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# First identification of rotational bands in $^{103}$Tc: Evolution of intrinsic proton states of the $^{97-105}_{43}$Tc isotopes

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**Abstract.** High-spin states of $^{103}_{43}$Tc have been identified for the first time, this nucleus being produced as fission fragment following the fusion reaction $^{37}$Cl + $^{176}$Yb at 170 MeV bombarding energy. The high-spin level scheme has been built from the prompt gamma rays detected using the Euroball III array. It exhibits similarities with those of the neighbouring isotopes and isotones. All the band head configurations observed in the $^{97-105}$Tc isotopes are identified from the behaviour of the rotational bands built on them. The single-proton states located around the Fermi level are discussed as a function of deformation of these nuclei.

**PACS.** 21.60.Ev Collective models – 23.20.Lv Gamma transitions and level energies – 25.85.Ge Charged-particle-induced fission – 27.60.+j $90 \leq A \leq 149$

## 1 Introduction

The level structure of the odd-$Z$ nuclei lying near the stability line for $39 \leq Z \leq 43$ is mainly governed by the $N = 50$ closed shell imposing spherical shapes. The proton active states are then restricted to the two subshells $\pi p_{1/2}$ and $\pi g_{9/2}$. Therefore these nuclei cannot provide information regarding the whole sequence of proton states. On the other hand, experimental results on the neutron-rich side of these odd-$Z$ isotopic series can be used with benefit. Thanks to the deformation of these nuclei, mainly driven by their neutron number ($N \sim 60$), the proton Fermi levels are located among orbits originating from various subshells, coming from either below the $Z = 38$ gap or above the $Z = 50$ gap. That could give indication on the relative location of the individual proton states, which can be then compared to different theoretical predictions allowing us to estimate their validity.

It is worth noting that most of the theoretical approaches aim to describe the properties of whole isotopic series, from the more neutron-rich nuclei towards the proton drip line. Therefore having obtained confidence in some theoretical calculations, we could predict more precisely the behaviour of the neutron-deficient nuclei of these isotopic series, which are arduous to produce and to study nowadays. A lot of shape coexistence and rapid shape transitions are predicted near the proton drip-line. Some of them have been identified from the early experimental results [1,2]. The existence of the involved gaps is determined by the exact location of individual nuclear states, which, in turn, strongly depends on the parametrization of the potential (when using modified-oscillator or Woods-Saxon potentials, see for instance [3]) or those of the effective force (when using self-consistent approaches, see for instance [4]). As a matter of fact, a new result has been

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recently obtained in the $N = Z$ nucleus $^{86}_{43}$Tc produced by the projectile fragmentation of a $^{92}$Mo primary beam at 60 MeV/nucleon [5]. An isomeric state, $\tau = 1.6 \pm 0.3\ \mu$s, has been measured through its decay towards the ground state. The two-quasiparticle configuration associated to this isomeric state could have been a stringent test of the various models. Unfortunately the experimental values of spin and parity are out of reach at present.

We report here new experimental results obtained in $^{103}_{43}$Tc. Since the usual (Heavy Ions, $xn\gamma$) fusion reactions cannot be used to produce neutron-rich nuclei, it has been populated as fragment of binary fission induced by heavy ions. Such a mechanism produces a lot of neutron-rich nuclei at high spin. Some of our recent results have been already published, particularly properties of the high-spin structures observed in neighbouring odd-$Z$ nuclei, $^{101}_{43}$Tc [6] and $^{107,109}_{45}$Rh [7].

The $^{103}$Tc high-spin level scheme, established for the first time, resembles those of neighbouring isotopes and isotones. From the comparison of the behaviour of their different rotational bands, the single-proton states located around the Fermi level can be now identified unambiguously in the deformed $^{101\text{-}105}_{43}$Tc isotopes. Preliminary results of this work have been reported in [8,9].

