Spectroscopy of neutron-rich odd-*A* Ce isotopes

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Neutron-rich nuclei ^{147,149,151}Ce have been studied via the prompt γ-ray spectroscopy of ^{248}Cm fission fragments. A partial level scheme for ^{151}Ce is presented for the first time, along with the high-spin structure in ^{147,149}Ce. A rapidly changing yrast structure with neutron number is observed and it is suggested that bands in ^{147}Ce and ^{151}Ce are built on the $\nu i_{13/2}$ Nilsson state. The level scheme of ^{149}Ce displays two bands with quite similar transition energies. There is no experimental evidence for octupole deformation in any of the three nuclei. [S0556-2813(97)02009-8]

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I. INTRODUCTION

Information on the structure of neutron-rich nuclei was limited for a long time to low spin states observed in the β decay of fission fragments. With the advent, ten years ago, of the first generation of γ-ray multidetector arrays, the high-spin structure of neutron-rich nuclei could be studied through the spectroscopy of the prompt γ rays emitted by fission fragments immediately after scission and neutron evaporation. The complementary information about spin states higher than those populated in radioactive decay is needed for the understanding of the structure of these neutron-rich nuclei and for their theoretical description. A specific aspect of the neutron-rich nuclei where such information is essential concerns nuclei in the vicinity of $Z=56$ which may have reflection-asymmetric shapes. Experimentally reflection-asymmetric nuclei are characterized by the presence of alternating parity quasimolecular bands, often strong electric dipole ($E1$) transitions connecting the opposite parity states and in odd-*A* nuclei the existence of parity doublets. Some of these features were first observed for $^{144,146}_{56}$Ba [1] and $^{146}_{58}$Ce [2]. Later, using more sophisticated γ-ray multidetector arrays such as EUROGAM or GAMMASPHERE and spontaneously fissioning ^{248}Cm and ^{252}Cf sources [3,4], the investigation of octupole deformation of nuclei has been extended to other isotopes of Ba and Ce, and to the neutron-rich Xe, Cs, and La nuclei [5–12]. A general remark concerning these studies is that the observation or nonobservation of the characteristics of very strong octupole correlations does not occur necessarily where nuclear theories predict them. For the even-even Ce isotopes, signatures for reflection asymmetric nuclei are, as expected [13], present in the level schemes of the isotopes with masses 144 [7] and 146 [2], and not with masses 148 and 150 [2]. In a specific theoretical investigation [13], the octupole barriers in the ground states of odd-*A* nuclei were calculated to be significantly larger compared to the barriers in the even-even neighbors. In order to check this prediction and to get a better understanding of the structure of the nuclei in this mass region, we decided to improve the experimental situation by studying the excited states of the odd-*A* neutron-rich Ce isotopes.

II. EXPERIMENTAL PROCEDURE AND DATA ANALYSIS

The cerium nuclei studied in the present work were obtained as secondary fragments in the spontaneous fission of the ^{248}Cm isotope. The source was a mixture of about 5 mg of ^{248}Cm, in the form of oxide, with 65 mg of KCl, compressed into a 7 mm diameter pellet. The radioactive source was placed in the center of the EUROGAM II array [14] located at the Center de Recherches Nucléaires in Strasbourg. The EUROGAM II array, which consisted in this experiment of 52 escape-suppressed Ge detectors including 24 four-crystal detectors (clover detectors), was augmented by the addition of 4 low-energy photon spectrometers. A total of approximately 2.5×10^9 threefold or higher coincidence events was collected within a period of 11 days.

The level schemes of ^{147,149,151}Ce were constructed by examining double gated monodimensional γ spectra. Information on the multipolarities of γ rays was obtained by analyzing triple angular correlations [15] in two different ways. Among triple γ coincidences, events which correspond to the detection of γ rays at specific angles to each other were selected : a first γ ray is detected in any direction, a second and a third γ ray are detected at roughly 90° and 180°, respectively, with respect to the direction of the first γ ray. In the first method, a cascade of three successive γ rays, γ_1-γ_2-γ_3, is considered and the DCO ratios (DCO$_1$) are defined by

$$[\gamma_1(90°)\gamma_2(\mathrm{ref})\gamma_3(180°)]/[\gamma_1(\mathrm{ref})\gamma_2(90°)\gamma_3(180°)].$$

