

COULOMB EXCITATION OF ^{99}Tc

L.-G. SVENSSON, D. G. SARANTITES[†] and A. BÄCKLIN

Uppsala University, Institute of Physics, Box 530, S-751 21 Uppsala, Sweden

Received 1 March 1976

Abstract: The nucleus ^{99}Tc has been studied in Coulomb excitation with ^4He and ^{16}O , and $\frac{13}{2}^+$ and $\frac{11}{2}^+$ states are suggested at 762.0 and 726.7 keV, respectively. Two new levels at 625.4 and 1081.4 keV were established on basis of γ - γ coincidence relations. The lifetimes of the levels at 726.7, 761.7, 762.0 and 1081.4 keV were measured by means of the Doppler shift attenuation method using ^{16}O ions and the half-lives obtained were 1.8 ± 0.2 , 0.7 ± 0.4 , 2.4 ± 0.3 and 0.9 ± 0.3 ps, respectively. With exception for the lowest $\frac{5}{2}^+$ state the level energies and reduced E2 and M1 transition probabilities are in fair agreement with the values calculated within the cluster-phonon coupling (Alaga) model.

NUCLEAR REACTIONS $^{99}\text{Tc}(\alpha, \alpha'\gamma)$, $E = 10$ MeV, $^{99}\text{Tc}(^{16}\text{O}, ^{16}\text{O}'\gamma)$, $E = 28$ –42 MeV; measured relative $\sigma(E, E_\gamma, \theta)$, $\gamma\gamma$ -coin, DSA. ^{99}Tc deduced levels, J , $T_{1/2}$, δ , $B(E2)$, $B(M1)$.

1. Introduction

The ground state in the odd mass Tc nuclei ($Z = 43$) is $\frac{9}{2}^+$, which is in accordance with the shell-model prediction for nuclei in which the $g_{7/2}$ subshell is being filled. In the simple weak-coupling picture one expects a $\frac{5}{2}^+ - \frac{13}{2}^+$ quintet of states grouped around the 2^+ excitation energy of the even core. These states may be studied in Coulomb excitation and have been observed at the end of the shell in the odd In nuclei ($1, 2$). In the middle of the $g_{7/2}$ subshell a $\frac{7}{2}^+$ state occurs at very low energy, in the Ag nuclei it is even below the lowest $\frac{9}{2}^+$ state, indicating that the coupling scheme is here more complex. In the heaviest Tc isotopes the situation is even more complicated by the fact that in addition to the $\frac{7}{2}^+$ state a $\frac{5}{2}^+$ state comes down almost to the $\frac{9}{2}^+$ ground state (3).

Various theoretical models have been considered for these nuclei. The E2 transition from the $\frac{7}{2}^+$ state to the ground state has been observed to be considerably enhanced (4 – 7). Therefore, approaches involving collective effects, such as the phonon coupling model of Goswami *et al.* ($8, 9$) involving coupling between forward- and backward-going amplitudes, the description in terms of “dressed three-quasiparticle states” by Kuriyama *et al.* ($10, 11$) or calculations involving the coupling of three-particle “clusters” to phonons ($12, 13$), seem to be more adequate than e.g. a description of the $\frac{7}{2}^+$ state as a pure three-quasiparticle state (14).

In addition to the low-lying $\frac{7}{2}^+$ state all the models mentioned predict several

[†] On sabbatical leave from Washington University, St. Louis, Missouri 63130, USA.

other positive parity states with spins up to $\frac{13}{2}^+$ in the low-energy region. Such states are also expected in a description in the deformed basis, which may not be excluded for the heaviest Tc nuclei in view of their vicinity to the deformed ^{102}Mo [ref. ¹⁵].

The nucleus ^{99}Tc is suitable for investigating low-lying positive parity states, since here they may be studied in Coulomb excitation from the $\frac{9}{2}^+$ ground state. In fact, such a study was reported in 1972 by Bond *et al.* ⁴), who, using 64 MeV ^{35}Cl ions, observed two fairly strongly excited states at 726.3 and 761.8 keV, respectively, both of which were tentatively assigned as $\frac{7}{2}^+$ or $\frac{9}{2}^+$ states. Surprisingly, no $\frac{11}{2}^+$ or $\frac{13}{2}^+$ states were observed. Quite recently such states have been observed ¹⁶) in ^{95}Tc at 882 keV ($\frac{13}{2}^+$) and 957 keV ($\frac{11}{2}^+$). Although there is a definite difference in the level structure between ^{95}Tc and ^{99}Tc in that the $\frac{7}{2}^+$ and $\frac{5}{2}^+$ states are observed at much lower energies in the latter nucleus, the higher spin states could have a low enough energy to be observable in ^{99}Tc in Coulomb excitation.

In the present paper we describe a Coulomb excitation experiment carried out under somewhat different conditions than that described in ref. ⁴). Alpha particles were used in order to get γ -ray spectra with as high resolution as possible. Using such light particles one also reduces the probability for multiple excitation, which makes it possible to interpret the γ -ray angular distributions in terms of spins and mixing ratios in a safer way. In addition, experiments were carried out with ^{16}O ions in order to obtain the level half-lives through the Doppler shift attenuation method. At variance with the experiment of ref. ⁴), in which a pressed powder target was used, a target of rolled Tc metal was used here, which makes the interpretation of the Doppler shifts in terms of level half-lives more reliable.

2. Experimental procedure

Coulomb excitation of the ^{99}Tc nucleus was performed using ^{16}O and ^4He ions from the EN tandem Van de Graaff accelerator at Uppsala University. A thick (self-supporting) 80 mg/cm² solid ^{99}Tc target was used in the lifetime, γ -ray angular distribution and the excitation yield measurements and an about 10 mg/cm² target was used in the γ - γ coincidence experiment.

