Identification of γ transitions in ^{147}Ba, ^{149}Ce, and ^{151,153}Nd

B. R. S. Babu,[1] S. J. Zhu,[1,2,3] A. V. Ramayya,[1] J. H. Hamilton,[1] L. K. Peker,[1,4] M. G. Wang,[2] T. N. Ginter,[1] J. Kormicki,[1,5] W. C. Ma,[6] J. D. Cole,[7] R. Aryaeinejad,[7] K. Butler-Moore,[7] Y. X. Dardenne,[7] M. W. Drigert,[7] G. M. Ter-Akopian,[8] Yu. Ts. Oganessian,[8] J. O. Rasmussen,[9] S. Asztalos,[9] I. Y. Lee,[9] A. O. Macchiavelli,[9] S. Y. Chu,[9] K. E. Gregorich,[9] M. F. Mohar,[9] S. Prussin,[10] M. A. Stoyer,[10] R. W. Lougheed,[10] K. J. Moody,[11] and J. F. Wild[11]

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

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

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

[4]*Brookhaven National Laboratory, Upton, New York 11973*

[5]*ORISE, Oak Ridge, Tennessee 37831*

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

[7]*Idaho National Engineering Laboratory, Idaho Falls, Idaho 83415*

[8]*Joint Institute for Nuclear Research, Dubna, 141980, Russia*

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

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

[11]*Nuclear Engineering Department, University of California, Berkeley, California 94720*

(Received 5 February 1996)

The γ transitions in ^{147}Ba, ^{149}Ce, and ^{151,153}Nd have been identified from γ-γ-γ, γ-γ, x-γ, and x-γ-γ coincidence studies of spontaneous fission of ^{252}Cf. The yrast positive parity band in ^{149}Ce is assigned to an $i_{13/2}$, neutron favored signature. The yrast negative parity band in ^{149}Ce is assigned a $h_{9/2}$ proton favored signature. The positive parity band in ^{151}Nd corresponds to the positive parity band in ^{149}Ce. The negative parity band in ^{153}Nd corresponds to the negative parity bands of ^{149}Ce and ^{161}Er. The band observed in ^{147}Ba is built on the $h_{9/2}$ orbital. The plots for J_1 in these isotopes are remarkably similar, supporting our assignments. [S0556-2813(96)03108-1]

PACS number(s): 23.20.Lv, 21.20.Re, 27.60.+j, 27.70.+q

I. INTRODUCTION

In the nuclear landscape, the extensions of experimental data over long isotopic chains provide valuable information on the origin of quadrupole deformation and the variation of single particle energies as a function of neutron number. In neutron-rich Nd nuclei, the yrast band energies drop continuously as N increases from 90 to 96. For $^{150-156}$Nd the E_{4^+}/E_{2^+} ratios are 2.9, 3.3, 3.2, and 3.3, respectively [1–3]. The ratios for $^{152-156}$Nd are in good agreement with the expected rotational model values, indicating that these nuclei are good rigid rotors. However, very little information is available for odd-A nuclei in this region. In $N=91,93$ nuclei Nilsson levels related to $i_{13/2}$ and $h_{9/2}$ ($N=6,5$) orbitals are located relatively close to each other to the Fermi surface. Therefore the rotational bands based on the above two orbitals are expected to occur at lower energies. These bands have some very specific features. At $I<j$ they look like normal strongly coupled bands (if $k\geqslant5/2$, i.e., large) or disturbed bands ($k<5/2$). But at $I\geqslant j$ they become typical strongly aligned bands with $\Delta I=2$ sequence. These aligned parts of $i_{13/2}$ and $h_{9/2}$ bands are easy to recognize. In fact these aligned bands ($i_{13/2}$, $h_{9/2}$) are present as the most distinctive parts of $N=91$, 93 neutron-deficient nuclei. In order to search for these bands typical of $N=91$, 93 isotopes, we have investigated the γ rays emitted by the nuclei following the spontaneous fission of ^{252}Cf. We have identified the γ rays of ^{147}Ba, ^{149}Ce, and ^{151,153}Nd and established the band structure. The configurations of these bands observed in these nuclei are assigned by comparing them with the other $N=91$, 93 isotones.

