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Phys. Rev. C **86**, 067302 — Published 4 December 2012

DOI: 10.1103/PhysRevC.86.067302

Identification of a new side-band and proposed octupole correlations in very neutron-rich ^{152}Ce

H. J. Li(李红洁),[1] S. J. Zhu(朱胜江),[1,2,*] J. H. Hamilton,[2] A. V. Ramayya,[2] J. K. Hwang,[2] Z. G. Xiao(肖志刚),[1] M. Sakhaee,[1] J. Y. Guo(郭建友),[3] S. W. Chen(陈寿万),[3] N. T. Brewer,[2] S. H. Liu,[2] K. Li,[2] E. Y. Yeoh(杨韵颐),[1] Z. Zhang(张钊),[1] Y. X. Luo,[2,4] J. O. Rasmussen,[4] I. Y. Lee,[4] G. Ter-Akopian,[5] A. Daniel,[5] Yu. Ts. Oganessian,[5] and W. C. Ma[6]

[1]*Department of Physics, Tsinghua University, Beijing 100084, People's Republic of China*
[2]*Department of Physics, Vanderbilt University, Nashville, Tennessee 37235 USA*
[3]*Department of Physics, Anhui University, Hefei 241000, People's Republic of China*
[4]*Lawrence Berkeley National Laboratory, Berkeley, California 94720 USA*
[5]*Flerov Laboratory for Nuclear Reactions, JINR, Dubna, Russia*
[6]*Department of Physics and Astronomy, Mississippi State University, Mississippi State, Mississippi 39762, USA*

High spin levels of the very neutron-rich ^{152}Ce have been investigated by measuring the prompt γ-rays in the spontaneous fission of ^{252}Cf. The yrast band is confirmed and a new side-band has been identified. The side-band is tentatively assigned with negative parity and an octupole band structure with $s = +1$ in ^{152}Ce has been proposed. Based on the theoretical calculations and systematic comparisons, the characteristics of the octupole correlations have been discussed.

PACS numbers: 21.10.Re, 23.20.Lv, 27.60.+j, 25.85.Ca

Theoretical calculations in the deformed shell model indicate that there exists an octupole deformation island around the $Z = 56$ and $N = 88$ neutron-rich nuclear region [1, 2]. Following the development of large detector arrays [3], octupole-deformed bands and octupole correlations have been observed in many nuclei in this region produced in spontaneous fission of ^{252}Cf and ^{248}Cm [3–9]. For the $Z = 58$ neutron-rich Ce isotopes, the octupole correlations have been identified in ^{144}Ce ($N = 86$) [3, 5, 7], ^{146}Ce ($N = 88$) [3, 7–9] and ^{148}Ce ($N = 90$) [6]. In a recent report, octupole correlations have been observed in $N = 92$, ^{150}Ce isotope by our collaboration [10]. However, until now, no octupole correlations have been reported in $N \geq 94$ isotones in this region.

The search for octupole correlations in very neuron-rich $N = 94$ ^{152}Ce is interesting to determine the range of the octupole deformation island and to understand the systematic characteristics of the octupole correlations in this region. In our previous publication [11], the level scheme of ^{152}Ce was first studied by using the early Gammasphere detector array with only 36 Ge detectors. By measuring the prompt γ-rays from a spontaneous fission source of ^{252}Cf, the ground band was constructed. Here we report the new results of the high spin states and side band in ^{152}Ce based on the the new fission data with high statistics.

Even in the fission experiments, it is very difficult to observe the new bands in very neutron-rich nuclei like ^{152}Ce, because their fission yield is very low. The experiment was carried out at the Lawrence Berkeley National Laboratory with the Gammasphere detector array consisting of 102 Compton-suppressed Ge detectors. A ^{252}Cf source was sandwiched between two Fe foils with the thickness of 10 mg/cm^2, which was placed in the center of the array of the detectors. Approximately 5.7 $\times$ 10^{11} triple- and higher-fold coincidence events were recorded. The coincidence data were analyzed with the RADWARE software package [12].

