Vibrational states in ^{250}Cf excited by the (d,d') reaction

I. Ahmad, A. M. Friedman, and S. W. Yates*
Chemistry Division, Argonne National Laboratory, Argonne, Illinois 60439
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Collective states in ^{250}Cf have been studied by inelastic deuteron scattering at 15 MeV. Deuterons scattered from a 10 $\mu g/cm^2$ ^{250}Cf target were momentum analyzed with an Enge split-pole magnetic spectrograph. Spectra were recorded at angles of 90°, 125°, and 140° with respect to the incident beam. The differential cross sections and angular distributions of inelastic deuteron groups confirm the assignments of the previously known $K\pi=2-$ state at 872 keV and the $K\pi=2+$ state at 1032 keV. Levels at 1211 and 1429 keV, which are strongly populated in the (d,d') reaction, are assigned as the $3-$ member of the $K\pi=1-$ and $3-$ bands, respectively. Reduced transition probabilities $B(E2)$ and $B(E3)$ have been extracted for the $2+$ and $3-$ level and are compared with the predictions of microscopic theories of vibrational states.

[NUCLEAR REACTION ^{250}Cf(d,d'), $E_d=15$ MeV; measured $\sigma(E_d,\Theta)$. ^{250}Cf deduced levels, J, K, π, $B(E2)$, $B(E3)$. Mass-separated ^{250}Cf target.]

I. INTRODUCTION

Coulomb excitation and deuteron inelastic scattering preferentially excite the collective states of nuclei. Because of this selective population, deuteron inelastic scattering experiments have recently been used[1-3] to excite vibrational states of even-even actinide nuclei and extract $B(E\lambda)$ values for these states. This technique is particularly suited to the heaviest actinides for which target materials are available in only limited quantities. Moreover, only a small amount of these materials can be used as targets because of the high level of alpha and fission radioactivity. A knowledge of $B(E\lambda)$ values in these nuclei is needed both to estimate the strength of the particle-hole interaction and to test the predictions of existing theories of nuclear vibrations.

A great deal is known about the two-quasiparticle states of ^{250}Cf. Several high-K rotational bands were identified in the radioactive decay studies[4] of 8.6-h ^{250}Es and in the ^{249}Cf(d,p) and ^{249}Bk(α,t) reactions.[5,6] Low-spin states in ^{250}Cf have been studied from investigations of ^{250}Bk β^- decay[7,8] and 2.2-h ^{250}Es electron capture decay.[9,10] Although spin-parity assignments have been made to most of the observed states, reduced γ-ray transition probabilities have not been measured for any of them. For this reason we have performed inelastic deuteron scattering experiments to identify the γ and octupole-vibrational bands in ^{250}Cf and to deduce the $B(E2)$ and $B(E3)$ values to these states.

II. EXPERIMENTAL PROCEDURE AND RESULTS

The present experiments were performed with the deuteron beam from the Argonne FN tandem Van de Graaff accelerator. A thin ^{250}Cf target was prepared by the deposition of ^{250}Cf ions on a 40-$\mu g/cm^2$ carbon foil from the decelerated beam of the Argonne electromagnetic isotope separator.[11] The target thus prepared was isotopically pure (>99.9% by mass) ^{250}Cf, and its thickness, as determined from the elastically scattered events in a monitor detector, was 10 $\mu g/cm^2$. Because of the high level of radioactivity (~10^8 α disint./min and ~10^5 spontaneous fission disint./min), special care had to be taken in handling this target.

A beam of 15.0-MeV deuterons was directed at the ^{250}Cf target, and the scattered deuterons were momentum analyzed with an Enge split-pole magnetic spectrograph.[12] The solid angle of acceptance of the spectrograph was 2.0 msr, and a 1 mm $\times$ 3 mm beam defining slit was used to collimate the beam onto the target. A 1-mm thick Au-Si surface-barrier detector was placed at 60° with respect to the incident beam to register elastically scattered deuterons. The deuterons arriving at the focal plane of the spectrograph were recorded on Kodak NTA-50 emulsion plates. Foils of cellulose triacetate (22 μm thick) were placed in front of emulsion plates in order to reduce the deuteron energy and produce denser tracks and to absorb heavier particles from transfer reactions. The emulsion plates were later developed and scanned manually in $\frac{1}{4}$ mm wide strips. A plot of the number of these tracks as a function of the plate distance was used to obtain the energies and intensities of the deuteron groups.