The second method is a modified treatment of triple angular correlations. For two successive γ rays, γ_1-γ_2, the DCO ratios (DCO$_2$) are defined by

$$[\gamma_1(90°)\gamma_2(\mathrm{ref})\gamma_3(180°)]/[\gamma_1(180°)\gamma_2(\mathrm{ref})\gamma_3(90°)],$$

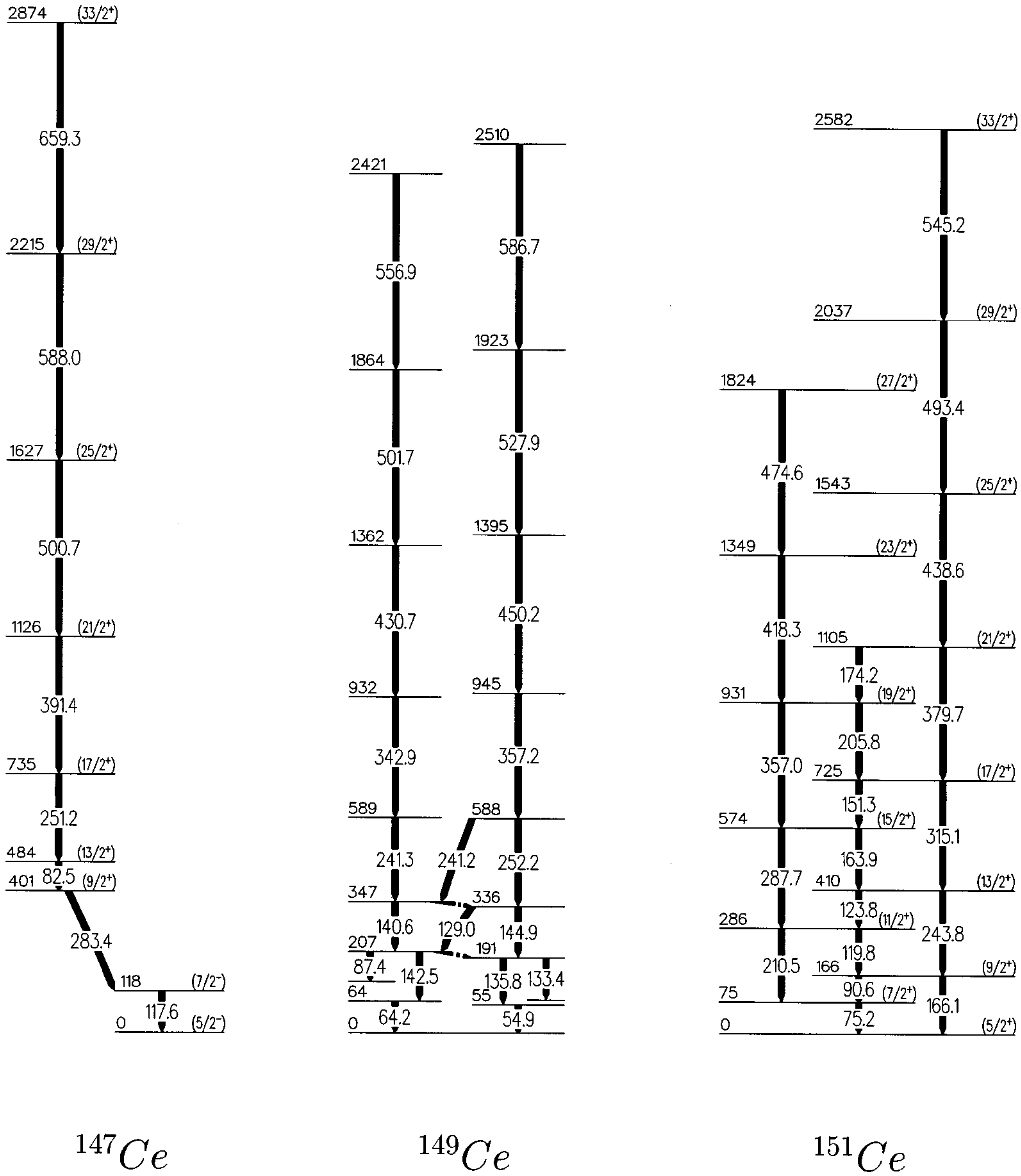

FIG. 1. Partial decay schemes for ^{147}Ce, ^{149}Ce, and ^{151}Ce. Dashed lines correspond to transitions whose existence are only confirmed by coincidence relations. The spins and parities of the ground states are discussed in the text.

