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Tilted axis rotation, candidates for chiral bands and wobbling motion in ^{138}Nd

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High-spin states in ^{138}Nd were investigated using the reaction $^{94}\text{Zr}(^{48}\text{Ca},4n)$ and γ -ray coincidences were acquired with the GASP spectrometer. A rich level scheme was developed including 4 bands of negative parity at low spins, 8 bands of dipole transitions and 8 bands of quadrupole transitions at medium spins. The unpaired version of the Cranked Shell Model, the Tilted Axis Cranking model and the cranked Nilsson+BCS calculations have been used to assign configurations to the observed bands. Various types of rotation are observed in ^{138}Nd : around a principal axis, like in the case for the negative-parity low-spin bands and most of the bands of quadrupole transitions, as well as around a tilted axis, like in the case of most of the observed dipole bands. The rotational mode in the dipole bands has an intermediate character, between magnetic and collective electric rotation. A pair of dipole bands are candidates for chiral partners, which is the first case in an even-even nucleus. The possible existence of the wobbling mode at low deformation and medium spins in ^{138}Nd is discussed. The consistent interpretation of the multitude of observed bands strongly supports the existence of stable triaxial deformation at medium spins in ^{138}Nd .

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Keywords: Nuclear reaction: $^{94}\text{Zr}(^{48}\text{Ca},4n)^{138}\text{Nd}$; $E = 195$ and 188 MeV; Measured $\gamma\gamma$ -coincidences; E_γ ; I_γ ; DCO ratios; ^{138}Nd deduced levels; spin and parity; model calculation

I. INTRODUCTION

The existence of triaxially deformed nuclei is a long standing debate. Soft and rigid triaxiality have been proposed since long time [1, 2], and many theoretical and experimental studies were devoted to this intriguing phenomenon. In more recent times two unique fingerprints of the triaxiality in nuclei, the wobbling motion [3] and the dynamic chirality [4, 5], were intensively studied. These exotic types of motion were observed in specific regions of the nuclear chart, the wobbling motion in the odd-even Lu nuclei with $A \sim 160$ [6], the chirality primarily in the odd-odd and odd-even nuclei with $A \sim 130$ nuclei [4, 7, 8]. In several nuclei around ^{138}Nd , the nucleus studied in the present paper, we have observed rotational bands as medium and high spins, like in $^{136-140}\text{Nd}$, with properties which are in agreement with model calculations predicting triaxial shapes [9–13]. In the same mass region nearly degenerate bands have been observed and interpreted as chiral partners, in nuclei like ^{134}Pr and ^{135}Nd [4, 7, 8], which have as primary prerequisite a triaxial shape of the nuclear

core. The shape evolution from axial to triaxial has been discussed in ^{136}Nd [9], the stable triaxiality at high-spin has been proposed in $^{138,139,140}\text{Nd}$ [11–13], a highly deformed band in ^{138}Nd [14] and a superdeformed (SD) band in ^{140}Nd [15].

The present study is devoted to ^{138}Nd and reports states at low and medium spins. The level scheme has been developed up to much higher spins and excitation energy of around $45 \hbar$ and 24 MeV, respectively, but the high-spin bands will be published in a separate paper [16]. Many new excited levels were established at low and medium spins, leading to a very rich and complete level scheme. Among those particular interest presents one band of quadrupole transitions which is interpreted as manifestation of the wobbling mode and several dipole bands interpreted within the cranking model as rotations around a principal or a tilted axis of the intrinsic reference system. Such a variety of excitations in a single nucleus, most of them being explained assuming a triaxial shape, makes ^{138}Nd one of the best example of stable triaxiality at medium and high spins.

The level structure of ^{138}Nd was first studied using a $(p, 4n)$ reaction by Yoshikawa [17] and through the β^+ decay of ^{138}Pm by Deslauriers *et al.* [18]. High-spin states in ^{138}Nd have been previously studied by Müller-Veggian *et al.* [19, 20] and de Angelis *et al.* [21] up to spin 19 and 21 \hbar , respectively. More recently, four high-spin bands were observed in ^{138}Nd using the $^{94}\text{Zr}(^{48}\text{Ca}, 4n)$ reaction at an energy 195 MeV [11]. Gamma-ray coincidences were measured with the 8π spectrometer consisting of 20 Ge detectors with anti-Compton shields and an inner ball of 71 BGO scintillator detectors. Two of the four observed bands were linked to low-lying states. A highly-deformed band was also reported from a GASP experiment using the same $^{94}\text{Zr}(^{48}\text{Ca}, 4n)$ reaction at beam energies of 188 and 195 MeV [14]. The linking transitions of the highly-deformed band to low-lying states were not identified, therefore the spins and parity were not determined experimentally.

The details of the experimental setup are briefly discussed in section II. The results including the level scheme are presented in section III. The configurations of the different bands are discussed in section IV on the basis of theoretical calculation using the unpaired version of the Cranked Shell Model (CSM) [22], the Tilted Axis Cranking (TAC) model [5, 23, 24] and the Cranked Nilsson+BCS formalism [25–27]. Finally, the configuration assignments, the summary and acknowledgment are given in sections V, VI and VII.

II. EXPERIMENTAL DETAILS

High-spin states in ^{138}Nd have been populated via the $^{94}\text{Zr}(^{48}\text{Ca}, 4n)$ reaction at beam energies of 188 and 195 MeV. The target consisted of a stack of two self-supporting ^{94}Zr foils of $400 \mu\text{g}/\text{cm}^2$ thickness each. The ^{48}Ca beam of 3 – 4 pA was provided by the XTU Tandem accelerator of the Laboratori Nazionali di Legnaro. The GASP array with 40 Compton-suppressed Ge detectors and the 80-element BGO ball has been used for a standard γ - γ coincidence measurement. Events were collected when at least three suppressed Ge detectors and three BGO detectors of the inner ball fired in coincidence. A total of 1.9×10^9 triple- or higher-fold events has been collected. The ^{138}Nd nucleus was one of the most intensely populated in the reaction, with about 30% of the fusion cross section.

In order to search for discrete bands we have produced a fully symmetrized cube of triple coincident γ -transitions, from which we extracted γ - γ matrices gated on selected transitions of ^{138}Nd . From the coincidence relationships we could assign to ^{138}Nd many new transitions which are organized in several bands. The transition multipolarities have been extracted from the DCO ratios using the procedure described in ref. [7].

III. RESULTS AND LEVEL SCHEME

The level scheme of ^{138}Nd is shown in Fig. 1. Most of the observed transitions were grouped in 4 bands of negative parity at low spins (N1 - N4), 8 bands at medium spins (L1 - L8) and 8 bands of dipole transitions (D1 - D8). We also draw the levels which were assigned to the γ -band from β -decay studies [18], even though they were not observed in the present experiment. The energies, relative intensities, DCO ratios and spin-parity assignments of the observed transitions are reported in Table I. The spectroscopic data on ^{138}Nd are very much enriched with respect to the previous studies [11, 17–21]. The newly developed level scheme will be discussed separately for the bands of quadrupole and dipole transitions.

^{138}Nd

(low- and medium-spin bands)

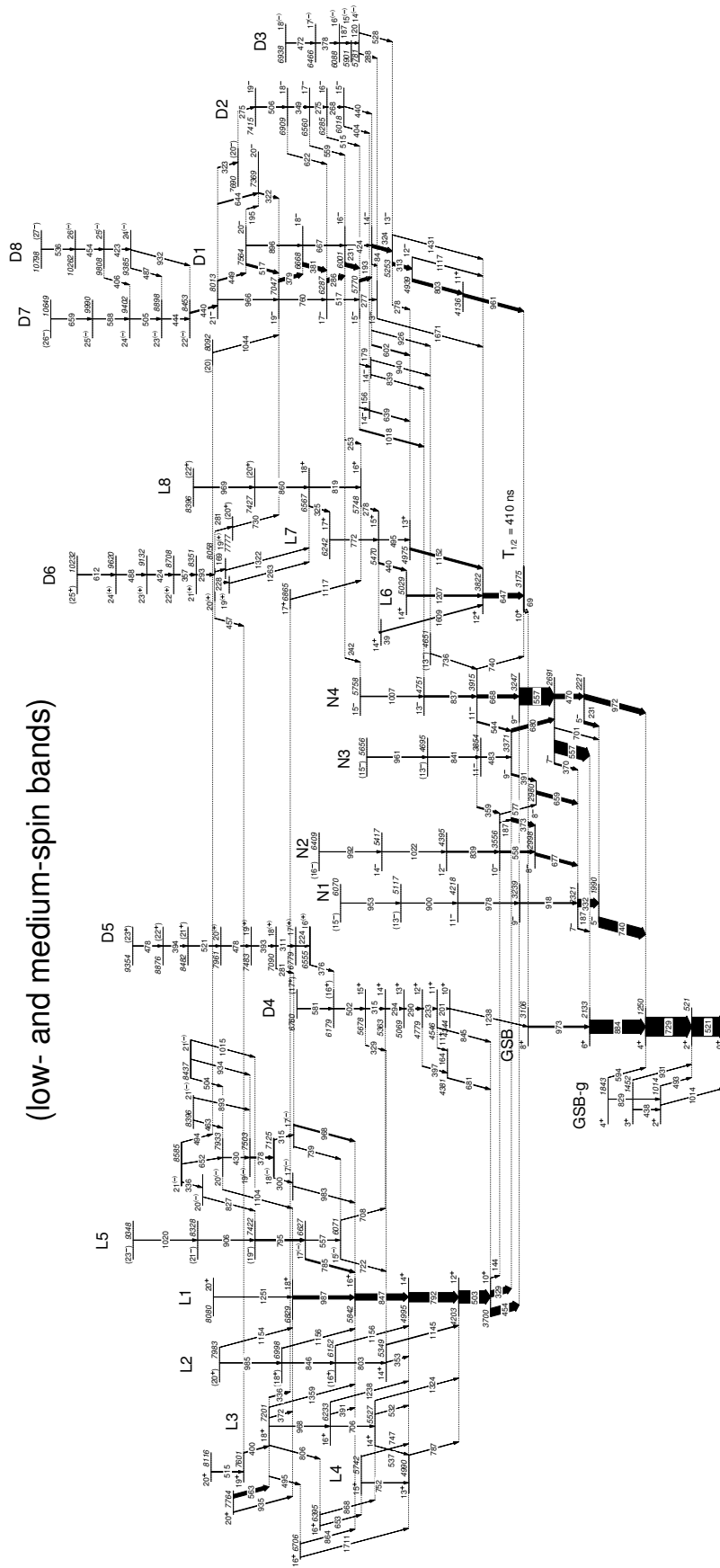


FIG. 1: Partial level scheme of ^{138}Nd showing the low- and medium-spin states.

TABLE I: Energies, intensities, DCO ratios, multipolarities and spin-parity assignments of γ -ray transitions of ^{138}Nd . The transitions are grouped in bands and the transitions connecting a given band to low-lying states are listed at the end of each band separated by a blank line.

γ -ray Energy ^a E $_{\gamma}$ (keV)	Intensity ^b I $_{\gamma}$ (%)	DCO ratios ^c		Multipolarity	J $_i^{\pi}$ \rightarrow J $_f^{\pi}$
		Gate on E2	Gate on M1		
g-Band					
520.8	100	0.90(5)		E2	2 ⁺ \rightarrow 0 ⁺
728.7	100	0.99(5)		E2	4 ⁺ \rightarrow 2 ⁺
883.9	70	1.03(4)		E2	6 ⁺ \rightarrow 4 ⁺
972.9	7.7		1.74(87)	E2	8 ⁺ \rightarrow 6 ⁺
γ-Band^d					
438					3 ⁺ \rightarrow 2 ⁺
829					4 ⁺ \rightarrow 2 ⁺
493					2 ⁺ \rightarrow 2 ⁺
594					4 ⁺ \rightarrow 4 ⁺
931					3 ⁺ \rightarrow 2 ⁺
1014					2 ⁺ \rightarrow 0 ⁺
Band N1					
186.5	3.5				7 ⁻ \rightarrow 6 ⁺
331.5	38.5	1.03(5)		E2	7 ⁻ \rightarrow 5 ⁻
918.1	4.9	1.09(28)	1.51(30)	E2	9 ⁻ \rightarrow 7 ⁻
978.2	3.7	1.16(38)		E2	11 ⁻ \rightarrow 9 ⁻
900.0	2.1				(13 ⁻) \rightarrow 11 ⁻)
952.6	0.8				(15 ⁻) \rightarrow 13 ⁻)
740.2	52	0.55(12)		E1	5 ⁻ \rightarrow 4 ⁺
Band N2					
558.0	10	0.95(18)		E2	10 ⁻ \rightarrow 8 ⁻
838.9	6	0.91(18)		E2	12 ⁻ \rightarrow 10 ⁻
1022.2	1.5	1.05(14)		E2	14 ⁻) \rightarrow 12 ⁻
991.9	<1				(16 ⁻) \rightarrow 14 ⁻
186.7	1.2				10 ⁻ \rightarrow 9 ⁻
576.9	1.5				10 ⁻ \rightarrow 8 ⁻
677.0	14.2	0.62(36)		M1/E2	8 ⁻ \rightarrow 7 ⁻
Band N3					
483.5	2	0.86(15)		E2	11 ⁻ \rightarrow 9 ⁻
840.6	2				(13 ⁻) \rightarrow 11 ⁻
960.9	1.8				(15 ⁻) \rightarrow (13 ⁻)
372.7	18.5	0.58(4)		M1/E2	9 ⁻ \rightarrow 8 ⁻
391.0	8.2	0.66(10)		M1/E2	9 ⁻ \rightarrow 8 ⁻
658.8	16.9	0.52(7)		M1/E2	8 ⁻ \rightarrow 7 ⁻
680.0	17.2	0.74(40)		E2	9 ⁻ \rightarrow 7 ⁻
Band N4					
469.8	23.4	1.02(13)		E2	7 ⁻ \rightarrow 5 ⁻
556.7	88.6	0.96(12)		E2	9 ⁻ \rightarrow 7 ⁻
668.0	16	1.09(9)		E2	11 ⁻ \rightarrow 9 ⁻
836.7	7.4	0.88(32)	1.47(17)	E2	13 ⁻ \rightarrow 11 ⁻
1007.1	3.0	0.90(25)		E2	15 ⁻ \rightarrow 13 ⁻
230.7	12.5				5 ⁻ \rightarrow 5 ⁻
359.0	6	0.76(49)		M1/E2	11 ⁻ \rightarrow 10 ⁻
369.8	6.6	1.08(10)		M1/E2	7 ⁻ \rightarrow 7 ⁻

543.9	6.3	1.00(60)		E2	$11^- \rightarrow 9^-$
557.3	63		1.21(8)	E1/M2	$7^- \rightarrow 6^+$
701.2	2.6				$7^- \rightarrow 5^-$
740.4	7				$11^- \rightarrow 10^+$
971.7	26	0.57(7)		E1	$5^- \rightarrow 4^+$
Band L1					
502.8	64	0.87(10)	1.55(9)	E2	$12^+ \rightarrow 10^+$
792.1	49.4	1.10(15)		E2	$14^+ \rightarrow 12^+$
846.7	33		1.95(53)	E2	$16^+ \rightarrow 14^+$
986.7	17.5	1.01(16)		E2	$18^+ \rightarrow 16^+$
1251.0	1.3	0.95(44)		E2	$20^+ \rightarrow 18^+$
143.7	0.7	0.63(35)		E1/M2	$10^+ \rightarrow 10^-$
329.1	32	0.69(5)		E1/M2	$10^+ \rightarrow 9^-$
453.6	42	0.62(2)		E1/M2	$10^+ \rightarrow 9^-$
Band L2					
803.0	0.6				$(16^+) \rightarrow 14^+$
845.9	2.5				$(18^+) \rightarrow (16^+)$
985.4	3				$(20^+) \rightarrow (18^+)$
353.4	2.3	0.74(15)	0.83(50)	M1/E2	$14^+ \rightarrow 14^+$
1145.4	3.2	1.53(35)	2.88(164)	E2	$14^+ \rightarrow 12^+$
1154.2	1				$(20^+) \rightarrow 18^+$
1155.5	1.8	0.93(40)		(E2)	$(18^+) \rightarrow 16^+$
1156.4	1.4				$(16^+) \rightarrow 14^+$
Band L3					
705.8	0.7		2.08(60)	E2	$16^+ \rightarrow 14^+$
967.8	2.2				$18^+ \rightarrow 16^+$
336.2	3.5		1.37(34)	M1/E2	$18^+ \rightarrow 17^+$
372.3	2.0				$18^+ \rightarrow 18^+$
390.9	1				$16^+ \rightarrow 16^+$
399.5	3.5		0.73(15)	M1/E2	$19^+ \rightarrow 18^+$
494.6	2.4	0.95(11)		E2	$18^+ \rightarrow 16^+$
514.4	1		1.06(18)	M1/E2	$20^+ \rightarrow 19^+$
532.1	0.6	1.09(25)		M1/E2	$14^+ \rightarrow 14^+$
537.3	0.5	0.58(25)		M1/E2	$14^+ \rightarrow 13^+$
806.2	2.2	0.88(19)		E2	$18^+ \rightarrow 16^+$
1237.7	1				$16^+ \rightarrow 14^+$
1323.7	0.4				$14^+ \rightarrow 12^+$
1358.6	1.0	0.88(20)		E2	$18^+ \rightarrow 16^+$
Band L4					
752.3	0.5				$15^+ \rightarrow 13^+$
653.1	1	0.29(19)		M1/E2	$16^+ \rightarrow 15^+$
747.0	1.2	0.27(4)		M1/E2	$15^+ \rightarrow 14^+$
786.8	1.9		0.50(20)	M1/E2	$13^+ \rightarrow 12^+$
864.5	2				$16^+ \rightarrow 16^+$
867.8	0.7				$16^+ \rightarrow 14^+$
1117.4	2		0.57(25)	M1/E2	$17^+ \rightarrow 16^+$
1711.4	0.7				$16^+ \rightarrow 14^+$
Band L5					
556.6	0.25				$17^{(-)} \rightarrow 15^{(-)}$
794.6	6.9		1.99(175)	(E2)	$(19^-) \rightarrow 17^{(-)}$
906.4	2.5		1.33(40)	(E2)	$(21^-) \rightarrow (19^-)$
1019.8	1.6				$(23^-) \rightarrow (21^-)$