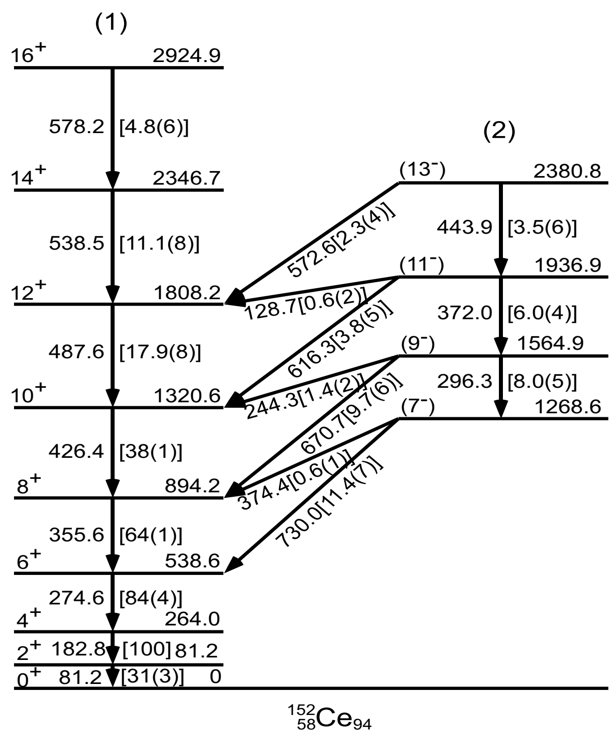

FIG. 1: The level scheme of ^{152}Ce in the present work. The relative transition intensities and errors are given in square brackets. The errors on the transition energies are about 0.5 keV.

*Electronic address: zhushj@mail.tsinghua.edu.cn

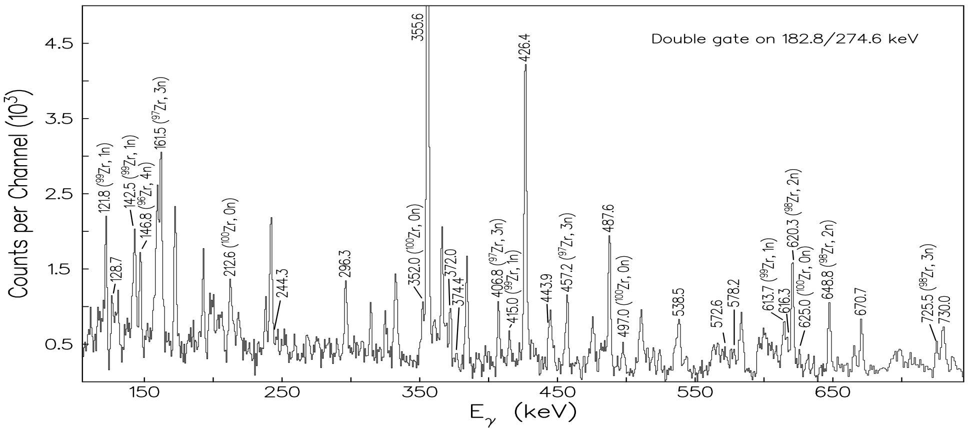

FIG. 2: Portion of γ-ray spectrum obtained by double gating on 182.8 and 274.6 keV γ-transitions in ^{152}Ce.