where the third coincident γ ray is undefined, i.e., it may have any energy and be emitted by any fragment. Theoretical values for DCO_1 and DCO_2 are given in Ref. [6]. Information on the parities of γ rays was obtained by analyzing directional linear-polarization correlations, separate crystals of clover detectors acting as Compton polarimeters [6]. Such an analysis requires the use of fourfold γ-ray coincidence events. Finally, the intensity balances of γ rays populating and depopulating levels were used to determine total internal conversion coefficients and consequently the nature of the considered transitions. The lightest Ce isotope could be identified through the presence of known γ lines. For the heavier isotopes, an unambiguous identification technique [3] was used. It is based on the mean mass of the complementary fragments which are emitted in coincidence with the nucleus being studied.

III. EXPERIMENTAL RESULTS AND DISCUSSION

A. ^{147}Ce nucleus

The partial level scheme of ^{147}Ce determined in the present work consists of a single γ cascade which is shown in Fig. 1. Recently another level scheme for the yrast states up to 1.6 MeV excitation energy has been proposed [16]. It agrees with our results, except that the order of the 283.4 and 82.5 keV γ transitions is reversed. Our order is supported by ^{147}La β^--decay studies [17] which found that the 283.4 keV γ ray feeds the first excited state of ^{147}Ce. DCO ratios agree with the 117.6 and 283.4 keV transitions being stretched dipoles and with the 251.2, 391.4, and 500.7 keV being stretched quadrupole transitions (see Table I). Figure 2, which displays the total internal conversion coefficients for the three lowest transitions in the γ cascade, shows that the 82.5 keV transition is probably of $E2$ character, although the

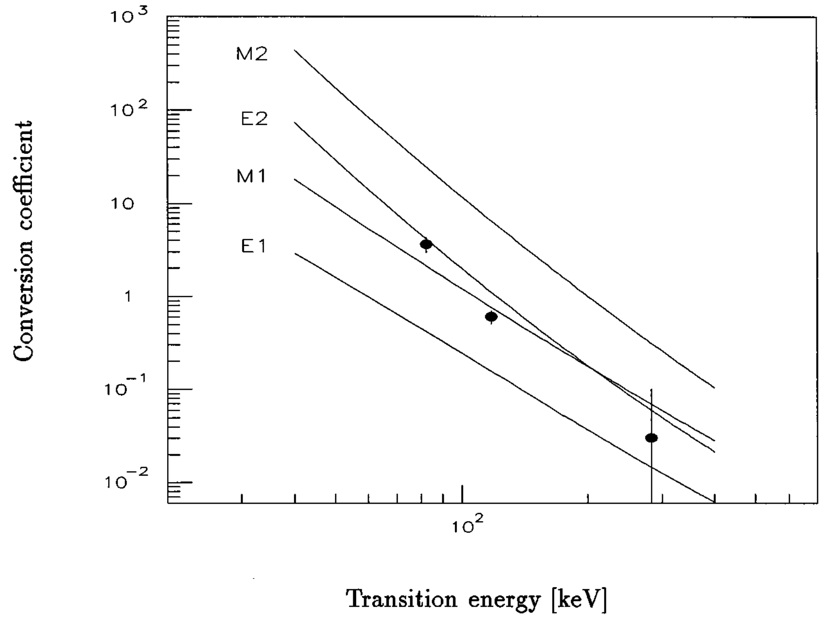

FIG. 2. Experimental and theoretical total internal conversion coefficients for the three lowest transitions in the ^{147}Ce γ cascade. The theoretical values are from the tables of Rösel *et al.* [18]. Experimental values are deduced from intensity balance measurements.

possibility of an $M1+E2$ character cannot be rejected. Linear polarization measurement yields a value of $P_\gamma=+0.07(7)$ for the 283.4 keV γ ray. This indicates that the transition has an $E1$ character (the theoretical values are $+0.09$ and -0.09 for electric and magnetic dipole transitions, respectively). Note that our results conflict with the $M1+E2$ multipolarity assignment presented in a communication to a conference in 1981 [19].