II. EXPERIMENTAL DETAILS

Identification of γ rays belonging to a particular isotope is very difficult since the fission yields are very low and approximately 100 different isotopes are produced in the fis-

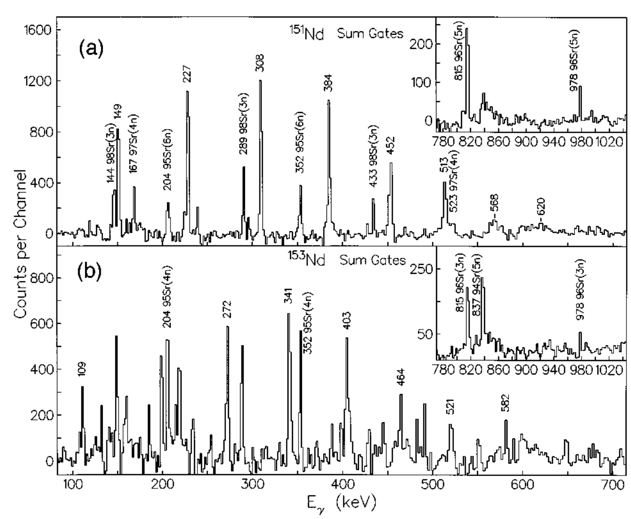

FIG. 1. (a) Sum double gate spectrum of ^{151}Nd with the partner transitions shown in the inset. (b) Sum double gate spectrum of ^{153}Nd with the partner transitions shown in the inset.

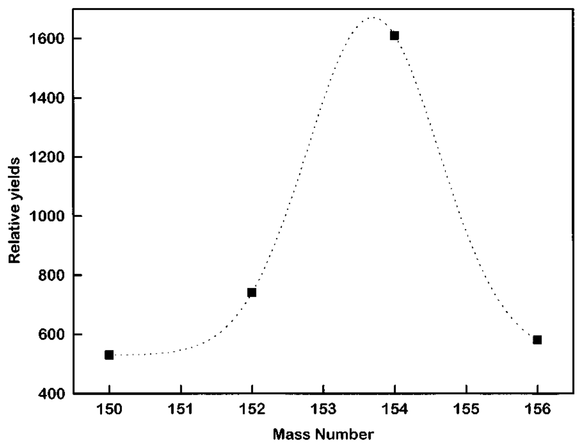

FIG. 2. Plot of relative yields of even-even Nd nuclei.

sion of ^{252}Cf and one often observes γ rays of the same or similar energy in different nuclei and has to perform several cross-checks to assign a set of γ rays uniquely to an isotope. In the first experiment a ^{252}Cf source of strength 6×10^4 fissions/s was placed at the center of the 20 Compton-suppressed Ge array at Oak Ridge National Laboratory and about 2×10^9 γ-γ events were collected. At Idaho National Engineering Laboratory in a second experiment both x-x and x-γ coincidences were measured with two x-ray detectors of resolution 280 eV at 14 keV and three germanium detectors. In a third experiment, at Lawrence Berkeley National Laboratory, a ^{252}Cf source of similar strength was used and γ-γ-γ data were collected with 36 Ge detectors in the early implementation of Gammasphere. A total of 9.8×10^9 triple- or higher-fold coincidence events were recorded. Two-dimensional matrices were built for the first two experiments and a three-dimensional cube for the third experiment. The ''cube'' data were analyzed using RADWARE [4].

Identification of transitions in a given nuclide in spontaneous fission is complicated further because there are always more than one pair of correlated partners. For example ^{96}Sr is the partner of ^{151}Nd with five neutrons emitted by the primary fragments. Similarly ^{95,97,98}Sr are also partners of ^{151}Nd with six, four, and three neutrons emitted, respectively. By gating on the known γ rays in different partner isotopes, one can identify the transitions of interest in a particular isotope. The γ-γ and x-γ data were used to identify low energy transitions in the nucleus of interest. When a few

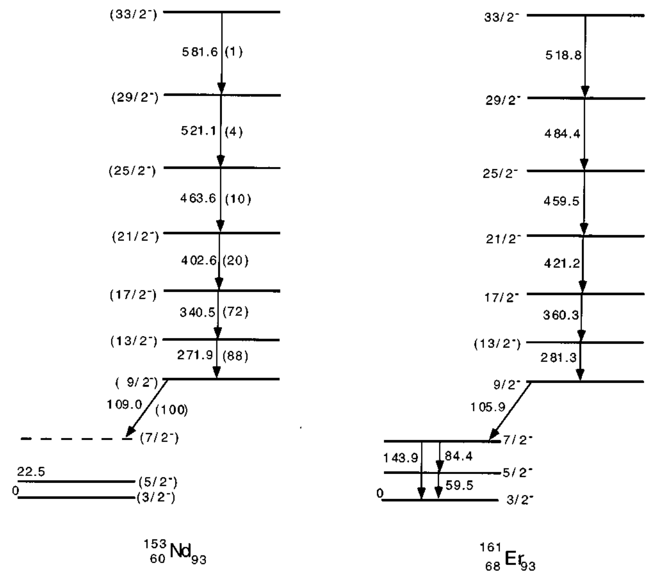

FIG. 4. Level schemes of ^{153}Nd and ^{161}Er nuclei.

transitions are identified in an isotope of interest, the ''cube'' data were used for double gating on different γ transitions to help eliminate the complexities arising from several other fission partners produced.

