RESEARCH ON OCTUPOLE CORRELATIONS IN NEUTRON-RICH EVEN-EVEN Ce ISOTOPES


1Department of Physics, Tsinghua University, Beijing 100084, P. R. of China
2Department of Physics, Vanderbilt University, Nashville, TN 37235 USA
3Lawrence Berkeley National Laboratory, Berkeley, CA 94720 USA

E-mail: zhushj@mail.tsinghua.edu.cn

The progress in experimental research on the octupole correlations in neutron-rich even-even Ce isotopes by our collaboration has been reviewed. The experiments were carried out by measuring the prompt γ-rays in the spontaneous fission of $^{252}$Cf. The octupole correlations with $s = +1$ band structure in $^{144,146,148,152}$Ce were identified or expanded. The $s = \pm 1$ double octupole band structure in $^{148}$Ce was discovered. Systematic characteristics of the octupole correlations in these even-even Ce isotopes have been discussed.

Keywords: nuclear structure; octupole correlations; neutron-rich Ce isotopes

1. Introduction

In the study of nuclear structure, octupole deformation is a very interesting topic. A nucleus with octupole deformation has reflection asymmetric shape. Theoretical calculations in the deformed shell model predict the existence of an island of octupole deformed nuclei with proton numbers near 56 and neutron numbers near 88. The octupole deformed island is located at the neutron-rich Ba-La-Ce region. In such nuclei, the level patterns are similar to the rotational bands observed in reflection-asymmetric molecules including two bands of parity doublets characterized with simplex quantum numbers $s = \pm 1$ in even-$A$ nuclei and $s = \pm i$ in odd-$A$ ones. The positive- and negative-parity rotational bands are intertwined by strong $E1$ transitions. For even-even nuclei, the spins and parities ($I^\pi$’s) of the levels in an octupole deformed structure are: $I^\pi = 0^+, 1^-, 2^+, 3^-$, $\cdots$ for the $s = +1$ band structure, and $I^\pi = 0^-, 1^+, 2^-, 3^+$, $\cdots$ for the $s = -1$ one. For odd-$A$ nuclei, $I^\pi = 1/2^+, 3/2^-, 5/2^+, 7/2^-$, $\cdots$ for the $s =$
Fig. 1. Level schemes of $s = +1$ octupole band structure in $^{144,146}$Ce

+ i band structure, and $I^\pi = 1/2^-, 3/2^+, 5/2^-, 7/2^+, \ldots$ for the $s = -i$ one.

However, in the experimental study, it is difficult to investigate the high spin states in these nuclei, as they are located in neutron-rich region. An efficient method is to measure the prompt $\gamma$-rays from fission of the heavy nuclei. Following the development of large detector arrays, much progress has been made in investigating the high spin states in these neutron-rich nuclei. In previous experimental studies, octupole deformed bands and strong octupole correlations have been observed in many nuclei in this region, such as, in $Z = 56$ $^{140-146}$Ba,5-11 and $Z = 57$ $^{143,145,147}$La.12-14 Generally, most of the observed octupole correlations in a nucleus belong to a single $s$-band structure. It is difficult to identify the double $s(s = \pm 1$ or $s = \pm i)$-band structure in a nucleus. In earlier reports, it was only observed in odd-A $^{143,145}$Ba10 and $^{145}$La14 by our collaboration in this region.
For the $Z = 58$ neutron-rich Ce isotopes, only in an earlier publication, the octupole correlations were reported in an even-even $^{146}$Ce. In this proceeding paper, we give a review of the observed octupole correlations in $^{144,146,148,150,152}$Ce by our collaboration.
2. Experimental Methods

The level structures of neutron-rich Ce isotopes in the present work have been studied by measuring the prompt $\gamma$-rays emitted from the fragments produced in the spontaneous fission of $^{252}$Cf. The experiments were carried out at the Lawrence Berkeley National Laboratory using a $^{252}$Cf source of strength $\sim 60 \mu$Ci. The source was sandwiched between two Fe foils of thickness of 10 mg/cm$^2$, and placed at the center of the Gammasphere detector array. The experiments were improved in step by step following the adopted detector number increasing from 36 to 72 and then to 102 in Gammasphere detector array. Corresponding collected triple- and higher-fold $\gamma$-coincidence events were $9.8 \times 10^9$, $2.9 \times 10^{10}$ and then $5.7 \times 10^{11}$, respectively. The coincidence data were analyzed with the Radware software package using $\gamma$-$\gamma$-$\gamma$ coincidence methods.

Fig. 3. Level schemes of $s = +1$ octupole band structure in $^{150,152}$Ce
3. Experimental Results

Most of results in $^{144,146,148,150}$Ce obtained by our collaboration have been published. They are: for $^{144}$Ce in Refs. [5,7,17], for $^{146}$Ce in Refs. [5,7,18], for $^{148}$Ce in Ref. [19], and for $^{150}$Ce in Ref. [20]. Recently, we have also identified the octupole correlations in very neutron-rich $^{152}$Ce, which have not been published.

Here we give the latest level schemes of the octupole band structure in $^{144}$Ce, $^{146}$Ce, $^{148}$Ce, $^{150}$Ce and $^{152}$Ce (to be published) by our collaboration, as shown in Figs. 1-3.

