Identification of levels in neutron-rich ^{145}Ce and ^{147}Ce nuclei

M. Sakhaee,[1] S. J. Zhu,[1,2,3] J. H. Hamilton,[2] A. V. Ramayya,[2] J. K. Hwang,[2] X. Q. Zhang,[2] L. M. Yang,[1] L. Y. Zhu,[1] C. Y. Gan,[1] E. F. Jones,[2] P. M. Gore,[2] T. N. Ginter,[2] B. R. S. Babu,[2] W. C. Ma,[4] J. Kormicki,[2] C. J. Beyer,[2] G. L. Long,[1] J. K. Deng,[1] K. Li,[1] J. D. Cole,[5] R. Aryaeinejad,[5] M. W. Drigert,[5] J. O. Rasmussen,[6] S. Asztalos,[6] I. Y. Lee,[6] A. O. Macchiavelli,[6] S. Y. Chu,[6] K. E. Gregorich,[6] M. F. Mohar,[6] M. A. Stoyer,[7] R. W. Lougheed,[7] K. J. Moody,[7] J. F. Wild,[7] S. G. Prussin,[8] G. M. Ter-Akopian,[2,3,9] A. V. Daniel,[2,3,9] and Yu. Ts. Oganessian[9]

[1]*Physics Department, Tsinghua University, Beijing 100084, People's Republic of China*

[2]*Department of Physics, Vanderbilt University, Nashville, Tennessee 37235*

[3]*Joint Institute for Heavy Ion Research, Oak Ridge, Tennessee 37831*

[4]*Department of Physics, Mississippi State University, Mississippi 39762*

[5]*Idaho National Environmental Engineering Laboratory, Idaho Falls, Idaho 83415*

[6]*Lawrence Berkeley National Laboratory, Berkeley, California 94720*

[7]*Lawrence Livermore National Laboratory, Livermore, California 94550*

[8]*University of California, Berkeley, California 94720*

[9]*Flerov Laboratory for Nuclear Reactions, Joint Institute for Nuclear Research, Dubna 141980, Russia*

(Received 30 July 1999; published 16 November 1999)

High-spin structures in the neutron-rich nuclei ^{145}Ce and ^{147}Ce produced in the spontaneous fission of ^{252}Cf have been investigated by prompt γ-ray spectroscopy. A collective band structure in ^{145}Ce is identified. Several sidebands along with the new high-spin states in ^{147}Ce are also identified. Particle-plus-rotor model calculations indicate that the yrast bands in ^{145}Ce and ^{147}Ce most probably originate from coupling of the $\nu i_{13/2}$ orbital to the ground states of ^{144}Ce and ^{146}Ce. The ground state configurations of ^{145,147}Ce are ($\nu h_{9/2} + \nu f_{7/2}$) and $\nu h_{9/2}$, respectively. [S0556-2813(99)05312-1]

PACS number(s): 21.10.Re, 23.20.Lv, 27.60.+j, 25.85.Ca

The neutron-rich odd-A ^{145,147}Ce with $Z=58$ and $N=87,89$ lie in a region where octupole correlations ($Z\sim56$ and $N\sim88$) have been reported. Recently, octupole correlations have also been observed in ^{139}Xe [1,2], $^{140-144,146,148}$Ba [1,3–7], ^{145,147}La [8,9], and ^{144,146}Ce [10,11]. A systematic study of the level structures of the odd-A nuclei in this region can provide important information on the nuclear shape changes, the single particle orbitals, and the octupole correlations. Since these neutron-rich nuclei cannot be produced in (HI, xn) reactions, an effective method is to measure the prompt γ rays of these neutron-rich nuclei produced in the spontaneous fission (SF) of transuranic nuclei [11]. In earlier work [12,13], some low-energy excited states of ^{145,147}Ce have been reported from the β-decay measurements. Recently, the yrast band in ^{147}Ce has been studied [14,15] by measuring the prompt γ rays emitted by the fission fragments. So far, no collective band structure has been seen in ^{145}Ce. In this paper, we report on our identification of the new levels in ^{145,147}Ce from prompt γ-ray studies in SF of ^{252}Cf.

The experiment was carried out with an $\approx 28\mu$Ci ^{252}Cf source sandwiched between two Ni foils of thickness 11.3 mg/cm^2, then sandwiched between 13.7 mg/cm^2 thick Al foils and placed at the center of Gammasphere with 72 Compton suppressed Ge detectors. A total of 9.8×10^9 triple or higher fold coincidence events were recorded. The coincidence data were analyzed by building a γ-γ-γ cube using RADWARE software [16].

