High-spin states in the ^{94}Nb nucleus

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High-spin states have been studied for the first time in the ^{94}Nb nucleus with the reaction ^{82}Se(^{19}F,$\alpha 3n\gamma$) at 68 MeV. A cascade of transitions has been observed, based on the $(6)^+$ ground state and extending up to 6.5 MeV excitation and spin of about 19.

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I. INTRODUCTION

Studies of high-spin states in nuclei near closed shells may give information on the core breaking mechanism. For such nuclei, with few nucleons outside closed shell configuration, the maximum spin that can be built by aligning the spins of the individual valence shell nucleons (the ''terminating'' configuration) is not so high. Consequently, states with higher spins, which can be obtained by promoting nucleons from the ''inert'' core into the higher shells, are easily accessible through fusion-evaporation reactions induced by heavy ions.

The purpose of the present work has been to study the structure of the odd-odd nucleus ^{94}Nb at high spins. With valence protons in the $p_{1/2}$ and $g_{9/2}$ orbitals and neutrons in the $d_{5/2}$ and $g_{7/2}$ orbitals, the maximum spin that can be built for the positive parity case is 12; higher spins can be made by breaking the quasimagic core ^{88}Sr.

Until now, no information existed on the high-spin states of ^{94}Nb. Low-spin states have been studied in detail through (n,γ) [1–3] and (p,n) [4,5] reactions, as well as the (d,p) reaction [6] (see also the works cited in the ENSDF data files [7]). The present study is the first one in which high spin states have been observed in ^{94}Nb by means of a heavy-ion fusion-evaporation reaction.

II. EXPERIMENTAL TECHNIQUES

The ^{94}Nb nucleus was populated and studied with the reaction ^{82}Se(^{19}F,$\alpha 3n\gamma$) at an incident energy of 68 MeV. The target was Se of thickness around 5 mg/cm^2 vacuum evaporated on a 2 mg/cm^2 Au foil, and having an enrichment of 92% in ^{82}Se. The ^{19}F beam, of 68 MeV, was delivered by the Bucharest FN tandem accelerator. The γ rays were measured with two intrinsic Ge detectors of 20% efficiency placed 9 cm from the target. Neutrons were detected with a 1 liter NE213 scintillator detector placed in the forward direction, shielded with 2.5 cm of lead and covering $\pm 28°$. Charged particles were detected and identified with a ΔE-E telescope of Si detectors, having thicknesses of 0.15 and 0.5 mm, respectively, and an active surface of 150 mm^2, mounted at 45° in the forward direction, at 2.5 cm from the target. A 70 μm thick Al absorber prevented scattered ^{19}F ions from entering the ΔE detector. γ-γ, n-γ, and charged-particle-γ coincidences have been recorded on the hard disk of a PC and then analyzed offline. Three different runs were made. In the first one, γ-γ and charged-particle-γ coincidences were measured, the two Ge detectors being positioned at $\pm 125°$ with respect to the beam direction. In the other two, γ-γ and neutron-γ coincidences were measured. In one, the two Ge detectors were kept in fixed positions, at 90° and $-45°$, respectively. In the other run one of the Ge detectors was kept in a fixed position, at $-145°$, while the other one was moved at the angles 15°, 35°, 45°, 55°, 75°, and 90°, respectively; this run