From Figs. 1 and 3, one can see that in $^{144,146,150,152}$Ce, one set of the positive- and negative-parity bands (1) and (2) with $\Delta I = 2$ transitions in each band and with linking $E1$ transitions between two bands forms an octupole band structure with a simplex quantum number $s = +1$ for each nucleus. From Fig. 2, one can see that in $^{148}$Ce, two sets of the positive- and negative-parity bands (1) and (2), and bands (3) and (4) with $\Delta I = 2$ transitions in each band and intertwined $E1$ transitions between two bands form a typical double octupole band structure with simplex quantum numbers $s = +1$ and $s = -1$, respectively. Thus, the octupole correlations are systematically observed in neutron-rich $^{144,146,148,150,152}$Ce isotopes.

4. Discussion

Now we make the systematic discussion for the levels in these observed octupole bands. Fig. 4 shows a comparison of observed levels in the $s = +1$ octupole band structure in $^{144,146,148,150,152}$Ce. They show very similar pattern with each other. It indicates that the assigned octupole band structures in these even-even Ce isotopes are reasonable. On the other hand, from Fig. 4 one can see that following the neutron number increasing, the level energies with the same spin systematically decrease. This is caused by the quadrupole deformation ($\beta_2$) increasing with the neutron number increase in these Ce isotopes.

A nucleus with octupole band structure decays through $E1$ and $E2$ transitions. The $B(E1)/B(E2)$ branching ratios can be obtained by the expression: \(^{19}\)

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

(1)

where $I_{\gamma}$ is the $\gamma$-transition intensity and $E_{\gamma}$ is the $\gamma$-transition energy.

The average $B(E1)/B(E2)$ values observed for $s = +1$ octupole band structure in $^{144,146}$Ce, $^{148}$Ce, $^{150}$Ce and $^{152}$Ce (to be published) are
Fig. 4. Systematic comparisons for the levels of \( s = +1 \) octupole band structure in \( ^{144,146,148,150,152}\text{Ce} \).

6.12, 1.70, 0.82, 0.040 and 0.023 \( \times (10^{-6}\text{fm}^{-2}) \), respectively. The average \( B(E1)/B(E2) \) value is \( 1.51 \times (10^{-6}\text{fm}^{-2}) \) for the \( s = -1 \) band structure in \(^{148}\text{Ce}\).\(^{19}\) Observed \( B(E1)/B(E2) \) values are reduced with the neutron number increasing, and it indicates that the octupole correlations are strong in \(^{144,146,148}\text{Ce}\), but in \(^{150,152}\text{Ce}\), they become weak.

In a nucleus with octupole correlations, the energy differences \( \delta E \) between the \( \pi = + \) and \( \pi = - \) bands can be used to discuss the octupole deformation stability with spin variation. Such \( \delta E \) between the \( \pi = + \) and \( \pi = - \) bands can be evaluated from the experimental level energies by using the relation:\(^{19}\)

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

Here the superscripts indicate the parities of the levels. Fig. 5 systematically shows plots of the \( \delta E(I) \) versus \( I \) of the \( s = +1 \) octupole band structures in \(^{144,146,148,150,152}\text{Ce}\). The \( \delta E \) should be close to zero in the limit of stable octupole deformation. As seen in Fig. 5, only in \(^{144}\text{Ce} \) and \(^{146}\text{Ce} \), the \( \delta E(I) \)'s reach the stable point at \( I \sim 7 \) \text{h} \) and \( 9 \text{h} \), respectively, and the \( \delta E(I) \)'s in
\[ ^{148,150,152}\text{Ce} \] do not yet reach the stable point until to the observed spins. This result shows that the octupole correlations become more unstable as the neutron number increasing in neutron-rich \( ^{\text{Ce}} \) isotopes. We notice that at the same spin value, the \( \delta\text{E}(I) \) value increases with the neutron number up to \( ^{150}\text{Ce} \), and then it reduces in \( ^{152}\text{Ce} \). The reason is not clear.

![Diagram](image_url)

**Fig. 5.** Systematic comparisons for \( \delta\text{E}(I) \) versus spin \( I \) for \( s = +1 \) band structure in \( ^{144,146,148,150,152}\text{Ce} \).

Plots of the kinematic moments of inertia \( (J_1) \) against the rotation frequency \( h\omega \) for the \( s = +1 \) octupole band structure in \( ^{144,146,148,150,152}\text{Ce} \) are shown in Fig. 6. In these \( \text{Ce} \) isotopes, the \( J_1 \) values of both positive- and negative-parity bands increase with the neutron number. This is also related to the quadrupole deformation variation. For each \( \text{Ce} \) isotope, \( J_1 \) varies smoothly with increasing spin. They agree with the systematics.

In \( ^{148}\text{Ce} \) The \( s = -1 \) octupole band structure has similar character with the \( s + 1 \) structure, as discussed in Ref. 19.

Above analysis indicates that the observed octupole band structure in neutron-rich \( ^{144,146,148,150,152}\text{Ce} \) agrees with the systematics. Examining these octupole bands, the alternating parity levels between the positive- and negative-parity bands have been observed in \( ^{144,146,148}\text{Ce} \). But in \( ^{150,152}\text{Ce} \), all the negative-parity levels are higher than the positive-parity ones, and no
alternating parity levels between the positive- and negative-parity bands are observed. This indicates that the observed octupole bands in $^{144,146,148,150,152}$Ce may show the character of stable octupole deformation, whereas observed negative parity bands in $^{150,152}$Ce may have octupole vibrational character.

5. Conclusion

The progress in experimental research on the octupole correlations in neutron-rich $^{144,146,148,150,152}$Ce by our collaboration has been reviewed. Octupole correlations with $s = +1$ structure in $^{144,146,150,152}$Ce were identified or expanded. The $s = \pm 1$ double octuple band structure in $^{148}$Ce was identified. Characteristics of the octupole correlations in these even-even Ce isotopes have been systematically discussed.
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