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Octupole states in ^{246}Cm and ^{248}Cm populated by inelastic deuteron scattering*

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Vibrational states in ^{246}Cm and ^{248}Cm have been investigated by inelastic deuteron scattering. The $K^\pi=0^-$, 1^-, and 2^- octupole states are identified in ^{246}Cm at 1251, 1080, and 842 keV, respectively. In ^{248}Cm several excited states above 1 MeV have been identified; however, definite assignments for these states, except a $J^\pi=3^-$ state at 1095 keV and a $J^\pi=2^+$ state at 1050 keV, could not be made. Differences between the ^{246}Cm and ^{248}Cm level spectra are interpreted in terms of their microscopic components. Reduced transition probabilities $B(E3)$ are extracted for the observed $J^\pi=3^-$ levels and are compared with theoretical values available in the literature.

[NUCLEAR REACTIONS ^{246,248}Cm(d,d'), $E_d=15$ MeV; measured $\sigma(E_{d'},\theta)$. ^{246,248}Cm deduced levels, J, K, π, $B(E3)$. Enriched targets.]

I. INTRODUCTION

Inelastic deuteron scattering by actinide nuclei has been shown[1,2] to preferentially populate collective states. The octupole vibrational bands of even-even nuclei in this region are characterized by well-known intensity patterns of the natural parity states in the (d,d') spectra and are, in general, the most strongly populated bands.

In the present work collective excitations in ^{246}Cm and ^{248}Cm were investigated using deuterons with energies above the Coulomb barrier. Recently these nuclei have also been studied[3] in Coulomb excitation experiments using ^{4}He ions. While the Coulomb excitation measurements provide reliable $B(E3)$ values, unique identification of octupole states is not possible since $E2$ excitations to vibrational states are seen with cross sections comparable to $E3$ excitations and only one member of a rotational band is populated. The focus of the present measurements was to locate and characterize the octupole states in these nuclei. An attempt is made to understand the properties of these states in terms of their microscopic components.

II. EXPERIMENTAL PROCEDURES

In the present experiments ^{246}Cm and ^{248}Cm targets were bombarded with 15-MeV deuterons from the Argonne FN tandem Van de Graaff accelerator. The scattered deuterons were analyzed with an Enge split-pole magnetic spectrograph[4] and were recorded on Kodak NTA-50 emulsion plates. These plates were later developed and were scanned in $\frac{1}{4}$-mm wide strips by an automatic plate scanner.[5]

The solid angle of acceptance of the spectrograph was 2 msr and a beam defining slit 1- × 3-mm was used in these measurements. With 15-MeV deuteron beams, a resolution of ~8 keV was obtained. The targets used in this study were prepared[6] in the Argonne electromagnetic isotope separator by the deposition of the respective Cm isotopes on 40 μg/cm^2 carbon foils. The thicknesses of targets thus prepared were typically 20 to 50 μg/cm^2.

Spectra were recorded at angles of 90°, 125°, and 140° with respect to the incident beam in the case of ^{246}Cm and at 90° and 125° for ^{248}Cm. Since the elastic group and the inelastic groups populating the ground-state band were too intense to be counted in a long exposure, three exposures of varying intervals were taken at each angle. The intensities of the inelastic groups were then measured relative to the elastic group, and the exposures at each angle were normalized using a NaI(Tl) monitor detector placed at 30°. Since the cross sections are vitally dependent on a knowledge of the elastic scattering cross sections, an angular distribution of the deuterons elastically scattered from ^{248}Cm was measured at 5° intervals from 20° to 150° using a small position-sensitive detector placed in the focal plane of the spectrograph. The absolute elastic scattering cross section at each angle was determined by assuming that the cross section at 20° was purely due to Rutherford scattering.

To gain additional insight into the role of $E2$ and $E3$ excitations and, hopefully, to be able to distinguish between these transitions, inelastic α-particle ($E_\alpha=29$ MeV, $\theta_{lab}=125°$) scattering measurements were made on the Cm targets using experimental procedures similar to those used for the inelastic deuteron scattering.

