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G. Simpson,[1] J. Genevey,[1] J.A. Pinston,[1] U. Köster,[2]
R. Orlandi,[3] A. Scherillo,[4] and I. A. Tsekhanovich[5]

[1]Laboratoire de Physique Subatomique et de Cosmologie, IN2P3-CNRS/Université Joseph Fourier, F-38026 Grenoble Cedex, France

[2]Institut Laue-Langevin, B.P. 156, F-38042 Grenoble Cedex 9, France

[3]INFN, Laboratori Nazionali di Legnaro, Legnaro, Italy

[4]Rutherford Appleton Laboratory, Chilton, Didcot OX11 0QX, United Kingdom

[5]University of Manchester, Manchester M13 9PL, United Kingdom

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Abstract

The already detailed study of ^{107}Tc nucleus was complemented by a search for microsecond isomers at very low energy. For this purpose, this neutron-rich nucleus was produced by thermal-neutron-induced fission of ^{241}Pu. We have found a new 30.1 keV microsecond isomeric state which deexcites to the ground state by a strongly-hindered $E1$ transition. This isomer was identified as the $3/2^+$ level of the $1/2^+[431]$ intruder band in ^{107}Tc and is also the lowest-lying member of the band. The very low energy of the band head suggests a large quadrupole deformation. From a comparison with ^{105}Tc, where more information is known about the intruder band, it is deduced that the $1/2^+[431]$ band has a quadrupole deformation, $\epsilon_2 \geq 0.35$ and a possible triaxial shape, $\gamma \approx 20°$.

I. INTRODUCTION

For odd-proton nuclei below $Z = 50$, it was shown that the $d_{5/2}$ and $g_{7/2}$ subshells intrude across the $Z = 50$ shell closure, giving rise to a $1/2^+$ band. This $1/2^+$ intruder band is present across a broad region extending from indium to rhodium isotopes and the band members can be traced from ^{107}In to ^{121}In [1–3], from ^{105}Ag to ^{115}Ag [2, 4–6] and from ^{103}Rh to ^{113}Rh [5, 7–9]. This intruder band coexists with normal states which are rather spherical or slightly deformed in indium and silver isotopes, or more deformed levels in rhodium nuclei. Attemps to describe the intruder bands as a single deformed band based on $1/2^+[431]$ Nilsson orbital have been made [2]. However, unrealistic decoupling parameters had to be assumed in order to reproduce the experimental energy sequence of levels in the spherical region [2]. In contrast, Bauchet [6] and Venkova *et al.* [7] have correctely reproduced the experimental signature splitting of the of the $1/2^+$ band in ^{107}Rh, in the framework of the particle-rotor model, assuming deformations $\epsilon_2 \approx 0.28, \gamma = 23°$.

Recently, the intruder band was also observed in ^{105}Tc and ^{107}Tc isotopes [6, 10]. However, while the two signatures of the band were observed in ^{105}Tc, only the $3/2^+, 7/2^+, 11/2^+$... sequence of levels was observed in ^{107}Tc. Moreover, no transitions connecting the band to other bands or the ground state are observed. In our work, we have searched for possible links of this band with the already known level scheme of ^{107}Tc. For this purpose, this nucleus has been produced through thermal-neutron-induced fission reaction of a ^{241}Pu target, at the ILL reactor in Grenoble. In this case, the LOHENGRIN mass spectrometer was used to look for μs isomers, and to measure delayed γ-rays and conversion electrons deexciting these isomers.

We have found that the intruder band is based on a 30.1 keV isomer which feeds the $3/2^-$-ground state of ^{107}Tc by a strongly-hindered single $E1$ transition. The quadrupole and triaxial deformations of the intruder band in ^{105}Tc and ^{107}Tc will be also discussed.