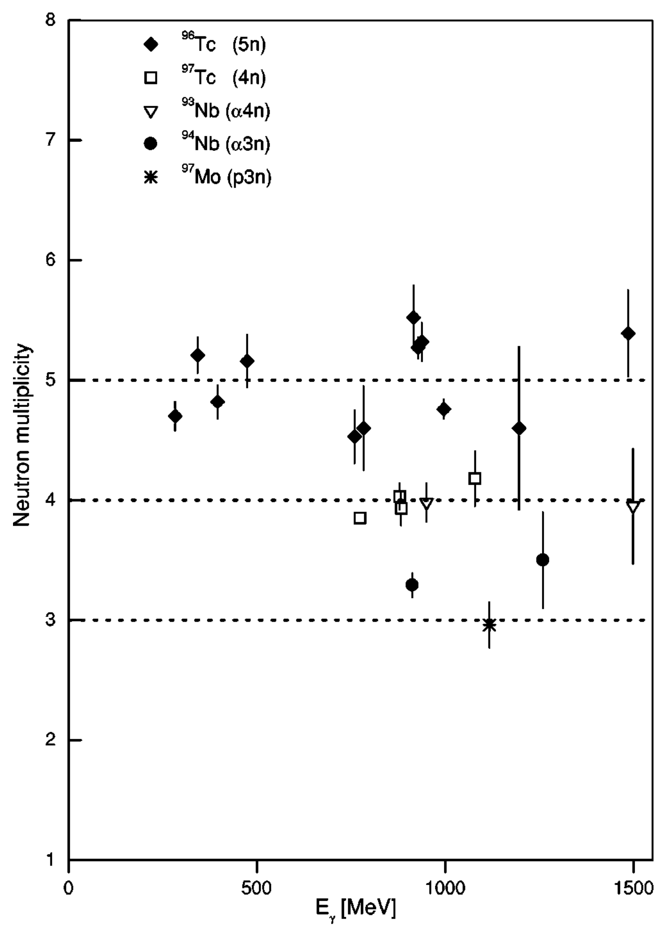

FIG. 1. Neutron multiplicities of typical γ rays observed in the ^{82}Se+^{19}F reaction at 68 MeV. They were determined as the ratios between the intensity of the respective γ ray in coincidence with neutrons and in singles, respectively, which were then normalized to a value of 4.0 for four strong γ rays known to belong to ^{97}Tc [8] (the $4n$ channel). Different symbols belong to the nuclei indicated, as shown in the figure legend, which also specifies the channel by which that nucleus is populated in our reaction.

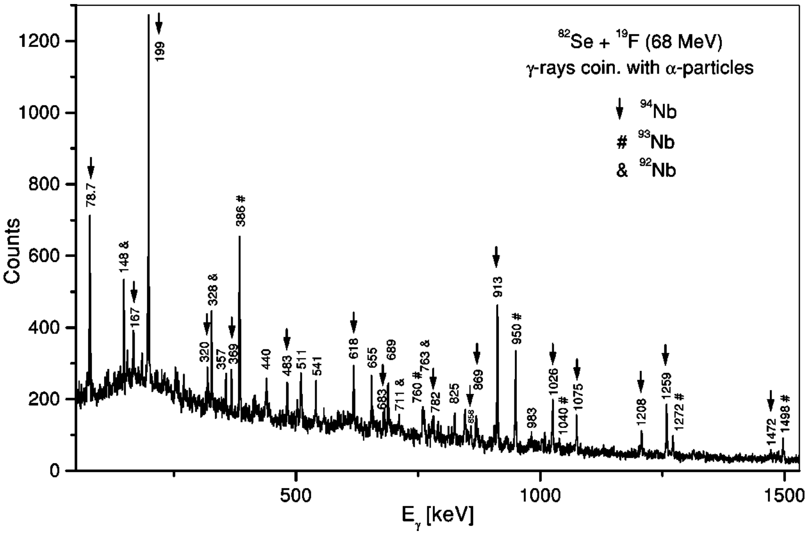

FIG. 2. The γ-ray spectrum observed in coincidence with the α particles, in the ^{82}Se+^{19}F (68 MeV) reaction. The γ rays from the $g_{9/2}$ band of ^{93}Nb [11], those from high-spin states in ^{92}Nb [13], as well as those assigned to ^{94}Nb in the present work are marked by different symbols, as indicated.

served to measure, in addition to γ-γ coincidences, the γ-ray angular distributions both in the singles and n-γ coincidence modes, the fixed detector acting as a monitor. Energy and efficiency calibrations were made with a ^{152}Eu source.

