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Near-yrast, medium-spin structure of the ^{109}Tc nucleus

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Excited levels in the ^{109}Tc nucleus, populated in the spontaneous fission of ^{248}Cm, have been studied using the EUROGAM2 array. In ^{109}Tc we have found a new band corresponding to the $\pi 5/2^-[303]$ configuration and a three-quasiparticle band with $I^\pi = (15/2^-)$ band-head level at 1749.5 keV. The structure of the 1749.5-keV level probably involves the $\{\pi 5/2^+[422]\nu(5/2^-[532], 5/2^+[413])\}_{15/2^-}$ prolate configuration. The quasiparticle-rotor model calculations performed in this work show that the odd-proton configurations observed in ^{107}Tc and ^{109}Tc are consistent with the scheme of proton excitations in a prolate triaxial potential. Significant differences between the degree of triaxiality observed for positive- and negative-parity excitations may be due to blocking of the triaxial shape by the odd proton populating negative-parity orbitals. The properties of the new 494.5-, 1440.7-, and 1748.8-keV levels found in ^{109}Tc may indicate a change toward an oblate shape in this nucleus.

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I. INTRODUCTION

Our recent work on the near-yrast structure of ^{107}Tc and ^{111}Tc nuclei [1,2] as well as other investigations [3–5] provided a rich systematics of proton excitations in neutron-rich Tc isotopes, allowing a better understanding of the near-yrast structure of nuclei in this region. This should help verifying the prediction, with implications for the astrophysical r-process [6], that around neutron number $N = 70$ nuclei from this region develop an oblate shape [7]. It is likely that the transition from a prolate to an oblate shape proposed in [7] proceeds via a triaxial shape around the middle of the shell at $N = 66$. Therefore, it is worth studying further the triaxiality in neutron-rich nuclei of this region, especially considering its influence on β decay rates, which govern the production of isotopes in the r-process [8].

Of particular interest is the structure of the ^{109}Tc nucleus, which has 66 neutrons. It has been proposed in Ref. [4] that ^{109}Tc has a triaxial deformation. This is natural, considering the evidence for triaxiality in the neighboring Mo [9–11] and Ru [12] core nuclei, as well as recent calculations [13] indicating that triaxiality may be at its maximum in the ^{108}Ru nucleus. To understand this better, it would be good to know the single-particle basis of triaxial deformation around ^{108}Ru. This can be probed by studies of odd-A nuclei in this region.

A partial scheme of the near-yrast single-particle excitations in odd-A Tc isotopes shown in Fig. 1 suggests that in ^{109}Tc three proton orbitals, $5/2^+[422]$, $3/2^-[301]$, and $5/2^-[303]$, are located close to each other. However, it is not obvious which one forms the ground state in ^{109}Tc because the $3/2^-[301]$ and $5/2^-[303]$ bands have not been observed there. Considering relative positions and populations of the three discussed orbitals in ^{107}Tc [1] and their expected positions in ^{109}Tc, as suggested by Fig. 1, the observation of the $5/2^-[303]$ and $3/2^-[301]$ negative-parity bands in ^{109}Tc should be possible in a measurement of prompt γ rays following fission.

An important confirmation of triaxiality in odd-A Tc nuclei would be the observation of the two-phonon gamma-vibrational states, analogous to those reported for the Mo core nuclei [9,10]. In a recent report on ^{107}Tc [14], the first case of such excitations has been proposed. It is worth searching for such states in ^{109}Tc as well.

To investigate the outlined problems, we have studied medium-spin excitations of ^{109}Tc populated in spontaneous fission of ^{248}Cm. Details describing our experiment and the obtained data are given in Sec. II. In Sec. III we discuss the experimental results and compare them to the quasiparticle-rotor model predictions. The work is summarized in Sec. IV.

II. EXPERIMENTAL STUDIES OF ^{109}Tc

To study the near-yrast excitations in ^{109}Tc, we have measured high-fold γ coincidences between prompt γ rays following spontaneous fission of ^{248}Cm using the EUROGAM2 array of Ge anti-Compton spectrometers [15] additionally equipped with four low-energy photon (LEP) detectors. The fission source consisted of 5 mg of curium oxide, embedded uniformly in a pellet of potassium chloride. In a two-week experiment we collected approximately 2×10^{10} triple-γ coincidences, which were sorted into three-dimensional histograms. More details on the experiment and data analysis techniques can be found in Ref. [16].

A. Excitation scheme of ^{109}Tc

Figure 2 shows a partial level scheme of ^{109}Tc as obtained in this work. The ground-state band reported by Luo *et al.* [4] is confirmed up to the 3439.7-keV level. Above this level we

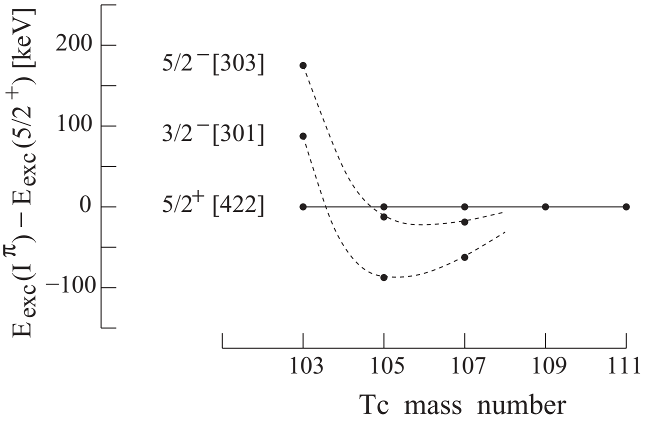

FIG. 1. Excitation energies of near-yrast $3/2^-$ and $5/2^+$ levels in neutron-rich, odd-*A* Tc isotopes, shown relative to the $5/2^-$ level. The data are from Refs. [1–4].

add a new 633.2-keV transition, and after that we place the 761-keV transition, reported in Ref. [4]. This change defines two new levels at 4072.8 and 4834 keV in the ground-state band.

In a γ spectrum, doubly gated on the 437.5- and the 633.2-keV lines, shown in Fig. 3, the major lines in the ground-state band are seen with comparable intensities, while the 761-keV line is weaker, confirming the proposed location of the 633.2-keV transition.

We confirm the 632.3-, 964.6-, 1262.2-, and 1636-keV levels with their decays reported in Ref. [4]. Three new levels at 494.5, 1440.7, and 1749.8 keV are introduced on the basis of the observation of new 308.9-, 425.4-, 494.6-, 808.4-, and 946.3-keV transitions. In Fig. 4 we show a spectrum doubly gated on the 946.3- and 308.9-keV lines, where the new lines at 425.4 and 494.6 keV are seen together with many new low-energy lines. Further gating on these low-energy lines has allowed their arrangement into a rotational band based on top of the 1749.8-keV level. We note that the 2137.2-, 2375.9-, and 2643.0-keV members of this band were reported in Ref. [4]. We confirm the 905.2-keV decay of the 2137.2-keV level but do not observe the 1053-keV branch from this level or the 691.6-keV decay of the 2643.0-keV level as reported in [4]. The 1930.8-keV member of this band decays to the known 1262.2-keV level via a new 668.5-keV branch.

Searching for new bands in ^{109}Tc, we set a double gate on the 288.1- and 1133.5-keV lines of ^{135}I [17], the most abundant fission-fragment partner of ^{109}Tc. In the resulting γ spectrum shown in Fig. 5, new lines at 165.0, 215.8, 380.8, and 433.7 keV are seen. A spectrum gated on the 165.0- and 433.7-keV lines, shown in Fig. 6, contains the 1111.3- and 1133.5-keV lines of ^{136}I and ^{135}I, respectively, indicating that both gating lines belong to a Tc isotope.

To assign the new 165.0- and 433.7-keV lines to a particular Tc isotope, we have applied the mass correlation technique, described in Refs. [1,2], which is based on the observation that in the spontaneous fission of ^{248}Cm no protons and, on average, 3.5 neutrons are emitted from both fission fragments. In Fig. 7 we show a mass correlation diagram for Tc isotopes, where the intensity ratio R for the 1111.3- and 1133.5-keV lines of ^{136}I and ^{135}I, respectively, is plotted (open circles); R was found in spectra doubly gated on known lines in various Tc isotopes. The dashed line fitted to these data provides a calibration curve for assigning new bands to Tc isotopes. Gating on the 165.0- and 433.7-keV lines provides an intensity ratio of the 1111.3- and 1133.5-keV lines of $R = 0.56(6)$ ($\log_{10} R = -0.25$). This ratio is plotted in Fig. 7 as a horizontal bar (we use the $\log_{10}$ scale on the ordinate to display a wide range of R values). The intersection of this bar with the calibration curve provides the mass $A = 108.8(2)$ for the relevant Tc isotope, indicating that the 165.0- and 433.7-keV lines belong to ^{109}Tc.