All experiments, except for the γ - γ coincidence experiment, were performed in a set-up especially designed for angular distribution measurements ¹⁷). In this arrangement the target is mounted on a flat holder with a 7 mm hole. The beam position is defined by a 3 mm tube, extended through an annular surface barrier detector of 20 mm diameter, which was used for detection of back-scattered ions. A 45 cm³ Ge(Li) detector with an energy resolution of 2.2 keV FWHM at 1332 keV was mounted on a movable wagon placed on a horizontal circular table and with a mechanical centre at the target position.

The γ - γ coincidences were recorded using two Ge(Li) detectors placed at 90° to the beam in opposite positions and about 3 cm from the target. The target was mounted in a narrow target chamber with a well shielded Faraday cup at a distance

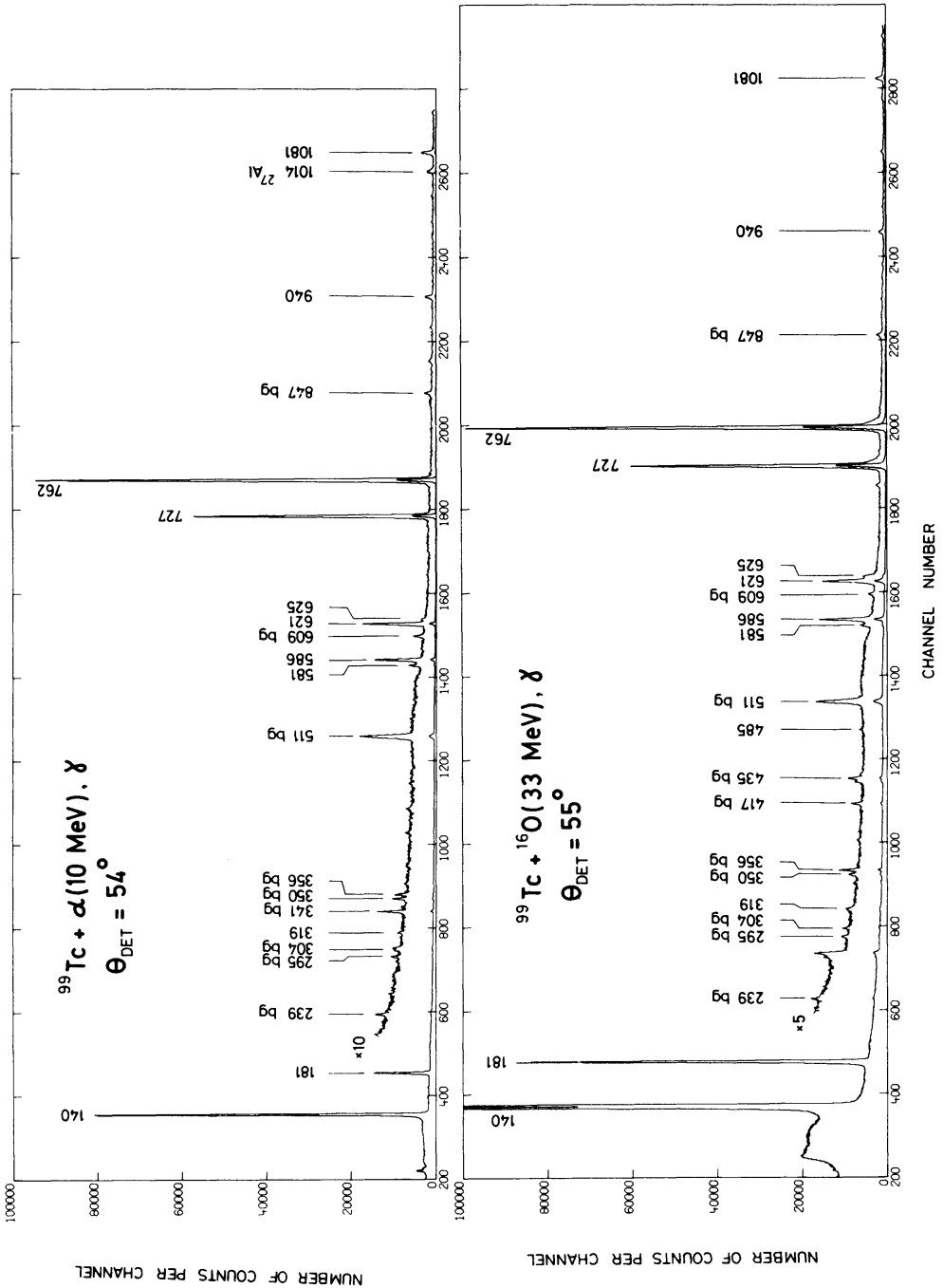


Fig. 1. Singles γ -ray spectra recorded with a $45 \text{ cm}^3 \text{ Ge(Li)}$ detector from the Coulomb excitation of ^{99}Tc with ${}^4\text{He}$ and ${}^{16}\text{O}$.