A. ^{151}Nd, ^{153}Nd nuclei

Figures 1(a) and 1(b) show the transitions assigned to ^{151}Nd and ^{153}Nd, respectively. The insets show the transitions in the partners ^{96}Sr and ^{94,96}Sr, respectively. The relative yields for the even-even Nd nuclei are extracted from a gate on $2^+\rightarrow0^+$ transition in ^{94}Sr. The yields are fitted to a Gaussian [5,1] and are shown in Fig. 2. From the yield curve, we expect a ratio of the relative yields of ^{153}Nd to ^{151}Nd to be $\sim$ 2.6. The ratio of the yields extracted from the transitions assigned to ^{153}Nd and ^{151}Nd is $\sim$ 2.6. Based on these yields, the transitions are assigned to ^{153}Nd and ^{151}Nd. The level scheme of ^{151}Nd extracted from the ''cube'' data is shown in Fig. 3 along with the $i_{13/2}$ neutron bands in $N=91$ isotones ^{155}Gd [6], ^{157}Dy [6], and ^{159}Er [7]. The ground state of ^{151}Nd is tentatively assigned as $3/2^+$ from β-decay studies [3]. However, below $\approx$ 60 keV, there are other levels with spins and parities $5/2^+$ and $3/2^-$. The tran-

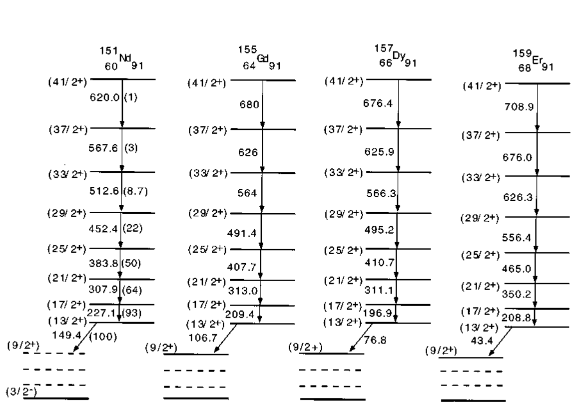

FIG. 3. Level schemes of ^{151}Nd, ^{155}Gd, ^{157}Dy, and ^{159}Er nuclei.

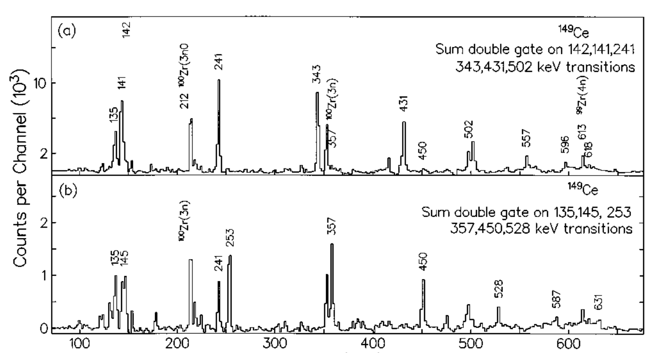

FIG. 5. (a) Sum double gate spectrum of the $i_{13/2}$ band in ^{149}Ce. (b) Sum double gate spectrum of the $h_{9/2}$ band in ^{149}Ce.

