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Lifetimes of states in ^{97}Tc

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The Doppler-shift-attenuation method has been employed following the ^{97}Mo(p,nγ)^{97}Tc reaction at 3.5 MeV to determine lifetimes for 11 states in ^{97}Tc and lower limits for 12 additional states. The lifetimes were extracted from singles spectra taken with the aid of an anti-Compton spectrometer at seven angles between 0° and 90° to the beam direction by employing centroid shift analysis of the data. For a number of transitions in ^{97}Tc, values or limits for $B(E1)$, $B(E2)$, and $B(M1)$ were obtained. The present results are compared with calculations based on the cluster-core coupling model of Bargholtz and Beshai.

I. INTRODUCTION

The systematic trends in the properties of the odd-Tc isotopes constitute a challenge for the various theoretical models of the nuclei in the nearly spherical mass-90 region. Numerous theoretical investigations for the odd-mass Tc isotopes have been carried out and are reported in Refs. 1–9. Recently, Bargholtz and Beshai[9] have described the positive-parity states in $^{93-101}$Tc by considering coupling of $(p_{1/2})^2(g_{9/2})^3$ and $(p_{1/2})^0(g_{9/2})^5$ proton configurations to quadrupole oscillations of the core. The negative parity states were described as a proton quasiparticle in the $p_{1/2}$, $p_{3/2}$, and $f_{5/2}$ states coupled to the quadrupole oscillations of the core. In this way they have calculated energies and electromagnetic moments for the excited states in the odd-Tc isotopes and have obtained improved agreement with the observed properties of the "anomalous" low lying $\frac{5}{2}^+$ and $\frac{7}{2}^+$ states.

Although there is an increasing body of experimental information[10–22] concerning ^{97}Tc, lifetimes for excited states in this isotope have been measured only for the 216- and 325-keV states.[10–12] In the present study the lifetimes for 11 states in ^{97}Tc and limits for 12 others were obtained from Doppler-shift-attenuation (DSA) measurements. The measured lifetimes in combination with existing data[10–22] on ^{97}Tc enabled the determination of the $B(\sigma L)$ values for many transitions. On the basis of the measured $B(E2)$ and $B(M1)$ values the collective nature of the states in ^{97}Tc is discussed and a comparison with the calculations of Bargholtz and Beshai[9] is carried out.

II. EXPERIMENT AND RESULTS

In the present study the mean lifetimes of levels in ^{97}Tc were measured via the DSA method from singles γ-ray spectra following the ^{97}Mo(p,nγ) reaction ($Q=-1.128$) at $E_p=3.5$ MeV, using the centroid-shift technique. Levels in ^{92}Tc up to an excitation of 2.2 MeV were populated by this reaction. The singles γ-ray spectra were obtained at seven angles between 0° and 90° relative to the incident beam direction. The beams were supplied by the 4 MV Van de Graaff accelerator at Queen's University. The target employed was a self-supporting foil, 3.77 mg/cm^2 thick, of molybdenum metal enriched to 92.80% in mass 97, which was prepared by rolling. The main target contaminants were ^{98}Mo (3.9%) and ^{96}Mo (1.69%). The target was positioned at 45° to the beam. In these lifetime measurements an 18% Ge(Li) detector with a resolution of 1.74 keV (FWHM) at 1332 keV was used. This detector was employed in a NaI(Tl)-Ge(Li) anti-Compton arrangement. The 29.2 cm diam by 30.5 cm long NaI(Tl) annulus is split into four equal, optically isolated segments, oriented so that the symmetry plane of two of the segments was in the reaction plane. The annulus was lead shielded and the Ge(Li) detector was Hevimet collimated. An electronic module was used to identify and tag events on the basis of their interaction with the NaI segments. The Compton suppression factor was 4:1 and the overall peak to Compton ratio was 200:1. A typical Compton suppressed spectrum of the γ rays from the ^{97}Mo(p,nγ)^{97}Tc reaction at $E_p=3.5$ MeV observed at 90° to the beam is shown in Fig. 1. In this spectrum the γ rays which belong to the ^{97}Tc scheme are simply indicated by their energy in keV. Peaks due to inelastic scattering or background radiations are labeled as p or b.

