New decay pattern of negative-parity states at $N = 90$

A. Chakraborty,[1,2,*] F. M. Prados-Estévez,[1,2] S. N. Choudry,[1] B. P. Crider,[1] P. E. Garrett,[3] W. D. Kulp,[4] A. Kumar,[1,2,†] M. T. McEllistrem,[1] S. Mukhopadhyay,[1] M. G. Mynk,[2] J. N. Orce,[1,5] E. E. Peters,[2] J. L. Wood,[4] and S. W. Yates[1,2]

[1]*Department of Physics and Astronomy, University of Kentucky, Lexington, Kentucky 40506-0055, USA*

[2]*Department of Chemistry, University of Kentucky, Lexington, Kentucky 40506-0055, USA*

[3]*Department of Physics, University of Guelph, Guelph, Ontario N1G 2W1, Canada*

[4]*School of Physics, Georgia Institute of Technology, Atlanta, Georgia 30332-0430, USA*

[5]*Department of Physics, University of the Western Cape, P.O. Box X17, Bellville ZA-7535, South Africa*

(Received 7 July 2012; revised manuscript received 4 August 2012; published 18 December 2012)

Excited states in ^{150}Nd have been investigated with the ^{150}Nd$(n,n'\gamma)$ reaction. In addition to the previously known $K^\pi = 0^-$ band, a new $K^\pi = 2^-$ band is established, and level lifetimes are determined for all the reported band members. These lifetime data reveal a pattern of enhanced $E1$ transition strengths, similar to that observed in ^{152}Sm and unprecedented in other nuclei, thus suggesting a systematic pattern for octupole collectivity in the $N = 90$ isotones. The pattern lies outside of the various model descriptions that have been put forward for nuclei in this or any other region.

DOI: 10.1103/PhysRevC.86.064314 PACS number(s): 21.10.Tg, 23.20.Lv, 25.40.Fq, 27.70.+q

I. INTRODUCTION

The nucleus ^{150}Nd is surprisingly poorly studied, considering that it is stable and that it lies in a region of rapidly changing shapes, which is of current interest. Experimental work on ^{150}Nd through 1995 is summarized in Ref. [1]. In addition, there are three more recent studies [2–4], but serious ambiguities exist above 1150 keV in excitation for many of the reported levels and transitions. The neighboring $N = 90$ isotone ^{152}Sm has been the focus of other investigations [5–9], and related studies in ^{154}Gd have also been performed [10–13]. Very recently, Garrett *et al.* [9] showed that ^{152}Sm exhibits coexisting $K^\pi = 0^-$ octupole bands, a new type of shape coexisting structure. The lowest-lying $K^\pi = 0^-$ band in ^{152}Sm has a large $B(E3)$ value [14] for its 3^- band member, establishing enhanced octupole correlations, which appear to give rise to strong $E1$ transitions between the band members of the $K^\pi = 0^-_1$ band and the $K^\pi = 0^+$ ground state band. This signature of enhanced $E1$ transition rates was also observed between the first excited $K^\pi = 0^-_2$ and $K^\pi = 0^+_2$ bands, leading to the assignment of the $K^\pi = 0^-_2$ band as an octupole excitation built on the 0^+_2 state. We report here another feature associated with the negative-parity octupole bands in ^{152}Sm and ^{150}Nd, namely that the pattern of unusually large $E1$ transition strength seen between a $K^\pi = 2^-$ band and the lowest $K^\pi = 2^+$ band in ^{152}Sm is repeated in ^{150}Nd. Such a relationship is not described by any model description presented to date for the negative-parity states at and near $N = 90$ [4,9,15–19] or for the states across the rare-earth region [20] or in the actinides [21].

II. EXPERIMENTAL METHODS, DATA ANALYSIS, AND RESULTS

The experiments were carried out at the University of Kentucky Accelerator Laboratory, where nearly monoenergetic neutrons, produced via the ^{3}H$(p,n)^3$He reaction with pulsed and time-bunched beams of protons, bombarded a 31.15-g sample of Nd_2O_3 enriched to 96.17% in ^{150}Nd. The γ rays produced by the inelastic scattering of neutrons from the sample were detected with HPGe detectors with relative efficiencies of 52% to 57%. By varying the neutron energy in steps of 100 keV (with energy spread typically about 70 keV) between 1.2 and 2.7 MeV, γ-ray excitation functions were obtained with a single Compton-suppressed HPGe detector placed at 125° with respect to the proton beam (incident on the tritium gas target). Angular distributions of γ rays were obtained at neutron energies of 1.2, 1.4, 2.05, and 2.7 MeV, where the detector was rotated through angles between 40° and 155°. For these measurements, the energy calibration was continuously monitored using γ rays of well known energies from radioactive ^{24}Na and ^{137}Cs sources. A γ-γ coincidence measurement was carried out at a neutron energy of 3.2 MeV, with four HPGe detectors placed ~5 cm from the ^{150}Nd sample. Offline analyses of the data were performed using the TV [22] and RADWARE [23] software packages.