708.4	0.06		0.52(30)	(E1)	$15^{(-)} \rightarrow 14^{+}$
722.4	0.18		1.38(28)	(E1/M2)	$15^{(-)} \rightarrow 14^{+}$
785.4	7.4	0.68(6)		(E1/M2)	$17^{(-)} \rightarrow 16^{+}$
Band L6					
646.9	24	0.87(13)	2.4(4)	E2	$12^{+} \rightarrow 10^{+}$
1206.7	7.2	1.00(11)		E2	$14^{+} \rightarrow 12^{+}$
Band L7					
494.7	2.2	0.96(40)		E2	$15^{+} \rightarrow 13^{+}$
772.4	2.7	0.97(31)		E2	$17^{+} \rightarrow 15^{+}$
38.7	< 1				$15^{+} \rightarrow 14^{+}$
440.2	6.4	0.61(17)		M1/E2	$15^{+} \rightarrow 14^{+}$
1152.3	10.7	0.37(4)		M1/E2	$13^{+} \rightarrow 12^{+}$
Band L8					
818.6	1.9		1.74(27)	E2	$18^{+} \rightarrow 16^{+}$
859.7	2.6		1.35(55)	(E2)	$(20^{+}) \rightarrow 18^{+}$
968.9	2.9	0.94(59)		(E2)	$(22^{+}) \rightarrow (20^{+})$
278.4	4.0	0.36(7)		M1/E2	$16^{+} \rightarrow 15^{+}$
324.8	3	0.39(12)		M1/E2	$18^{+} \rightarrow 17^{+}$
1608.7	3.4	0.90(15)	1.28(28)	E2	$14^{+} \rightarrow 12^{+}$
Band D1					
83.6	0.16				$14^{-} \rightarrow (13^{-})$
193.4	12.3	0.60(7)	0.90(13)	M1/E2	$15^{-} \rightarrow 14^{-}$
277.0	0.3				$15^{-} \rightarrow 13^{-}$
230.6	18.2	0.57(9)	0.87(4)	M1/E2	$16^{-} \rightarrow 15^{-}$
286.2	21.4	0.61(5)		M1/E2	$17^{-} \rightarrow 16^{-}$
380.8	19	0.58(5)		M1/E2	$18^{-} \rightarrow 17^{-}$
378.8	16	0.54(7)		M1/E2	$19^{-} \rightarrow 18^{-}$
517.5	10		0.91(8)	M1/E2	$20^{-} \rightarrow 19^{-}$
448.7	5.3		0.83(5)	M1/E2	$21^{-} \rightarrow 20^{-}$
156.4	1.5	0.63(17)		M1/E2	$15^{-} \rightarrow 14^{-}$
179.0	0.3	0.97(12)		M1/E2	$15^{-} \rightarrow 14^{-}$
193.6	0.8				$20^{-} \rightarrow 20^{-}$
242.2	0.3				$16^{-} \rightarrow 15^{-}$
252.9	0.04		0.92(20)	E1	$16^{-} \rightarrow 16^{+}$
278.0	0.7				$13^{-} \rightarrow 13^{+}$
313.4	15.4	0.77(19)		M1/E2	$13^{-} \rightarrow 12^{-}$
323.2	1.2				$21^{-} \rightarrow (20^{-})$
322.4	3.3				$20^{-} \rightarrow 19^{-}$
323.7	15.8	0.60(10)		M1/E2	$14^{-} \rightarrow 13^{-}$
424.0	1				$16^{-} \rightarrow 14^{-}$
516.7	2.1				$17^{-} \rightarrow 15^{-}$
602.2	4.9	0.52(6)		E1	$14^{-} \rightarrow 13^{+}$
639.3	3.4	0.53(15)		E1	$14^{-} \rightarrow 13^{+}$
643.6	4.4		1.04(15)	M1/E2	$21^{-} \rightarrow 20^{-}$
667.0	1				$18^{-} \rightarrow 16^{-}$
736.4	1				$(13^{-}) \rightarrow 11^{-}$
759.6	1				$19^{-} \rightarrow 17^{-}$
803.1	15		0.93(9)	E1	$12^{-} \rightarrow 11^{+}$
838.8	0.2				$14^{-} \rightarrow 13^{-}$
896.3	0.6				$20^{-} \rightarrow 18^{-}$
925.6	1.2				$14^{-} \rightarrow (13^{-})$
939.5	0.2				$14^{-} \rightarrow (13^{-})$
961.1	15		0.61(5)	M1/E2	$11^{+} \rightarrow 10^{+}$
966.2	0.8				$21^{-} \rightarrow 19^{-}$

1018.3	5.9	1.06(20)	1.8(8)	E2	$15^- \rightarrow 13^-$
1117.3	2.6	0.75(15)		E1/M2	$12^- \rightarrow 12^+$
1430.9	1				$13^- \rightarrow 12^+$
1670.9	1.2	0.79(47)	1.45(45)	(E1)	$(13^-) \rightarrow 12^+$
Band D2					
267.5	0.13		1.05(10)	M1/E2	$16^- \rightarrow 15^-$
275.2	1.9		1.06(10)	M1/E2	$17^- \rightarrow 16^-$
349.0	1.0		0.95(10)	M1/E2	$18^- \rightarrow 17^-$
505.6	0.8		0.86(34)	M1/E2	$19^- \rightarrow 18^-$
275.1	<1				$(20^-) \rightarrow 19^-$
403.5	<0.1		0.97(25)	M1/E2	$15^- \rightarrow 14^-$
440.1	<0.1		0.94(20)	M1/E2	$15^- \rightarrow 14^-$
514.6	1.1		0.86(23)	M1/E2	$16^- \rightarrow 15^-$
559.2	0.3		0.72(36)	M1/E2	$17^- \rightarrow 16^-$
622.0	<0.06				$18^- \rightarrow 17^-$
Band D3					
120.3	0.1		1.19(16)	M1/E2	$15^{(-)} \rightarrow 14^{(-)}$
186.8	1.2		1.44(36)	M1/E2	$16^{(-)} \rightarrow 15^{(-)}$
377.6	1		0.75(8)	M1/E2	$17^{(-)} \rightarrow 16^{(-)}$
471.8	0.1		0.86(25)	M1/E2	$18^{(-)} \rightarrow 17^{(-)}$
288.0	1.2		0.88(19)	(M1/E2)	$14^{(-)} \rightarrow (13^-)$
528.2	0.5		1.00(35)	(M1/E2)	$14^{(-)} \rightarrow 13^-$
Band D4					
201.2	2.5	0.73(25)		M1/E2	$11^+ \rightarrow 10^+$
233.0	4.9		0.90(23)	M1/E2	$12^+ \rightarrow 11^+$
290.3	4.7		0.93(10)	M1/E2	$13^+ \rightarrow 12^+$
293.8	4.0		0.84(15)	M1/E2	$14^+ \rightarrow 13^+$
314.9	1.8		1.12(32)	M1/E2	$15^+ \rightarrow 14^+$
501.6	2.8				$(16^+) \rightarrow 15^+$
580.6	0.9				$(17^+) \rightarrow (16^+)$
164.1	0.2		0.46(18)	M1/E2	$11^+ \rightarrow 11^+$
328.9	1				$15^+ \rightarrow 14^+$
397.3	2.8		0.78(11)	M1/E2	$12^+ \rightarrow 11^+$
681.2	3.0		0.77(12)	M1/E2	$11^+ \rightarrow 10^+$
845.0	1.9				$11^+ \rightarrow 10^+$
1238.0	0.7		1.96(98)	E2	$10^+ \rightarrow 8^+$
Band D5					
224.4	1.1		0.97(15)	M1/E2	$17^{(+)} \rightarrow 16^{(+)}$
310.6	1.1		1.09(16)	M1/E2	$18^{(+)} \rightarrow 17^{(+)}$
393.4	1.0		1.00(12)	M1/E2	$19^{(+)} \rightarrow 18^{(+)}$
394.4	0.2		1.00(12)	(M1/E2)	$(22^+) \rightarrow (21^+)$
477.9	0.2		1.00(55)	(M1/E2)	$(23^+) \rightarrow (22^+)$
478.0	0.5		1.00(55)	M1/E2	$20^{(+)} \rightarrow 19^{(+)}$
521.3	<0.2				$(21^+) \rightarrow 20^{(+)}$
280.9	0.7		0.99(20)	(E1)	$18^{(+)} \rightarrow 17^{(-)}$
376.1	0.5		1.32(47)	(M1/E2)	$16^{(+)} \rightarrow (16^+)$
Band D6					
228.0	1.5		1.22(18)	M1/E2	$20^{(+)} \rightarrow 19^{(+)}$
293.4	3.9	0.20(14)	1.00(60)	M1/E2	$21^{(+)} \rightarrow 20^{(+)}$
356.7	3.8	0.27(30)		M1/E2	$22^{(+)} \rightarrow 21^{(+)}$
424.4	4.3		1.00(15)	M1/E2	$23^{(+)} \rightarrow 22^{(+)}$
487.9	3		0.91(15)	M1/E2	$24^{(+)} \rightarrow 23^{(+)}$

611.6	3.7				$(25^+) \rightarrow 24^{(+)}$
169.9	1.0			(M1/E2)	$20^{(+)} \rightarrow 19^{(+)}$
281.4	0.06				$20^- \rightarrow (20^+)$
456.9	2.4		0.95(12)	(M1/E2)	$20^{(+)} \rightarrow 19^+$
730.3	0.06				$(20^+) \rightarrow 19^-$
1262.8	1.1	0.40(28)	0.65(52)	(M1/E2)	$19^{(+)} \rightarrow 18^+$
1322.4	1			(M1/E2)	$19^{(+)} \rightarrow 18^+$
Band D7					
444.4	2.7		0.87(5)	M1/E2	$23^{(-)} \rightarrow 22^{(-)}$
504.6	2.3		1.05(25)	M1/E2	$24^{(-)} \rightarrow 23^{(-)}$
587.7	1.5		1.06(35)	M1/E2	$25^{(-)} \rightarrow 24^{(-)}$
659.3	<1				$(26^-) \rightarrow 25^{(-)}$
439.9	6.7		0.87(5)	M1/E2	$22^{(-)} \rightarrow 21^-$
Band D8					
423.4	2.0		0.95(20)	M1/E2	$25^{(-)} \rightarrow 24^{(-)}$
454.4	0.8		1.12(20)	M1/E2	$26^{(-)} \rightarrow 25^{(-)}$
536.0	< 0.3				$(27^-) \rightarrow 26^{(-)}$
406	<0.1				$25^{(-)} \rightarrow 24^{(-)}$
487.8	<1		1.06(16)	M1/E2	$24^{(-)} \rightarrow 23^{(-)}$
931.5	< 2				$24^{(-)} \rightarrow 22^{(-)}$
High-spin negative-parity levels					
300.0	1.0		1.41(50)	M1/E2	$18^{(-)} \rightarrow 17^{(-)}$
315.2	1.8		1.04(25)	M1/E2	$18^{(-)} \rightarrow 17^{(-)}$
335.9	0.2	0.61(5)		M1/E2	$21^{(-)} \rightarrow 20^{(-)}$
378.0	5.9	1.11(11)	0.73(15)	M1/E2	$19^{(-)} \rightarrow 18^{(-)}$
430.4	2.3		0.68(17)	M1/E2	$20^{(-)} \rightarrow 19^{(-)}$
462.5	1.2		0.94(7)	M1/E2	$21^{(-)} \rightarrow 20^{(-)}$
493.8	0.37				$21^- \rightarrow (20)$
651.9	1.1		1.10(25)	M1/E2	$21^{(-)} \rightarrow 20^{(-)}$
738.9	1.0				$17^{(-)} \rightarrow 15^{(-)}$
826.7	0.2		1.65(81)	M1/E2	$20^{(-)} \rightarrow (19^-)$
893.1	0.8				$21^{(-)} \rightarrow 19^{(-)}$
934.3					$21^{(-)} \rightarrow 19^{(-)}$
968.5	6.3	0.50(12)		(E1)	$17^{(-)} \rightarrow 16^+$
983.1	1.5				$17^{(-)} \rightarrow 16^+$
1015.2					$21^{(-)} \rightarrow (19^-)$
1044.7	0.4				$(20) \rightarrow 19^-$
1104.1					$20^{(-)} \rightarrow 18^+$

^a The error on the transition energies is 0.2 keV for transitions below 1000 keV and intensities larger than 5% of the ^{138}Nd reaction channel, 0.5 keV for transitions above 1000 keV and intensities lower than 5%, and 1 keV for transitions above 1200 keV and/or weaker than 1%.

^b Relative intensities corrected for efficiency. The transition intensities were obtained from a combination of total projection and gated spectra.

^c The DCO ratios have been deduced from an asymmetric γ - γ coincidence matrix. The tentative spin-parity of the states are given in parenthesis.

^d From NNDC

A. Ground-state band and the negative-parity states

The ground-state band is yrast up to spin 6^+ . The 69 keV transition connecting the 10^+ isomer to the 8^+ state was not observed in our measurement. Evidence for the existence of this transition was given in ref. [20], where the measured energy

was 66.9 keV. We give credit to the 69 keV value which results from the difference between the 8^+ and 10^+ states whose energies are well established through the connecting transitions between many high-spin states of the present level scheme which were not observed in ref. [20]. The only other observed transition populating the 8^+ state is the newly observed 1238 keV transition de-exciting the dipole band D4.

Most of the population intensity above the 8^+ state passes through the negative-parity states via the two 556.7 and 557.3 keV members of the 557 keV triplet peak. We observed all the previously reported transitions between the negative-parity states and towards the ground-state band and their position in the level scheme are confirmed, with the exception of the 563, 839 and 1022 keV transitions. The 563 keV transition belongs to ^{138}Nd but de-excites the 20^+ state at 7764 keV towards which decays the strongest high-spin rotational band which will be published separately [16]. The 839 and 1022 keV transitions are in mutual coincidence and were placed in the newly observed band N2. We observed several new transitions between the low-lying negative-parity states with energies of 144, 187, 359, 558 and 577 keV, and inverted the order of the transitions in the cascades 373–677 and 391–659. We also changed the parity of the two non-yrast 8^+ states to negative parity. The three newly observed transitions with energies of 187, 558 and 577 keV firmly define the new 10^- state at 3556 keV, on top of which are placed the 839, 1022 and 992 keV quadrupole transitions of band N2. The 8^- state at 2998 keV has an unbalanced intensity, with twice more intensity feeding the state than the intensity de-exciting it. This can be an indication of the isomeric character of the 8^- state with a lifetime of the order of several nanoseconds, which was not possible to deduce from the present data set.

The high-lying levels of these bands are non-yrast and therefore collect a very weak intensity flux. The most intense are the N3 and N4 bands which receive an intense population from the 10^+ state through the 329 and 454 keV transitions, respectively. We identified one more transition on top of both bands N1 and N2, with energies of 953 and 992 keV, respectively. The new 926 keV transition populating the 11^- state of band N4 at 3915 keV is in cascade with the new 736 keV transition de-exciting the 14^- state lying below band D1. We have also identified a new weak transition

of 242 keV linking the 16^- state of band D1 to the 15^- state of band N4, which most probably is an M1/E2 transition.

An important experimental result is that we confirm the DCO for the 1018 keV transition populating the 13^- state of band N4, which is in agreement with a stretched quadrupole transition. We assign an E2 multipolarity to the 1018 keV transition, which therefore de-excites a 15^- state and induces a negative parity for band D1. This result, together with the observation of the 242 keV transition and of the 736-926 keV cascade linking band D1 to N4, are all arguments in favor of negative parity for band D1, which is in disagreement with ref. [21] which proposed a positive-parity for band D1.

Spectra obtained by doubly gating on selected transitions of the different bands are shown in Fig. 2.

B. The medium-spin bands L1–L5

The most intense band above the 10^+ state at 3700 keV is band L1 which has assigned a $\pi h_{11/2}^2$ configuration from the systematics of the 10^+ states in the sequence of the N=78 isotones and from the comparison with the ^{136}Ce proton core [21]. In addition to band L1 we identified four more bands labelled L2–L5 which mainly decay towards band L1. Spectra showing the transitions in the different bands are given in Fig. 3.

Some of the transitions connecting states of these bands to band L1 were observed previously [21]. Bands L3 and L4 decay to band L1 via both stretched and non-stretched E2 transitions. Band L5 decays via the 785 keV transition to band L1, but also to bands L2 and D4 via the weak 722 and 708 keV transitions, respectively. The parity of band L5 is uncertain and therefore is indicated in parenthesis in the level scheme, but its behavior relative to band L1 is similar to that of the negative-parity bands N1–N4 relative to the ground-state band, giving preference to the negative parity.

Several states with spin between $17^{(-)}$ and $21^{(-)}$ were also observed, which decay to bands L1 and L5. We grouped these states together since they could represent negative-parity two-quasiparticle

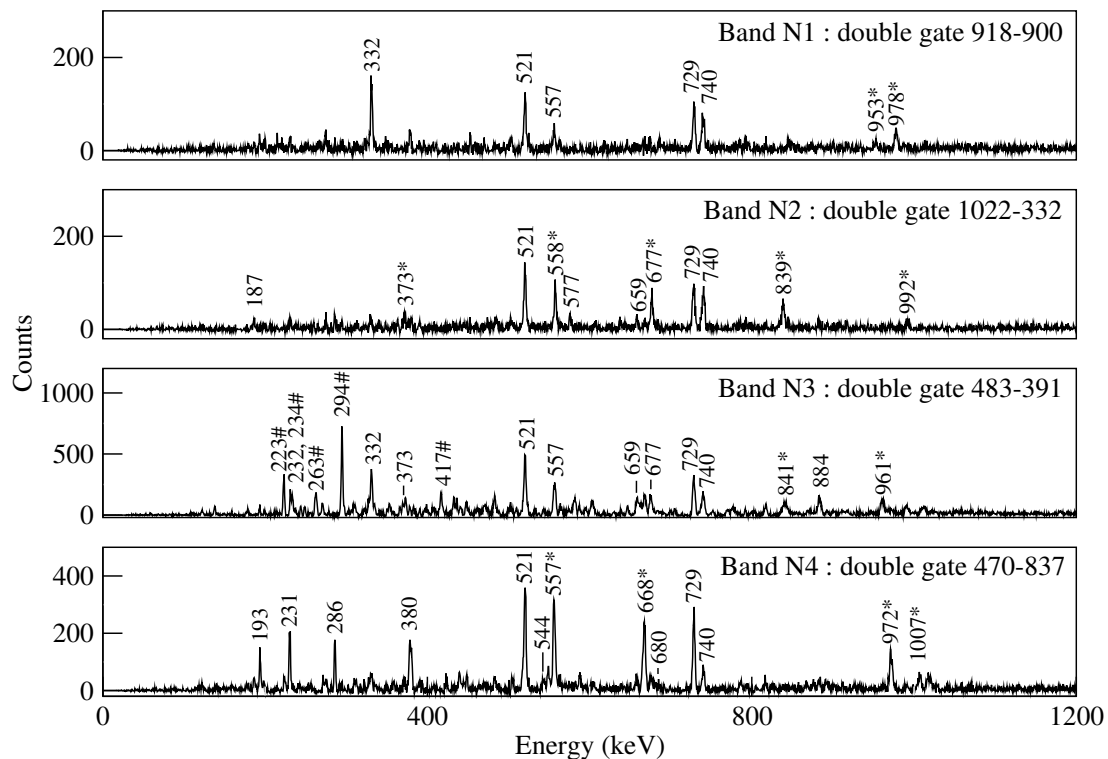


FIG. 2: Double-gated sum spectra for the negative-parity bands N1, N2, N3 and N4 in ^{138}Nd . The gates were set on selected transitions of each band. The transitions marked with asterisks represent the members of the band, while the peaks marked with a # are contaminants from other nuclei.