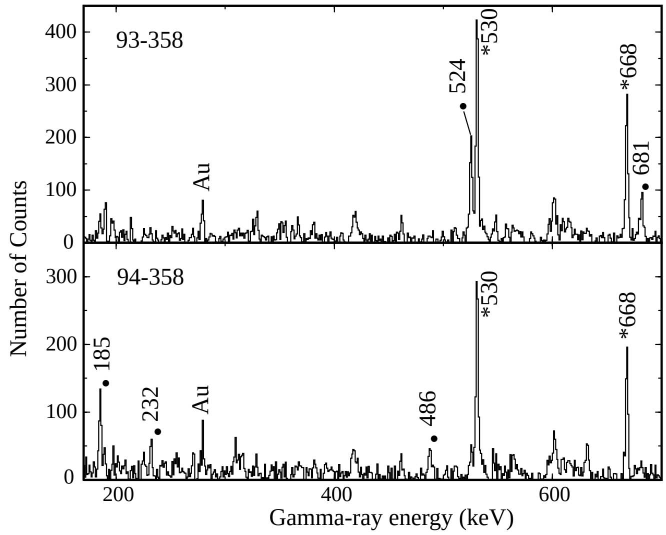


**Fig. 1.** Spectra of $\gamma$-rays in double coincidence with one transition of $^{104}$Ru (358 keV) and one transition of $^{103}$Tc (93 or 94 keV), built from the data obtained in the fusion-fission reaction $^{37}$Cl (170 MeV) + $^{176}$Yb. The transitions marked with $*$ belong to $^{104}$Ru and those with $\bullet$ are assigned to $^{103}$Tc.

## 2 Experimental procedures and analysis

The $^{99\text{-}105}$Tc isotopes have been produced as fission fragments of francium isotopes obtained in the fusion reaction $^{37}$Cl+$^{176}$Yb at 170 MeV beam energy. The beam was provided by the Legnaro XTU Tandem accelerator. A 1.5 mg/cm$^2$ target of $^{176}$Yb was used, onto which a backing of 15 mg/cm$^2$ Au had been evaporated in order to stop the recoiling nuclei. The prompt $\gamma$-rays were detected with the EUROBALL III array [10]. For this experiment, the array contained 25 large-volume coaxial detectors positioned at forward angles with respect to the beam axis, 26 four-element "clover" detectors, arranged in two rings close to 90° to the beam direction, and 14 seven-element "cluster" detectors positioned at backward angles. The data were recorded in an event-by-event mode with the requirement that a minimum of four unsuppressed Ge detectors fired in prompt coincidence. A total of 882 million coincidence events were collected on tapes, out of which 483 million were three-fold, 250 million four-fold, 89 million five-fold and 23 million six-fold.

The off-line analysis consisted of both usual $\gamma$-$\gamma$ sorting and multiple-gated spectra [11]. In addition, we analysed a three-dimensional "cube" built with the software of ref. [12]. The latter technique was useful to make fast inspection of the data, which contain $\gamma$-ray cascades emitted by about 120 fission fragments as well as by many other nuclei (either from fusion-evaporation exit channels or after Coulomb excitation).

The identification of transitions depopulating high-spin levels, which are completely unknown, such as those of $^{103}$Tc, is based on the fact that the prompt $\gamma$-rays emitted by complementary fragments are detected in coincidence [13,14]. From the studies of other couples of complementary fragments observed in this experiment, we have deduced that the main complementary fragment of $^{103}$Tc is $^{104}$Ru. Therefore some unknown transitions depopulating high-spin states of $^{103}$Tc can be identified from double gates set on two transitions of $^{104}$Ru. In such spectra we have noticed the appearance of several transitions belonging to the low-energy part of the $^{103}$Tc level scheme, which is known from $\beta$-decay measurement [15]. Then spectra of $\gamma$-rays in double coincidence with one transition of $^{104}$Ru and one of these transitions of $^{103}$Tc have been investigated.

This method (illustrated in fig. 1) has allowed us to identify i) two transitions (524 and 681 keV) of the band built on the $9/2^+$ state located at 139 keV, which decays by a 93 keV transition towards the first $7/2^+$ state, and ii) three transitions (185, 232, and 486 keV) of the band built on the $5/2^-$ state located at 178 keV, which decays by a 94 keV transition towards the first $3/2^-$ state. Then these new transitions have been used for further investigations of the coincidence data. The identification of all these transitions have been confirmed by using data from our previous experiment dealing with fission of polonium nuclei [16,17] in which the complementary partners of Tc isotopes were Nb nuclei [18]. Indeed, the spectra of $\gamma$-rays in double coincidence with two transitions assigned to $^{103}$Tc also exhibit some transitions deexciting high-spin states of Nb nuclei, as shown in fig. 2.