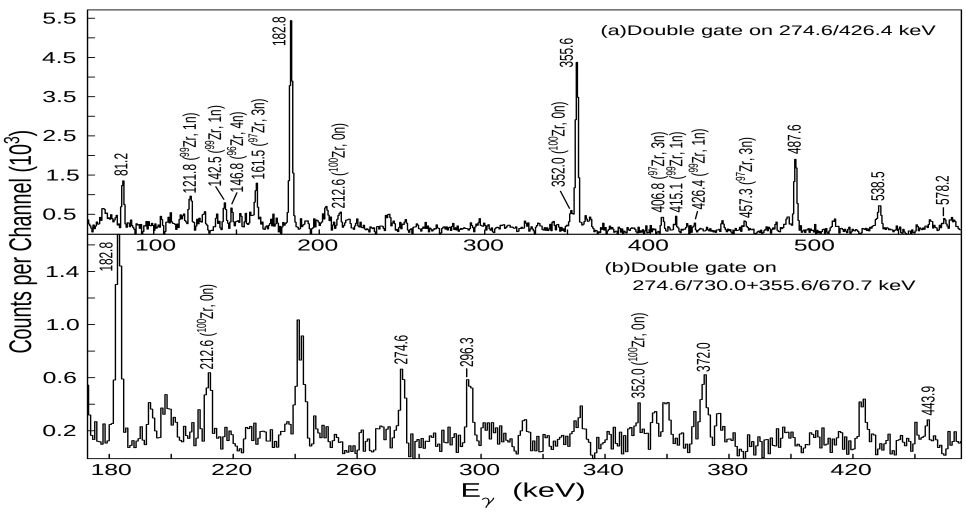

FIG. 3: Portion of the γ-ray spectra obtained by (a) double gating on 274.6 and 426.4 keV γ-transitions, and (b) summing the coincidence spectra obtained by double gating on 274.6 and 730.0 keV, and 355.6 and 670.7 keV γ-transitions in ^{152}Ce.

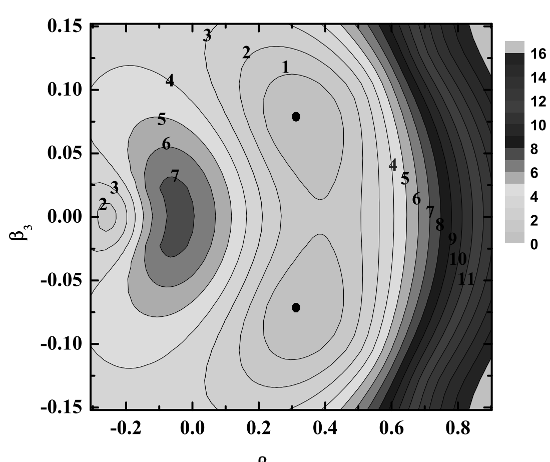

FIG. 4: The contour plots of total energies for ^{152}Ce in (β_2, β_3) plane obtained from the reflection-asymmetric relativistic mean-field calculation with NL1.The energy separation between contour lines is 1.0 MeV.

The level scheme of ^{152}Ce deduced from the present work is shown in Fig. 1. Two bands are labeled on top of the bands with numbers (1) and (2). The yrast band (1) has been reported in Ref. [11], and we confirmed this band in the present work. Band (2) is newly identified in the present work. Seven new linking transitions between bands (1) and (2) are also observed. As examples, Figs. 2 and 3 show some double-gated γ-ray spectra in ^{152}Ce. In Fig. 2, by double gating on 182.8 and 274.6 keV $\gamma-$transitions, all the transitions above the 538.6 keV level in Fig. 1 can be seen. In Fig. 3(a), the coincidence spectrum is generated by double gating on 274.6 and 426.4 keV $\gamma-$transitions in band (1), one can see the γ-peaks at 81.2, 182.8, 355.6, 487.6, 538.5 and 578.2 keV in band (1). In Fig. 3 (b), the coincidence spectrum is generated by summing the coincidence spectra obtained by double gating on 274.6 and 730.0 keV, and 355.6 and 670.7 keV γ-transitions, one can see the 182.8 and 274.6 keV γ-peaks in band (1) as well as the 296.3, 372.0 and 443.9 keV γ-peaks in band (2). In these spectra, some