Figures 1 and 2 illustrate the levels and transitions which are the focus of this report. The J^π(E_x in keV) = 1^-(853), 3^-(935), and 5^-(1129) levels in ^{150}Nd, shown in Fig. 1(a), are well established [1] and closely match a similar set of levels in ^{152}Sm shown in Fig. 1(b). The γ-γ coincidence relations and the excitation function data permit the firm placement of γ rays from the excited states in ^{150}Nd. Selected portions of the γ-ray coincidence spectra for gates taken on the 932-keV γ ray (the 1062 keV $2^+_3 \rightarrow$ 130 keV 2^+_1 transition) and the 1070-keV γ ray (the 1200 keV $3^+_1 \rightarrow$ 130 keV 2^+_1 transition) are shown in Fig. 3. These spectra reveal the γ rays at 373 and 421 keV feeding the 1062-keV level and the 365-keV γ ray feeding the 1200-keV level. The observation

*Present address: Department of Physics, Krishnath College, Berhampore 742101, India.

†Present Address: Department of Physics, Panjab University, Chandigarh 160014, India.

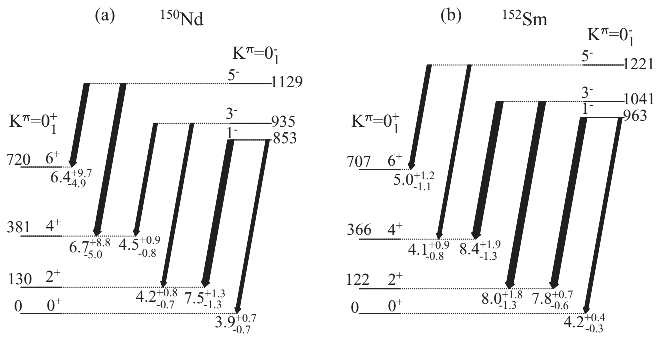

FIG. 1. Comparison of $B(E1)$ values (in mW.u. = 10^{-3} W.u.) for the transitions between the levels of the $K^\pi = 0_1^-$ and $K^\pi = 0_1^+$ bands of (a) ^{150}Nd and (b) ^{152}Sm. The widths of the arrows are proportional to the central $B(E1)$ values of the corresponding transitions. The $B(E1)$ values with the associated uncertainties for the corresponding decays are shown at the bottom of the transition arrows.

of the 365-keV γ ray supports the placement of the new 1565-keV level.

Excitation functions of the γ-ray yields following the ^{150}Nd$(n,n'\gamma)$ reaction display a sensitivity to the spin of the level. The excitation function data for the 365-, 373-, and 421-keV γ rays are shown in Fig. 4. They support spin assignments of 2, 3, and 4 to the 1435-, 1483-, and 1565-keV levels, respectively.

The γ-ray angular distribution data were used to determine the multipolarities of the deexciting transitions. For this process, the variation of yield of a particular γ ray as a function of angle (θ) was fitted with a polynomial of the form

$$W(\theta) = A_0\,[1 + a_2 P_2(cos(\theta)) + a_4 P_4(cos(\theta))]\,, \quad (1)$$

where the angular distribution coefficients a_2 and a_4 depend on the level spins, multipolarities, and multipole mixing ratios of the transitions involved. The experimental values of the angular distribution coefficients were then compared to the results from statistical model calculations, obtained from the code CINDY [24], to determine the multipolarities and the possible mixing ratios of the transitions. Figure 5 displays the angular distribution results for selected γ rays in ^{150}Nd. The minima in the χ^2 vs δ plots (see the bottom panel of Fig. 5) are indicative of the possible spin values for the levels from which the transitions occur. The δ values corresponding to the χ^2 minima provide the associated mixing ratios for the transitions involved.

The 1435-keV level, shown in Fig. 2(a), was previously assigned $J^\pi = 4^+$ [25,26]. The excitation function data, however, are in clear disagreement with a spin 4 assignment and favor spin 2 (see Fig. 4). The angular distribution data for the 373-keV γ ray (decaying from the 1435-keV level) shown in Fig. 5, which feeds the 1062-keV 2_3^+ state, is consistent with a pure dipole transition. The excitation function data for the 421-keV γ ray, deexciting the 1483-keV level, support a spin 3 assignment and are consistent with the earlier spin assignment [4] for the level. This state is observed to be strongly populated in the (p,p') reaction with $L = 3$ [26] (see also Fig. 1 in Ref. [27]), which supports its collective octupole character. A spin 4 assignment is made for the newly established 1565-keV level following the excitation function data for the 365-keV γ ray from the level. The angular distributions for these γ rays, shown in Fig. 5, are also consistent with pure dipole transitions. These facts, and the strong similarity to the structure in ^{152}Sm [1,9], lead to the assignment of the 1435-, 1483-, and 1565-keV levels as members of the $K^\pi = 2_1^-$ band.

