Structure and directional-correlation measurements in ^{97}Tc from ^{97}Mo(p,n) ^{97}Tc*(γ) spectrometry

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The level structure and the decay properties of levels in ^{97}Tc up to 2208 keV excitation have been investigated via measurements of excitation functions of singles γ rays and via $\gamma\gamma$-coincidence experiments following the ^{97}Mo(p,$n\gamma$) reaction with proton energies between 1.5 and 8.0 MeV. From these experiments and from high resolution singles energy and directional-correlation measurements an extended scheme has been obtained which includes 69 levels of which about 40 are new. The directional correlations provided unique J^π assignments for 14 levels, limits for a few others, and multipole mixing ratios for several electromagnetic transitions. The results are compared with unified model calculations.

[NUCLEAR REACTIONS ^{97}Mo(p,n)^{97}Tc*(γ), E = 1.5 – 8.0 MeV; measured E_γ, I_γ, $I_\gamma(\vartheta)$, $\gamma\gamma$ coincidences; deduced ^{97}Tc levels, J, π, branching ratios, $\delta(E2/M1)$; enriched targets, Ge(Li) detectors.]

I. INTRODUCTION

Although numerous theoretical investigations have been devoted to the study of odd-mass Tc isotopes,[1-7] only very recently has an extensive and detailed description of properties of states in such isotopes been reported.[8-10] Abecasis *et al.*[8] have inferred the coupling of a three-quasiparticle valence-shell cluster to the quadrupole vibrational field of the core and concluded the coexistence of quasivibrational and quasirotational features in the spectra of odd-mass Tc isotopes. In an alternative approach Xenoulis[7] considers the coupling of a $0g_{9/2}$ quasiparticle proton to a slightly deformed core. In this way the five lowest positive-parity levels are interpreted as bandheads on which rotational states are built. Bargholtz and Beshai[9] have described 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. A more fundamental approach in the framework of the shell-model has been followed by Skouras and Dedes[10] who have allowed full configuration mixing of the $1d_{5/2}$, $2s_{1/2}$, $1d_{3/2}$, and $0g_{7/2}$ neutron orbitals. The improved results of all three most recent calculations, which are due mainly to the larger configuration space employed, compare reasonably well with experimental level spacings and transition probabilities, at least for ^{95}Tc for which a substantial amount of experimental information is available. A more severe test for the applicability of the different models, therefore, should be a comparison with heavier Tc isotopes, which are characterized by similar but more dense and complicated spectra of excited states. With regard to the ^{97}Tc isotopes, however, the existing experimental information is limited and even conflicting.

The nuclear structure of ^{97}Tc has been investigated experimentally in recent years via nuclear reaction spectroscopy employing the (^{3}He,d) reaction,[11-13] and the (d, n) reactions.[14,15] Kim *et al.*[16] have studied the ^{97}Mo(p, n) ^{97}Tc reaction by neutron time-of-flight techniques, while Kim *et al.*[17] have made spin-parity assignments in ^{95,97}Tc via neutron decay studies of the 0^+ and 2^+ analog states. The level and decay schemes of ^{97}Tc have been investigated via the (p, $n\gamma$) reaction by Picone *et al.*[18] and by the (p, γ) reaction by Close and Bearse.[19] The ^{97}Ru decay has been studied by Phelps and Sarantites[20] and more recently by Huber and Krämer.[21] Rates for two transitions in ^{97}Tc have been obtained by means of internal-conversion electron spectroscopy and delayed electron-electron coincidence by Bergman *et al.*[22] Finally, angular correlations have been measured recently for several cascades in ^{97}Tc following the decay of the ^{97}Ru isotope.[23-25] Properties of the ^{97}Tc nucleus have been compiled by Medsker.[26]

In the present study the level structure and decay properties in ^{97}Tc were investigated by detailed in beam γ-ray spectrometry using the reaction ^{97}Mo(p, $n\gamma$) ^{97}Tc in order to obtain the necessary experimental information on ^{97}Tc which would render a comparison with the various theories meaningful. Thus a consistent decay scheme was constructed in which many new levels were added while others previously reported were not adopted, on the evidence of γ-ray excitation function and $\gamma\gamma$-coincidence data. Spin and mixing ratio values for several states and transitions were determined from directional correlation measurements of single γ rays.

II. EXPERIMENTS AND RESULTS

In the present study four types of measurements were performed using the $^{97}Mo(p,n)\,^{97}Tc^{*}(\gamma)$ reaction. In the first type of measurement the energies of the γ rays from the above reaction were accurately determined. In the second type of measurement the excitation functions of individual γ rays were measured at several energies between 1.5 and 8.0 MeV. The third type of measurement involved the determination of coincidence relationships and the evaluation of cascade intensities of the γ-rays produced in the reaction. This type of measurement was decisive in the unambiguous assignment of γ rays in a detailed decay scheme. In the fourth type of measurement the angular distributions of several γ rays following the $^{97}Mo(p,n)\,^{97}Tc^{*}(\gamma)$ reaction were measured.

A. γ-ray energy and excitation function measurements

The γ-ray energies were measured by taking singles spectra at 90° to the beam direction, in the presence of radioactive sources. The proton beams were supplied by the high intensity 5.5 MV Tandem Van de Graaff accelerator of the Nuclear Research Center "Demokritos." The targets employed were self-supporting foils, 4 mg/cm^2 thick, of molybdenum metal enriched to 94.6% in mass 97, which were prepared by rolling of the metal. In these and subsequent singles experiments a high-resolution 45 cm^2 Ge(Li) detector which had full width at half maximum (FWHM) of 1.8 keV at 1332 keV was used. Standard sources of ^{57}Co, ^{133}Ba, ^{137}Cs, ^{22}Na, ^{60}Co, and ^{56}Co were used in different combinations for internal calibration. These sources were mounted in front of the collimator of a heavy lead shield which protected the Ge(Li) detector from unwanted radiation. Standard electronics were employed for the accumulation of spectra over 4096 channels in a PDP-15 on-line computer.

A spectrum of the γ rays from the $^{97}Mo(p,n)\,^{97}Tc^{*}(\gamma)$ reaction at 4.0 MeV is shown in Fig. 1. In this spectrum the γ rays assigned in the ^{97}Tc decay scheme are simply indicated by their energy in keV. Peaks due to inelastic scattering, back-

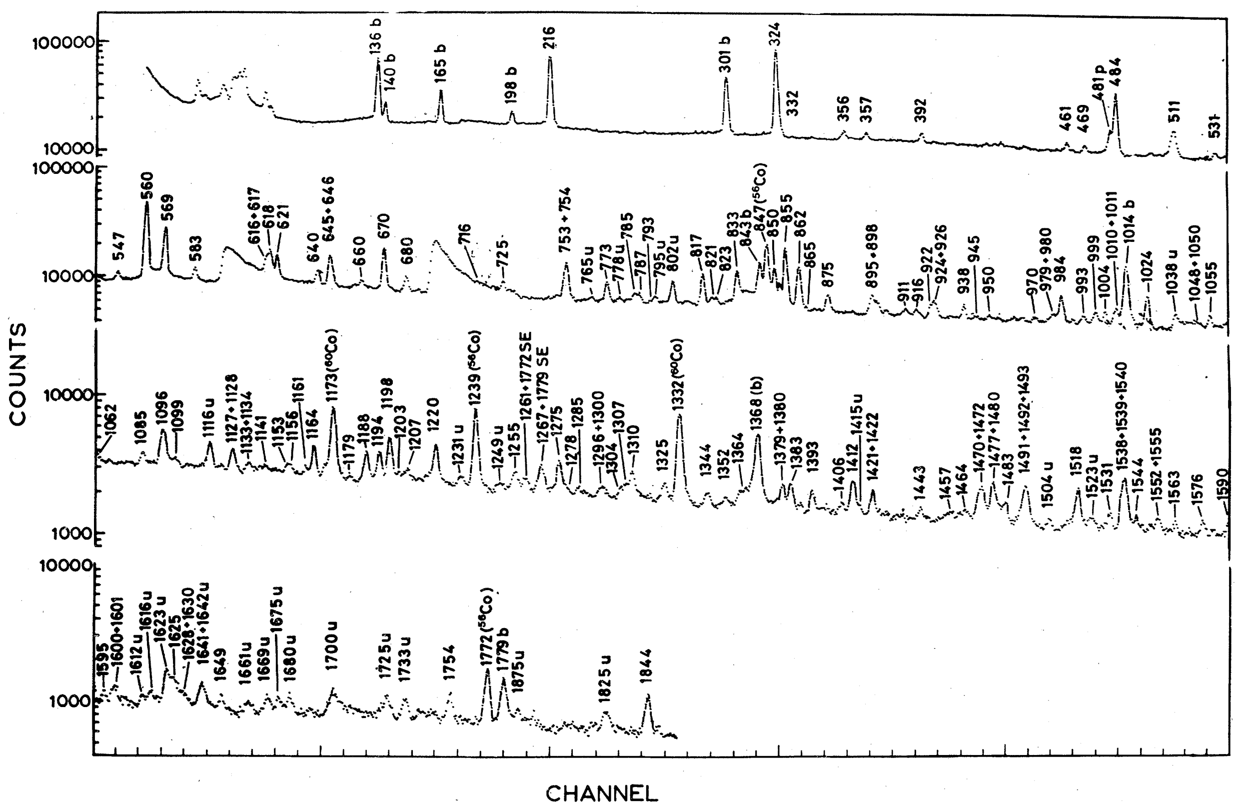

FIG. 1. Spectrum of the γ rays from the $^{97}Mo(p,n\gamma)\,^{97}Tc$ reaction at 4.0 MeV taken at 90° to the beam direction. The γ rays labelled only by energy have been assigned to ^{97}Tc. Peaks labelled p are associated with $(p,p'\gamma)$; peaks labelled by b are due to background radiation and those labelled by u are unassigned.

ground, or unidentified radiations are labeled as *p*, *b*, or *u*. The majority of the unidentified peaks are most probably associated with the ^{97}Mo$(p, n\gamma)$ reaction. The γ-ray energies measured are given in the fifth column of Table I. The γ-ray excitation functions were measured by taking singles γ-ray spectra at 55° to the beam direction for ten proton bombarding energies covering the range 1.5 to 4.5 MeV. A measurement at 8.0 MeV proton energy was carried out with the aim of observing the enhanced yield of those γ rays which originated from higher spin states. In the bombarding energy range between 2.00 and 3.00 MeV the relative yield of the γ rays was measured in 100.0 keV increments of the bombarding energy. Some typical excitation functions are shown in Fig. 2. In these experiments the charge was collected and integrated in an isolated miniature scattering chamber. Dead time and amplifier pileup corrections were made using a pulser fed into the Ge(Li) preamplifier.