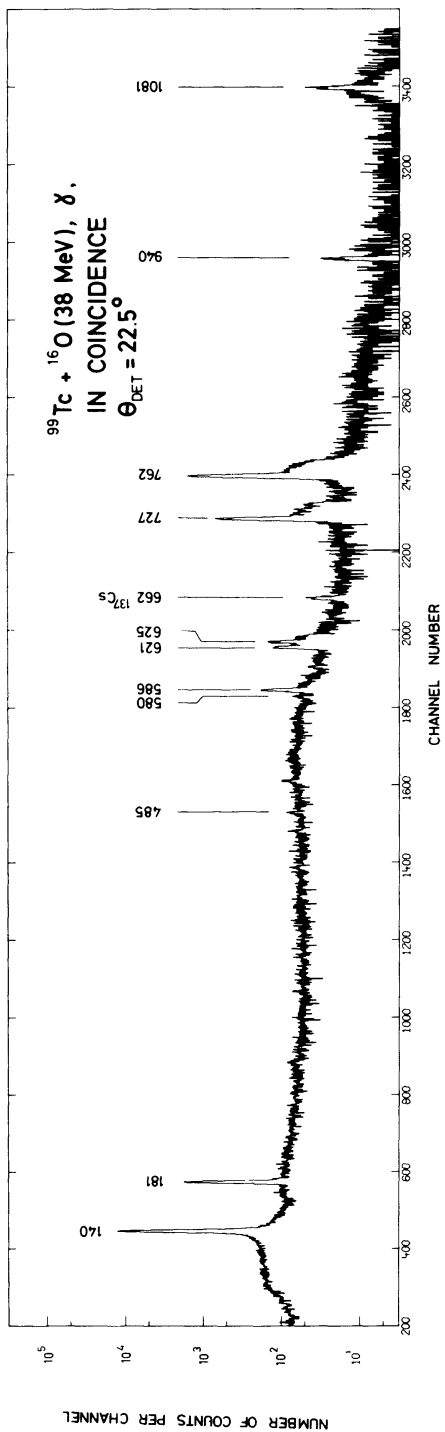


Fig. 2. The γ -ray spectrum recorded in coincidence with back-scattered ^{16}O ions with the Ge(Li) detector at 22.5° to the beam. The total number of counts is about one third of that used in the Doppler shift attenuation analysis.

of about 3 m. The coincidence system used was of conventional fast-slow type with a time-to-pulse-height converter (TPHC) and amplitude and rise-time compensating (ARC) timing circuits¹⁸). A time window about 20 ns wide was set with a single channel analyzer on the coincidence peak in the TPHC time spectrum. The lowest detectable energy for the ARC circuits was about 50 keV with the detectors used. The coincidences were recorded with a two-parameter system in pairs of events which were stored on a magnetic tape. A total of about 10^6 events were recorded. With a 250 nA beam of 33 MeV ^{16}O ions a coincidence rate of about 50 p/s with singles counting rate of about 6000 p/s in each channel was obtained. The coincidence relations obtained in this experiment are shown in the decay scheme, fig. 6.

The transition energies were deduced from singles γ -ray spectra recorded at 90° to the beam simultaneously with ^{57}Co , ^{22}Na , ^{207}Bi and ^{137}Cs radioactive sources used for internal energy calibration. This technique allows energy determination with good accuracy. The peak positions were determined with the GAMMAN¹⁹) computer program. The γ -ray intensities were calculated with the CESAR²⁰) computer program using standard radioactive γ -ray sources for efficiency calibration of the detector.

All data collection and most of the analysis of the experiments were performed with the PDP-15 on-line computer at the Tandem Laboratory.

2.1. EXCITATION YIELD AND ANGULAR DISTRIBUTION MEASUREMENTS

The experiments were performed with 10 MeV ^4He ions. The reduced transition probabilities for excitation were determined from the average γ -ray intensities calculated from the observed intensities at 55° . The thick target excitation yields were calculated relative the yield of the 181 keV level. Since the $B(E2)$ value of the 181 keV transition earlier has been determined in radioactive measurements²¹) it was possible to deduce the $B(E2)$ values for excitation of the other levels. The calculations were performed using the total conversion coefficient $\alpha = 0.145$ [ref. ²²)] for the 181 keV transition and $\alpha = 0.104$ [refs. ²³)] for the 140 keV transition. The intensity of the 41 keV transition between the 181 and 140 keV levels was determined from the ratio $I_\gamma(41)/I_\gamma(181) = 0.138$ [refs. ²³)] and $\alpha = 3.9$ [refs. ^{21, 22})].

For a thick target the excitation yield can be expressed in terms of an effective target thickness δE_2 by

$$I_{\text{ex}} = \sigma(E_0) \frac{E_0 N}{(dE/ds)_0} \frac{\delta E_2}{E_0},$$

as given by Alder *et al.*²⁴). Here σ is the excitation cross section and dE/ds is the stopping power of the target material evaluated at the bombarding energy E_0 . The reduced transition probability for excitation is related to the cross section σ according to formula (II.C.15) given by Alder *et al.*²⁴). The effective target thickness δE_2 has been obtained from figs. III.9 and III.10 in ref. ²⁴) and is expected to be certain to

TABLE I

Properties of states and transitions in ^{99}Tc observed in the Coulomb excitation with ^{16}O and ^4He ions

Level energy ^{a)} (keV)	$T_{1/2}$ (ps)	Deexciting transition ^{a)} (keV)	γ -ray intensity ^{b)}	Angular distribution coefficient ^{c)}		Assigned initial spin ^{e)} I^π
				a_2 ^{d)}	A_2^{exp}	
140.5 \pm 0.1	160 \pm 20 ^{f)}	140.5 \pm 0.1	556 \pm 40	0.175	0.139 \pm 0.030	$\frac{7}{2}^+$
181.1 \pm 0.1	3610 \pm 60 ^{f)}	181.1 \pm 0.1	72 \pm 7	0.234	0.083 \pm 0.030	$\frac{5}{2}^+$
625.4 \pm 0.1		625.4 \pm 0.1	1.6 \pm 0.2	0.666	0.117 \pm 0.050	$\frac{7}{2}^+, \frac{9}{2}^+$
		484.9 \pm 0.2	\leq 0.4			
726.7 \pm 0.1	1.8 \pm 0.2	726.7 \pm 0.1	100 \pm 5	0.719	-0.005 \pm 0.005	$\frac{11}{2}^+, (\frac{9}{2}^+)$
		586.1 \pm 0.1	15.6 \pm 0.8		0.007 \pm 0.011	
		101.3 \pm 0.2 ^{g)}				
761.7 \pm 0.1	0.7 \pm $^{0.5}_{0.3}$	761.7 ^{h)}	3.9 ^{h)}	0.743		$\frac{5}{2}^+, (\frac{7}{2}^+)$
		621.1 \pm 0.1	21.3 \pm 1.0		-0.069 \pm 0.011	
		580.7 \pm 0.1	3.5 \pm 0.3		0.050 \pm 0.040	
762.0 \pm 0.1	2.4 \pm 0.3	762.0 \pm 0.1	179 \pm 5	0.743	0.163 \pm 0.005	$\frac{13}{2}^+$
		621.5	< 4			
		580.9	< 1			
1081.4 \pm 0.1	0.9 \pm 0.3	1081.3 \pm 0.1	8.9 \pm 0.6	0.855	-0.010 \pm 0.016	$\frac{9}{2}^+, \frac{11}{2}^+$
		940.9 \pm 0.1	4.8 \pm 0.3		-0.007 \pm 0.016	
		319.2 \pm 0.2	\leq 0.6			

^{a)} The errors given in the table are the total errors obtained with an internal calibration of the energy spectrum using radioactive calibration sources.