Table I lists the spectroscopic data for selected low-lying levels, where the relative γ-ray intensities are based on γ-ray singles measurements. For levels with short lifetimes, measurements of the γ-ray energy as a function of angle reveal a Doppler shift, given by the expression

$$E_\gamma(\theta) = E_0\left(1 + F(\tau)\frac{v_{\rm cm}}{c}\cos\theta\right), \quad (2)$$

where E_0 is the energy of the unshifted γ ray, $F(\tau)$ is the experimental Doppler-shift attenuation factor, $v_{\rm cm}$ is the recoil velocity of the nucleus in the center-of-mass frame, and c is the speed of light. The lifetimes of the levels of interest were determined by comparing the measured $F(\tau)$ value(s) [28] [following Eq. (2)] with those calculated using the Winterbon formalism [29].

The data from which the lifetimes of the negative-parity states were deduced are shown in Fig. 6. The only previous report of the lifetime of a negative-parity state in ^{150}Nd is by Zielińska [3] for the 1^- state at 853 keV. This value ($0.52^{+0.07}_{-0.13}$ ps), inferred from Coulomb excitation γ-ray yields, is an order of magnitude longer than ours. The photon scattering study by Pitz *et al.* [18] yields a $B(E1;0_1^+ \to 1_1^-)$ value of $(1.61 \pm 0.63)\times 10^{-4}\ e^2$b [or, $B(E1)\!\downarrow = 3.0(12)$ mW.u.], which agrees well with our value of 3.9(7) mW.u. . Table I presents the $B(E1)$ values deduced from the present work and includes the transitions shown in Figs. 1 and 2 and all other (weaker) $E1$ decays from the negative-parity states. From the observed decay pattern shown in Fig. 1, it is obvious that the negative-parity band is built on the ground-state band rather than on the other excited band as suggested in Ref. [3].

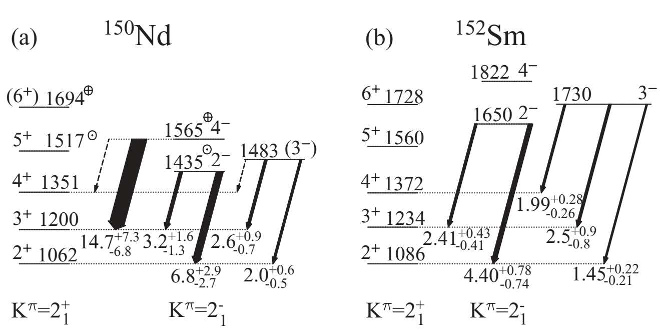

FIG. 2. Comparison of $B(E1)$ values for the transitions between the levels of the $K^\pi = 2_1^-$ and $K^\pi = 2_1^+$ bands of (a) ^{150}Nd and (b) ^{152}Sm. See the caption of Fig. 1 for additional details. Newly established levels and newly assigned spins for the existing levels are marked with ⊕ and ⊙, respectively.