The measurements at 55° were also used for the determination of the branching ratios for those levels for which angular distribution of the deexciting transitions was not feasible to obtain. Coincidence intensities were also used in the determination of branching ratios, especially in cases of overlapping multiplets.

B. $\gamma\gamma$-coincidence relationships

The coincidence relationships for the γ-ray cascades in ^{97}Tc were established in an experiment with the (p, n) reaction at 4.0 MeV. In this experiment the 45 cm^3 detector described in Sec. II A was used in conjunction with a 65 cm^3 Ge(Li) detector which had FWHM of 1.9 keV at 1332 keV. The Ge(Li) detectors were positioned at 55° on each side of the beam. The coincidence resolving time was 10 nsec and the total coincidence rate was 300 counts/sec. Ten coincidence spectra of 1024-channel configuration each were recorded in the PDP-15 computer, with gates placed on peaks of interest and on Compton backgrounds near each

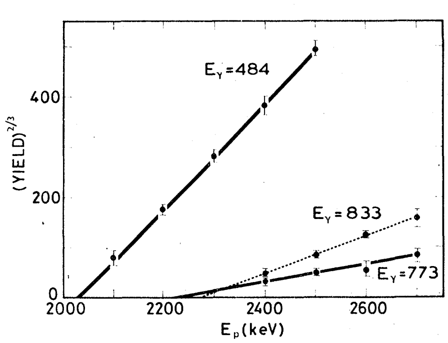

FIG. 2. Yields of three ^{97}Tc γ rays as a function of proton laboratory energy.

peak. The coincidence spectra after background subtraction are shown in Figs. 3 and 4, while in Table II are summarized the γ rays observed in coincidence with the indicated γ rays in each gate.

C. Angular distributions

Spins of levels and multipole mixing ratios of several electromagnetic transitions were obtained from singles angular distributions measured at 3.8 MeV bombarding energy. Singles γ-ray spectra were taken at nine detector angles $\Theta_d = 0°$, 15°, 26°, 37°, 45°, 55°, 63°, 71°, and 90° with respect to the incident proton beam. The normalization of the spectra was carried out with the help of high intensity peaks in the associated spectra of a fixed Ge(Li) monitor. The detection systems described in Secs. II A and II B were used in these measurements. The obtained angular distributions were first analyzed by a least-square fit of the data to the function

$$W(\Theta_d) = A_0[1 + A_2P_2(\cos\Theta_d) + A_4P_4(\cos\Theta_d)] \ . \quad (1)$$

The coefficients of the Legendre polynomials obtained in this way were not corrected for solid angle due to the large distance of the detector from the target, 15 cm, which essentially reduces the corresponding geometrical attenuation coefficients to unity. The A_0 obtained give the branching ratios. The experimental A_2 and A_4 coefficients for those transitions for which the angular distribution analysis gave meaningful results are given in Table III.

The angular distributions were further analyzed to yield evidence for J assignments and to extract δ values. For this purpose the Hauser-Feshbach theory[27] for nuclear reactions was applied.

In order to ensure the applicability of the statistical theory in the ^{97}Mo$(p, n)^{97}$Tc$^*(\gamma)$ reaction the proton bombarding energy was chosen to avoid the excitation of analog states in the ^{98}Tc compound nucleus. Thus for incident proton energies of 3.8 MeV and a target positioned at 45° to the beam one obtains energy spread of 134 keV which is sufficient to average over the statistical fluctuations. Furthermore, one finds that the nonresonant region[17] between the 0^+ and 2^+ analog resonances in ^{98}Mo was actually excited in these experiments.

The evaluation of the theoretical distributions was performed with the program MANDY (Ref. 28) which was modified in order to fit the theoretical distribution to the experimental $W(\Theta_d)/A_0$ data and yield an approximate X^2 as a function of δ. Transmission coefficients for the proton channels were obtained from the penetrability tables of Mani *et al.*,[29] while the coefficients for the neutron channel were obtained from the tables of Auerbach and

TABLE I. Summary of level energies, J^{π} values, γ-ray energies, and branching fractions for transitions ^{97}Tc determined in this work.

Level No.	Level energy (keV) [a]	J^{π}	Transition	γ-ray energy (keV)	Branching (%)
0	0	$\frac{9}{2}^{+}$			
1	96.5 1	$\frac{1}{2}^{-}$			
2	215.70 5	$\frac{7}{2}^{+}$	2→0	215.70 5	100
3	324.46 5	$\frac{5}{2}^{+}$	3→2	108.8	1 [b]
			3→0	324.46 5	99
4	580.10 14	$\frac{3}{2}^{-}$	4→1	483.60 4	100
5	656.85 11	$\frac{5}{2}^{-}$	5→3	332.4 3	0.9 5
			5→1	560.35 5	99.1 8
6	772.6 1	$(\frac{13}{2}^{+})$	6→0	772.6 1	100
7	785.07 12	$\frac{5}{2}^{+}$	7→3	460.59 7	12 1
			7→2	569.37 5	80 3
			7→0	785.3 2	8 1
8	832.7 1	$\frac{11}{2}^{+}, \frac{9}{2}^{+}$	8→2	616.9 3	uncertain [c]
			8→0	832.8 1	uncertain [c]
9	855.45 12	$\frac{7}{2}^{+}$	9→3	531.05 10	6.3 2
			9→2	639.7 1	13.7 8
			9→0	855.4 1	80 3
10	861.6 1		10→2	645.8 2	14 5
			10→0	861.6 1	86 1
11	895.3 2	$(\frac{7}{2}^{-})$	11→2	679.6 1	96 5
			11→0	895.4 2	4 3
12	940.4 2	$\frac{3}{2}^{\pm}$	12→4	360.0 3	3 2
			12→3	616.0 3	95 4
			12→2	(724.7 1)	2 1
13	946.8 2	$\frac{3}{2}^{-}$	13→4	366.6 2	18 2
			13→1	850.1 1	82 4
14	969.7 2	$\frac{7}{2}^{+}$	14→9	114.3 3 [d]	1.0 5 [b]
			14→7	184.7 4	2 1
			14→3	645.2 2	39 5
			14→2	753.9 1	57 3
			14→0	969.9 3	1.0 5
15	994.7 2	$\frac{3}{2}^{(-)}$	15→3	670.2 1	90 4
			15→1	898.0 3	10 2
16	1004.1 2		16→3	679.6 1	100
17	1049.2 2	$(\frac{3}{2}^{-})$	17→5	392.2 1	38 2
			17→4	469.2 1	23 3
			17→3	724.7 1	39 3
18	1126.6 1	$\frac{11}{2}^{+}$	18→2	911.0 2	26 3
			18→0	1126.6 1	74 4

TABLE I. *(Continued)*.

Level No.	Level energy (keV) [a]	J^{π}	Transition	γ-ray energy (keV)	Branching (%)
19	1141.2 2	$(\frac{3}{2}-\frac{7}{2})^{+}$	19→7	356.2 1	26 3
			19→3	816.7 1	70 5
			19→2	925.5 3	4 1
20	(1160.6 3)		20→2	945.0 4	30 5
			20→0	1160.5 3	70 6
21	(1165.2 6)		21→2	949.5 5	100
22	(1194.3 6)		22→2	978.6 5	100
23	1199.5 3	$\frac{9}{2}^{+}$	23→3	875.3 2	15 2
			23→2	983.5 2	44 4
			23→0	1199.0 4	41 7
24	1219.9 3	$(\frac{5}{2}-\frac{9}{2})^{+}$	24→3	895.4 2	45 4
			24→2	1004.2 2	10 3
			24→0	1219.8 2	45 3
25	1240.0 2	$\frac{5}{2}^{-}, \frac{7}{2}^{-}$	25→5	583.16 5	49 2
			25→4	659.6 1	43 2
			25→3	915.7 2	8 4
			25→2	1024.4 2	14 4
26	1274.6 5		26→5	617.5 3	76 3
			26→4	694.8 6	24 1
			26→1	(1179)	
27	1277.8 3		27→9	(422.6)	
			27→5	620.9 1	86 3
			27→2	1062.0 4	14 2
28	1310.1 2	$\frac{9}{2}^{+}, \frac{7}{2}^{+}$	28→2	1094.5 2	54 3
			28→0	1310.0 3	46 2
29	(1334.1 4)		29→3	1009.6 3	100
30	1349.0 3		30→3	1024.4 2	85 7
			30→2	1133.6 4	15 4
31	1372.0 2	$(\frac{3}{2}^{+})$	31→5	715.9 5	34 5
			31→4	793.2 4	21 4
			31→3	1048.0 6	22 4
			31→1	1275.0 5	23 3
32	1379.6 3		32→8	(547.2 2)	41 2
			32→3	1054.8 3	10 2
			32→2	1163.8 3	49 3
			32→0	(1380)	
33	1396.8 3		33→4	816.7 1	75 6
			33→1	1300.0 6	35 5
34	1401.1 3		34→4	821.0 2	100
			34→1	(1304)	

TABLE I. *(Continued)*.