Spectra of scattered deuterons were recorded

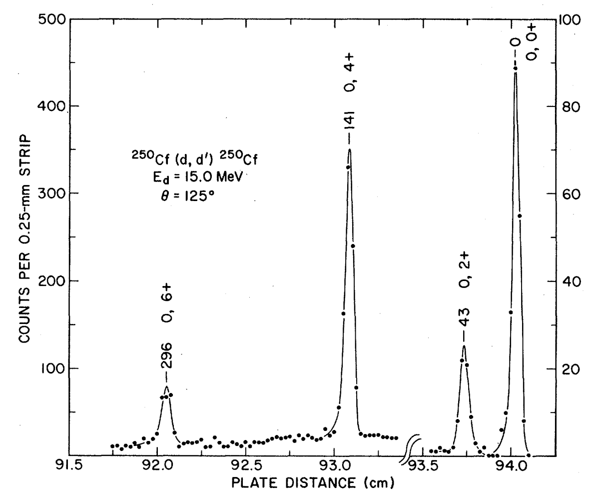

FIG. 1. Deuteron spectrum from the ^{250}Cf(d,d') reaction, showing the population of the ground state band. The incident deuteron energy was 15.0 MeV and the spectrograph angle with respect to the beam was 125°. Energy scale is 3.6 keV per $\frac{1}{4}$-mm strip.

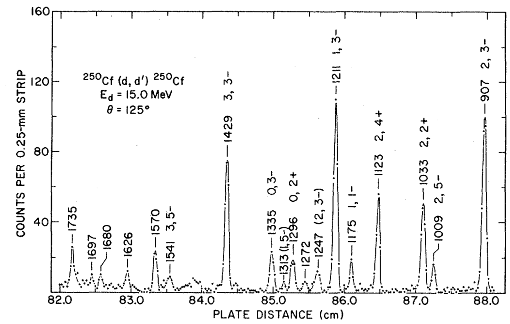

FIG. 2. Deuteron spectrum from the ^{250}Cf(d,d') reaction measured with an Enge split-pole magnetic spectrograph. The incident deuteron energy, spectrograph angle, and energy scale are the same as in Fig. 1.

at angles of 90°, 125°, and 140° with respect to the incident beam. A short exposure was also taken at 60° to register the elastically scattered deuterons and was used to relate the spectrograph solid angle to the solid angle of the monitor detector. Since the elastic group and the inelastic group exciting the 2+ member of the ground-state band were too intense to be counted in one long exposure (because of the saturation of the emulsion plate with tracks), three exposures of varying intervals were taken at each angle.

The energies and integrated counts of deuteron groups were determined from hand-plotted graphs. Absolute differential cross sections were calculated from the above intensities using the computer program AUTOPLOT[13]; the target thickness used was obtained from the number of elastically scattered deuteron events in the monitor detector. The ratio of the elastic cross section to the Rutherford scattering cross section used in this calculation was taken from the measured[3] angular distribution of 15-MeV deuterons elastically scattered from a ^{248}Cm target. Figures 1 and 2 display the ^{250}Cf(d,d') spectrum measured at 125° and the differential cross sections at the three angles of measurement are given in Table I. The uncertainties represent statistical contributions only.