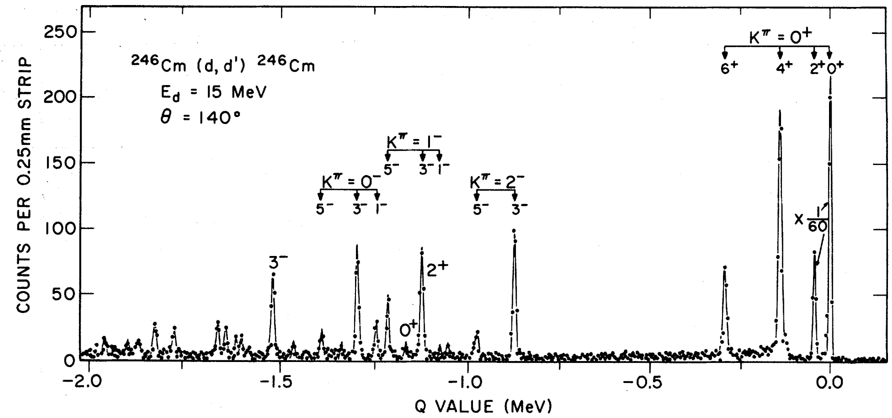

FIG. 1. Deuteron spectrum from the ^{246}Cm(d,d') reaction at 140°. Assigned states are labeled and are discussed further in the text.

III. EXPERIMENTAL RESULTS

The deuteron spectra obtained in the present measurements are shown in Figs. 1 and 2, while Tables I and II give the differential cross sections at the angles of measurement. Tables I and II also contain the spin-parity assignments for levels populated by inelastic deuteron scattering.

The level assignments, which will be discussed in detail in the next section, are based on observed cross sections and rotational spacings from the present experiments as well as published data from radioactive decay studies. The Coulomb excitation measurements of McGowan *et al.*[3] are consistent with all of our assignments. The ratio $d\sigma(90°)/d\sigma\,(125°)$ was not used for l-value assignments because, as noted by other workers,[1,2] the contribution from multiple-step excitations may be important and assignments made using this ratio are not as reliable in the heavy-element region as in lighter nuclei.[7] The results of the inelastic α-particle scattering experiments were only of limited value due partially to the poor experimental resolution. Moreover, no consistent systematics for population of states by this reaction was evident. It was noted that the 2^+ γ-vibrational state was the most strongly populated state in ^{246}Cm and this observation was used for the identification of the γ-vibrational state in the ^{248}Cm spectrum.

IV. LEVEL ASSIGNMENTS

A. Levels in ^{246}Cm

Many of the levels populated by the ^{246}Cm(d,d') reaction have been previously identified in radioactive decay studies[8-13] of ^{246}Bk and the isomers of ^{246}Am. The ground state band in ^{246}Cm was located up to the 8^+ member in investigations[11]

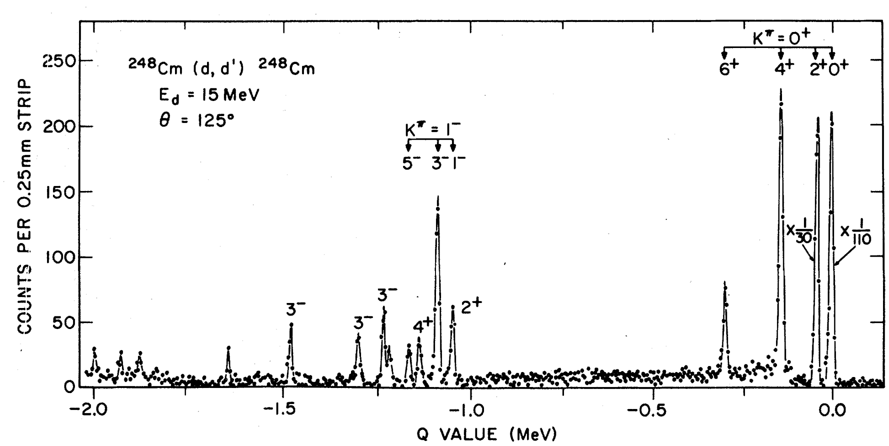

FIG. 2. Deuteron spectrum from the ^{248}Cm(d,d') reaction at 125°. Assigned states are labeled and are discussed further in the text.