II. EXPERIMENTAL PROCEDURES AND THE RESULTS

Microsecond isomers were investigated in the mass chain A=107 at the ILL reactor in Grenoble. These nuclei were produced by thermal-neutron-induced fission, using a thin target of about 280 μg/cm^2 of ^{241}Pu. The LOHENGRIN mass spectrometer was used to

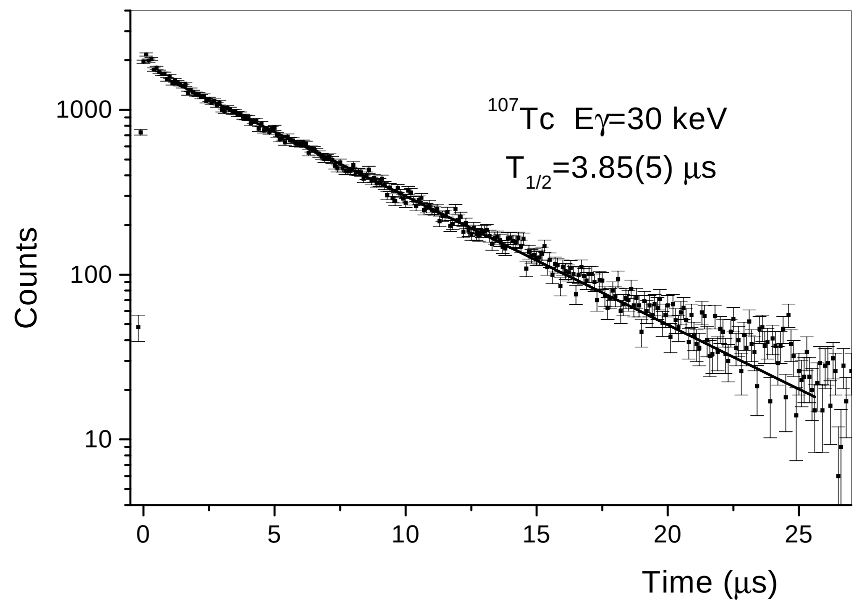

FIG. 1: Time spectrum of the 30.1 keV γ line in ^{107}Tc measured with the Clover detectors.

separate the fission fragments (FFs) recoiling from the target, according to their mass to ionic charge ratios (A/q). Two different setups were used. In the first one the FFs were detected in a gas detector of 13 cm active length, and subsequently stopped in a thin 12 μm Mylar foil. Behind the foil, two cooled adjacent Si(Li) detectors covering an area 2×6 cm^2 were placed to detect the conversion electrons and X-rays, while the γ-rays were detected by two 60 % Ge detectors placed perpendicular to the beam. This setup allows conversion electrons to be detected down to low energy (15 keV) and allows γ-electron coincidences to be obtained. Details on this experimental setup can be found in [11].

In the second setup the FFs were detected in an ionization chamber filled with isobutane at a pressure of 47 mb. This ionization chamber has good nuclear charge (Z) identification. It consists of two active regions of gas $\Delta E1$ and $\Delta E2$, separated by a grid, which are 9 cm and 6 cm long, respectively. This system is able to identify the nuclear charge in the Z≈40 region, with a resolution ($FWHM$) of about two units. The γ rays deexciting the isomeric states were detected by two Clover detectors [12]. These detectors were placed perpendicular to the ion beam in a tightly packed geometry, possible because the ionization chamber was only 6 cm thick. The total efficiency for the γ-ray detection was 20 % and 4 % for photons