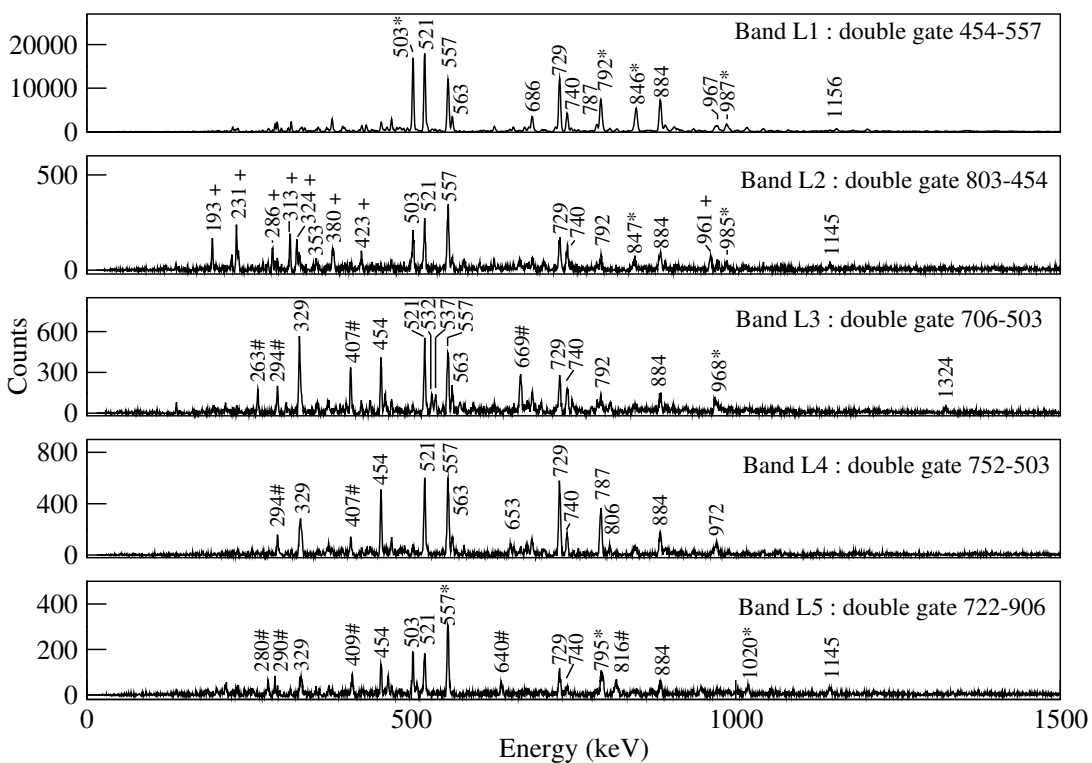


FIG. 3: Double-gated sum spectra for the bands L1–L5 in ^{138}Nd . The gates were set on selected transitions of each band. The transitions marked with asterisks represent the members of the band, the peaks marked with a + are members of band D1 which appear in the spectrum of band L2 because they are in cascade with the 803 and 454 keV transitions, while the peaks marked with a # are contaminants from other nuclei.

excitations built on the $\pi h_{11/2}^2$ configuration of band L1, being the replica of the low-spin negative-parity states which are two-quasiparticle excitations built on the ground-state configuration. It is towards these states that the intense high-spin triaxial band T3 decays [16].

C. The positive-parity bands L6–L8

The next most intense structure above spin 10^+ is band L6 which is built on the yrast 10^+ isomer with $T_{1/2} = 0.41 \mu\text{s}$ which has assigned a $\nu h_{11/2}^2$ configuration [21]. Spectra showing the transitions in the different bands are given in Fig. 4.

We confirm nearly all transitions observed in ref. [21] and add several new transitions, like the 1430 keV $13^- \rightarrow 12^+$ and 1671 keV ($13^- \rightarrow 12^+$ transitions de-exciting non-yrast negative-parity states towards the yrast 12^+ state, and the 969 keV transition on top of band L8. One can note the difference between the structures built on the 10^+ isomer which has assigned from systematics a $\nu h_{11/2}^2$ two-neutron configuration and that built on the $\pi h_{11/2}^2$ two-proton configuration which is much more regular and exhibits a behavior characteristic for collective rotational bands. The structures related to the 10^+ isomer are more fragmented. Interesting to note the strong population of the 11^+ state at 4136 keV.

D. The dipole bands

A particular feature of the level scheme of ^{138}Nd at medium spins is the existence of 8 cascades of dipole transitions, that we call dipole bands and label D1–D8. Only band D1 was observed previously [21]. The seven newly observed bands are weaker, but are all connected to low-lying states and therefore have spin-parity assignments. Spectra showing the transitions in the different bands are given in Fig. 5 and 6.

Band D1 starting at spin 13^- decays mainly to states built on the 10^+ isomer, but also towards the 13^- and 15^- states of band N4 via the 1018 and 242 keV transitions, respectively, and towards the 13^- state at 4841 keV via the 736 keV tran-

sition. The quadrupole multipolarity of the 1018 keV transition fixes the parity of band D1 as negative. The quadrupole character of the 1018 keV transition was also observed in ref. [21], but no parity was assigned to the state with spin 15 at 5770 keV de-excited by this transition. The parity of the next higher state of band D1 with spin 16 was instead assigned positive on the basis of a 973 keV transition towards the 10^+ isomer, transition which is not observed in our experiment. The parity of band D1 was therefore assigned as positive in ref. [21] and its theoretical interpretation was based on this assignment. We assign instead a negative parity to band D1, which is in agreement with the systematics of bands observed in even-even and odd-even nuclei in this mass region.

Band D2 starting at spin 15^- decays only to band D1 and to the non-yrast 14^- state at 5614 keV.

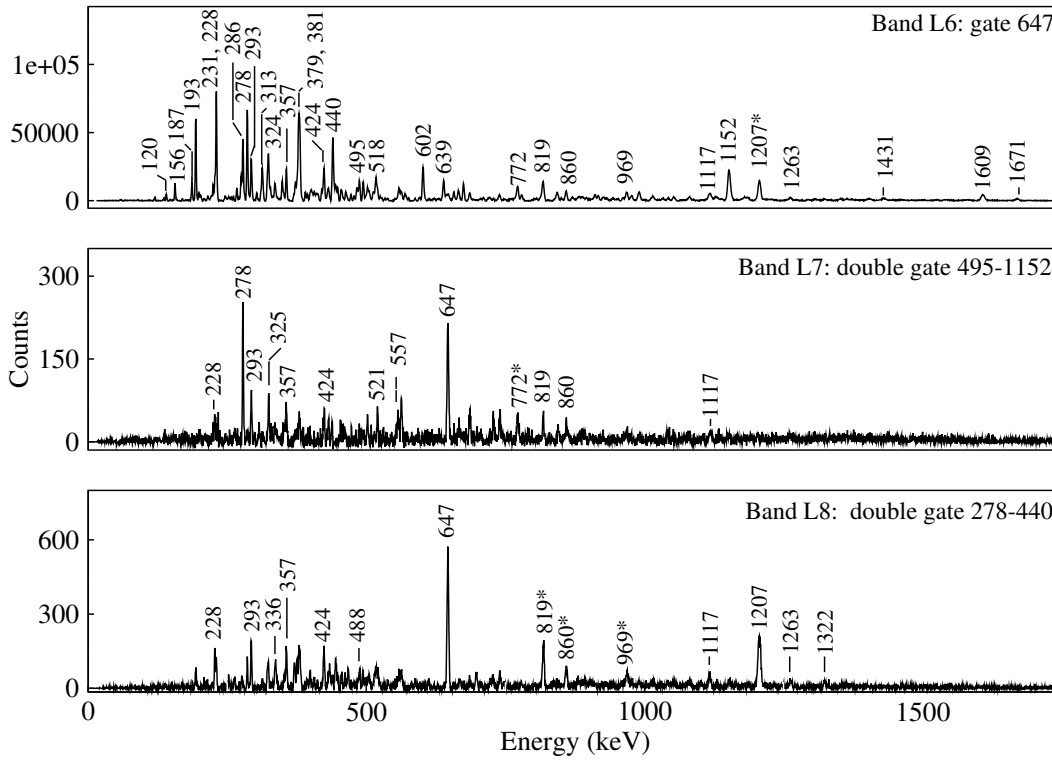
Band D3 starting at spin $14^{(+)}$ becomes rapidly non-yrast and decays to the group of negative-parity states above the 10^+ isomer via the 288 and 528 keV transitions.

Band D4 starts at spin 10^+ , which is the lowest band-head spin among the observed dipole bands. It decays to the ground-state band and to band L1. The energy of the 14^+ state is very close to the energy of the 14^+ state of band L2 (only 14 keV difference), which apparently leads to the mixing of the two states and explains the existence of the 329 keV $15^+ \rightarrow 14^+$ transition connecting bands D4 and L2, and also the decay of band L5 to the 14^+ states of bands L2 and D4 via the 722 and 708 keV transitions, respectively.

Band D5 is observed above spin $16^{(+)}$. The transition energies increase regularly up to spin 21 and becomes irregular at the highest observed spins. The decay is towards band D4 and the $17^{(-)}$ state at 6810 keV.

Band D6 starting at spin $19^{(+)}$ is the most regular one, with an energy difference between successive transitions of around 70 keV, being an ideal candidate for magnetic rotation. It mainly decays to states of band L8, but also to band L3 via the 457 keV transition and to band D1 via the cascade of transitions 281–730 keV.

Bands D7 and *D8* are observed above spin $22^{(-)}$ and feed the highest observed state of band D1. Band D8 decays only to band D7.



2

FIG. 4: Double-gated sum spectra for the positive-parity L6, L7 and L8 bands in ^{138}Nd . The gates were set on selected transitions of each band. The gates were set on selected transitions of each band. The transitions marked with asterisks represent the members of the band.

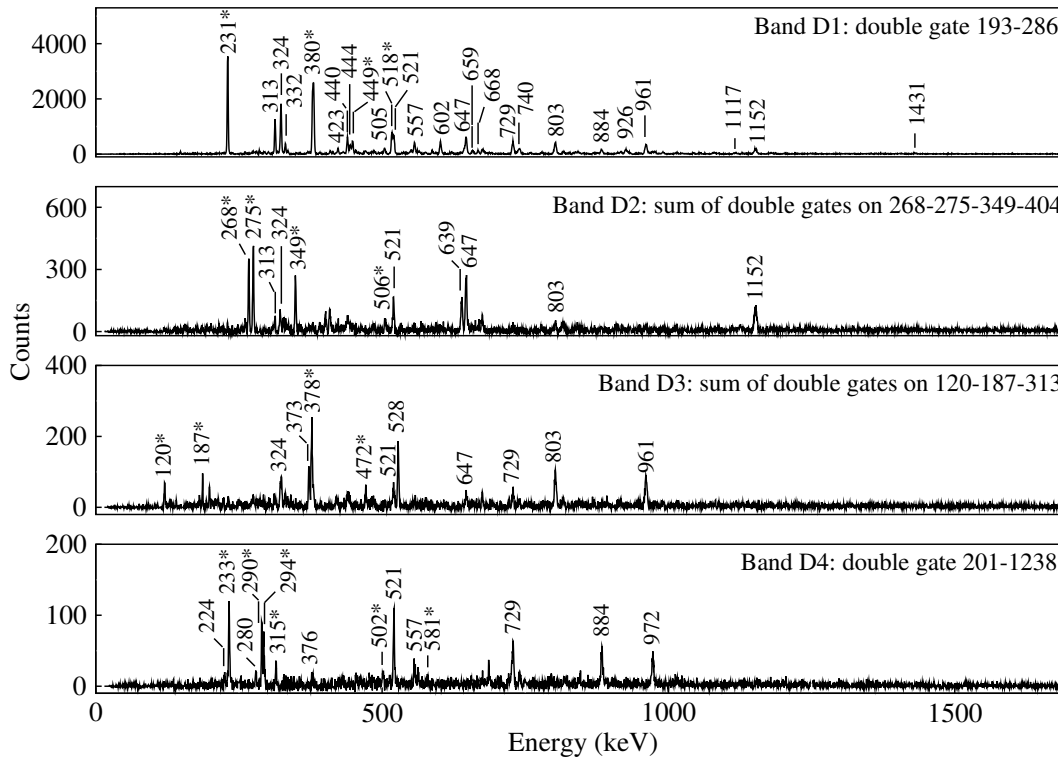


FIG. 5: Double-gated sum spectra for the dipole bands D1 to D4 in ^{138}Nd . The gates were set on selected transitions of each band. The transitions marked with asterisks represent the members of the band.

IV. DISCUSSION

The level scheme of ^{138}Nd presents a very rich and complex structure at low and medium spins. We have arranged some of the states in sequences of transitions such that they resemble bands structures, but we are aware that this choice is somewhat arbitrary. We will discuss here the majority of the observed states at low and medium spins. Some of them have been observed and already discussed employing the interacting boson model and TRS calculations in ref. [21] and employing the CNS model in ref. [11].

A. Framework for the CSM and TAC calculations

All but the ground-state band (g-band) have at least two quasiparticles excited, which reduces strongly the pair correlations. This allows us to qualitatively interpret the bands in terms of single-particle configurations in the rotating potential. Figs. 7 and 8 show the single-particle Routhians calculated by means of the TAC code [24] for a deformation of $\varepsilon_2 = 0.17$ and $\gamma = 30^\circ$, which is a typical value for this mass region [9–13]. The TAC model considers the rotation about an axis that is tilted by the angles θ and ϕ from the principal axes. The long, short, and medium principal axes correspond to (θ, ϕ) equal to $(0^\circ, 0^\circ)$, $(90^\circ, 0^\circ)$, and $(90^\circ, 90^\circ)$, respectively. We will consider quasiparticle configurations for a strongly reduced pair gap. A compact and unambiguous notation for the configurations is needed that allows one to change from quasiparticle configurations to single-particle configuration as $\Delta \rightarrow 0$.

In this paper we apply the Cranked Shell Model (CSM) [22], which classifies the bands as quasiparticle configurations in the rotating potential. With a slight modification it is extended to the unpaired version, which classifies the bands as particle-hole configurations. We discuss the band properties using the extension of the CSM to Tilted Axis Cranking (TAC) [23] defined by

$$h' = h -$$

$$\hbar\omega_{\text{rot}}(\sin\theta\cos\phi J_x + \sin\theta\sin\phi J_y + \cos\theta J_z), \quad (1)$$

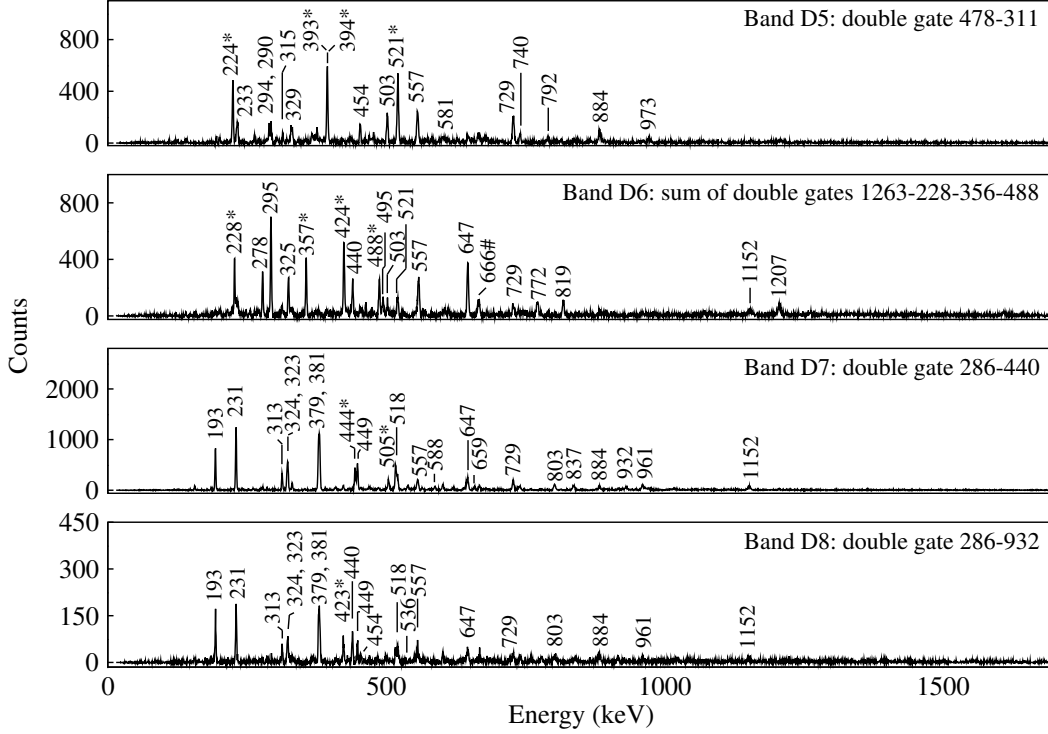
$$h = h_{\text{Nil}} - \Delta_\tau(P_\tau^\dagger + P_\tau) - \lambda_\tau N_\tau, \quad (2)$$

$$h_{\text{Nil}} = \frac{\mathbf{p}^2}{2M} + \frac{1}{2}M(\omega_x^2 x^2 + \omega_y^2 y^2 + \omega_z^2 z^2) + v_{ls}\mathbf{l} \cdot \mathbf{s} + v_{ll}(\mathbf{l}^2 - \langle \mathbf{l}^2 \rangle_{N_{\text{osc}}}). \quad (3)$$

In Eq. (2), P_τ is the pair annihilation operator, $\tau = 1$ and 2 denote neutron and proton, respectively, and the chemical potentials λ_τ are determined so as to give the correct average particle numbers $\langle N_\tau \rangle$. The oscillator frequencies in Eq. (3) are related to the quadrupole deformation parameters ε_2 and γ in the usual way. Here the orbital angular momentum is defined by the singly-stretched coordinates, and v_{ls} and v_{ll} are taken from ref. [25]. The standard CSM, which allows only for rotation about one of the principal axes, (Principal Axes Cranking - PAC), usually uses x as the rotational axis ($\theta = 90^\circ$, $\phi = 0^\circ$), which is the short axis for $0^\circ < \gamma < 60^\circ$, the medium axis for $-60^\circ < \gamma < 60^\circ$, and the long axis for $-120^\circ < \gamma < -60^\circ$. In the sector $0^\circ < \gamma < 60^\circ$ the short, medium, and long axes correspond to $(\theta, \phi) = (90^\circ, 0^\circ)$, $(90^\circ, 90^\circ)$, and $(0^\circ, 0^\circ)$, respectively.