An $I^\pi=(5/2^-)$ assignment to the ground state of ^{147}Ce agrees with systematics for the $N=89$ isotones ^{145}Ba, ^{149}Nd, and ^{151}Sm. Since fission populates predominantly yrast states, values of $J^\pi=7/2^-$ and $9/2^+$ are proposed for the 118 and 401 keV levels, respectively. The proposition is strengthened by the existence of a $9/2^+$ state in the $N=89$ isotones with $A>149$. The study of the isomerism of these $9/2^+$ states [20] suggests that the main amplitudes of the $7/2^-$ and $9/2^+$ state wave functions are from [523]$5/2^-$ or [532]$3/2^-$ and [660]$1/2^+$ orbitals, respectively. In view of the $E1$ hindrance factors observed in the decay of the $9/2^+$ isomers, the mean life of the $9/2^+$ state at 401 keV should be close to 10^{-9} s, and such a short lifetime would not influence the experimental determination of the observed intensities of the γ rays in the cascade. The positive parity energy levels are reasonably well fitted by the rotational energy formula

$$E_{K=1/2}(I)=E_{K=1/2}+A[I(I+1)-1/4]+B[I(I+1)-1/4]^2 +(-1)^{I+1/2}(I+1/2)A_1$$

assuming that this band is a strongly decoupled $K=1/2$ band. The fit yields a value $A=\hbar^2/(2\mathcal{J})=23.2$ keV for the inertial parameter. The presence of only states separated by two units of angular momentum may also be explained with a rotation-alignment scheme, where the separation in energy between

TABLE I. DCO1 and DCO2 values in ^{147,149}Ce. Calculations for stretched dipole (D) and quadrupole (Q) transitions detected in the EUROGAM II array yield the following values for DCO1 and DCO2: *Q-Q-Q* (1.00), *Q-D-D* (1.13), *Q-Q* (0.89), *D-D* (0.94). DCO1 and DCO2 values for other combinations are given in Ref. [6].

Nucleus	Cascade	DCO1	DCO2	Assignment
^{147}Ce	283.4-117.6		0.88(9)	*D-D* [a]
	251.2-283.4-117.6	1.20(7)		*Q-D-D*
	391.4-251.2		0.94(6)	*Q-Q*
	391.4-283.4-117.6	1.17(13)		*Q-D-D*
	500.7-391.4-251.2	0.97(10)		*Q-Q-Q*
^{149}Ce	342.9-241.3		0.96(6)	*D-D* or *Q-Q*
	430.7-342.9		0.90(5)	*D-D* or *Q-Q*

[a]The 117.6 keV transition is a magnetic dipole transition (see Fig. 2).

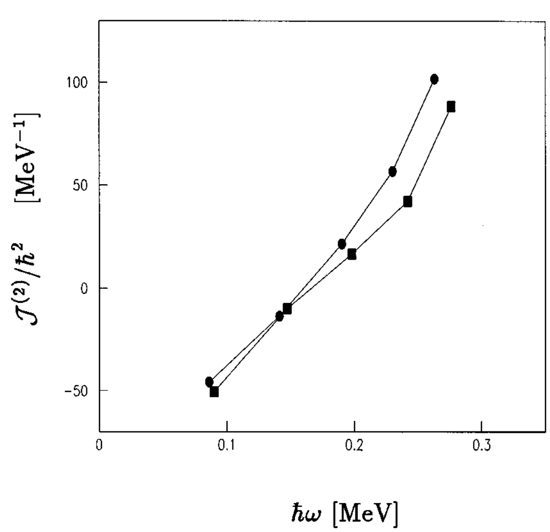

FIG. 3. Dynamic moments of inertia $\mathcal{J}^{(2)}$ for ^{149}Ce. Circles and squares refer to the bands built on the 207 and 191 keV levels, respectively.

