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Short note

High-spin states in the ^{96}Tc nucleus

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Abstract. High-spin states in the ^{96}Tc nucleus have been studied with the reactions ^{82}Se(^{19}F,5nγ) at 68 MeV and Zn(^{36}S,αpxn) at 130 MeV. Two γ-ray cascades (irregular bandlike structures) have been observed up to an excitation energy of about 10 MeV and spin 21-22$\hbar$.

PACS. 21.10.Pc Single particle levels and strength functions – 23.20.Lv Gamma transitions and level energies – 27.60.+j $90 \leq A \leq 149$

1 Introduction

The doubly odd nuclei with $Z < 50$ and $A \approx 100$ have low-energy configurations where the odd proton occupies orbitals situated below the $Z = 50$ shell gap and the odd neutron in orbitals situated above the $N = 50$ shell gap. The transitional nuclei in this region are usually γ-soft and have rather small quadrupole deformations at low and moderate spin. Thus, they have complex level structures, often characterized by coexisting spherical and deformed shapes. In addition, studies of their high-spin states may provide information on their terminating structures, which were predicted yrast in many of these nuclei [1], and also found experimentally during the last years [2,3]. For nuclei near closed shells, with few nucleons outside closed shell configuration, the spin of the terminating configuration is not so high. States with higher spins, which can be made by promoting nucleons from the "inert" core into the higher shells, are easily accessible through fusion-evaporation reactions induced by heavy ions.

One of the odd-odd nuclei from this region for which not much is known about the higher-spin states is ^{96}Tc. With three protons in the $p_{1/2}$, $g_{9/2}$ shells and three neutrons in the $d_{5/2}$, $g_{7/2}$ shells (outside the doubly quasi-magic ^{90}Zr core), the terminating state of this basic configuration is $I^{\pi} = 19^{+}$. ^{96}Tc nucleus was rather thoroughly studied in the low-spin region via the (p,n) [4–6], (d,2n) [7] and (^{3}He,d) [8] reactions, while higher-spin states were studied with the (α,n) reaction [9–11] and recently with a heavy-ion reaction [12]. The present study reports results of two in-beam γ-ray spectroscopy experiments with heavy-ion induced reactions which extend the present knowledge of the structure of ^{96}Tc at high spins.

2 Experimental techniques and results

The first reaction used was ^{82}Se(^{19}F,5nγ) performed with a 68 MeV ^{19}F beam at the tandem Van de Graaff accelerator in Bucharest. The target was Se (94% enriched in ^{82}Se) of 5 mg/cm^2 vacuum evaporated on a 2 mg/cm^2 Au foil. γ-γ and neutron-γ coincidences were measured with two intrinsic Ge detectors of 20% efficiency and a 1 litre NE213 scintillator detector. Gamma-ray angular distributions were also measured both in the singles and neutron-coincident modes.

Secondly, ^{96}Tc has been reached through the reactions of a ^{36}S beam of 130 MeV delivered by the Strasbourg Vivitron accelerator, with a stack of two self-supported 0.44 mg/cm^2 Zn targets having the following composition: ^{70}Zn - 69.70%, ^{68}Zn - 13.16%, ^{67}Zn - 1.64%, and ^{66}Zn - 7.31%. The reactions on ^{70}Zn were used to study a num-

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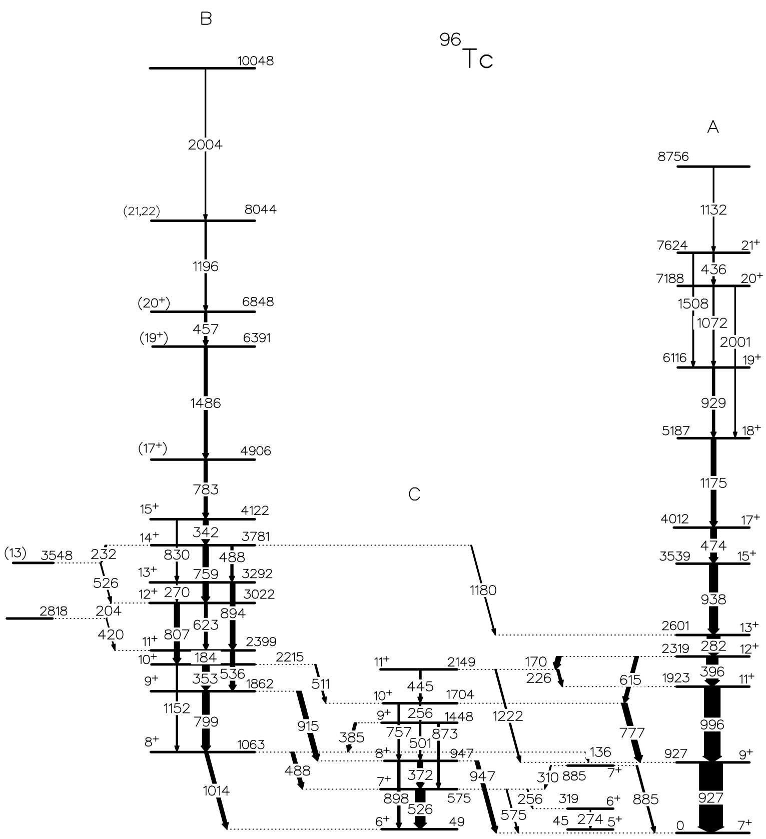