Briefly, the centroid shift is given by

$$\langle \Delta E_\gamma \rangle = E_\gamma^0 \beta_{\text{c.m.}} \widetilde{F}(\tau)\cos\theta_{\text{d}} , \tag{1}$$

$$\widetilde{F}(\tau)=\frac{1}{\beta_{\text{c.m.}}}\int F(\tau)\beta(0)\cos\theta_{\text{N}} W(\theta_{\text{N}},\theta_{\text{d}})d\Omega(\theta_{\text{N}}) , \tag{2}$$

and

$$F(\tau)=\frac{1}{\beta(0)\tau}\int_0^\infty \beta(\tau)\cos\phi(t)\exp\left[-\frac{t}{\tau}\right]dt , \tag{3}$$

where $\widetilde{F}(\tau)$ is the attenuation factor averaged over all initial velocities of the recoil nucleus by employing the angular correlation function $W(\theta_{\text{N}},\theta_{\text{d}})$ as a weighting factor according to Moazed *et al.*,[23] and $\cos\phi(t)$ is the average collision cosine as given by Blaugrund.[24] For the calculation of $\beta(t)$ the stopping power theory of Lindhard, Scharff, and Schiøtt[25] as modified by Blaugrund[24] was used with the stopping power taken as

$$T_t=f_{\text{e}}T_{\text{e}}+f_n T_n , \tag{4}$$

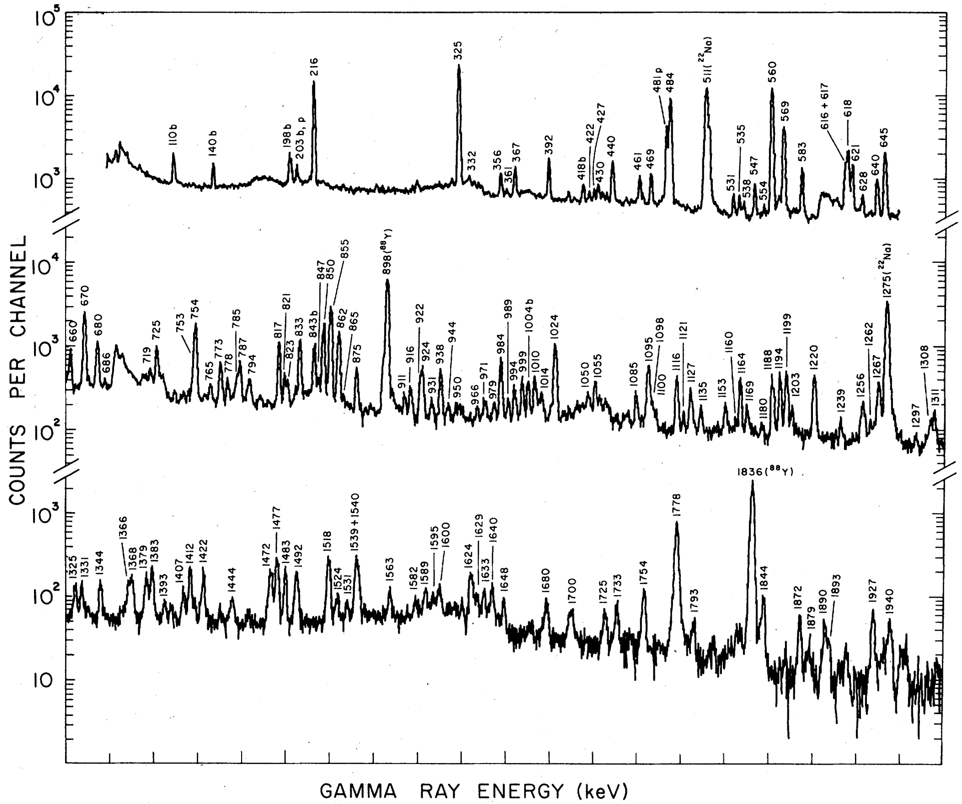

FIG. 1. Spectrum of the γ rays from the ^{97}Mo(p,nγ)Tc reaction at $E_p = 3.5$ MeV taken at 90° to the beam direction. In this spectrum the γ rays which belong to the ^{97}Tc scheme are simply indicated by their energy in keV. Peaks due to inelastic scattering or background radiations are labeled as p or b.

where T_t is the total stopping power, e and n refer to electronic and nuclear stopping powers, and f_e and f_n are adjustable parameters. Previous studies[26–29] have indicated that f_e and f_n can differ by 20% for unity. Since in this work the recoil energies are low, the nuclear term dominates the stopping power and the result of varying f_e by 20% with constant f_n is a negligible change in the $\tilde{F}(\tau)$ values. For this reason the lifetimes reported in this work were obtained with $f_e = 1.0$ and $f_n = 1.0 \pm 0.2$.