Further gating allowed the construction of a new band, as shown on the left-hand side of Fig. 2. We do not observe any transition depopulating this band to the ground state. We also note that gating on the $5/2^+$ band does not show any transition depopulating this band. Considering the observation limit in our measurements, we conclude that the head of the new band is located within 30 keV of the present ground state.

In Table I we show experimental values of γ energies and intensities for transitions in ^{109}Tc, as observed in triple-γ coincidence data measured in the fission of ^{248}Cm, together with the information on their initial levels.

B. Spin and parity assignments to levels in ^{109}Tc

In Refs. [18,19] a tentative $5/2^+$ spin and parity has been proposed for the ground state of ^{109}Tc. However, the spin and parity of the ground state in ^{109}Tc is still not certain because it is not clear which of the three configurations shown in Fig. 1 corresponds to the ground state in ^{109}Tc. Furthermore, none of the band heads shown in Fig. 2 have a unique spin and parity assignment. Therefore, all spin and parity assignments listed later in this work should be considered as tentative. Consequently, spins and parities in Fig. 2 and in Table I are shown in parentheses.

The band head of the band containing the 69.1-, 137.0-, 298.0-, 437.5-keV, etc., transitions was first assigned a tentative spin and parity of $5/2^-$ [20], which was later changed to a tentative $5/2^+$ assignment [4,21]. Analogous $5/2^+$ bands are observed in ^{105}Tc, ^{107}Tc, and ^{111}Tc. In Fig. 8 we show the staggering in the $5/2^+$ band of ^{105,107,109,111}Tc (filled symbols). The $5/2^+$ band in ^{109}Tc (filled symbols connected by the dashed line) has similar staggering as the $5/2^+$ bands in the other Tc isotopes, supporting the $5/2^+$ spin and parity for its band head. We note that in all four bands the lowest-spin data point is lower than expected. This irregularity may be due to aligning spin of the $5/2^+$ band head.

The angular momentum alignment in the ground-state (g.s.) band of ^{109}Tc is different from that reported in Ref. [4] because of the observation of the 633.2-keV transition. In Fig. 9 the total angular momentum alignment I_x for both signatures α of the $5/2^+$ band in ^{109}Tc is compared to the alignment in the ^{108}Mo core nucleus. In Fig. 9 we also show the alignment for the $5/2^+$ band in ^{107}Tc. The alignment i in the $5/2^+$ band in ^{109}Tc is $i \approx 1.5$ for the $\alpha = +1/2$ branch and $i \approx 0.5$ for the $\alpha = -1/2$ branch, which gives a total alignment of $2\hbar$ in this band. This is consistent with the expectation for an odd proton in the

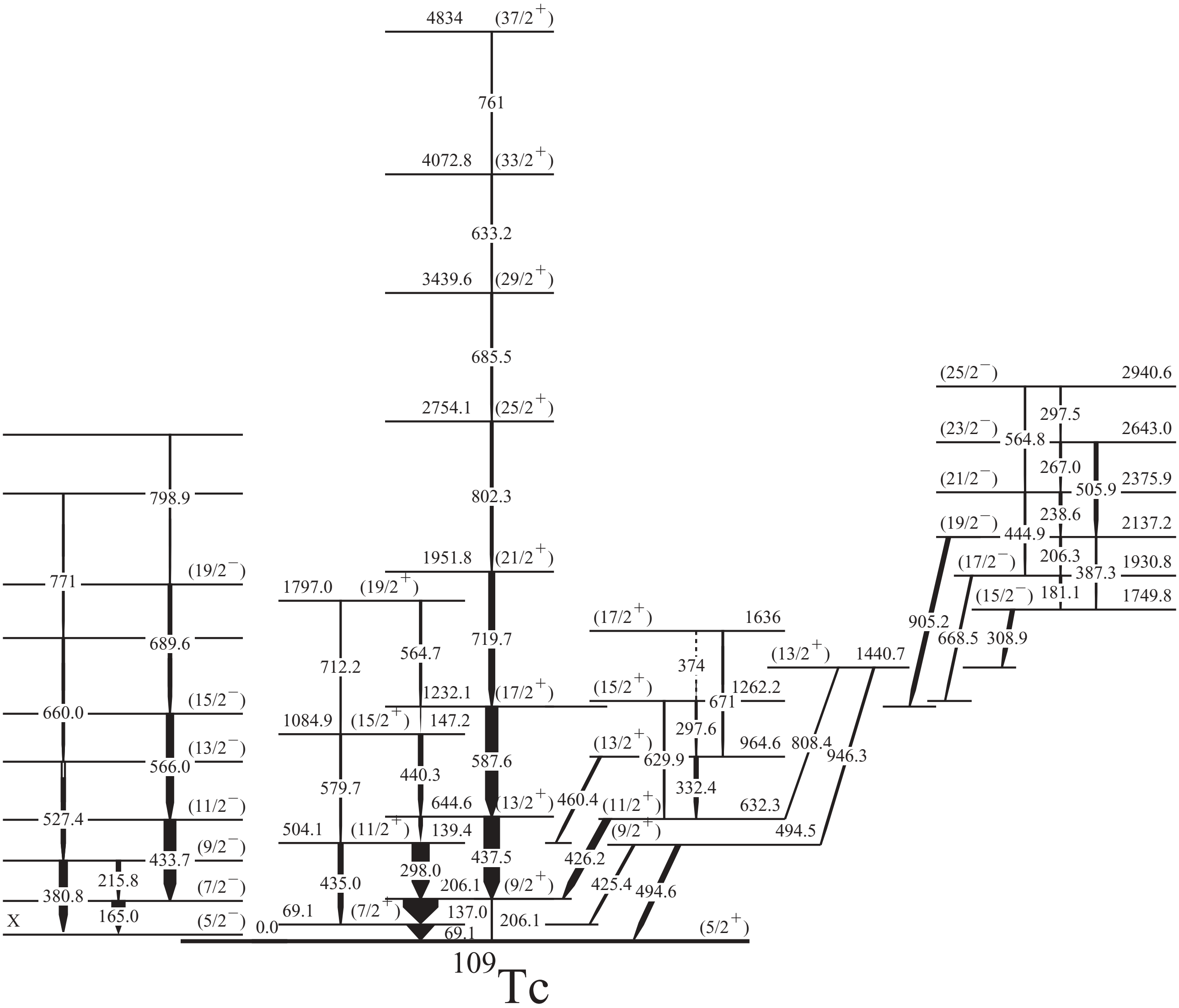

FIG. 2. Partial level scheme of ^{109}Tc obtained in this work. Errors on γ transition energies range from 0.1 keV for strong lines to 0.3 keV for weak lines.

$K = 5/2$ orbital originating from the $h_{9/2}$ shell. Similar results are obtained for the $5/2^+$ band in ^{107}Tc. At $\hbar\omega \approx 0.36$ MeV the I_x value for the $5/2^+$ band in ^{109}Tc increases due to the alignment of a pair of nucleons in the core, gaining about $8\hbar$ of angular momentum, as observed in the $\alpha = +1/2$ branch of this band. Such a large increase in alignment is most likely due to aligning a pair of $h_{11/2}$ neutrons in the core. Unfortunately, to date, no crossing has been reported in the g.s. band of ^{108}Mo. In ^{107}Tc the crossing in the $5/2^+$ band is observed at slightly higher rotational frequency of $\hbar\omega \approx 0.38$, as already noted by Luo *et al.* [4]. The complete crossing picture is not seen, but the available data suggest a similar gain in the I_x value.

Spins and parities of other excited levels in ^{109}Tc, shown in Fig. 2, were proposed based on angular correlations, on γ decay intensities shown in Table I, and in some cases on conversion coefficients, as discussed below. We have also assumed that spin values are increasing with increasing excitation energy, based on the observation that the fission process populates predominantly yrast levels.

In Fig. 10 we show a γ spectrum measured by LEP detectors placed in the EUROGAM2 array. The spectrum is doubly gated on the 137.0- and 437.5-keV lines of the $5/2^+$ band in ^{109}Tc. In the spectrum one can see the 69.1-keV line from this band and the K_α and K_β technetium x-ray lines at 18.3 and 20.6 keV. There are also iodine x rays at 28.5 and 32.3 keV, the 87.0- and 135.2-keV lines of ^{136}I [23] (the most abundant fission-fragment partner to ^{109}Tc), and the 154.4-keV line of ^{137}I [24]. Assuming that the entire intensity of the K_α line of technetium, shown in Fig. 10, is due to the internal conversion of the 69.1-keV transition, we calculated the conversion coefficient for this transition of $\alpha_K = 2.9(8)$. The theoretical α_K values of 0.38, 0.70, and 3.52 for the $E1$, $M1$, and $E2$ multipolarites, respectively, indicate that the 69.1-keV transition has a mixed $M1 + E2$ multipolarity and that the parity of the 69.1-keV level is positive. We adopt spin and parity of $7/2^+$ for this level.