^{b)} The relative intensities given in the table were obtained from a γ -ray spectrum recorded at an angle of 54° to a beam of 10 MeV ^4He ions.

^{c)} The angular distribution coefficients are defined in subsect. 2.1.

^{d)} The a_2 coefficients are the thick target coefficients ²⁴⁾ calculated for 10 MeV incident α -particles.

^{e)} If more than one alternative is given, the first one is regarded as most probable.

^{f)} Value given by McDonald *et al.* ²¹⁾.

^{g)} The transition was only observed in coincidence with other γ -transitions.

^{h)} The transition was not observed in the Coulomb excitation but has been seen in the ^{99}Mo decay ³¹⁾ from which the branching ratio was used to calculate the intensity of this transition.

about 2%. The $B(E2)$ values given in table 2 are those for decay, calculated by $B(E2)_d = B(E2)_{\text{ex}}(2I_0 + 1)/(2I + 1)$ where I_0 and I are the spins of the ground state, respectively.

The angular distributions were measured using the intensities of the strong 140 and 181 keV γ -rays as detected by a second Ge(Li) detector at a fixed angle for normalization. The deadtime of each ADC was recorded and correction of the normalization due to deadtime differences in the two γ -ray channels could be made. The γ -ray angular distributions were measured at seven angles from 0° to 90° in equal steps in $\cos^2 \theta$. Each γ -ray spectrum was recorded for about 30 min with a beam current of about 200 nA. During this time about 3×10^5 counts were collected in the 140 and 181 keV peaks in the reference spectrum. The measurement was repeated three times. The measured angular distributions are shown in fig. 3. The distributions were corrected for the γ -ray attenuation in the target. The corrections were about 1–5%

TABLE 2
E2/M1 mixing ratios and transition probabilities for transitions in ^{99}Tc

Level energy (keV)	Transition energy (keV)	Assigned initial spin I^π	$B(E2)\downarrow$ deduced from exc. yield ^{a)} ($e^2 \cdot b^2 \times 10^{-2}$)	δ^b	$B(E2)\downarrow^c$ ($e^2 \cdot b^2 \times 10^{-2}$)	$B(M1)\downarrow^d$ $\left(\frac{eh}{2Mc}\right)^2 \times 10^{-2}$	Theory			
							$B(E2)\downarrow^b$ ($e^2 \cdot b^2 \times 10^{-2}$)	$B(M1)^b$ $\left(\frac{eh}{2Mc}\right)^2 \times 10^{-2}$		
140.5	140.5	$\frac{7}{2}^+$	13 \pm 2	$-0.20^{+0.08}_{-0.06}$	14 \pm 2 ^{f)}	7.6 \pm 0.9	11.6	11.2	0.05	4.4
181.1	181.1	$\frac{7}{2}^+$	4.4 \pm 0.5 ^{e,f)}	∞	4.4 \pm 0.5 ^{f)}		8.0	4.0		
	40.6				16 \pm 4 ^{f)}	1.16 \pm 0.15 ^{f)}	2.4			7.1
625.4	625.4	$\frac{7}{2}^+$	0.14 \pm 0.04	-0.16 ± 0.13 $-(4.5-\infty)$			0.89			12.3
		$\frac{9}{2}^+$	0.11 \pm 0.03	$1-\infty$				3.6	0.9	0.12
	726.7	$\frac{1}{2}^+$	6.8 \pm 1.0	$-(0-\infty)$	< 13		10.5	2.1		
		$\frac{9}{2}^+$	8.1 \pm 1.2	0.55 \pm 0.05	3.2 \pm 0.4	3.8 \pm 0.4	3.6	0.9		0.12
		$\frac{7}{2}^+$	10.2 \pm 1.5	$-(2.6 \pm 0.2)$	12 \pm 1	0.64 \pm 0.11				
				0.11 \pm 0.03	0.16 \pm 0.08	4.9 \pm 0.5	0.89			12.3
				4.7 \pm 0.3	12.8 \pm 1.2	0.21 \pm 0.04				
	586.1	$\frac{11}{2}^+$		∞	6.1 \pm 0.7		0.84			
		$\frac{9}{2}^+$		-0.14 ± 0.04	0.12 \pm 0.07	1.4 \pm 0.2	1.6		38	
				> 22	≈ 6	≈ 0.003				
		$\frac{7}{2}^+$		0.54 \pm 0.08	1.4 \pm 0.3	1.1 \pm 0.2	5.0			4.0
				-4.0 ± 0.9	5.8 \pm 0.3	0.09 \pm 0.04				
			3.3 \pm 0.5		4.8 \pm 2.9		0.18			
761.7	761.7	$\frac{5}{2}^+$		-0.19 ± 0.06	2.6 \pm 2.2	19 \pm 11	3.8			43.8
	621.1	$\frac{5}{2}^+$		< -13	≈ 73	< 0.12				

