High-K Band in ^{140}Gd

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High-spin states in the neutron-deficient^{140}Gd nucleus have been studied with the ^{92}Mo(^{54}Fe,$\alpha 2p$) reaction at a beam energy of 240 MeV. The level scheme of ^{140}Gd was considerably extended from what was previously known. In this work we concentrate on one of the 9 bands observed, which presents relatively strong M1 transitions and negligible signature splitting, and has an isomeric band-head, indicating a strongly coupled or high-K configuration. We compare this band to the $K^{\pi} = 8^{-}$ bands observed in N=74 isotones and propose a similar configuration assignment, but with a somewhat larger deformation.

Keywords: Nuclear reactions; ^{92}Mo(^{54}Fe, α2p), E=240 MeV; Measured E_{γ}, I_{γ}, $\gamma\gamma$-coincidence; ^{140}Gd deduced high-spin levels, J, π, configurations; Isomer

I. INTRODUCTION

Several high-K states are known to exist in the mass 130-140 region. For the N=74 even-even isotones, $K^{\pi} = 8^{-}$ isomers, with lifetimes ranging from ns to ms, are known in ^{128}Xe[1], ^{130}Ba[2], ^{132}Ce[3], ^{134}Nd[4], ^{136}Sm[5], and ^{138}Gd[6]. The systematics of the $K^{\pi} = 8^{-}$ isomeric states in N=74 isotones has been studied by A.M. Bruce *et al.* [7]. These states decay towards the $K = 0$ ground state band, and the transitions are K-forbidden. The variation of the strengths of the transitions, however, is not clearly understood. The explanation might involve a variation of the structure of the isomer or of the ground state band. In the present work have extended the level scheme of ^{140}Gd from what was previously known[8], and, in particular, we have observed for the first time a band also based on an $I^{\pi} = 8^{-}$ state. This could be the first case of a $K^{\pi} = 8^{-}$ state observed in an N=76 even-even nucleus. The ^{140}Gd case presents strong similarities but also some significant differences with relation to the N=74 isotones. The interpretation of this band is quite difficult, in particular because the addition of the 2 neutrons is expected, in principle, to modify the configuration with respect to the one observed in the N=74 cases, fully occupying the orbitals involved and decreasing the deformation as the N=82 closed shell is approached. We propose that the deformation is larger in ^{140}Gd and a pair of neutrons from the N=5 shell coupled to angular momentum zero is incorporated, from which the $7/2[404]^{-1} \otimes 9/2[514](K^{\pi} = 8^{-})$ neutron excitation (in particle-hole terminology) is built.

II. EXPERIMENTAL PROCEDURE AND ANALYSIS

The ^{92}Mo(^{54}Fe,α2p) reaction at 240-MeV was employed to populate high-spin states in ^{140}Gd. The incident beam was provided by the tandem XTU accelerator of the Legnaro National Laboratories. A self–supporting and isotopically enriched (>97%) ^{92}Mo target of approximately 1.0 mg/cm^2 thickness was used. The GASP array [9] was used for obtaining gamma–ray double and triple coincidence spectra. The photopeak efficiency of the array is approximately 3% for 1.3 MeV. The charged-particle detector array (ISIS) [10] enabled the selection of evaporated charged particles in coincidence with the γ–rays. The recoil mass spectrometer (Camel) [11] allowed for mass identification. Events were collected on tape when at least two HPGe detectors fired in coincidence. The data were taken for a period of 136 hours. A total of 85×10^6 Compton-suppressed events were collected. The data were sorted into *charged particle fold*–$\gamma - \gamma$, $A - \gamma - \gamma$ and $\gamma - \gamma - \gamma$ cubes, from which specific matrices for the various exit channes were extracted, and were analyzed using the VPAK [12] and RADWARE [13] spectrum analysis codes. The detectors were energy and efficiency calibrated with standard ^{152}Eu and ^{133}Ba radioactive sources.