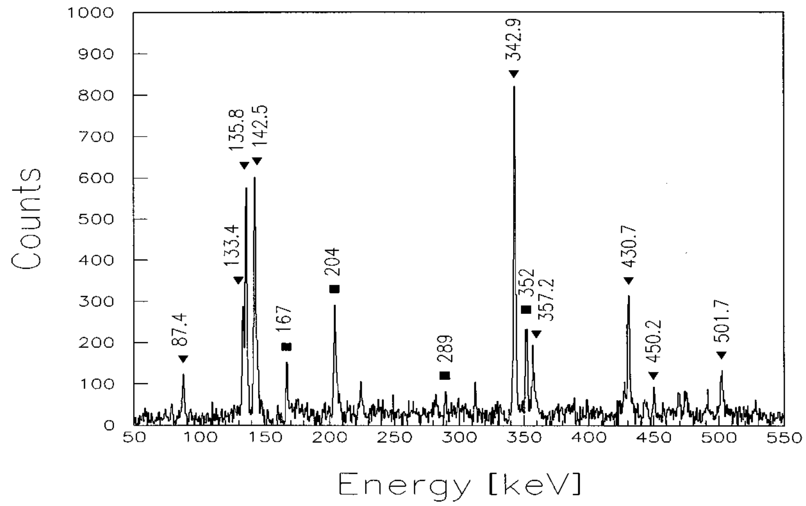

FIG. 4. Spectrum of γ rays in coincidence with gates set simultaneously on the 141 and 241 keV γ lines. Transitions in ^{149}Ce are marked by full triangles and γ rays corresponding to complementary Sr fragments by full rectangles.

states with spins $j, j+2, j+4 \cdots$ are those of the ground state band of the core nucleus. In the present case, the band would be built on the $i_{13/2}$ state at 484 keV. The ratio of the energy spacings of the decoupled band to the ^{146}Ce core varies from 0.95 to 1.07, showing thereby an almost complete decoupling. The two descriptions lead to different deformations of the ^{147}Ce nucleus. Stephens [21] has shown that the rotational constant can be linked to the β deformation using the Grodzins' relation between $B(E2,2^+ \rightarrow 0^+)$ and E_{2^+}:

$$E_{2^+} = 6\hbar^2/(2\mathcal{J}) = 1225/(A^{7/3}\beta^2) \ \text{MeV}.$$

The first description $[\hbar^2/(2\mathcal{J}) = 23.2$ keV$]$ leads to $\beta \simeq 0.28$, whereas the second ($E_{2^+} = 251.2$ keV) indicates $\beta \simeq 0.21$. The latter description is the most likely one since ^{147}Ce lies in a region of weakly deformed nuclei, but also because in the other $N=89$ isotones the wave functions of the $9/2^+$ states include several orbitals of the $i_{13/2}$ shell, showing thereby that these states are not well described as members of $K=1/2$ bands. Certainly more experimental work on this nucleus is needed, especially to search for manifestations of octupole correlations which at the present moment have not been observed.

Recently a band of positive parity states with spin changes $\Delta I = 2$ has been observed in the lighter $N=89$ isotone ^{145}Ba [6,7]. Whereas the spin assignments to the positive parity states by Jones *et al.* [6] support a similar description of this band in all of the $N=89$ isotones in the vicinity of ^{147}Ce, the proposed spins in another published investigation of ^{145}Ba [7] show a major change in the yrast structure of these nuclei.

B. ^{149}Ce nucleus

Several γ transitions which are assigned in the present work to the ^{149}Ce nucleus were already known from previous spontaneous fission studies, but not placed in a level scheme [22,23]. The complexity of the lower part of the level scheme and the relatively weak γ intensity of the low-energy transitions hampered the observation of all the γ decays and also the determination of DCO and P_γ values. A striking feature of the level scheme displayed in Fig. 1 is the presence of two bands, a strongly populated one based on the 207 keV level and a moderately populated one based on the 191 keV level. DCO2 values given in Table I for cascades involving the 241.3, 342.9, and 430.7 keV transitions are in agreement with calculated DCO2 values for cascades of transitions of identical multipolarities. In view of their energies, the transitions may be considered with some confidence as $E2$ transitions. Spins and parities of the ground state and first excited states in ^{149}Ce are unknown. However, a tentative $K=3/2$ assignment is proposed for both bands, since this K value yields the best fits of the rotational energy formula to the excitation energies. These bands could eventually be as-

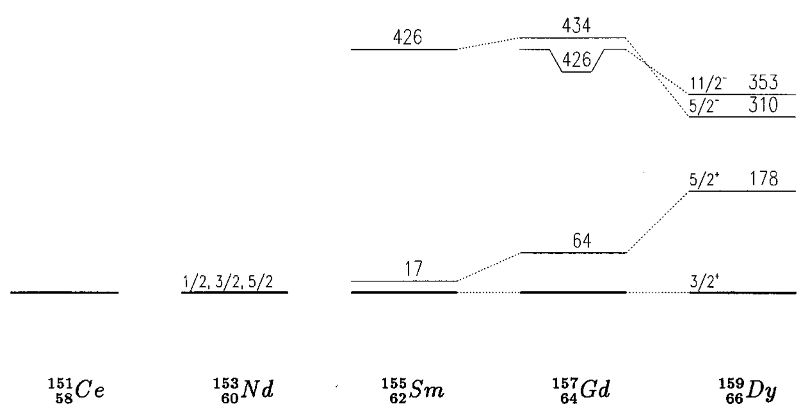

FIG. 5. Systematics for $N=93$ isotones of band heads corresponding to the $[521]3/2^-$, $[642]5/2^+$, $[523]5/2^-$, and $[505]11/2^-$ orbitals [25–27].