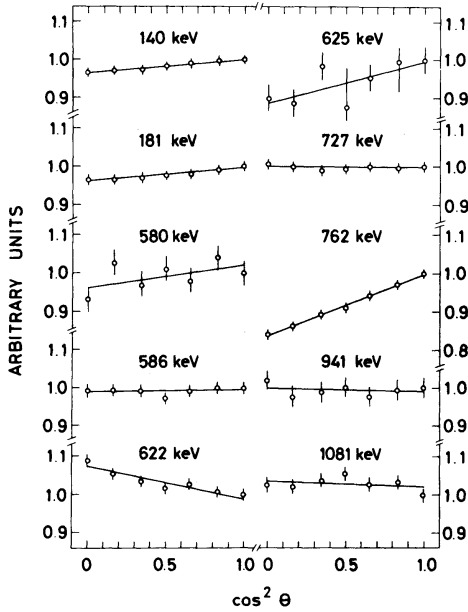


Fig. 3. The γ -ray angular distributions recorded in the Coulomb excitation of ^{99}Tc with 10 MeV α -particles. The solid curves are the least squares fits of the formula given in subsect. 2.1. Corresponding parameter values are given in table 1.

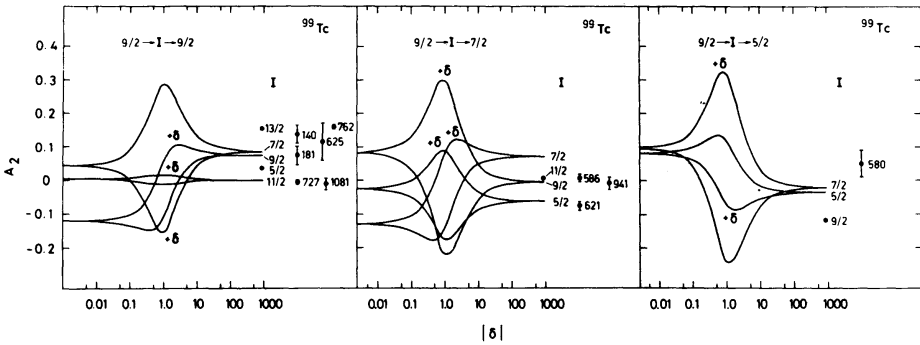


Fig. 4. The figure shows the theoretical A_2 angular distribution coefficient calculated for various excitation and deexcitation modes. The notation $\frac{9}{2} \rightarrow I \rightarrow \frac{7}{2}$ means an excitation of the nucleus from the ground state to a state with spin I which de-excites to a final state with spin $\frac{7}{2}$. The experimental A_2 coefficients are shown with error bars and marked with corresponding transition energies.

for the 140 and 181 keV transitions but almost negligibly small at transition energies higher than 500 keV.

The experimental angular distributions were analyzed by least squares fits to the relation

$$W(\theta) = 1 + a_2 Q_2 A_2 P_2(\cos \theta) + a_4 Q_4 A_4 P_4(\cos \theta),$$

where A_2 and A_4 are the angular distribution coefficients sensitive to the multipole character of the observed transition. The a_2 , a_4 and Q_2 , Q_4 factors are the thick target coefficients ²⁴⁾ and the finite angular resolution corrections, respectively. In this experiment Q_2 and Q_4 were equal to 1. Since no significant A_4 values were observed this parameter was set equal to zero in the final analysis. The a_2 values calculated for 10 MeV incident ^4He ions are given in table 1 together with the deduced A_2 coefficients. The corresponding theoretical angular distribution coefficients was calculated assuming the excitation process to be of pure E2 character and assuming the de-excitation to proceed by mixed M1 and E2 radiation. The A_2 coefficient was calculated for various values of δ^2 , the ratio between the E2 and M1 γ -rays intensities, using the tabulated angular correlation coefficients by Ferentz and Rosenweig ²⁵⁾. The sign of δ is that defined by Rose and Brink ²⁶⁾. The experimental and theoretical angular correlation coefficients are shown in fig. 4 for various possible spins of the excited states. These curves were used to determine the δ -values of the transitions (table 2) in conjunction with the spin assignments of the corresponding levels. From the δ -values and the experimental lifetimes deduced from the DSA measurements the reduced transition probabilities for several transitions were calculated (table 2).

2.2. DOPPLER SHIFT ATTENUATION MEASUREMENTS

The mean lifetimes of the 726.7, 761.7, 762.0 and 1081.4 keV levels were determined from Doppler shift attenuation (DSA) measurements of the 726.7, 621.1, 762.0 and 940.9 keV γ -rays observed in coincidence with the ^{16}O ions detected in a ring counter in the backward direction. In these measurements the γ -ray were detected at 22.5° to the beam. Two-parameter spectra were recorded and analyzed corresponding to ^{99}Tc recoiling energies in the range of 14.15 to 16.76 MeV. The line shapes of the shifted γ -rays were analyzed as described in ref. ²⁷⁾. Briefly, the energy shift of a γ -ray emitted at an angle θ_d to the beam direction from an ensemble of nuclei moving with velocity $\beta(\theta_R, t) = v(t)/c$ is given by

$$\Delta E_\gamma = E_\gamma^0 \beta(\theta_R, t) \cos \theta_c(t) \{ \cos \theta_R \cos \theta_d + \sin \theta_R \sin \theta_d \sin \phi_R \}, \quad (1)$$

where the polar angles θ_R , ϕ_R define the direction of the recoils at $t = 0$ and $\cos \theta_c(t)$ is the average collision cosine as given by Blaugrund ²⁸⁾. The fraction of decays between t and $t + dt$ that give an energy shift ΔE_γ is

$$\frac{dN(\Delta E_\gamma)}{N^0} = R(t) dt \frac{d\sigma(\theta_R)}{d\Omega} d\Omega d\phi_R W(\theta_R, \phi_R, \theta_d), \quad (2)$$

where $R(t)$ is the fraction of nuclei decaying per unit time through the state of interest at time t , $d\sigma(\theta_R)/d\Omega$ is the differential cross section for the initial emission of recoils at an angle θ_R , and $W(\theta_R, \phi_R, \theta_d)$ is the correlation function between the recoil direction and γ -ray emission. In coincidence measurements the latter two terms can be ignored. The line spectrum is obtained via eqs. (1) and (2) by allowing t , θ_R and ϕ_R to take their possible values.