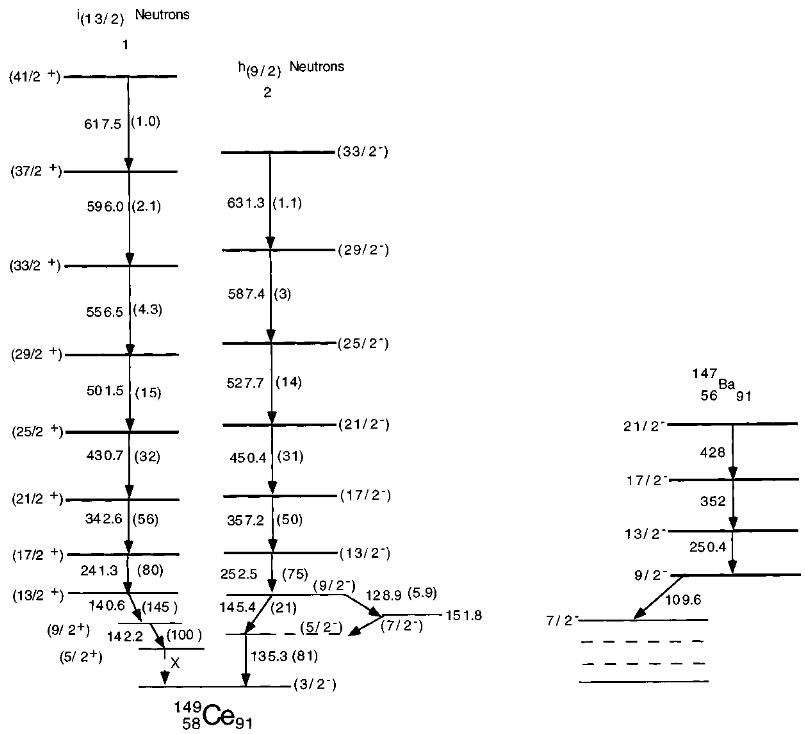

FIG. 6. Level schemes of ^{147}Ba and ^{149}Ce nuclei.

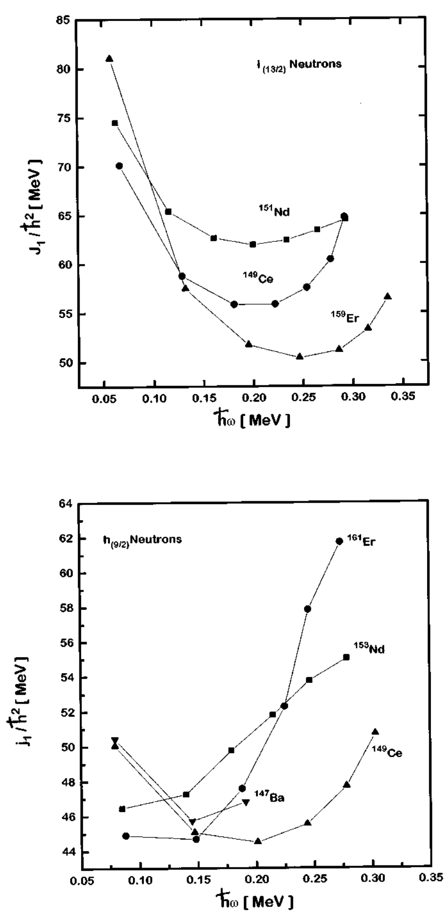

FIG. 7. J_1 plots for $i_{13/2}$ and $h_{9/2}$ bands in Ba, Ce, Nd, and Er nuclei.

sitions observed in ^{151}Nd have energies very similar to the ones observed in $i_{13/2}$ neutron bands in the other $N=91$ isotones. From these systematics, the observed band in ^{151}Nd is assigned as an $i_{13/2^+}$ band built either on a $3/2^+$ [651] or $5/2^+$ [642] configuration.

The $h_{9/2}$ band in ^{161}Er [8] and the new band in ^{153}Nd are shown in Fig. 4. Because of the very close similarity between the bands in these two $N=93$ nuclei, the new band in ^{153}Nd is assigned as a band built on the $3/2^-$ [521] configuration. Our new levels in $N=91$ ^{147}Ba can be fitted into a similar band structure built on the $h_{9/2}$ orbital.

B. ^{147}Ba nucleus

The 109.6 keV transition in ^{147}Ba is known earlier from the β decay [9]. Also the yields of correlated Mo/Ba pairs with average neutron multiplicities have been reported by Hamilton *et al.* [1]. Based on these and the partner transitions, we have assigned the other γ transitions in ^{147}Ba.

C. ^{149}Ce nucleus

Prior to our investigation, ^{149}Ce was separated chemically as a fission fragment from ^{252}Cf. Two γ rays of energies 135.6 and 142.2 keV are known from the chemically separated source [10]. The data on the excited states in ^{149}Ce remain unknown. The partners of ^{149}Ce are ^{99,100}Zr with four and three neutrons emitted, respectively. By gating on the transitions in these two Zr nuclei and using the previously known energies of γ rays, we have identified several transitions in ^{149}Ce. After assigning a few transitions to ^{149}Ce the ''cube'' data were used to find other γ rays. Figure 4(a) shows the γ spectrum obtained by summing over all the double gates of band in ^{149}Ce. The transitions used for double gating are shown on the Fig. 5(a). A similar spectrum for band 2 in ^{149}Ce is shown in Fig. 5(b). The level structure for ^{149}Ce constructed from the present studies is shown in Fig. 6. The two bands labeled 1 and 2 in Fig. 5 are assigned as $i_{13/2^+}$ and $h_{9/2^-}$ bands, respectively.