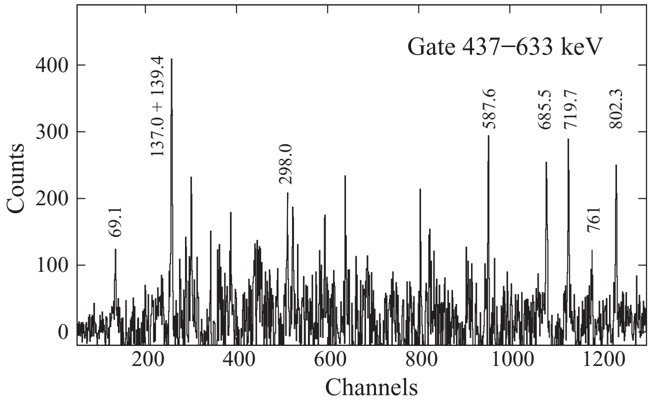

FIG. 3. A γ spectrum gated on the 437.5- and the 633.2-keV lines in ^{109}Tc, as observed in this work.

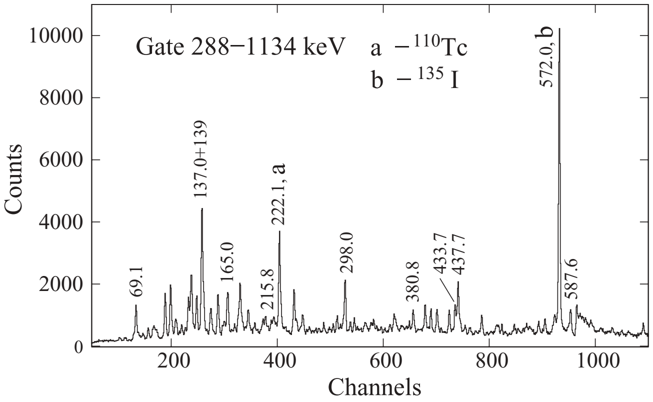

FIG. 5. A γ spectrum gated on the 288.1- and 1133.5-keV lines in ^{135}I, as observed in this work.

In Fig. 11 we show the angular correlation data obtained in this work, which are drawn against the theoretical angular correlations for the EUROGAM2 array [25], for the stretched quadrupole-quadrupole (QQ) and stretched quadrupole-dipole (QD) cascades. The experimental data have been obtained using techniques described in detail in Refs. [16,26] .

The data for the 437.5–137.0- and 437.5–587.6-keV cascades, shown in Fig. 11(a), are consistent with the stretched-quadrupole multipolarity for the 437.5- and 587.6-keV lines and a $\Delta I < 2$ character of the 137.0-keV line. Therefore, we adopt spin 9/2 for the 206.1-keV level. Positive parity is preferred because of the observation of the 206.1-keV prompt decay of this level to the $5/2^+$ level. Spins and parities of $13/2^+$ and $17/2^+$ are assigned to the 644.6- and 1232.1-keV levels, respectively, because of the stretched-quadrupole multipolarity of the 437.5- and 587.6-keV prompt transitions. The angular correlations shown in Fig. 11(b) are consistent with the stretched-quadrupole multipolarity for the 719.7- and 587.6-keV lines and a $\Delta I < 2$ character of the 147.2.0-keV line. Therefore, we assign spin and parity $21/2^+$ to the 1951.8-keV level and spin 15/2 to the 1084.9-keV level. Spin 11/2 is assigned to the 504.1-keV level because of the observed branchings. Due to the prompt character of the 435.0- and 579.7-keV transitions positive parity is assigned to the 504.1- and 1084.9-keV levels. The angular correlations shown in Fig. 11(c) are consistent with the stretched-quadrupole multipolarity for the 685.2- and 633.2-keV prompt γ lines. Therefore, we assign spins and parities of $29/2^+$ and $33/2^+$ to the 3439.6- and 4072.8-keV levels, respectively. The 4834-keV level, which continues the band, probably has spin $37/2^+$.

In Fig. 8 the staggering in the band based on level X in ^{109}Tc is compared to the staggering in $5/2^-$ bands of ^{105}Tc and ^{107}Tc (empty symbols). We have assumed that the band head, marked as level X in Fig. 2, has spin and parity of $5/2^-$. The observed similarity of the staggering in all three nuclei (empty symbols) supports the $5/2^-$ assignment for level X.

In Fig. 12 we show the total angular momentum alignment I_x for both signatures of the $5/2^-$ band in ^{107}Tc and the negative-parity band in ^{109}Tc; we adopted a $K = 5/2$ value for both bands. The I_x values in both bands are very similar, again supporting the $5/2^-$ spin-parity assignment for level X in ^{109}Tc.

Figure 11(e) shows angular correlations for the 566.0-keV line with the 433.7- and 689.6-keV lines. These correlations are consistent with the stretched-quadrupole multipolarity for all three lines. Similarly, angular correlations for the 380.8- and 527.4-keV lines, shown in Fig. 11(f), are consistent with the stretched-quadrupole multipolarity for these two lines. However, the correlation for the 433.7- and 165.0-keV lines is

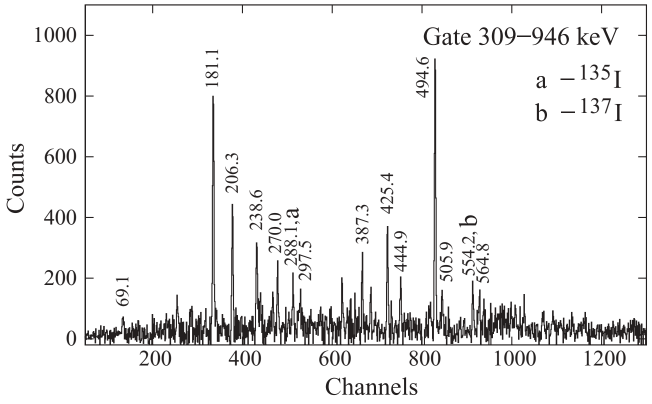

FIG. 4. A γ spectrum gated on the 308.9- and 946.3-keV lines in ^{109}Tc, as observed in this work.

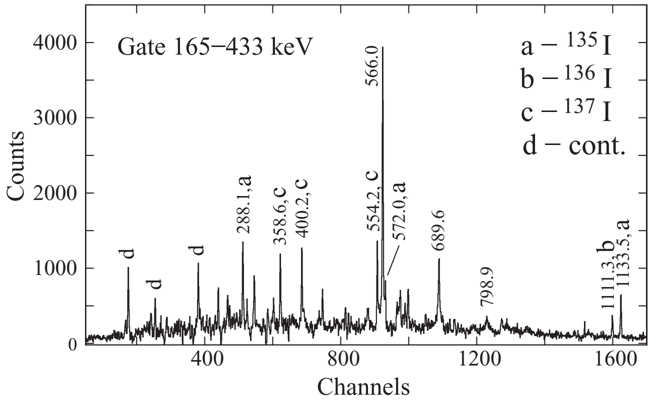

FIG. 6. A γ spectrum gated on the 165.0- and 433.7-keV lines in ^{109}Tc, as observed in this work. Here d denotes a contamination line.

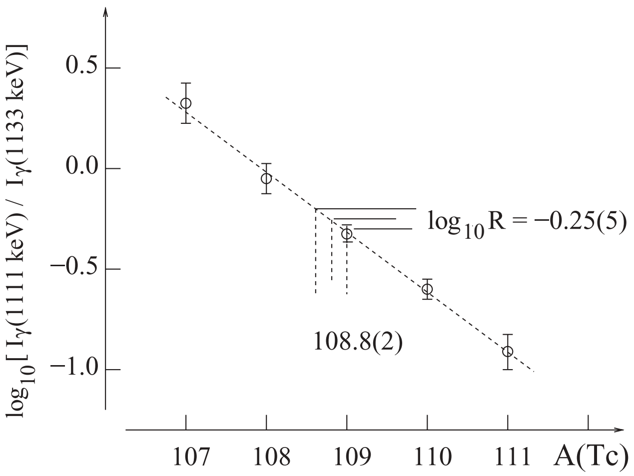

FIG. 7. Mass correlation diagram for various bands in Tc isotopes. R is the intensity ratio of the 1111.3-keV line in ^{135}I and the 1133.5-keV line in ^{136}I. See text for further explanation.