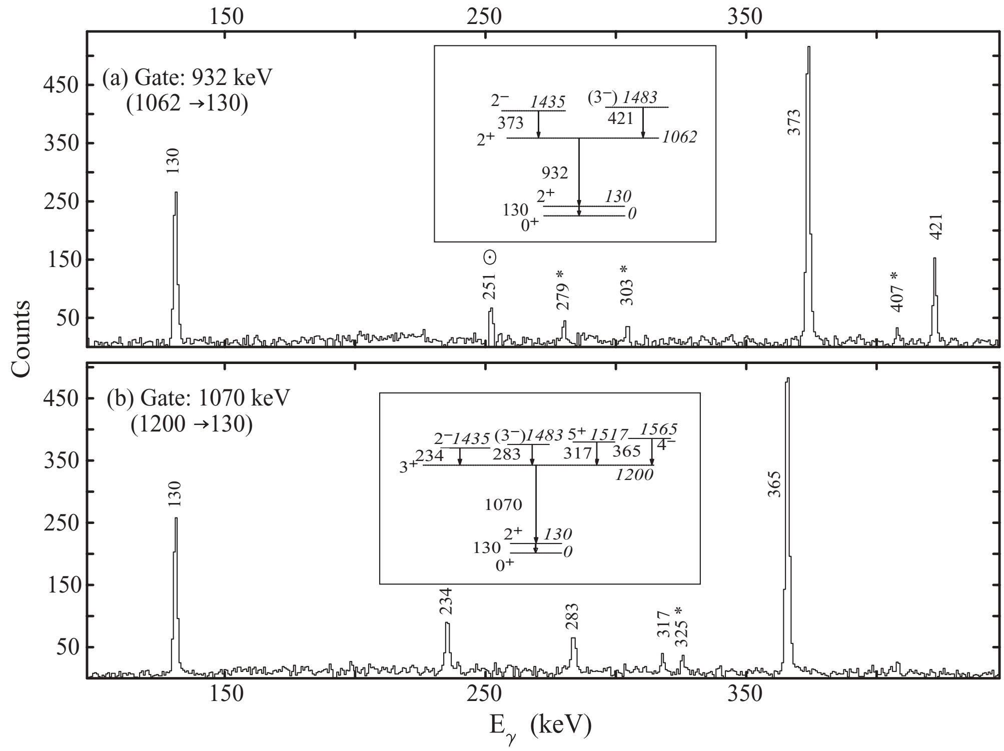

FIG. 3. Portions of γ-γ coincidence spectra with gates set on (a) the 932-keV ($2_3^+ \rightarrow 2_1^+$) γ ray and (b) the 1070-keV ($3_1^+ \rightarrow 2_1^+$) γ ray, which deexcite the 1062- and 1200-keV levels, respectively [cf. Fig. 2(a)]. The transitions marked with an asterisk are assigned to the decays of levels with $E_x > 1.6$ MeV. The 251-keV γ ray, marked with $\odot$, is in coincidence with a second 932-keV γ ray which deexcites an 1867-keV level.

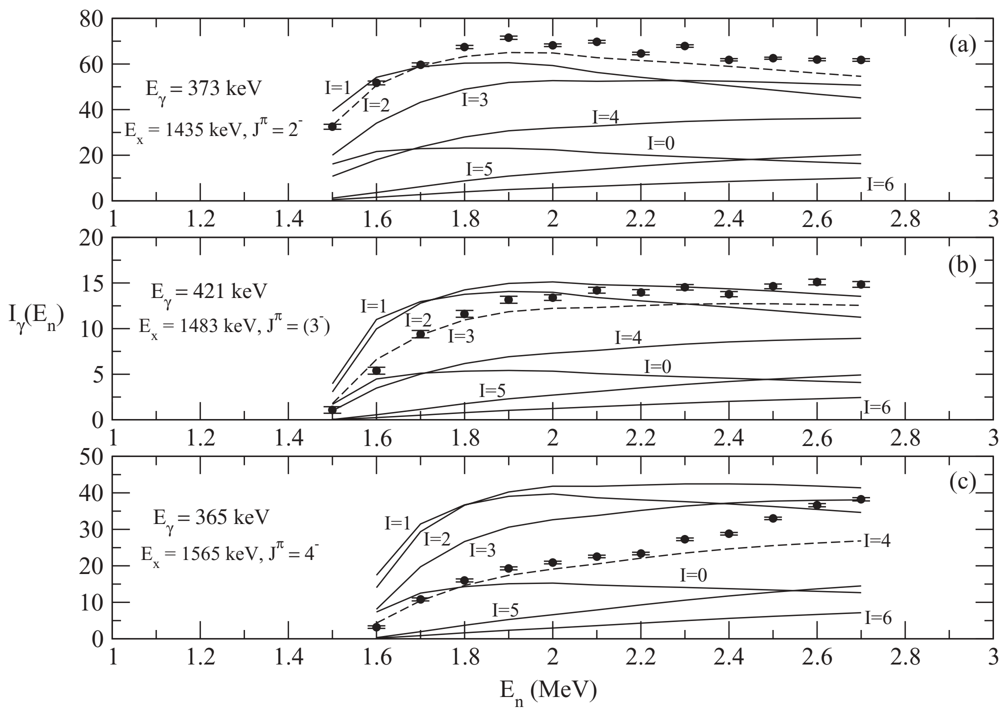

FIG. 4. The excitation function curves of (a) 373-, (b) 421-, and (c) 365-keV γ rays from the 1435-, 1483-, and 1565-keV levels, respectively [cf. Fig. 2(a)]. The experimental results are compared with calculations from the code CINDY [24] for possible spins of the levels with negative parities. The theoretical calculations giving the best fits to the experimental data are shown as dashed lines. The theoretical curves do not include feeding from higher-lying states.