In order to evaluate $\beta(\theta_R, t)$ the stopping power theory of Lindhard, Scharff and Schiøtt²⁹⁾ (LSS) as modified by Blaugrund was employed with the stopping power taken as

$$\frac{d\varepsilon}{d\rho} = f_e \left(\frac{d\varepsilon}{d\rho} \right)_e + f_n \left(\frac{d\varepsilon}{d\rho} \right)_n, \quad (3)$$

where $(d\varepsilon/d\rho)_e = k\varepsilon^{\frac{1}{2}}$ and $(d\varepsilon/d\rho)_n = \varepsilon^{\frac{1}{2}}/(0.67 + 2.07\varepsilon + 0.03\varepsilon^2)$ are the electronic and nuclear stopping powers, respectively. The quantities ε and ρ are LSS dimensionless parameters for energy and length²⁹⁾. In the present analysis the adjustment factors f_e and f_n were taken as unity. If not so, for $f_e = f_n$, correction of the deduced mean lifetimes can be made as they vary approximately as $1/f_e$.

The calculated line shapes are calculated via a program called SHAPES translated in Algol for the TRASK computer at AFI at Stockholm, and the lifetimes are varied to yield a minimum χ^2 fit to the data. The obtained line-shapes that give minimum χ^2 fits for the 726 and 762 keV γ -rays are shown in fig. 5. It is seen that the experimental line-shapes are quite well reproduced. The results for four measured transitions are summarized in table 1. The reported uncertainties include a 10 % error in order to account for possible errors in the stopping power values used.

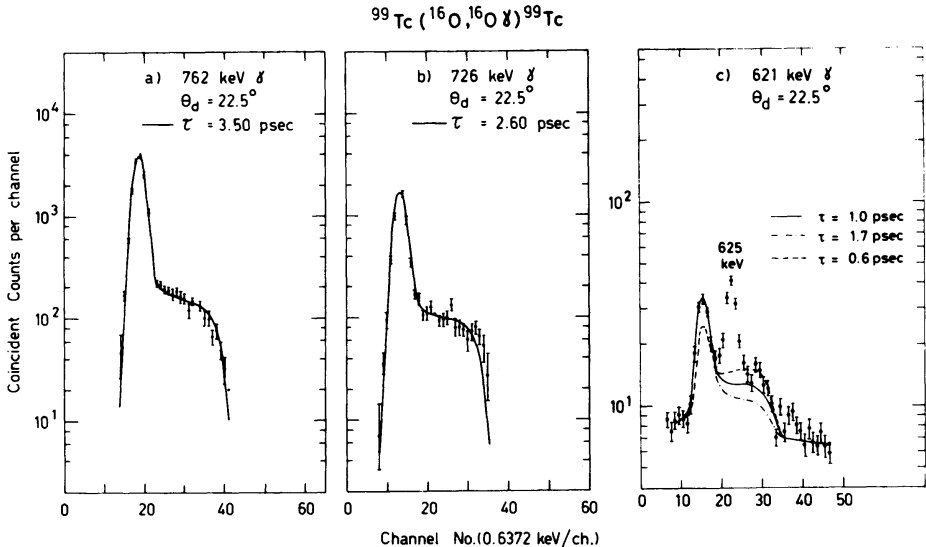


Fig. 5. Doppler shift attenuation spectra obtained in coincidence with back-scattered ^{16}O ions. The solid curves show the computed line-shapes, which are functions of the lifetime of the levels and the stopping power of the target. The details of the analysis are given in subsect. 2.2. The curve shown in (c) are the computed line-shapes of the 621 keV transition for various assumed lifetimes of the 761.7 keV level. The contribution of the 625 keV transition to the total line-shape could not be calculated since corresponding lifetime is not known. However, the shape of the Doppler distribution of the 625 keV transition, as obtained from the difference between the experimental points and the calculated profile of the 621 keV transition, is only compatible with theoretically calculated shapes if the 621 keV transition corresponds to a lifetime within the assumed limits.

The lifetimes extracted for the 726 and 762 keV transitions are appreciably larger than the previously reported τ -values of 1.1 ± 0.3 and 2.0 ± 0.5 ps, by Bond *et al.* ⁴). This is probably due to systematic errors introduced in the previous measurement from use of pressed powdered targets ⁴).

The value for the 621 keV transition was obtained as an estimate stripping of a nearby interfering γ -ray at 625 keV, see fig. 5c.

3. The level scheme of ^{99}Tc

The two lowest excited states, the $\frac{7}{2}^+$ state at 140.5 keV and the $\frac{5}{2}^+$ state at 181.1 keV are well known from earlier work ^{4, 21, 30}). In this study the level scheme as shown in fig. 6 was constructed primarily on the basis of γ -ray spectra coincident with the 140.5 and 181.1 keV transitions. Except for the 761.7 keV level the five levels observed above 0.5 MeV were different from earlier published level schemes obtained from studies of the β -decay of $\frac{1}{2}^+$ ^{99}Mo [ref. ³⁰)]. Transitions from the 726.7 keV state and the close doublet at 762 keV were observed in the earlier Coulomb excitation experiment ⁴). However, the angular distributions obtained in