Level No.	Level energy (keV) [a]	J^π	Transition	γ-ray energy (keV)	Branching (%)
35	1409.7 3		35→5	752.7 4	41 4
			35→3	1084.9 4	37 4
			35→2	1193.8 2	63 3
36	1423.4 6		36→3	1099.3 5	79 4
			36→2	1207.4 5	21 2
37	(1480.3 6)		37→5	823.4 5	100
38	1512.1 3	$(\frac{5}{2}^{\pm})$	37→5	855.4 1	33 2
			37→3	1187.7 3	54 2
			37→2	1296.0 6	13 1
39	1518.4 4	$\frac{1}{2},\frac{3}{2}^-$	39→4		66 3
			39→1	1422.0 5	34 2
40	1522.7 4		40→3	1198.4 3	86 4
			40→2	1306.5 8	14 2
41	1579.9 6	$\frac{3}{2}^+,\frac{5}{2}^-$	41→5	923.9 6	46 2
			41→4	999.0 5	30 2
			41→3	1255.1 5	11 1
			41→2	1364.4 5	13 1
			41→1	(1483.0 5)	
42	1636.9 14		42→5	980.0 3	100
43	1649.3 8		43→7	864.5 9	29 5
			43→3	1324.7 6	71 6
44	1676.1 7		44→4	1096.0 6	68 7
			44→3	1351.7 6	32 4
45	1692.4 5		45→3	1367.6 9	19 5
			45→2	1476.9 4	81 6
46	1707.2 8		46→7	922.2 6	37 6
			46→5	1049.5 10	13 5
			46→3	1382.6 4	33 5
			46→2	1492.0 7	17 5
47	1733.1 7		47→4	1152.7 9	34 5
			47→2	1517.5 5	66 5
48	1754.6 10		48→2	1539.4 8	26 5
			48→0	1754 1	74 4
49	1778.4 9		49→7	992.7 9	62 5
			49→2	1563.3 8	38 2
50	1797.0 10		50→7	1011.2 9	40 4
			50→5	1141.3 10	24 4
			50→3	1472.3 8	36 5
51	1816.0 8		51→3	1491.1 7	70 6
			51→2	1600.6 9	30 4

TABLE I. *(Continued)*.

Level No.	Level energy (keV) [a]	J^{π}	Transition	γ-ray energy (keV)	Branching (%)
52	1844.7 10		52→2	1629.6 9	26 4
			52→0	1844 1	74 3
53	1850.5 5		53→5	1193.6 4	100
54	1855.7 9		54→3	1530.8 10	32 3
			54→2	1640.5 8	68 5
55	1859.0 11		55→5	1202.5 10	56 5
			55→4	1278.4 10	44 5
56	1864.2 8		56→3	1539.4 8	86 6
			56→2	1648.7 7	14 3
57	1914.9 10		57→7	1128.3 9	75 5
			57→3	1590.0 9	25 3
58	1918.7 11		58→7	1133.2 10	19 3
			58→5	1261.3 9	43 4
			58→3	1595.0 10	38 4
59	1924.0 8		59→5	1267.1 6	76 4
			59→4	1343.5 7	18 3
			59→3	1599.8 10	6 3
60	1949.2 5		60→7	1164.2 3	68 4
			60→3	1624.6 7	32 4
61	1986.3 11		61→5	1329.5 10	49 4
			61→4	1406.1 9	51 4
62	2000.6 8		62→5	1343.5 7	28 3
			62→4	1420.6 6	72 5
63	2023.3 9		63→4	1443.1 8	100
64	2035.4 9		64→5	1378.5 8	100
65	2068.5 7		65→5	1411.6 6	100
66	2120.0 10		66→4	1539.9 9	100
67	2149.4 11		67→5	1492.5 10	100
68	2201.3 11		68→5	1544.4 10	100
69	2207.9 11		69→4	1627.8 10	100

[a] Level energy obtained as a weighted average of the energy sums of γ rays deexciting each level. The underlined numbers in all columns are the estimated uncertainties referring to the last quoted significant figures.
[b] Branching ratio from Ref. 21.
[c] See text.
[d] Energies from Ref. 21.

Perey.[30] The distributions were further analyzed with the program MINUIT,[31] which was modified in this laboratory, in a search for a precise minimum X^2 in which a step in δ of 0.001 was used. The theoretical A_2 and A_4 coefficients from these calculations for various assumptions on the spin of the decaying state are given in Table III below the corresponding experimental quantities. Initial spin values were considered in a range permitted by the modes of decay of the state under consider-

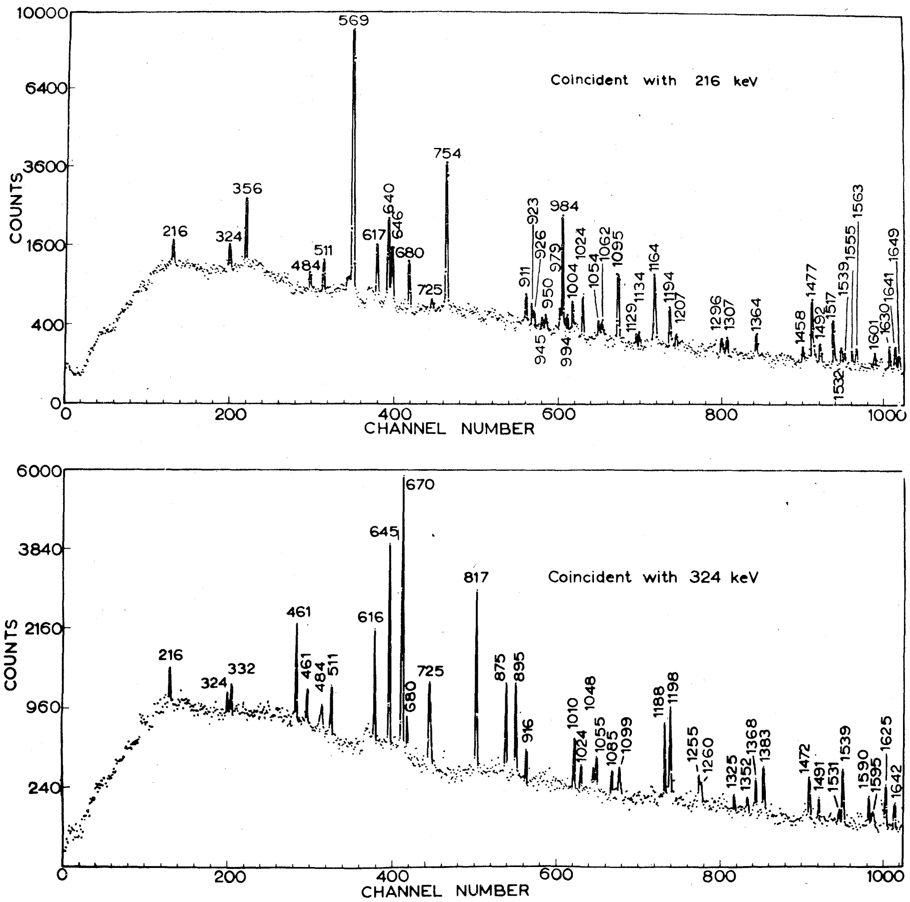

FIG. 3. Spectra of the γ rays from the $^{97}Mo(P,n\gamma)$ ^{97}Tc reaction at 4.0 MeV in coincidence with the indicated γ ray peaks. The contribution from the underlying Compton events has been subtracted.

ation. Spin value limits imposed by the fact that certain states were populated in the decay of ^{97}Ru were also taken into account. The parity values used in the calculations are indicated also in Table III. The parity is not given when no significant difference in the results was obtained by parity change. The minimum X^2 value divided by the degrees of freedom and the corresponding δ value at the minimum are contained in the fourth and fifth columns of Table III. The uncertainties quoted with the present δ values refer to the 95.5% confidence limit and are evaluated according to the procedure prescribed by Rogers.[32] The mixing ratio δ is defined in terms of emission matrix elements according to Krane and Steffen.[33] In the last column of Table III the proposed δ value is contained, which in some instances is a weighted average of currently and previously determined values. In most cases, however, for which no previous values are available, of the currently determined δ values the one repeated in the last column serves to mark the most probable J^π value, which has been selected according to criteria delineated below. In some cases, the comparison between the experimental relative cross section for direct formation of a level and the predictions of the statistical theory obtained with MANDY,[28] helped to eliminate some J^π values. The experimental cross sections were obtained by summing the intensities of the γ rays deexciting a level and subtracting the feeding from higher-lying states.