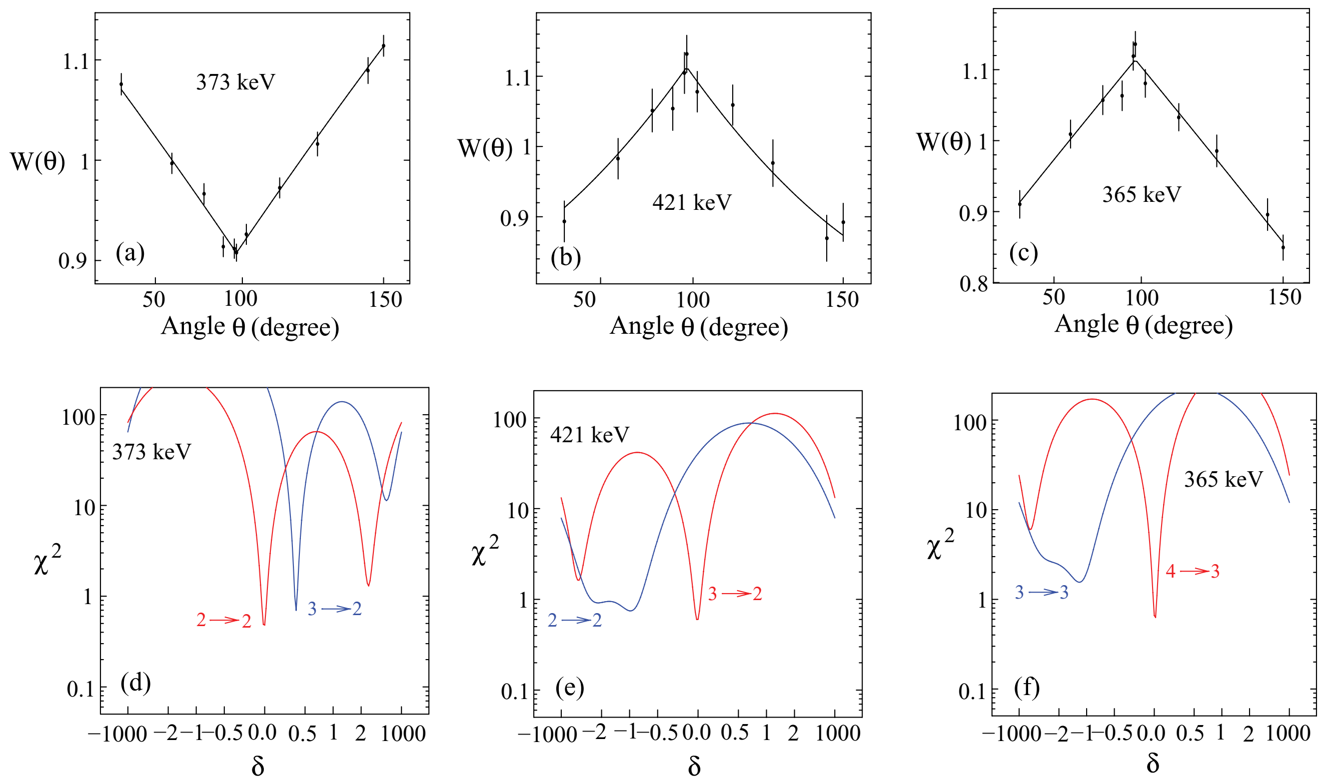

FIG. 5. (Color online) (Top panels (a), (b), and (c): Angular distributions of the 373-, 421-, and 365-keV γ rays from the 1435-, 1483-, and 1565-keV levels, respectively. The abscissa is linear in $\cos^2\theta$, but the axis labels indicate θ. Bottom panels (d), (e), and (f): χ^2 vs δ plots for the transitions [cf. Fig. 2(a)] of interest. Note the logarithmic scale for χ^2. From the fit to the data, the values of [a_2, a_4] obtained for the transitions are [0.18(1), $-$0.00(1)], [$-$0.20(3), 0.03(4)], and [$-$0.23(2), $-$0.00(3)], respectively. The minima at $\delta = 0$ support pure dipole transition assignments, which indicate that the 373-, 421-, and 365-keV transitions are $E1$ in nature and that the 1435-, 1483-, and 1565-keV levels have $J^\pi = 2^-$, 3^-, and 4^-, respectively.

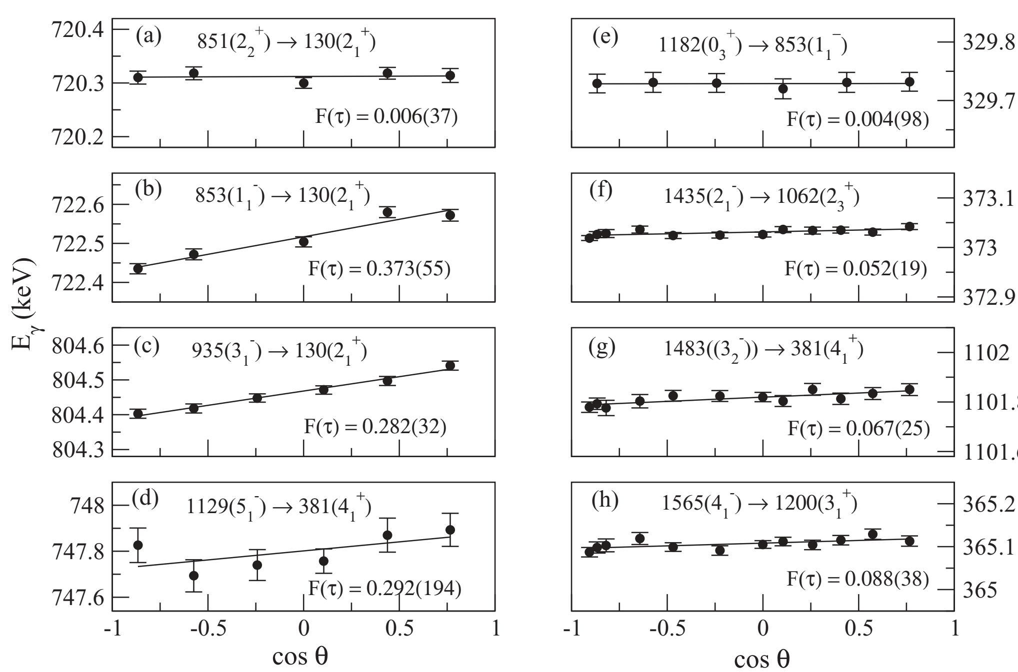

FIG. 6. The measured energies as a function of cos θ for γ rays from several levels of interest. The data presented are from the angular distribution measurements at $E_n = 1.2$ [(a), (b)], 1.4 [(c)–(e)], and 2.05 [(f)–(h)] MeV. Linear fits to the data are shown, and the corresponding $F(\tau)$ values are indicated. The lifetimes of the levels are extracted from these data (see Table I and text for details).