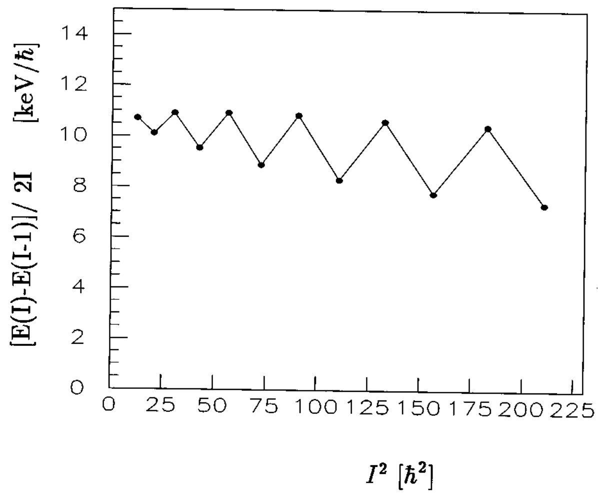

FIG. 6. Signature splitting for the assumed $K=5/2$ band in ^{151}Ce.

TABLE III. γ branching ratios in ^{149,151}Ce.

Nucleus	Level (keV)	E_γ (keV)	γ branching ratio (%)
^{149}Ce	336	129.3	41(2)
		144.9	59(2)
	588	241.2	41(2)
		252.2	59(2)
^{151}Ce	166	90.6	67(3)
		166.1	33(3)
	286	119.8	52(4)
		210.5	48(4)
	410	123.8	30(2)
		243.8	70(2)
	574	163.9	25(4)
		287.7	75(4)
	725	151.3	26(2)
		315.1	74(2)
	931	205.8	26(5)
		357.0	74(5)

sociated with the $[521]3/2^-$ and $[532]3/2^-$ Nilsson orbitals originating from the $1h_{9/2}$ shell and $2f_{7/2}$ shell, respectively. A rather unexpected aspect of the decay scheme is the presence of quite similar transition energies and nearly identical dynamic moment of inertia $\mathcal{J}^{(2)}$ in both bands (see Figs. 1 and 3). This suggests that the deformation of ^{149}Ce is roughly the same in these very similar bands.

Since the completion of this work, a level scheme has been proposed for ^{149}Ce on the basis of the γ-ray spectroscopy of the fragment produced in the spontaneous fission of ^{252}Cf [24]. This level scheme presents three more transitions above 2.4 MeV excitation energy than ours, but the main difference lies in the abscence of the lowest energy transitions and of the transitions connecting the right-hand side and the left-hand side of the decay scheme shown in Fig. 1. The existence of these connections, which are attested by the lines displayed in the double gated monodimensional γ spectrum shown in Fig. 4, is not compatible with the spins and parities proposed by Babu *et al.* [24]. For example, with such spins and parities, the intense transition from the 207 to the 191 keV level, which is revealed by the observation of the 135.8 keV γ line in Fig. 4, would be a low-energy ($\sim$16 keV) $M2$ transition. Such a transition could not compete with the 142.5 keV $E2$ transition in the decay of the 207 keV level. Note that the connecting lines are necessary to explain the γ lines present in the gated γ spectra displayed in Ref. [24].

TABLE II. Fits of the rotational energy formula to the levels in ^{151}Ce for $K=1/2$, 3,2, 5/2, 7/2, and 9/2.