Figure 1 presents the background subtracted sum spectra of the 246 and 287 keV gates. The in-band M1, E2 crossovers (except the 533 keV which is the crossover of the gating transitions) and the ground-state band (gsb) transitions from the levels fed by the band can be clearly seen. Table I presents the list of transitions and intensities observed. DCO (Directional Correlation from Oriented states) measurements confirm some of the multipolarity assignments presented [14]. Details will be given in a forthcoming article. The same DCO procedure has been employed in previous analises from the same experiment [15, 16]. A careful re-examination of the efficiency was performed and corrections have been applied due to the variation of the electronic response at low $\gamma-$ray energies. As a result, the assignment of the band-head spin is different from that of ref. [14], and is discussed in the next section.

TABLE I: Energies, intensities, and spin assignments to the transitions belonging to the strongly coupled band observed in ^{140}Gd (the first two rows are linking transitions to the ground state band). The energies of the transitions are given in keV. The intensities are normalized (to 100%) with respect to the 507.6 keV transition ($4^+ \to 2^+$) of the ground state band.

E_γ(keV)	I_γ	$I_i^{\pi_i} \to I_f^{\pi_f}$
71.3(2)	0.77(12)	$8^- \to 8^+$
747.1(3)	0.80(18)	$8^- \to 6^+$
245.8(1)	2.38(20)	$9^- \to 8^-$
287.0(1)	2.00(13)	$10^- \to 9^-$
317.4(1)	1.40(10)	$11^- \to 10^-$
342.1(1)	1.08(8)	$12^- \to 11^-$
363.7(1)	0.54(6)	$13^- \to 12^-$
383.3(1)	0.64(7)	$14^- \to 13^-$
403.1(3)	0.23(5)	$15^- \to 14^-$
423.0(15)	0.04(5)	$16^- \to 14^-$
532.9(10)	0.36(7)	$10^- \to 8^-$
604.0(3)	0.53(8)	$11^- \to 9^-$
658.8(3)	1.08(15)	$12^- \to 10^-$
704.9(3)	0.60(8)	$13^- \to 11^-$
747.1(8)	0.16(7)	$14^- \to 12^-$
785.7(3)	0.71(11)	$15^- \to 13^-$
826.3(3)	0.65(8)	$16^- \to 14^-$

Figure 2 presents the relevant partial level scheme of ^{140}Gd obtained in the present measurement. This level scheme is based on the coincidence relationships, intensity balances on each level and energy sums from different paths using the $1\alpha 2p$–gated matrix.

III. ASSIGNMENTS OF BAND-HEAD SPIN, PARITY, AND LIFETIME

The spin and parity of the $I^\pi = 8^-$ state was established by the following arguments: Firstly the experimental total electronic conversion coefficient of the 71 keV transition was determined from the ratio of gamma intensities of itself to that of the 676 keV gsb transition, as observed in the 246 and 287 keV gated spectra. The value obtained corresponds to a conversion coefficient of $\alpha_{exp} = 0.72(20)$, consistent with the expected value for a pure E1 ($\alpha_{teo} = 0.736$). The experimental value is clearly in disagreement with other possible assignments like M1 or E2 which present very different electronic conversion coefficient values. This establishes that the 71 keV line is of E1 character, and the band has negative parity. Secondly, if the 747 keV transition (from the same state) were of the same multipolarity (E1), it's decay to the gsb should be governed by an intrinsic transition matrix element of the same order of magnitude as that for the 71 keV, assuming not too different structure of the 8^+ and 6^+ gsb states. In this case, the energy factor should favor by three orders of magnitude the 747 keV with relation to the 71 keV transition. However, the experimental intensities of both transitions have been calculated to be of the same order of magnitude. This, therefore, indicates a multipolarity with weaker strength, viz. M2, with $\triangle I = 2$, to the 747 keV transition. In conclusion, the only assignment consistent with these results is of an 8^- for the strongly coupled band head.