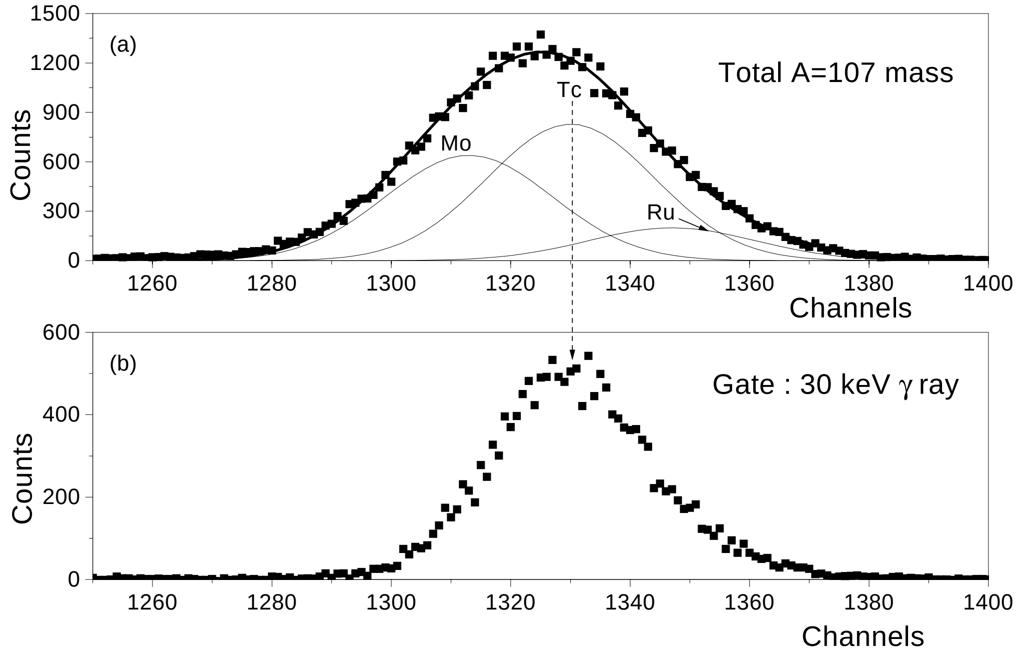

FIG. 2: Comparison of the energy lost by the FFs of mass $A = 107$ in the first region of gas of the ionization chamber:(a) without any coincidence conditions, (b) in coincidence with the 30.1 keV transition. It is clear from this figure that the 30.1 keV transition belongs to Tc.

of 100 keV and 1 MeV, respectively. More details on this experimental setup can be found in [13].

With this setup a new μs isomer deexciting by a single γ ray of 30.1 keV has been observed in coincidence with ions of A=107. Based on the time spectrum of the isomer, shown in Fig. 1, a half-life value of 3.85(5) μs was determined. The assignment of the isomer to the atomic number Z=43 was confirmed by the measurement of the energy loss of the ions in the first stage of the ionization chamber. The energy loss was measured in coincidence with the γ ray deexciting the 30.1 keV isomer. This energy loss can be compared with the energy loss of the whole yield distribution of mass A=107 from the reaction ^{241}Pu(n$_{th}$, F) [14], which was also measured. The comparison shown in Fig. 2 allows an unambiguous nuclear charge identification.

The delayed spectrum obtained from the Si(Li) detector is shown in Fig. 3. One gamma line at 30.1 keV and two K-X rays of Tc are observed. In addition, the L-electron line of the 30.1 keV transition is also seen. However, this low-energy line of 27 keV is broad and

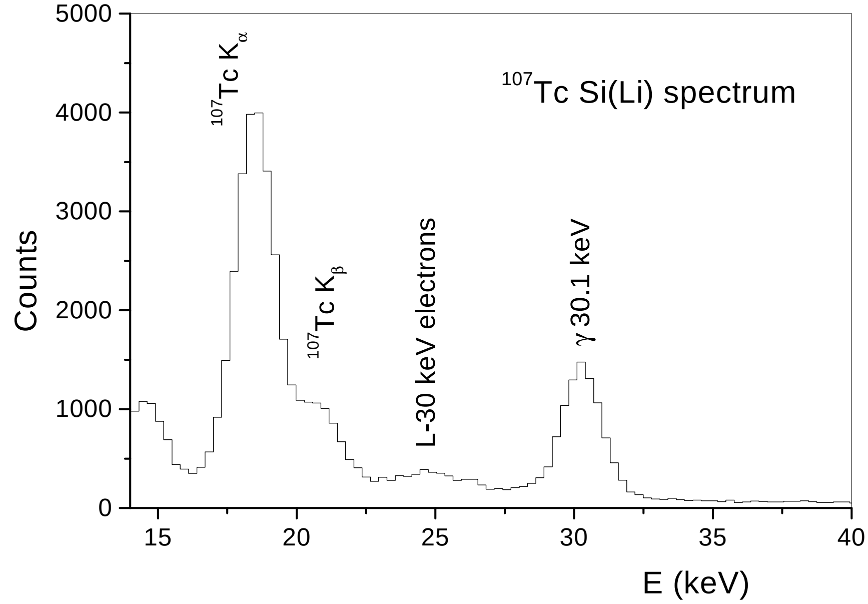

FIG. 3: Si(Li) spectrum obtained in delayed coincidence with the incident ions of ^{107}Tc. The γ ray and a weak L-conversion component of the 30.1 keV transition, and the X rays of Tc are observed.

