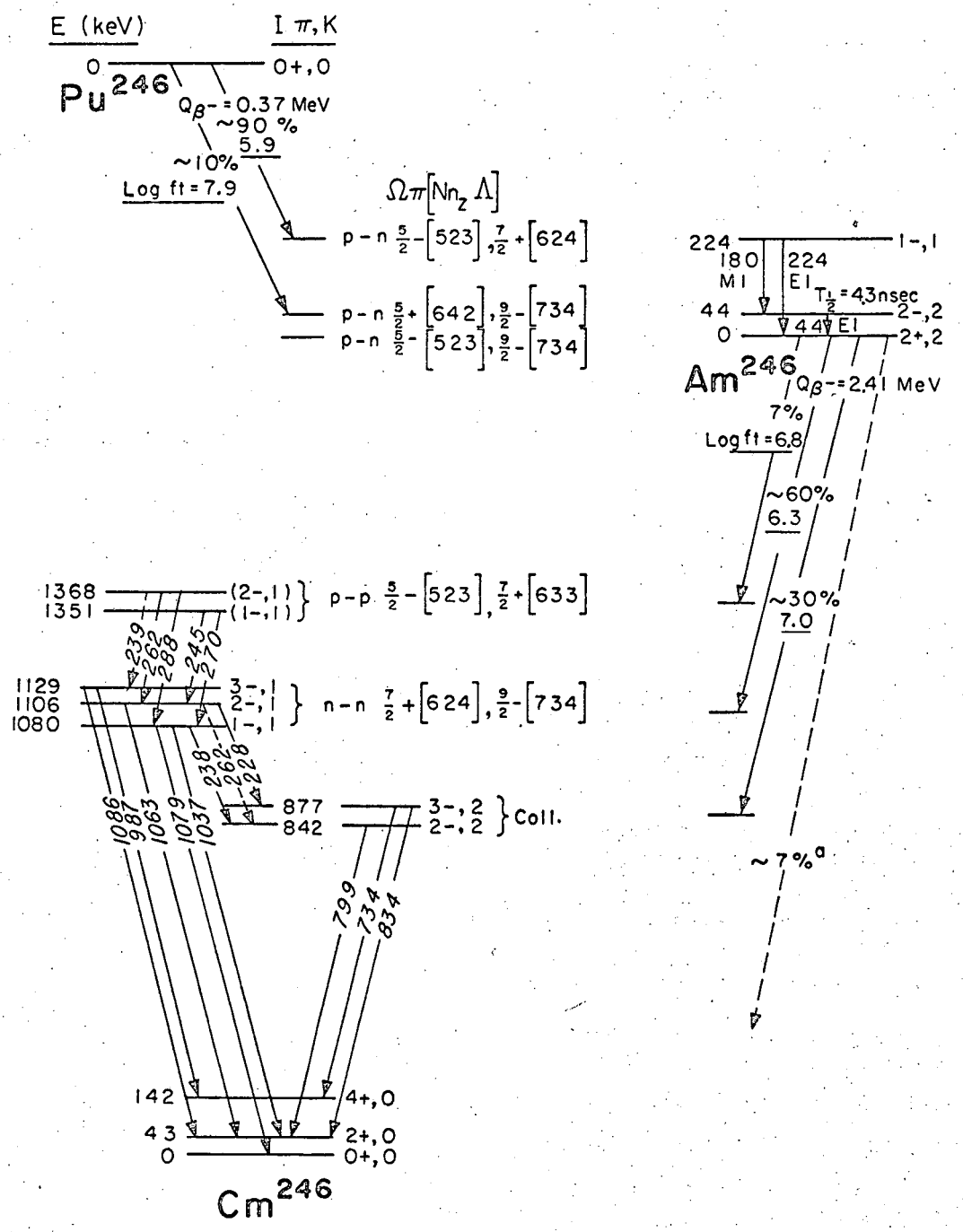
Figure Captions

Fig. 1. Gamma-ray spectra from the beta decay of Pu^{246} and Am^{246}.

Fig. 2. Decay schemes of Pu^{246} and Am^{246}. a, this intensity was measured by other workers (see reference 3).


