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

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High spin levels of the very neutron-rich $^{152}$Ce have been investigated by measuring the prompt $\gamma$-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.

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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 neutron-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 $\gamma$-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 sideband 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 × 10$^{11}$ triple- and higher-fold coincidence events were recorded. The coincidence data were analyzed with the RADWARE software package [12].
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 $\gamma$-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 $\gamma$-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 $\gamma$-transitions in $^{152}$Ce.
assigned as 7. The equation (66) in Ref. [4], which is close to experimental comparisons with the neighboring B values in (2), the spin and parity for the 1268.6 keV level could be excluded explicitly. Further considering the systematic comparisons for the negative-parity band. Thus, in 152Ce as a negative-parity band. Thus, in 152Ce, 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 144,146,148,150Ce isotopes. Thus octupole correlations are proposed in 152Ce.

In order to understand the structural characteristics of 152Ce, 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 $\beta_2$ and the octupole deformation parameter $\beta_3$ of 152Ce 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 152Ce has a small octupole deformation in its ground state. The calculated contour of total energies for 152Ce 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 152Ce indeed has a small octupole deformation.

The systematic comparisons for the levels of $s = +1$ octupole bands in 144,146,148,150Ce and 152Ce are shown in Fig. 5. One can see that they exhibit very similar pattern. This shows that the assigned octupole band structure in 152Ce 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 $(\beta_2)$ 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:

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

where $E_{\gamma}$ is the energy of the transition (in MeV), and $I_{\gamma}$ is the corresponding intensity. The calculated values for 152Ce from the present work are shown in Table I. The average $B(E1)/B(E2)$ value for $s = +1$ octupole structure in 152Ce is 0.023$\times(10^{-6}, fm^{-2})$, while the average values are 6.12 in 144Ce [7], 1.70 in 146Ce [9], 0.82 in 148Ce [6] and 0.04$\times(10^{-6}, fm^{-2})$ in 150Ce [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 144Ce [7], 258.6 keV for 146Ce [9], 158.8 keV for 148Ce [6], 97.4 keV for 150Ce [10] and 81.2 keV for 152Ce 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 144,146,148,150,152Ce 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 152Ce have similar pattern to that of octupole bands.
the neutron number up to 152 at the same spin value, the relations become more unstable as the neutron number observed spins. This result shows that the octupole correlations in 152Ce. However, it shows that the observed octupole correlations in 152Ce are weakest in the known Ce isotopes. Note, since all the negative-parity levels in 152Ce are higher in energy than the positive-parity ones with ∆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 152Ce has more octupole vibrational character, similar with that in 150Ce [10].

In summary, the high-spin structure of the very neutron-rich 152Ce 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 parameter. Observed B(E1)/B(E2) branching ratios indicate that the octupole correlations in 152Ce 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 152Ce 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.

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Above analysis gives evidences for the octupole correlations in 152Ce. However, it shows that the observed octupole correlations in 152Ce are weakest in the known Ce isotopes. Note, since all the negative-parity levels in 152Ce are higher in energy than the positive-parity ones with ∆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 152Ce has more octupole vibrational character, similar with that in 150Ce [10].

In summary, the high-spin structure of the very neutron-rich 152Ce 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 parameter. Observed B(E1)/B(E2) branching ratios indicate that the octupole correlations in 152Ce 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 152Ce 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.

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### TABLE I: Calculated B(E1)/B(E2) branching ratios in 152Ce.

<table>
<thead>
<tr>
<th>Eγ (keV)</th>
<th>Iγ −→ Iγ′</th>
<th>B(E1)/B(E2) (10−6 fm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>670.7</td>
<td>(9−) → 8+</td>
<td>9.7(6)</td>
</tr>
<tr>
<td>296.3</td>
<td>(9−) → (7−)</td>
<td>8.0(5)</td>
</tr>
<tr>
<td>616.3</td>
<td>(11−) → 10+</td>
<td>3.8(5)</td>
</tr>
<tr>
<td>372.0</td>
<td>(11−) → (9−)</td>
<td>6.0(4)</td>
</tr>
<tr>
<td>572.6</td>
<td>(13−) → 12+</td>
<td>2.3(4)</td>
</tr>
<tr>
<td>443.9</td>
<td>(13−) → (11−)</td>
<td>3.5(6)</td>
</tr>
</tbody>
</table>

observed in 144, 146, 148, 150Ce, 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]:

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

(2)

The δE should be close to zero in the limit of stable octupole deformation. As seen in Fig. 7, only in 144Ce and 146Ce the δE(I) values approach the stable point at I ∼ 7 h and 9 h, respectively, while the δE(I) values in 148, 150, 152Ce 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 δE(I) value increases with the neutron number up to 150Ce, and then it reduces in 152Ce. The reason is not clear.