TABLE I. Excitation energies and spin parities of initial (E_i,J_i^π) and final (E_f,J_f^π) levels, γ-ray energies (E_γ), relative γ-ray intensities (I_γ), average experimental level attenuation factors [$\bar{F}(\tau)$], lifetimes (τ), and reduced $E1$ transition probabilities [$B(E1)$ (mW.u. = 10^{-3} W.u.)] for the transitions of interest in ^{150}Nd. The quoted uncertainties of the lifetimes are statistical only. A 3% uncertainty in the efficiencies has been included for the uncertainties of the measured intensities of the transitions.

E_i,J_i^π (keV)	E_f,J_f^π (keV)	E_γ (keV)	I_γ	$\bar{F}(\tau)$	τ (fs)	$B(E1)\downarrow$ (mW.u.)
852.73(3), 1^-	130.19(3), 2^+	722.52(5)	100.0(37)	0.403(35)[a]	66^{+10}_{-8}	7.5(13)
	0.0, 0^+	852.72(5)	85.5(33)			3.9(7)
934.66(4), 3^-	381.43(3), 4^+	553.24(5)	34.8(18)	0.280(29)[b]	117^{+18}_{-15}	$4.5^{+0.9}_{-0.8}$
	130.19(3), 2^+	804.47(5)	100.0(39)			$4.2^{+0.8}_{-0.7}$
1129.19(5), 5^-	720.46(4), 6^+	408.73(6)	15.9(20)	0.292(194)[b]	107^{+288}_{-59}	$6.4^{+9.7}_{-4.9}$
	381.43(3), 4^+	747.80(6)	100.0(48)			$6.7^{+8.8}_{-5.0}$
1434.76(4), 2^-	1200.27(4), 3^+	234.47(5)	12.1(8)	0.052(19)[c]	851^{+510}_{-239}	$3.2^{+1.6}_{-1.3}$
	1061.73(3), 2^+	373.03(5)	100.0(33)			$6.8^{+2.9}_{-2.7}$
	852.73(3), 1^-	582	<1			
	850.51(3), 2^+	584.27(6)	2.9(6)			$0.05^{+0.03}_{-0.02}$
	130.19(3), 2^+	1305	<1			
1483.27(3), (3^-)	1351.24(4), 4^+	132	$\lesssim 27$[d]	0.084(19)[c]	509^{+159}_{-100}	
	1200.27(4), 3^+	283.03(5)	26.4(16)			$2.4^{+0.8}_{-0.7}$
	1137.51(4), 4^+	345.74(9)	6.8(13)			$0.34^{+0.17}_{-0.13}$
	1061.73(3), 2^+	421.49(5)	67.2(26)			$2.0^{+0.4}_{-0.6}$
	850.51(3), 2^+	632.77(6)	9.0(10)			$0.07^{+0.03}_{-0.02}$
	381.43(3), 4^+	1101.83(5)	100.0(39)			0.16(4)
	130.19(3), 2^+	1353.10(5)	87.1(35)			$0.07^{+0.03}_{-0.02}$
1565.38(6), 4^-	1351.24(4), 4^+	214	$\lesssim 9$	0.088(38)[c]	479^{+407}_{-159}	
	1200.27(4), 3^+	365.11(5)	100			$14.7^{+7.3}_{-6.8}$
	381.43(3), 4^+	1184	$\leqslant 2$			

[a]Determined from the 1.2-MeV angular distribution data.
[b]Determined from the 1.4-MeV angular distribution data.
[c]Determined from the 2.05-MeV angular distribution data.
[d]The 132-keV γ ray is obscured by the intense 130-keV ground-state transition, and only an upper limit for the γ-ray intensity is quoted.

III. DISCUSSION

Two aspects of the $B(E1)$ values determined in the present measurements should be noted. First, $B(E1)$ values of >1 mW.u. are regarded as large [9]. Second, as in ^{152}Sm, the yrast $K^\pi = 0^-$ band in ^{150}Nd has large $B(E1)$ values for decay to the $K^\pi = 0^+$ ground-state band. As the octupole nature of the yrast $K^\pi = 0^-$ band in ^{152}Sm is well established, the strong similarity in the $K^\pi = 0^-_1$ bands allows for the firm assignment of the $K^\pi = 0^-_1$ band as an octupole band in ^{150}Nd. Further, the large $B(E1)$ values from the $K^\pi = 2^-_1$ band strongly suggest that octupole correlations are playing a significant role in this excitation as well. This is implicit in the strong population of the 3^- band member at 1483 keV in the (p,p') reaction study by Wu *et al.* [27].