For zero pairing the CNS notation by Ragnarsson has become quite common [26–28]. It indicates how many particles are in the intruder orbitals and how many in the normal-parity states. We use the $\pi h^n(dg)^m$ notation to indicate that relative to the $Z = 50$ core there are n protons in the $h_{11/2}$ intruder subshell and m protons in the normal-parity states which are a mixture of $d_{5/2}$ and $g_{7/2}$ orbitals. For example, the configuration of band L1 is $\pi h^2(gd)^8$. For the neutrons it is more convenient to quote the number of neutron holes in the $N = 82$ core. With this notation, the configuration of band L6 is $\nu h^{-2}(dg)^{-2}$.

The CNS notation does not distinguish between the various configurations that are possible for a given $\pi h^n(dg)^m$. It also does not well extend to the case of pairing, because in that case there is pair scattering between the intruder and normal parity orbitals, and n and m are not well defined. In CSM calculations one assigns letters to the lowest quasiparticle orbitals for a compact notation [22, 29]. The convention is to use A, B, C, D for the intruder



4

FIG. 6: Double-gated sum spectra for the dipole bands D5 to D8 in ^{138}Nd . The gates were set on selected transitions of each band. The transitions marked with asterisks represent the members of the band, while the peaks marked with a # are contaminants from other nuclei.

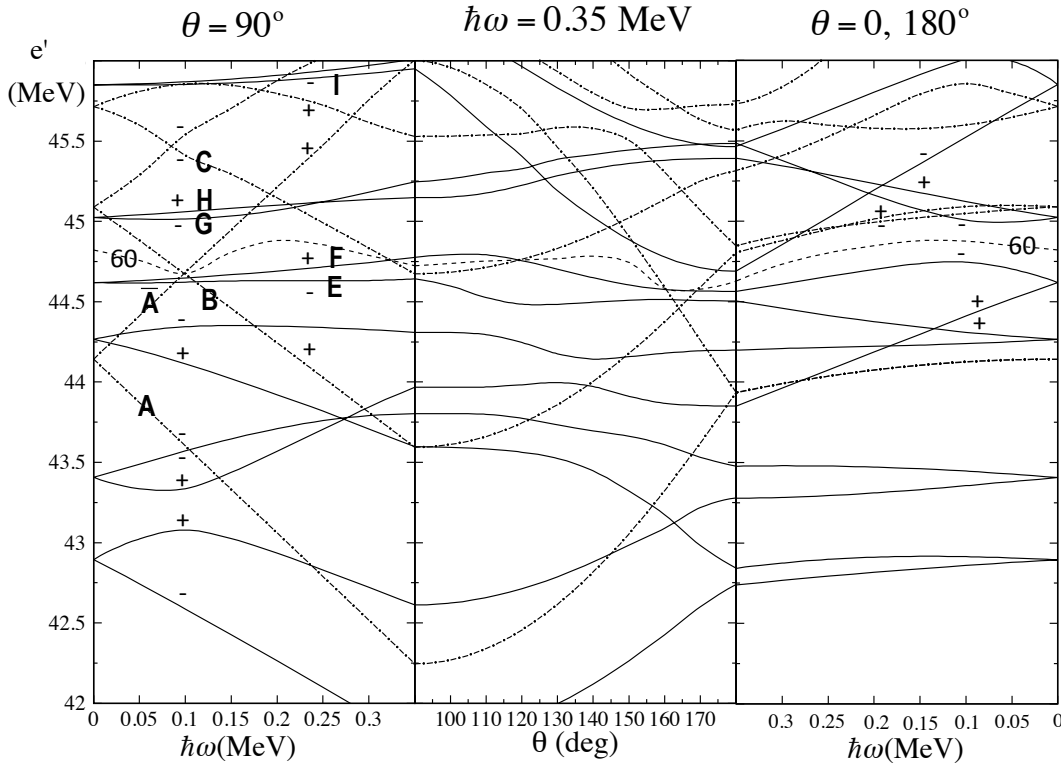


FIG. 7: Single-particle proton Routhians around the Fermi surface of ^{138}Nd calculated for the deformation parameters $\varepsilon_2 = 0.17$, $\gamma = 30^\circ$. Full line $\pi = +$, dash-dot line $\pi = -$. In case of principal axis rotation the signatures $\alpha = \pm 1/2$ are indicated by \pm , respectively. $\theta = 0$ long axis ($\gamma = -90^\circ$), $\theta = 90^\circ$ short axis ($\gamma = 0^\circ$.) The middle panel connects the two axis at indicated frequency.

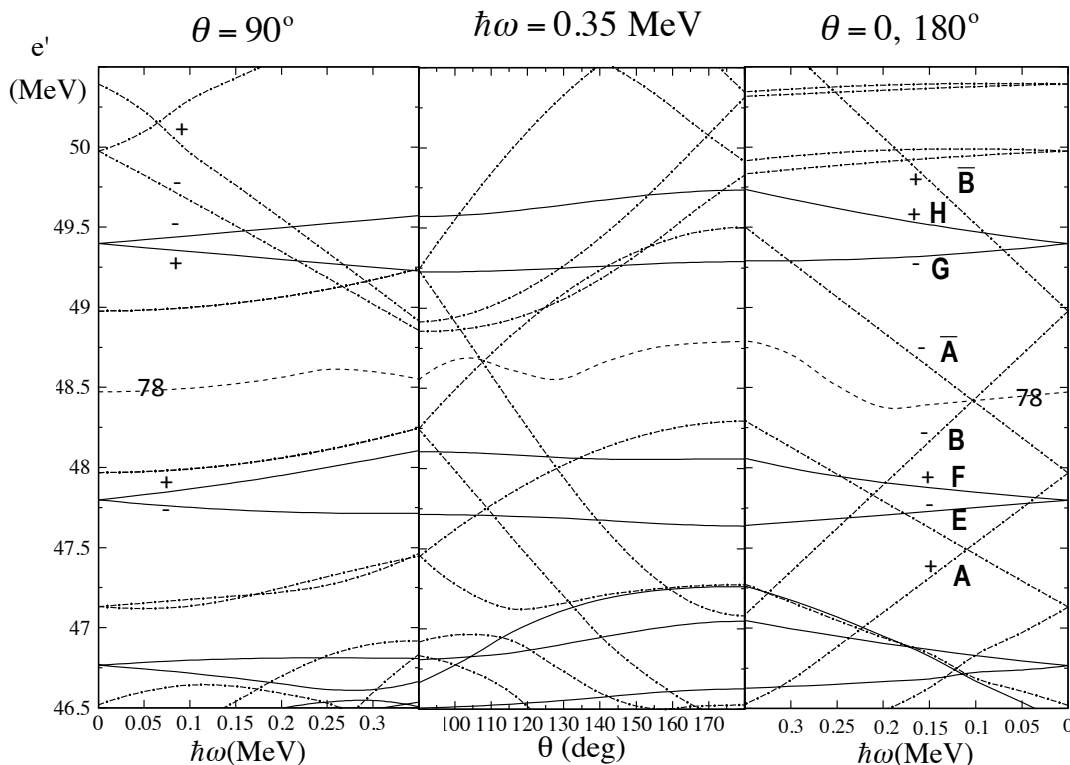


FIG. 8: Single-particle neutron Routhians around the Fermi surface of ^{138}Nd calculated for the deformation parameters $\varepsilon_2 = 0.17$, $\gamma = 30^\circ$. The line and label conventions are similar to those in Fig. 7.

states h , where A is assigned to the lowest state with the favored signature $\alpha = j + 2n$. The letters E, F, G, H, \dots are used for the normal-parity states (dg). We extended the group A, B, C, D by \bar{A} , which is the anti-aligned (approximately the time reversed) partner of A . We use two ways to specify the unpaired configurations:

i) We specify the configuration by indicating the occupation of the four highest single-particle Routhians. For example the configuration $\pi 10$ which corresponds to the proton S-band L1, is $\pi AB EF$.

ii) We specify the configuration by indicating the particle-hole excitations relative to the S-configuration $\pi 10$, which we use as reference (particle-hole vacuum). For example the $\pi ABCE$ is generated by exciting F to C , and therefore we will denote it by $\pi F^{-1}C$.

The particle-hole notation naturally extends to the case of finite pairing. In the limit $\Delta \rightarrow 0$ a quasiparticle becomes either a particle or a hole. There are twice as many quasiparticle states as single-particle states. Each state has a conjugate partner with opposite energy, which is labelled by a dagger, *e.g.* A^\dagger is the conjugate of A . Conventionally, the Routhians that have negative energy

for $\omega = 0$ are labelled by the dagger. However, it is completely open which state of the conjugate pair is given the dagger. Here we use the freedom to additionally indicate whether the quasiparticle is predominantly a particle (no dagger) or a hole (dagger). We indicate this by using the plain letters for quasiparticles that become particles and attach the dagger to the quasiparticles that become holes. For example the quasiparticle G becomes the particle G and the quasiparticle F^\dagger becomes the hole F^{-1} . The quasiparticle vacuum is taken as the paired proton S-band. The quasiparticle configuration $\pi F^\dagger G$ becomes $\pi F^{-1}G$ for zero pairing. For moderate pairing the notation still indicates that F^\dagger is predominantly a hole and G predominantly a particle. Of course, for strong pairing the lowest quasiparticles are approximately half particle and half hole. Figs. 9 and 10 illustrate the notation.

Table II lists the low-lying quasiparticle configurations and their unpaired particle-hole limits. It is important to point out that certain quasiparticle configurations do not have a zero pairing limit. For example $\pi E^\dagger F^\dagger$ becomes a $Z = 58$ configuration for $\Delta \rightarrow 0$ and λ fixed. In principle one could fix this by adjusting λ . However, the CSM uses one set of quasiparticle Routhians for a fixed λ , which

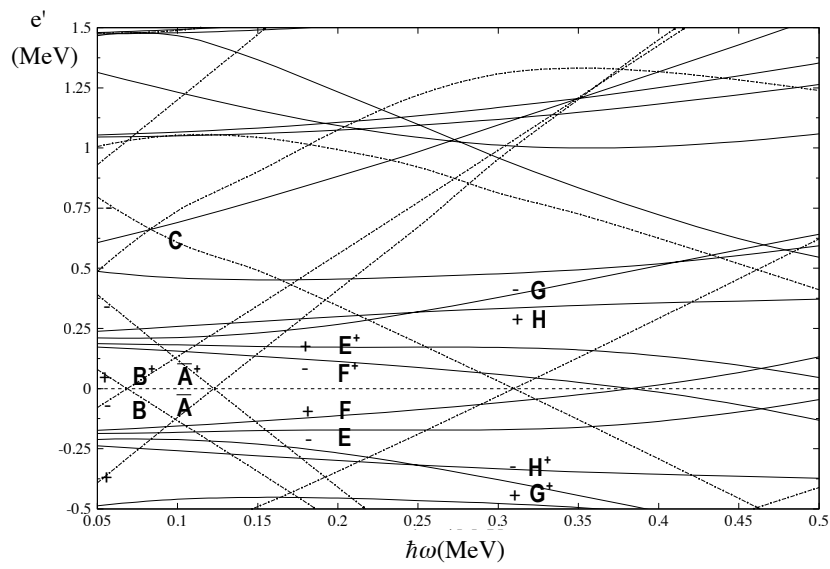


FIG. 9: Quasiproton Routhians around the Fermi surface of ^{138}Nd calculated for $\Delta = 0$ MeV. The deformation parameters are $\varepsilon_2 = 0.17$, $\gamma = 30^\circ$. Particle excitations are denoted by letters, hole excitations by a dagger attached to the letter. Only two-quasiparticle excitations combining a particle with a hole are physical.

ensures that the configurations are mutually orthogonal. This simplicity of the CSM would go away with λ individually adjusted for each configuration, because the configurations are not longer orthogonal. For large pairing the condensate provides a hole pair such that *e.g.* $\pi E^\dagger F^\dagger$ has the right expectation value for Z . For zero (small) pairing

$\pi(EF)^{-1}GH$ is the lowest configuration with one proton hole each on E and F . There are more such configurations with the pair on other orbitals. They will combine to generate a pair addition vibration. Analogously, the quasiparticle configuration GH has no $\Delta = 0$ limit and will approach a combination with a pair removal mode.

TABLE II: Proton and neutron low-lying configurations for $\Delta I=2$ bands of ^{138}Nd in the particle-hole and quasiparticle notations. The parity, signature and band assignment are also included.

Configuration last 4 nucleons	Particles-holes <i>vs.</i> S-vacuum	Quasiparticles <i>vs.</i> S-vacuum	Quasiparticles <i>vs.</i> g-vacuum	$\pi \alpha$	Bands
$\pi 0 = A\bar{A}EF$	$\pi B^{-1}\bar{A}$	$\pi B^\dagger\bar{A}$	$\pi 0$	+ 0	
$\pi 10 = ABEF$	$\pi 10$	$\pi 10$	$\pi\bar{A}^\dagger B, \pi h^2$	+ 0	L1
$\pi AEF G$	$\pi B^{-1}G$	$\pi B^\dagger G$	$\pi\bar{A}^\dagger G, \pi h(dg)$	- 1	N3
$\pi AEFH$	$\pi B^{-1}H$	$\pi B^\dagger H$	$\pi\bar{A}^\dagger H, \pi h(dg)$	- 0	N2
$\pi A\bar{A}BF$	$\pi E^{-1}\bar{A}$	$\pi E^\dagger\bar{A}$	$\pi BE^\dagger, \pi h(dg)$	- 1	N4
$\pi A\bar{A}BE$	$\pi F^{-1}\bar{A}$	$\pi F^\dagger\bar{A}$	$\pi BF^\dagger, \pi h(dg)$	- 0	
$\pi ABCE$	$\pi F^{-1}C$	$\pi F^\dagger C$	$\pi\bar{A}^\dagger BF^\dagger C, \pi h^3(dg)$	- 1	L5
$\pi ABCF$	$\pi E^{-1}C$	$\pi E^\dagger C$	$\pi\bar{A}^\dagger BE^\dagger C, \pi h^3(dg)$	- 0	
$\pi ABEG$	$\pi F^{-1}G$	$\pi F^\dagger G$	$\pi\bar{A}^\dagger BF^\dagger G, \pi h^2(dg)^2$	+ 1	
$\pi ABEH$	$\pi F^{-1}H$	$\pi F^\dagger H$	$\pi\bar{A}^\dagger BF^\dagger H, \pi h^2(dg)^2$	+ 0	L2
$\pi ABFG$	$\pi E^{-1}G$	$\pi E^\dagger G$	$\pi\bar{A}^\dagger BE^\dagger G, \pi h^2(dg)^2$	+ 0	L3
$\pi ABFH$	$\pi E^{-1}H$	$\pi E^\dagger H$	$\pi\bar{A}^\dagger BE^\dagger H, \pi h^2(dg)^2$	+ 1	L4
	p.rem.+p.add.	$\pi E^\dagger F^\dagger$	$\pi\bar{A}^\dagger BE^\dagger F^\dagger, \pi h^2(dg)^2$	+ 0	L2
$\pi ACEF$	$\pi B^{-1}C$	$\pi B^\dagger C$	$\pi\bar{A}^\dagger C, \pi h^2$	+ 1	
$\pi BEFG$	$\pi A^{-1}G$	$\pi A^\dagger G$	$\pi BG, h(dg)$	- 0	
$\pi BEFH$	$\pi A^{-1}H$	$\pi A^\dagger H$	$\pi BH, \pi(dg)$	- 1	
$\nu 0 = A\bar{A}EF$	$\nu B^{-1}\bar{A}$	$\nu B^\dagger\bar{A}$	$\nu 0$	+ 0	
$\nu 10 = ABEF$	$\nu 10$	$\nu 10$	$\nu\bar{A}^\dagger B, \nu h^2$	+ 0	L6
$\nu AEF G$	$\nu B^{-1}G$	$\nu B^\dagger G$	$\nu A^\dagger G, \nu h(dg)$	- 0	
$\nu AEFH$	$\nu B^{-1}H$	$\nu B^\dagger H$	$\nu A^\dagger H, \nu h(dg)$	- 1	N1
$\nu A\bar{A}BE$	$\nu F^{-1}\bar{A}$	$\nu F^\dagger\bar{A}$	$\nu BF^\dagger, \nu h(dg)$	- 1	
$\nu A\bar{A}BF$	$\nu E^{-1}\bar{A}$	$\nu E^\dagger\bar{A}$	$\nu BE^\dagger, \nu h(dg)$	- 0	

B. The $\Delta I = 2$ bands

If the nucleus rotates about a principal axis, the signature α is a good quantum number and one observes $\Delta I = 2$ bands with $I = \alpha + 2n$ [22].

1. Unpaired CSM calculations

In this section we apply the unpaired version of the Cranked Shell Model (CSM) [22], which classifies the bands as particle-hole configurations in the rotating potential. Disregarding the g-band, we consider only bands with at least two excited

quasiparticles, which substantially block the pair correlations. The underlying independent particle approximation of the CSM applies only to relative energies and angular momenta. In contrast to the standard version of CSM in which the g-band is used as reference, in this paper we will use the proton S-band L1 as reference.

