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Band structure of ^{149}Ce

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The ^{149}Ce nucleus has been studied via prompt γ-ray spectroscopy using the EUROGAM2 Ge array. The $3/2^-$ ground-state band has been extended to medium spins and the $3/2^+$ band has been connected to low-spin excitations established previously in β^- decay. No evidence for parity doublets in ^{149}Ce was found.

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The strongest octupole correlations in the lanthanides have been reported in barium isotopes, with the maximum effect in ^{144}Ba, at the neutron number $N = 88$ [1,2]. In the neighboring ^{148}Ce, the $B(E1)/B(E2)$ branching ratios are on the same level as in ^{144}Ba [3,4]. One may thus expect octupole correlations in odd-A cerium isotopes, as observed in odd-A barium [5,6]. Recently, the presence of octupole deformation has been tested at the neutron number $N = 93$ [7]. It was found that $B(E1)$ rates in ^{151}Ce can be explained by quasiparticle-rotor calculations by assuming a reflection-symmetric potential and single-particle rates. It might be argued that at $N = 93$ octupole effects are washed out by the strong quadrupole deformation. It is of interest, then, to check the strength of octupole correlations in the $N = 91$ isotones.

In ^{149}Ce two medium-spin bands of opposite parity have been proposed in Ref. [8], while a single band of unspecified parity has been reported in Ref. [9]. These results have been further verified in β^- decay of ^{149}La [10], where the two cascades reported in Ref. [8] have been merged into one band, interpreted as the $3/2^+[651]$ neutron configuration. In Ref. [10], the $3/2^-[521]$ ground-state band has also been proposed, though with three levels, only. Levels in ^{149}Ce were described as excitations in a reflection-symmetric potential [10] but the electric dipole moment, D_0, was found to be similar to that in ^{144}Ba [11]. It is an open question whether this is due octupole vibrations or due to static octupole deformation. In the latter case one should observe parity-doublet bands in ^{149}Ce, similar to that proposed in ^{145}Ba [5,6].

In this work we have studied medium-spin excitations in ^{149}Ce populated in spontaneous fission of ^{248}Cm, in order to firmly establish the band structure of this nucleus. We used the data from a measurement of prompt γ rays performed with the EUROGAM2 array of anti-Compton spectrometers [12], additionally equipped with four low-energy photon spectrometers (LEPS). More details about the experiment and the data analysis can be found in Refs. [13,14].

The level scheme of ^{149}Ce as observed in this work is shown in Fig. 1 and the properties of γ lines seen in this work are listed in Table I.

The 55.1-135.8-keV cascade and the 55.1- and 190.8-keV levels in ^{149}Ce, proposed by Hoellinger *et al.* [9], have been confirmed in Ref. [10], but there were significant changes in other parts of the scheme. The positions of the 87.5-, 133.5-, and 142.6-keV transitions have been changed and two new levels at 133.5 and 142.6 keV have been introduced [10], which were fixed by the 78.4- and 48.4-keV transitions, newly observed in Ref. [10]. In the present work we confirm the scheme proposed in Ref. [10]. The 63.9-keV transition, reported in Ref. [9], was not seen in Ref. [10] but it was assumed to depopulate the 206.6-keV level, proposed in Ref. [9]. This connection between the medium-spin excitations reported by Hoellinger *et al.* [9] and the low-spin scheme established in β decay [10] is firmly confirmed in the present work.