its low energy tail extends into the X-ray group. From the ratio of the X-rays (corrected for the $\varpi_K = 0.782$ yield) over γ-ray intensities it is possible to extract a conversion coefficient $\alpha_K = 3.52(15)$ for the 30.1 keV transition. This value is consistent with the theoretical $\alpha_K = 3.45$ intensity expected for a pure $E1$ transition.

III. NATURE OF THE 30.1 KEV ISOMER

At this point of the discussion, one may conclude that a new isomer of 30.1 keV energy and $E1$ multipolarity has been observed in the ^{107}Tc nucleus. This transition is strongly hindered ($F_W = 1.70(15) \times 10^6$). For $Z = 43$ ^{107}Tc, the single-proton orbitals expected near the Fermi level, are $3/2^-[301]$(0 keV), $3/2^-[301]$(46 keV), $5/2^+[422]$(66 keV), and the $1/2^+[431]$(unknown) intruder [10, 15]. All these bands have been observed and their band-head energies are also reported in parenthesis after the Nilssson configuration assignment. For simplicity, we have used the notation used for axial nuclei, although this nucleus was found to be non axial [10], with a triaxal deformation $\gamma = 22.5°$, on the prolate side. However, no transitions connecting the $1/2^+[431]$ levels in ^{107}Tc to other bands or to the

TABLE I: Calculated values of the $J_i^\pi = 5/2^+$ to $J_f^\pi = 1/2^+$ and $J_f^\pi = 3/2$ gamma half lives, for the $1/2^+[431]$ band of ^{105}Tc. Comparison with the measurements is given.

$J_i^\pi \to J_f^\pi$	$\epsilon_2 = 0.33, \gamma = 0°$	$\epsilon_2 = 0.35, \gamma = 19°$	Experiment
$5/2^+ \to 1/2^+$	388 ps	390 ps	396(55) ps
$5/2^+ \to 3/2^+$	186 ps	627 ps	719(150) ps

ground state were observed in the past. Luo *et al.* [10] have concluded that these linking transitions are too low in energy to be observed with any reasonable efficiency in their experiment or that the $3/2^+$ band head decays out with a lifetime longer than 1 μs. Bauchet [6] has suggested that this band could be built on the ground state of ^{107}Tc. Our new data strongly suggest that the $3/2^+$ state of the $1/2^+[431]$ intruder band is the 3.85 μs isomer, on which the favored signature is built. This assertion is supported by a comparison with the ^{105}Tc nucleus [10]. In this nucleus, the $3/2^+$ band head of the $1/2^+[431]$ band at 304.0 keV partially decays by an $E1$ transition to the $3/2^-$ ground state. A half life $T_{1/2} = 6.8(10)$ ns was previouly reported for the 304 keV level and a partial half life $T_{1/2} = 20.2(47)$ ns may be deduced for the 304 keV transition [16]. From these data it is possible to deduce a hindrance factor ($F_W = 1.9(4) \times 10^6$) which is comparable to the value found for ^{107}Tc, $F_W = 1.70(15) \times 10^6$. It is worth noting that highly-retarded $E1$ transitions ($F_W = 2 - 30 \times 10^6$) which depopulate the $J^\pi = 1/2^+, 3/2^+$ of the intruder band to the $J^\pi = 3/2^-, 1/2^-$ states are characteristic of the decay-out of the $1/2^+[431]$ band, in the whole region extending from Tc to In [2].