These large $E1$ transition rates between a $K^\pi = 2^-$ and a $K^\pi = 2^+$ band are, to our knowledge, unprecedented beyond the instances in ^{152}Sm and ^{150}Nd. Even for the deformed rare-earth region, members of the observed $K^\pi = 2^-$ bands that have been identified as octupole states [20] decay to the members of the corresponding $K^\pi = 2^+$ bands with $E1$ transition strengths typically less than 1 mW.u. . This observed feature of nuclear structure in ^{150}Nd and ^{152}Sm has not been predicted, as far as we know, and is absent from the recent theoretical descriptions [4,9,15–19] of collective octupole states in nuclei and is also absent from earlier theoretical studies [20,30,31].

We note in the $E1$ decay patterns, evident in Figs. 1 and 2 and Table I, and in the ^{152}Sm study by Garrett *et al.* [9], that the large $B(E1)$ values occur for $\Delta K = 0$ transitions. The $\Delta K = 1$ decays from the $K^\pi = 1^-$ band to the ground-state band are approximately an order of magnitude weaker. The decay preference of $\Delta K = 0$ over $\Delta K = 1$ is similar to other studies (see, e.g., Ref. [32]). To our knowledge this is the first time that such a preference has been established for the decays of a $K^\pi = 2^-$ band to a $K^\pi = 2^+$ γ band.

Some further remarks are in order. A simple coupling of an octupole degree of freedom ($K^\pi = 0^-$, 1^-, 2^-, or 3^-) to a γ vibration ($K^\pi = 2^+$) would result in a range of possible K-bands ($K = 2$; 1 and 3; 0 and 4; 1 and 5). The operation of a $\Delta K = 0, \pm 1$ selection rule for $E1$ transitions would favor the decay pattern $K^\pi = 2^- \rightarrow K^\pi = 2^+$, as observed. However, we are aware of no prediction, or expectation, that the structure reported here should be a systematic feature of nuclei in this (or any other) region.

The properties of ^{150}Nd and ^{152}Sm discussed in the present work depend on radiative strengths which, for parity-changing transitions, are dominated by the $E1$ decay process. However, the underlying structures are believed to be collective octupoles, which are most directly examined by Coulomb excitation and inelastic scattering of charged particles [27]. The present results make a compelling case for such studies of ^{150}Nd.

ACKNOWLEDGMENTS

This material is based upon work supported by the US National Science Foundation under Grant No. PHY-0956310 and by NSERC, Canada. The authors are indebted to H.E. Baber for his expertise in providing excellent proton beams during these experiments. One of the authors (A.C.) would like to thank the governing authority of Krishnath College, Berhampore, West Bengal, India for sanctioning a leave to carry out this research.

[1] E. der Mateosian and J. K. Tuli, Nucl. Data Sheets **75**, 827 (1995).

[2] R. Krücken, B. Albanna, C. Bialik, R. F. Casten, J. R. Cooper, A. Dewald, N. V. Zamfir, C. J. Barton, C. W. Beausang, M. A. Caprio, A. A. Hecht, T. Klug, J. R. Novak, N. Pietralla, and P. von Brentano, Phys. Rev. Lett. **88**, 232501 (2002).

[3] M. Zielińska, Int. J. Mod. Phys. E **13**, 71 (2004).

[4] M. Elvers, S. Pascu, T. Ahmed, T. Ahn, V. Anagnostatou, N. Cooper, C. Deng, J. Endres, P. Goddard, A. Heinz, G. Ilie, E. Jiang, C. Küppersbusch, D. Radeck, D. Savran, N. Shenkov, V. Werner, and A. Zilges, Phys. Rev. C **84**, 054323 (2011).

[5] N. V. Zamfir, H. G. Börner, N. Pietralla, R. F. Casten, Z. Berant, C. J. Barton, C. W. Beausang, D. S. Brenner, M. A. Caprio, J. R. Cooper, A. A. Hecht, M. Krtička, R. Krücken, P. Mutti, J. R. Novak, and A. Wolf, Phys. Rev. C **65**, 067305 (2002).

[6] W. D. Kulp, J. L. Wood, J. M. Allmond, J. Eimer, D. Furse, K. S. Krane, J. Loats, P. Schmelzenbach, C. J. Stapels, R.-M. Larimer, E. B. Norman, and A. Piechaczek, Phys. Rev. C **76**, 034319 (2007).

[7] W. D. Kulp, J. L. Wood, P. E. Garrett, J. M. Allmond, D. Cline, A. B. Hayes, H. Hua, K. S. Krane, R.-M. Larimer, J. Loats, E. B. Norman, P. Schmelzenbach, C. J. Stapels, R. Teng, and C. Y. Wu, Phys. Rev. C **71**, 041303(R) (2005).

