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Short Note

Candidates for chiral doublet bands in ^{136}Nd

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Abstract. The even-even nucleus ^{136}Nd was studied via in-beam γ-ray spectroscopy using the ^{16}O + ^{125}Te reaction at 100 MeV and the EUROBALL array. One new dipole band was observed. Together with a previously identified dipole band, whose position in the level scheme is revised, the new band forms a doublet structure similar to the recently observed chiral bands in the odd-odd neighboring nuclei. This would be the first case of a chiral doublet in an even-even nucleus.

PACS. 23.20.Lv Gamma transitions and level energies – 21.10.Re Collective levels – 21.60.Ev Collective models – 27.60.+j $90 \leq A \leq 149$

Great progress was recently made in the study of neutron-deficient nuclei in the $A \sim 130$ mass region, mainly due to the use of very large γ-ray detector arrays, like EUROBALL, GAMMASPHERE and GASP, in conjunction with charged particle and/or neutron detectors. In that context particular attention was paid to the Nd isotopes, because of their softness with respect to γ deformation. Multiple bands that were observed in the ^{136}Nd nucleus [1–3] were explained by microscopic-macroscopic calculations as being built on triaxial minima with $\gamma \sim -30°$. It was shown that at high spin the ground band and the negative-parity two-quasiparticle band develop into bands with stable triaxiality based on four-quasiparticle configurations. The total Routhian surface calculations predict a triaxial nucleus with $\gamma \sim -30°$ rotating around the intermediate axis [1]. Stable triaxiality at high spin was also observed in ^{138,139}Nd [4], but in this case the predicted triaxiality is $\gamma \sim +30°$, corresponding to a rotation around the shortest axis.

Chiral twin bands of degenerate states with the same spin and parity, that are predicted in nuclei with maximal triaxiality [5], were until now observed only in odd-odd nuclei [6,7]. In these cases the $h_{11/2}$ valence proton is aligned along the short axis, while the $h_{11/2}$ valence neutron hole is aligned along the long axis of the triaxial core. The core rotational angular momentum can align in either direction of the intermediate axis, so that the three mutually perpendicular angular momenta form either a left- or right-handed system. This defines an intrinsic chirality in the body-fixed frame. Restoration of the chiral symmetry in the laboratory frame results in two bands in which states of the same spin are almost degenerate in energy. An interesting question is whether such bands can also exist in even-even nuclei. While the odd-odd systems provide the simplest example of this symmetry, there is no *a priori* reason why this effect would not occur in even-even or odd-mass nuclei. In the most likely scenario the

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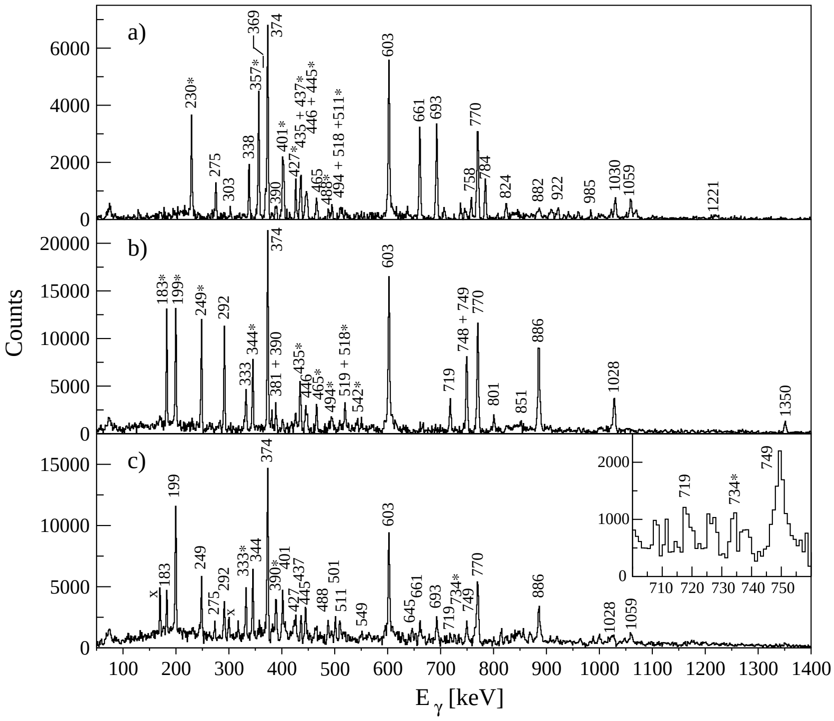