Due to the low initial recoil velocity ($\beta \simeq 0.9 \times 10^{-3}$), the observed shifts are very small. In order to obtain accurate results for the centroid positions of the γ rays the spectra were accumulated in the presence of sources of ^{22}Na and ^{88}Y. Care was also taken to keep the beam current low (the counting rate was $\sim$2.5 kHz) and steady to avoid rapid changes in the energy stability of the system.

In the extraction of the centroid of a peak the underlying background was fitted to a polynomial function. The distribution over several measurements was peaked around the mean value and had a standard deviation well represented by the error in the centroid. The E vs $\cos\theta_d$ curve of the 1274.5-keV γ ray from ^{22}Na is shown in Fig. 2. The energy slope was consistent with zero for this γ ray and is a good indication of the reliability of the experiment in the extraction of the γ ray energy shifts.

The centroid shifts measured in this work for several transitions in ^{97}Tc are plotted vs $\cos\theta_d$ in Fig. 3. The straight lines in Fig. 3 were obtained as weighted least-square fits to the data. The slopes obtained are given in parentheses in keV and correspond to the shifts of Eq. (1) for $\cos\theta_d = 1$. From these slopes the experimental values for $\tilde{F}(\tau)$ were calculated using Eq. (1) and are summarized in the third column of Table I. In the first column of Table I the level energies are given. The second column gives the γ rays used in the DSA measurements. The fourth column gives the presently determined mean lifetimes in fs (10^{-15} s) for the corresponding levels in ^{97}Tc. These were deduced from a comparison with the theoretical $\tilde{F}(\tau)$ curves as a function of τ, evaluated for

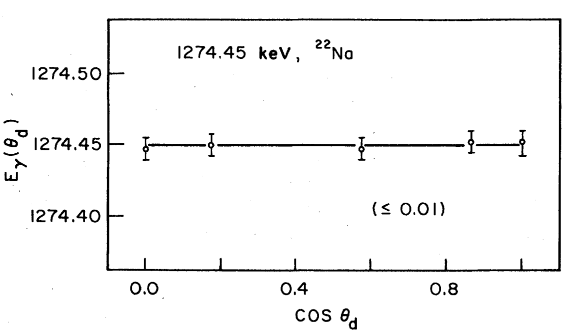

FIG. 2. Plot of the E vs $\cos\theta_d$ for the 1274.5-keV γ ray of ^{22}Na. The number in parentheses is the least-squares slope for a straight line fit to the data.