K	$\chi^2(K)/\chi^2(K=5/2)$
1/2	10.0
3/2	2.5
5/2	1.0
7/2	1.4
9/2	2.2

C. ^{151}Ce nucleus

The level scheme of ^{151}Ce, for which no excited states were known up to now, is shown in Fig. 1. The intensity balance indicates that the 75.3 and 90.6 keV transitions are not $E1$ transitions and consequently the observed excited states do not form an alternating parity band. Spin and parity for the ground state of ^{151}Ce are not known, but as shown in Fig. 5 the variations of the low-lying band heads in the odd-A $N=93$ isotones suggest to associate the $[642]5/2^+$ state from the $\nu i_{13/2}$ subshell to the ground state configuration. Levels belonging to such an orbit with a large j and a rather small K value usually display a rather significant signature splitting. This is precisely the case for the present $\Delta I=1$ band as shown in Fig. 6. Furthermore the best fit to the rotational energy formula

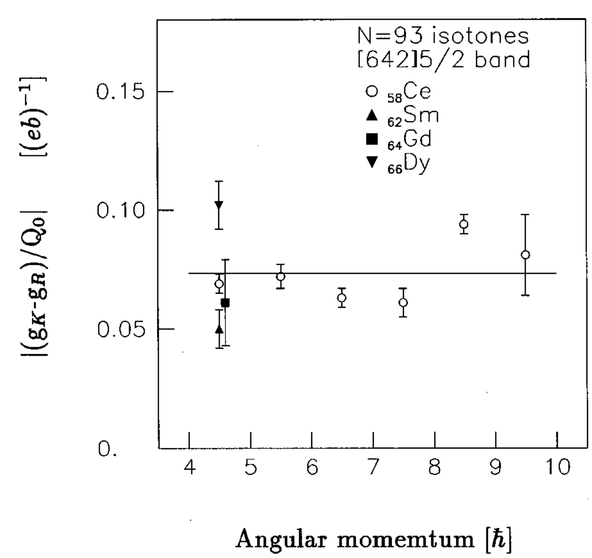

FIG. 7. Values of $|(g_K-g_R)/Q_0|$ ratios as a function of angular momentum for the rotational band in ^{151}Ce and for $[642]5/2^+$ bands in other $N=93$ isotones.

$$E_K(I)=E_K+A[I(I+1)-K^2]+B[I(I+1)-K^2]^2+\begin{cases}(-1)^{I+1/2}(I+1/2)A_1 & \text{for } K=1/2,\\ (-1)^{I+3/2}(I-1/2)(I+1/2)(I+3/2)A_3 & \text{for } K=3/2,\\ \text{etc.,}\end{cases}$$

is obtained for $K=5/2$ (see Table II). This $K=5/2$ assignment agrees with the observed intraband branching ratios (see Table III). Within the rotational model these ratios allow the determination of the magnitude of the parameter $(g_K-g_R)/Q_0$, where g_K and g_R are the intrinsic and rotational gyromagnetic ratios and Q_0 the intrinsic quadrupole moment of the band. As shown in Fig. 7, the mean value 0.07(1) $(e\ \text{b})^{-1}$ is close to the values calculated in known $[642]5/2^+$ bands in other $N=93$ isotones. This agreement may, however, not be considered as a strong support to the assignment of the band to the $[642]5/2^+$ Nilsson orbital since the value calculated for $K=3/2$, 0.13(1) $(e\ \text{b})^{-1}$, shows a similar agreement with the mean values deduced from the properties of ground-state bands associated to the $[521]3/2^-$ Nilsson orbital in several $N=93$ isotones. Calculations lead indeed to $|(g_K-g_R)/Q_0|=0.16(2)$ for ^{155}Sm [25], 0.12(1) for ^{157}Cd [26], and 0.14(1) for ^{159}Dy [27].

IV. SUMMARY

In summary, the level structure of three neutron-rich, odd-A Ce isotopes with masses 147, 149, and 151 have been investigated by observing prompt γ rays emitted in the spontaneous fission of ^{248}Cm with the EUROGAM spectrometer. Bands in the three isotopes are interpreted as either decoupled or strongly coupled bands. The yrast-state sequence in ^{147}Ce is identified up to $I^\pi=(33/2^+)$. The level scheme displays no experimental evidence for the expected reflection asymmetry in this nucleus. It is, however, possible that effects of octupole correlations are present in the yrare structure which could not be observed in the present experiment. Two very similar bands are identified in ^{149}Ce and tentatively assigned to the $[521]3/2^-$ and $[532]3/2^-$ Nilsson orbitals. The partial level scheme for the neutron-rich ^{151}Ce nucleus has been determined for the first time. Systematics of odd-A $N=93$ isotones and features observed in the decay scheme favor a $[642]5/2^+$ configuration assignment to the $\Delta I=1$ ground-state band.

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