Fig. 1. Coincidence $\gamma\gamma$-spectra obtained by gating on clean in-band transitions: a) band 12, gates on 501 and 308; b) band 14, gates on 645 and (183 or 199 or 249 or 344); c) transitions from band 12 to band 14, gates on (645 or 183 or 249) and (437 or 427 or 488). The in-band and connecting transitions are indicated by an asterisk. Contamination from ^{135}Nd is marked with x in panel c).

proton and neutron $h_{11/2}$ excitations would still define a left- or right-handed system together with the core angular momentum, with two additional natural-parity protons and neutrons acting essentially as "spectators". The nucleus ^{136}Nd appears to be a good candidate to search for such structures, since several dipole bands built on presumably triaxial four-quasiparticle configurations have been observed [2]. However, since the candidates for the chiral doublets in even-even nuclei are expected to be built on multiple-quasiparticle configurations, they lie at high excitation energy in a region of high-level density. Therefore, they will be populated with low intensity and are difficult to observe. Guided by these ideas, we have studied ^{136}Nd at high spins to search for chiral doublet bands in a high-statistics experiment preformed with the EUROBALL spectrometer array [8]. Several new transitions connecting already-known dipole bands in ^{136}Nd to low-lying states were found, which resulted in a different placement of one of these bands in the level scheme. The new placement of the band, together with a newly observed band, establishes a doublet of dipole bands with nearly degenerate states of the same spin and parity. These two bands are the first candidates for a chiral doublet in an even-even nucleus.

High-spin states in ^{136}Nd were populated by bombarding two 0.3 mg/cm^2 thick ^{125}Te targets, evaporated on 20 μg/cm^2 C films, with a 100 MeV ^{16}O beam of 3 pnA intensity. The beam was provided by the Vivitron Tandem accelerator of the Institute de Recherches Subatomiques at Strasbourg. The γ-rays were measured by the EUROBALL array, which comprised 26 clovers and 15 clusters. The 30 Ge-tapered detectors were removed to accomodate three mini-orange spectrometers for the measurement of conversion electrons (which were not used in the present work). The events were written to tape when at least six individual raw Ge detectors fired in coincidence. After the presorting of the data a total of 2.2×10^9 three- and higher-fold coincidence events remained for further analysis.

The coincidence events were sorted into a three- and four-dimensional cube and hypercube, respectively. Several E_γ-E_γ matrices gated on various γ-ray transitions known in ^{136}Nd were sorted, in order to enhance the peaks of the newly observed transitions in the spectra. An E_γ-E_γ matrix was sorted to determine the directional correlations from oriented states (DCO ratios), with the clover detectors near 90° on one axis and all cluster detectors at backward angles on the other axis. The DCO ratios were obtained by setting gates on unmixed stretched quadrupole transitions, which are calculated to be 1.00 for a stretched quadrupole-quadrupole sequence and 0.55 for a stretched dipole-quadrupole sequence.

The analysis of the data revealed a new band of dipole transitions, which we call band 14, and many transitions linking this band to lower-lying states. Furthermore, due to the high efficiency of the composite clover and cluster detectors of the EUROBALL array [8], many new transitions with energies above 1 MeV in the decay of the previously known [2] bands 10 and 12 were identified. Coincidence spectra for the new band 14 and for band 12