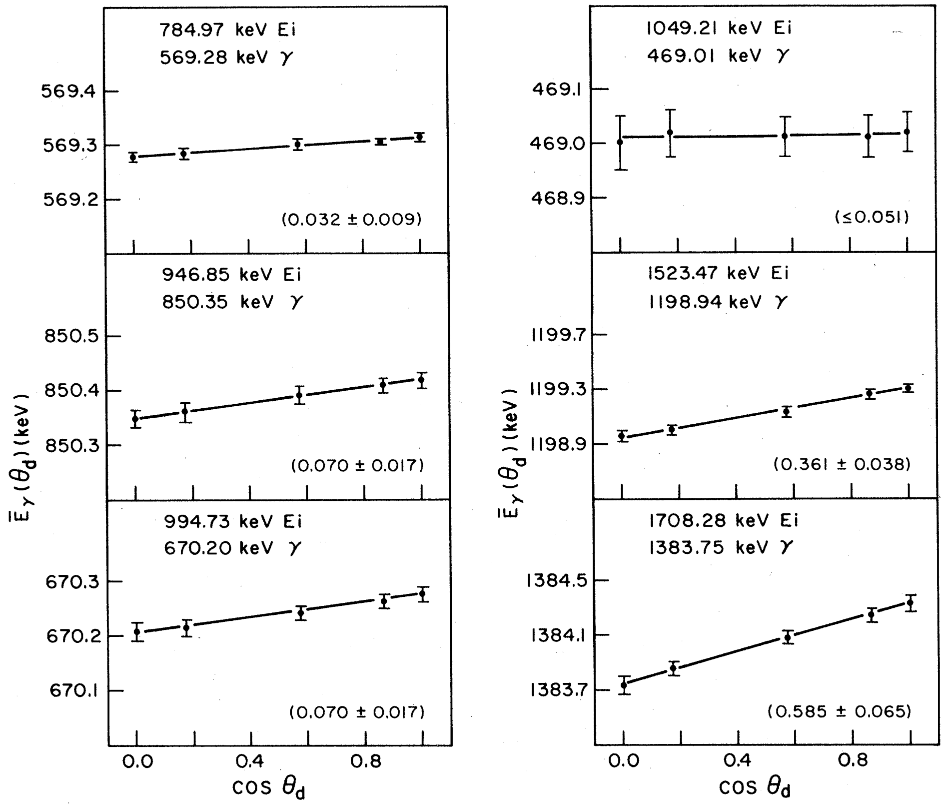

FIG. 3. Plots of the centroid energy in keV for the indicated γ rays from ^{97}Tc observed in singles measurements vs $\cos\theta_d$. The initial state is also indicated on the plot. The numbers in parentheses are the least-squares slopes for a straight line fit to the data. Data at $E_p = 3.5$ MeV.

TABLE I. Summary of the lifetimes for levels in ^{97}Tc determined via the DSA method from centroid shifts and comparison with other available data.

E_{level} (keV)	γ ray used in DSA experiments	$\tilde{F}(\tau)$	τ_{level} (fs) Present[a]	Previous[b]
215.8				$(10\pm2)\times10^4$
324.5				$(56\pm3)\times10^4$
656.9	560.4	≤ 0.022	≥ 1100	
773.0	773.0	≤ 0.051	≥ 510	
785.0	460.5, 569.3	0.065 19	470^{+250}_{-138}	
832.9	832.9	≤ 0.052	≥ 500	
855.6	639.7, 855.6	≤ 0.048	≥ 540	
861.8	861.8	≤ 0.047	≥ 550	
946.9	850.4	0.094 23	315^{+135}_{-82}	
994.7	670.2	0.120 29	240^{+107}_{-61}	
1049.2	392.3, 469.0, 724.9	≤ 0.083	≥ 300	
1141.4	816.9	0.076 34	400^{+354}_{-147}	
1199.8	875.4, 983.9	0.084 48	350^{+539}_{-146}	
1240.0	583.2	≤ 0.069	≥ 375	
1380.2	547.3, 1164.4	0.205 59	130^{+72}_{-44}	
1441.3	1116.8	≤ 0.083	≥ 300	
1512.8	1188.3	0.082 32	365^{+263}_{-125}	
1518.6	938.5	0.098 49	302^{+318}_{-120}	
1523.5	1198.9	0.346 37	64^{+20}_{-15}	
1650.0	1325.5	$0.038 \leq \tilde{F}(\tau) \leq 0.198$	$112 \leq \tau \leq 1000$	
1708.3	1383.8	0.485 54	36^{+13}_{-9}	
1733.6	1517.8	≤ 0.033	≥ 780	
1850.8	1754.3	0.099 48	300^{+320}_{-115}	

[a]The quoted errors include statistical errors and the effects of a 20% uncertainty in the stopping power.
[b]Mean lifetimes obtained as weighted averages from Refs. 10—12.

TABLE II. Summary of the electromagnetic properties of the transitions in ^{97}Tc determined in this and previous works for levels up to 1380 keV in excitation and comparison with the theory.