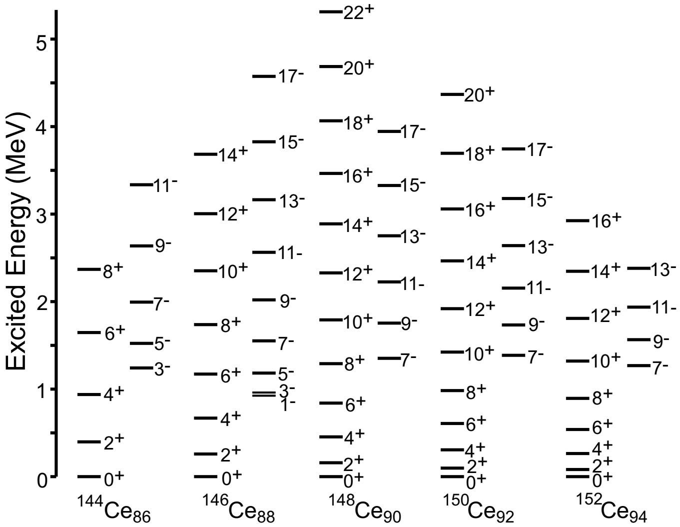

FIG. 5: The systematic comparisons for the levels of s=+1 octupole bands in ^{144}Ce [7], ^{146}Ce [9], ^{148}Ce [6], ^{150}Ce [10] and ^{152}Ce (present work).

stronger γ-peaks in partner Zr isotopes can be seen. The unmarked peaks should belong to the background peaks from other fission products.

Based on the transition pattern between bands (1) and (2), the spin and parity for the 1268.6 keV level could be assumed as 6^+, 7^+, 7^- or 8^+. By using the formulas in Ref. [13], the ratios for reduced transition probabilities between 374.4 and 730.0 keV transitions calculated from measured branching ratios are $3.79 \times (10^{-2} \cdot e^2 \cdot fm^4 \cdot \mu_N^{-2})$ for 6^+, 0.37 for 7^+ and 7^-, and 13.82 $(e^{-2} \cdot fm^{-4} \cdot \mu_N^2)$ for 8^+, respectively. For 6^+ or 8^+ assignment, the $B(E2)$ value is much smaller than $B(M1)$ value, which is very unlikely in a deformed nucleus. As for 7^- assignment, the calculated theoretical $B(E1)$ ratio is 1.14 by using the equation (66) in Ref. [4], which is close to experimental value. Therefore, the 1268.6 keV level is tentatively assigned as 7^-. However, the 7^+ assignment can not be excluded explicitly. Further considering the systematic comparisons with the neighboring ^{144,146,148,150}Ce isotopes [6, 7, 9, 10], we assigned the band (2) in ^{152}Ce as a negative-parity band. Thus, in ^{152}Ce, the set of positive- and negative-parity bands (1) and (2) with $\Delta I = 2$ transitions in each band and with linking $E1$ transitions between the two bands forms an octupole band structure with a simplex quantum number $s = +1$, as observed in the neighboring even-even ^{144,146,148,150}Ce isotopes. Thus octupole correlations are proposed in ^{152}Ce.

In order to understand the structural characteristics of ^{152}Ce, we have carried out theoretical calculations in a reflection asymmetric relativistic mean-field (RAS-RMF) approach, for which more detail can be seen in Refs. [14, 15]. The quadrupole deformation parameter β_2 and the octupole deformation parameter β_3 of ^{152}Ce can be obtained from the constrained RAS-RMF calculation with parameter set NL1 [16]. For axially symmetric reflection-asymmetric system, the RMF equation is solved by expanding the Dirac spinor in terms of the eigenfunctions of the two-center harmonic-oscillator (TCHO) potential. In this calculation, the TCHO basis with 18 major shells for both fermions and bosons is used. The pairing correlation is treated by the BCS approximation with a constant pairing gap $\delta = 11.2/\sqrt{A}$ MeV. The calculated matter density distribution suggests that ^{152}Ce has a small octupole deformation in its ground state. The calculated contour of total energies for ^{152}Ce is shown in Fig. 4. One can see that the theoretical value of global minimum of energy contour is located at $(\beta_2, \beta_3) \sim (0.31, \pm 0.08)$ which indicate that ^{152}Ce indeed has a small octupole deformation.

The systematic comparisons for the levels of $s = +1$ octupole bands in ^{144,146,148,150}Ce and ^{152}Ce are shown in Fig. 5. One can see that they exhibit very similar pattern. This shows that the assigned octupole band structure in ^{152}Ce agrees with the systematics. On the other hand, the level energies in the both positive- and negative-parity bands with the same spin smoothly decrease as the neutron number increases. This is caused by an increase in quadrupole deformation (β_2) when the neutron number increases in these Ce isotopes, as discussed in Ref. [10].