III. DISCUSSION

A. Level assignments

Spins and parities of most of the levels excited in the present (d,d') reaction have been established from radioactive decay studies. In deuteron inelastic scattering experiments only those natural parity states which are connected by fast collective $E2$ and $E3$ transitions to the ground state are expected to receive strong population. We observe the population of the first four members of the ground-state band in ^{250}Cf. The 907-keV level is well established[4] as the $K,I\pi=2,3-$ state on the basis of measured multipolarities of transitions in ^{250}Cf. The large cross section to this state clearly shows that it is an octupole vibrational state. The 1009-keV level observed in the present work was also seen in the EC decay[4] of 8.6-h ^{250}Es and was assigned to the 5 – member of the $K\pi=2-$ octupole vibrational band. The ratio of the cross section at 90° to that at 125° for the 907-keV state is consistent with the 3 – assignment.[14]

The large cross section to the previously known[15] $K,I\pi=2,2+$ state at 1032 keV suggests that it is the γ-vibrational state. The 1123-keV level is assigned to the $I=4$ member of this band because the observed energy is in excellent agreement with the value of 1124 keV expected from the known[8] energies of the 2+ and 3+ members. We note that the 1123-keV state is excited quite strongly; at 125° its intensity is equal to the intensity of the 1033-keV level. Similar population of $I=4$ members of γ-vibrational bands has also been observed in rare earth nuclei[16] and in ^{248}Cm. The featureless angular distribution of the 1123-keV group provides additional support for the above assignment.[14]

The state at 1211 keV is given an $I\pi=3-$ assignment because of the large population of this state. In the radioactive decay studies[10] of 2.2-h ^{250}Es, a 1175.5-keV level, also observed in the present (d,d') reaction, was given a $K,I\pi=1,1-$ assignment. For this reason the 1175.5-, 1211-, and 1313-keV levels are assigned to the $I=1$, 3,

TABLE I. Summary of ^{250}Cf(d,d') reaction data.

Level energy (keV)	$\frac{d\sigma}{d\Omega}$ (μb/sr) [a] 90°	125°	140°	$R=\frac{d\sigma(90°)}{d\sigma(125°)}$	Assignment $K, I\pi$
0	$(9.0 \pm 0.5)\times 10^4$	$(1.85 \pm 0.12)\times 10^4$	$(1.36 \pm 0.09)\times 10^4$	4.86	$0,0^+$
43 ± 1	$(11.7 \pm 0.6)\times 10^3$	$(5.4 \pm 0.3)\times 10^3$	$(4.7 \pm 0.3)\times 10^3$	2.17	$0,2^+$
141 ± 1	210 ± 9	196 ± 8	198 ± 8	1.07	$0,4^+$
296 ± 1	24 ± 3	51 ± 4	75 ± 7	0.47	$0,6^+$
907 ± 1	98 ± 6	80 ± 5	79 ± 6	1.23	$2,3^-$
1009 ± 2	b	10.0 ± 1.8	5.5 ± 1.5		2.5^-
1033 ± 1	84 ± 5	40 ± 3.3	33 ± 3	2.10	$2,2^+$
1123 ± 1	34 ± 3	35 ± 3	40 ± 3	0.97	$2,4^+$
1175 ± 2	b	8.0 ± 1.7	9.0 ± 2.0		$1,1^-$
1211 ± 1	88 ± 10 [c]	80 ± 5	77 ± 6	1.10	$1,3^-$
1247 ± 2	b	7.0 ± 1.5	8.6 ± 1.8		$2,3^-$
1272 ± 2	b	4 ± 1	~3		
1296 ± 2	b	16 ± 2	24 ± 3		$0,2^+$
1313 ± 2	b	3 ± 1	7 ± 2		$1,5^-$
1335 ± 2	21 ± 5 [d]	19 ± 2	18 ± 2	1.1	$0,3^-$
1429 ± 1	57 ± 4	55 ± 4	55 ± 4	1.04	$3,3^-$
1541 ± 2	b	13 ± 2	10 ± 2		$(3,5^-)$
1570 ± 2	10 ± 2	13 ± 2	10 ± 0.2	0.77	
1626 ± 3	b	10 ± 3	~5		
1735 ± 2	20 ± 3	15 ± 3	10 ± 2	1.3	
1915 ± 3	b	b	14 ± 3		
2015 ± 3	18 ± 4	25 ± 5	14 ± 3	0.72	

[a] The uncertainties contain statistical contributions only.
[b] Peak was not seen at this angle because of high background.
[c] This peak was on top of a broad background and hence has a large uncertainty.
[d] This peak was broader than normal peaks. The area was determined from its peak height relative to that of 1429-keV peak.

