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ABSTRACT

Measurements have been made of the energies and intensities of the E2 transitions which de-excite the gamma (K=2) vibrational band in $_{100}Fm^{254}$ following the beta decay of 38.5 hour $_{99}E^{254}$. The measured relative intensities are interpreted within the framework of the Bohr-Mottelson nuclear model, including the effect of mixing of the K=2 and K=0 ground bands. It is found that the rotation-vibration constant of the ground state band is very small [$B = (-0.4 \pm 1.8) \cdot 10^{-3}$ keV] and can be accounted for completely by the (K=2) mixing amplitude calculated from the intensity data.

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I. INTRODUCTION

There have been many investigations of the energy levels of heavy even nuclei, and at present a large body of data exists which supports the description of these levels in terms of collective rotations and vibrations of ellipsoidal nuclei. Although the vibrational states of these nuclei are characterized in general by theory and are clearly identified in a number of cases, our knowledge of them is hindered by the scarcity of quantitative data on their de-excitation behavior. In a recent analysis of E2 transition probabilities from the K=2 (gamma) band to the ground band of deformed even nuclei, Nielsen[1] described the relative intensity data, with four cases available in the heavy region, in terms of the mixing between two bands.

It is of interest to perform further relative intensity determinations with high accuracy, and to extend this type of measurement and analysis to more nuclei in the heavy element region, particularly of higher Z.

This report presents the results of a preliminary investigation of the transitions that de-excite the K=2 band in $_{100}Fm^{254}$, following the beta decay of $_{99}E^{254}$. Two isomers of $_{99}E^{254}$ are known; the shorter-lived isomer, with half-life 38.5 hours, was discovered by Fields et al.[2] and by Thompson et al.[3] as the product of the neutron irradiation of $_{99}E^{253}$. From a study of the gamma-ray spectrum Asaro and Perlman[4] established the location of

the K=2 band at ~684 keV, and more recently Unik, Day, and S. Vandenbosch[5] have studied the conversion electron spectrum at 2.7% resolution and have given 692 ± 2 keV as the energy of the 2,2 + state. In neither of the previous studies was the resolution high enough to resolve all the transitions, hence the energies and relative transition intensities were inferred from L - x-ray gamma-ray coincidence data.

In order to measure the electron intensities directly and also to determine the energies of the levels more precisely, we have examined a source of E^{254} in a 50-cm iron-free double focusing spectrometer which, for this study, was set for resolution R = 0.4% and transmission T = 1%. This instrument has been discussed briefly[6] and will be more fully described in a subsequent report.

II. EXPERIMENTAL PROCEDURES

For this investigation the spectrometer was fitted with a phosphorus-doped silicon type semiconductor detector covered with a 6 mm - wide slit. Although the background of the counter was only 1-2 counts per minute, this advantage was nullified to a great degree by a high continuous electron background from the fission products of Cf^{252}, present in the source to the extent of about 7%.

The sample of E^{254}, containing about 3×10^6 disintegrations per minute when our measurements began, was prepared as a part of the Radiation Laboratory heavy element program, and in this case the source was a mixed target of Pu^{242} and Am^{241} that had undergone neutron irradiation in the Materials Testing Reactor at Arco, Idaho for two years at an average neutron flux of 4×10^{14} neutrons /sec/cm^2. Because of the intense radiation level of the capture and fission products, the chemical purification was performed

entirely by remote control in the Berkeley "Cave" facility under the direction of Dr. Sherman Fried. The purification involved dissolution of the aluminum "slugs" in KOH, followed by rare earth - actinide separations with cation exchange columns using α-hydroxy isobutyric acid as eluant and finally purification of the einsteinium (Z = 99) fraction with a cation exchange column using HCl as eluant. The time involved in separating the einsteinium fraction was 10 days (6 1/2 half lives), after which the essentially carrier-free source was liquid-deposited on a platinum strip 1 mm wide x 10 mm long.

Because of the limited amount of activity available at the end of chemistry, the relatively short half-life of E^{254} (38.5 hours) and the difficulty due to the high background from fission products, it was not possible to scan the entire internal conversion spectrum. We therefore concentrated on the observation of the known lines in the decay of the K=2 vibrational band. Each line was measured twice, to verify that it decayed with the half-life of E^{254}. One scan of the strongest line took 3.5 hours, and each scan of the weakest line consumed 8 hours. The data are summarized in Table I, and the portion of the spectrum containing the observed lines is given in Fig. 1.