IV. DEFORMATIONS OF THE $1/2^+$[431] BAND IN ^{105}TC AND ^{107}TC

To estimate the deformation of the intruder band in ^{107}Tc we have first reanalyzed ^{105}Tc where more information is available. In contrast to ^{107}Tc the two signatures of the $1/2^+[431]$ band are known in ^{105}Tc and a half life $T_{1/2} = 175(6)$ ps was previously reported [16] for the $5/2^+$ level at 530.2 keV. We have made use of these data to deduce the deformations of this band. For this purpose, the partial half lives $T_{1/2} = 396(55)$ ps and $T_{1/2} = 719(150)$ ps were deduced for the $5/2^+ \to 1/2^+$ and $5/2^+ \to 3/2^+$ intra-band transtions deexciting the $5/2^+$ level at 530.2 keV, respectively, knowing the previously measured branching ratios.

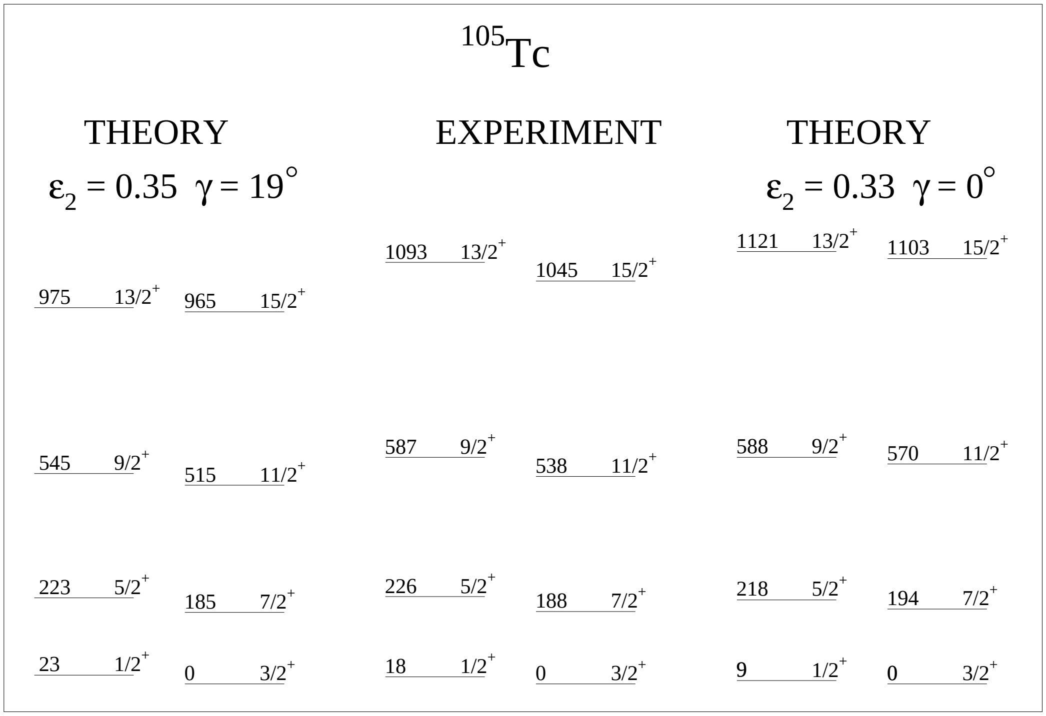

FIG. 4: Comparison of the experimental low-energy states of the intruder band in ^{105}Tc with particle-rotor model predictions. A symmetric and an asymmetric shape are assumed in the calculations. The experimental and theoretical band-head energies are normalized to 0 keV.