and 5 members of the $K\pi = 1-$ octupole vibrational band. The energies of the first two members of the band give a rotational constant, $\hbar^2/2\mathscr{I}$, of 3.5 ± 0.1 keV, which is unusually small (normal values are 5.5 to 6.0 keV). This band is quite similar to the $K\pi = 1-$ octupole-vibrational band in ^{248}Cm ($\hbar^2/2\mathscr{I} = 4.5 \pm 0.2$ keV). This reduction of the rotational constant can be understood in terms of Coriolis mixing between this band and other negative-parity low-K bands.

The 1296-keV state is most likely the $K, I\pi = 0, 2+$ state identified in the EC decay studies[9] of 2.2-h ^{250}Es. The level at 1247 keV is interpreted as the 3 − member of the $K\pi = 2-$ band at 1210.0 keV identified in ^{250}Es decay. Of the remaining levels only the strongly populated levels at 1335 and 1429 keV and the weak group at 1541 keV are given tentative assignments of $K, I\pi = 0, 3-$, 3, 3 −, and 3, 5 −, respectively.

B. Reduced transition probabilities

The inelastic deuteron scattering cross section to any state depends, to first order, on the reduced transition probability $B(E\lambda)$ between the ground state and that state. In the macroscopic model $B(E\lambda)$ is given by the expression

$$B(E\lambda)\uparrow = \left(\frac{3}{4\pi} Z e R^{\lambda}\right)^2 \beta_\lambda^2, \tag{1}$$

where R is the nuclear radius ($R = R_0 A^{1/3}$, with $R_0 = 1.2$ fm, Z is the nuclear charge, and β_λ is the vibrational amplitude of the nuclear charge distribution. The quantity β_λ needed to deduce $B(E\lambda)$ values is extracted from the inelastic differential cross section $d\sigma/d\Omega$ using the equation

$$\left(\frac{d\sigma}{d\Omega}\right)_{0+\to J=\lambda} = N\beta_\lambda{}^2 \sigma_{\mathrm{DWBA}}. \tag{2}$$

In the above equation σ_{DWBA} is the theoretical cross section calculated with the distorted wave Born approximation (DWBA) method, and N is a normalization constant.

In the present work the DWBA cross sections were calculated with the computer code DWUCKS2[17] using the potential parameters of Elze and Huizenga.[1] Cross sections were calculated for several excitation energies and a plot of cross section vs excitation energy was used to obtain the DWBA cross sections for the observed levels. The parameter N is usually obtained by normalizing to some known $B(E\lambda)$ value in the same nucleus. Since no $B(E2)$ or $B(E3)$ values have been measured for ^{250}Cf, we used $B(E\lambda)$ values[18,19] in ^{248}Cm and ^{246}Cm for normalization.

The values of N for reduced $E2$ transition probabilities were determined from the known[18] $B(E2;0,0+\rightarrow 0,2+)$ in ^{248}Cm for the 90° and 125° data, and from the ^{246}Cm $B(E2;0,0+\rightarrow 0,2+)$ value[18] for the 140° spectrum, and were found to be 3.2, 6.6, and 8.1, respectively. The fact that N varies with angle reflects the contribution of multistep excitations to the inelastic scattering cross section. The $B(E2)$ values thus obtained in ^{250}Cf showed a systematic decrease with increasing angle; e.g., $B(E2)$ at 90° was ~15% larger than that at 125°. The average $B(E2)$ values for the 2+ state at 43 keV and the γ-vibrational state at 1033 keV are found to be 16 ± 1.6 e^2b^2 and 0.11 ± 0.01 e^2b^2, respectively. Ivanova *et al.*[20] have calculated the excitation energy of the γ-vibrational state in ^{250}Cf as 930 keV and its $B(E2)$ value as 0.25 e^2b^2.