III. DATA ANALYSIS AND LEVEL SCHEME OF ^{94}Nb

A first indication that high-spin states in ^{94}Nb are populated in this reaction was the observation of some unknown γ rays in coincidence with the 78.7 keV γ ray, which was assigned to the transition from the known $(5,6,7)^+$, 78.6681(8) keV excited state to the $(6)^+$ ground state of this nucleus [7]. The complete proof that these γ rays belong indeed to ^{94}Nb was based on the neutron-γ and the charged-particle-γ coincidences. From γ-ray spectra in coincidence with neutrons one could determine the neutron multiplicity of the reaction channel. This is essentially the ratio between the intensity of a γ ray in the spectrum coincident with the neutrons, and the intensity of the same γ ray in the singles spectrum measured in the same time. We have normalized this ratio to 4.0 for γ rays known to belong to ^{97}Tc [8] (populated in the same reaction via the $4n$ channel). Figure 1 shows the neutron multiplicities of different other γ rays populated in this reaction. One can see that for γ rays of ^{96}Tc [9] (channel $5n$), the average multiplicity is 5, for the 950 and 1498 keV γ rays of ^{93}Nb [11] (channel $\alpha 4n$), it is close to 4.0, and for the 1117 keV γ ray of ^{97}Mo [12] (channel $p3n$) it is close to 3. For the two strongest γ rays tentatively assigned to ^{94}Nb, 913 and 1259 keV, one can see that the multiplicity determined in the same way is close to 3.0, indicating their origin in a channel with three evaporated neutrons. The same γ rays were *not* seen in coincidence with protons, but were seen in coincidence with the α particles. This is shown in Fig. 2, where it can be seen that the γ-ray spectrum coincident with α particles is dominated by the transitions tentatively assigned to ^{94}Nb on the basis of their coincidence with the 78.7 keV γ ray, and in addition by transitions known to belong to ^{93}Nb [11] and to ^{92}Nb [13]. The combined results finally allow one to unambiguously assign these γ rays to the $\alpha 3n$ channel, and therefore to transitions in ^{94}Nb.

The level scheme of ^{94}Nb has then been constructed by analyzing γ-ray intensities as well as coincidence relationships within a symmetrized E_{γ_1}-E_{γ_2} matrix. As an example,

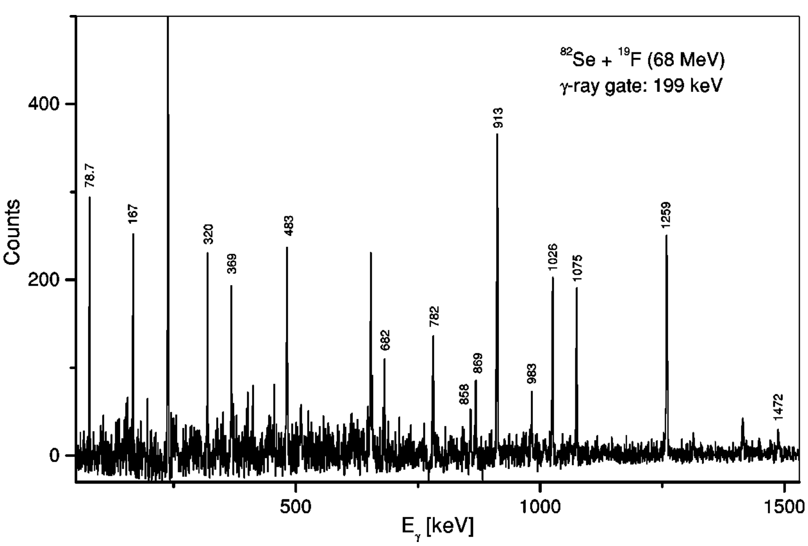

FIG. 3. Example of spectrum obtained by gating on a γ ray in the symmetric γ-γ coincidence matrix. Transitions not marked by their energy are due to a contaminant line close to 199 keV.