III. PROPOSED DECAY SCHEME AND ASSIGNMENT OF J^π VALUES

From the evidence obtained in the present work, a detailed scheme of the decay of many new states in ^{97}Tc was constructed and it is shown in Figs. 5 and 6. Some of the previously proposed levels were rejected while those adopted were unambiguously reobserved here. The position and decay of many levels have been established by the works

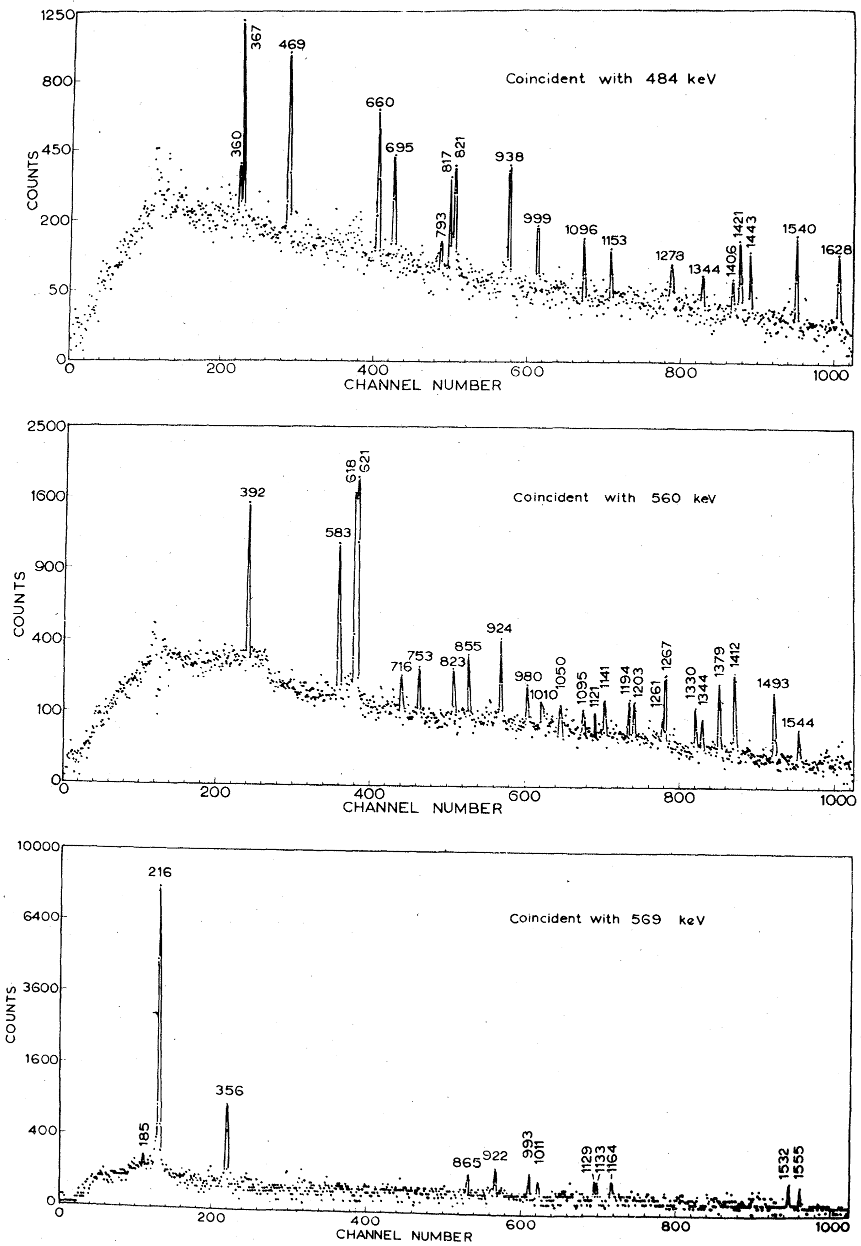

FIG. 4. Spectra of the γ rays from the ^{97}Mo $(p,n\gamma)$ ^{97}Tc reaction at 4.0 MeV in coincidence with the indicated γ-ray peaks. The contribution from the underlying Compton has been subtracted.

summarized in Ref. 26 and by Huber and Krämer.[21] In what follows, arguments are given for more definitive J^π assignments of previously established levels and for the proposed new levels and their J^π values based on evidence from this work.

The $\frac{9}{2}^+$ ground and $\frac{1}{2}^-$ isomeric state in ^{97}Tc were assigned from previous work and systematics.[13,26]

The J^π assignment for the 215.7 keV level is definitely $\frac{7}{2}^+$ on the basis of the angular distribution which excludes a $\frac{5}{2}^+ \to \frac{9}{2}^+$ sequence for this transition. The present angular-distribution measurements give $\delta(E2/M1) = 0.31 \pm 0.05$ which corresponds to $(8.8 \pm^{3.6}_{3.2})\%$ $E2$ admixture. This result is in good agreement with the average of (7 ± 4) and $(10 \pm 4)\%$ $E2$ reported in Refs. 20 and 22, respectively, from measurements of k-conversion coefficients. In an angular distribution measurement following the decay of oriented ^{97}Ru nuclei Barclay *et al.*[24] have extracted a mixing ratio of 0.27 ± 0.02, while $\delta(216) = 0.20 \pm 0.05$ was deter-

TABLE II. Summary of the observed $\gamma\gamma$-coincidence relationships in the decay of levels in ^{97}Tc populated in the ^{97}Mo($p,n\gamma$) reaction at E_p=4.0 MeV.

Fig.	γ-ray energy in the Ge(Li) gate (keV)	γ-ray seen in the Ge(Li) coincidence spectrum (keV)
2	216	569, 617, 640, 646, 680, 725, 754, 911, 926, 945, 950, 979, 984, 1004, 1024, (1054), 1062, 1095, (1134), 1164, 1194, (1207), (1296), (1307), 1364, 1477, 1492, 1517, 1539, 1563, (1601), 1630, 1641, 1649
2	324	332, 461, 531, 616, 645, 670, 680, 725, 817, 875, 895, 916, 1010, 1024, (1048), 1055, 1085, 1099, 1188, 1198, 1255, (1260), (1325), (1352), (1368), 1383, 1472, (1491), (1531), 1539, (1590), (1595), 1625, 1642
3	484	360, 367, 469, 660, 695, 793, 817, 821, 938, 999, 1096, 1153, 1278, (1344), (1406), 1421, 1443, 1540, 1628
3	560	392, 583, 618, 621, 716, 753, 823, 855, 924, 980, 1010, (1050), (1095), (1121), 1141, 1194, 1203, (1261), 1267, 1330, 1344, 1379, 1412, 1493, 1544
3	569	185, 216, 356, (865), 922, 993, 1011, (1129), 1133, (1164), 1532, 1555

mined by Beshai *et al.*[25] by angular correlation measurements.

The 324.5 keV state is populated in the ^{97}Ru decay by an allowed transition.[21] This and its mode of decay to $\frac{7}{2}^+$ and $\frac{9}{2}^+$ states limits its J^π value to $\frac{5}{2}^+$ or $\frac{7}{2}^+$. No conclusive result can be obtained from the angular distribution of the 324.5 keV γ ray. As can be seen in Table III the data cannot distinguish between $J=\frac{5}{2}$ and $\frac{7}{2}$. Conversion coefficient measurements,[20] however, as well as the results of the (^{3}He,d) reaction study[11] have determined a $\frac{5}{2}^+$ J^π value for the 324.5 keV state.

The results obtained in the present study permit one to resolve a controversy which exists with respect to the fourth excited state in ^{97}Tc and clarify its position and decay properties. A level at 574 keV was assigned in the ^{97}Mo($p,n\gamma$) study to be deexcited by a very weak transition,[18] although this level had been observed to be populated with a large cross section in the ^{97}Mo(p,n) time-of-flight study.[16] This inconsistency can be resolved if the strong 483.6 keV transition is assigned to deexcite a level at 580.1 keV to the 96.5 keV metastable state. This assignment is supported by the excitation function measurements, as well as by the $\gamma\gamma$-coincidence results which assigned transitions to the 580.1 keV level from established states of higher excitation energy. The present results fully substantiate a similar suggestion based on the evidence of a very weak 483.76 keV γ ray observed in the most recent ^{97}Ru decay study.[21] A level at 575 keV was inferred as a $\frac{3}{2}^-$ level in a study via the neutron decay of analog states,[17] while this level was also observed in the (^{3}He,d) reaction[11] to be populated with $l=1$. The distribution of the 483.6 keV γ ray measured here permits a definite $\frac{3}{2}^-$ spin assignment to the 580.1 keV state since it is not consistent with $\frac{1}{2}$ or $\frac{5}{2}$ possibilities.

The level at 656.9 keV was assigned as $\frac{5}{2}^-$ by Kim, Robinson, and Johnson from angular correlation measurements of the emitted neutrons in the ^{97}Mo(p,n) reaction,[17] while it was observed to be populated in the (^{3}He,d) reaction[11] with $l=3$. This level was found in the present study to decay mainly to the $\frac{1}{2}^-$ 96.5 keV state and by a weak branch to the $\frac{5}{2}^+$ 324.46 keV state. The angular distribution of the 560.35 keV transition is consistent with the previous $\frac{5}{2}^-$ assignment.

A new state at 772.6 keV is proposed on the following evidence. A 772.6 keV γ ray was observed in the excitation-function measurements, Fig. 2, to originate from a level with excitation energy below 1 MeV. The fact that this γ ray is not observed in coincidence with either the 215.7 or 324.5 keV γ rays indicates that the 772.6 keV transition proceeds either to the ground or the meta-

TABLE III. Summary of angular distribution analysis.