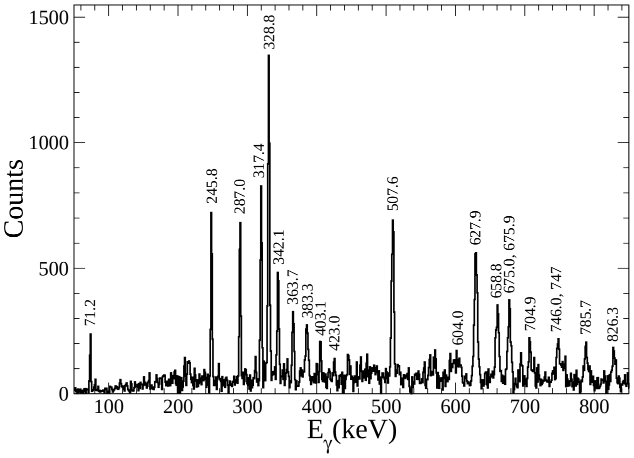

FIG. 1: Sum spectrum of the 246 and 287 keV gate transitions from the $1\alpha 2p$−gated matrix. The energies of the γ−ray lines are indicated in keV (see Sec. III with regards to the 71 and 746 keV line energies).

The lifetime of the $I^\pi = 8^-$ band-head was estimated to be of about 1.5 ns. This comes from two independent evidences: First, in the 287 keV gate, the intensity of the 328 keV transition ($2^+ \to 0^+$) is reduced to about 85% when compared to that of the 246 keV. This is due to the loss of efficiency when the γ−decay occurs off-center in the GASP spectrometer. The flight velocity of the recoils after traversing the target is about 1cm/ns. Second, the gsb transitions appear to be shifted to lower energies, when gated in-band from above the isomer, by about −0.15% relative to the usual Doppler corrected γ−ray energies. This is again due to the decay off-center, since the transitions become observed by the detectors at larger angles than those originally used in the Doppler corrections of the spectra, which assume decay in the center of the target. Simulations with the GEANT code applied to the specific experimental setup of GASP show that these results are consistent with a lifetime of 1.5 ns for the negative parity band-head, with an uncertainty of about 0.4 ns. The apparent energies of the transitions from the isomeric state are therefore also expected to be slightly shifted. For this reason the 0.15% correction has been applied to the energy values of the transitions from the 8^- state quoted in table I. For the 747 keV line, this correction is significant and the peak position is close to 746 keV in the spectrum (Fig.1).

IV. DISCUSSION

As stated in the introduction, the systematics of the $K^\pi = 8^-$ isomeric states in N=74 isotones has been discussed by A.M. Bruce *et al.*[7]. In general, the configuration proposed for the isomers is the $7/2^+[404] \otimes 9/2^-[514]$ two quasineutron structure, although other possibilities have been considered such as a two proton oblate configuration in ^{130}Ba, too far from Gd to be of interest here. The lifetimes vary consid-

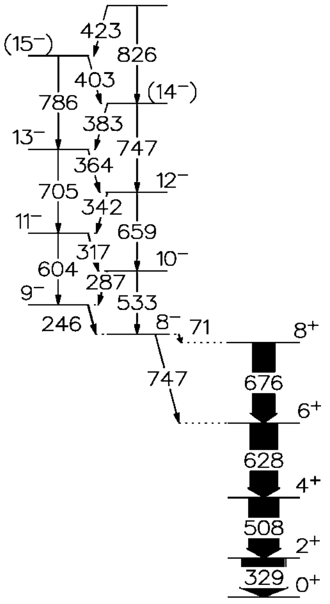

FIG. 2: Partial level scheme of ^{140}Gd showing the strongly coupled band discussed in this work and its decay to the gsb. The transition energies are indicated in keV. The transition intensities are proportional to the arrow widths.

erably, generally decreasing from 11 ms in ^{130}Ba to 6 μs in ^{138}Gd. The hindrance per degree of K forbideness (f_ν) of the decay is defined as $F_W^{1/\nu}$, where $\nu = \Delta K - \lambda$, λ is the transition multipolarity, and $F_W = t_{1/2}(E\lambda)/t^w_{1/2}(E\lambda)$ is the hindrance factor, the ratio of the experimental partial half-life to that of the Weisskopf single particle estimate. The values of f_ν for the N=74 isotones are around 25 for Nd, Sm and Gd, while for Ba it is 44. This variation can be reasonably well interpreted in terms of admixture of $K = 8$ in the gsb due to interaction with the s (Stockolm) band near band crossing.