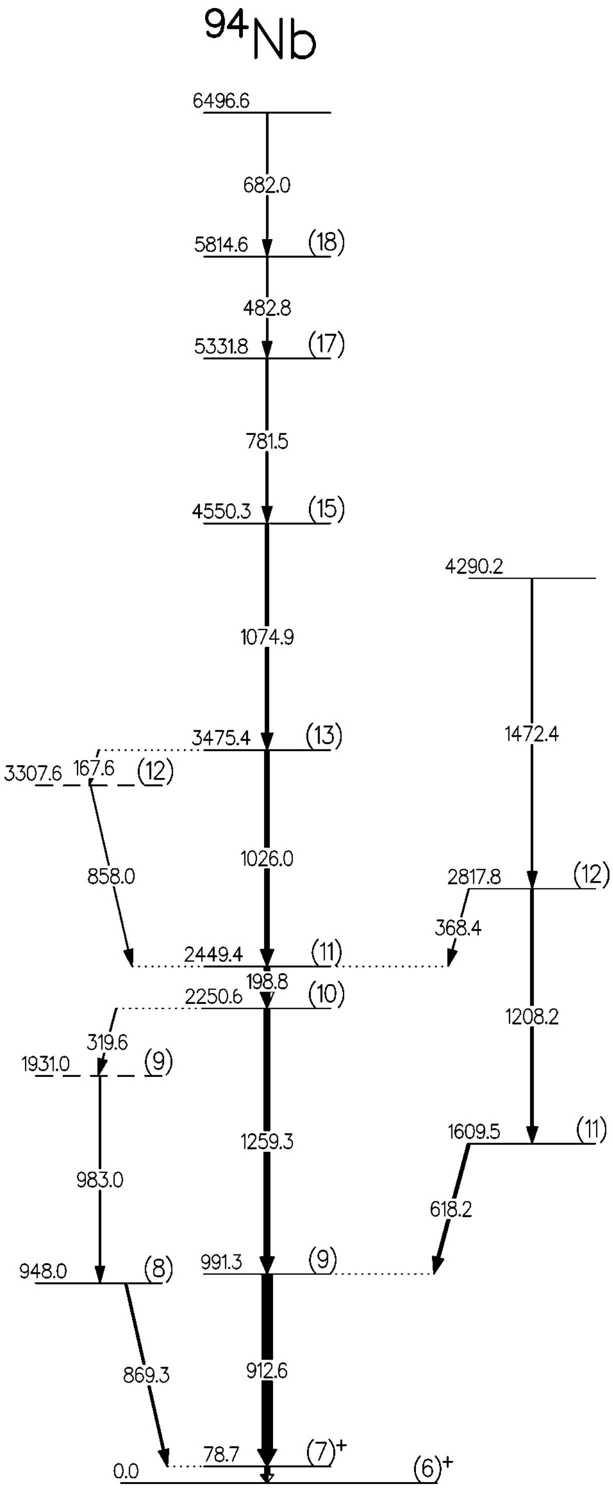

FIG. 4. The level scheme of ^{94}Nb, as determined from the present experiment. The tentative spin values are based on the assumption that the ground state and the 78.7 keV state have spin values of 6 and 7, respectively [7] (see also text and Table I for details).

we show in Fig. 3 the spectrum obtained by gating on the 199 keV γ ray. Since all the transitions were found in coincidence with the 78.7 keV γ ray, they were placed above the 78.7 keV state. The resulted level scheme is shown in Fig. 4. Due to the relatively large errors in the intensities of the γ rays (Table I) one cannot definitely decide the order of the transitions 167.4 and 858.0 keV, and 319.6 and 983.0 keV, respectively, therefore the positions of the 3308 and 1931 keV levels are only tentative.

The channels most strongly populated in our reactions were $5n$ (^{96}Tc) and $4n$ (^{97}Tc), in good agreement with the predictions of the code CASCADE [15] of having 55% and 14% of the fusion cross section, respectively. The observed ratios between the populations of the channels $4n$ (^{97}Tc), $\alpha 3n$ (^{94}Nb), $\alpha 4n$ (^{93}Nb), and $p3n$ (^{97}Mo) are 1/0.25(2)/0.23(2)/0.24(2), in good agreement with the calculations which predict 1/0.28/0.29/0.36, respectively. The calculated cross section for ^{94}Nb is 27 mb.