In Fig. 2(a) we show a γ spectrum, measured by LEPS, which is doubly-gated on the 142.6- and 241.4-keV lines. The spectrum confirms that the two gating lines are in a cascade with 64.0- and 140.5-keV transitions as proposed in Ref. [9]. Present in the spectrum are also lines at 48.1, 129.0, and 144.9 keV, which support the 16- and 11-keV decays of the 206.6- and 347.1-keV levels, respectively, proposed in Ref. [9] (but note that the corresponding γ lines are not seen in the spectra due to the detection limits). These coincidences are also seen in Fig. 2(b), which shows a LEPS γ spectrum, doubly-gated on the 241.4- and 343.2-keV lines. In this spectrum one observes all the lines seen in Fig. 2(a) and in addition the 87.5-, 133.5-, 135.8-, and 142.6-keV lines, which confirms the 9.1-keV decay of the 142.6-keV level, as proposed in Ref. [10]. In Figs. 2(a) and 2(b) there is also a weak line at 57.4 keV, which most likely corresponds to a transition from the 190.8- to the 133.5-keV level. In Ref. [10] a line at 57 keV was observed, which was assigned to the 57.7-keV transition in ^{149}Pr, produced in β decay. Such a line of ^{149}Pr should not be seen in our fission data [15].

In Fig. 3 we show a γ spectrum measured by Ge detectors of EUROGAM2, which is doubly-gated on the 241.4- and 343.2-keV lines of ^{149}Ce, proposed in Refs. [8,9]. We confirm the 431.0-, 503.0-, 557.2-, and 596.2-keV transitions in ^{149}Ce, reported previously [8,9]. The 617.5-keV transition reported in Ref. [8] does not appear consistently in coincidence spectra. We also confirm the 144.9-, 241.1-, 252.2-, 357.2-, 450.4-, 527.9-, and 587.0-keV transitions, reported in Refs. [8,9]. The 631.3-keV transition reported in Ref. [8] is not seen in our data. In Fig. 3 there are also lines corresponding to transitions

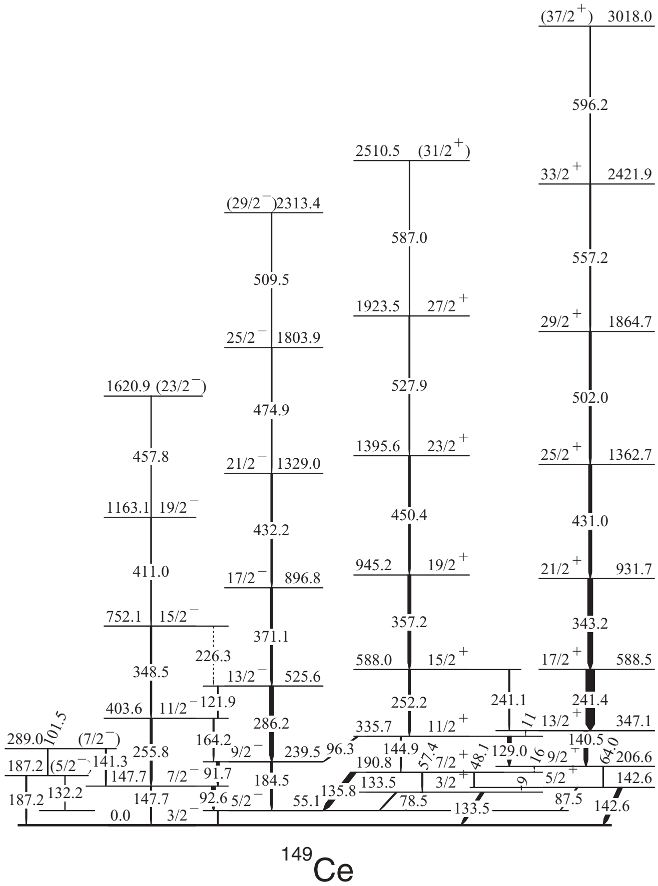

FIG. 1. Level scheme of ^{149}Ce, as observed in this work.

in $^{94-98}$Sr isotopes, which are the partners to ^{149}Ce in the fission of ^{248}Cm [16].