As it turned out, only four of the five lines from the gamma vibrational band in E^{254} could be measured. The weak transition between the 2,2+ and the 0,4+ levels, predicted to have energy 543.2 ± 0.5 keV, was not seen. At about the magnet current corresponding to the K- line of this transition (E_K = 402.1 ± 0.5 keV) we observed instead a line at 403.4 ± 0.2 keV. Not only was this line about ten times stronger than the predicted intensity of the 543.2 keV K- line but its energy was well outside our limits of error for this line, and also it did not decay with the 38.5 hour half-life of E^{254}. We conclude that the 403.4 keV line arose from one of the products of the spontaneous fission of Cf^{252}, known to be a weak contaminant in the source.

Table I. E^{254} Internal Conversion Electron Data

Electron[a] energy (keV)	Z = 100[7] binding energy	Transition[b] energy (keV)	Relative electron intensity	$\alpha_K(E2)$[8]	Calculated relative photon intensity
442.16 ± 0.13	141.10 (K)	583.26 ± 0.40	0.080 ± 0.005	2.78×10^{-2}	2.87
507.02 ± 0.10	141.10 (K)	648.12 ± 0.40	0.45 ± 0.02	2.32×10^{-2}	19.4
547.10 ± 0.14	141.10 (K)	688.20 ± 0.40	0.15 ± 0.01	2.10×10^{-2}	7.15
551.95 ± 0.10	141.10 (K)	693.05 ± 0.40	0.28 ± 0.02	2.07×10^{-2}	13.6

(a) The errors quoted in this column are obtained only from the uncertainties in localizing the line peaks.

(b) The errors quoted in this column include the error in the spectrometer calibration.

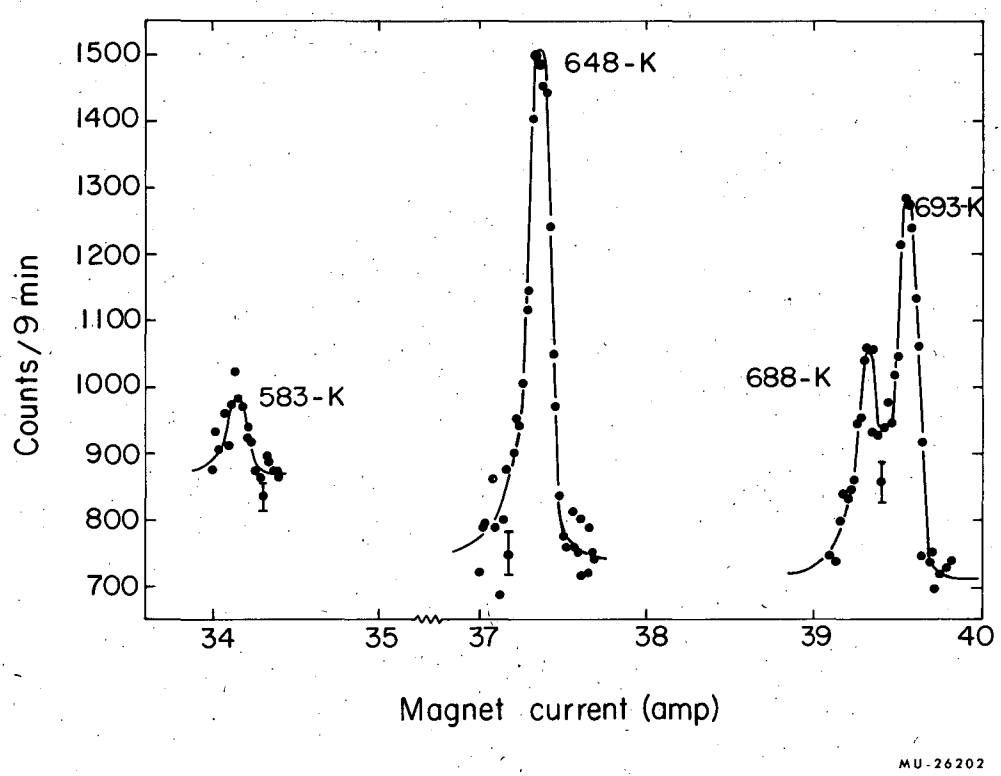

Fig. 1. Portion of conversion electron spectrum of $_{99}E^{254}$.