E_i (keV)	E_γ (keV)	$J_i^\pi \rightarrow J_f^\pi$ [a]	Branching fraction[b] (%)	Mixing ratio $\delta(E2/M1)$ Expt.[c]	Mixing ratio $\delta(E2/M1)$ Theory[d]	$B(M1)$ or $(B(E1)$ in W.u. Expt.	$B(M1)$ or $(B(E1)$ in W.u. Theory[d]	$B(E2)$ in W.u. Expt.	$B(E2)$ in W.u. Theory[d]
215.84	215.84	$\frac{7}{2}_1^+ \rightarrow \frac{9}{2}_1^+$	100	0.27 ± 0.02	0.41	0.028 ± 0.005	0.01	43 ± 11	34
324.53	108.69	$\frac{5}{2}_1^+ \rightarrow \frac{7}{2}_1^+$	2 1	1.6 ± 0.4	-0.04	0.00014 ± 0.00008	0.05	30 ± 16	6
	324.53	$\frac{5}{2}_1^+ \rightarrow \frac{9}{2}_1^+$	98 1	$E2$	$E2$			14 ± 1	49
656.86	560.36	$\frac{5}{2}_1^- \rightarrow \frac{1}{2}_1^-$	99.4 10	$E2$	$E2$			≤ 513	32
772.95	772.95	$\frac{13}{2}_1^+ \rightarrow \frac{9}{2}_1^+$	100	$E2$	$E2$			≤ 219	45
784.97	460.50	$\frac{5}{2}_2^+ \rightarrow \frac{5}{2}_1^+$	10 1	-0.03 ± 0.12		$0.078^{+0.023}_{-0.027}$		≤ 8	
	569.28	$\frac{5}{2}_2^+ \rightarrow \frac{7}{2}_1^+$	80 3	0.128 ± 0.014		0.29 ± 0.10		15 ± 5	
	784.97	$\frac{5}{2}_2^+ \rightarrow \frac{9}{2}_1^+$	10 1	$E2$				24 ± 9	
832.88	832.88	$\frac{11}{2}_1^+ \rightarrow \frac{9}{2}_1^+$	100	0.45 ± 0.11	-0.92	<0.10	0.027	≤ 26	34
				or		or		or	
				4.4 ± 0.1		<0.0035		≤ 92	
855.59	639.74	$\frac{7}{2}_2^+ \rightarrow \frac{7}{2}_1^+$	14.1 9	$-2.3^{+0.6}_{-0.1}$		<0.007		≤ 67	
	855.59	$\frac{7}{2}_2^+ \rightarrow \frac{9}{2}_1^+$	80.2 3	0.4 ± 0.3		<0.07		≤ 33	
861.76	861.76	$\frac{9}{2}_2^+ \rightarrow \frac{9}{2}_1^+$	87 1	-0.51 ± 0.21	1.7×10^2	<0.07	4.5×10^{-7}	≤ 35	17
946.85	850.35	$\frac{3}{2}_2^- \rightarrow \frac{1}{2}_1^-$	83.8 4	$-10.5<\delta<3.0$		$0.002\leq B(M1)\leq 0.17$		≤ 231	
994.73	670.20	$\frac{7}{2}_3^+ \rightarrow \frac{5}{2}_1^+$	94 4	$-0.81^{+0.38}_{-0.68}$		0.25 ± 0.19		354^{+431}_{-276}	
1049.21	392.26	$\frac{3}{2}_3^- \rightarrow \frac{5}{2}_1^-$	41 2	$(M1)$		≤ 0.75			
	469.01	$\frac{3}{2}_3^- \rightarrow \frac{3}{2}_1^-$	25 3	$(M1)$		≤ 0.28			
1141.38	356.41	$\frac{7}{2}_4^+ \rightarrow \frac{5}{2}_2^+$	27 3	-0.3 ± 0.2		$0.43^{+0.26}_{-0.21}$		≤ 762	
1199.84	875.40	$\frac{9}{2}_3^+ \rightarrow \frac{5}{2}_1^+$	39	$0.4^{+0.5}_{-0.9}$ [e]				58 ± 42	
	983.91	$\frac{9}{2}_3^+ \rightarrow \frac{7}{2}_1^+$	61	-0.58 ± 0.4		$0.043^{+0.033}_{-0.030}$		≤ 32	
1240.01	583.15	$\frac{7}{2}_1^- \rightarrow \frac{5}{2}_1^-$	44 2	-0.34 ± 0.24	-0.08	<0.18	0.23	≤ 135	4
	915.9	$\frac{7}{2}_1^- \rightarrow \frac{5}{2}_1^+$	7 4	$-0.81^{+0.51}_{-1.0}$		$<1\times10^{-4}$			
1380.18	547.28	$\frac{9}{2}_4^+ \rightarrow \frac{11}{2}_1^+$	41 2	$0.33^{+0.10}_{-0.08}$		0.55 ± 0.20		195^{+126}_{-106}	
	1164.35	$\frac{9}{2}_4^+ \rightarrow \frac{7}{2}_1^+$	49 3	$0.31^{+0.04}_{-0.03}$		0.069 ± 0.025		5 ± 2	
				or		or		or	
				$-1.96^{+0.12}_{-0.18}$		0.016 ± 0.006		43 ± 15	