Transition (keV) $J_i^\pi \to J_f^\pi$	A_2 Experimental [a] Theoretical	A_4	X^2	Mixing ratio Present	Previous	Proposed [b]
215.7 → 0	−0.08 $\underline{2}$	−0.01 $\underline{2}$				
$\frac{5}{2}^+ \to \frac{9}{2}^+$	−0.04	0.00	9.4			
$\frac{7}{2}^+ \to \frac{9}{2}^+$	−0.08	0.00	0.2	0.31 ± 0.05	0.27 ± 0.02 [c]	0.27 ± 0.03
					0.20 ± 0.05 [d]	
324.5 → 215.7						
$\frac{5}{2}^+ \to \frac{7}{2}^+$					1.6 ± 0.4 [d]	1.6 ± 0.4
324.5 → 0	−0.05 $\underline{2}$	−0.02 $\underline{2}$				
$\frac{5}{2}^+ \to \frac{9}{2}^+$	−0.04	0.00	0.5	any δ	$E2$ [e]	$E2$
$\frac{7}{2}^+ \to \frac{9}{2}^+$	−0.04	0.00	0.5	0.20 ± 0.05		
580.1 → 96.5	−0.04 $\underline{2}$	−0.01 $\underline{2}$				
$\frac{3}{2}^- \to \frac{1}{2}^-$	−0.01	0.00	1.6	−0.6 ± 0.5		−0.6 ± 0.5
$\frac{5}{2}^- \to \frac{1}{2}^-$	0.01	0.00	3.8	any δ		
656.9 → 96.5	−0.007 $\underline{15}$	−0.002 17				
$\frac{3}{2}^- \to \frac{1}{2}^-$	−0.005	0.000	0.8	$-0.07^{+0.17}_{-0.22}$		
$\frac{5}{2}^- \to \frac{1}{2}^-$	0.011	0.006	1.3	−0.5 ± 0.6		$E2$
772.6 → 0	0.21 $\underline{4}$	−0.05 $\underline{4}$				
$\frac{7}{2} \to \frac{9}{2}^+$	0.06	0.00	3.1	−0.9 ± 0.3		
$\frac{9}{2} \to \frac{9}{2}^+$	0.16	0.00	0.8	0.37 ± 0.38		
$\frac{11}{2} \to \frac{9}{2}^+$	0.18	0.01	0.7	0.40 ± 0.09		
$\frac{13}{2}^+ \to \frac{9}{2}^+$	0.20	−0.03	0.4	−0.05 ± 0.08		$E2$
772.6 → 96.5						
$\frac{3}{2} \to \frac{1}{2}^-$	0.01	0.00	7.0			
$\frac{5}{2}^- \to \frac{1}{2}^-$	0.04	−0.01	3.0			
785.1 → 324.5	0.07 $\underline{8}$	0.03 $\underline{11}$				
$\frac{5}{2}^+ \to \frac{5}{2}^+$	0.03	0.01	0.6	$0.5^{+0.1}_{-0.4}$	−1.6 ± 0.4 or −0.01 ± 0.10 [d]	
					$-0.56^{+0.43}_{-0.31}$ [f]	−0.01 ± 0.10
785.1 → 215.7	−0.02 $\underline{2}$	−0.03 $\underline{2}$				
$\frac{5}{2}^+ \to \frac{7}{2}^+$	−0.04	0.00	0.9	$0.67^{+0.24}_{-0.67}$	0.12 ± 0.05 or >16 [c]	
					0.13 ± 0.05 or 2.8 ± 0.5 [d]	
					0.128 ± 0.014 or 2.84 ± 0.13 [f]	0.128 ± 0.014
832.7 → 0	0.15 $\underline{4}$	0.04 $\underline{4}$				
$\frac{7}{2} \to \frac{9}{2}^+$	0.07	0.00	2.8	−0.9 ± 0.3		
$\frac{9}{2} \to \frac{9}{2}^+$	0.17	0.00	0.6	0.3 ± 0.4		
$\frac{11}{2} \to \frac{9}{2}^+$	0.18	0.01	0.5	0.4 ± 0.1		
or	0.16	0.04	0.4	4.4 ± 0.1		0.4 ± 0.1 or 4.4 ± 0.1
$\frac{13}{2}^+ \to \frac{9}{2}^+$	0.20	−0.03	0.8	−0.1 ± 0.1		
855.5 → 215.7	−0.11 $\underline{4}$	0.07 $\underline{5}$				
$\frac{5}{2}^+ \to \frac{7}{2}^+$	−0.04	0.00	3.8	$1.2^{+0.1}_{-0.8}$		

TABLE III. *(Continued)*.

Transition (keV) $J_i^\pi \to J_f^\pi$	A_2 Experimental[a] Theoretical	A_4	X^2	Mixing ratio Present	Previous	Proposed[b]
$\frac{7}{2}^+ \to \frac{7}{2}^+$	−0.05	0.00	3.6	$-2.3^{+0.6}_{-0.1}$		$-2.3^{+0.6}_{-0.1}$
855.5 → 0	−0.09 2	0.03 2				
$\frac{5}{2}^+ \to \frac{9}{2}^+$	−0.03	0.00	3.1	1.7 ± 0.5		
$\frac{7}{2}^+ \to \frac{9}{2}^+$	−0.08	0.00	1.8	0.3 ± 0.2		0.3 ± 0.2
861.6 → 0	−0.02 2	0.01 3				
$\frac{5}{2}^+ \to \frac{9}{2}^+$	0.01	0.00	1.5	any δ		
$\frac{7}{2} \to \frac{9}{2}^+$	−0.03	0.00	1.0	any δ		
$\frac{9}{2} \to \frac{9}{2}^+$	−0.03	0.00	1.0	−0.75 ± 0.3		
940.4 → 324.5	0.06 4	−0.00 5				
$\frac{3}{2}^+ \to \frac{5}{2}^+$	0.02	0.00	2.0	$1.2^{+0.2}_{-1.3}$		
$\frac{5}{2}^- \to \frac{5}{2}^+$	0.03	0.00	1.7	$0.6^{+0.1}_{-0.4}$		
$\frac{7}{2}^- \to \frac{5}{2}^+$	0.05	0.00	1.6	$0.4^{+0.4}_{-0.2}$		
946.8 → 96.5	−0.03 3	−0.02 3				
$\frac{3}{2}^- \to \frac{1}{2}^-$	−0.006	0.00	0.7	any δ		$M1+E2$
$\frac{5}{2}^- \to \frac{1}{2}^-$	0.007	0.01	1.2	$-0.7^{+0.2}_{-0.1}$		
969.7 → 215.7	−0.06 4	−0.03 4				
$\frac{5}{2}^+ \to \frac{7}{2}^+$	−0.04	0.00	1.0	1.1 ± 0.5	19^{+15}_{-6} [d]	
$\frac{7}{2}^+ \to \frac{7}{2}^+$	−0.05	0.00	0.8	−2.2 ± 0.8	−0.16 ± 0.2 or −3.9 ± 0.7[d]	−3.2 ± 0.7
994.7 → 324.5	−0.04 4	−0.03 5				
$\frac{3}{2}^+ \to \frac{5}{2}^+$	−0.005	0.00	0.4	−0.8 ± 0.3		
$\frac{3}{2}^- \to \frac{5}{2}$	−0.004	0.00	0.4	any δ		$E1$
1049.2 → 656.9	−0.03 4	0.00 4				
$\frac{3}{2}^+ \to \frac{5}{2}^-$	−0.005	0.00	0.6	$-0.8^{+0.5}_{-0.2}$		
$\frac{3}{2}^- \to \frac{5}{2}^-$	−0.003	0.00	0.6	any δ		$E1$
$\frac{5}{2}^+ \to \frac{5}{2}^-$	−0.01	0.00	0.5	$-1.8^{+0.5}_{-0.2}$		
$\frac{5}{2}^- \to \frac{5}{2}^-$	−0.01	0.00	0.5	$-1.6^{+0.3}_{-0.2}$		
1049.2 → 580.1	−0.16 7	0.15 11				
$\frac{3}{2}^- \to \frac{3}{2}^-$	−0.01	0.00	2.4	any δ		$E1$
$\frac{5}{2} \to \frac{3}{2}^-$	−0.04	0.00	2.0	−0.8 ± 0.8		
$\frac{7}{2}^- \to \frac{3}{2}^-$	0.00	0.01	2.5	−0.9 ± 0.4		
1126.6 → 0	−0.50 9	−0.01 14				
$\frac{5}{2}^+ \to \frac{9}{2}^+$	−0.02	0.00	5.4	$1.7^{+0.1}_{-1.1}$		
$\frac{7}{2} \to \frac{9}{2}^+$	−0.12	0.00	3.6	1.1 ± 0.5		
$\frac{9}{2} \to \frac{9}{2}^+$	−0.12	−0.01	3.6	−2.8 ± 0.4		
$\frac{11}{2}^+ \to \frac{9}{2}^+$	−0.50	0.02	0.8	$-0.7^{+0.4}_{-0.5}$		$-0.7^{+0.4}_{-0.5}$