The experimental particle-hole Routhians e' and alignments i for each band are obtained by following the standard procedure as described *e.g.* in refs. [22, 23] for extracting total Routhians $E'(I)$, angular momenta $J(I)$, and frequencies $\omega(I)$ from the level energies $E(I)$, where the expression for $K = 0$ are used. The reference functions $E'_{L1}(\omega)$ and $J_{L1}(\omega)$ are constructed as smooth interpolations between the points $E'(\omega(I))$ and $J(\omega(I))$

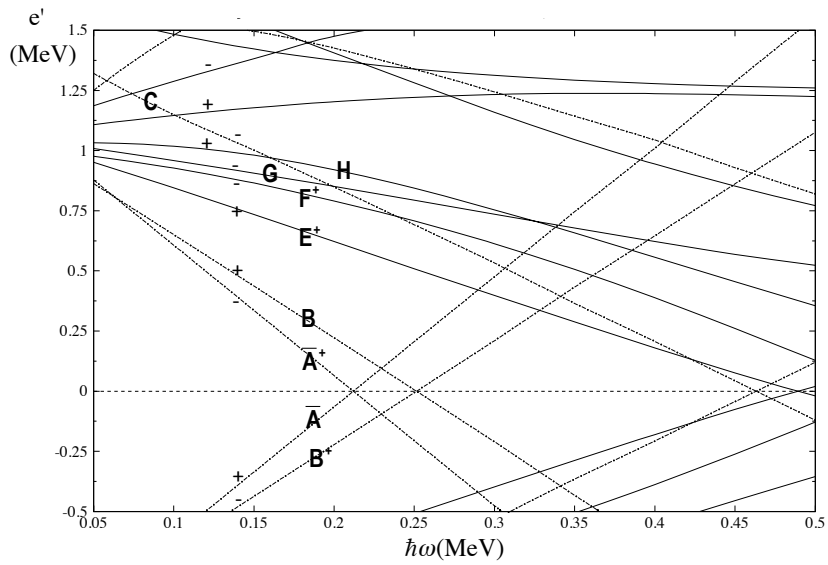


FIG. 10: Quasiproton Routhians around the Fermi surface of ^{138}Nd calculated for $\Delta = 1$ MeV. The deformation parameters are $\varepsilon_2 = 0.17$, $\gamma = 30^\circ$. Plain letters indicate that the particle character dominates and letters with dagger indicate that the hole character dominates. For the lowest quasiparticles, the particle and hole components are about the same. The letter code is chosen according to their limit $\Delta \rightarrow 0$. Combinations of two plain letters or two letters with dagger are physical two-quasiparticle excitations for the lowest Routhians.

obtained for band L1. From the $E_n'(\omega(I))$ and $J_n(\omega(I))$ values of a given band n we subtract the $E_{L1}'(\omega)$ and $J_{L1}(\omega)$ values of band L1 calculated at the same frequencies,

$$e_n'(\omega(I)) = E_n'(\omega(I)) - E_{L1}'(\omega(I)), \quad (4)$$

$$i_n(\omega(I)) = J_n(\omega(I)) - J_{L1}(\omega(I)). \quad (5)$$

The experimental Routhians e' and the single-particle alignments i relative to the L1 reference are shown in the upper panels of Figs. 11 and 20, 21 for the bands of quadrupole and dipole transitions, respectively. The reference band L1 appears as an horizontal line in all figures.

The main features of rotational spectra can be understood in a simple way that has been discussed before (cf. *e. g.* [5, 23]). There are two $h_{11/2}$ protons which align their angular momenta with the short axis, because this orientation corresponds to maximal overlap of their doughnut-like density distribution with the triaxial core. As a consequence, the $h_{11/2}$ protons favor rotation about the short axis. As seen in the middle panel of Fig. 7, the Routhians A and B have a pronounced minimum at $\theta = 90^\circ$. There are two $h_{11/2}$ neutron holes, which align their angular momenta with the long axis, because this orientation minimizes the overlap with the triaxial core. As a consequence, the $h_{11/2}$ neutron holes favor rotation about the long axis. As seen in the middle panel of Fig. 8, the neutron Routhians \bar{A} and \bar{B} have pronounced maxima at $\theta = 0^\circ$, which means that holes in these two orbitals drive the rotational axis to $\theta = 0^\circ$. Alternatively one may say that the two neutrons on A and B favor the long axis. The $h_{11/2}$ neutrons on the lower orbitals do not drive the rotational axis significantly, because to each Routhian corresponds a conjugate one (barred) that nearly compensates the drive. The collective angular momentum originating from the rest of the nucleons is maximal for the medium axis, for which the deviation from axial symmetry is maximal.

The TAC calculations show that the proton configurations with at least one of the $h_{11/2}$ orbitals A , B , C occupied combined with the neutrons in the ground configuration $\nu 0 = \nu A\bar{A}EF$ all rotate about the short axis (90° , 0°). Table II list the low-lying proton configurations, which combined with the neutron g-configuration $\nu 0$ generate the regular $\Delta I = 2$ bands. The possible assignments to the observed bands of quadrupole transitions in ^{138}Nd are included as well.

The lower panels of Fig. 11 display the calculated Routhians and single-particle alignments relative to the proton S-configuration $\pi 10 = \pi ABEF$, which is associated with band L1. Optimizing the deformation for this band gives a deformation of $\varepsilon_2 = 0.15$ and $\gamma = 30^\circ$ for $\hbar\omega = 0.3$ MeV. The calculated moment of inertia $\mathcal{J}^{(2)} = 17.5 \hbar^2/\text{MeV}$ compares well with the experimental value of $19 \hbar^2/\text{MeV}$ obtained as the slope of a straight line fit to the function $J_{L1}(\omega)$. The negative-parity bands N2, N3, N4 contain only one rotational aligned $h_{11/2}$ orbital as compared to the reference proton S-configuration containing two of them. The panel with experimental single-particle alignments in Fig. 11 shows in fact two groups, one below and one above the zero line corresponding to the L1 reference: the group below is formed by the bands N2-N4 which involve one $h_{11/2}$ orbital, the group above is formed by the bands L2-L5 which involve two or three aligned $h_{11/2}$ orbitals. The concrete configuration assignment is based on parity, signature and alignment. Additionally we took into account that the two bands in ^{136}Nd that correspond to N2 and N3 show a backbend [9]. The backbends are interpreted as the respective configuration changes $\pi B^{-1}G \rightarrow \pi(EF)^{-1}CG$ and $\pi B^{-1}H \rightarrow \pi(EF)^{-1}CH$, which are assisted by the residual pair correlations. The alternative configurations $\pi E^{-1}\bar{A}$ and $\pi F^{-1}\bar{A}$ do not allow such backbend. For this reason, the N2 and N3 bands are assigned to the higher pair of configurations $\pi B^{-1}H$ and $\pi B^{-1}G$ shown in Fig. 11. (The wrong energy order should not be of too much concern, because the neglected correlations may lead to comparable energy shifts.) Exciting one or two protons from (E, F) into (G, H) generates the positive-parity configurations with nearly the same alignment, slightly above the reference, which are assigned to the bands L2, L3, L4. Band L5 has a higher alignment than L1, which indicates an extra $h_{11/2}$ proton. For this reason we interpret it as $\pi F^{-1}C$. All the bands associated with configurations involving only protons display a regular rotational sequence with a similar value of $\mathcal{J}^{(2)}$ as the reference L1.

The TAC calculations show that the neutron S-configuration $\nu 10$ with the two $h_{11/2}$ orbitals A and B occupied, combined with the proton in the g-configuration $\pi 0$ rotates about the long axis with $(\theta, \phi) = (0^\circ, 0^\circ)$. The equilibrium deformation for $\hbar\omega = 0.4$ MeV is $\varepsilon_2 = 0.14$ and $\gamma = 38^\circ$. The calculated moment of inertia of $\mathcal{J}^{(2)} = 6.5 \hbar^2/\text{MeV}$ is too small to support an extended regular ro-

tational sequence, which reflects the proximity of the $N = 82$ shell closure and the suppression of the proton angular momentum by the pair correlations. We assign the three states of band L6 with this configuration, which is used as reference for configurations that rotate about the long axis. The reference functions $E'_{L6}(\omega)$ and $J_{L6}(\omega)$ are generated analogous to the reference for rotation about the short axis, replacing L6 for L1. The straight line fit to J_{L6} has a slope of $\mathcal{J}^{(2)} = 8 \hbar^2/\text{MeV}$, which compares well with the TAC value. Because of the small collectivity of rotation about the long axis, other configurations are not expected to support extended regular rotational bands, rather they may show up as sequences with roughly constant transition energies (tidal waves cf. [30]). The sequences N1, L7, and L8 are of this kind. They may correspond to the configurations indicated in Table II. The other configurations with the correct parity and signature are alternatives. An unambiguous assignment is not possible. The configurations in Table II implying the excitation of neutrons from the (E, F) into the (G, H) orbitals require around 2 MeV, which is too high (see in Fig. 8) to qualify for bands L7 and L8. Possible alternative configurations for bands L7 and L8 can involve the excitation of one or two protons from (E, F) into (G, H, I) coupled to the neutron S-configuration, as in the case of band L2 which involves one- or two-proton excitation coupled to the proton S-configuration. Such configurations will be considered in section IV B 2. However, it also seems possible that band L7 is the one-phonon wobbling excitation built on the neutron S-configuration, which will be discussed in section IV B 3.

Fig. 11 shows that the unpaired calculations fairly well reproduce the relative alignments of the different bands, which was used to make the configuration assignments. The experimental alignments are shifted up by about $2 \hbar$. Such a shift can be attributed to residual dynamic pair correlations, which reduce the angular momentum of the proton S-band L1 (reference) stronger than in the other bands. This kind of modification has been discussed in ref. [31]. The calculated Routhians cross around $\hbar\omega = 0.2$ MeV while with the experimental ones cross around 0.45 MeV. Again, this is to be attributed to the neglected correlations in our extremely simplifying CSM interpretation. In particular dynamic pair correlations, but also shape polarization may be responsible for the energy shifts. As will be demonstrated in a forthcoming publica-

tion, one may derive experimental single-particle Routhians from the neighboring odd- Z isotones, which place the crossing to the right frequency [32].

One should note that bands with even-spin and negative-parity like band N2 were also observed in neighboring nuclei like ^{136}Nd [33] and ^{136}Ce [34], being interpreted as proton $\pi(dg)^1h^1$ and $\nu(sd)^1h^1$, respectively. The more collective behavior of the bands in ^{136}Nd allowed their observation up to high spins after two band crossings, whereas the bands in ^{136}Ce are very similar to those observed in ^{138}Nd . They were interpreted as rotational bands of a nucleus with nearly axial shape around a principal axis of the intrinsic reference system. We adopt the two-proton $\pi B^{-1}H$ configuration for band N2, which is similar to that assigned to the low-lying even-spin negative-parity band of ^{136}Nd .

Band N4 mainly decays towards the ground-state band, and has weak connecting transitions towards the other negative-parity bands. It is interpreted as the $\pi E^{-1}\bar{A}$ configuration. This interpretation is in agreement with the feeding and depopulation pattern of the band, which is mainly fed at the 9^- state from band L1 band through the strong 454 keV E1 transition, which can be explained by a simple quasi-proton excitation from the $\pi(dg)$ orbitals active in band N4 to the πh orbital active in band L1. The E1 transitions from band N4 to the g-band whose states are dominated by the $\pi(dg)$ configuration, can also be explained by a de-excitation from the πh orbital active in band N4 to the $\pi(dg)$ orbitals active in the g-band. Another feature supporting the interpretation of band N4 as based on the $\pi E^{-1}\bar{A}$ configuration is that band D1 which is consistently interpreted as based on the $\pi F^{-1}\bar{A} \otimes \nu 10$ configuration (see below), decay only to the 13^- and 15^- states of band N4 and not to the other negative-parity bands. Furthermore, the two 9^- states of bands N1 and N4 have energies of 3239 and at 3247 keV, respectively. Despite the very small energy difference of only 8 keV the two states do not interact. This further supports the assignment of very different configurations to bands N1 and N4, with band N1 built on the $\nu B^{-1}H$ configuration and band N4 built on the $\pi E^{-1}\bar{A}$ configuration.

The 8^- state at 2980 keV is weakly populated by the 577 and 391 keV transitions from bands N2 and N3, respectively. This can be explained by a $\pi F^{-1}\bar{A}$ proton configuration, and would complete

the set of four two-quasiparticle negative-parity bands based on proton configurations with even and odd spins, as also predicted by the calculations shown in Fig. 11.

2. Paired CSM calculations

In the preceding subsection, unpaired CSM calculations, including possible variation of the direction of the axis of stationary rotation with respect to the deformation of the body were performed, in order to understand the global features of the excited band structure. As discussed there, however, some deviations from the observed data remain. Then, to look into the observed medium-spin bands more closely, keeping in mind possible collective excitations, the cranked shell model with pairing [22, 35] should be resorted to. Here observed $\Delta I = 2$ positive-parity bands are compared with quasiparticle excited bands calculated by means of the principal-axis cranked Nilsson + BCS model.

The πh^2 configuration ($\pi 10$) assigned to band L1 is also based on systematics and IBM calculations [21]. As one can see in Figs. 12 and 13, which show the experimental excitation energy relative to a rotating liquid drop reference [36], the average slope of band L1 is smaller than that of the g-band, suggesting a larger moment of inertia for band L1. This is in agreement with the results of the TRS calculations which show a triaxial shape with $\varepsilon_2 = 0.17$ and $\gamma = +30^\circ$ for the assigned πh^2 configuration [21].

There are four bands, L2 – L5, which mainly decay to band L1. For them, we repeated calculations adopting constant mean field parameters appropriate for the πh^2 aligned configuration of band L1, $\varepsilon_2 = 0.17$, $\gamma = +30^\circ$ (short axis), $\Delta_n = 1.0$ MeV, and $\Delta_p = 0.3$ MeV, whereas chemical potentials are adjusted at each rotational frequency so that the quasiparticle vacuum has correct particle numbers. With these parameters, the proton S-configuration $\pi h^2 \pi 0 \nu 0 = \pi 10 \nu 0$ becomes yrast at $\hbar\omega_{\text{rot}} = 0.12$ MeV as can be seen in Fig. 14.

As for the zero pairing calculations, we examine two-quasiparticle excitations relative to this configuration. Figure 15(a), extracted from Fig. 11, shows the experimental Routhians of bands L2 –L5 relative to that of band L1. Their slopes

represent relative alignments. Although e'_{L2} relative to the L1 reference does not reach zero because the highest transition in band L1 corresponds to $\hbar\omega_{\text{rot}} = 0.626$ MeV, which is larger than $\hbar\omega_{\text{rot}} = 0.493$ MeV corresponding to the highest transition observed in band L2, this figure indicates that bands L2 and L5 cross L1 at $I \sim 20$ as shown in Figs. 12 and 13. Based on the quasiparticle Routhians in Fig. 14 we search for candidate configurations for the observed bands.

Figure 15(b) shows the results of calculation. The lowest even-spin, positive-parity configuration is $\pi E^\dagger F^\dagger$, which does not have a particle-hole limit, can be assigned to band L2, alternatively to the $\pi F^\dagger H$ assignment resulting from zero pairing calculations. The second lowest even-spin, positive-parity configuration is $\pi F^\dagger H$ which can be assigned to band L3.

The third low-lying even-spin, even-parity configuration is $\pi E^\dagger G$ with negative alignments, which in unpaired calculations has been assigned to band L3. It has not an experimentally observed counterpart judging from its alignment. For the odd-spin “band” L4, only one transition was observed. It can be accounted for by the lowest $\pi E^\dagger H$ odd-spin excitation shown in Fig. 15(b), which is the same as in unpaired calculations.

Regarding band L5 whose parity is not established, a primary possibility is $\pi F^\dagger C$, as discussed in subsections IV A and IV B. However as deduced from Fig. 14, this configuration gives a too low excitation energy for $\hbar\omega > 0.3$ MeV, even below the energy of the $\pi 10$ configuration assigned to band L1. Another possible configuration for band L5 are the odd-spin νh^2 configurations, $(-, -1/2)^2$ or $(-, +1/2)^2$, on top of L1 shown in Fig.15(c). This accounts naturally for the crossing around $\hbar\omega_{\text{rot}} = 0.5$ MeV that corresponds to $I \sim 20$.

Next we discuss the bands L7 and L8, which decay to L6, based on a calculation with mean field parameters $\varepsilon_2 = 0.17$, $\gamma = -90^\circ$ (long axis), $\Delta_n = 0.3$ MeV, and $\Delta_p = 1.0$ MeV. As already discussed, the TAC calculations with these parameters show that configurations containing $\nu h^2 \nu 0 = \nu 10$ prefer rotation about the long axis, with a moment of inertia that is too small to support a regular rotational band extended over several spins. Band L6, defined as the $14^+ - 12^+ - 10^+$ sequence, is assigned to the configuration $\pi 0 \nu h^2 \nu 0 = \pi 0 \nu 10$.