In fission experiments, spin values could be assigned from angular correlation results [19]. The statistics of our present data was unfortunately too poor to perform such an analysis. Therefore, spin assignments are based upon i) the already known spins of the band head states [15], ii) the assumption that in yrast decays, spin values in-

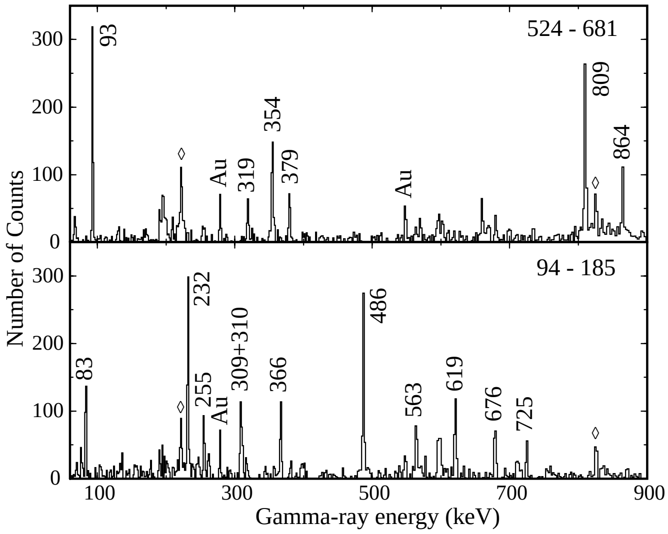


**Fig. 2.** Spectra of $\gamma$-rays in double coincidence with two transitions of $^{103}$Tc (their energies are written in the top right corner of each spectrum), built from the data obtained in the fusion-fission reaction $^{28}$Si (145 MeV) + $^{176}$Yb [16,17]. The transitions marked with ◇ belong to the Nb complementary fragments [18].

crease with excitation energy, and iii) analogy with the level structures of the lighter Tc isotopes [20–25,6].

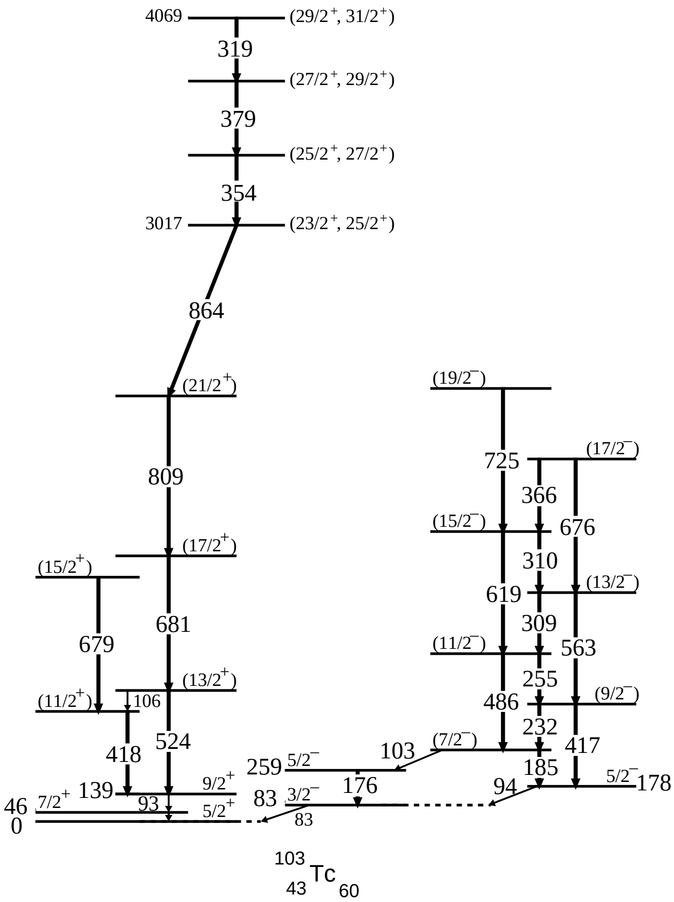


**Fig. 3.** High-spin level scheme of $^{103}$Tc, obtained as a fission fragment in the fusion $^{37}$Cl+$^{176}$Yb reaction at 170 MeV beam energy. The spin and parity values of excited states established from stripping reaction measurements [27] are given without parentheses. All the levels with spin and parity values given with parentheses are identified for the first time.