TABLE I. Summary of ^{246}Cm(d, d') data.

Level energy (keV)	$\frac{d\sigma}{d\Omega}$ (μb/sr) 90°	125°	140°	Assignment $J^{\pi}K$
0	$(7.88\pm 0.39)\times 10^4$	$(1.68\pm 0.10)\times 10^4$	$(1.11\pm 0.08)\times 10^4$	0^+0
43 ± 1	$(8.51\pm 0.80)\times 10^3$	$(4.53\pm 0.34)\times 10^3$	$(4.31\pm 0.40)\times 10^3$	2^+0
142 ± 1	217 ± 27	188 ± 15	156 ± 10	4^+0
296 ± 1	48 ± 7	56 ± 9	57 ± 6	6^+0
877 ± 1	140 ± 13	82 ± 5	94 ± 6	3^-2
980 ± 3	18 ± 6	13 ± 5	19 ± 3	5^-2
1059 ± 3	a	5 ± 2	5 ± 2	
1080 ± 4	a	11 ± 2	4 ± 2	1^-1
1128 ± 1	148 ± 13	94 ± 5	75 ± 5	3^-1+2^+2
1175 ± 3	a	a	8 ± 3	0^+0
1221 ± 2	56 ± 32	34 ± 4	39 ± 4	$5^-1(+4^+2)$
1251 ± 2	24 ± 11	18 ± 3	26 ± 3	1^-0
1301 ± 1	160 ± 67	88 ± 5	71 ± 6	3^-0
1343 ± 4	b	5 ± 2	8 ± 3	
1397 ± 3	b	17 ± 4	17 ± 4	5^-0
1471 ± 3	29 ± 9	12 ± 3	7 ± 2	
1527 ± 2	79 ± 18	74 ± 6	59 ± 6	3^-
1609 ± 3	a	16 ± 4	13 ± 2	
1624 ± 4	a	a	8 ± 2	(3^-2)
1652 ± 3	22 ± 9	15 ± 4	16 ± 2	
1672 ± 2	42 ± 11	18 ± 5	27 ± 3	(3^-1)
1786 ± 4	27 ± 11	11 ± 2	13 ± 4	
1836 ± 3	26 ± 4	28 ± 6	21 ± 4	
1912 ± 4	a	11 ± 3	5 ± 2	
1965 ± 4	12 ± 3	13 ± 3	8 ± 3	

[a] Too weakly populated to be observed at this angle.
[b] Obscured by an impurity group in the 90° spectrum.

TABLE II. Summary of ^{248}Cm(d, d') data.

Level energy (keV)	$\frac{d\sigma}{d\Omega}$ (μb/sr) 90°	125°	Assignment $J^{\pi}K$
0	$(7.87\pm 0.39)\times 10^4$	$(1.74\pm 0.09)\times 10^4$	0^+0
43 ± 1	$(9.64\pm 1.00)\times 10^3$	$(4.59\pm 0.28)\times 10^3$	2^+0
144 ± 1	373 ± 40	245 ± 18	4^+0
299 ± 2	52 ± 13	76 ± 7	6^+0
1050 ± 2	136 ± 18	68 ± 5	2^+2+1^-1
1095 ± 2	204 ± 11	148 ± 8	3^-1
1144 ± 2	47 ± 10	37 ± 4	4^+2
1172 ± 3	9 ± 5	31 ± 4	5^-1
1222 ± 4	18 ± 8	24 ± 4	
1236 ± 2	126 ± 18	62 ± 5	(3^-)
1305 ± 3	92 ± 41	37 ± 6	(3^-)
1484 ± 2	63 ± 5	48 ± 6	(3^-)
1651 ± 4	27 ± 10	23 ± 6	
1883 ± 3	40 ± 7	22 ± 6	
1938 ± 4	13 ± 3	20 ± 3	
1969 ± 4	13 ± 7	6 ± 3	
2000 ± 4	a	25 ± 10	

[a] Too weakly populated to be observed at this angle.

of the decay of the 39-min high-spin ^{246}Am isomer.