Fig. 1. Level scheme of ^{96}Tc established in the present work. Energies are given in keV. The intensities of the transitions are proportional to the widths of the arrows.

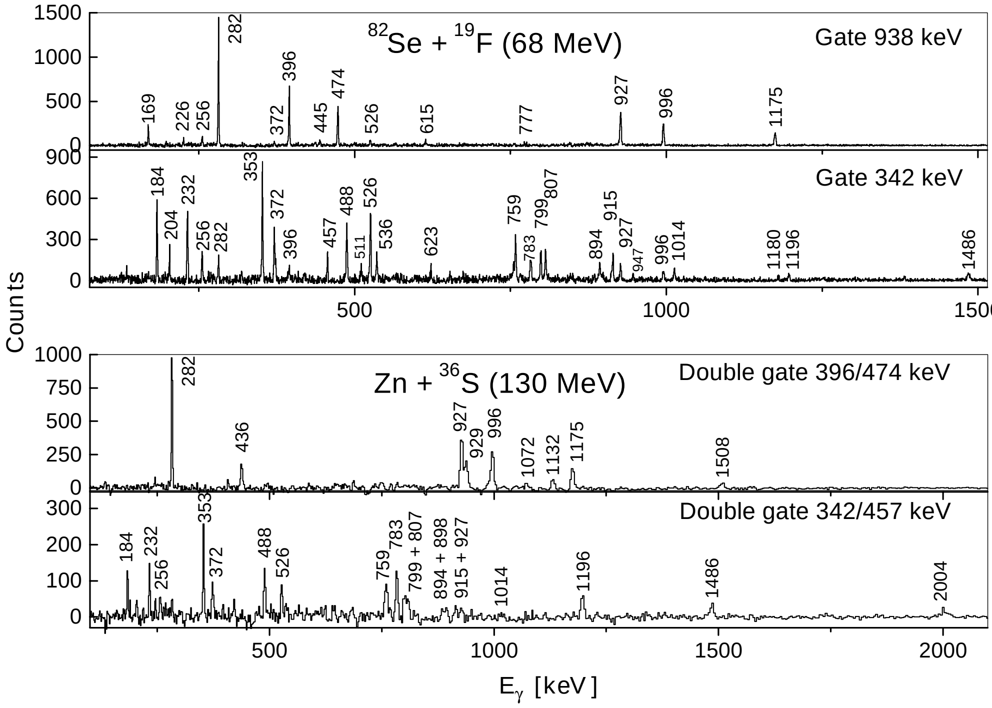

Fig. 2. Examples of gated spectra from the two experiments.

Table 1. Gamma-ray transitions in ^{96}Tc from the ^{82}Se(^{19}F,5nγ) reaction at 68 MeV. Intensities, Legendre polynomial coefficients of the γ-ray angular distributions and DCO ratios are given. Unless specified, R_{DCO} are determined by gating on dipole transitions. For close doublets (256.0+256, 487.7+488.1, 525.9+526.0), these quantities are given for both transitions taken together. When angular distribution coefficients are not given, I_γ was determined from the 55° spectrum.