TABLE III. *(Continued).*

Transition (keV) $J_i^\pi \to J_f^\pi$	A_2 Experimental[a] Theoretical	A_4 Experimental[a] Theoretical	X^2	Mixing ratio Present	Mixing ratio Previous	Mixing ratio Proposed[b]
1141.2 → 785.1	−0.09 8	−0.04 10				
$\frac{3}{2}^+ \to \frac{5}{2}^+$	−0.006	0.00	0.6	$-0.8^{+0.5}_{-0.2}$		
$\frac{5}{2} \to \frac{5}{2}^+$	−0.02	0.00	0.5	−1.8 ± 0.3		
$\frac{7}{2} \to \frac{5}{2}^+$	−0.01	0.00	0.3	$-0.2^{+0.5}_{-0.3}$		
or	−0.10	−0.01	0.3	$-2.1^{+0.3}_{-0.6}$		
$\frac{9}{2}^+ \to \frac{5}{2}^+$	−0.04	−0.03	0.4	−1.0 ± 0.5		
1199.5 → 215.7	−0.24 8	0.06 11				
$\frac{5}{2}^+ \to \frac{7}{2}^+$	−0.03	0.00	1.7	$1.1^{+0.1}_{-1.1}$		
$\frac{7}{2} \to \frac{7}{2}^+$	−0.06	0.00	1.3	−2.2 ± 0.6		
$\frac{9}{2}^+ \to \frac{7}{2}^+$	−0.23	0.00	0.3	$-0.2^{+0.2}_{-0.4}$		
or	−0.23	0.01	0.3	−2.4 ± 0.3		
1199.5 → 324.5	0.07 7	−0.07 10				
$\frac{9}{2}^+ \to \frac{5}{2}^+$	0.07	0.00	0.6	$0.4^{+0.5}_{-0.9}$		
1219.9 → 215.7	0.03 11	0.04 14				
$\frac{5}{2}^+ \to \frac{7}{2}^+$	0.01	0.00	0.5	any δ		
$\frac{7}{2} \to \frac{7}{2}^+$	0.03	0.01	0.5	any δ		
$\frac{9}{2}^+ \to \frac{7}{2}^+$	0.03	0.01	0.5	0.30 ± 0.25		
1219.9 → 0	−0.02 8	0.05 10				
$\frac{5}{2}^+ \to \frac{9}{2}^+$	−0.02	0.00	0.2	any δ		
$\frac{7}{2} \to \frac{9}{2}^+$	−0.02	0.00	0.2	−0.1 ± 0.3		
$\frac{9}{2}^+ \to \frac{9}{2}^+$	−0.02	−0.01	0.2	3^{+2}_{-1}		
1240.0 → 656.9	−0.01 4	0.00 5				
$\frac{3}{2}^+ \to \frac{5}{2}^-$	−0.01	0.00	0.5	any δ		
$\frac{5}{2} \to \frac{5}{2}^-$	−0.01	0.00	0.5	any δ		
$\frac{7}{2}^- \to \frac{5}{2}^-$	−0.01	0.00	0.5	0.1 ± 0.2		
1277.8 → 656.9	0.08 6	0.03 5				
$\frac{3}{2}^+ \to \frac{5}{2}^-$	0.02	0.00	1.5	any δ		
$\frac{5}{2} \to \frac{5}{2}^-$	0.02	0.00	1.5	$0.5^{+\infty}_{-1.5}$		
$\frac{7}{2} \to \frac{5}{2}^-$	0.08	0.00	0.3	0.5 ± 0.4		
$\frac{9}{2}^- \to \frac{5}{2}^-$	0.08	−0.01	0.3	$-0.2^{+0.1}_{-0.2}$		
1310.1 → 215.7	−0.04 4	−0.02 5				
$\frac{7}{2}^+ \to \frac{7}{2}^+$	−0.04	0.00	0.5	$-1.0^{+0.5}_{-1.0}$		
$\frac{9}{2}^+ \to \frac{7}{2}^+$	−0.04	0.00	0.5	0.10 ± 0.05		

[a] The underlined numbers are estimated uncertainties referring to the last quoted significant figures.
[b] The proposed δ value marks the most probable spin.
[c] From Ref. 24.
[d] From Ref. 25.
[e] From Ref. 20.
[f] From Ref. 23.

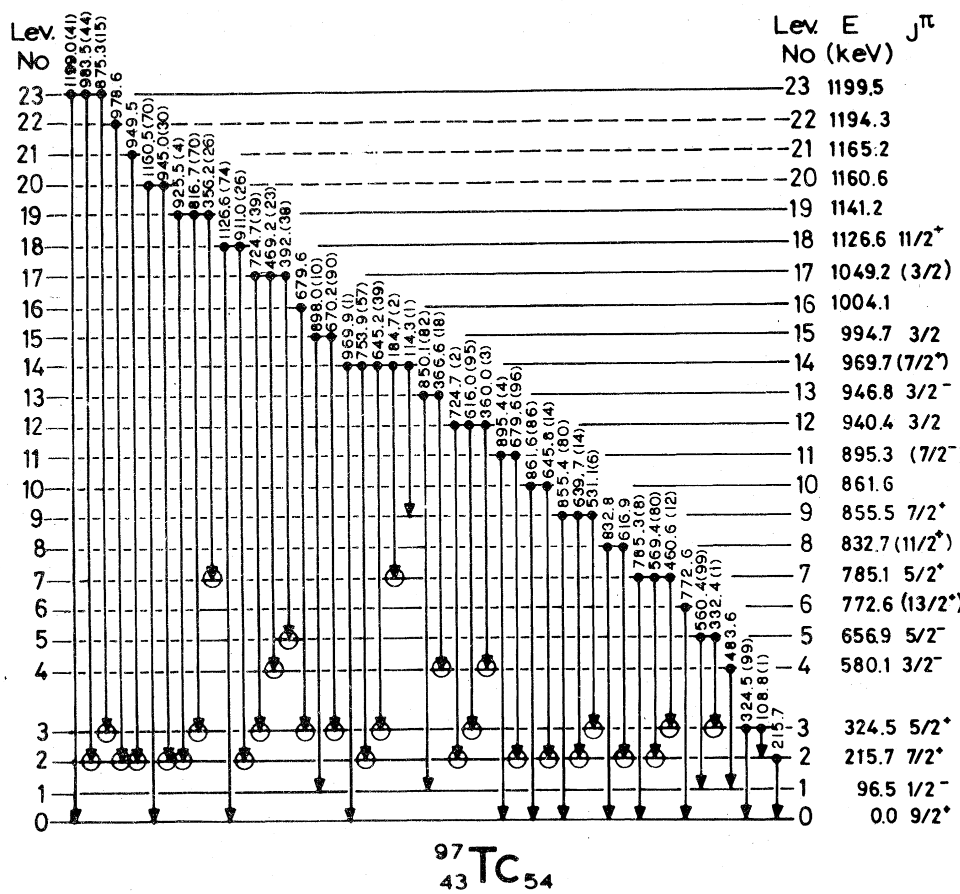

FIG. 5. Proposed scheme for the decay of levels in ^{97}Tc following excitation via the ^{97}Mo $(p,n\gamma)$ reaction. Only the first 41 levels are shown in this figure. The energies are in keV and the numbers in parentheses are the percent branching fractions for γ decay. The open circles indicate coincidence relationships.

stable state. A substantial relative increase in the intensity of the 772.6 keV γ ray observed in a bombardment at 8.0 MeV suggests high J value for this level and consequently feeding to the $\frac{9}{2}^+$ ground state. Such an assignment is, furthermore, supported by the measured angular distribution of the 772.6 keV γ ray which, as can be seen in Table III, was found consistent with $\frac{9}{2}\rightarrow\frac{9}{2}^+$, $\frac{11}{2}\rightarrow\frac{9}{2}^+$, or $\frac{13}{2}^+\rightarrow\frac{9}{2}^+$, but incompatible with $\frac{3}{2}\rightarrow\frac{1}{2}^-$ or $\frac{5}{2}^-\rightarrow\frac{1}{2}^-$ sequence which would be the case if the transition proceeds to the metastable state. The negative A_4 term, furthermore, suggests the $\frac{13}{2}^+\rightarrow\frac{9}{2}^+$ sequence.

The level at 785.1 keV and its decay are well established.[26] Although a unique $\frac{5}{2}^+$ assignment has been adopted for this level,[26] it is only recently that the other possible value of $\frac{7}{2}^+$ has been excluded on the evidence of angular correlation measurements.[25] From the distribution of the 460.6 and 569.4 keV γ rays measured here, a unique mixing ratio for each of these two transitions was obtained. Previous correlation measurements[23-25] offered a pair of solutions for the mixing ratio for each of the above transitions. The present δ values, although they have comparatively large errors, coincide with only one of the two solutions previously reported for each transition, thus helping to select unique multipole mixing ratios.