## 3 Experimental results

Several Tc isotopes ($^{99\text{-}105}$Tc) are populated in the fusion-fission reaction used in this work, the maximum of the yields is centered around $A = 102$. Therefore the statistics is larger for $^{101,103}$Tc as compared to the two other odd-$A$ isotopes $^{99,105}$Tc. All the high-spin states of $^{99}$Tc, previously studied by means of ($^{6}$Li,3n$\gamma$) reaction up to spin (25/2) [23], have been observed in this experiment. As for $^{101}$Tc, this work has given the same results as those obtained in our previous experiment, in which new rotational structures had been identified between 2.5 and 4 MeV excitation energy [6]. The high-spin level scheme of $^{105}$Tc, which has been observed in this work up to 2 MeV excitation energy, confirms the one recently published from a study of spontaneous fission using a $^{252}$Cf source [26].

The present work has allowed us to identify, for the first time, the high-spin states of $^{103}$Tc. The high-spin level scheme of $^{103}$Tc, built from the analysis of all the coincidence relationships observed in our data set, is drawn in fig. 3.

The positive-parity band, related to the triplet of states located very close in energy ($5/2^+$ ground state, $7/2^+$ state at 46 keV, $9/2^+$ state at 139 keV) is identified up to spin (21/2) and is crossed by another structure which extends up to 4 MeV excitation energy, as observed in $^{101}$Tc [6]. It is worth noting the existence of two transitions having very close energies (679 and 681 keV) in the low-energy part of the yrast positive-parity band. This has been clearly observed in the spectra of $\gamma$-rays in double coincidence with 93 and 524 keV transitions on the one hand and with 93 and 418 keV transitions on the other hand: while the peak at 681 keV is narrow in the former spectrum, it is very large in the latter one, since it includes a new contribution at lower energy.

Another branch develops above 3017 keV excitation energy. It is made of three transitions having similar energies, the order of this cascade has been determined from the relative intensities of the three $\gamma$-rays.

The rotational band built on the $5/2^-$ state located at 178 keV excitation energy, is characterized by a signature splitting which increases with the spin value. The lowest states of this structure ($7/2^-$ and $5/2^-$) decay towards two other negative-parity states, $5/2^-$ at 259 keV and $3/2^-$ at 83 keV, respectively.

## 4 Discussion

The $^{103}$Tc isotope, with $N = 60$, is at the border of the $A \sim 100$ deformed region. The shape transition, which oc-

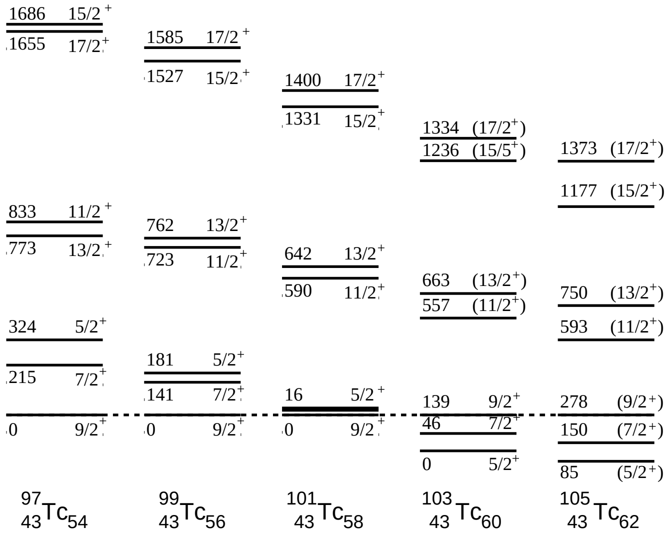


**Fig. 4.** Evolution of the yrast positive-parity states in Tc isotopes: $^{97}$Tc ([20–22]) $^{99}$Tc ([23–25]) $^{101}$Tc ([6]) $^{103}$Tc (this work) $^{105}$Tc ([26]). The energies of the $9/2^+$ states have been taken as a reference.

curs as neutrons are added beyond $N = 58$, has been well studied in the even-even nuclei: it is extremely sharp for $Z \leq 40$, while it becomes more soft for $Z > 42$, because of the appearance of triaxiality. The behaviour of the odd-$Z$ isotopes is less known. In these cases, the evolution of the shapes has to be studied as a function of the occupied proton orbit. Indeed the proton orbits which are the closest to the Fermi level depend on the nuclear shapes. Conversely the study of the behaviour of the excited states of several nuclei of one isotopic series allows us to identify shape variations as a function of the neutron number. In experiments dealing with yrast states such as that done in this work, it can happen that the behaviour of one particular proton orbit could not be followed from the lightest to the heaviest isotopes under study, as pointed out below.