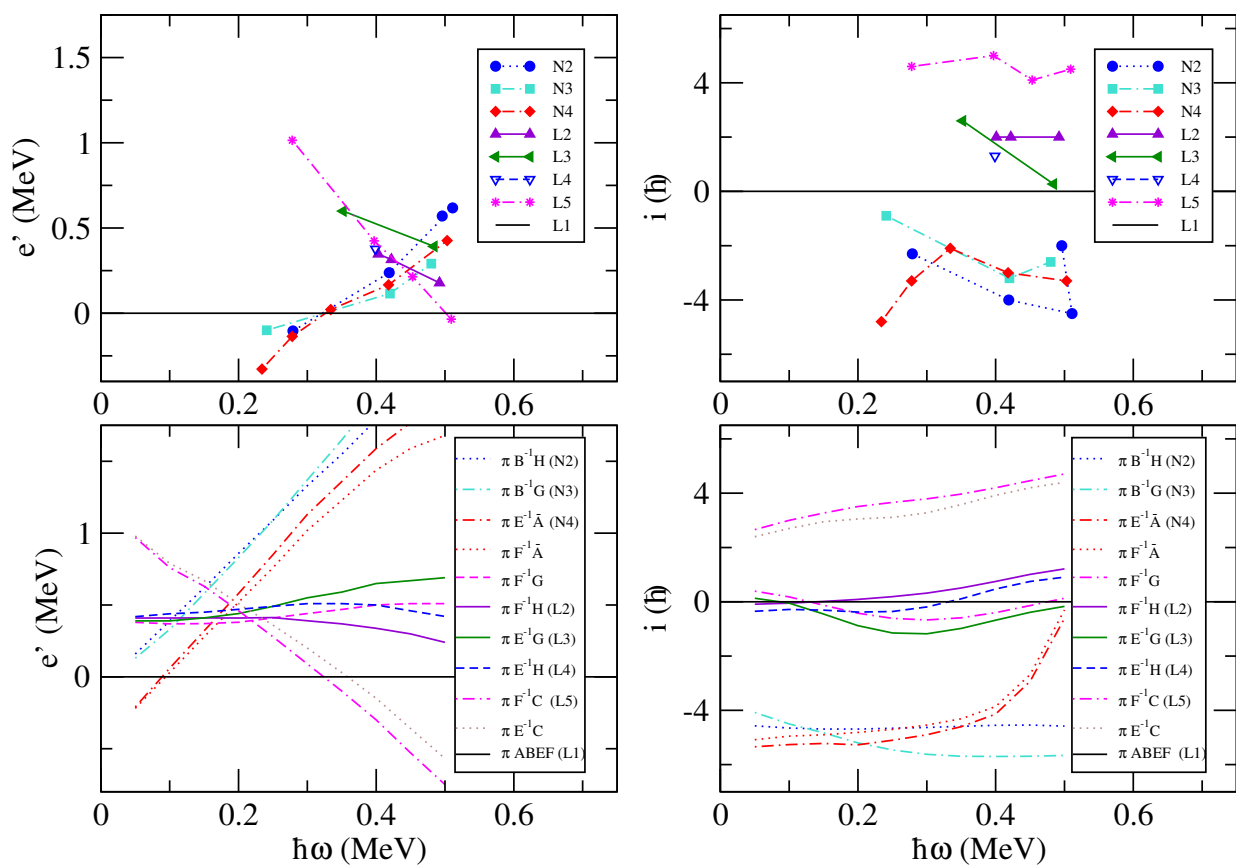


FIG. 11: Experimental and calculated Routhians and single-particle alignments relative to band L1 for the $\Delta I=2$ bands L2-L5 and N2-N4 of ^{138}Nd . Parity and signature (π, α) are indicated by the line type: full (+,0), dash (+,1), dot (-,0), dash-dot (-, 1).

Figure 16 indicates that the lowest even-spin excitation is $\pi F^\dagger I \otimes \nu 10$. Here and further in this paragraph the proton configurations are taken relative to the g-vacuum. Actually the blue dotted curve in Fig. 17(b) can be identified with the observed band L8 in terms of the Routhian relative to that of L6 in Fig. 17(a). In contrast, the observed odd-spin band L7 can not be identified with any calculated two-quasiparticle excitation. In fact, as one can see in Fig. 17(b), the lowest odd-spin configuration $\pi GI \otimes \nu 10$, which does not have a particle-hole limit, is calculated at a much higher excitation energy than the lowest even-spin $\pi F^\dagger I \otimes \nu 10$ configuration. This is in disagreement with the experimental data shown in Fig. 17(a), which exhibit a near degeneracy of the Routhians for the odd- and even-spin states of bands L7 and L8, respectively.

3. RPA calculations for wobbling

The configuration of band L7 can be investigated looking for the possible collective excitations built on the νh^2 configuration. We have performed random-phase approximation (RPA) calculations built on two-quasiparticle configurations, in which the residual interaction between quasiparticles is taken into account using a quadrupole-quadrupole force.

The RPA equation for odd-spin excitations can be cast into the form that is appropriate for wobbling motion [37]

$$\omega^2 = \omega_{\text{rot}}^2 \frac{(\mathcal{J}_x - \mathcal{J}_y^{(\text{eff})}(\omega))(\mathcal{J}_x - \mathcal{J}_z^{(\text{eff})}(\omega))}{\mathcal{J}_y^{(\text{eff})}(\omega)\mathcal{J}_z^{(\text{eff})}(\omega)}, \quad (6)$$

although this gives also non-collective solutions. Here \mathcal{J}_x is the usual kinematic moment of inertia including the contribution from the aligned quasiparticle(s), whereas $\mathcal{J}_{y,z}^{(\text{eff})}(\omega)$ are calculated self-consistently with ω .

Figure 18 shows almost all solutions located lower than 1 MeV. We will focus on the two lowest solutions which develop over larger frequency interval and are well separated from the higher excited ones. For the lowest solution, judging from its excitation energy that is well separated from other states, from the calculated three moments of

inertia in Fig. 19(a), from the calculated wobbling angles [38] in Fig. 19(b), from the quadrupole transition amplitudes with fully mixed $K = 1$ and 2 components, and from the distribution of the wave functions, one can state that the lowest RPA solution is a well-developed wobbling mode in the frequency range in which band L7 is observed. The calculated moments of inertia can be understood as irrotational-like γ -dependence ($\mathcal{J}_x < \mathcal{J}_z$) superimposed by the contribution to \mathcal{J}_x from the aligned νh^2 pair that makes $\mathcal{J}_x > \mathcal{J}_z$ as in the celebrated case of ^{163}Lu case with a $\pi i_{13/2}$ that makes $\mathcal{J}_x > \mathcal{J}_y$ [6, 39]. Thus we propose to interpret the observed band L7 as wobbling mode although its vacuum is not a well-deformed state.

In the frequency range in which the lowest solution is collective, the second lowest solution is an almost pure πGI state whose unperturbed state is shown by the green dotted curve. As rotation frequency increases, this πGI component in the RPA wave function moves gradually from the second to the lowest solution and eventually the lowest solution becomes unstable.

In general, the instability of a collective mode leads to a “phase transition” of the mean field to that with lower symmetry. In the case of the wobbling mode around a principal axis, the corresponding new mean field is a tilted-axis rotating state [38]. Rotation about a tilted axis is expected to be observed as a $\Delta I = 1$ dipole band [23], as will be discussed in the next section. In the present case the instability is triggered by the steep lowering of the lowest πGI state. Although the frequency of the observed upper transition in band L7, $\omega_{\text{rot}} = 0.386$ MeV, is lower than the calculated instability at $\hbar\omega_{\text{rot}} \sim 0.5$ MeV, it can be conjectured that tilted-axis rotating states that contain νh^2 and one or two $\pi(dg)$ would appear accompanying to this instability.

Once band L7 is interpreted as one-phonon wobbling, a first glance at the level scheme of L6 – L8 gives an expectation that L8 is the two-phonon wobbling from its spin and excitation energy. But Fig. 17(a) indicates that the frequency ranges of L7 and L8 are displaced from each other and L8 is lower than L7 even if they are extrapolated to common frequency, although they have similar alignments.

Finally, an interesting feature of the level scheme of ^{138}Nd above the 10^+ isomer with νh^2 configuration is the existence of three excited states with

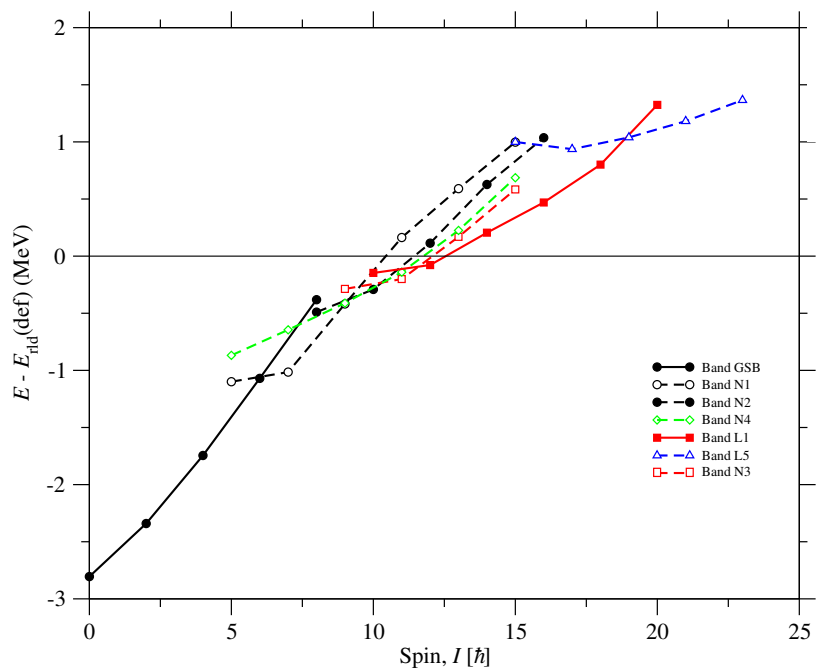


FIG. 12: (Color online) Experimental excitation energy relative to a rotating liquid drop reference for the negative-parity bands, the ground-state band and the L1 band in ^{138}Nd . Solid and dashed lines are used for positive and negative parity configurations, respectively. Closed symbols are used for signature $\alpha = 0$ and open symbols for signature $\alpha = 1$.

spins 11^+ , 12^- and 13^- which are strongly populated from the decay of the dipole band D1. We did not observe collective cascades built on these states, which suggests that they are of single particle nature. In fact, we can simply explain the of the 11^+ state by including two more neutrons in $(s_{1/2})_{1+}$, leading to a total maximum aligned spin for this configuration of 11^+ . The 12^- and 13^- states can be explained by 4-quasiparticle maximum aligned configurations with two protons in $(d_{5/2}g_{7/2})_{6+}$ coupled to two neutrons in $(h_{11/2}s_{1/2})_{6-}$ or $(h_{11/2}d_{3/2})_{7-}$, respectively. Such configurations would nicely explain the strong connecting transitions between the $11^+, 12^-$ and 13^- states, as well as the important population received by the 13^- state from band D1 for which a $\pi h^1(dg)^1 \otimes \nu h^2$ configuration is assigned (see below). We mention that negative-parity states with spins 12^- and 13^- were also observed in the neighboring ^{140}Nd nucleus in the de-excitation of the 20^+ 6-quasiparticle isomer with $\pi(dg)^4 \otimes \nu h^2$ configuration and interpreted as maximum aligned states $\pi(dg)^2 \otimes \nu h^1(sd)^1$ configurations [40].

C. The $\Delta I = 1$ bands

The experimental Routhians and particle-hole alignments of bands D1-D8 relative to band L1 in ^{138}Nd and the corresponding calculated quantities relative to the $\pi 10 = \pi ABEF$ configuration assigned to band L1 are shown in Figs. 20 and 21. The large number of dipole bands originates from the combination of $h_{11/2}$ protons, which align with the short axis, and $h_{11/2}$ neutrons, which align with the long axis. As a compromise, the rotational axis lies in the short-long principal plane being tilted away from the principal axes by a large angle. The tilt breaks the $\mathcal{R}_x(\pi)$ symmetry that induces the signature quantum number, and one observes a $\Delta I = 1$ sequence of rotational states, *i.e.* a dipole band [5]. The rotational mode is predominantly of magnetic nature, because the mutually perpendicular angular momenta of the proton and neutron $h_{11/2}$ orbitals combine to a large transverse magnetic moment, which generates strong M1 transitions.

Most of the dipole bands result from changing the neutron configuration of the various proton configurations in Table II from $\nu 0$ to $\nu 10$, which contains the two $h_{11/2}$ neutron holes that align

TABLE III: Single-particle configurations for the $\Delta I=1$ bands of ^{138}Nd .

Configuration	π	bands
$\pi 10 \otimes \nu 10$	+	D5
$\pi B^{-1}G \otimes \nu 10$	-	D3
$\pi B^{-1}H \otimes \nu 10$	-	
$\pi E^{-1}\bar{A} \otimes \nu 10$	-	D2
$\pi F^{-1}\bar{A} \otimes \nu 10$	-	D1
$\pi F^{-1}C \otimes \nu 10$	-	D7
$\pi E^{-1}C \otimes \nu 10$	-	D8
$\pi E^{-1}G \otimes \nu 10$	+	
$\pi E^{-1}H \otimes \nu 10$	+	
$\pi F^{-1}G \otimes \nu 10$	+	
$\pi F^{-1}H \otimes \nu 10$	+	
$\pi F^{-1}\bar{A} \otimes \nu B^{-1}G$	+	
$\pi B^{-1}C \otimes \nu 10$	+	
$\pi F^{-1}I \otimes \nu 0$	+	D4
$\pi F^{-1}I \otimes \nu 10$	+	D6

their angular momentum with the long axis. Table III lists the configurations that originate from these combinations and suggests how to interpret the observed dipole bands. Fig. 22 shows that the $B(M1)$ values of these bands are large, reflecting the long angular momentum vectors of the $h_{11/2}$ particles, which enclose a large angle with the rotational axis. The $B(M1)$ values only weakly change with the angular frequency not showing the decrease that is characteristic for pure magnetic rotation [41]. The reason is that the deformation is still substantial. Hence the rotational mode has an intermediate character, being in between magnetic and collective electric rotation [41]. The ratios $B(M1)/B(E2) > 50 \mu_N^2/(eb)^2$. For many bands they are larger than $1000 \mu_N^2/(eb)^2$. This explains the absence of any E2 crossover transitions in all dipole bands observed in this experiment, with the only exception of band D1, for which the $B(M1)/B(E2) \sim 30 \mu_N^2/(eb)^2$.

The configuration assigned to band D1, $\pi F^{-1}\bar{A} \otimes \nu 10$, is supported by the comparison with the odd-even ^{139}Nd neighboring nucleus, in which a 3-quasiparticle band has been observed at an excitation energy relative to the 10^+ isomer which is similar to that of band D1 (see Fig. 23). The configuration assigned to the band in ^{139}Nd is $\pi h^1(dg)^1 \otimes \nu h^1$ [13, 42]. Such a dipole band was also observed in the neighboring isotone ^{136}Ce [34] and interpreted as a $\pi h^1(dg)^1 \otimes \nu h^2$ configuration with rotation around a tilted axis. The measured transition probabilities support the interpretation

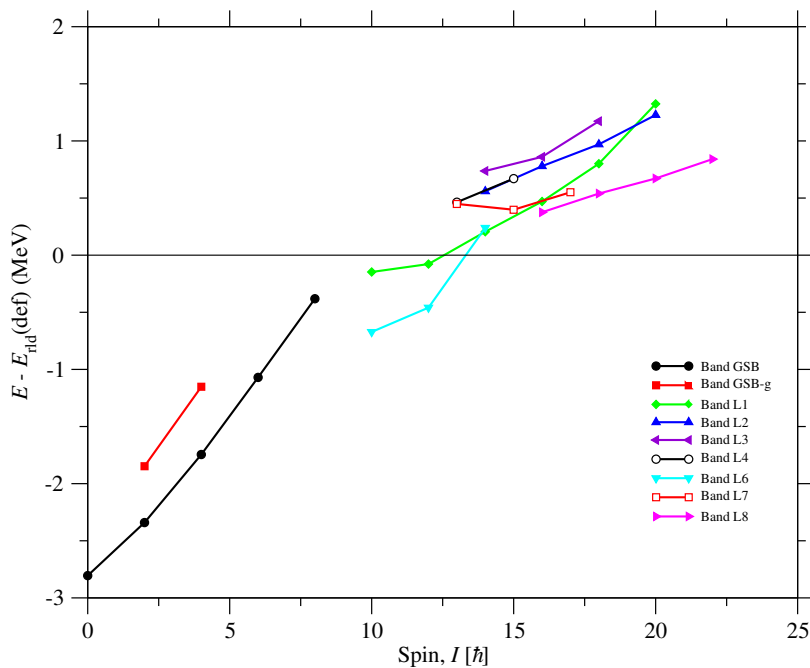


FIG. 13: The same as in figure 12 for the low- and medium-spin positive-parity bands.

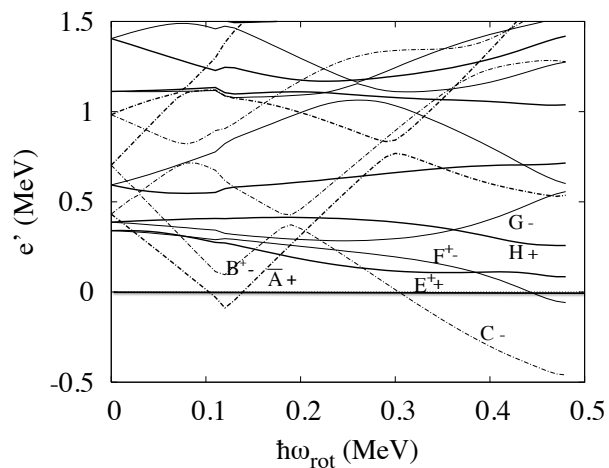


FIG. 14: Proton Routhians as function of rotational frequency for ^{138}Nd , calculated using the constant mean field parameters $\varepsilon_2 = 0.17$, $\gamma = +30^\circ$, and $\Delta_p = 0.3$ MeV. The chemical potential is adjusted at each rotational frequency so that the quasiparticle vacuum has the correct particle number. This causes a small irregularity at the crossing at $\hbar\omega_{\text{rot}} = 0.12$ MeV. Positive- and negative-parity states are drawn by solid and dot-dashed curves, respectively. Some of them are explicitly labeled conforming to unpaired ones in Fig. 7.

of the band in ^{136}Ce as "magnetic rotation". The similarity of the two corresponding dipole bands in ^{139}Nd and ^{136}Ce , and band D1 of ^{138}Nd strongly supports the $\pi F^{-1}\bar{A} \otimes \nu 10$ [$\pi h^1(dg)^1 \otimes \nu h^2$] configuration to band D1, which is in disagreement with the $\pi h^2 \otimes \nu h^2$ configuration proposed in ref. [21].

The TAC calculation for the configuration $\pi F^{-1}\bar{A} \otimes \nu 10$ gave a shallow minimum outside the short-long principal plane at $\phi \approx 30^\circ$, which indicates instability with respect to intrinsic chirality around $\hbar\omega \approx 0.35$ MeV. Indeed, band D2 decays through dipole transitions towards band D1 and is nearly parallel to it. This is characteristic to the chiral bands and the band D2 could be the first candidate in an even-even nucleus. Those claimed in the neighboring ^{136}Nd nucleus were not confirmed neither by lifetime measurements nor by calculations [43, 44]. However, one cannot exclude possible configurations for band D2, closely related to that of band D1, like that in which one of the two protons is excited from E to F , giving rise to the $\pi E^{-1}\bar{A} \otimes \nu 10$ configuration.

Band D3 starts at spin $14^{(-)}$ and decays to negative-parity non-yrast states which in turn decay to the 10^+ isomer with $\nu 10$ configuration. A possible configuration which account for its decay pattern is $\pi B^{-1}G \otimes \nu 10$.