In Ref. [10] two excited levels in the ground-state (g.s.) band have been proposed at 55.1 and 147.7 keV. In Fig. 4(a) we show a γ spectrum from EUROGAM2, doubly-gated on the 814.8-keV line of ^{96}Sr and the 92-keV line of ^{149}Ce, which appears in the 814.8-keV gate as a doublet. One component of the doublet is the 92.6-keV line reported in Ref. [10]. The other component has an energy of 91.7 keV. In the spectrum in Fig. 4(a) the 92-keV doublet appears again, which suggests a 91.7-keV transition above the 147.7-keV level in ^{149}Ce. There is also a new line at 286.2 keV. The double gate set on the 286.2- and 814.8-keV lines is shown in Fig. 4(b). In the spectrum there is the 92-keV doublet and a new line at 184.5 keV. These data allow the introduction of a new level at 239.5 keV in ^{149}Ce.

In Fig. 4(a) one observes a new line at 96.3 keV, which can also be seen in Fig. 3. There are also the 241.4- and 343.2-keV lines from the positive-parity band in ^{149}Ce. Further gating allowed the 96.3-keV line to be placed as a new decay from the 335.7-keV level, further supporting the level scheme shown in Fig. 1.

In Fig. 4 there are other new lines at 164.2, 255.8, 371.1, 432.2, and 474.9 keV. In Fig. 5 we show two more doubly-gated spectra, gated on some of these lines. Together with

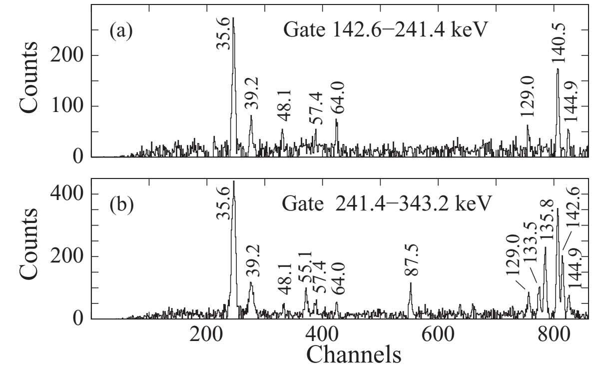

FIG. 2. Spectra of γ lines measured by LEPS detectors, doubly gated on lines of ^{149}Ce. Lines at 34.6 and 39.2 keV correspond to x rays of cerium.

TABLE I. Properties of γ transitions in ^{149}Ce nucleus, populated in spontaneous fission of ^{248}Cm, as observed in the present work. Intensities of γ lines are in relative (rel.) units.[a]

$E_\gamma(\Delta E_\gamma)$ (keV)	$I_\gamma(\Delta I_\gamma)$ (rel.)	$E_\gamma(\Delta E_\gamma)$ (keV)	$I_\gamma(\Delta I_\gamma)$ (rel.)	$E_\gamma(\Delta E_\gamma)$ (keV)	$I_\gamma(\Delta I_\gamma)$ (rel.)
48.1(2)	8(3)	140.5(2)	55(3)	348.5(1)	17(2)
55.1(3)	18(3)	141.3(3)	7(1)	357.2(1)	19(2)
57.4(3)	12(3)	142.6(2)	44(3)	371.1(1)	16(2)
64.0(2)	6(2)	144.9(1)	18(2)	411.0(2)	6(1)
78.5(2)	7(2)	147.7(3)	7(1)	431.0(1)	38(2)
87.5(1)	13(2)	164.2(2)	8(1)	432.2(2)	9(2)
91.7(2)	14(2)	184.5(1)	32(3)	450.4(2)	11(1)
92.6(2)	20(2)	187.2(3)	8(2)	457.8(3)	2(1)
96.3(3)	2.7(4)	226.3(4)	2(1)	474.9(2)	5(1)
101.5(3)	3(1)	241.1(2)	14(2)	502.0(2)	25(2)
121.9(2)	4(1)	241.4(1)	100(4)	509.5(9)	3(1)
129.0(1)	14(2)	252.2(1)	19(2)	527.9(2)	7(1)
132.2(3)	4(2)	255.8(2)	18(2)	557.2(2)	9(1)
133.5(1)	20(2)	286.2(1)	24(2)	587.0(3)	4(1)
135.8(1)	49(3)	343.2(1)	72(4)	596.2(3)	5(1)

[a]The total transition intensities for unseen γ lines of 9, 11, and 16 keV are estimated to be 40(15), 7(2), and 60(20), respectively.