TABLE I. Properties of γ transitions and excited levels in ^{109}Tc, as observed in this work. The excitation energy X of the new $(5/2^-)$ level is not higher than 30 keV.

E_γ (keV)	I_γ (rel.)	$E_{\rm lev}^{\rm ini}$ (keV)	$I_{\rm lev}^{\rm ini}$
X		X	$(5/2^-)$
69.1 (1)	192(12)	69.1	$(7/2^+)$
137.0 (1)	220(4)	206.1	$(9/2^+)$
139.4 (2)	29(2)	644.6	$(13/2^+)$
147.2 (3)	8(1)	1232.1	$(17/2^+)$
165.0 (1)	76(4)	$X + 165.0$	$(7/2^-)$
181.1 (1)	8.7(6)	1930.8	$(17/2^-)$
206.1 (2)	4.1(9)	206.1	$(9/2^+)$
206.3 (1)	7(1)	2137.2	$(19/2^-)$
215.8 (2)	21(1)	$X + 380.8$	$(9/2^-)$
238.6 (2)	12(3)	2375.9	$(21/2^-)$
267.0 (2)	7(2)	2643.0	$(23/2^-)$
297.5 (3)	3(1)	2940.6	$(25/2^-)$
297.6 (2)	7(1)	1262.2	$(15/2^+)$
298.0 (1)	100(3)	504.1	$(11/2^+)$
308.9 (1)	19.2(14)	1749.8	$(15/2^-)$
332.4 (2)	20(4)	964.6	$(13/2^+)$
374 (0.5)	4(1)	1636	$(17/2^+)$
380.8 (1)	44(3)	$X + 380.8$	$(9/2^-)$
387.3 (1)	3.8(7)	2137.2	$(19/2^-)$
425.4 (1)	9(1)	494.5	$(9/2^+)$
426.2 (1)	37(4)	632.3	$(11/2^+)$
433.7 (1)	67(5)	$X + 598.7$	$(11/2^-)$
435.0 (2)	25(2)	504.1	$(11/2^+)$
437.5 (1)	90(3)	644.6	$(13/2^+)$
440.3 (2)	22(2)	1084.9	$(15/2^+)$
444.9 (2)	5(1)	2375.9	$(21/2^-)$
460.4 (2)	11(2)	964.6	$(13/2^+)$
494.6 (1)	24(2)	494.5	$(9/2^+)$
505.9 (3)	18(4)	2643.0	$(23/2^-)$
527.4 (2)	30(2)	$X + 908.2$	$(13/2^-)$
564.7 (3)	7.9(14)	1797.0	$(19/2^+)$
564.8 (3)	3(1)	2940.6	$(25/2^-)$
566.0 (2)	39(3)	$X + 1164.7$	$(15/2^-)$
579.7 (2)	6.0(15)	1084.9	$(15/2^+)$
587.6 (1)	70(2)	1232.1	$(17/2^+)$
629.9 (3)	8(1)	1262.2	$(15/2^+)$
633.2 (3)	4(1)	4072.8	$(33/2^+)$
660.0 (3)	8.9(19)	$X + 1568.2$	
668.5 (2)	7(1)	1930.8	$(17/2^-)$
671 (0.5)	5(1)	1636	$(17/2^+)$
685.5 (2)	8(1)	3439.6	$(29/2^+)$
689.6 (2)	16(2)	$X + 1854.3$	$(19/2^-)$
712.2 (3)	2.3(6)	1797.0	$(19/2^+)$
719.7 (1)	31(1)	1951.8	$(21/2^+)$
761 (0.5)	2(1)	8834	$(37/2^+)$
771.0 (4)	4.1(17)	$X + 2339$	
798.9 (3)	3.6(18)	$X + 2653.2$	
802.3 (2)	12(1)	2754.1	$(25/2^+)$
808.4 (2)	1.8(4)	1440.7	$(13/2^+)$
905.2 (2)	6.7(5)	2137.2	$(19/2^-)$
946.3 (2)	6.7(6)	1440.7	$(13/2^+)$

not conclusive. We can reject the stretched $E1$ multipolarity for the 165.0-keV line, but three solutions remain, namely, a nonstretched $E1$, a mixed $M1 + E2$ of $\Delta I < 2$ character, and the stretched-quadrupole multipolarity for the 165.0-keV line. The $M1 + E2$ multipolarity for the 165.0-keV line is preferred because of the staggering observed in in the negative-parity band, shown in Fig. 8.

An estimate of the α_K for the 165.0-keV line, made in a way similar to that for the 69.1-keV transition, also does not help. The experimental value of $\alpha_K = 2.2(7)$, obtained by comparing the γ intensity of the 165.0-keV line to the intensity of the Tc K_α x rays, observed in a LEP spectrum double gated on the 433.7- and 566.0-keV lines, is too large as compared with the theoretical K_α values of 0.027, 0.62, and 0.17, calculated at 165 keV for the $E1$, $M1$, and $E2$ multipolarities, respectively. A possible solution is the assumption that the band head level, marked as X in Fig. 2, decays via a lowenergy transition, which has a conversion coefficient of about 2. The energy of this transition has to be higher than 18.3 keV, and it should have an $E1$ multipolarity, considering the decay from level X with spin $(3/2^-,5/2^-)$ to the level with spin $5/2^+$. The theoretical K_α value for the $E1$ transition with an energy of 20 keV is 1.78. Unfortunately, the estimated intensity of the γ line corresponding to such a 20-keV transition is below the observation limit of our measurement.

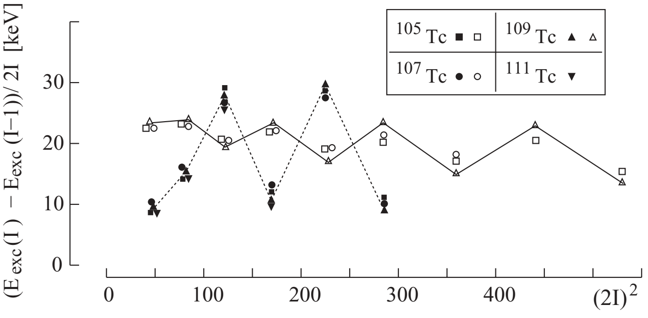

FIG. 8. Staggering in the $5/2^+$ (filled symbols) and $5/2^-$ (empty symbols) bands in Tc isotopes. The data are from Refs. [1,2,4,22]. See text for further explanation.

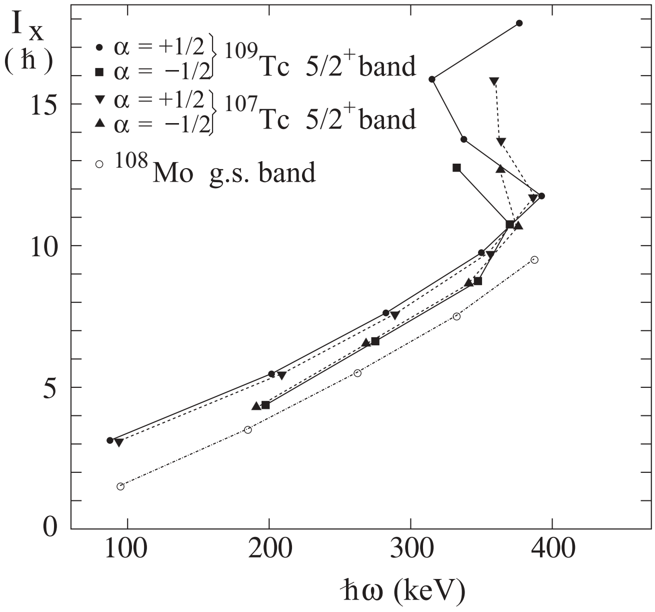

FIG. 9. Total angular momentum alignment I_x for the $5/2^+$ band in ^{107}Tc and ^{109}Tc (for both signatures) compared to the alignment in the ^{108}M core nucleus.

A dedicated β^--decay measurement of ^{109}Mo could resolve this problem.

III. DISCUSSION OF THE EXPERIMENTAL RESULTS

A. Interpretation of excited levels in ^{109}Tc

To help interpret excited levels in ^{109}Tc, we have performed the quasiparticle-rotor model (QPRM) calculation using the codes ASYRMO and PROBI [27]. In our calculations we have used a quadrupole deformation of $\epsilon_2 = 0.32$ ($\beta_2 = 0.38$), an inertia parameter $a = 23.3$ keV, and a Coriolis attenuation parameter $\xi = 0.72$. Standard values for the κ and μ parameters of the ls and l^2 terms were used [28]. The triaxial-deformation parameter γ has been fitted to reproduce the staggering in the positive-parity band. To calculate the γ intensities, we took the collective g factor for the core of $g_R = 0.2$ and an effective value of the free neutron g factor of $g_s^{\mathrm{eff}} = g_s^{\mathrm{free}}$. More information on such calculations can be found in Refs. [29,30]. With the codes mentioned above we could not calculate three-quasiparticle configurations, such as the one based on the 1749.8-keV level.