Stephens *et al.*[8] first suggested that the $K^\pi = 2^-$ band at 842 keV was primarily of collective character on the basis of the observed β^- decay properties of the 25-min ^{246}Am isomer to this band and the fact that the band is at such low excitation energy. The population of this band in the present inelastic scattering measurements confirms this interpretation.

The $K^\pi = 1^-$ band at 1079 keV is observed following the decays of both 25-min ^{246}Am and 1.8-day ^{246}Bk. Multhauf *et al.*[12] interpreted this band as a collective excitation. It should be noted that a $K^\pi = 2^+$ band at 1124 keV has been assigned[12] as the γ vibration in ^{246}Cm. Since this level and the 3^- level of the $K^\pi = 1^-$ octupole band lie within 4 keV, the deuteron group at 1128 keV in the (d, d') spectrum undoubtedly contains contributions from both states. As noted previously, a peak at this energy is the most intense excitation above the ground state band in the (α, α') spectra. This large cross section is caused by a more intense excitation of the 2^+ γ-vibrational state and confirms the earlier assignment. The 4^+ member of the γ-vibrational band would be expected to occur at approximately the same energy as the 5^- member of the $K^\pi = 1^-$ octupole band; thus the deuteron group at 1221 keV probably contains contributions from both states.

Multhauf *et al.*[12] also proposed a band at 1250 keV in which only the 1^- and 3^- members were seen. This sequence is characteristic of the $K^\pi = 0^-$ octupole vibrational band. Moreover, they noted that the distortion of the $K^\pi = 1^-$ bands at 1079 and 1349 keV suggests that both are Coriolis coupled to a $K^\pi = 0^-$ band lying between them. The observed population of the 1^-, 3^-, and 5^- members of this band in the present experiments is entirely consistent with their assignments. The fact that we do not observe any population of the 1349-keV band suggests that it is of two-quasiparticle character.

Of the remaining levels previously seen in radioactive decay,[12] the 3^- levels at 1622 and 1671 keV most probably correspond to the inelastic deuteron groups at 1624 ± 4 and 1672 ± 2 keV. The population of these states suggests mixing with the lower-lying $K^\pi = 2^-$ and $K^\pi = 1^-$ octupole bands. In a study[13] of the ^{248}Cm(p, t) reaction, a state at 1176 keV was observed in ^{246}Cm and was assigned 0^+ spin-parity on the basis of its characteristic $l = 0$ angular distribution. In addition, an $E0$ transition to the ground state of ^{246}Cm from a level at 1175 keV was observed in a conversion electron study[14] of 25-min ^{246}Am decay. This level was suggested as the β-vibrational state in ^{246}Cm. The deuteron group at 1175 keV observed in our 140° spectrum probably corresponds to this excitation. No evidence is found for its 2^+ member, which was identified in the previous reaction[13] and decay[14] studies.

The only strongly populated state not yet identified is the state at 1527 keV which has an intensity characteristic of a $J^\pi = 3^-$ octupole excitation. This state, along with the state at 1652 keV, could be the $J^\pi = 3^-$ and 5^- members of the $K^\pi = 3^-$ octupole vibrational band. The rotational constant for this band is, however, approximately 25% larger than the observed rotational constants for the other octupole bands. This large spacing cannot be entirely explained by Coriolis mixing with other octupole bands. On the other hand, the 1471-keV state could be the $J^\pi = 1^-$ member of a $K^\pi = 0^-$ or 1^- octupole band with the 3^- member at 1527 keV and the 5^- member being the previously assigned level at 1624 keV. Since $K^\pi = 0^-$ and 1^- octupole bands have already been identified, this band (if it has $K^\pi = 0^-$ or 1^-) should be a two-quasiparticle state with its population occurring due to strong mixing with the lower $K^\pi = 0^-$ or 1^- band. We prefer a $K^\pi = 3^-$ assignment for the 1527-keV state because the strong population of this state is characteristic of an octupole excitation. The present study affords a unique case where all four of the octupole bands are seen.