E_γ (keV)	I_γ (rel. units)	a_2/a_0	a_4/a_0	R_{DCO}	Assignment E_i (keV)	E_f (keV)	$J_i^{\pi_i} \to J_f^{\pi_f}$
135.7	2.7(3)				1063	927	$8^+ \to 9^+$
169.7	19.7(7)	−0.074(6)	−0.062(7)	1.05(7)	2319	2149	$12^+ \to 11^+$
183.6	13.6(5)	−0.214(5)	−0.060(7)	0.79(18)	2399	2215	$11^+ \to 10^+$
203.8	2.3(4)				3022	2818	$12^+ \to$
226.0	10.2(3)	0.096(51)	0.004(67)		2149	1923	$11^+ \to 11^+$
232.4	7.9(3)	−0.096(64)	−0.099(84)	0.79(18)	3781	3548	$14^+ \to (13)$
256.0	16.8(5)	−0.020(5)	−0.069(7)	1.78(40)	1704	1448	$10^+ \to 9^+$
256	”	”	”	”	575	319	$7^+ \to 6^+$
270	0.90(24)	−0.28(16)	0.12(22)		3292	3022	$13^+ \to 12^+$
282.3	55.7(4)	−0.152(11)	−0.023(15)	0.46(2)[a]	2601	2319	$13^+ \to 12^+$
341.7	22.1(7)	−0.214(5)	0.016(7)	1.00(18)	4122	3781	$15^+ \to 14^+$
352.7	28.7(3)	−0.122(22)	−0.005(28)	1.09(21)	2215	1862	$10^+ \to 9^+$
372.0	21.8(6)	−0.028(27)	−0.011(35)	0.97(7)	947	575	$8^+ \to 7^+$
385.3	10.7(6)	0.311(47)	−0.053(67)		1448	1063	$9^+ \to 8^+$
395.8	49.7(4)	−0.086(13)	0.000(17)	0.57(3)[a]	2319	1923	$12^+ \to 11^+$
419.5	2.6(5)				2818	2399	$\to 11^+$
444.9	7.9(3)	−0.40(8)	0.28(10)		2149	1704	$11^+ \to 10^+$
457.1	10.3(5)	−0.313(5)	0.011(7)	1.14(20)	6848	6391	$(20^+) \to (19^+)$
473.7	25.5(3)	0.339(24)	−0.077(30)	1.04(6)[a]	4012	3539	$17^+ \to 15^+$
487.7	24.2(7)	−0.114(40)	0.010(61)	1.16(8)	3781	3292	$14^+ \to 13^+$
488.1	”	”	”	”	1063	575	$8^+ \to 7^+$
500.9	5.9(6)	−0.20(11)	−0.06(15)		1448	947	$9^+ \to 8^+$
510.8	∼6				2215	1704	$10^+ \to 10^+$
525.9	43.7(6)	−0.272(22)	−0.037(28)	0.92(8)	3548	3022	$(13) \to 12^+$
526.0	”	”	”	”	575	49	$7^+ \to 6^+$
536.3	19.1(12)	0.315(58)	−0.145(76)	2.34(88)	2399	1862	$11^+ \to 9^+$
575.0	4.2(5)	1.1(3)	0.4(3)		575	0	$7^+ \to 7^+$
614.6	15.2(6)	0.79(11)	0.00(14)		2319	1704	$12^+ \to 10^+$
623.2	12.2(15)	0.70(13)	−0.25(17)	0.95(26)	3022	2399	$12^+ \to 11^+$
757.3	7.9(9)	0.25(9)	−0.31(13)		1704	947	$10^+ \to 8^+$
758.8	23.8(7)	0.241(6)	−0.052(7)	1.73(31)	3781	3022	$14^+ \to 12^+$
777.0	23.6(5)	0.311(39)	−0.008(51)		1704	927	$10^+ \to 9^+$
783.2	14.1(5)	0.262(6)	−0.038(8)	1.50(42)	4906	4122	$(17^+) \to 15^+$
799.3	28.9(9)	−0.107(63)	−0.054(79)	1.21(18)	1862	1063	$9^+ \to 8^+$
807.0	22.2(6)	0.422(60)	−0.135(69)	1.80(34)	3022	2215	$12^+ \to 10^+$
830.0	4.7(10)	0.19(18)	−0.15(25)		4122	3292	$15^+ \to 13^+$
872.8	7.5(4)	0.48(11)	0.16(13)		1448	575	$9^+ \to 7^+$
885.1	6.9(4)	0.57(11)	−0.27(14)		885	0	$7^+ \to 7^+$
893.7	20.7(4)	0.263(40)	−0.118(53)	1.67(18)	3292	2399	$13^+ \to 11^+$
898.0	10.1(5)	0.36(10)	−0.14(13)		947	49	$8^+ \to 6^+$
914.9	20.3(5)	−0.263(43)	−0.058(56)	0.97(10)	1862	947	$9^+ \to 8^+$
927.1	100.0(5)	0.361(13)	−0.103(17)		927	0	$9^+ \to 7^+$
929.2	10.1(4)	0.094(68)	0.008(88)		6116	5187	$19^+ \to 18^+$
937.8	35.5(4)	0.408(21)	−0.141(28)	1.03(10)[a]	3539	2601	$15^+ \to 13^+$
947.0	16.2(4)	−0.026(48)	−0.200(63)		947	0	$8^+ \to 7^+$
995.8 [b]	68.2(8)	0.337(13)	−0.086(18)		1923	927	$11^+ \to 9^+$
1013.6	15.1(4)	0.47(5)	0.03(7)	1.77(35)	1063	49	$8^+ \to 6^+$
1174.9	20.8(5)	−0.318(33)	0.021(43)	0.55(11)[a]	5187	4012	$18^+ \to 17^+$
1179.5	3.8(3)	−0.25(15)	0.16(19)		3781	2601	$14^+ \to 13^+$
1152	5.7(3)	0.51(18)	−0.20(13)		2215	1063	$10^+ \to 8^+$
1196.0	6.2(4)	0.18(11)	0.09(15)	1.53(50)	8044	6848	$(21,22) \to (20^+)$
1221.9	5.6(8)	0.38(12)	−0.09(16)		2149	927	$11^+ \to 9^+$
1485.5	13.7(5)	0.250(6)	−0.113(8)	1.48(23)	6391	4906	$(19^+) \to (17^+)$