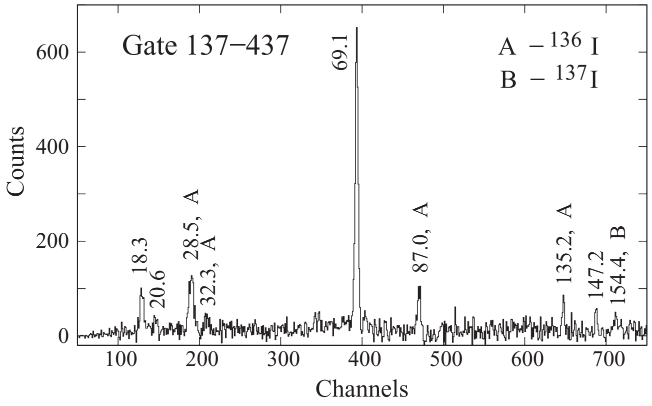

FIG. 10. The LEP γ spectrum doubly gated on the 137.0- and 437.5-keV lines of ^{109}Tc.

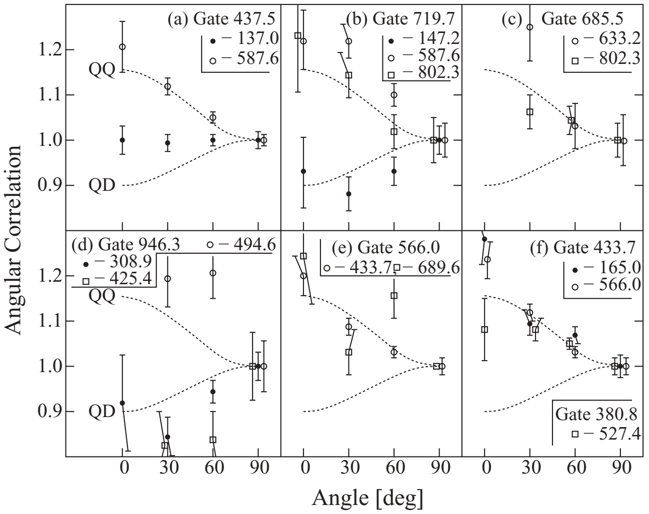

FIG. 11. Angular correlations between γ lines of ^{109}Tc, as observed in this work. Dashed lines represent theoretical expectations for the stretched quadrupole-quadrupole (QQ) and the stretched quadrupole-dipole (QD) cascades.

A comparison between the experimental and calculated energies of the excited states in ^{109}Tc is shown in Fig. 13. The overall reproduction of the experimental scheme is satisfactory, both qualitatively and quantitatively.

The positive-parity excitations are reproduced as rotational states on top of the proton $5/2^+[422]$ configuration, originating from the $\pi g_{9/2}$ intruder orbital. This configuration dominates the solution for the $5/2^+_1$ level. The wave function corresponding to this level contains two major components, with $K = 5/2$ and $K = 7/2$, for which amplitudes are 0.91 and 0.34, respectively. The $K = 5/2$ part is dominated by the $5/2^+[422]$ configuration (with an amplitude of 0.92), and the

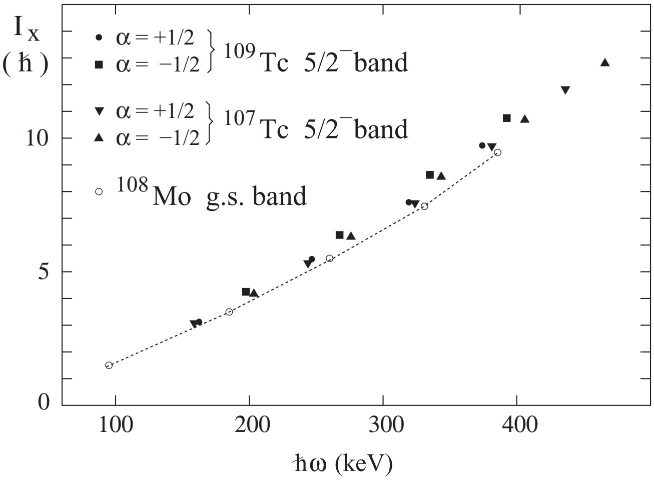

FIG. 12. Total angular momentum alignments I_x for the negative-parity band in ^{109}Tc and the $5/2^-$ band in ^{107}Tc compared to the alignment in the ^{108}M core nucleus.

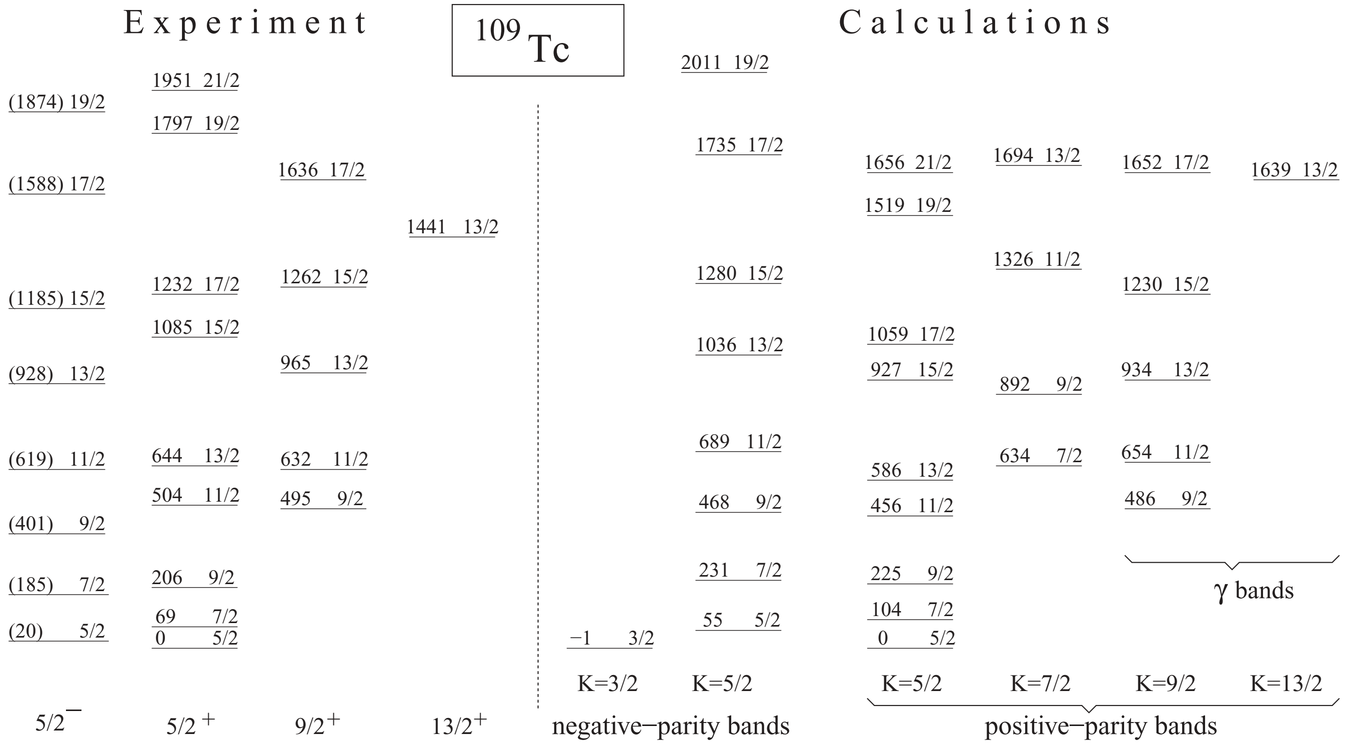

FIG. 13. Comparison of the experimental and calculated levels in ^{109}Tc, as obtained in the present work.

$K = 7/2$ part is dominated by the $7/2^+[413]$ configuration (with an amplitude of 0.94). The best reproduction of the positive-parity levels has been obtained with the triaxial-deformation parameter $\gamma = 24^\circ$. (An accuracy of 1° may be assigned to this theoretical value).

The nonyrast positive-parity levels, marked in the experiment as $9/2^+$ and $13/2^+$ bands, have been reproduced as $K = 9/2$ and $K = 13/2$ γ bands built on top of the $5/2^+[422]$ dominating configuration. The calculations thus indicate the rather simple explanation that all the observed positive-parity excitations are due to a rotation of a nucleus with triaxial deformation. In particular, the $K = 13/2$ state (1441 keV in the experiment and 1639 keV in the calculations) is an analog of the two-γ vibration seen in ^{106}Mo [9].