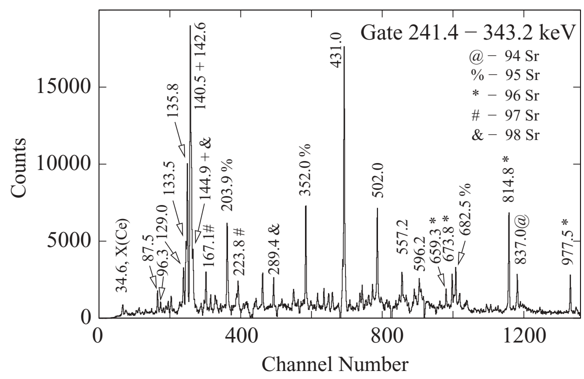

FIG. 3. γ spectrum measured with EUROGAM2, doubly gated on 241.4- and 343.2-keV lines of ^{149}Ce.

further gates, these data allowed us to add to the ground-state band new levels at 403.6, 525.6, 752.1, 896.8, 1163.1, 1329,0, 1620.9, 1803.9, and 2313.4 keV. We note that in Fig. 5(a) more than one complementary Sr isotope is seen and the intensity ratio of the 814.8- and 837.0-keV lines of ^{96}Sr and ^{94}Sr, respectively, is the same as in Fig. 3. This indicates that the 286.2- and 371.1-keV lines belong to ^{149}Ce.

In Fig. 4(a) there is a line at 141.2 keV. It is likely that it corresponds to the decay of the 289.0-keV level, reported in Ref. [10]. In our data we also observe a line at 101.5 keV, which most likely corresponds to a decay of this level to the 187.2-keV level, reported in Ref. [10], because it is seen in a spectrum doubly-gated on the 814.8- and 187.2-keV lines. The population of the 187.2- and 289.0-keV levels in fission suggests spins of 5/2 and 7/2, respectively, while branchings favor negative parity for these levels.

Parity assignments in Ref. [10] were made based on estimates of internal conversion coefficients for the 55.1-, 78.4-, 87.5-, and 92.6-keV transitions. The firm conclusion was that the band based on the 133.5-keV level has opposite parity to that of the ground state. Spin and parity $3/2^-$ for the ground state in ^{149}Ce has been tentatively proposed in Ref. [10], based on the similarity between the $5/2^-$ and $7/2^-$ excitation energies in the g.s. band of ^{149}Ce and in the heavier $N = 91$ isotones. With the g.s. band in ^{149}Ce extended in

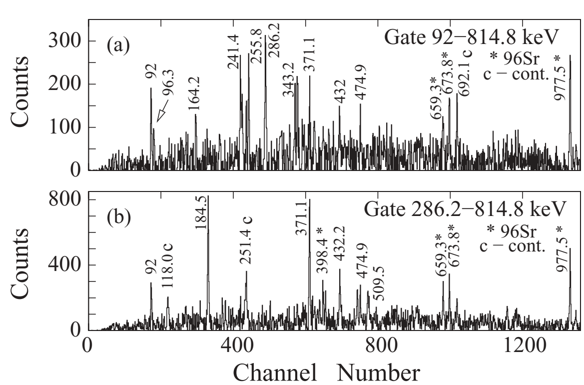

FIG. 4. γ spectra measured by Ge detectors of EUROGAM2, doubly gated on the 814.8-keV line of ^{96}Sr and (a) the 92-keV doublet and (b) the 286.2-keV line of ^{149}Ce. Major unknown contamination lines have been labeled with "c."