In SF, a pair of correlated partners is produced along with several neutrons. For given fission fragment pairs, there can be several partner isotopes because 0 to 10 neutrons can be emitted. The γ rays emitted by the partners during deexcitation will be in coincidence with each other. If the transitions in one of the partner nuclei are known, one can identifiy uniquely the γ rays belonging to the other partner nuclei because one can compare the fission yields with calculated ones from Wahl's tables [17]. As an example, Fig. 1 shows two coincidence spectra obtained by double gating on the transitions. In Fig. 1 (bottom), a double gate on the 140.3 and 312.5 keV transitions in ^{104}Zr reveals several new γ transitions of energies 98.3, 381.0, 383.1, and 565.3 keV in addition to γ rays at 473 and 624 keV in ^{104}Zr as well as the partner transitions 118.1, 283.5, and 251.4 keV in ^{147}Ce($1n$), 259, 409, 503 keV in ^{146}Ce($2n$), and 397, 541 keV in ^{144}Ce($4n$). From the coincidence relationship between these new γ transitions and the transitions with the partner nuclei, we assigned 98.3, 381.0, 383.1, and 520.7 keV transitions to ^{145}Ce. In Fig. 1 (top), the spectrum for a double gate on the 383.1 and 565.3 keV transitions shows γ rays at 98.3, 381.0, 520.7, 673.3, and 738.5 keV in ^{145}Ce as well as transitions in the partner nuclei ^{104}Zr($3n$), ^{103}Zr($4n$), and ^{102}Zr($5n$).

The order of the transitions in the level schemes of ^{145}Ce and ^{147}Ce in Figs. 2 and 3 has been determined by considering the transition intensities and the coincidence relationships between the new γ transitions. The different bands observed in ^{147}Ce are shown in Fig. 2. All the levels in ^{145}Ce were identified for the first time and no linking transitions were observed between the new levels and the earlier levels observed in the β-decay measurements [12]. In ^{147}Ce, all the transitions reported in Refs. [14,15] have been observed in the present work. The 274.3 keV level is observed to decay

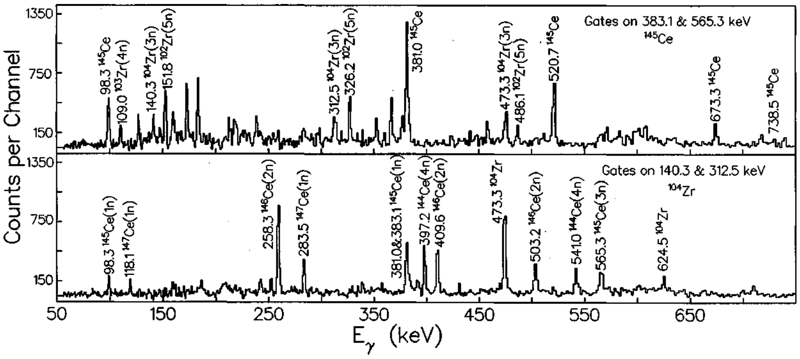

FIG. 1. Coincidence spectra with double gates on (top) 383.1 and 565.3 keV transitions in ^{145}Ce and (bottom) 140.3 and 312.5 keV transitions in ^{104}Zr.

to the ground state by emitting two γ rays of energies 156.2 and 118.1 keV. The 274.3 keV level and the transitions have been reported in Ref. [12], but not in Refs. [14,15]. A new sideband (2) built on the 274.3 keV level with stretched γ transitions of energies 360.6, 521.8, and 614.4 keV has been observed. Two other new sidebands (3) and (4), along with some weak transitions, also have been observed.

In the earlier β-decay studies [12,13] the spin and parity (I^π) of the ground state of the ^{145}Ce and ^{147}Ce were tentatively assigned as ($3/2^-$) and ($5/2^-$), respectively. Based on the internal conversion coefficients, branching ratios, and triple angular correlation measurements, the I^π of yrast levels in ^{147}Ce up to ($33/2^+$) have been assigned by Hoellinger *et al.* [14]. We agree with these assignments. Based on the structural similarity with ^{147}Ce, the I^π's of the levels at 946.3 and 1044.6 keV in ^{145}Ce are assigned as ($9/2^+$) and ($13/2^+$), respectively. It is suggested that the four transitions of energies 383.1, 520.7, 673.3, and 738.5 keV in ^{145}Ce form a collective rotational band built on the 13/2 level.