### 4.1 Positive-parity band

The evolution of the yrast positive-parity states in Tc isotopes is presented in fig. 4. First of all, $^{97}$Tc exhibits the typical behaviour of the weak-coupling scheme: the $11/2^+$ and $13/2^+$ levels form a doublet, very close in energy to the $2_1^+$ state of the core $^{96}$Mo (778 keV); it is the same for the $15/2^+$ and $17/2^+$ levels as compared to the $4_1^+$ state of the core (1628 keV). Then the excited states of heavier Tc isotopes evolve towards the strong-coupling scheme which is observed in $^{105}$Tc whilst a large signature splitting remains. This means that the proton Fermi level, which is close to the low-$\Omega$ ($1/2^+$ and $3/2^+$) of the $\pi g_{9/2}$ subshell for $^{97}$Tc with low deformation, comes near the $5/2^+$ of the $\pi g_{9/2}$ subshell for $^{103\text{-}105}$Tc, having a larger deformation. One can notice that $^{103}$Tc is the first isotope showing the regular order of the first states of the rotational band, even though the staggering remains very large.

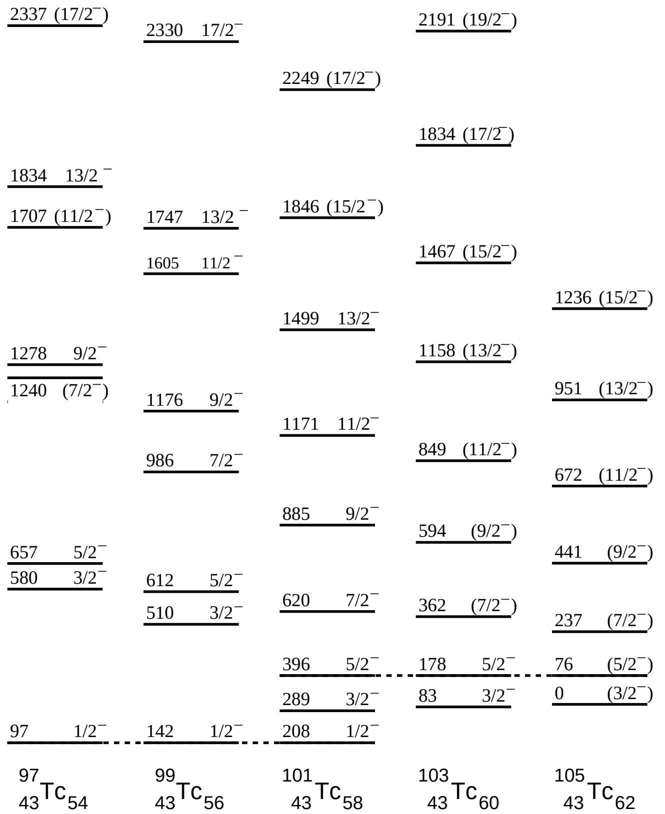


**Fig. 5.** Evolution of the yrast negative-parity states in Tc isotopes: $^{97}$Tc ([20–22]) $^{99}$Tc ([23–25]) $^{101}$Tc ([6]) $^{103}$Tc (this work) $^{105}$Tc ([26]). The energies of the $5/2^-$ states of $^{103,105}$Tc have been adjusted to the one of $^{101}$Tc.

### 4.2 Negative-parity bands

The behaviour of the yrast negative-parity bands observed in $^{97\text{-}105}$Tc nuclei (see fig. 5) reveals a clear-cut change between $^{97\text{-}99}$Tc and $^{101\text{-}105}$Tc. The value of the decoupling parameter of the $\pi 1/2^-[301]$ orbit from the $p_{1/2}$ subshell, $a \sim 1$, explains the large signature splitting observed in $^{97\text{-}99}$Tc. On the other hand, no signature splitting can be noticed in the yrast states of $^{101}$Tc, even though the first state has the same spin value ($I = 1/2$) as the one of lighter isotopes. The new structures identified for the first time in $^{103}$Tc allow us to present a comprehensive analysis of the yrast negative-parity states of $^{101\text{-}105}$Tc isotopes, as explained now.