B. Levels in ^{248}Cm

In contrast to ^{246}Cm where a considerable amount of spectroscopic information is available from radioactive decay, little is known about ^{248}Cm except for levels of the ground state band. States at 1050 and 1100 keV were observed[3] in ^{248}Cm by Coulomb excitation with ^{4}He ions, but it was not possible to make assignments other than to propose spin-parities of 2^+ or 3^-. The level structure of ^{248}Cm has also been examined by inelastic scattering of 16-MeV deuterons in a study[15] concurrent with ours.

In our α-particle inelastic scattering experiment, we observe the 1050-keV level to be populated with greater intensity than the 1095-keV level. This is in contrast to the (d, d') result, where the 1095-keV level receives greater population. These observations are consistent with a 2^+ assignment for the 1050-keV state and a 3^- assignment for the 1095-keV state. The state at 1144 keV is then assigned as the 4^+ member of the γ-vibrational band and the state at 1172 keV is quite likely the 5^- member of the same octupole band as the 3^- state at 1095 keV. If this octupole band has $K^\pi = 0^-$ or 1^-, the lowest member of the band would be obscured by the more intense excitation of the 2^+ level at 1050

TABLE III. Reduced transition probabilities for octupole states in ^{246}Cm and ^{248}Cm.

Octupole state	Experimental measurements Energy (MeV)	Experimental measurements $B(E3)$ [a] ($10^{-74}e^2$cm^6)		Theoretical calculations Komov *et al.* [b] Energy (MeV)	Komov *et al.* $B(E3)$ ($10^{-74}e^2$cm^6)	Neergård and Vogel [c] Energy (MeV)	Neergård and Vogel $B(E3)$ ($10^{-74}e^2$cm^6)
				^{246}Cm			
$K^\pi=0^-$	1.251	33.3	Total = 107	1.0	13.9	1.23	9.0
$K^\pi=1^-$	1.080	29.7		1.0	3.5	0.81	1.5
$K^\pi=2^-$	0.842	26.6		0.95	7.6	0.75	31.6
$K^\pi=3^-$	(1.527)	17.7		2.0	0.9	1.29	12.0
				^{248}Cm			
$K^\pi=0^-$				1.1	14.8	1.30	3.0
$K^\pi=1^-$	1.050	41	Total [d] = 98	1.1	4.6	0.94	7.0
$K^\pi=2^-$				1.0	8.7	0.80	33.4
$K^\pi=3^-$				1.6	0.005	1.28	13.4

[a] Normalized to the $B(E3)$ value for the 1095-keV state obtained in Coulomb excitation studies of ^{248}Cm (Ref. 3).
[b] Reference 20.
[c] Reference 16.
[d] The total $B(E3)$ strength to octupole bands in ^{248}Cm is obtained by assuming that the states at 1236, 1305, and 1484 keV are the $J^\pi=3^-$ states of the remaining octupole bands.

keV with which it would be nearly degenerate in energy. For reasons to be given in the next section, the lowest-lying octupole vibrational band in ^{248}Cm is interpreted as the $K^\pi=1^-$ octupole. The energy spacings between the members of this octupole band are somewhat smaller than for the octupole bands in ^{246}Cm and give evidence of considerable Coriolis mixing with higher-lying octupole bands. Neergård and Vogel[16] have pointed out that, since almost all of the octupole state in this region are rather collective, the Coriolis matrix elements are close to the spherical limit and are given by

$$\langle K+1|J_+|K\rangle=[(3-K)(3+K+1)]^{1/2}. \tag{1}$$

Our calculations show that the energy spacings of this band can be readily explained by a Coriolis coupling calculation when the matrix elements are reduced to ~75% of the spherical value.

Additional moderately strongly populated states are seen in the (d,d') spectrum at 1236, 1305, and 1484 keV. Although no obvious intensity patterns are seen, it is quite likely that these states are also $J^\pi=3^-$ octupole excitations.

