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 $Pu^{246}(\beta-/11\ \text{day})Am^{246}(\beta-/25\ \text{min})Cm^{246}$, 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 coprecipitation 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 mil 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.[1-3]

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- to 1200-keV region (Ge); (2) 1050 ± 50 keV (NaI) vs 100- to 500-keV region (Ge); (3) 800 ± 50 keV (NaI) vs 100- to 500-keV region (Ge); and (4) 44 keV (NaI) vs 15- to 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]

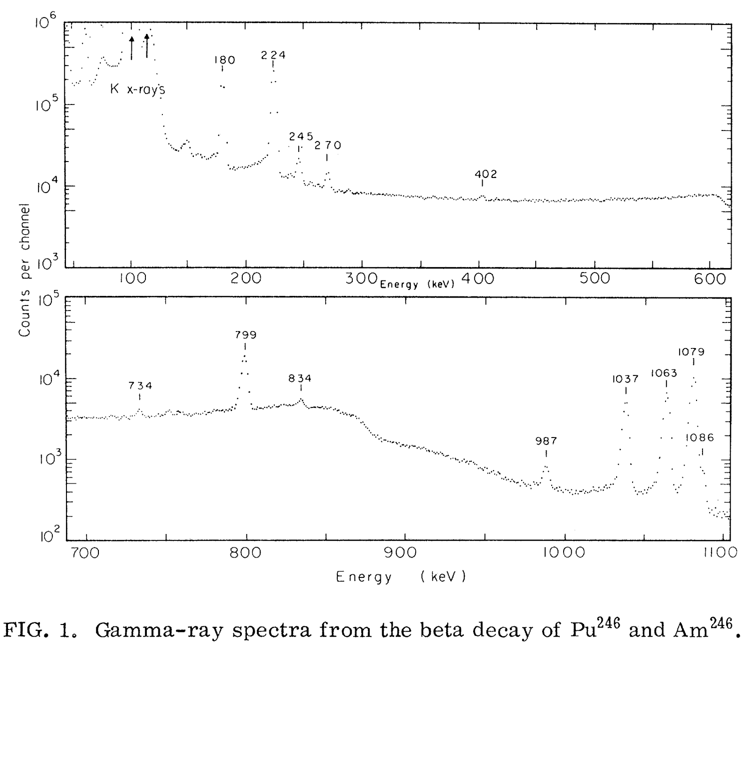

FIG. 1. Gamma-ray spectra from the beta decay of Pu^{246} and Am^{246}.

Table I. Gamma-ray and coincidence data.

E_γ	Relative intensity[a]	Coincidence with L x ray[b]	Coincidence with 44-keV transition[c]	Coincidence with 1050-keV transition[d]	Coincidence with 800-keV transition[d]
44	e				
K x rays			~50	3.7	(0.6)[f]
171				0.1	
180.4	10.2		(10.2)[g]		
224.0	25.3				
228					0.08
238	0.3			~0.08	0.2
244.6	1.5			0.6	f
245.4	1.5				
256	0.2				
262	0.14			0.2	(0.04)[f]
270.3	1.0			(1.0)[g]	f
288	0.1			0.1	
402	0.3			0.3	
734	1.2	2.5			
752	1	1.7			
759	0.8	1.7			
799.0	28.6	30.3			
834	2.2	2.5			
987	1.1	2.1			
1037	14.4	13.9			
1063	19.3	(19.3)[g]			
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 between E_γ of 44 and 402 not observed in this experiment.
[c]Region between E_γ of 402 and 1086 not observed in this experiment.
[d]Region between E_γ of 734 and 1086 not observed in this experiment
[e]An intensity for the 44-keV photons of ~30 % was determined from coincidence measurements.
[f]Corrected for a contribution due to gates from Compton scattered ~1-MeV photons.
[g]Normalized.

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 $(4.3\pm0.3)\times10^{-9}$ sec. The ~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 151st neutron is almost surely $\frac{9}{2}^-[734]$(cf. Cf^{249}),[6] and for the 95th proton it should by $\frac{5}{2}^-[523]$, with $\frac{5}{2}^+[642]$ 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, ob-