Two negative-parity intrinsic states have been identified in the low-energy part of the level schemes of two very deformed neighbouring $N = 60$ isotones, $^{101}_{41}$Nb [28] and $^{99}_{39}$Y [29], namely the $3/2^-[301]$ issued from $p_{3/2}$ subshell and $5/2^-[303]$ issued from $f_{5/2}$ subshell. In $^{101}_{41}$Nb, the two band-head states are nearly degenerated (their excitation energies are 205.7 and 208.4 keV, respectively), and the values of the two moments of inertia are very close [28]. Higher spin states of this nucleus have been recently populated from spontaneous fission of $^{252}$Cf [30], the rotational band built on $3/2^-[301]$ is now known up to spin $(11/2^-)$ while the one built on $5/2^-[303]$, being yrast, has been

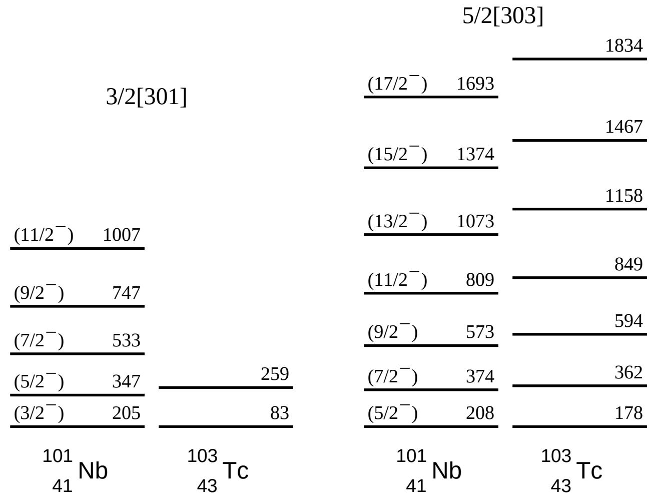


**Fig. 6.** Comparison of the negative-parity bands observed in the two $N = 60$ isotones, $^{101}$Nb ([28,30]) and $^{103}$Tc (this work).

extended up to spin (21/2$^-$). The comparison of the rotational states built on these two band heads in $^{101}_{41}$Nb and the excited states observed in this work for its neighbouring isotone $^{103}_{43}$Tc is drawn in fig. 6. This leads to the identification of proton configurations in $^{103}$Tc, the 3/2$^-$ state located at 83 keV as the 3/2$^-$[301] orbital and the 5/2$^-$ state located at 178 keV as the 5/2$^-$[303] orbital.

In fig. 5, the energies of the $5/2^-_1$ states of $^{103,105}$Tc have been adjusted to the one of $^{101}$Tc. With such a shift, the resulting drawing clearly demonstrates that the excited states of $^{101}$Tc strongly resemble the ones of the heavier isotopes. Therefore, it can be concluded that the rotational band built on the 5/2$^-$[303] orbit forms the negative-parity yrast states of the three heaviest isotopes, $^{101,103,105}$Tc.

As for the first negative-parity state of $^{101}$Tc located at 208 keV excitation energy (see fig. 5), it can be identified as the 1/2$^-$[301] configuration, as in $^{97,99}$Tc. Some non-yrast levels populated by means of ($^3$He, pn$\gamma$) reaction [31] could be proposed as the first excited states built on the 1/2$^-$[301]. Namely the 3/2$^-$ level at 616 keV, the 5/2$^-$ at 676 keV, the 7/2$^-$ at 1191 keV, and the (9/2$^-$) at 1279 keV exhibit the expected sequence in relative excitation energy.

Moreover the $3/2^-_1$ state in $^{101,105}$Tc (located at 289 and 0 keV, respectively, see fig. 5) would correspond to the 3/2$^-$[301] configuration, as the 83 keV state of $^{103}$Tc. It is worth noting that the identification of the second member of the 3/2$^-$[301] rotational band in $^{103}$Tc (the $5/2^-_2$ level at 259 keV, see figs. 3 and 6) has been a clue for all the identifications presented here: up to now the *whole* yrast negative-parity band of $^{105}$Tc was interpreted as rotational band directly built on the 3/2$^-$[301] band head [26].