Information on the multipolarity of the γ-ray transitions in this scheme have been obtained from both γ-ray angular distributions and directional correlation from oriented states (DCO) ratios. For the strongest transitions, of 913 and 1259 keV, respectively, we could determine accurate angular distributions both in the singles and neutron-coincident mode. Their Legendre polynomial coefficients are given in Table I; they are consistent with a quadrupole multipolarity for the 913 keV transition, and dipole multipolarity for the 1259 keV one, respectively. Starting from these two transitions, DCO ratios [14] have been determined for the upper transitions, from gates set on an asymmetric matrix, with the detector at 45° on one axis and the detector at 90° on the other axis. In this geometry the DCO ratio ($R_{\rm DCO}$) for a dipole transition should be close to 0.5 when gating on a quadrupole transition and 1.0 when gating on a dipole transition, whereas a quadrupole transition is seen with a ratio of 1.0 when gating on another quadrupole, and about 2.0 when gating on a dipole. Table I gives all these results, as well as the multipolarities assigned to different transitions. Since in fusion-evaporation reactions one usually populates mainly the yrast sequence, it is reasonable to assume that the cascade built above the 78.7 keV state has increasing spin.

A key point in assigning absolute spin values for the newly assigned states are the spins of the lowest states. The ground state itself is not assigned with certainty, as its adopted J^π is $(6)^+$ [7]. Even if the ground state were unambiguously characterized, another problem is the spin of the 78.7 keV level. From previous measurements of internal conversion coefficients, one knows that the 78.7 keV transition is of the $M1$ type [2,7], therefore $J^\pi = (5,6,7)^+$ for this state. Our results for the angular distribution of this transition, although not very precise, are also consistent with a dipole multipolarity (Table I). This state was not observed in the $(p,n\gamma)$ reaction studies [4,5], a fact which suggests a higher spin value (larger than 6). Our results also support a high spin value for this state; since we observe a γ-ray cascade above it in a heavy-ion fusion-evaporation reaction, it is very likely that at least in its lower part, this cascade represents the yrast positive-parity sequence, therefore the 78.7 state most probably has the spin $J=7$ (assuming that the ground state has $J=6$). Finally, different shell model calculations (see below) also predict a 6^+ ground state and a low-lying 7^+ state. In Fig. 4 we adopt therefore spins of 6 and 7 for the ground state and the 78.7 keV state, respec-

TABLE I. γ-ray transitions in ^{94}Nb from the ^{82}Se(^{19}F,$\alpha 3n\gamma$) reaction at 68 MeV. Legendre polynomial coefficients result from fits to the γ-ray angular distributions; the DCO ratios are determined from the asymmetric matrix with the two detectors placed at 45° and 90°, respectively, by gating on dipole transitions, except for those marked with an asterisk, when the gate was on quadrupoles. Intensities are from the 55° spectrum measured in coincidence with the α particles; their errors result from the statistical uncertainties and the errors of the efficiency curve.