The present data confirm a level at about 833 keV tentatively proposed by Picone *et al.*[18] Specifically, a coincidence relationship was established between a 616.9 keV γ ray and the gate at 215.7 keV. Furthermore, an 832.8 keV γ ray was placed to deexcite this level to the ground state on the basis of good energy agreement. This γ ray was observed in the excitation-function measurements, Fig. 2, to originate from a level below 1 MeV, while an increased relative yield of this γ ray at 8.0 MeV bombardment indicated a high J value of the 832.7 keV level. A complication arises from the fact that the ratio of the intensities of the 832.8 and 616.9 keV γ rays does not remain constant as a function of bombardment energy. One therefore

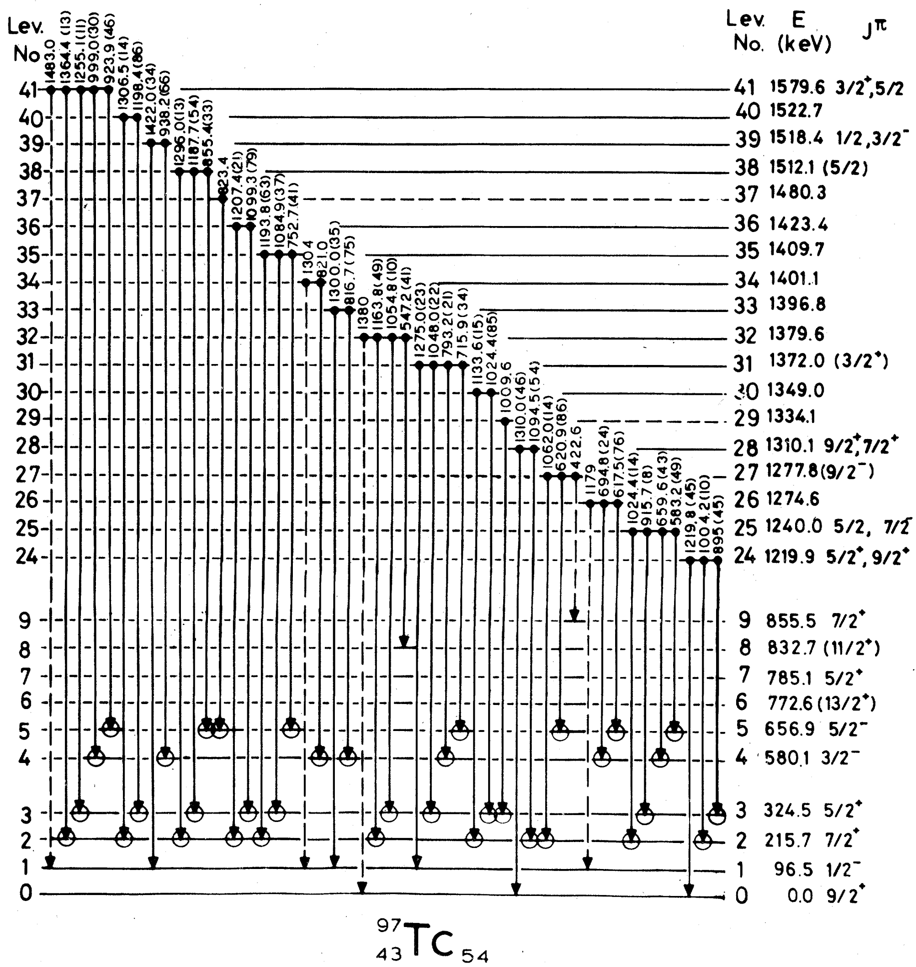

FIG. 5. (*Continued*).

must conclude that either one at least of these γ rays is an unresolvable doublet, or there exist two states at the same excitation. We are in favor of the latter possibility. The angular distribution of the 832.7 keV γ ray was found to be consistent with $\frac{9}{2}$, $\frac{11}{2}$, and $\frac{13}{2}$ J values. The positive value of the A_4 term favors a $\frac{9}{2}$ or $\frac{11}{2}$ assignment.

The state at 855.45 keV is well established.[26] The previous results suggest $\frac{5}{2}^+$ or $\frac{7}{2}^+$ J^π possibilities. The currently measured distribution of the 855.43 γ ray clearly selects the $\frac{7}{2}^+$ value.

A new level at 861.4 keV was identified in this work on the basis of a 645.5 keV γ ray which was observed in coincidence with the 215.7 keV gate. An 861.5 keV γ ray was assigned to deexcite this level to the ground state on the basis of good energy agreement. The angular distribution of this latter γ ray was found isotropic within the experimental error, therefore no conclusive information about J^π values of this newly proposed level at 861.4 keV could be extracted. It should be added that the 645.5 keV γ photopeak is a doublet since it is also observed in coincidence with the 324.46 keV transition. This second 645.5 keV γ ray, however, is due to the deexcitation of the 969.7 keV level to the one at 324.5 keV.

A level at 896 keV tentatively adopted previously[26] has been reestablished at 895.3 keV, on the evidence of a 679.6 keV γ ray which was observed in coincidence with the 215.7 keV gate and a 895.3 keV γ ray which was observed in the singles spectra. The latter was assigned to deexcite this level to the ground state with small intensity. However, the photopeaks of the 679.6 and 895.3 keV γ rays which gave evidence for the proposed level at 895.3 keV appear to be doublets. First, a 679.6 keV γ ray was also observed in coincidence with the 324.46 keV transition and was assigned to deexcite a level at 1004.2 keV, as it is discussed later. Furthermore, the $\gamma\gamma$ coincidence measurements indicated that the 895.3 keV γ ray originated mostly from a level at 1219.9 keV. Nevertheless, the

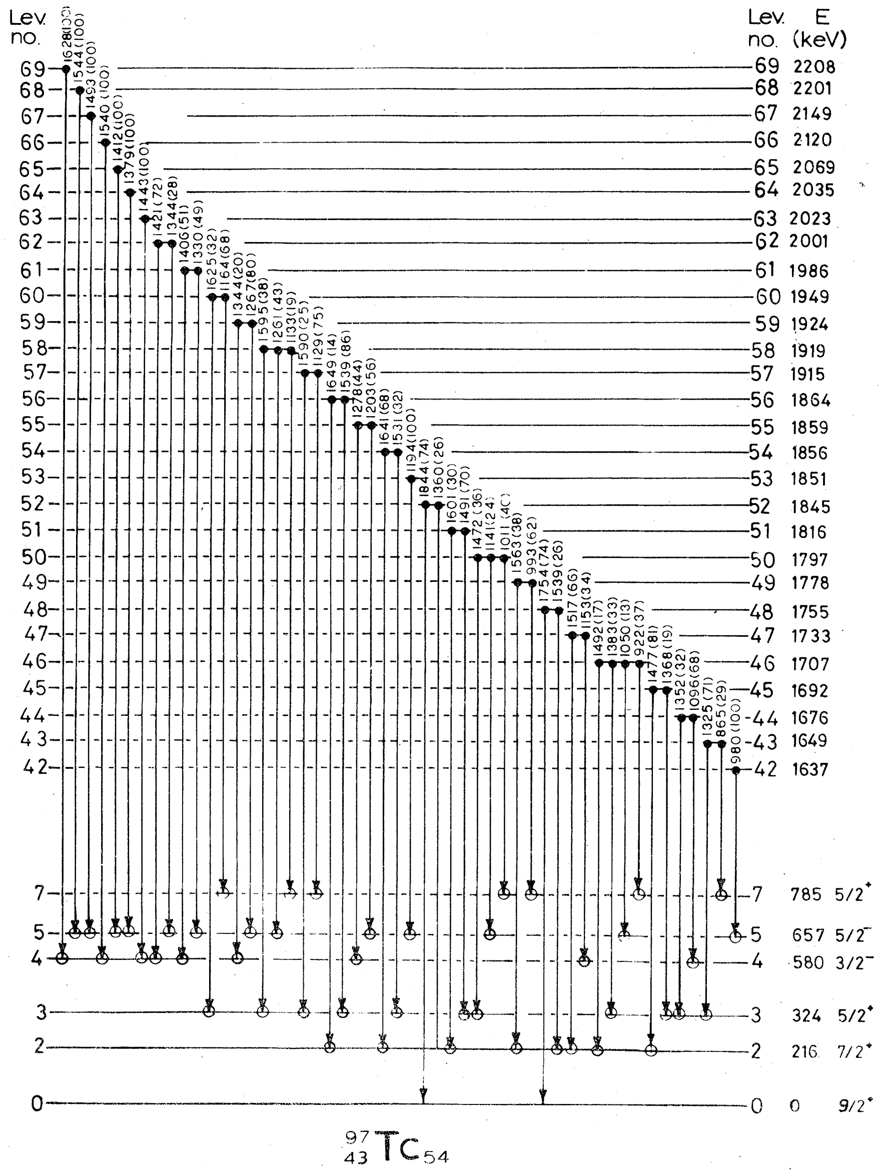

FIG. 6. Proposed scheme for the decay of levels in ^{97}Tc following excitation via the ^{97}Mo ($p,n\gamma$) reaction. Only levels No. 42 through 69 are shown together with those below which are populated in their decay. The energies are in keV and the numbers in parentheses are the percent branching fractions for γ decay. The open circles indicate coincidence relationships.

coincidence data indicated also that the transition from the 1219.9 keV level to the one at 324.5 keV does not exhaust the intensity of the 895.3 keV γ ray. Thus a transition from the 895.3 keV level to the ground state was adopted on the basis of good energy agreement. The fact that this level was not populated in the decay of ^{97}Ru and its modes of decay suggests a $\frac{7}{2}^-$ J^π assignment.

A level at 940.0 keV has been previously identified and a $(\frac{1}{2}, \frac{3}{2})^-$ J^π assignment has been proposed.[26] In addition to the 616.0 keV transition deexciting this level to the 324.5 keV level, two weak transitions to the 215.7 and 580.1 keV levels below have been identified from coincidence evidence. The modes of decay of the 940.3 keV level established here permit $\frac{3}{2}^\pm$, $\frac{5}{2}^\pm$, or $\frac{7}{2}^\pm$ J^π possibilities, while the lack of population of this level in the decay of ^{97}Ru indicates negative parity. The $\frac{7}{2}^-$ and $\frac{5}{2}^-$ values, however, seem less probable since the analysis of the 616.0 keV γ ray demonstrated that it would contain a large $M2$ contribution. Thus, the $\frac{3}{2}^\pm$ value is adopted as the most probable.