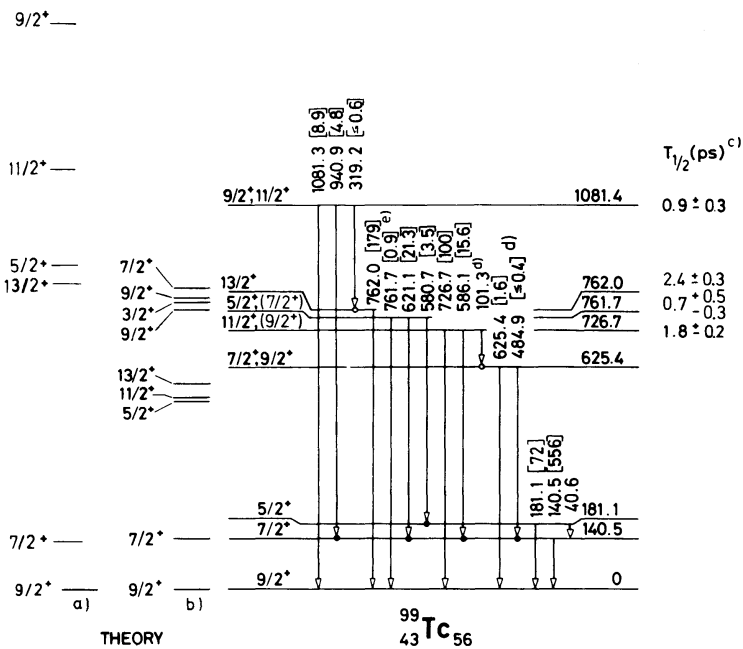


Fig. 6. The level scheme of ^{99}Tc as deduced from γ - γ coincidence relations. The coincidence relations are marked in the level scheme by rings at the end of corresponding transition. A filled ring indicate a two-way coincidence relation. The spin and parity assignments of the levels are discussed in sect. 3. Notes in the figure: (a) Theoretical level scheme as predicted by Kuriyama *et al.* ^{10, 11}). (b) Theoretical level scheme as predicted by Bargholtz ¹³). (c) Lifetimes measured by the Doppler shift attenuation method. (d) The transition was only seen in coincidence with other γ -rays. (e) Intensity calculated from branching ratio given in ref. ³¹).

the present work differ considerably from those of ref. ⁴⁾, resulting in different spin assignments.

The 625.4 keV level. This level has not been observed earlier. The A_2 value of the 625 keV transition is compatible with a spin of $\frac{7}{2}$, $\frac{9}{2}$ or $\frac{13}{2}$. However, the $\frac{13}{2}$ alternative is excluded due to the 485 keV transition to the $\frac{7}{2}^+$ level.

The 726.7 keV level. The A_2 value of the 727 keV transition gives alternative $\frac{7}{2}$, $\frac{9}{2}$ or $\frac{11}{2}$ spin for this level. The A_2 value of the 586 keV transition is also compatible with these three spin values. In view of the missing transition to the $\frac{5}{2}^+$ state the $\frac{7}{2}^+$ alternative is less likely than the other two alternatives. Additional information on the spin may be obtained from a comparison between the $B(E2)$ values of the ground-state transition obtained with the two different methods used, cf. table 2. It is immediately seen that the Coulomb excitation data and the DSA data disagree if a spin of $\frac{9}{2}$ is assumed. Neither the $\frac{7}{2}$ alternative gives a very good agreement and we therefore prefer an $\frac{11}{2}$ assignment.

The 761.7 and 762.0 keV levels. This pair of levels deserves special consideration. The 761.7 keV transition to the ground state was earlier observed in the ⁹⁹Mo decay together with the 621.1 and 580.7 keV transitions with the relative intensities 0.183, 1.0 and 0.207 [ref. ³¹⁾]. However, the 762.0 keV transition appeared much stronger in the Coulomb excitation γ -ray spectrum, which could only be explained as due to a close lying doublet. The A_2 values of the 621.1 and 580.7 keV transitions give both possible spin of $\frac{5}{2}$ or $\frac{7}{2}$ units. The comparatively weak feeding of the ground state from 761.7 keV level, as observed in ref. ³¹⁾ slightly favours the $\frac{5}{2}^+$ alternative and is in agreement with the spin suggested in the β -decay work ^{30, 31)}.

The 762.0 keV transition from the 762.0 keV level has an A_2 value which fits very well with a $\frac{13}{2}$ assignment although a $\frac{7}{2}$ value cannot be excluded. In order to investigate if the 762.0 keV level is also deexciting to the 140 and 181 keV levels an attempt was made to resolve the 621.1 and 580.7 keV lines into two possible components. Using the computer code CESAR ²⁰⁾ and interpolated line-shapes from single lines detected in the ⁴He experiment gave the upper limits for the 621.5 and 580.9 keV lines shown in table 1. These small limits indicate that the spin alternative $\frac{13}{2}^+$ is preferred to the $\frac{7}{2}^+$ alternative.

Further support for this assignment is obtained from the two values of $B(E2)$ of the 762 keV transition given in table 2. Decent agreement is obtained between the Coulomb excitation data and the DSA data if the level spin is taken as $\frac{13}{2}$, while no agreement is obtained for the $\frac{7}{2}$ alternative.

The 1081.4 keV level. This proposed new state is based on the observation of the 940.9 keV transition in coincidence with the 140.5 keV transition. The 1081.3 and 940.9 keV transitions show A_2 values which are consistent with spin of $\frac{7}{2}$, $\frac{9}{2}$ or $\frac{11}{2}$.

However, the observed transition to the 762.0 keV $\frac{13}{2}^+$ state, rules out the $\frac{7}{2}^+$ alternative.