In an octupole band structure, the $B(E1)/B(E2)$ branching ratios can be calculated by:

$$\frac{B(E1)}{B(E2)} = 0.771 \frac{I_\gamma(E1)}{I_\gamma(E2)} \frac{E_\gamma(E2)^5}{E_\gamma(E1)^3} (10^{-6} \cdot fm^{-2}) \quad (1)$$

where E_γ is the energy of the transition (in MeV), and I_γ is the corresponding intensity. The calculated values for ^{152}Ce from the present work are shown in Table I. The average $B(E1)/B(E2)$ value for $s = +1$ octupole structure in ^{152}Ce is $0.023 \times (10^{-6} \cdot fm^{-2})$, while the average values are 6.12 in ^{144}Ce [7], 1.70 in ^{146}Ce [9], 0.82 in ^{148}Ce [6] and $0.04 \times (10^{-6} \cdot fm^{-2})$ in ^{150}Ce [10]. The decreasing trend of $B(E1)/B(E2)$ with the neutron number indicates that the octupole correlations become weaker in Ce isotopes since $B(E1)$ becomes smaller as the neutron number is increasingly far from the $N = 88$ octupole quantum number. In addition, it may be caused by an increase in $B(E2)$ values, which are the result of enhanced quadrupole deformation. The 2^+ level energies, which correlate with the quadrupole deformation, are 397.2 keV for ^{144}Ce [7], 258.6 keV for ^{146}Ce [9], 158.8 keV for ^{148}Ce [6], 97.4 keV for ^{150}Ce [10] and 81.2 keV for ^{152}Ce in the present work.

The systematic comparisons for the kinematic moments of inertia (J_1) against the rotation frequency $\hbar\omega$ for the $s = +1$ octupole structure in ^{144,146,148,150,152}Ce are shown in Fig. 6. In these Ce isotopes, the values of J_1 in both the positive- and negative-parity bands increase as the neutron number. This is also related to the quadrupole deformation variation. For each Ce isotope, J_1 varies smoothly with increasing spin. The J_1 values in ^{152}Ce have similar pattern to that of octupole bands

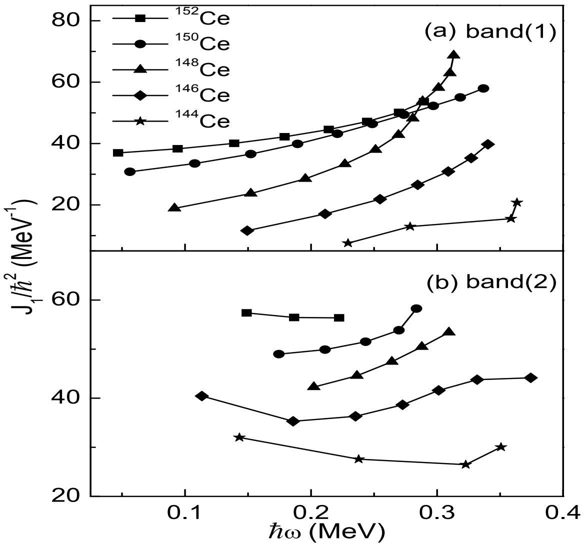

FIG. 6: Plots of the moments of inertia of (a) the positive-parity bands and (b) the negative-parity bands for the levels of s = + 1 octupole bands in ^{144}Ce [7], ^{146}Ce [9], ^{148}Ce [6], ^{150}Ce [10] and ^{152}Ce (present work).

TABLE I: Calculated $B(E1)/B(E2)$ branching ratios in ^{152}Ce.