[a]From Refs. 18–20 and 22.
[b]Branching ratios obtained as weighted averages from Refs. 14 and 18–20.
[c]Mixing ratios obtained as weighted averages from Refs. 13 and 15–20.
[d]Cluster-core coupling calculations of Bargholtz and Beshai (Ref. 9).
[e]Mixing ratio for $\delta(M3/E2)$.

each level from Eq. (2). The majority of the observed levels had little (< 10%) or no feeding from higher-lying levels. For the 657- and 785-keV levels an ~15% feeding from higher-lying levels was observed, while for the 833-keV level this feeding was 33%. The feeding from above for the 833-keV level came almost totally from the 1380-keV level, while the one for the 657- and 785-keV levels was mainly due to the 1240- and 1141-keV levels, respectively. This feeding from above of the 657-, 785-, and 833-keV levels was properly included in the calculation of the $\tilde{F}(\tau)$ curves according to the description of Hoffman *et al.*[30] The uncertainties quoted with the present τ values include the statistical error and the effect of a 20% uncertainty in the stopping power. The last column of Table I gives the previously determined mean lifetimes for states in ^{97}Tc.

III. REDUCED TRANSITION PROBABILITIES IN ^{97}Tc

From the level lifetimes measured in the present study and the previously existing data on ^{97}Tc the reduced transition probabilities for a number of transitions in ^{97}Tc were deduced. Those values are summarized in the seventh and ninth columns of Table II. The $B(E2)$, $B(M1)$, and $B(E1)$ values are given in Weisskopf units (W.u.) and were calculated via the expression given in the Appendix of Ref. 26.

It is clear from the procedure employed for the determination of $B(\sigma L)$ values that when limits are found for the lifetimes, limits are also obtained for the $B(\sigma L)$ values. When the lifetime was measured more precisely the more accurate $B(E2)$ values were obtained for the pure $E2$ transitions. For most of the mixed $M1+E2$ transitions the major contribution to the large quoted errors in the $B(E2)$ originates from the errors in the multipole mixing ratio $\delta(E2/M1)$. In contrast, more accurate values are in general obtained for $B(M1)$ or $B(E1)$ rates.

IV. DISCUSSION

The measured lifetimes have helped to make the following clarifications concerning the structure of ^{97}Tc. A 1199-keV γ ray was assigned by Xenoulis and Kalfas[18] on the basis of good energy agreement to decay from the 1199-keV level to the ground state. In the present study the $\tilde{F}(\tau)$ value found for the 1199-keV γ ray is drastically different from the $\tilde{F}(\tau)$ values of the 875- and 983-keV γ rays which were definitely assigned[18,20] to deexcite the 1199-keV level to the 325- and 216-keV levels, respectively, on the basis of coincidence events. This fact suggests that the 1199-keV γ ray originates from a different level, in agreement with Kajrys *et al.*[20] who have assigned this γ ray to deexcite a 1523-keV level on the basis of an observed (325-1199) keV coincidence.

The spin of the 1141-keV level was limited by Xenoulis and Kalfas[18] to $\frac{3}{2}^+$, $\frac{5}{2}^+$, and $\frac{7}{2}^+$. On the basis of the lifetime of this state measured in this study and the multipole mixing ratios found in Ref. 18 for the 356-keV γ ray, the $\frac{3}{2}^+$ and $\frac{5}{2}^+$ possibilities can be excluded because they would result in an unreasonably high $B(E2)$ value[31] for the 356-keV γ ray. Thus the spin of the 1141-keV state is uniquely determined to be $\frac{7}{2}^+$, in agreement with the results of Ref. 20. The higher δ value for the $\frac{7}{2}^+ \to \frac{5}{2}^+$, 356-keV transition proposed in Refs. 18 and 20 is rejected as it would result in an improbably high $B(E2)$ value.[31] Thus the mixing ratio of the 356-keV ray is also uniquely determined to be -3.0 ± 0.2 (weighted average value from Refs. 18 and 20).

In Ref. 20 the mixing ratio for the 547-keV γ ray which deexcites the 1380-keV, $\frac{9}{2}^+$ state to the 833-keV, $\frac{11}{2}^+$ state was found to be $\delta=4.0^{+1.7}_{-1.1}$ or $\delta=0.33^{+0.10}_{-0.08}$.

TABLE III. Comparison of the electromagnetic properties of the low lying states in ^{97}Tc and ^{99}Tc.