Band D4 is the lowest-lying dipole band, starts at spin 10^+ and decay to band L1 and to the ground-state band. Its alignment of $i < 2\hbar$ relative to the reference is too low to involve two $h_{11/2}$ protons and two $h_{11/2}$ neutron holes. There are two possibilities for generating positive parity and low alignment. i) One may combine the negative parity proton configurations listed in Table II with the negative parity neutron configurations listed in the same table. One example is $\pi F^{-1}\bar{A} \otimes \nu B^{-1}G$, which is included in Table III and Fig. 20. (The other combinations, which look similar, are left out for clarity.) This type has $B(M1)/B(E2) > 300 \mu_N^2/(eb)^2$. ii) The pure proton excitation $\pi F^{-1}I \otimes \nu 0$ has a smaller ratio of $B(M1)/B(E2) \approx 4\mu_N^2/(eb)^2$. We tentatively adopt the $\pi F^{-1}I \otimes \nu 0$ assignment, because the calculated alignment and Routhian correlate better with experiment, and the assignment is consistent with the interpretation of D6, which decays into D4, as generated by the alignment of the two $h_{11/2}$ neutrons. However, the non-observation of cross-over quadrupole transitions in band D4 put a limit of the $B(M1)/B(E2) > 500 \mu_N^2/(eb)^2$, which

speaks in favor of the $\pi F^{-1}\bar{A} \otimes \nu B^{-1}G$ configuration.

Band D5 decays to band D4 and starts at spin $16^{(+)}$. It can be based on the $\pi 10 \otimes \nu 10$ configuration, since both the Routhian and the aligned angular momentum are in agreement with experiment.

Band D6 starts at spin $19^{(+)}$ and decays to band L8 whose configuration is $\nu E^{-1}G$ and to band L3 whose configuration is $\pi E^{-1}G$. The configurations $\pi F^{-1}I \otimes \nu 10$ and $\pi E^{-1}H \otimes \nu 10$ shown in Fig. 21 are possible candidates, while the $\pi F^{-1}\bar{A} \otimes \nu B^{-1}G$ positive-parity configuration can be excluded since it has a Routhian with completely different behavior and the aligned angular momentum is too low. None of the $\pi F^{-1}I \otimes \nu 10$ and $\pi E^{-1}H \otimes \nu 10$ configurations fit well to band D6, since $\pi F^{-1}I \otimes \nu 10$ has the Routhian too high, while $\pi E^{-1}H \otimes \nu 10$ has the alignment too low. Based on the better agreement of the aligned angular momentum we give preference to the $\pi F^{-1}I \otimes \nu 10$ configuration.

The two bands D7 and D8 are observed above spin $22^{(-)}$ and fed the top level of band D1. They can be built on the 6-quasiparticle configurations $\pi F^{-1}C \otimes \nu 10$ and $\pi E^{-1}C \otimes \nu 10$, respectively.

V. CONFIGURATION ASSIGNMENTS

The configuration assignments to the low- and medium-spin states are summarized in Table IV

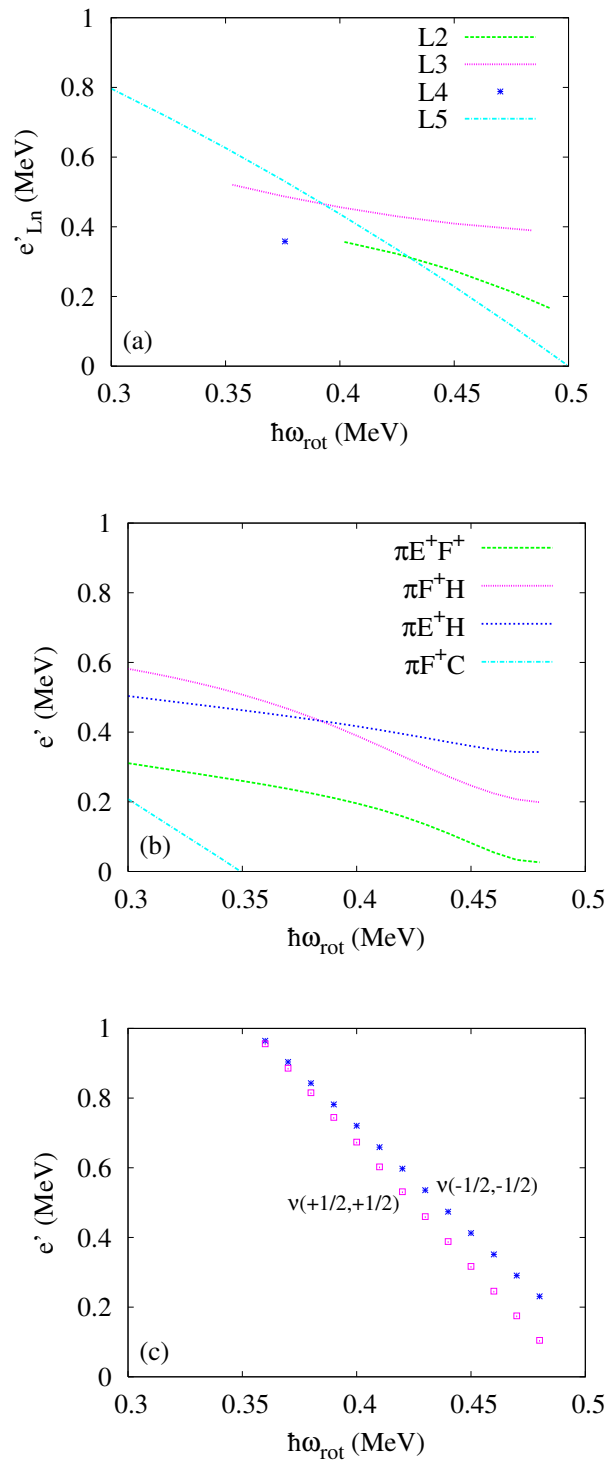


FIG. 15: (a) Experimental Routhians of bands L2 – L5 relative to that of band L1. (b) and (c) Energy difference between the different calculated (two-quasiparticle $\otimes \pi 10$) configurations and the $\pi 10$ configuration assigned to band L1. The calculations are performed at constant mean field parameters $\varepsilon_2 = 0.17$, $\gamma = +30^\circ$, and $\Delta_p = 0.3$ MeV.

TABLE IV: Configuration assignments to the low- and medium-spin bands of ^{138}Nd in terms of particle-hole excitations with respect to the $\pi ABEF = \pi 10$ reference configuration assigned to band L1 or the corresponding quasiproton vacuum for small finite pairing. The rotation axis is also indicated, which can be tilted (TAC) or parallel to a principal axis (PAC) of the intrinsic reference system of the nucleus. In the case of PAC, l and s indicate the long and short axes, respectively.

Band	Intensity (%)	Configuration	Rotation type	States	Comments
g-band	100	$\pi 0 \otimes \nu 0$		$2^+ \div 8^+$	
γ -band		γ -band		$2^+ \div 4^+$	Decays to g-band
N1	39	$\pi 0 \otimes \nu B^{-1} H \nu 10$	PAC-l	$5_1^- \div 15^-$	Decays to g-band
N2	14	$\pi B^{-1} H \pi 10 \otimes \nu 0$	PAC-s	$8_2^- \div 16^-$	Decays to N1, N3, 8_1^-
N3	2	$\pi B^{-1} G \pi 10 \otimes \nu 0$	PAC-s	$9_2^- \div 15^-$	Decays to N2, N4, 8_1^-
N4	89	$\pi E^{-1} \bar{A} \pi 10 \otimes \nu 0$	PAC-s	$7_2^- \div 15^-$	Decays to N1, N3, GSB
8_1^-	17	$\pi F^{-1} \bar{A} \pi 10 \otimes \nu 0$	PAC-s	$8_1^-, 8_2^-$	Decays to N1
L1	64	$\pi 10 \otimes \nu 0$	PAC-s	$10^+ \div 20^+$	Decays to N2, N3
L2	6	$\pi F^{-1} H \pi 10 \otimes \nu 0$ or $\pi E^{\dagger} F^{\dagger} \pi 10 \otimes \nu 0$	PAC-s	$14^+, 16^+, 18^+$	Decays to L1
L3	2	$\pi E^{-1} G \pi 10 \otimes \nu 0$ or $\pi F^{\dagger} H \pi 10 \otimes \nu 0$	PAC-s	$14^+ \div 20^+$	Decays to L1, L4
L4	2	$\pi E^{-1} H \pi 10 \otimes \nu 0$	PAC-s	$13^+, 15^+$	Decays to L1, L3
L5	8	$\pi F^{-1} C \pi 10 \otimes \nu 0$ or $\pi 10 \otimes \nu h^2$	PAC-s	$15^{(-)} \div 23^{(-)}$	Decays to L1, D4
L6	24	$\pi 0 \otimes \nu 10$	PAC-l	$10^+ \div 14^+$	Band head is isomeric
L7	11	wobbling or $\pi 0 \otimes \nu F^{-1} G \nu 10$ or $\pi G I \pi 0 \otimes \nu 10$	PAC-l	$13^+ \div 17^+$	Decays to L6
L8	2	$\pi 0 \otimes \nu E^{-1} G \nu 10$ or $\pi F^{\dagger} I \pi 0 \otimes \nu 10$	PAC-l	$16^+ \div 22^+$	Decays to L7
D1	21	$\pi F^{-1} \bar{A} \pi 10 \otimes \nu 10$	TAC	$13^- \div 21^-$	Decays to N4, L8
D2	2	$\pi E^{-1} \bar{A} \pi 10 \otimes \nu 10$ or chiral	TAC	$15^- \div 19^-$	Decays to D1
D3	1	$\pi B^{-1} G \pi 10 \otimes \nu 10$	TAC	$14^- \div 18^-$	Decays to non-yrast $\pi = -$
D4	5	$\pi F^{-1} I \pi 10 \otimes \nu 0$ or $\pi F^{-1} \bar{A} \otimes \nu b^{-1} g$	TAC	$10^+ \div 17^+$	Decays to L1 and GSB
D5	1	$\pi 10 \otimes \nu 10$	TAC	$16^{(+)} \div 23^{(+)}$	Decays to D4 and $\pi = -$
D6	4	$\pi F^{-1} I \pi 10 \otimes \nu 10$ or $\pi E^{-1} H \otimes \nu 10$	TAC	$19^{(+)} \div (25^+)$	Decays to L7
D7	3	$\pi F^{-1} C \pi 10 \otimes \nu 10$	TAC	$22^{(-)} \div (26^-)$	Decays to D1
D8	2	$\pi E^{-1} C \pi 10 \otimes \nu 10$	TAC	$24^{(-)} \div (27^-)$	Decays to D7

VI. SUMMARY

High-spin states in ^{138}Nd have been populated in the reaction $^{94}\text{Zr}(^{48}\text{Ca}, 4n)$ at a beam energies of 188 and 195 MeV. The GASP spectrometer was used to detect the γ -ray coincidences. A very rich and complete level scheme was developed and most of the existing information was confirmed. New bands were observed at low and medium spins (4 negative-parity bands at low spins, 8 bands of quadrupole transitions and 8 bands of dipole transitions at medium spins). The observed bands were discussed using the CSM, TAC and the random phase approximation based on the cranking model. A discussion of the possible existence of wobbling motion in this mass region is also presented. Possible configurations for the different dipole bands are discussed, showing that rotations can occur in ^{138}Nd either around a principal or a tilted axis of

the intrinsic reference system, depending on the presence in the configurations of protons and neutrons in the $h_{11/2}$ orbital. Two dipole bands have properties which are consistent with a chiral character, representing the first candidates for chiral partners in an even-even nucleus. The global understanding of the observed bands brings a strong support to the existence of a stable triaxial deformation at medium spin in this mass region.

VII. ACKNOWLEDGMENT

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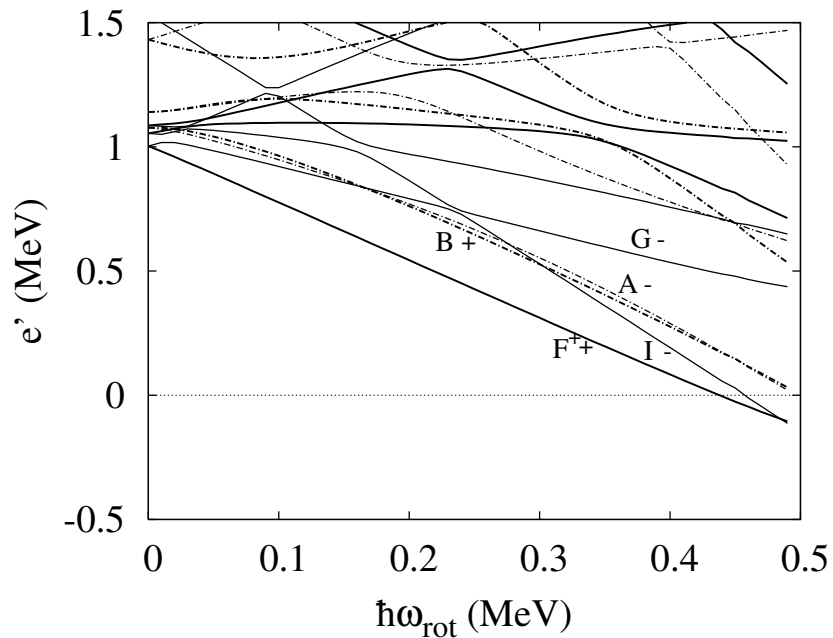


FIG. 16: Proton Routhians as function of rotational frequency for ^{138}Nd , calculated using the constant mean field parameters $\epsilon_2 = 0.17$, $\gamma = -90^\circ$, and $\Delta_p = 1.0$ MeV. The chemical potential is adjusted at each rotational frequency so that the quasiparticle vacuum has the correct particle number. Positive- and negative-parity states are drawn by solid and dot-dashed curves, respectively. Some of them are explicitly labeled conforming to unpaired ones in Fig. 7.

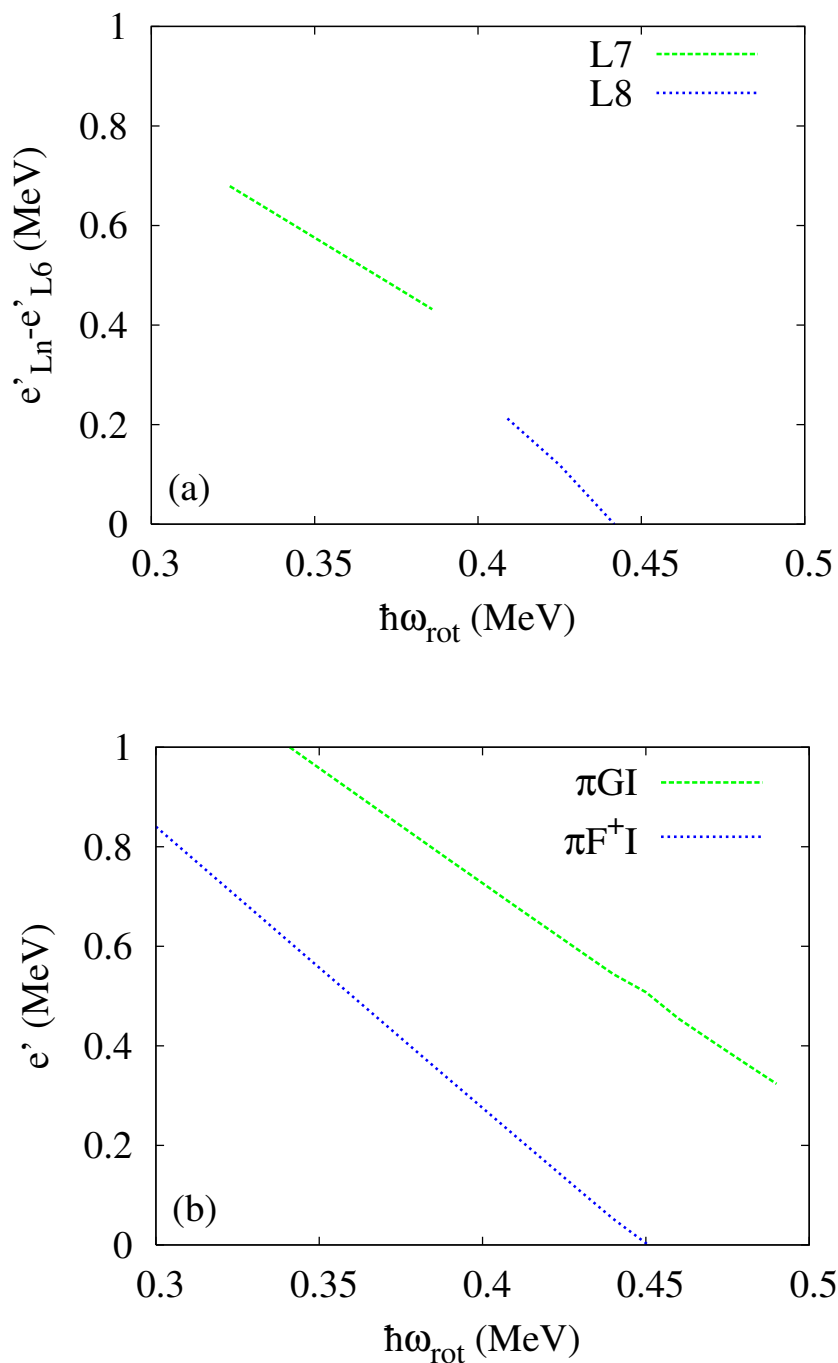


FIG. 17: (a) Experimental Routhians of bands L7 and L8 relative to that of band L6. (b) Energy difference between the different calculated (two-quasiparticle $\otimes \nu 10$) configurations and the $\nu 10$ configuration assigned to band L6. The calculations are performed at constant mean field parameters $\varepsilon_2 = 0.17$, $\gamma = -90^\circ$, and $\Delta_p = 1.0$ MeV.