E_γ (keV)	I_γ (Rel. units)	a_2/a_0	a_4/a_0	R_{DCO}	Multipolarity	Assignment E_i(keV)	E_f(keV)	$J_i^{\pi_i} \to J_f^{\pi_f}$
78.7	31.6(32)	−0.39(17)	−0.14(18)		D	78.7	0.0	$(7)^+ \to (6)^+$
167.6	6.6(13)			0.49(5)*	D	3475.4	3307.6	$(13) \to (12)$
198.8	52.2(39)			0.88(10)	D	2449.4	2250.6	$(11) \to (10)$
319.6	9.0(11)			1.00(20)	D	2250.6	1931.0	$(10) \to (9)$
368.8	8.0(10)			1.17(50)	D	2817.8	2449.4	$(12) \to (11)$
482.8	13.4(19)			0.94(25)	D	5814.6	5331.8	$(18) \to (17)$
618.2	27.6(33)			1.05(47)*	(Q)	1609.5	991.3	$(11) \to (9)$
682.0	7.6(26)					6496.6	5814.6	$\to (18)$
781.5	15.2(21)			2.4(8)	Q	5331.8	4550.3	$(17) \to (15)$
858.0	6.4(14)					3307.6	2449.4	$(12) \to (11)$
869.3	19.0(19)			0.91(20)	D	948.0	78.7	$(8) \to (7)^+$
912.6	100.0(40)	0.306(11)	−0.036(10)	2.09(26)	Q	991.3	78.7	$(9) \to (7)^+$
983.0	9.0(18)			1.0(5)	(D)	1931.0	948.0	$(9) \to (8)$
1026.0	44.0(36)			1.87(31)	Q	3475.4	2449.4	$(13) \to (11)$
1074.9	31.6(30)			2.19(55)	Q	4550.3	3475.4	$(15) \to (13)$
1208.2	24.5(34)			0.41(17)*	D	2817.8	1609.5	$(12) \to (11)$
1259.3	53.8(40)	−0.136(26)	−0.075(34)	0.62(13)*	D	2250.6	991.3	$(10) \to (9)$
1472.4	12.0(33)					4290.2	2817.8	$\to (12)$

tively, and propose spins for the upper levels relative to these values (cf. Table I), but we emphasize that this is only a tentative assignment. Also, although we have no direct indication on the parity of the structure built above the $(7)^+$ state, from the fact that it feeds the positive parity 78.7 keV state one can tentatively assign positive parity to the newly added states; this would mean that the observed quadrupole and dipole transitions are of the $E2$ and $M1$ (or $E2/M1$) type, respectively. However, a change of parity somewhere along the sequence cannot be ruled out (see the discussion below).

To conclude this part, with the present measurements we have observed excited states in ^{94}Nb up to an excitation energy of 6.5 MeV and a spin around 19; the main cascade observed may represent, at least in the lowest part, the positive parity yrast line.

IV. DISCUSSION

The structure of ^{94}Nb was considered so far only in connection with the lowest excitation energy states. Mainly the multiplet resulting from a $\pi g_{9/2} \otimes \nu d_{5/2}$ configuration has been discussed in the literature; it consists of six states with J^π between 2^+ and 7^+ which has been identified in the states at 0.0 keV, $(6)^+$, 40.9 keV, 3^+, 58.7 keV, $(4)^+$, 78.7 keV (assumed 7^+), 113.4 keV, $(5)^+$, and a state at 334 keV (which might be the 2^+ member) [7]. This multiplet was well described by shell-model calculations which considered

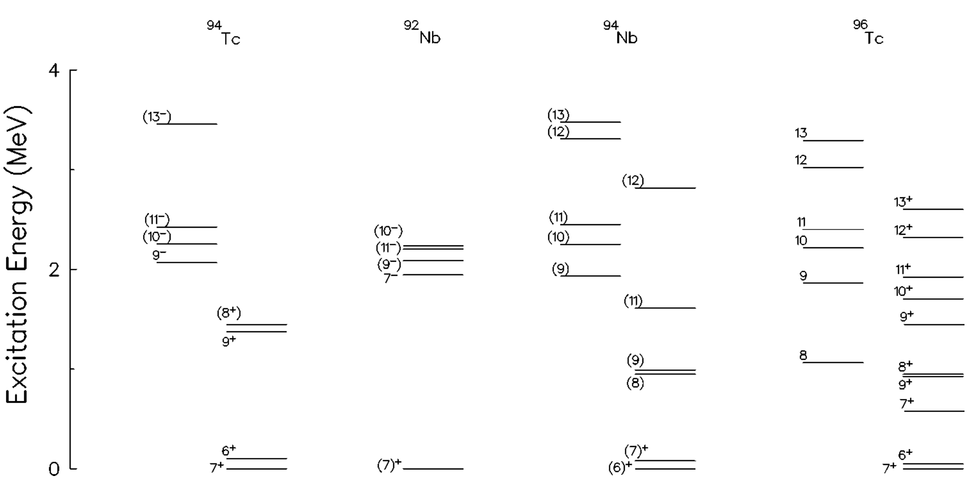

FIG. 5. Comparison of the high-spin states in ^{94}Nb to those known in its isotone ^{96}Tc [9,10] and its lighter isotope ^{92}Nb [13]; some states in ^{94}Tc [18] are also shown.