[8] P. E. Garrett, W. D. Kulp, J. L. Wood, D. Bandyopadhyay, S. Christen, S. Choudry, A. Dewald, A. Fitzler, C. Fransen, K. Jessen, J. Jolie, A. Kloezer, P. Kudejova, A. Kumar, S. R. Lesher, A. Linnemann, A. Lisetskiy, D. Martin, M. Masur, M. T. McEllistrem, O. Möller, M. Mynk, J. N. Orce, P. Pejovic, T. Pissulla, J. M. Regis, A. Schiller, D. Tonev, and S. W. Yates, J. Phys. G **31**, S1855 (2005).

[9] P. E. Garrett, W. D. Kulp, J. L. Wood, D. Bandyopadhyay, S. Choudry, D. Dashdorj, S. R. Lesher, M. T. McEllistrem, M. Mynk, J. N. Orce, and S. W. Yates, Phys. Rev. Lett. **103**, 062501 (2009).

[10] D. Tonev, A. Dewald, T. Klug, P. Petkov, J. Jolie, A. Fitzler, O. Möller, S. Heinze, P. von Brentano, and R. F. Casten, Phys. Rev. C **69**, 034334 (2004).

[11] W. D. Kulp, J. L. Wood, K. S. Krane, J. Loats, P. Schmelzenbach, C. J. Stapels, R.-M. Larimer, and E. B. Norman, Phys. Rev. Lett. **91**, 102501 (2003).

[12] W. D. Kulp, J. L. Wood, K. S. Krane, J. Loats, P. Schmelzenbach, C. J. Stapels, R.-M. Larimer, and E. B. Norman, Phys. Rev. C **69**, 064309 (2004).

[13] J. F. Sharpey-Schafer, S. M. Mullins, R. A. Bark, J. Kau, F. Komati, E. A. Lawrie, J. J. Lawrie, T. E. Madiba, P. Maine, A. Minkova, S. H. T. Murray, N. J. Ncapayi, and P. A. Vymers, Eur. Phys. J. A **47**, 5 (2011).

[14] T. Kibédi and R. H. Spear, At. Data Nucl. Data Tables **80**, 35 (2002).

[15] N. Minkov, P. Yotov, S. Drenska, W. Scheid, D. Bonatsos, D. Lenis, and D. Petrellis, Phys. Rev. C **73**, 044315 (2006).

[16] W. Zhang, Z. P. Li, S. Q. Zhang, and J. Meng, Phys. Rev. C **81**, 034302 (2010).

[17] P. G. Bizzeti and A. M. Bizzeti-Sona, Phys. Rev. C **81**, 034320 (2010).

[18] H. H. Pitz, R. D. Heil, U. Kneissl, S. Lindenstruth, U. Seemann, R. Stock, C. Wesselborg, A. Zilges, P. von Brentano, S. D. Hoblit, and A. M. Nathan, Nucl. Phys. A **509**, 587 (1990).

[19] M. Babilon, N. V. Zamfir, D. Kusnezov, E. A. McCutchan, and A. Zilges, Phys. Rev. C **72**, 064302 (2005).

[20] A. F. Barfield, B. R. Barrett, J. L. Wood, and O. Scholten, Ann. Phys. (NY) **182**, 344 (1988).

[21] N. V. Zamfir and D. Kusnezov, Phys. Rev. C **67**, 014305 (2003).

[22] J. Theuerkauf, S. Esser, S. Krink, M. Luig, N. Nicolay, O. Stuch, and H. Wolters, computer code TV, 1993 (unpublished), http://www.ikp.uni-koeln.de/~fitz

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

[24] E. Sheldon and V. C. Rogers, Comput. Phys. Commun. **6**, 99 (1973); P. A. Moldauer, Phys. Rev. C **14**, 764 (1976).

[25] R. K. J. Sandor, H. P. Blok, M. Girod, M. N. Harakeh, C. W. de Jager, and H. de Vries, Nucl. Phys. A **551**, 349 (1993).

[26] M. Pignanelli, N. Blasi, J. A. Bordewijk, R. De Leo, M. N. Harakeh, M. A. Hofstee, S. Micheletti, R. Perrino, V. Yu. Ponomarev, V. G. Soloviev, A. V. Sushkov, and S. Y. van der Werf, Nucl. Phys. A **559**, 1 (1993).

[27] H. C. Wu, A. E. L. Dieperink, O. Scholten, M. N. Harakeh, R. De Leo, M. Pignanelli, and I. Morrison, Phys. Rev. C **38**, 1638 (1988).

[28] T. Belgya, G. Molnár, and S. W. Yates, Nucl. Phys. A **607**, 43 (1996).

[29] K. B. Winterbon, Nucl. Phys. A **246**, 293 (1975).

[30] P. Butler and W. Nazarewicz, Rev. Mod. Phys. **68**, 349 (1996).

[31] K. Neergård and P. Vogel, Nucl. Phys. A **145**, 33 (1970).

[32] J. Konijn, F. W. N. De Boer, A. Van Poelgeest, W. H. A. Hesselink, M. J. A. De Voigt, H. Verheul, and O. Scholten, Nucl. Phys. A **352**, 191 (1981).