III. DISCUSSION OF RESULTS

Fig. 2 shows the known levels of the ground (K=0) and gamma vibrational (K=2) bands in $_{100}Fm^{254}$. The energies of the levels are those deduced from our data, together with the estimated errors. These errors have been deduced from a consideration of the reproducibility and definition of the line positions, plus the uncertainty in the energy of the standard line used for calibration and also the uncertainty in the method used to compare source with standard. As a standard we used the K-line of the 311.91 ± 0.13 keV transition of $_{91}Pa^{233}$.(9)

The energy of the first and second excited states in Fm^{254} are 44.93 ± 0.14 and 149.9 ± 0.2 keV respectively. From these values and from the equation describing the rotational spectrum

$$E_I = \frac{\hbar^2}{2\mathfrak{J}} I (I+1) - B I^2(I+1)^2$$

we obtain the following values of the two constants: $\frac{\hbar^2}{2\mathfrak{J}} = 7.49 \pm 0.05$ keV

$$B = \frac{\Delta E}{I^2(I+1)^2} = (-0.4 \pm 1.8) \cdot 10^{-3} \text{ keV}$$

The precision of these values is rather low because the energies of the first and second excited states were determined only by differences between relatively large numbers. It is obvious, however, that the rotation-vibration interaction parameter B is very small. In a future experiment these transitions will be measured directly, so that the value of B can be obtained with high accuracy.

From the energies of the 2,2+ and 2,3+ states, we obtain for the gamma vibrational band the value of the rotational constant $\frac{\hbar^2}{2\mathfrak{J}} = 6.69 \pm 0.05$ keV. Thus, the moment of inertia of the gamma vibrational band is 10.7% higher than that of the ground band. This is a somewhat greater difference than has been noted in other cases, in which the differences vary from 1% to 6%.

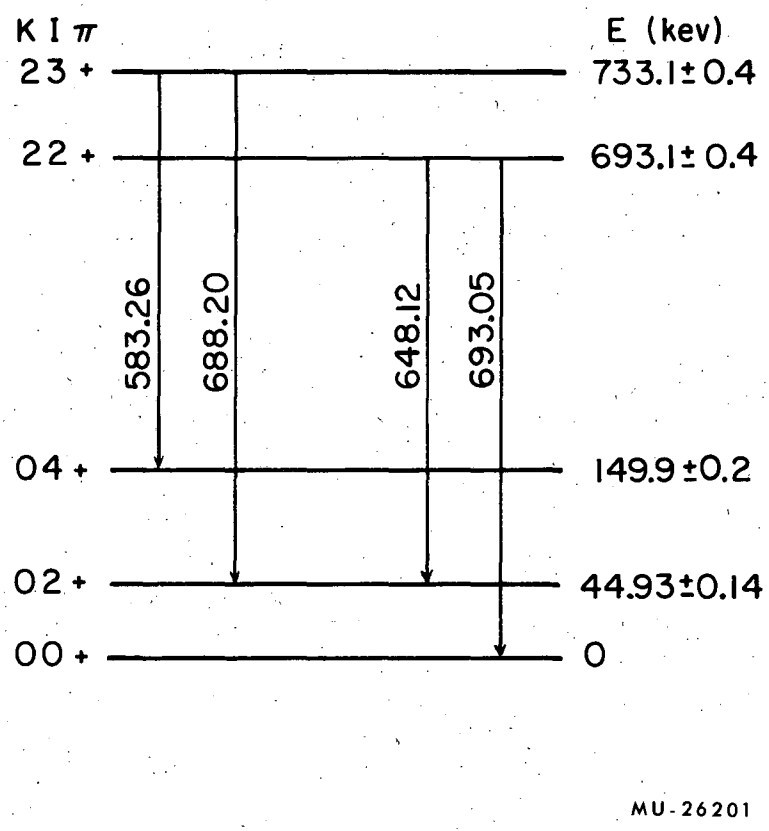

Fig. 2. Partial level scheme of $_{100}Fm^{254}$.