The yrast bands built on the ($13/2^+$) level in ^{145}Ce and ^{147}Ce have similar structures. The moments of inertia J_1 vs the rotational frequencies, $\hbar\omega$, plot (not shown) show that with increasing $\hbar\omega$, the J_1's decrease, and then increase at the highest observed states for $\hbar\omega > 0.27$ MeV in ^{147}Ce and $\hbar\omega > 0.36$ MeV in ^{145}Ce. Since the average moment of inertia (J_1) for ^{147}Ce is larger than that of ^{145}Ce, the β_2 of ^{147}Ce ($N=88$) may be larger than that of ^{145}Ce ($N=87$).

Hoellinger *et al.* [14] proposed that the yrast band (1) in ^{147}Ce could be built on a $\nu i_{13/2}$ state at 485 keV. The new collective band (1) observed in ^{145}Ce could also be built on a $\nu i_{13/2}$ state at 1044.6 keV. In order to interpret these bands built on the $13/2^+$ levels in ^{145}Ce and ^{147}Ce, the particle-plus-rotor model with variable moment of inertia (VMI) of the core [18,19] has been performed. The negative and positive parity states are calculated, separately. That is, first we performed the negative parity state calculation, then do the positive parity state calculation. As no experimental ε_2 values in ^{145,147}Ce are available, we take initial ε_2 values around 0.10–0.20 from systematics in this region. Then, by varying the ε_2 value, and by carefully comparing the calculated energy levels with the corresponding experimental ones, we arrived at the value for ε_2 used in this calculation. The parameters used in the calculations are as follows: $\varepsilon_2 = 0.14$ ($\beta_2 = 0.17$), $\varepsilon_4 = 0$, $\gamma = 0$ for ^{145}Ce and $\varepsilon_2 = 0.16$ ($\beta_2 = 0.25$), $\varepsilon_4 = 0$, $\gamma = 0$ for ^{147}Ce, respectively. The calculations indicate that the energy levels and configurations are very sensitive to the parameter ε_2, but not to ε_4.

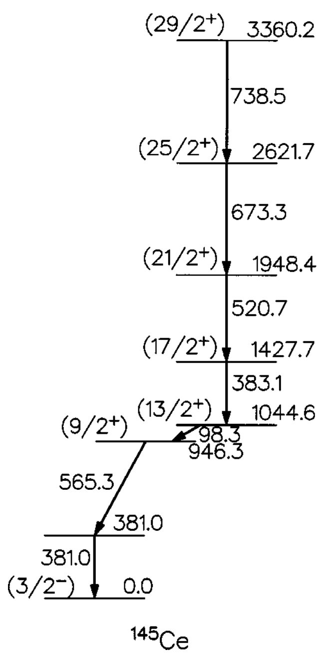

FIG. 2. Partial level scheme for ^{145}Ce.

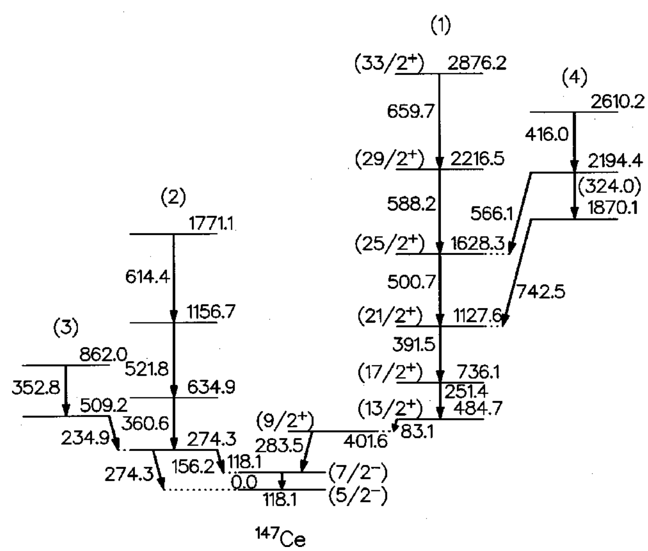

FIG. 3. Partial level scheme for ^{147}Ce.