^{88}Sr as core, and allowed $p_{1/2}, g_{9/2}$ proton excitations and $d_{5/2}$ neutron excitations [16,17,4]. A notable similarity of this multiplet in the ^{92,94,96}Nb isotopes with the corresponding one in their isotones ^{94,96,98}Tc has also been noted [5].

Apart from this, high-spin states in odd-odd nuclei in the vicinity of this nucleus have rarely been discussed. As pointed out in the introduction, considering ^{88}Sr as a closed-shell core, we have three protons in the $p_{1/2}$ and $g_{9/2}$ shells and three neutrons in the $d_{5/2}$ and $g_{7/2}$ shells. The maximum spin that can be constructed by aligning the spins of the individual valence particles in these orbitals is rather low; thus, for the $(\pi s_{1/2} g_{9/2})^3 (\nu d_{5/2})^3$ configuration this maximum spin is 9. Obviously, to explain higher spins, one has to excite one $g_{9/2}$ neutron over the $N=50$ shell gap. The observed high-spin state sequence in ^{94}Nb is rather irregular in energy; this fact indeed suggests individual particle alignments along it. Similar structures have been recently observed in the Tc isotopes 94 and 96 and shell-model calculations both in a limited basis and a truncated enlarged basis were performed in this case [18]. A reasonable description of the higher-spin states seems to require, however, a much larger basis. Data such as those provided by the present measurements are therefore appropriate for comparison with such calculations.

Qualitative conclusions can also be drawn by comparing the levels reported in this work with high-spin states known in neighboring isotopic and/or isotonic nuclei. Unfortunately, not much is known in these nuclei, to extract systematic trends. In the neighboring isotopes, several high-spin states are known only in ^{92}Nb [13], while in the neighboring isotones ^{92}Y and ^{96}Tc, only in ^{96}Tc is there such information [9,10,18]. We have already remarked above on the resemblance of the lowest multiplets $g_{9/2} \otimes d_{5/2}$ in ^{94}Nb and ^{96}Tc. In Fig. 5 we compare the known high-spin states in these two nuclei; for completeness we have added the similar information known in ^{92}Nb and ^{94}Tc. One can first remark on a good similarity of the levels evidenced in ^{94}Nb with certain high-spin levels known in ^{96}Tc. Up to the state of spin $J=(9)$ at 991 keV, the ^{94}Nb sequence is very similar to the positive parity yrast sequence of ^{96}Tc. Then, starting with the second $J=(9)$ level at 1931 keV the ^{94}Nb sequence up to spin (13) is very similar to another sequence (or ''quasiband'' structure) in ^{96}Tc above a state of spin 8 at 1063 keV (observed up to the state of spin 12 in [9], and recently extended above that in [10]—although shown here is only the state of spin 13). The parity of this sequence in ^{96}Tc was tentatively assigned as positive by Mach *et al.* [9], but we note that although in that work some internal conversion coefficients have been measured, there is no direct support for this parity assignment. As seen in Fig. 5, these structures in ^{94}Nb and ^{96}Tc are rather similar, both in spin and excitation energies, to *negative* parity structures in ^{92}Nb [13] and ^{94}Tc [18]. This discussion is only qualitative, since the level sequences presented in Fig. 5, although suggesting some common features, have nevertheless some differences in the γ-ray decay characteristics. We thus emphasize again both the lack of systematic information on the high-spin states of odd-odd nuclei in this mass region, and the need of more complete (although more difficult) measurements of the level characteristics.

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