In Table II we compare the calculated branching ratios to the experimental values. (The experimental values have been obtained from γ intensities shown in Table I and, where possible, by double gating on transitions feeding the level of interest, which usually results in cleaner γ spectra and more precise branchings). In order to reproduce the experiment we had to lower the g_R parameter from its standardZ/A value of$g_R = 0.4$ for ^{109}Tc to $g_R = 0.2$. Such low g_R values have been reported before in this region [31,32]. In general, the theory reproduces the experiment well, showing correctly which of the two decays in a branching ($\Delta I = 1$ or $\Delta I = 2$) is stronger. However, for the decay of the $9/2^+_2$, 494.5-keV level to the $5/2^+$ and $7/2^+$ levels, calculations differs by an order of magnitude from the experiment and show an "opposite" branching ratio. This indicates that the $5/2^+_1$, $7/2^+_1$, and $9/2^+_2$ levels in ^{109}Tc need more attention.

The band head of the positive-parity band has been tentatively assigned a parity of $5/2^+$ [4], based on systematics. In Ref. [4] it was also stated that the positive-parity band in ^{109}Tc corresponds to the $\pi 7/2^+[413]$ configuration. This was based on an analogy with the results obtained in that work for ^{107}Tc, for which triaxial-rotor-plus-particle calculations were performed. In those calculations the $5/2^+$ level was found to be dominated by a configuration with $K = 5/2$, but it was calculated above the $7/2^+$ level, which is opposite to the order observed experimentally. Unfortunately, no calculations for ^{109}Tc were performed in Ref. [4], and the nature of the $5/2^+$ level in ^{109}Tc has not been explained. It is therefore not possible to compare directly our interpretation for ^{109}Tc with that of Ref. [4]. To help understand the relation between the $5/2^+$ and $7/2^+$ levels in ^{107}Tc and ^{109}Tc, we provide in Sec. III B our calculations for the ^{107}Tc nucleus.

The $K = 7/2$ band dominated by the $\pi 7/2^+[413]$ configuration appears in our calculations 634 keV above the $K = 5/2$ band. This band is dominated (with an amplitude of 0.89) by the $K = 7/2$ component, in which the $\pi 7/2^+[413]$ configuration appears with an amplitude of 0.94. Because of its high excitation energy this $K = 7/2$ band does not reproduce any of the positive-parity experimental levels. The $K = 11/2$ head of the γ band built on top of this $K = 7/2$ level is calculated at 1102 keV, which is well above the experimental $11/2^+_2$ level observed at 654 keV. We also note that the $K = 3/2$ band head with the dominating $\pi 3/2^+[431]$ configuration is calculated 760 keV above the $K = 5/2$ band head. The theory thus provides a consistent picture of the 43rd proton placed on the $\pi 5/2^+[422]$ orbital, with the $\pi 3/2^+[431]$ orbital below and the $\pi 7/2^+[413]$ orbital above

TABLE II. Experimental and calculated γ branching ratios for selected levels in ^{109}Tc and ^{107}Tc. The experimental data are from this work and for the 495.9-keV level from Ref. [43].

E_{exc}	E_γ	I_γ^{exp}	I_γ^{th}	E_{exc}	E_γ	I_γ^{exp}	I_γ^{th}
^{109}Tc							
206.1	206.1	100(22)	100	494.5	494.6	100(4)	100
	137.0	5333(93)	2000		425.4	36(3)	454
504.1	435.0	100(8)	100	964.0	332.4	100(16)	100
	298.0	400(12)	303		460.4	47(9)	167
644.6	437.5	100(3)	100	1262.2	629.9	100(5)	
	139.4	32(3)	48		297.6	110(6)	
1084.9	579.7	100(25)	100	1636	671	100(20)	
	440.3	363(28)	164		374	86(14)	
1232.1	587.6	100(4)	100	1440.7	946.3	100(4)	
	147.2	11(2)	14		808.4	26(3)	
1797.0	712.2	100(25)		$X + 380.9$	380.8	100(5)	
	564.7	340(64)			215.8	42(4)	
^{107}Tc							
275.1	209.7	100(18)	100	1142.7	574.9	100(24)	100
	138.2	2018(36)	2000		415.3	490(28)	149
567.8	431.0	100(10)	100	1329.7	602.3	100(11)	100
	292.7	476(8)	313		187.0	28(4)	25
727.4	452.3	100(5)	100	495.9	430.1	100	100
	159.6	60(4)	38		358.5	213	1000

it, in accordance with the Nilsson scheme. It is the 45th proton, corresponding to the ground states in Rh isotopes,that is placed in the $\pi 7/2^+[413]$ orbital, according to this scheme. This is confirmed by the experiment, where the $7/2^+$ ground state is observed in ^{105,107,109,111,113,115}Rh isotopes [33–40].

Finally, we note that the low $B(E2)$ rate of decay from the γ band to the g.s. is an expected feature of a triaxial system, as already discussed in Ref [4]. Our calculations predict a $B(E2)$ value of only 11 Weisskopf units (W.u.) for the $9/2_2^+ \rightarrow 5/2_1^+$ transition as compared to 120 W.u. for the $9/2_1^+ \rightarrow 5/2_1^+$ transition. In this context, the enhanced intensity of the 494.6-keV transition in ^{109}Tc is a phenomenon beyond the capability of the presently used triaxial model and needs to be studied further.

The negative-parity excitations in ^{109}Tc are rather complex because the underlying "normal-parity" orbitals mix strongly. In our calculation the wave function of the $5/2_1^-$ level contains comparable contributions from the $5/2^-[303]$, $3/2^-[301]$, and $1/2^-[301]$ configurations. In Fig. 13 we compare this calculated band with the dominating $K = 5/2$ component to the new negative-parity band observed in ^{109}Tc. The calculated levels compare well with the experimental band, for which we have drawn level X at 20 keV in Fig. 13. All other experimental levels in the band are labeled with energies calculated relative to this value.

The configuration proposed for the negative-parity band in ^{109}Tc is consistent with the observation in Fig. 12 that there is no aligned angular momentum in this band ($i = 0$ when compared to I_x in the ^{108}Mo core nucleus). Such a result is expected for orbitals with the maximum spin projection value Ω, which are present in the proposed configuration.

The solution for the negative-parity levels shown in Fig. 13 is a part of a more complex excitation pattern of a triaxial rotation on top of the yrast $K = 5/2$ configuration, as shown in Fig. 14. The $K = 5/2$ band is clearly yrast, although the $K = 3/2$ band head is the lowest level of this system. The $3/2^-$ level is calculated 1 keV below the $5/2^+$ band head and is therefore the ground state in our calculated scheme of ^{109}Tc. (This level is also shown in Fig. 13.) For this rich scheme

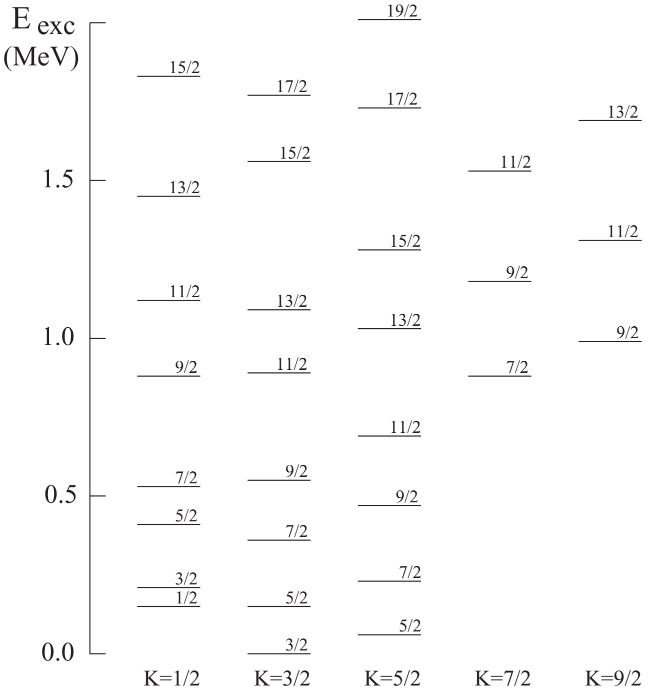

FIG. 14. Calculated energies of the negative-parity levels in ^{109}Tc, as obtained in the present work.