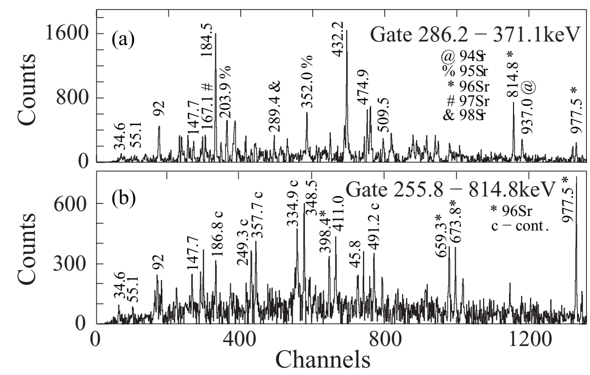

FIG. 5. γ spectra measured by Ge detectors of EUROGAM2, doubly gated on lines of ^{149}Ce. Major unknown contamination lines have been labeled with "c."

this work we can verify the properties of this band more quantitatively.

In Fig. 6 we show plots of aligned angular momentum I_x in the two bands of ^{149}Ce, relative to the alignment in the ground-state band of ^{148}Ce. The summed alignment for both signatures of the $3/2^+$, decoupled band is $9.6\hbar$, which can only be explained as being due to a $K = 3/2$ orbital originating from the $\nu i_{13/2}$ intruder shell. The alignment in the favored branch is higher by $1\hbar$, as expected. The summed alignment in the negative-parity ground-state band is $5.5\hbar$. With $K = 3/2$ this can only be explained as being due to the $\nu h_{9/2}$ shell. The favored branch corresponds to the signature $\alpha = +1/2$, which again supports the $\nu h_{9/2}$ shell as the dominating structure.

In Fig. 7 we show the staggering in the $3/2^-$ and $3/2^+$ bands of ^{149}Ce and compare it to staggering in the $3/2^-$ and $3/2^+$ bands of ^{153}Sm and ^{155}Gd, where these bands have been identified with high confidence. The staggering in the positive-parity band of ^{149}Ce is nearly identical to the staggering in the $3/2^+[651]$ band of ^{153}Sm and very similar to the staggering in the $3/2^+[651]$ band of ^{155}Gd (since the band in ^{155}Gd most likely contains an admixture of the $3/2^+[402]$ configuration [18], causing some deviation at low spins). The staggering in the ground-state band in ^{149}Ce is very similar

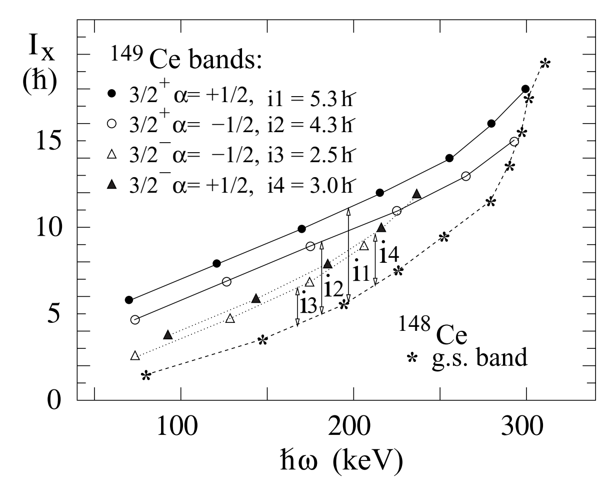

FIG. 6. Alignments in bands of ^{149}Ce relative to the alignment in the ground-state band of ^{148}Ce [4].