It is of interest to compare the experimentally measured branching ratios with those predicted from theory. We shall assume, from the measurements of Unik et al.[5] that the four transitions discussed here are pure electric quadrupole. The relative intensities of the E2 photons from a pure K=2 band to a pure K=0 band are given by the squares of vector addition coefficients, and deviations from the ratios so predicted may be interpreted in terms of K mixing between the two bands. A method of treating the effect of the mixing, suggested by Mottelson, has been applied in several cases[1, 10-13] and it is instructive to follow this analysis in this case. The mixing between the K=0 and K=2 bands is described by a parameter $z \approx \epsilon\sqrt{24}\, Q_{oo}/Q_{20}$ where ϵ is equal to the admixed amplitude, Q_{oo} is the mean quadrupole moment of the two bands, and Q_{20} is the E2 transition amplitude from the K=2 band to the K=0 band. The relative intensities of E2 transitions between the admixed bands are given by

$$B(E2,\ I_i \rightarrow I_f) = f\ (z, I_i, I_f)\ \langle I_i, 2, K_i, K_f - K_i \mid I_f, K_f \rangle^2$$

where the function $f\ (z,\ I_i,\ I_f)$ has been tabulated explicitly in the paper of Gregors Hansen et al.[10] for the case of interest here.

We find, for the transitions in Fm^{254}, that the experimental relative reduced transition probabilities deviate considerably from the simple rules for states of pure K, as shown by the data in Table II. However, for both transition ratios in Fm^{254} the data can be correlated with theory with the value for z approximately 0.06 (the actual value for each ratio is given in Table II). This value is about a factor of two higher than the values given for Pu^{238},[13] the only other nucleus in the same mass region for which data are available, but it is close to the values for some of the rare earth nuclei shown in the table of Nielsen[11].

The band mixing also causes shifts in the energies of the states.

Table II. Branching ratios from K=2 to K=0 band in Fm^{254}

Reduced E2 photon ratio	Expt'l	Theoretical	
		pure K=2	Calculated admixture parameter z
$\frac{B\ (2+ \rightarrow 0+)}{B\ (2+ \rightarrow 2+)}$	0.50 ± 0.04	0.70	0.057
$\frac{B\ (3+ \rightarrow 4+)}{B\ (3+ \rightarrow 2+)}$	0.92 ± 0.09	0.40	0.068

The energy displacement of a state from the simple I(I + 1) value is given by

$$\frac{\Delta E}{I^2(I+1)^2} = \epsilon^2 \hbar\omega$$

in which $\hbar\omega$ is the energy difference between the 02+ and 22+ states. Also

$$\epsilon = \frac{z}{\sqrt{24}} \cdot \frac{Q_{20}}{Q_{00}} = z\sqrt{\frac{B(E2,\ 00 \rightarrow 22)}{B(E2,\ 00 \rightarrow 02)} \frac{1}{24}}$$

Therefore

$$\frac{\Delta E}{I^2(I+1)^2} = \frac{z^2}{24} \cdot \frac{B(E2,\ 00 \rightarrow 22)}{B(E2,\ 00 \rightarrow 02)} \hbar\omega$$

The B(E2) values are not known for Fm^{254}, but we shall use a value for the ratio which seems approximately valid in this region, that is $\frac{B(E2,\ 00 \rightarrow 22)}{B(E2,\ 00 \rightarrow 02)} \approx 10^{-2}$. With the value $\hbar\omega$ = 648 keV and $z \approx 0.063$, we find $\frac{\Delta E}{I^2(I+1)^2} \approx 1$ eV. Since our measured value of $\frac{\Delta E}{I^2(I+1)^2}$ is so small (-0.4 ± 1.8 eV.) it appears that in this case the energy shift can be accounted for entirely by the mixing of the gamma band with the ground band. So small an energy displacement has probably not been observed in any other case. Perhaps the beta (K=0) vibrational band, which normally may account for a large part of the observed energy displacements because of interaction with the ground (K=0) band, lies at a relatively higher energy in Fm^{254} than in other cases in which these effects have been studied.

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FOOTNOTES AND REFERENCES

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