From our data we can estimate a value of $f_\nu \approx 13$ for the ^{140}Gd 71 keV transition. The partial lifetime for the 747 keV M2 transition results in essentially no hindrance with respect to the Weisskopf estimate.

Total Routhian Surfaces Calculations (TRS), together with the presence of a gamma-vibrational band at low excitation energy, indicate a large degree of triaxiality for ^{140}Gd and a reduced β_2 deformation (from about 0.28 in N=74 Sm and Gd to 0.21 in ^{140}Gd), near the ground state. This could also favor high-K admixture in the structure of the gsb, and reduce the hindrance factor. The interpretation is not clear, however, because no high-K configuration appears to be near yrast according to the same TRS calculations, since the $7/2^+[404]$ orbits become fully occupied and away from the Fermi energy as an effect of the addition of 2 neutrons and reduction of deformation. Besides that, the alignment angular momentum (the projection on the rotational axis) of the strongly coupled band relative to the gsb is much larger in ^{140}Gd (4-5$\hbar$) than in the nearby N=74 isotones (Gd, Sm and Nd, around 1$\hbar$). This is not expected since in a high-K configuration the quasi-particle angular momentum tends to couple along the deformation axis, perpendicularly to the rotation axis. A 4-quasiparticle configuration would be very unlikely since the excitation energy of the $K^\pi = 8^-$ relative to the ground state is quite small (2.21 MeV), and in fact, quite similar to the one of the N=74 isotones (2.23 and 2.27 MeV in Gd and Sm respectively). A proton configuration, which could present large alignment, would have a low-K, and should be discarded (see also the electromagnetic properties discussed in the next paragraph). We tentatively propose, therefore, that the strongly coupled band is built on a quite deformed shape core containing 2 paired particles from the N=5 shell, and in addition the $7/2^+[404] \otimes 9/2^-[514]$ two quasi-neutron excitation coupled to $I^\pi = 8^-$ as in the N=74 nuclei. The N=5 single-particle states $1/2[541]$ (from $f_{7/2}$) and $1/2[660]$ (from $i_{13/2}$) in the deformed shell model are strongly down-sloping as a function of β_2 and are therefore "$\beta-$driving", the excitation energy of the former being lower than the latter. A larger deformation could explain why the alignment is apparently so high in ^{140}Gd. Since the band would have a larger moment of inertia in comparison to the gsb, it develops more collective angular momentum at the same rotational frequency and the concept of quasiparticle alignment becomes inadequate. The difficulty in such explanation resides in the comparatively high strength of the inter-band transition for such a significant shape change and, still, in the small experimental excitation energy. However, this appears to be the most likely interpretation with comparison to the other possibilities. It should be noted that highly deformed bands have been observed at relatively low excitation energy in odd-nuclei of this region, such as ^{137}Sm and ^{139}Gd [17]. These bands are built upon the $\nu 1/2[660]$ (from $i_{13/2}$) configuration, with large quadrupole moments ($Q_0 = 5 - 7$eb, [18, 19]). In ^{133}Nd [20] the $\nu 1/2[541]$ band (with an estimated deformation of $\beta_2 = 0.29$) can be found at much lower excitation energy than the $\nu 1/2[660]$.