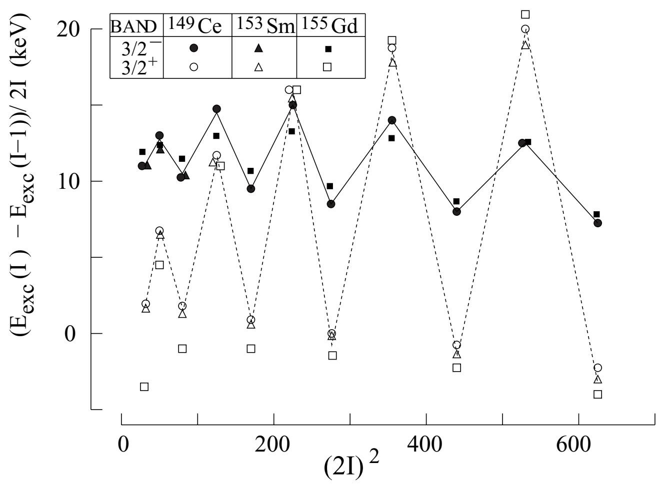

FIG. 7. Staggering in bands of ^{149}Ce and other $N = 91$ isotones. The data for ^{153}Sm and ^{155}Gd are from Refs. [17,18].

to the staggering in the $3/2^-[532]$ band of ^{153}Sm (which exhibits a limited range of spins, unfortunately) and is similar (at medium spins) to the staggering in the $3/2^-[521]$ band of ^{155}Gd.

The alignment and the staggering observed in the bands of ^{149}Ce strongly support spin and parity assignments in ^{149}Ce as shown in Fig. 1. Spin assignments are also consistent with the common observation that spins of excited states populated in spontaneous fission increase with increasing excitation energy [19].

The two bands in ^{149}Ce can be explained as being due to the dominating $3/2^+[651]$ (the decoupled band) and $3/2^-[532]$ (the g.s. band) neutron configurations. The $3/2^+[651]$ has been also proposed in Ref. [10], based on detailed calculations, but for the ground state the $3/2^-[521]$ configuration, originating from the $\nu f_{7/2}$ shell, has been proposed in Ref. [10]. The $3/2^-[521]$ configuration of the ground state was also reported in another calculation [20]. This is at variance with the present analysis of the alignment and staggering of the ground-state band. We note that after a slight variation of the Fermi-level parameter, the $3/2^-[532]$ configuration is also consistent with the calculations of Ref. [10]. While further attention is needed to explain the nature of the $3/2^-$ ground state, the band structure of ^{149}Ce seems to be explained, given that the 187.2- and 289.0-keV levels are good candidates for the $5/2^-[512]$ band. This band completes the set of neutron configurations expected in the vicinity of the Fermi level in ^{149}Ce.

Finally, we look at the octupole collectivity in ^{149}Ce. In this work we have observed two new $B(E1)/B(E2)$ branching ratios, for the 190.8- and 335.7-keV levels, which yield branchings of 0.0083(19) and 0.00065(16), respectively, in units of 10^{-6} fm^{-2}. Taking $Q_0 = 475\ e\,\text{fm}^2$ as the quadrupole moment, as estimated for the $3/2^+[651]$ band in ^{149}Ce in Ref. [11], one obtains dipole moments D_0 of 0.020(3) and 0.023(4) e fm for the $7/2^+$ and $11/2^+$ levels, respectively. These values are similar to the $D_0 = 0.034(7)\ e$ fm moment deduced for the $3/2^+$ level at 133.5 keV from the half-life of the 133.5-keV level [11]. Together, these results indicate that octupole correlations in ^{149}Ce are on a similar level as in barium isotopes. On the other hand, there is no indication of parity doublets in ^{149}Ce, while such are expected in an odd-A nucleus with octupole deformation. Therefore, the conclusion is that the octupole collectivity in ^{149}Ce is most likely of a vibrational nature, as already suggested in Ref. [11]. It would be interesting to check whether certain excited levels below 0.5 MeV in ^{149}Ce, observed in β decay [10], which still do not have spin and parity assignments, could belong to such hypothetical parity-doublet bands. Further studies are needed to answer this question.

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