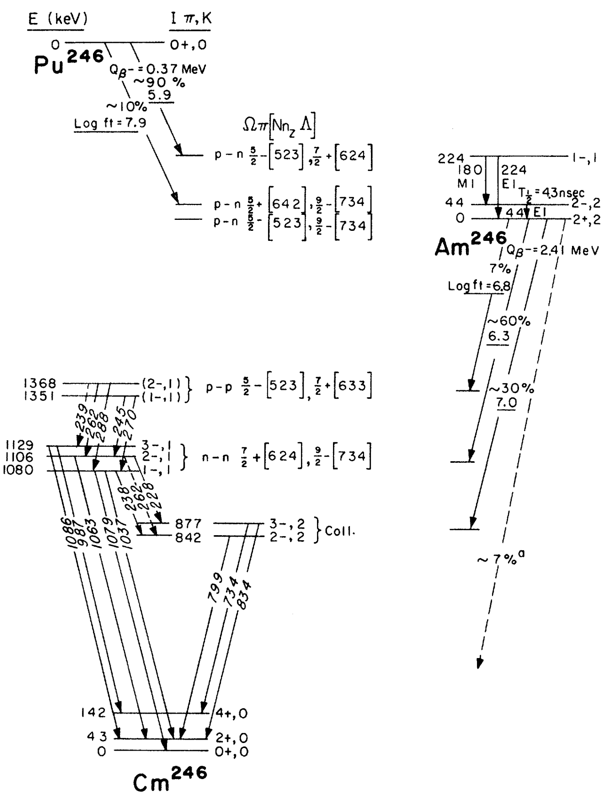

FIG. 2. Decay schemes of Pu^{246} and Am^{246}. The intensity denoted by (a) was measured by other workers.

served 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 logft for bata 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 $\frac{9}{2}^-$ neutron and the $\frac{5}{2}^\pm$ 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 logft 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 $\frac{5}{2}^-[523]$ and neutron $\frac{7}{2}^+[624]$, or (2) proton $\frac{7}{2}^+[633]$ and neutron $\frac{9}{2}^-[734]$. These have predicted logft 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 logft value of 5.9 strongly suggests the former assignment. With assignment (2) above, the 180-keV $M1$ transition ought to be much (~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} ($Q_{\beta^-} \approx 400$ 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-quasiparticle 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, $\frac{7}{2}^+[624] + \frac{9}{2}^-[734]$, $E_{calc} = 1.1$ MeV; (2) p-p, $\frac{5}{2}^-[523] + \frac{7}{2}^+[633]$, $E_{calc} = 1.3$ MeV; and (3) p-p, $\frac{5}{2}^+[642] + \frac{3}{2}^-[521]$, $E_{calc} = 1.5$ MeV. The logft 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 quasiparticles). The 1080-keV band is in excellent agreement with the energy of configuration (1) above, and the observed logft of 6.3 is quite consistent with the expected one for this assignment. Similarly, the 1315-keV band, with an observed logft 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., $B(E1;1^- \to 0^+)/B(E1;1^- \to 2^+) = 1.94 \pm 0.08$, cf. 2.00 for $K=1$; and $B(E1;3^- \to 2^+)/B(E1;3^- \to 4^+) = 1.13 \pm 0.25$, 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 Nathan and Nilsson),[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, $\frac{5}{2}^+[622] + \frac{9}{2}^-[734]$, $E_{\rm calc} = 1.4$ MeV; and (2) p-p, $\frac{3}{2}^-[521] + \frac{7}{2}^+[633]$, $E_{\rm calc} = 1.7$ MeV. Thus, while Soloviev and Siklos are in excellent agreement with the energies of the $K=1^-$ bands, the lowest calculated two-quasiparticle $K=2^-$ state lies about 600 keV too high. This immediately suggests a collective nature for the 842-keV bands; 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 logft value for the beta decay to this band. One would predict a value of 5.8 for configuration (1) above (cf. $Pu^{241} \to Am^{241}$, $Am^{239} \to Pu^{239}$, and $U^{239} \to Np^{239}$), and no decay to configuration (2). The observed logft 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-quasiparticle components in the collective band [e.g., configuration (1) above] could account for the observed logft 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 ($Q_\beta = 2.4$ 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 single transition to the ground band. No other collective band thus far known in deformed nuclei decays in this manner, and not many two-quasiparticle states would be expected to do so. Thus the occurrence of single 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 Coulombexcite 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 crossovers 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.

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$\tilde{U}(12)$ PREDICTIONS FOR $N\bar{N}$ ANNIHILATION AT REST INTO FOUR MESONS*

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In an earlier note[1,2] we have, together with Delbourgo and Strathdee, reported some predictions based on the $\tilde{U}(12)$ symmetry scheme[3] for $p\bar{p}$ annihilation at rest into three mesons (annihilation at rest into two mesons is forbidden). Most of these predictions are in reasonable agreement with experiments, and they are interesting because none of these results can be reached using SU(6) alone.

In this note we apply the same procedure to the study of the problem of $N\bar{N}$ annihilation at rest into four mesons. The aim of the present analysis is to obtain predictions for annihilation modes where the final products consist entirely of pseudoscalar mesons, since experimental information on these is most easily accessible. In particular, final products containing two K mesons are of special interest as these modes are forbidden in the previously considered case. Toward this aim we have reached conclusions which are very specific.

In the present as well as the previous analyses, we consider the annihilation amplitudes to consist only of the "regular" couplings, which are $\tilde{U}(12)$-invariant quantities before an actual identification of the external lines with physical particles is made. In this manner, one obtains the interesting results that (a) $N\bar{N}$ an-