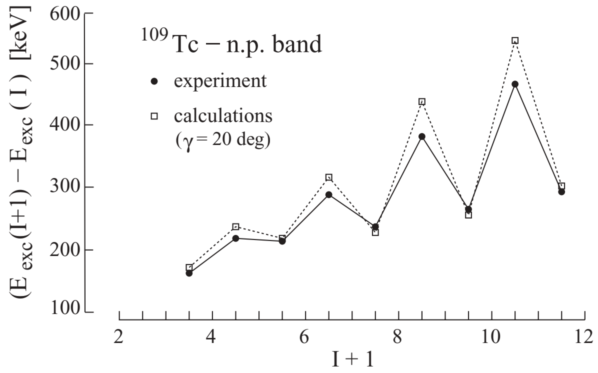

FIG. 15. The experimental and calculated staggering in the $5/2^-$ band in ^{109}Tc.

of negative-parity excitations, we see in our measurements only the $K = 5/2$ band. It is of interest to study the nonyrast excitations in ^{109}Tc, which can be populated in the β^- decay of the ground state of ^{109}Mo with an expected spin $5/2^+$ or $3/2^+$ [41].

As discussed in Ref. [30] the staggering in the band depends strongly on the level of triaxiality in a nucleus. To reproduce properly the staggering in the $5/2^-$ band of ^{109}Tc, we had to use a lower value of the triaxiality parameter $\gamma = 20°$, as compared to $\gamma = 24°$ used for the positive-parity band. The result is shown in Fig. 15.

The significant lowering of the γ value in the negative-parity band indicates the role of different orbitals in forming triaxiality. As discussed, the negative-parity orbitals of different Ω mix strongly in a triaxial potential. In contrast, the positive-parity solutions have rather simple single-particle configurations, suggesting that they are "spectators" only. It is therefore possible that an odd proton placed in the negative-parity orbital blocks its contribution to triaxiality.

B. QPRM calculations for ^{107}Tc

The ^{107}Tc nucleus has been studied intensively in recent years [1,4,5,14,20,42]. Because of many differences in these studies we decided to review the published data and to perform calculations for ^{107}Tc similar to the calculations for ^{109}Tc described here.

In the first report on the medium-spin yrast levels the positive-parity band in ^{107}Tc has been reported with the $7/2^+$ band head at 137.4 keV, and the 65.7-keV level has been reported with spin and parity of $5/2^-$ [20]. We have shown [1] that the 65.7-keV level has spin and parity $5/2^+$ and proposed that this level should be the band head of the positive-parity cascade. We have also found a new negative-parity, $K = 5/2$ band based on the 45.6-keV level. Both bands are shown in Fig. 16. The $5/2^+$ assignment for the 65.7-keV level has been also proposed in Ref. [4], but it has been stated there that the relation of this level to the positive-parity band is not clear and the $7/2^+$ level at 137.4-keV was proposed again as the band head. In their calculations, performed with the triaxiality parameter $\gamma = 22.5°$, the $5/2^+$ level was found above the $7/2^+$ level. The $5/2^-$ band was not reported in Ref. [4].

Two other bands have been reported in ^{107}Tc in Refs. [4,20], a γ band, for which a mixture of $K = 9/2$ and $K = 11/2$ components has been proposed in their calculations, and a $K = 1/2$ band Ref. [4] interpreted as the proton intruder $1/2^+[431]$, by analogy with similar bands seen in Rh isotopes [39,40]. For the $K = 1/2$ band, with a $3/2^+$ band

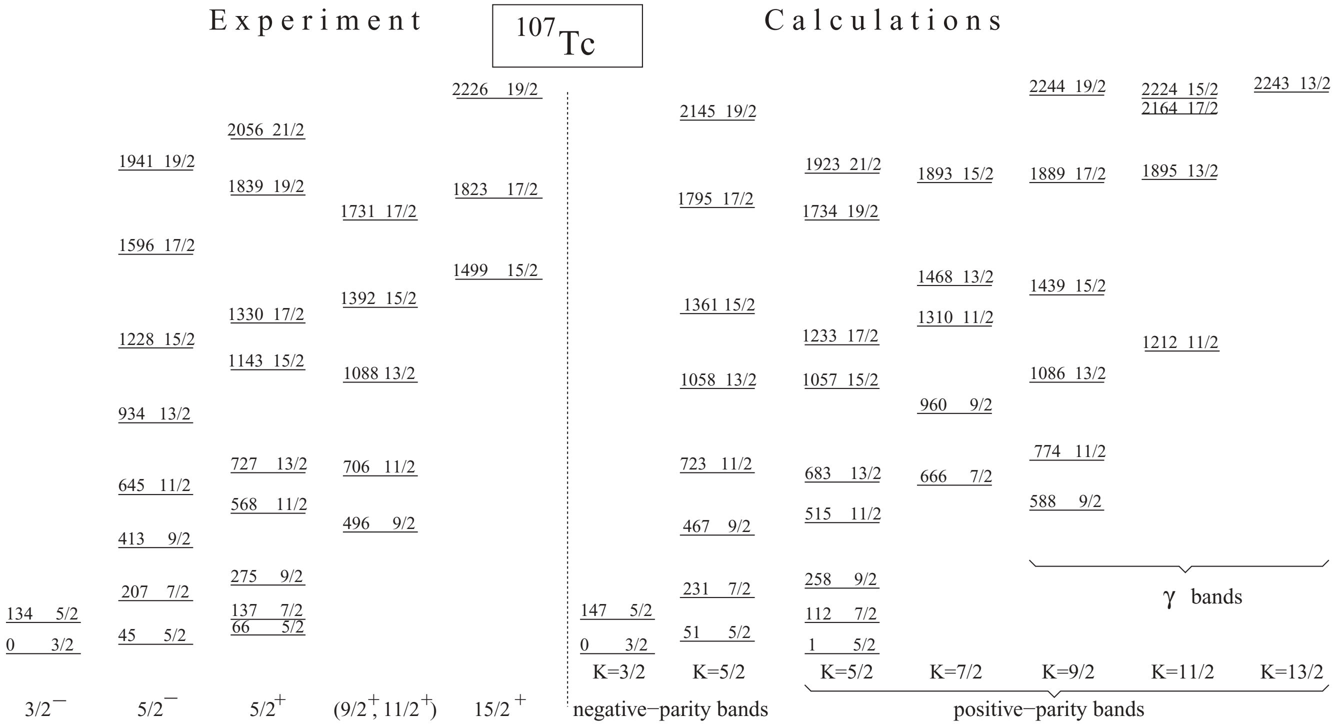

FIG. 16. Comparison of the calculated levels in ^{107}Tc, as obtained in the present work, to the experimental levels reported in Refs. [1,14].

head of unknown energy X large discrepancies between the experimental and calculated cascades were reported [4]. The band head of the $1/2^+[431]$ band in ^{107}Tc was later found at 30.1 keV as a long-lived isomer with $T_{1/2} = 3.85\ \mu$s [42]. The isomer and $K = 1/2$ band on top of it have been well reproduced in Ref. [42] using $\gamma = 19^\circ$ and a large value of $\epsilon_2 = 0.35$.

In two subsequent works reporting on ^{107}Tc [5,14], the $5/2^-$ band has been confirmed, and new arguments have been proposed in favor of the $\pi 7/2^+[422]$ band head for the positive-parity band, based on the g-factor analysis for this band. This analysis assumes that the K quantum number is well defined for the levels in question. However, the calculation for the positive-parity band performed in Ref. [4] predicts two main components for the lowest $7/2^+$ state, with $K = 5/2$ and $K = 7/2$. Moreover, the standard value of $g_R = Z/A$ has been used, which may not be valid in this region, as discussed here. Therefore, the proposed g-factor analysis needs further justification before any definite conclusions are drawn. We note that in the present work the positive-parity band in ^{109}Tc has been calculated as a rather clean $K = 5/2$ configuration, while the $K = 7/2$ configuration has been found at significantly higher excitation energy. Therefore, it is of interest to perform analogous calculations for ^{107}Tc.

In Fig. 16 we compare the results of our calculations for ^{107}Tc to the experimental data reported in Refs. [1,4,5,14]. We have included in the data the 495.9-keV level [43], which is a good candidate for the $9/2^+$ γ excitation.

In our calculations we have employed the computer codes mentioned and used the same model parameters as for ^{109}Tc. The best reproduction of the experimental data for the positive-parity excitations has been obtained with the triaxiality parameter $\gamma = 23^\circ$, in good agreement with Ref. [4], and for the negative-parity excitations, it has been obtained with $\gamma = 18^\circ$. The overall reproduction of the data is good, as can be seen in Fig. 16. The dominating configuration in the positive-parity excitations is the $5/2^+[422]$ proton orbital. The $K = 5/2$ rotational band built on top of this configuration describes well the yrast cascade in ^{107}Tc. The $5/2^+$ level is calculated below the $7/2^+$ level in this cascade. The $K = 7/2$ band, which is dominated by the $7/2^+[413]$ proton configuration, is predicted at much higher excitation energies.