V. DISCUSSION

The inelastic scattering cross section for $E3$ excitation of a particular state should be proportional to the reduced transition probability to that state when only single excitations are involved. For this reason, in the present work the $B(E3)$ values were determined only for the most forward angle (90°) where the contribution from multiple excitations should be less important.[17] The $E3$ reduced transition probability is given by[16,18]

$$B(E3;0^+\rightarrow 3^-)=\left(\frac{3}{4\pi}ZeR_0^3\right)^2\beta_{E3}^2\,, \tag{2}$$

where R_0 is the nuclear radius. The parameter β_{E3} which classically is the vibrational amplitude of the nuclear charge distribution can be determined from the relationship

$$\left(\frac{d\sigma}{d\Omega}\right)_{\rm exp}=N\beta_{E3}^2\sigma_{\rm DWBA}, \tag{3}$$

where $(d\sigma/d\Omega)_{\rm exp}$ and $\sigma_{\rm DWBA}$ are the experimental and theoretical differential cross sections and N is a normalization constant.

Elze and Huizenga[1] have observed that the absolute magnitude of $B(E3)$ values calculated in the above manner differs systematically from values obtained by Coulomb excitation measurements, presumably due to deficiencies in the DWBA calculation. To avoid this difficulty, the $B(E3)$ values obtained in the present experiments are normalized to the Coulomb excitation value for the first $J^\pi=3^-$ octupole state in ^{248}Cm. The normalization for ^{248}Cm is used for the ^{246}Cm data since no meaningful Coulomb excitation measurement is available for this nucleus.

Since the inelastic scattering cross sections are expected to be somewhat dependent on excitation energy, the experimental cross sections were corrected for Q dependence using the distorted wave code DWUCK.[19] The optical model parameters of Elze and Huizenga,[1] which gave a reasonable fit to the angular distribution of deuterons elastically scattered from ^{248}Cm, were used in these calculations. The normalized experimental $B(E3)$ values for octupole states in ^{246}Cm and ^{248}Cm are given in Table III. Also shown in this table for comparison are the theoretical values of Komov, Malov, and Soloviev[20] and Neergård and Vogel.[16]

In comparing the data obtained by inelastic deuteron scattering on ^{246}Cm and ^{248}Cm, it is quite apparent that the distribution of the octupole strength is radically different in these nuclei while the total $B(E3)$ strength (assuming the states at 1236, 1305, and 1484 keV in ^{248}Cm are $J^{\pi}=3^-$) is nearly constant. This change in $B(E3)$ values is quite probably related to the changes in the neutron single-particle spectra incurred in going from ^{246}Cm to ^{248}Cm which determine the microscopic composition of the octupole bands.

In the superfluid model of the nucleus the vibrational states are viewed as the superposition of several two-quasiparticle states with the same K^{π}. The calculations of Soloviev and Siklos[21] gave the configurations $\{\frac{5}{2}^+[622]\nu;\ \frac{9}{2}^-[734]\nu\}$ and $\{\frac{7}{2}^+[633]\pi;\ \frac{3}{2}^-[521]\pi\}$ as the principal two-quasiparticle components in the $K^{\pi}=2^-$ octupole vibrational state in ^{246}Cm. In ^{248}Cm, however, the addition of two neutrons to ^{246}Cm, which fills the $\frac{9}{2}^-[734]\nu$ orbital,[22] should diminish the contribution of the $\{\frac{5}{2}^+[622]\nu;\ \frac{9}{2}^-[734]\nu\}$ component in the $K^{\pi}=2^-$ octupole vibrational state. The $K^{\pi}=2^-$ octupole in ^{248}Cm would then be expected to receive less population in the (d,d') reaction. Moreover, the $\{\frac{7}{2}^+[613]\nu;\ \frac{9}{2}^-[734]\nu\}$ configuration would now be expected to become a more important component in the $K^{\pi}=1^-$ octupole state with a subsequent increase in the collectivity of this band. Although the $B(E3)$ values calculated by Neergård and Vogel[16] (see Table III) for the $K^{\pi}=1^-$ and 2^- octupoles are certainly not in agreement with the experimentally observed values for either Cm isotope, these calculations show a nearly fivefold increase in the collectivity of the $K^{\pi}=1^-$ octupole band in ^{248}Cm over that in ^{246}Cm. On the basis of the above arguments the lowest-lying octupole band in ^{248}Cm is assigned $K^{\pi}=1^-$ and it is believed that the $J^{\pi}=1^-$ member of this band is obscured by the 2^+ γ-vibrational state in the experimental spectra.

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