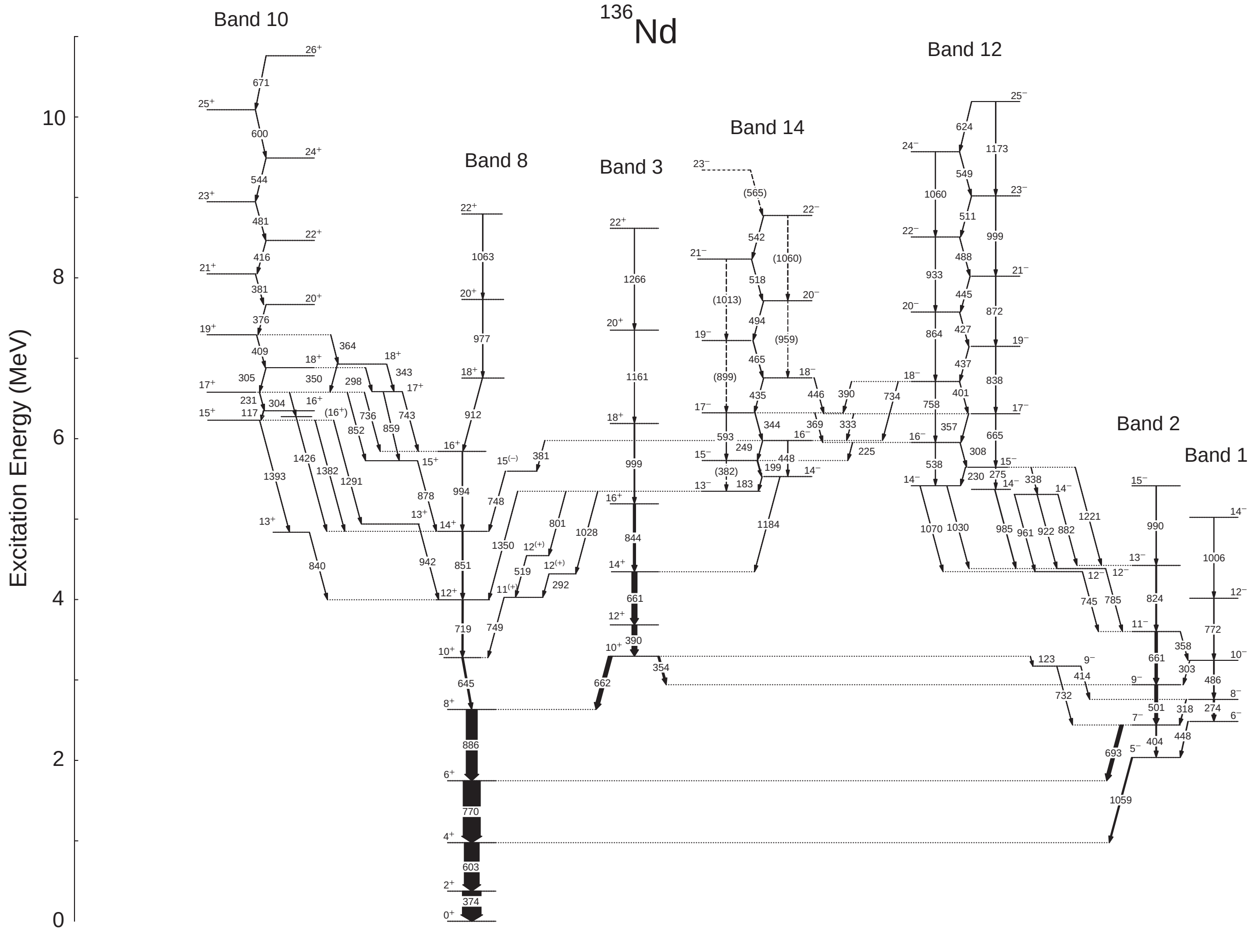

Fig. 2. Level scheme of ^{136}Nd deduced from the present work. The transition intensities are proportional to the width of the arrows. Transitions indicated by dashed lines are tentative.

are displayed in fig. 1, where we also include a spectrum double gated on transitions of both bands 12 and 14 to show the connecting transitions between the bands. The partial level scheme of ^{136}Nd resulting from the present analysis is given in fig. 2.

In the decay of band 10 eight new transitions with energies of 304, 343, 840, 852, 859, 1291, 1393 and 1426 keV were identified. The position of band 12 in the level scheme as reported previously in ref. [2] has to be revised. We observe ten new transitions with energies of 275, 745, 785, 882, 922, 961, 985, 1030, 1070 and 1221 keV, which firmly link band 12 to levels of band 2 and move it up in excitation energy by about 1.5 MeV. The decay of band 12 is quite fragmented and is shared between seven high-energy transitions which are more efficiently detected with the EUROBALL array used in the present experiment than in the previous GASP experiment [2]. Moreover, the EUROBALL data have higher coincidence fold data allowing us to observe the weak linking transitions of band 12 also in clean double- and triple-gated spectra.