E (keV)
I π, K
0
0+,0
Pu246
Qβ- = 0.37 MeV
~90 %
5.9
~10%
Log ft = 7.9
Ωπ[Nnz Λ]
p-n 5/2-[523], 7/2+[624]
p-n 5/2+[642], 9/2-[734]
p-n 5/2-[523], 9/2-[734]
224
1-,1
180
M1
224
E1
T1/2 = 43nsec
44
2-,2
0
44
E1
2+,2
Am246
Qβ- = 2.41 MeV
7%
Log ft = 6.8
~60%
6.3
~30%
7.0
~7%
1368
1351
(2-,1)
(1-,1)
p-p 5/2-[523], 7/2+[633]
239
262
288
245
270
1129
1106
1080
3-,1
2-,1
1-,1
n-n 7/2+[624], 9/2-[734]
238
262
228
1086
987
1063
1079
1037
877
842
3-,2
2-,2
Coll.
799
734
834
142
4+,0
43
2+,0
0
0+,0
Cm246

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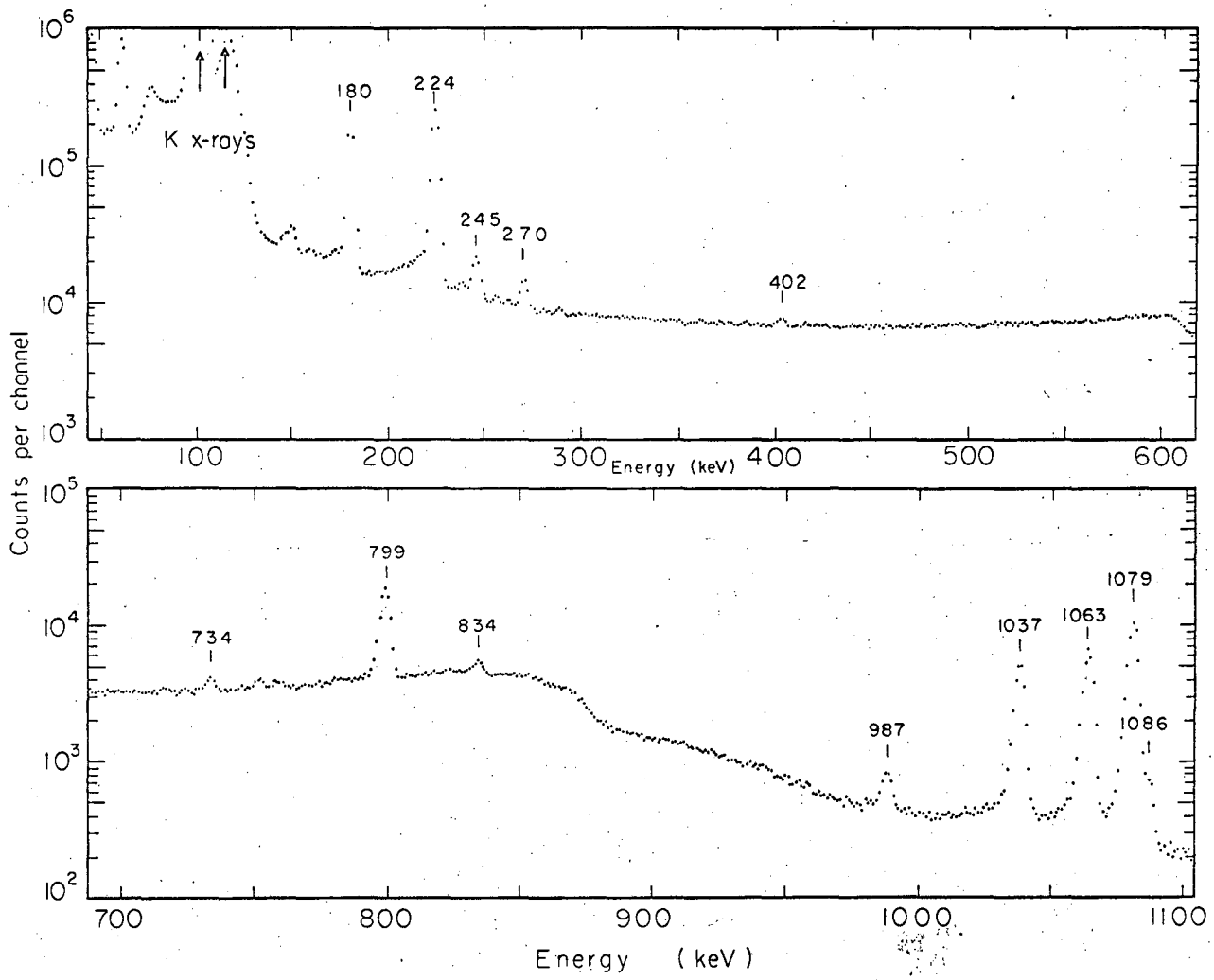
K x-rays
180
224
245
270
402
Energy (keV)
Counts per channel
734
799
834
987
1037
1063
1079
1086
Energy (keV)

MUB-6620

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