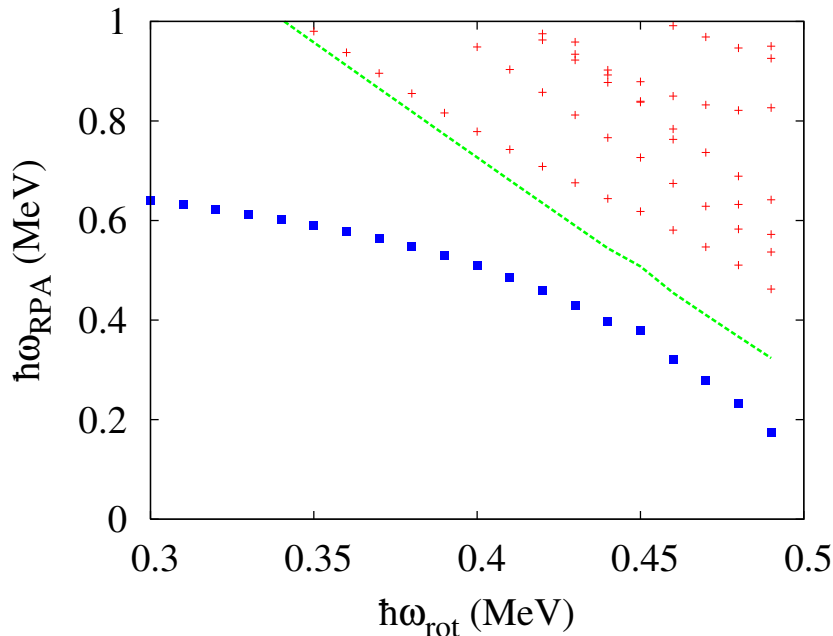


FIG. 18: Calculated excitation energies of the RPA solutions built on the aligned $\nu 10$ configuration as function of the rotational frequency in ^{138}Nd . Among them, the collective solution is emphasized by blue squares. Note that a few purely non-collective solutions are occasionally overlooked in the present algorithm but this does not influence the discussion. The green dotted curve is the unperturbed πGI state.

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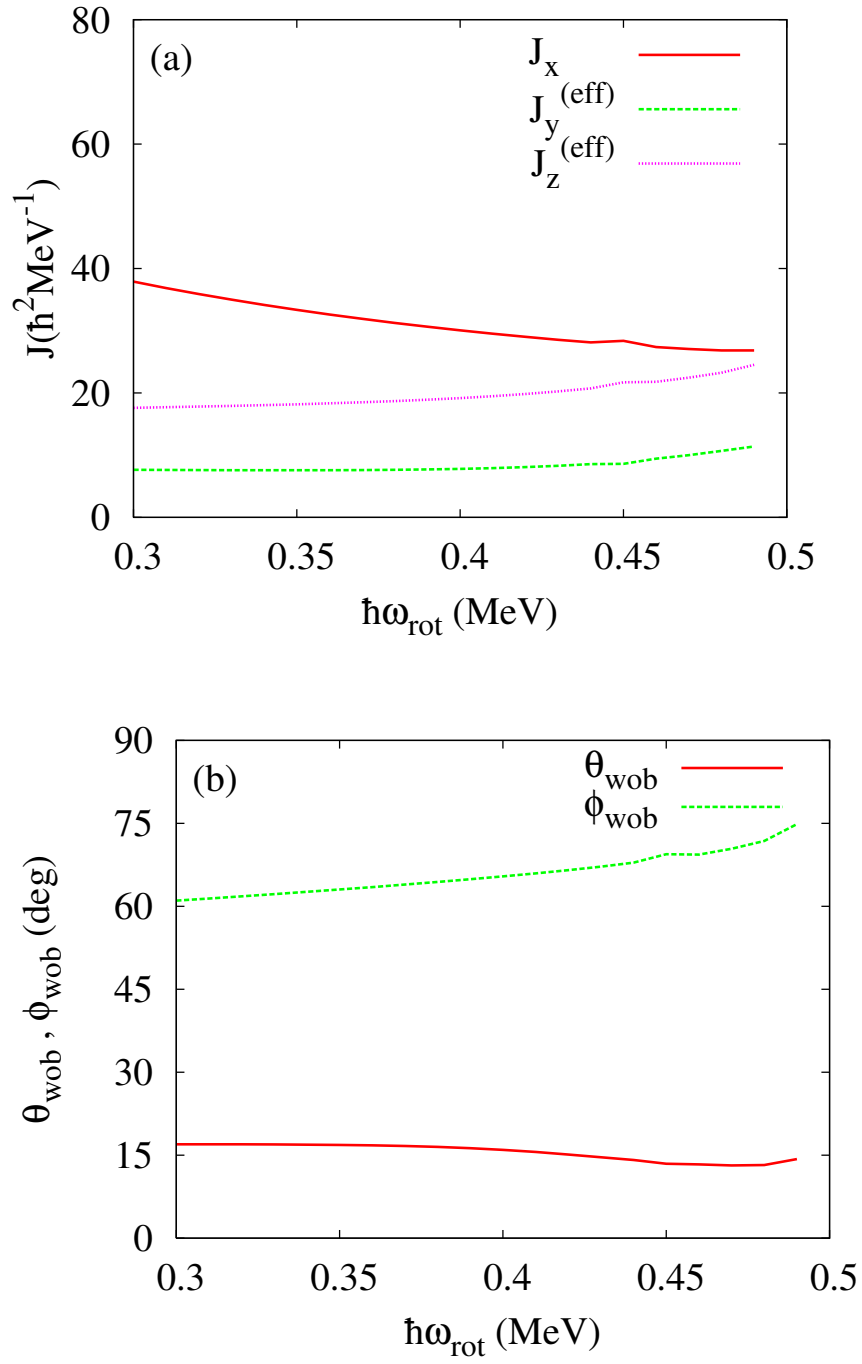


FIG. 19: (a) Calculated moments of inertia and (b) wobbling angles as function of the rotational frequency in ^{138}Nd .

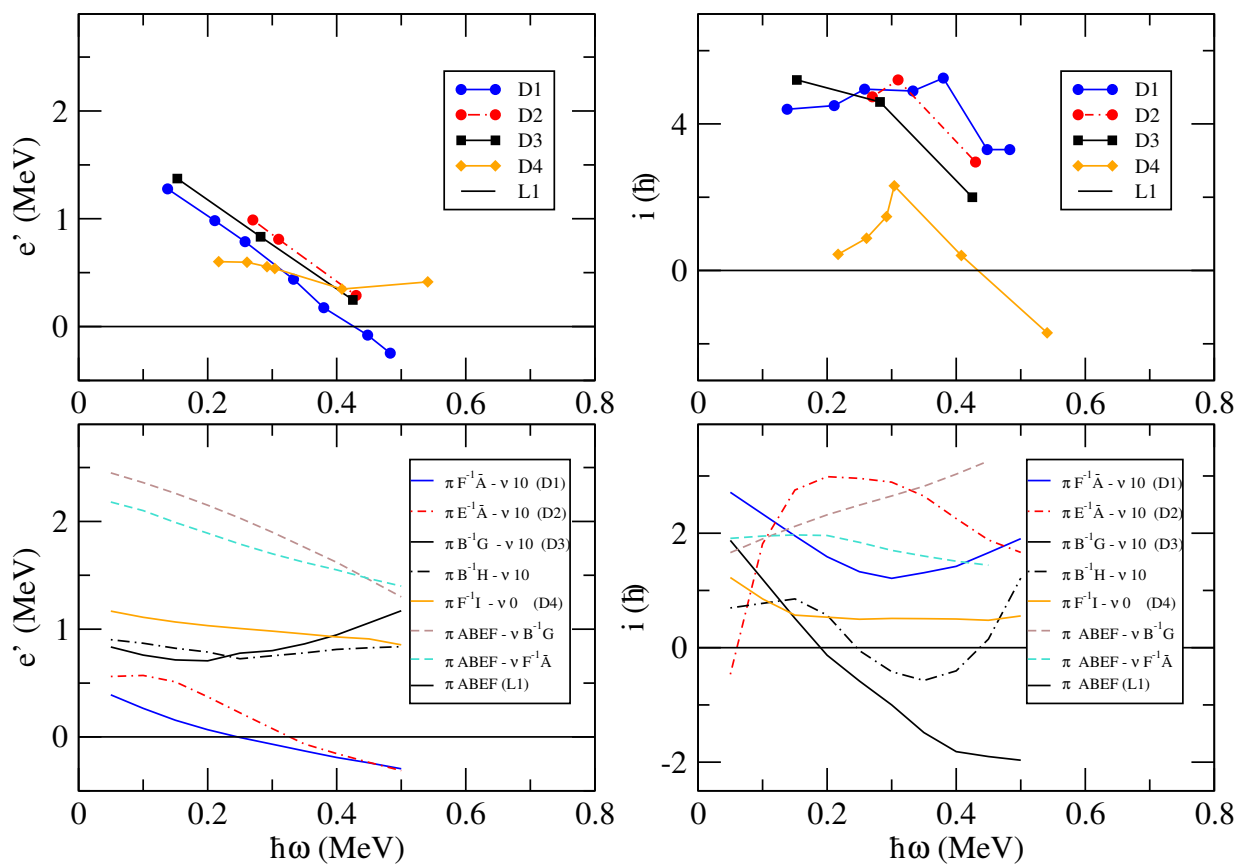


FIG. 20: Experimental and calculated Routhians and single-particle alignments relative to band L1 for the $\Delta I=1$ bands D1-D4 of ^{138}Nd . The line type indicates the parity: full $\pi = +$, dash-dot $\pi = -$. All calculated routhians, except $\pi ABEI\nu 0$, are shifted by $E_{exp,L6}(10^+) - (E_{calc,\nu 10}(\omega = 0) - E_{calc,\nu 0}(\omega = 0))$ in order to account for the energy needed breaking a neutron pair.

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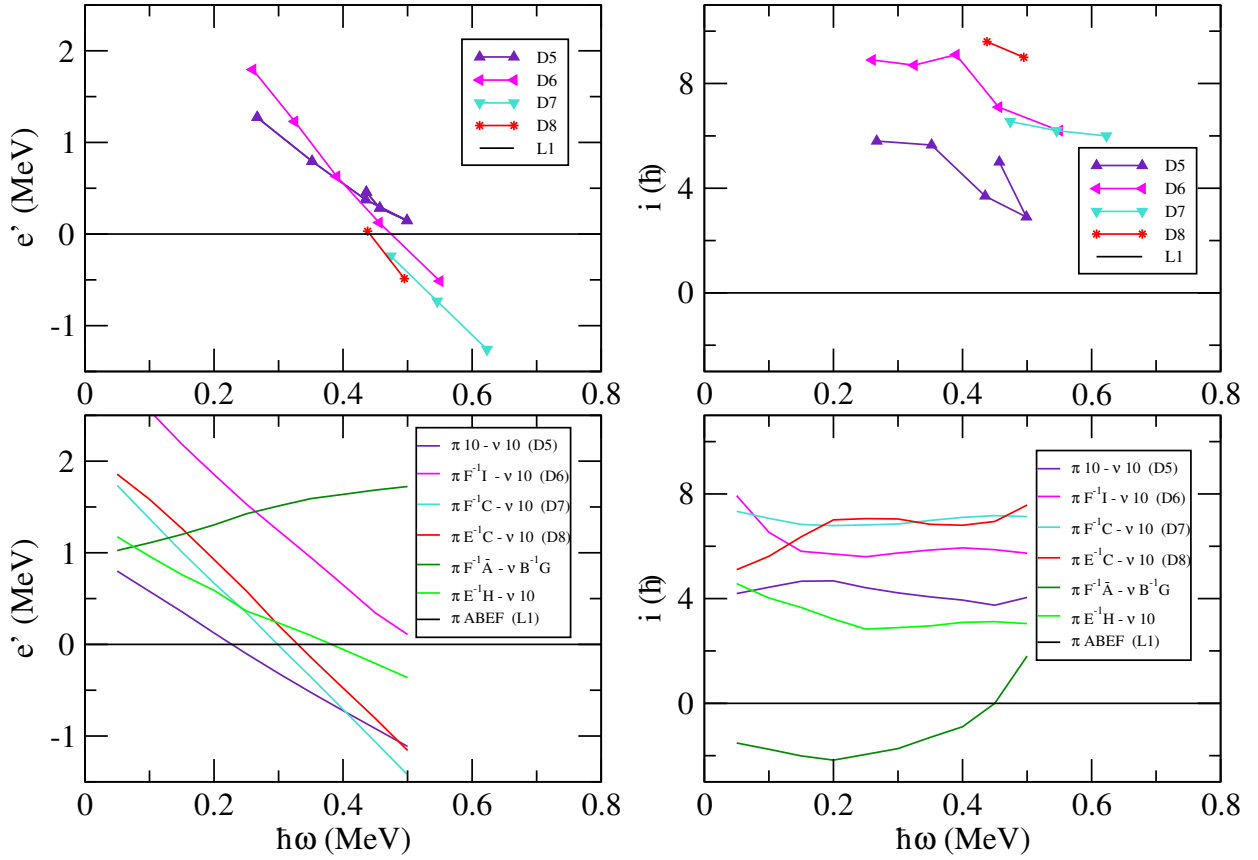


FIG. 21: Experimental and calculated Routhians and single-particle alignments relative to band L1 for the $\Delta I=1$ bands D5-D8 of ^{138}Nd . The line type indicates the parity: full $\pi = +$, dash-dot $\pi = -$. All calculated routhians, except $\pi ABEF\nu 0$, are shifted by $E_{exp,L6}(10^+) - (E_{calc,\nu 10}(\omega = 0) - E_{calc,\nu 0}(\omega = 0))$ in order to account for the energy needed breaking a neutron pair.

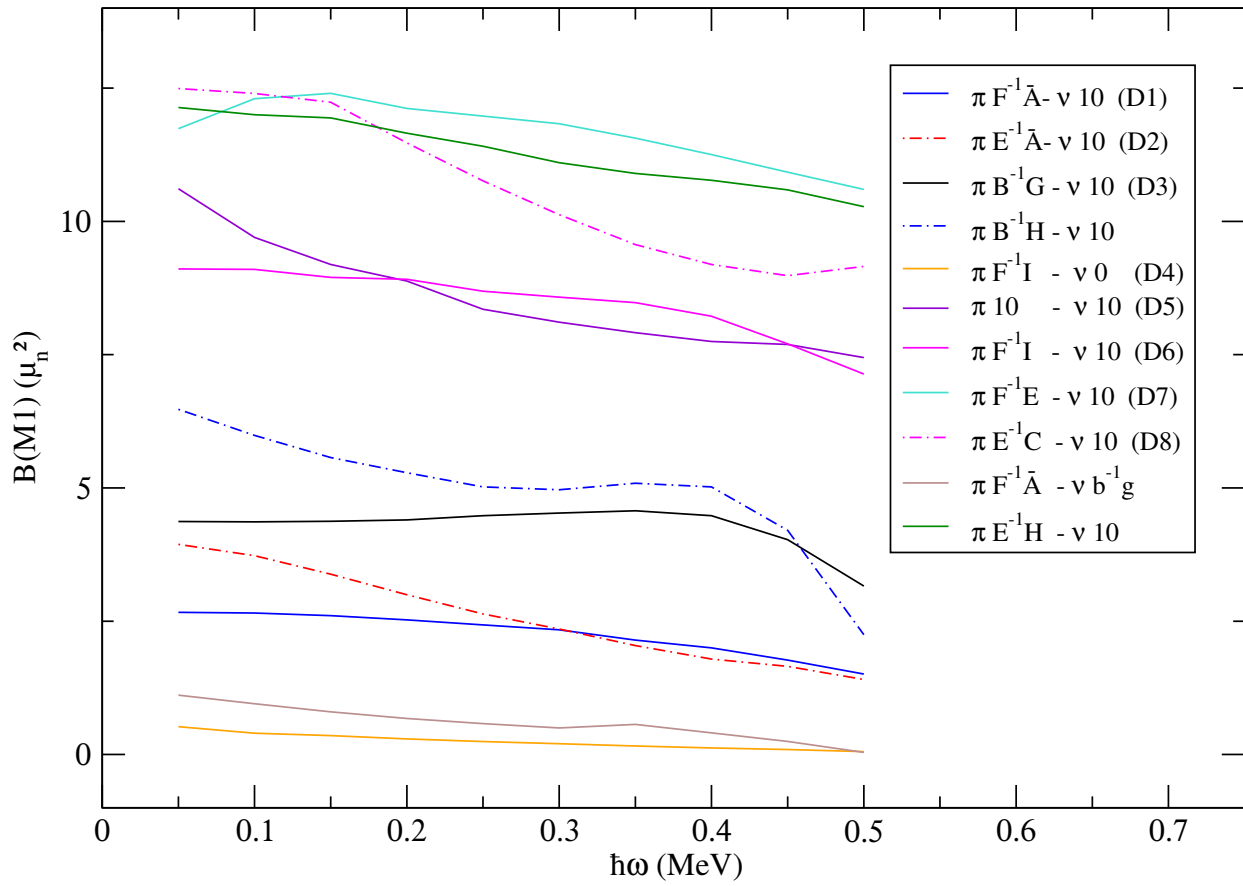


FIG. 22: Calculated $B(M1)$ for the configurations assigned to the dipole bands of ^{138}Nd .

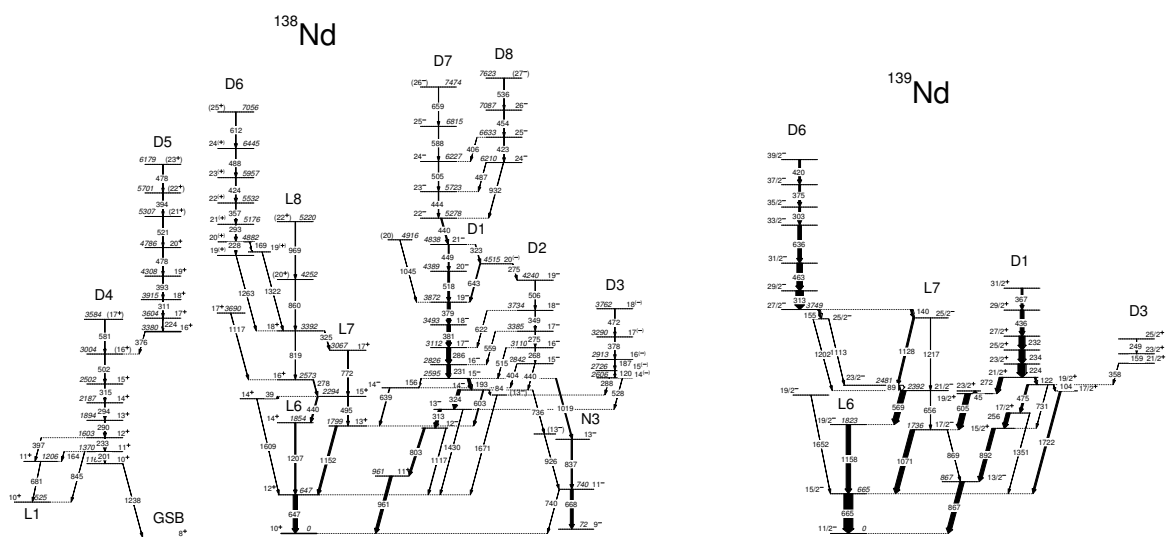


FIG. 23: Comparison between the partial level scheme of ^{138}Nd and ^{139}Nd showing the similarity of the level structure above the 10^+ isomer.