Figure 7 displays the first members of the rotational bands built on the negative-parity configurations in $^{101,103,105}$Tc. The bands built on the 1/2$^-$[301] and 3/2$^-$[301] configurations comprise the first *non-yrast* excited states populated by ($^3$He, pn$\gamma$) reaction for $^{101}$Tc [31] and by beta decay for $^{105}$Tc [15].

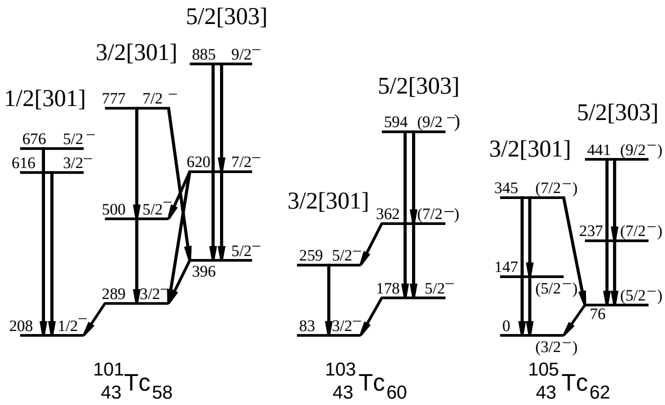


**Fig. 7.** Comparison of the negative-parity bands which can be proposed from observed excited states in $^{101}$Tc ([31]), $^{103}$Tc (this work), and $^{105}$Tc ([15]).

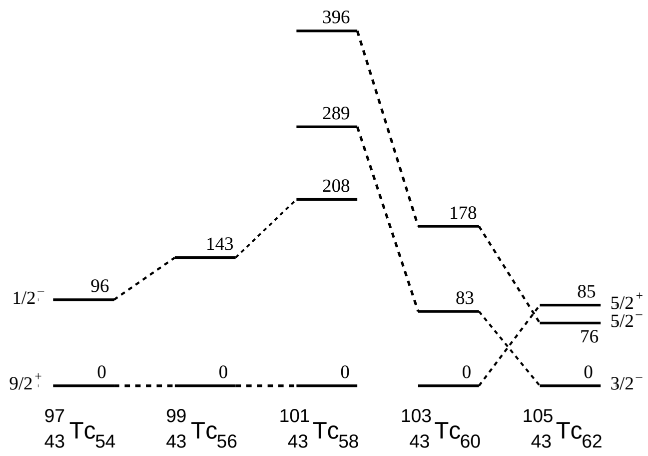


**Fig. 8.** Evolution of the individual proton states as a function of neutron number in the odd-$A$ $^{97\text{-}105}$Tc.

### 4.3 Intrinsic-proton states in $^{97\text{-}105}$Tc

The systematics of all the proton intrinsic states identified in the odd-$A$ $^{97\text{-}105}$Tc nuclei thanks to the collective motion built on them, is presented in fig. 8. This shows clearly the large changes of the location of the $Z = 43$ Fermi level with the neutron number. They are mainly due to variations of the nuclear shape (which also induce changes in the behaviour of the collective excited states) but also to changes of the relative location of the proton orbits in the nuclear potential which varies with the number of neutrons.

## 5 Conclusion

Several Tc isotopes have been produced as fission fragments following the fusion reaction $^{37}$Cl + $^{176}$Yb at

170 MeV bombarding energy; prompt gamma rays emitted in the reaction were detected using the Euroball III array. High-spin states of $^{103}$Tc have been identified for the first time, thanks to its $\gamma$-ray cascades detected in coincidence with those emitted by its main complementary fragment. The $^{103}$Tc high-spin level scheme exhibits similarities with those of neighbouring isotopes and isotones. The proton intrinsic states of $^{101\text{-}105}$Tc have been identified from the properties of the collective motion built on them.

From such results obtained not only in $_{43}$Tc isotopes but also in other odd-$Z$ neighbouring nuclei (such as $_{41}$Nb [30,18], $_{45}$Rh [7], and $_{47}$Ag [32]), the evolution of the individual proton states can be mapped as functions of the location of the Fermi level and of the nuclear deformation. Such a work is in progress and the results will be compared to different approaches aiming to predict the properties of neutron-rich nuclei in the $A \sim 100$ mass region. This will also provide crucial tests about predictions on some $N = Z$ nuclei with $A \sim 80$–90.

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