The spins of the levels in band 12 are increased by 3 $\hbar$ compared to the previous work [2], based on the analysis of the DCO ratios of the new linking transitions. The 1221 keV transition has an $E2$ character, leading to spin-parity 15^- for the second level assigned to band 12. The DCO ratios for the other connecting transitions also agree with this assignment.

The new band 14, consisting of a sequence of eight dipole transitions, decays mainly into band 8 via eight transitions with energies of 292, 381, 519, 748, 749, 801, 1028 and 1350 keV, and towards band 3 via the 1184 keV transition. In addition, band 14 decays into states of band 12 and receives feeding from levels of band 12. The DCO ratios of the connecting transitions of band 14 to band 8 and band 3 are compatible with spin 13 $\hbar$ for the lowest observed state of band 14. In particular, the 1184 keV transition has DCO ratios consistent with a $\Delta I = 0$ transition: 1.83(69) in the 199 keV gate and 1.00(62) in the 661 keV gate. For comparison, the DCO ratio of the 183 keV transition in the 199 keV gate is 1.06(3), as expected for a stretched dipole-dipole correlation. The parity of band 14 could not be established directly experimentally. However, the DCO ratios of the relatively high-energy transitions of 801, 1028 and 1350 keV connecting band 14 to band 8 indicate pure $\Delta I = 1$ transitions, which most probably are of $E1$ character. Furthermore, we observe a weak transition of 734 keV between the 18^- state of band 12 and the level with spin 16 of band 14 (see fig. 1c) which is most likely an $E2$ (and not a $M2$) transition. Therefore, we assign negative parity to band 14.

The levels with the same spin and parity in the two bands 12 and 14 lie very close in energy, as one would expect for a chiral doublet. They most likely have four-quasiparticle configurations, involving a pair of $h_{11/2}$ neutrons, which would explain the multiple connections with band 8 assigned as $(\nu h_{11/2})^2$ and two protons in opposite-parity orbitals ($h_{11/2}$ and $d_{5/2}/g_{7/2}$). Such four-quasiparticle configurations are predicted to be based on shapes with nearly maximal triaxiality $\gamma \approx 30°$ and moderate quadrupole deformation $\beta_2 \approx 0.2$ [1]. Furthermore, the extended total Routhian surface calculations reported in ref. [1] show that the triaxial minimum remains quite stable over a large range of rotational frequencies. These conditions, together with the existence around the Fermi surface of orbitals with angular momenta which couple orthogonally, are the main requirements for the occurrence of chiral doublet bands [5]. However, only the two-quasiparticle configurations in odd-odd nuclei which lead to chiral structures were investigated theoretically and calculations for even-even nuclei like ^{136}Nd would be desirable. If the observed doublet bands in ^{136}Nd are indeed chiral bands, they may result from the following coupling of the angular momenta of four quasiparticles: the angular momenta of two $h_{11/2}$ quasineutrons aligned along the long axis, the angular momentum of a $h_{11/2}$ quasiproton aligned along the short axis and the positive-parity $d_{5/2}/g_{7/2}$ proton acting as a spectator.

To summarize, high-spin states in ^{136}Nd have been reinvestigated with the EUROBALL spectrometer array. A new band of dipole transitions, band 14, has been discovered and many new transitions linking previously known bands to lower-lying states were found. The revised level scheme shows that states with the same spin and parity of bands 12 and 14 lie very close in energy. Based on this observation and on the suggested four-quasiparticle configurations with a triaxiality of $\gamma \approx 30°$ it is suggested that they are the first candidates for chiral twin bands in an even-even nucleus.

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References

1. C.M. Petrache *et al.*, Phys. Lett. B **373**, 275 (1996).
2. C.M. Petrache *et al.*, Phys. Rev. C **53**, R2581 (1996).
3. S. Perriès *et al.*, Phys. Rev. C **60**, 064313 (1999).
4. C.M. Petrache *et al.*, Phys. Rev. C **61**, 011305 (2000).
5. S. Frauendorf, J. Meng, Nucl. Phys. A **617**, 131 (1997).
6. C.M. Petrache *et al.*, Nucl. Phys. A **597**, 106 (1996).
7. K. Starosta *et al.*, Phys. Rev. Lett. **86**, 971 (2001).
8. J. Simpson, Z. Phys. A **358**, 139 (1997).