III. CONCLUSIONS

The moments of inertia (j_1) for the $i_{13/2}$ and $h_{9/2}$ bands in these nuclei are shown in Fig. 7. For the $i_{13/2}$ bands the moments of inertia decrease, initially, followed by an increase. The plots are very similar in shape. However, for the $h_{9/2}$ bands the J_1's increase monotonically for ^{153}Nd and ^{161}Er where as in case of ^{149}Ce there is an initial decrease and then an increase.

In summary, we have identified the levels in ^{147}Ba, ^{151,153}Nd, and ^{149}Ce and they are identified as $h_{9/2}$ and $i_{13/2}$ bands. Further we demonstrated that these bands are also the most distinctive features of $N=91$, 93 neutron-rich nuclei: $^{147}_{56}\mathrm{Ba}_{91}$, $^{149}_{58}\mathrm{Ce}_{91}$, $^{151}_{60}\mathrm{Nd}_{91}$, and $^{153}_{60}\mathrm{Nd}_{93}$.

ACKNOWLEDGMENTS

The work at Vanderbilt University is supported in part by the U.S. Department of Energy under Grant No. DE FG05 88ER40407. The work at Tsinghua University is partially supported by the National Natural Science Foundation and the Nuclear Industrial Science Foundation of China. The Joint Institute for Heavy Ion Research is supported by its members, the University of Tennessee, Vanderbilt University, and the U.S. Department of Energy through Contract No. DE-FG05-87ER40361 with the University of Tennessee. The work at Idaho National Engineering Laboratory is supported in part by the U.S. Department of Energy under Contract No. DE-AC07-76ID01570. The work at Lawrence Berkeley National Laboratory is supported in part by the U.S. Department of Energy under Grants No. DE-FG03-87ER40323, W-7405-ENG48, and DE-AC03-76SF00098.

[1] J.H. Hamilton, A.V. Ramayya, S.J. Zhu, G.M. Ter-Akopian, Yu.Ts. Oganessian, J.D. Cole, J.O. Rasmussen, and M.A. Stoyer, Prog. Part. Nucl. Phys. **35**, 635 (1995).

[2] S.J. Zhu, J.H. Hamilton, Q.H. Lu, A.V. Ramayya, M.G. Wang, B.R.S. Babu, T.N. Ginter, W.C. Ma, J.K. Deng, D. Shi, J. Kormicki, J.D. Cole, R. Aryaeinejad, Y.X. Dardenne, M.W. Drigert, N.R. Johnson, I.Y. Lee, F.K. McGowan, G.M. Ter-Akopian, Yu.Ts. Oganessian, J.O. Rasmussen, M.A. Stoyer, S.Y. Chu, K.E. Gregorich, M.F. Mohar, and S. Prussin, J. Phys. G **21**, L75 (1995).

[3] B. Singh, J.A. Szucs, and M.W. Johns, Nucl. Data Sheets **55**, 185 (1988).

[4] D.C. Radford, Nucl. Instrum. Methods Phys. Res. A **361**, 297 (1995).

[5] A.C. Wahl, At. Data Nucl. Data Tables **39**, 1 (1988).

[6] M.A. Riley, J. Simpson, M.A. Bentley, P. Fallon, P.D. Forsyth, J.C. Lisle, J.D. Morrison, E.S. Paul, J.F. Sharpey-Schafer, and P.M. Walker, Z. Phys. A **345**, 121 (1993).

[7] M.A. Deleplanque, J.C. Bacelar, E.M. Beck, R.M. Diamond, J.E. Draper, R.J. McDonald, and F.S. Stephens, Phys. Lett. B **193**, 422 (1987).

[8] J.D. Garrett, G.B. Hagemann, B. Herskind, J. Bacelar, R. Chapman, J.C. Lisle, J.N. Mo, A. Simcock, J.C. Willmott, and H.G. Price, Phys. Lett. **118B**, 297 (1982).

[9] F. Schussler, B. Pfeiffer, H. Lawin, E. Monnand, J. Munzel, J.A. Pinston, and K. Sistemisch, in Proceedings of the International Conference on Nuclei far from stability, Helsinger, Denmark, 1981 (unpublished), Vol. 2, p. 589.

[10] R.G. Clark, L.E. Glendenin, and W.L. Tabert, Jr., *Proceedings of the Third Symposium on the Physics and Chemistry of Fission*, Rochester, New York, 1973 (International Atomic Energy Agency, Vienna, 1974), Vol. 2, p. 221.