4. Concluding remarks

In fig. 6 the experimentally observed levels in ^{99}Tc are compared with the theoretical predictions ¹³⁾ of the cluster-phonon coupling (Alaga) model (col. b). In this calculation the single particle energies in the $28 < Z < 50$ shell together with the phonon energy and quadrupole coupling strength were fitted to the negative parity states in ^{103}Rh . These parameters were then used directly with a minor correction for the difference in phonon energy for calculating the levels in ^{99}Tc . It is seen that these calculations well predict the qualitative features of the level scheme, although the energies in general are somewhat low. Also the calculations by Kuriyama *et al.* ^{10,11)} yield a number of positive parity states, essentially dressed three-quasiparticle states, with the proper spins in the 1 MeV region, although the calculated energies are generally too high (col. a). In these calculations the quadrupole force constant χ_0 was adjusted in order to reproduce the position of the first $\frac{7}{2}^+$ state assuming no coupling to the $g_{\frac{3}{2}}$ state in the shell above. Introducing mixing between the dressed three-quasiparticle states with spins $\frac{9}{2}$, $\frac{7}{2}$ and $\frac{5}{2}$ and the nearest one-quasiparticle states, i.e. the ground state and the $g_{\frac{3}{2}}$ and $d_{\frac{3}{2}}$ states in the next shell, does not in general affect the levels very much. The only exception is that the lowest $\frac{5}{2}^+$ state is lowered about 250 keV relative to the ground state, which is an effect in the right direction but not strong enough to give agreement with experiment. It is thus evident that neither this model nor the cluster-phonon coupling model is able to predict the very low energy of the first $\frac{5}{2}^+$ state. Also the electromagnetic properties of this state, table 1, deviate fairly strongly from the predicted while for the rest of the states the cluster-phonon coupling calculations ¹³⁾ in general seem to yield transition probabilities of the right order of magnitude.

The authors are grateful to Prof. A. Johansson and the staff at the Tandem Accelerator Laboratory for providing excellent working facilities. We are most obliged to Drs. L. O. Norlin and K. Johansson for the use of their carefully designed arrangement for angular distribution measurements and to Mr. R. Didriksson and Mr. L. Einarsson for making the ^{99}Tc target. One of us (D.G.S.) expresses his thanks to Prof. I. Bergström and the staff at AFI in Stockholm for a stimulating year and for support that made possible participation in this experiment. The work was financially supported by the Swedish Atomic Research Council.

References

- 1) F. S. Dietrich, B. Herskind, R. A. Naumann, R. G. Stokstad and G. E. Walker, Nucl. Phys. **A155** (1970) 209
- 2) W. Tuttle, P. H. Stelson, F. K. McGowan, W. T. Milner, S. Raman and R. L. Robinson, Bull. Am. Phys. Soc. **20** (1975) 686
- 3) Nuclear Data Group, Nuclear level schemes (Academic Press, New York, 1973)
- 4) P. D. Bond, E. C. May and S. Jha, Nucl. Phys. **A179** (1972) 389
- 5) C. Bergman, B. Svahn, L.-G. Svensson, A. Bäcklin and J. Lindskog, Nucl. Phys. **A223** (1974) 342

- 6) L.-G. Svensson, A. Bäcklin, H. Solhed and J. Lindskog, UUIP-873, University of Uppsala, Institute of Physics (1974)
- 7) L.-G. Svensson, O. Bergman, A. Bäcklin, N.-G. Jonsson and J. Lindskog, UUIP-904, University of Uppsala, Institute of Physics (1975)
- 8) A. Goswami and A. I. Sherwood, *Phys. Rev.* **161** (1967) 1232
- 9) A. Goswami and O. Nalcioglu, *Phys. Lett.* **26B** (1968) 353
- 10) A. Kuriyama, T. Marumori and K. Matsuyanagi, *Prog. Theor. Phys.* **47** (1972) 498
- 11) A. Kuriyama, T. Marumori and K. Matsuyanagi, *Prog. Theor. Phys. Suppl.* **58** (1975) 53
- 12) V. Paar, *Nucl. Phys.* **A211** (1973) 29
- 13) C. Bargholtz, USIP-Report 75-05 (1975) and private communication
- 14) L. S. Kisslinger, *Nucl. Phys.* **78** (1966) 341
- 15) E. Cheifetz, R. C. Jared, S. G. Thompson and J. B. Wilhelmy, *Phys. Rev. Lett.* **25** (1970) 38
- 16) D. G. Sarantites, *Phys. Rev.*, in press
- 17) K. Johansson and L.-O. Norlin, UUIP-866, University of Uppsala, Institute of Physics
- 18) J. Kozyczkowski and J. Bialkowski, to be published
- 19) B. Nyman, *Nucl. Instr.* **108** (1973) 237
- 20) L.-G. Svensson, CESAR, a computer routine for energy and intensity analysis of complex energy spectra, TLU 31/75, Tandem Laboratory, Uppsala
- 21) J. McDonald, A. Bäcklin and S. G. Malmkog, *Nucl. Phys.* **A162** (1971) 365
- 22) R. S. Hager and E. C. Seitzer, *Nucl. Data Tables* **A4** (1968) 1
- 23) C. W. E. Van Eijk, B. Van Nooijen, F. Schutte, S. M. Brahmavar, J. H. Hamilton and J. J. Pinajian, *Nucl. Phys.* **A121** (1968) 440
- 24) K. Alder and A. Winther, *Coulomb excitation* (Academic Press, New York and London, 1966)
- 25) M. Ferentz and N. Rosenweig, Table of *F*-coefficients, ANL-5324, Argonne National Laboratory, Lemont, Illinois
- 26) H. J. Rose and D. M. Brink, *Rev. Mod. Phys.* **39** (1967) 306
- 27) E. J. Hoffman, D. M. Van Patter, D. G. Sarantites and J. H. Barker, *Nucl. Instr.* **109** (1973) 3
- 28) A. E. Blaugrund, *Nucl. Phys.* **88** (1966) 501
- 29) L. Lindhard, M. Scharff and H. E. Schiott, *Mat. Fys. Medd. Dan. Vid. Selsk.* **33** (1963) no. 14
- 30) W. B. Cook, L. Schellenberg and M. W. Johns, *Nucl. Phys.* **A139** (1969) 277
- 31) R. L. Meyer, private communication and UCRL Report 76 207