Figure 3 presents the experimental ratio of reduced transition probabilities $B(M1)/B(E2)$ in comparison with the nearby nuclei and theoretical estimates. It can be observed that for all nuclei presented the values have the same order of magnitude, being on average lower in ^{140}Gd than in the N=74 isotones. The dotted line corresponds to a prediction based on the rotational model with an intrinsic quadrupole moment of $Q_0 = 4.5$ eb , the value measured from the lifetime of the first 2^+ state in ^{136}Sm [21], while the dashed line is calculated with $Q_0 = 5.5$ eb. This last value reproduces better the^{140}Gd data, in agreement with the hypothesis of large deformation.

The absolute value of the difference between valence and collective g-factors $|g_K - g_R|$ for the band states can be obtained from the experimental mixing ratios δ (obtained from the $\Delta I = 2$ to $\Delta I = 1$ branching ratios) according to the procedure of refs.[5, 6], based on the rotational model, assuming a value for the quadrupole moment Q_0. The results are presented in fig. 4. For the N=74 nuclei the value of $Q_0 = 4.5$ eb was adopted, while for ^{140}Gd $Q_0 = 5.5$ eb was used. Again the same order of magnitude is observed for all the presented nuclei and the values are consistent with the expected for the $7/2^+[404] \otimes 9/2^-[514]$ quasi-neutron configuration, according to the estimates of ref. [5] (the dotted line at $|g_K - g_R| = 0.4$ in fig.4). For this configuration, the 2 quasiparticle g-factors mutually cancel, remaining the collective

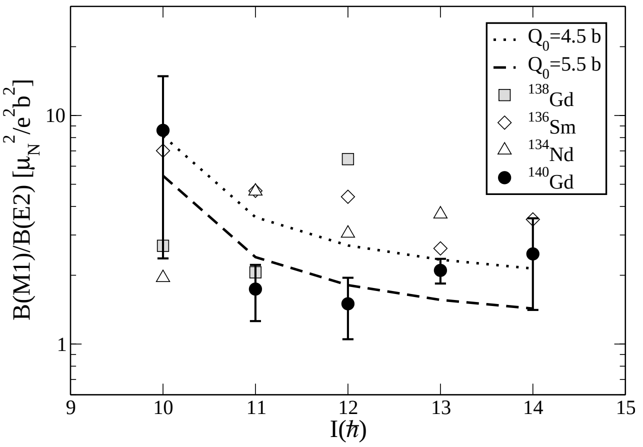

FIG. 3: The experimental ratio of reduced transition probabilities $B(M1)/B(E2)$ as a function of the spin of the state in ^{140}Gd. The values for the N=74 isotones are also shown for comparison (the errorbars are roughly of the same order of magnitude as in ^{140}Gd, but are not shown for clarity of the figure). Theoretical estimates from the pure rotational model for two values of intrinsic electric quadrupole moments are also shown by the lines (considering the value of $|g_K - g_R| = 0.4$).

value of $g_R = 0.4$. This result also corroborates our assumptions. It should be noted that for 2 quasi-proton configuration with large K the g-factor difference would be much larger and could not be consistent with the present experimental results.

V. CONCLUSION

A strongly coupled band has been observed for the first time in ^{140}Gd. The band-head was determined to be an $I^\pi = 8^-$ isomer state, with a lifetime of about 1.5ns. The band presents strong similarities to the high-K bands in neighboring N=74 isotones, based on the $7/2^+[404] \otimes 9/2^-[514]$ two quasi-neutron configuration coupled to $K^\pi = 8^-$. The apparent alignment, relative to the ground state band is, however, larger than in the lower N isotones, and can perhaps be explained by an increase in deformation. With a significantly deformed shape (say, $\varepsilon > 0.25$), 2 paired particles from the N=5 shell from the 1/2[541] Nilsson state (from $f_{7/2}$) are incorporated, and the $\nu 7/2^+[404] \otimes 9/2^-[514]$ ($K^\pi = 8^-$) excitation would become the lowest available negative parity configuration, providing the necessary characteristics to explain the presently observed band. This assignment is corroborated by the experimental B(M1) and B(E2) branching and mixing ratio values. It remains to be explained the large reduction of the hindrance factor of the isomer decay to the gsb and the relatively low excitation energy of the structure. Search for additional cases of strongly coupled bands in N=76 isotones would be of great interest, as well as the measurement of in-band transition lifetimes.