The $(9/2^+,11/2^+)$ side band is well reproduced as the $K = 9/2$ band dominated by the $\pi 5/2^+[422]$ proton configuration. Therefore, it can be interpreted as the γ band on top of the $5/2^+$ ground state. In Table II we show experimental and calculated γ branchings for the positive-parity levels in ^{107}Tc. The theory reproduces properly the observation of which of the two decays in a branching ($\Delta I = 1$ or $\Delta I = 2$) is stronger, and the discrepancy for the 495.9-keV level is smaller than that observed for the 494.5-keV level in ^{109}Tc. We note that in Ref. [4] the $9/2^+$ level with the dominating $K = 9/2$ component has been calculated below the $11/2^+$ level, but the experimental counterpart has not been observed there.

The $15/2^+$ side band could not be reproduced satisfactorily. The 15/2 and 17/2 members of the $K = 11/2$ band with the dominating $\pi 7/2^+[413]$ configuration are calculated with too high an energy. Similarly, the $K = 13/2$ band with the dominating $\pi 5/2^+[422]$ configuration is calculated at a much higher excitation energy than in ^{109}Tc.

Both negative-parity bands in ^{107}Tc are well reproduced. They appear in the calculation as strong mixtures of the $\pi 3/2^-[301]$ and $\pi 5/2^-[303]$ configurations, as seen in ^{109}Tc. Moreover, similar to what was observed in ^{109}Tc, a proper reproduction of negative-parity excitations in ^{107}Tc requires a significant lowering of the γ parameter, as compared to the calculation of positive-parity levels. This effect may have a similar explanation to the one proposed for ^{109}Tc.

C. Possible oblate configurations in ^{109}Tc

A specific prediction of Ref. [7] is that at neutron number $N = 66$ the low-lying, $\nu(9/2[514] \otimes 1/2[420])_{5^-}$, two-neutron excitation, corresponding to a well-deformed oblate shape, should appear. In the ^{109}Tc$_{66}$ nucleus we have found a three-quasiparticle (3-qp) excitation at 1749.5 keV with spin $15/2^-$. Similar 3-qp configurations are also observed in the neutron-rich rhodium isotopes [4,40]. The 3-qp band in ^{111}Rh has been interpreted in Ref. [40] as being due to the $g_{9/2}$ proton and a pair of $h_{11/2}$ and $g_{7/2}$ neutrons. We note that the 1749.5-keV band in ^{109}Tc differs from that in ^{111}Rh. Its excitation energy is about 400 keV lower than in ^{111}Rh, and its spin of 15/2 is also lower than in ^{111}Rh.

In the odd-A Mo isotopes of the $A \sim 110$ region the $3/2^+[411]$, $5/2^+[413]$, $5/2^-[532]$, and $7/2^-[523]$ orbitals are near the Fermi surface [30,41,44]. Therefore, around neutron number $N = 66$ the $\nu(5/2^+[402], 5/2^-[532])_{5^-}$ and $\nu(3/2^+[411], 7/2^-[525])_{5^-}$ two-quasiparticle *prolate* configurations may be expected. These 2-qp configurations coupled to the $\pi 5/2^+[422]$ odd proton could explain the 1749.5-keV band head in ^{109}Tc$_{66}$. However, the total-Routhian-surface (TRS) calculations performed in Ref. [7] suggest that no prolate multiquasiparticle configurations should be present in heavy Mo, Ru, and Pd isotopes. Instead, they predict that the oblate $\nu(9/2[514], 1/2[420])_{5^-}$ neutron configuration should produce a well-deformed, low-energy $K^\pi = 5^-$ state in the $N = 66$ isotones, which may be isomeric due to its high $K = 5$ number. In ^{109}Tc this $K = 5$ oblate neutron coupling could produce the $\{\pi 5/2^+[422] \otimes \nu(9/2[514], 1/2[420])_{5^-}\}_{15/2^-}$ configuration that explains the 1749.5-keV level.

We note that the $\nu(9/2[514], 1/2[420])_{5^-}$ two-quasiparticle oblate structure proposed in Ref. [7] should not have high alignment because the high-j, $\nu 9/2[514]$ orbital has little alignment. In Fig. 17 we show the total angular momentum alignment I_x for the $15/2^-$ band in ^{109}Tc. Relative to the ^{108}Mo core nucleus, there is $5\hbar$ more alignment in this band than in the $5/2^+$ ground-state band. This result favors the $\nu(5/2^+[402], 5/2^-[532])_{5^-}$ two-quasiparticle *prolate* configuration, which may produce such high alignment. We propose that this configuration coupled to the $\pi 5/2^+[422]$ ground-state configuration forms the $15/2^-$ band in ^{109}Tc. The expectation of Ref. [7] that such high-K levels should be isomeric is not fulfilled in ^{109}Tc because the 1749.5-keV level can decay to the 1440.7-keV level with $K = 13/2$.

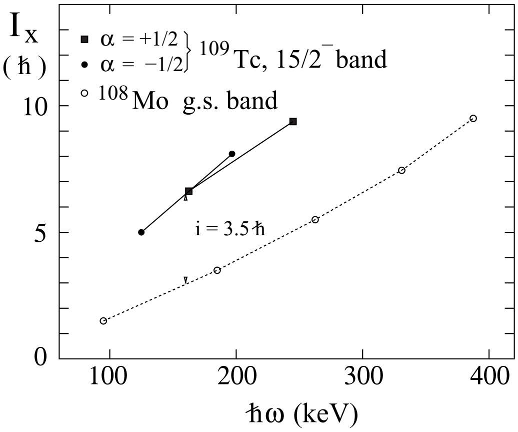

FIG. 17. Total angular momentum alignment I_x for the $15/2^-$ band in ^{109}Tc (both signatures) compared to the alignment in the ^{108}Mo core nucleus.

Furthermore, the presence of the $5/2^-[303]$ band close to the Fermi level is in favor of a prolate deformation in this region because around $N = 66$ such a configuration is not expected near the Fermi level on the oblate side. We also note that in our calculations for the positive-parity yrast levels in ^{107}Tc and ^{109}Tc, a prolate triaxial deformation has been assumed.

To summarize, the present work provides prevailing evidence for prolate configurations in ^{109}Tc. It is possible, however, that some properties of the $9/2^+_2$ and $13/2^+_2$ levels, which cannot be explained assuming prolate deformation, indicate a change toward an oblate shape. We have shown that such a change may be in progress in the ^{110}Mo nucleus at $N = 68$ [45]. More studies are needed to verify the nature of the $9/2^+_2$, $13/2^+_2$, and $15/2^-$ 1749.8-keV levels in ^{109}Tc. Finally, let us mention that mixing of both prolate and oblate shapes is also being considered to explain properties of neutron-rich nuclei in the $A = 110$ region [46], and, consequently, pure oblate-deformed states may not appear in these nuclei.

IV. SUMMARY

Excited levels in the ^{109}Tc nucleus, populated in spontaneous fission of ^{248}Cm, have been studied by measuring prompt γ rays following fission, using the EUROGAM2 array. In ^{109}Tc we have found a new band corresponding to the $\pi 5/2^-[303]$ configuration, located within 30 keV of the previously reported $5/2^+$ ground state. There are some arguments that the new $5/2^-$ level is an excited level rather than a new ground state in ^{109}Tc. In ^{109}Tc we have also found a three-quasiparticle band based on the 1749.5-keV level with spin $I^\pi = 15/2^-$. This high-K band decays promptly to a new $K = 13/2$ level at 1440.7 keV, interpreted as the two-γ vibration coupled to the $5/2^+$ ground state. The QPRM calculations performed in this work show that the odd-proton configurations observed in ^{107}Tc and ^{109}Tc correspond to excitations in a prolate, triaxially deformed potential, although some properties of the $9/2^+_2$ and $13/2^+_2$ levels in ^{109}Tc may indicate a change toward an oblate shape in this nucleus.

A significant difference has been observed between the degree of the triaxiality in the positive- and negative-parity excitations in ^{109}Tc (^{107}Tc), calculated with $\gamma = 23^\circ$ and $\gamma = 19^\circ$, respectively ($\gamma = 22^\circ$ and $\gamma = 18^\circ$, respectively). This large difference may indicate blocking of the formation of the triaxial shape when the odd proton occupies negative-parity orbitals in these nuclei. Another conclusion from our work is that the positive-parity excitations in ^{107}Tc and ^{109}Tc correspond to a triaxial band based on the $5/2^+[422]$ orbital, rather than the $7/2^+[413]$ orbital, as claimed in other works.

ACKNOWLEDGMENTS

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