	^{97}Tc			^{99}Tc^{c}		
$J_i^\pi \to J_f^{\pi\,a}$	$\delta(E2/M1)^b$	$B(E2)$ (W.u.)	$B(M1)$ (W.u.)	$\delta(E2/M1)$	$B(E2)$ (W.u.)	$B(M1)$ (W.u.)
$\frac{7}{2}^+_1 \to \frac{9}{2}^+_1$	0.27 2	43 11	0.028 5	0.20^{+8}_{-6}	53 8	0.042 5
$\frac{5}{2}^+_1 \to \frac{9}{2}^+_1$	$E2$	14 1		$E2$	17 2	
$\to \frac{7}{2}^+_1$	1.6 4	30 16	$(14\pm8)\times10^{-5}$	0.12	60 15	$(6\pm0.8)\times10^{-3}$
$\frac{7}{2}^+_2 \to \frac{9}{2}^+_1$	0.4 3	≤ 33	≤ 0.07	0.16 13	0.5 2	
$\frac{11}{2}^+_1 \to \frac{9}{2}^+_1$	0.45 11	≤ 26	≤ 0.10	$(0-\infty)$	26 4	≤ 0.028
$\frac{5}{2}^+_2 \to \frac{9}{2}^+_1$	$E2$	24 9		$E2$	13 2	
$\to \frac{7}{2}^+_1$	0.128 *14*	15 5	0.29^{+9}_{-15}	0.19 6	10 8	0.10 6
$\to \frac{5}{2}^+_1$	-0.03 12	≤ 8	0.078^{+23}_{-27}	-0.15 20	≤ 5	$\simeq 0.02$
$\frac{13}{2}^+_1 \to \frac{9}{2}^+_1$	$E2$	≤ 219		$E2$	35 5	
$\frac{9}{2}^+_2 \to \frac{9}{2}^+_1$	-0.51 21	≤ 35	≤ 0.07	-0.51 12	10 2	0.010 3

^{a}From Refs. 18–20, 22, and 33. For ^{99}Tc we have used the most probable spins proposed in Ref. 33.
^{b}Mixing ratios obtained as weighted averages from Refs. 13 and 15–20.
^{c}From Refs. 33 and 34.

The possible $4.0^{+1.7}_{-1.1}$ value can be rejected because the lifetime of the 1380-keV state (measured here to be 130^{+72}_{-44} fs) implies a $B(E2)$ value exceeding 1100 W.u.[31] Thus the mixing ratio for the 547-keV transition is uniquely determined to be $0.33^{+1.10}_{-0.08}$.

In Table II the transition probabilities deduced in this work are found to be considerably enhanced, which indicates the collective nature of the states in ^{97}Tc. In the same table the experimental rates are compared with those calculated on the basis of the cluster-core coupling model.[9] The theoretical information reported in Ref. 9 is limited to the first excited state of a given spin because the calculation of Bargholtz and Beshai employed a very small configuration space and treated the single particle degrees of freedom rather schematically, thus making the validity of their model somewhat questionable for states beyond the first one of each spin.[32] From Table II it is seen that within the limits of the experimental results the agreement between theory and experiment for the $B(E2)$ values is good except for the transitions from the first $\frac{5}{2}^+$ state for which the $E2$ strengths deviate fairly strongly from the predicted values. More specifically, while experimentally the $B(E2;\ \frac{5}{2}{}^+_1 \rightarrow \frac{7}{2}{}^+_1)$ is stronger than the $B(E2; \frac{5}{2}{}^+_1 \rightarrow \text{g.s.})$, the calculations predict the opposite. Disagreements also exist in the $M1$ transition probabilities. For example, the theoretical $M1$ strength is drastically overestimated for the $\frac{5}{2}{}^+_1 \rightarrow \frac{7}{2}{}^+_1$ transition.

In Table III we compare the electromagnetic properties of several low lying states in ^{97}Tc with the corresponding ones in ^{99}Tc.[33,34] From this table it is seen that the corresponding electromagnetic properties in these two isotopes are very similar and in most cases overlap within error, with the exception of the $M1$ strength of the $\frac{5}{2}{}^+_1 \rightarrow \frac{7}{2}{}^+_1$ transition, which is two orders of magnitude greater in ^{99}Tc. Although the cluster-core coupling model[9] can account for these similarities between ^{97}Tc and ^{99}Tc, it does not explain the large differences observed for the $\frac{5}{2}{}^+_1 \rightarrow \frac{7}{2}{}^+_1$ transition in these two odd-mass Tc isotopes.

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