[a] DCO ratio determined by gating on a quadrupole transition.
[b] Intensity corrected for that of the 996 keV transition from ^{97}Tc ($25/2^+ \to 21/2^+$) [14].

ber of nuclei in the region $A \approx 100$ (see *e.g.*, [2,3]). The ^{96}Tc nucleus was populated via the αpn and αp3n channels of the reactions with the ^{66}Zn and ^{68}Zn components, respectively, with an intensity of $\sim 1\%$ of the ^{70}Zn + ^{36}S fusion cross-section. The γ-rays were detected with the EUROGAM II array (30 tapered coaxial Ge detectors and 24 clover detectors, all with Compton suppression shields [13]), with a trigger defined by the coincidence of at least four Compton suppressed Ge detectors.

The level scheme of ^{96}Tc, established on the basis of the two γ-γ coincidence experiments, is shown in fig. 1. The characteristics of the γ-ray transitions assigned to ^{96}Tc are listed in table 1. Gamma-ray multipolarities have been deduced from directional correlation of oriented states ratios ($R_{\mathrm{DCO}} = \frac{I_{\gamma_1}(\theta_1);\ \text{gated by } \gamma_2 \text{ at } \theta_2}{I_{\gamma_1}(\theta_2);\ \text{gated by } \gamma_2 \text{ at } \theta_1}$, with $\theta_1 = 45°$ and $\theta_2 = 90°$, respectively) and/or γ-ray angular distributions measured in the Bucharest experiment.

Our data support the level scheme at lower excitation energies established by Mach *et al.* [10,11] and provide two cascades (denoted by A and B in fig. 1) which are placed above the $I^\pi = 13^+$, 2601 keV and $I^\pi = 12^+$, 3022 keV levels, respectively.

The two cascades are seen up to the levels at 8756 keV (quasiband A) and 10048 keV (quasiband B), the highest transitions above 6116 keV in band A and 8044 keV in band B being observed only in the EUROGAM II experiment. Figure 2 shows typical γ-ray gates from the two experiments, which illustrate the two quasibands from fig. 1. Quasiband A was also reported in [12], but differs from ours through the order of the 474 and 938 keV transitions and the multipolarity of the 1175 keV transition. Transitions with the energies 589, 1199, and 1450 keV (placed in ref. [12] in the upper part of cascade A) have also been observed in the EUROGAM experiment as connected with cascade A but their placement remains uncertain.

Up to the states $I^\pi = 13^+$ at 2601 keV in quasiband A and $I^\pi = 11^+$ at 2399 keV in quasiband B, the (α,n) study of ref. [11] established unambiguously positive parity, on the basis of measurements of internal conversion coefficients and γ-ray linear polarization. For the continuation of quasiband A (fig. 1) we assume also positive parity, based on its strong population which suggests it as the yrast sequence. In quasiband B we also assume that the positive parity is kept above the 11^+ state. Due to the interweaving of dipole and quadrupole transitions, this is rather sure up to the 4122 keV state, while above that a change of parity is not excluded.

3 Discussion

The present experiments established two bandlike structures (A and B in fig. 1) which continue up to spins of the order of 21-22$\hbar$, both probably having positive parity. They are not connected with each other, with the exception of the 1180 keV transition ($14^+ \rightarrow 13^+$). A trial to understand the higher-spin states in this nucleus has been made in ref. [12], on the basis of shell model calculations. However, for this nucleus the model space used was restricted to $[\pi(p_{1/2}, g_{9/2}), \nu(d_{5/2}, s_{1/2})]$, with a ^{88}Sr core. The positive-parity yrast states could be reasonably well described only up to the 13^+ state. With the new assignments made in the present work in band A, the agreement improves also for the 15^+ state which is now at 3.54 MeV, but this state is still predicted about 0.5 MeV too high. The 17^+ state is predicted very high in energy. This could mean, first of all, the need of enlarging the basis space with other higher-lying orbitals, such as $g_{7/2}$ and $h_{11/2}$. Still, calculations performed in such an enlarged basis but using a truncation scheme were unable, for ^{94}Tc, to describe states above 11^+ and 15^-, respectively [12], which may indicate also the need of a better effective interaction. Thus, the present data on high-spin states in ^{96}Tc, together with those of other nuclei from this mass region, will be valuable in calibrating more realistic, large basis shell model calculations.

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