The excited states of the $1/2^+[431]$ band were also calculated using the rigid triaxial-rotor-plus-particle ASYRMO code. The details of the model can be found in Ref. [17, 18]. We have observed that the standard parameters [18] used for the $N = 4$ proton shell, $\kappa_4 = 0.065$ and $\mu_4 = 0.57$, were not able to reproduce the signature splitting of the intruder band. It is worth noting that large discrepancies between experiment and theory were also reported by Luo *et al.* [10]. However, Bauchet [6] has shown that the agreement with theory can be improved by introducing the parameters $\kappa_4 = 0.065$ and $\mu_4 = 0.45$ to reproduce the energy splitting of the intruder band in ^{109}Rh. These parameters were chosen to correctly reproduce the energy difference of about 400 keV measured between the $g_{7/2}$ and $d_{5/2}$ sub-shells, for spherical nuclei. The other parameters entering in the level calculations are pairing introduced via a standard BCS calculation, the deformation parameters ϵ_2 and γ, the constant inertia parameter, a, of the band and it is possible to reduce the strength of the Coriolis force by an attenuation factor ξ. The best fit to reproduce simultaneously the experimental energy levels of the band and the partial half life of the $5/2^+ \rightarrow 1/2^+$ transition is obtained for $\epsilon_2 = 0.33(2)$, assuming an axially symmetric shape, and $\epsilon_2 = 0.35(2)$ and $\gamma = 19^\circ$ assuming an asymmetric shape. The other fitting parameters a= 22.5 keV and ξ=0.7 are kept unchanged throughout the calculation. Finally, the $M1$ transition strengths are computed with a collective g-factor value of the core, $g_R = Z/A$, and an effective value of the free neutron g factor, $g_s^{eff} = 0.7 \times g_s^{free}$. Figure 4 shows that the experimental levels of the intruder band are both equally well reproduced assuming a symmetric or an asymmetric shape. In Table I, the partial half lives of the $5/2^+ \rightarrow 1/2^+$ and $5/2^+ \rightarrow 3/2^+$ transitions of the intruder band are reported and compared to the experimental values. The theoretical deformations are fitted to obtain a half life comparable to the experimental value for the $E2$, $5/2^+ \rightarrow 1/2^+$ transition. For the comparison of the half lives with experiment, the experimental energies were used in place of the theoretical ones in the calculations. From Table I, it is worth noting that the $5/2^+ \rightarrow 3/2^+$ transition is only correctly reproduced when the hypothesis of triaxial deformation is used. We have verified that changes of the g_R value do not change significantly the calculated half-life value. Consequently, the calculation strongly suggests that the intruder band has deformations $\epsilon_2 \approx 0.35$ and $\gamma \approx 19^\circ$. This quadrupole deformation value is very likely the strongest deformation in the mass $A = 100$ region.

The $1/2^+[431]$ intruder orbital is very strongly prolate deformation driving and thus we would expect that the maximum quadrupole deformation coincides with the minimum excitation energy, for a chain of isotopes. This assertion is consistent with the observation of minimum excitation energy of the band-head intruder near the mid-point of the neutron shell, at $N = 64$ for Tc and Rh, $N = 66$ for Ag and $N \approx 68$ for In. The excitation energy of the $3/2^+$ band head of the intruder band is 274 keV lower in ^{107}Tc than in ^{105}Tc. This result suggests that ^{107}Tc is very likely still more deformed than ^{105}Tc. This result agrees also with a Hartree-Fock-Bogolioubov + blocking calculation of Bauchet [6] which predicts that the intruder band in ^{107}Tc is the most deformed of the technecium isotopes and that its band head has the minimum excitation energy. A triaxial shape is also expected, by analogy with ^{105}Tc. It is worth noting that the quadrupole deformation increases almost linearly from Ag to Tc : $\epsilon_2 = 0.23$ for ^{115}Ag [4], $\epsilon_2 = 0.29$ for ^{109}Rh [5] and $\epsilon_2 \approx 0.35$ for ^{105,107}Tc. These three nuclei are close to the minimum excitation energy in each isotopic chain.

V. CONCLUSIONS

We have found a new 30.1 keV microsecond isomer in ^{107}Tc, which decays to the $3/2^-$ ground state by a strongly hindered $E1$ transition. This state is identified as the bandhead of the $1/2^+[431]$ intruder band. It is the lowest excitation energy ever observed for the intruder bandhead in the indium to technecium region. This low energy suggests a large quadrupole deformation. From a comparison with ^{105}Tc, where more information is known about this band, it is deduced that the $1/2^+[431]$ band has a quadrupole deformation, $\epsilon_2 \geq 0.35$ and a possible triaxial shape, $\gamma \approx 19°$. Consequently, it is very likely the most deformed band in the whole $A = 100$ region. Finally, the analysis of the band in the framework of the particle-model has shown that the intruder band in ^{105}Tc is well described as a deformed band based on the $1/2^+[431]$ orbital

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