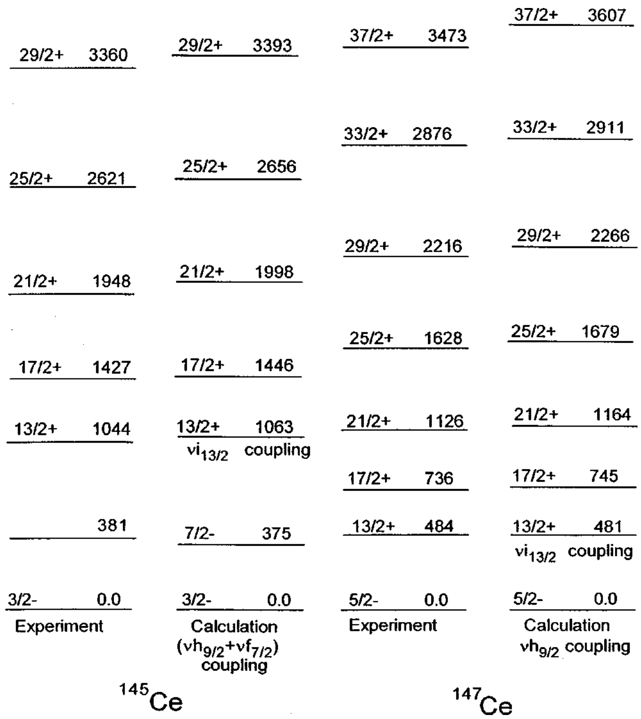

FIG. 4. Calculated (PRM) levels (band $i_{13/2}$) and comparison with experiment for ^{145}Ce and ^{147}Ce.

The ε_2 values in our calculations are close to those expected from calculations in this region [8,19]. Another parameter sensitive to the calculated results is the Coriolis attenuation factor χ. These parameters were determined by a method similar to that used in the case of ε_2. The parameter χ has different values for the negative and positive bands. They are as follows: $\chi = 0.200, 0.650$ for negative and positive parity states in ^{145}Ce, and 0.750,0.820 for negative and positive parity states in ^{147}Ce, respectively. Other parameters were taken as standard. The results of our calculations and comparison with the experimental data are shown in Fig. 4. The general good agreement between theoretical and experimental results indicates that the yrast bands built on the proposed 13/2 levels in ^{145}Ce and ^{147}Ce most probably originate from the mixing of a $\nu i_{13/2}$ single particle orbital with a very weak component of $\nu g_{9/2}$ coupled with the even-even nuclear cores of ^{144,146}Ce. These results support the I^π assignments of the 13/2 band in ^{145}Ce. On the other hand, the energy spacings of the $\nu i_{13/2}$ band in ^{145}Ce are close to those of the yrast band in the ^{144}Ce core [2,11], and show almost complete decoupling with similar characteristics discussed for ^{147}Ce [14]. Our calculations also indicate that the ground states $(3/2^-)$ and $(5/2^-)$ in ^{145}Ce and ^{147}Ce may originate from $(\nu h_{9/2} + \nu f_{7/2})$ and $\nu h_{9/2}$ configurations, respectively. The I^π of the 381 keV level in ^{145}Ce is tentatively assigned as $(7/2^-)$ as the level is close to the calculated $7/2^-$ level (375 keV) and only this assignment allows this state to connect to $9/2^+$ and $3/2^-$ levels. The I^π of the new weak sidebands (2) and (3) cannot be determined by our experiment. The band (3) is supposed to be the $h_{9/2}$ band, since it is similar to the $h_{9/2}$ band in the neighboring nuclei [20,21].

Although no obvious octupole correlations in ^{145}Ce and ^{147}Ce are observed in the present work, the weak sideband (3) in ^{147}Ce may be of negative parity and the bands (1) and (3) may show some weak octupole correlations. The transitions in band (3) are too weak to determine the $B(E1)/B(E2)$ values.

The work at Tsinghua University was supported by the National Natural Science Foundation under Grant No. 19775026, and the Science Foundation for Nuclear Industry of China under Grant No. Y7197AY509. The work at Vanderbilt University was supported in part by the U.S. Department of Energy under Grant No. DE-FG05-88ER40407. The Joint Institute for Heavy Ion Research is supported by its members University of Tennessee, Vanderbilt University, Oak Ridge National Laboratory, and the U.S. Department of Energy through Contract No. DE-FIG-87ER40311 with the University of Tennessee. The work at Idaho National Environmental and Engineering Laboratory, Lawrence Berkeley National Laboratory, and Lawrence Livermore National Laboratory is supported in part by the U.S. Department of Energy under Contract Nos. DE-AC07-761DO1570, DE-AC03-76SF00098, and W-7405-ENG48, respectively.

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