For determining the $B(E3)$ values, the normalization constant N for the 90° and 125° runs was calculated from the $B(E3)$ value for the 1100-keV state in ^{248}Cm measured by precision Coulomb excitation experiments.[19] The parameter N for the 140° spectrum was evaluated from the known[3] $B(E3)$ value for the 877-keV state in ^{246}Cm. The reduced transition probabilities thus deduced at the three angles of measurement agreed extremely well with each other. The excitation energies and average $B(E3)$ values for the octupole vibrational states in ^{250}Cf are given in Table II. Also included in this table for comparison are the theoretical values of Ivanova *et al.*[20] and Neergård and Vogel.[21]

C. Composition of octupole vibrational states

In the superfluid model of the nucleus vibrational states are viewed as the superposition of several two-quasiparticle states with the same $K\pi$. The major two-quasiparticle components of the octupole-vibrational states in ^{250}Cf can be obtained from the known[22,23] single-particle spectra of neighboring odd-mass nuclei ^{249}Bk and ^{249}Cf. It is interesting to note that the first excited $K\pi=0+$ state[9,24] and the $K\pi=1-$ octupole vibration[3] in the two $N=152$ isotones lie at almost identical energies (in ^{248}Cm $E_{0+}=1.08$ MeV, $E_{1-}=1.05$ MeV; in ^{250}Cf $E_{0+}=1.15$ MeV, $E_{1-}=1.18$ MeV). This excellent agreement suggests that these states are composed of predominantly neutron configurations. Indeed, the ^{246}Cm (t,p) reaction has established[24] that the 1.08-MeV state in ^{248}Cm is the lowest neutron pair vibration.

The distorted level spacings of the $K\pi=1-$ band at 1175.5 keV can be easily understood in terms of Coriolis mixing of this band with the nearby $K\pi=2-$ band at 1210 keV. A two-band calculation with a Coriolis matrix element of 1.0 and rotational constant of 5.5 keV reproduced the observed energies for the 3 – levels to within 3 keV and the 5 – level to within 10 keV. The level spacings were found to be very sensitive to the choice of the rotational constant. The above matrix element is close to that estimated from the composition of these two bands. The major components of the $K\pi=1-$ band are expected to be the $\{\frac{9}{2}-[734]n;\frac{7}{2}+[613]n\}$ and $\{\frac{9}{2}-[734]n;\frac{7}{2}+[624]n\}$ configurations. Single nucleon transfer reactions have established[5,6] that the 1210-keV state is an almost pure $\{\frac{9}{2}-[734]n;\frac{5}{2}+[622]n\}$ two-quasiparticle state. Thus the interaction between the $K\pi=1-$ and $2-$ bands takes place via the $\frac{5}{2}+[622]$ and $\frac{7}{2}+[613]$ single particle states which have a matrix element[25] of 4.0 keV. Correction for pairing[25] $(U_iU_f+V_iV_f=0.5)$ and the fact that the $\{\frac{9}{2}-[734]n;\frac{7}{2}+[613]n\}$ configuration has only ~50% contribution to the $K\pi=1-$ state reduces the Coriolis matrix element to ~1.

TABLE II. Reduced transition probabilities for octupole states in ^{250}Cf.

Octupole state	Excitation energy (MeV) Expt.	Theory 1 [a]	Theory 2 [b]	$B(E3;\ 0^+\rightarrow 3^-)/e^2\times 10^{-74}$ cm^6 Expt. [c]	Theory 1 [a]	Theory 2 [b]
$K,I\pi=2,3^-$	0.906	0.98	0.70	20.2 ± 2.0	17.7	30
$K,I\pi=1,3^-$	1.211	1.03	1.05	19.3 ± 1.9	31.0	7.8
$K,I\pi=0,3^-$	1.335 [d]	1.12	1.40	4.6 ± 0.5	35	6.3
$K,I\pi=3,3^-$	1.429 [d]		1.20	13.3 ± 1.3		11.5

[a] Reference 20; 1 single particle unit $=2.6\times 10^{-74}$ e^2 cm^6.

[b] Reference 21.

[c] These were obtained with $N=5.4$, 11.8, and 17.5 for 90°, 125°, and 140° data, respectively.

[d] Assignment for this state is only tentative.

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*Present address: Department of Chemistry, University of Kentucky, Lexington, Kentucky 40506.

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