E_γ (keV)	$I_i{}^\pi \rightarrow I_f{}^\pi$	I_γ	$\frac{B(E1)}{B(E2)}$ ($10^{-6}\cdot fm^{-2}$)
670.7	$(9^-) \rightarrow 8^+$	9.7(6)	0.0071(6)
296.3	$(9^-) \rightarrow (7^-)$	8.0(5)	
616.3	$(11^-) \rightarrow 10^+$	3.8(5)	0.015(2)
372.0	$(11^-) \rightarrow (9^-)$	6.0(4)	
572.6	$(13^-) \rightarrow 12^+$	2.3(4)	0.046(11)
443.9	$(13^-) \rightarrow (11^-)$	3.5(6)	

observed in ^{144,146,148,150}Ce, and agree with the systematics.

The energy displacement δE between the positive- and the negative-parity bands in some of the Ce isotopes is displayed in Fig. 7. The δE can be obtained by using the equation given below [10]:

$$\delta E(I) = E(I^-) - \frac{(I+1)E(I-1)^+ + IE(I+1)^+}{2I+1} \quad (2)$$

The δE should be close to zero in the limit of stable octupole deformation. As seen in Fig. 7, only in ^{144}Ce and ^{146}Ce the $\delta E(I)$ values approach the stable point at I $\sim$ 7 $\hbar$ and 9 $\hbar$, respectively, while the $\delta E(I)$ values in ^{148,150,152}Ce do not yet reach the stable point over the observed spins. This result shows that the octupole correlations become more unstable as the neutron number increases in the neutron-rich Ce isotopes. We notice that at the same spin value, the $\delta E(I)$ value increases with the neutron number up to ^{150}Ce, and then it reduces in ^{152}Ce. The reason is not clear.

Above analysis gives evidences for the octupole correlations in ^{152}Ce. However, it shows that the observed octupole correlations in ^{152}Ce are weakest in the known Ce isotopes. Note, since all the negative-parity levels in ^{152}Ce are higher in energy than the positive-parity ones with $\Delta I = -1$, no transitions can occur from the positive-parity band to the negative-parity one. This may indicate that the identified negative-parity band (2) in ^{152}Ce has more octupole vibrational character, similar with that in ^{150}Ce [10].

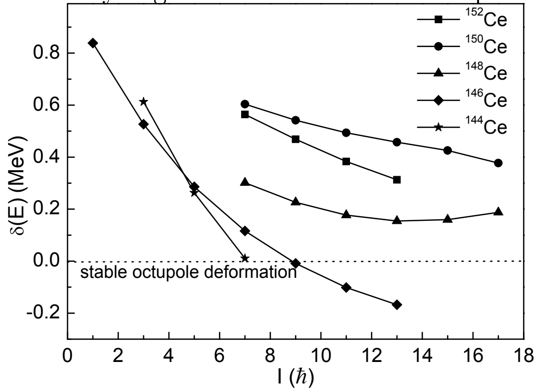

FIG. 7: The systematic comparison for $\delta E(I)$ versus spin I in ^{144}Ce [7], ^{146}Ce [9], ^{148}Ce [6], ^{150}Ce [10] and ^{152}Ce (present work).

In summary, the high-spin structure of the very neutron-rich ^{152}Ce has been studied. The yrast band has been confirmed and a negative-parity band has been observed for the first time. An octupole band structure with $s = +1$ has been proposed. The theoretical calculations using reflection-asymmetric relativistic mean-field shows that ^{152}Ce has small octupole deformation parameter. Observed $B(E1)/B(E2)$ branching ratios indicate that the octupole correlations in ^{152}Ce are much weaker than that in the lighter Ce isotopes. Other characteristics of octupole correlations in neutron-rich Ce isotopes are systematically discussed. The result also shows that the negative-parity band in ^{152}Ce may have an octupole vibrational character. This is a first observation of the octupole correlations in $N = 94$ isotones in $Z = 56$, $N = 88$ octupole deformed island, and the range of this island is expanded.

The work at Tsinghua University was supported by the National Natural Science Foundation of China under Grants No.11175095, 10975082, 10975083, the Special Program of Higher Education Science Foundation under Grant No. 2010000211007. The work at Vanderbilt University, Lawrence Berkeley National Laboratory, Mississippi state university, was supported, respectively, by U. S. Department of Energy under Grant and Contract No. DE-FG05-88ER40407, DE-AC03-76SF00098, and DE-FG02-95ER40939.

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