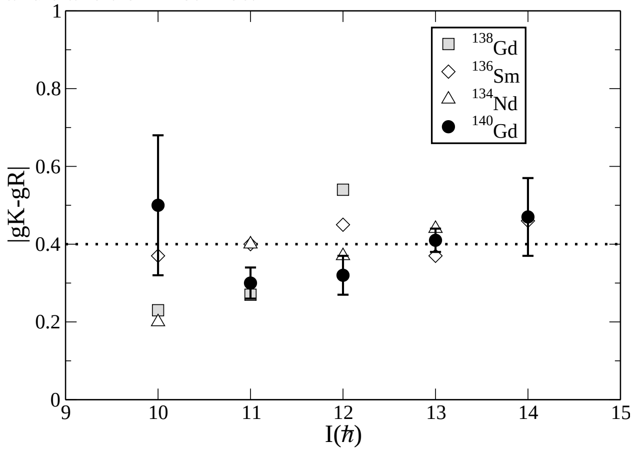

FIG. 4: The experimental and theoretical values of $|g_K - g_R|$ as a function of the state spin in ^{140}Gd, and in N=74 isotones (with values of the quadrupole moment $Q_0 = 5.5$ eb, and $Q_0 = 4.5$ eb, respectively). The value expected for the $\nu 7/2^+[404] \otimes 9/2^-[514]$ ($K^\pi = 8^-$) configuration is shown by the dotted line.

VI. ACKNOWLEDGMENTS

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[1] L. Goettig *et al.,* Nucl. Phys. A **357**, 109 (1981).
[2] H.F. Brinkman *et al.,* Nucl. Phys. **81**, 233 (1966).
[3] D. Ward, Nucl. *et al.,* Phys. A **117**, 309 (1968).
[4] D.G. Parkinson *et al.,* Nucl. Phys. A **194**, 443 (1972).
[5] P.H. Regan *et al.,* Phys. Rev. C **51**, 1745 (1995).
[6] D.M. Cullen *et al.,* Phys. Rev. C **58**, 846 (1998).
[7] A.M. Bruce *et al.,* Phys. Rev. C **55**, 620 (1997).
[8] E. S. Paul *et al.,* Phys. Rev. C **39**, 153 (1989).
[9] D. Bazzacco, in Proc. of the Int. Conf. on Nucl. Struct. at High Ang. Momentum, Ottawa, 1992, Report No. AECL 10613, Vol. 2, p. 376.
[10] E. Farnea *et al.*, Nucl. Instrum. Meth. A, **400**, 87 (1997).
[11] P. Spolaore, *et al.*, Nucl. Instr. Meth. A **238**, 381 (1985).
[12] W. T. Milner, Holifield Heavy Ion Research Facility Computer Handbook, Oak Ridge National Laboratory, Oak Ridge, Tennessee, USA (1987).
[13] D. Radford, Nucl. Instr. Meth. Phys. Res. A **361**, 297 (1995).
[14] F. Falla-Sotelo, MSc Thesis, Universidade de S. Paulo, IFUSP, Brazil, (2002).
[15] F.R. Espinoza-Quinones *et al.*, Phys. Rev. C **60**, 054304 (1999).
[16] J.R.B. Oliveira *et al.*, Phys. Rev. C **62**, 064301 (2000).
[17] C.A. Rossi-Alvarez, *et al.*, Nucl. Phys. A **624**, 225 (1997).
[18] E.S. Paul *et al.*, J. Phys. **G 18**, 121 (1992).
[19] P.H. Regan *et al.*, J. Phys. G **18**, 847 (1992).
[20] D. Bazzacco *et al.*, Phys. Rev. C **58**, 2002 (1998).
[21] R. Wadsworth *et al.*, J. Phys. G **13**, 205 (1987).