A state at 946 keV which had been tentatively proposed by Phelps and Sarantites[20] was not adopted in consequent studies of ^{97}Tc. Our data confirmed the existence of a level at 946.8 keV since the coincidence results established the decay of such a level to the $\frac{3}{2}^-$ level at 580.1 keV. The 850.3 keV transition from this level to the $\frac{1}{2}^-$ metastable state, proposed by Phelps and Sarantites[20] was also adopted in the present study. The fact that this level is very weakly populated in the decay of ^{97}Ru selects the $J^\pi = \frac{3}{2}^-$ and $\frac{5}{2}^-$ possibilities from the three J values permitted by the mode of decay of the 946.8 keV level. The distribution of the 850.1 keV γ ray favors the $\frac{3}{2}^-$ because of the high $M3$ contribution obtained when a $\frac{5}{2}^-$ value is assumed. The $\frac{3}{2}^-$ assignment to the 946.8 keV state permits one to associate it with a $\frac{3}{2}^-$ or $\frac{1}{2}^-$ level observed in reaction-particle studies at similar excitation.[11,26]

The level at 969.7 keV and its decay have been well characterized.[21,26] Since this level is strongly populated in the EC decay of ^{97}Ru its J^π value is limited to $\frac{5}{2}^+$ and $\frac{7}{2}^+$, with the $\frac{3}{2}^+$ value excluded due to the decay to the $\frac{9}{2}^+$ ground state. The measured angular distribution of the 753.9 keV γ ray is consistent with both $\frac{5}{2}^+$ and $\frac{7}{2}^+$ J^π values. Beshai *et al.*[25] have determined the mixing ratio of the 753.9 keV transition for both $\frac{5}{2}^+$ and $\frac{7}{2}^+$ cases. The fact that the mixing ratio determined here and that of Beshai *et al.*[25] agree only for the latter J^π value indicates a $\frac{7}{2}^+$ assignment to the 969.7 keV level.

The state at 994.7 keV has been previously established[21,26] and a $J^\pi = \frac{3}{2}^\pm$ assignment has been proposed on the basis of $\log ft$ value and its mode of decay. The measured angular distribution of the 670.22 keV γ ray is compatible with both parity values.

A new level at 1004.1 keV is proposed on the basis of an observed coincidence of a γ ray at 679.6 keV with the 324.46 keV gate.

The existence of a level at about 1049.2 keV has been previously established.[18] The J^π value and even the position of this level, however, have been the subject of some controversy. In the present work this level has been also identified, with the additional evidence of a 469.2 keV γ ray which was observed in coincidence with the 483.6 keV gate and thus was assigned to deexcite the 1049.2 keV level to the $\frac{3}{2}^-$ 580.1 keV state. A $(\frac{5}{2})^-$ value has been adopted by Medsker[26] on the evidence of the (p,γ) study.[19] It is clear, however, that the 1060 keV level proposed in Ref. 19 and that at 1049.2 keV do not coincide, as was assumed by Medsker,[26] since different decay modes are reported. No evidence for a level at 1060 keV deexciting to the 215.7 keV state has been obtained in the present study. The mode of decay of the 1049.2 keV level permits $\frac{3}{2}^\pm$, $\frac{5}{2}^\pm$, and $\frac{7}{2}^-$ J^π values. The $\frac{5}{2}^+$ and $\frac{7}{2}^-$ values can be rejected because of the high $M2$ and $M3$ contribution obtained in the analysis of the 392.2 and 469.2 keV γ ray distribution when a $\frac{5}{2}^+$ or $\frac{7}{2}^-$ value is assumed. The $\frac{3}{2}$ and $\frac{5}{2}^-$ values, however, remain equally probable. The relative cross section for the production of this level favors the $\frac{3}{2}^-$ value. One can rather safely associate the 1049.2 keV level with an 1053 keV level observed to be populated with an $l=1$ stripping in the $(^3\text{He},d)$ reaction.[11]

A level at 1126.6 keV has been previously identified in the ^{97}Mo$(p,n\gamma)$ study.[18] In the present work this level was confirmed on the evidence of an observed coincidence between a 911.0 keV γ ray and the 215.7 keV gate. In an additional mode of its decay an 1126.6 keV γ ray was assigned to deexcite this level to the ground state on the basis of good energy agreement and the excitation-function measurements. Of the $J^\pi = \frac{5}{2}^+$, $\frac{7}{2}^\pm$, $\frac{9}{2}^\pm$, and $\frac{11}{2}^+$ values permitted for this state by its mode of decay only the last is compatible with the measured distribution of the 1126.6 keV γ ray.

The level at 1141.2 keV is well established from the $(p,n\gamma)$ work.[18] The present data give evidence of an additional mode of decay of this level, namely, that to the $\frac{7}{2}^+$ 215.71 keV state. It should be mentioned that this state does not coincide with the 1138 keV level reported by Close and Bearse[19] because of the different decay modes observed. We found no indication for the existence of a level with the characteristics reported in Ref. 19. The distribution of the 356.2 keV γ ray excludes the $\frac{5}{2}^-$ and $\frac{9}{2}^+$ J^π possibilities.

Three new levels at 1160.6, 1165.2, and 1194.3 keV, have been identified on evidence based on coincidences. The cascade intensity of the related γ rays was rather low, so these three levels are tentatively proposed.

A level at 1199.5 keV has been previously established in the $(p,n\gamma)$ study.[18] The angular distribution of the 983.5 keV γ ray does not differentiate between $\frac{5}{2}$, $\frac{7}{2}$, or $\frac{9}{2}$ spin values.

The distribution of the γ rays deexciting the 1219.9 keV level cannot distinguish between the $\frac{5}{2}^+$, $\frac{7}{2}^\pm$, and $\frac{9}{2}^+$ J^π values permitted to this level by its mode of decay. The comparison of the relative cross section for the production of this level with the statistical model predictions helps to eliminate the negative parity.

A level at 1240.0 keV tentatively proposed previously[18] has been definitely established on the evidence of four observed coincidence relationships. The distribution of the 583.2 keV γ ray is compatible with all J values permitted by the decay mode. The relative cross section, however, favors the $\frac{5}{2}^-$ and $\frac{7}{2}^-$ values.

A new level at 1274.6 keV has been established and on evidence from the coincidences was found to decay to negative parity states.

A level at 1310.7 keV has been already identified and $\frac{7}{2}^+$ or $\frac{9}{2}^+$ possibilities have been proposed for its J^π value.[11,26] The measured distribution of the 1094.5 keV γ ray as well as the relative cross section has been found consistent with either of these J^π values.

Two new levels at 1334.1 and 1349.0 keV, of which the first is tentative, are proposed on the basis of observed coincidence relationships.

No evidence was obtained in support of the existence of a level at 1360 keV which has been previously proposed.[26]

A new level at 1372.0 keV has been identified from evidence based on coincidences. Its modes of decay permit $\frac{1}{2}^-$, $\frac{3}{2}^\pm$, and $\frac{5}{2}^-$ J^π values. On the basis of this information one can associate this level with a 1374 keV level observed in the (^{3}He,d) reaction study for which $\frac{3}{2}^+$ or $\frac{5}{2}^+$ J^π possible values were obtained,[11] and thus decide in favor of the $\frac{3}{2}^+$ which is the only common among those previously and currently proposed as possible J^π values.

Two new levels have been identified at 1396.8 and 1401.1 keV on the basis of coincidences, while a level at 1409.6 keV tentatively proposed in previous work[18] has been firmly established here. Two new levels at 1423.4 and 1480.3 keV, of which the second is tentative, are proposed on the basis of coincidences.

A level at 1513 keV tentatively proposed by Picone *et al.*[18] was not adopted in a later ^{97}Tc compilation.[26] From the present data, however, a level at 1512.7 keV was firmly established; it was observed to decay to levels with J^π values $\frac{5}{2}^+$, $\frac{5}{2}^-$, and $\frac{7}{2}^+$. Nevertheless, it should be mentioned that of the four transitions proposed by Picone *et al.*[18] to deexcite this level only one at 1187.7 keV has been retained in the present study. The strong branching of this level to $\frac{5}{2}^+$ states below indicates a $\frac{5}{2}^\pm$ assignment.

A $\frac{1}{2}^-$ or $\frac{3}{2}^-$ level at 1517 keV has been assigned in the (p,γ) study,[19] while a level at 1537 keV, most probably corresponding to the 1517 keV level, has been assigned a $\frac{1}{2}^+$ value in a (^{3}He,d) work.[11] A level at 1518.4 keV has been established in the present study to deexcite with a 938.2 keV γ ray to the 580.1 keV, $\frac{3}{2}^-$ state and via a 1422.0 keV transition to the $\frac{1}{2}^-$ first excited state. The present and previous results indicate $\frac{1}{2}^\pm$ and $\frac{3}{2}^-$ possibilities.

A level at 1579.9 keV previously reported[26] has been also established in the present study. Transitions from this level to states with $\frac{3}{2}^-$, $\frac{5}{2}^\pm$, and $\frac{7}{2}^+$, and very likely $\frac{1}{2}^-$ J^π values have been observed. These modes of decay restrict the J^π range of the 1579.9 keV level between $\frac{3}{2}^+$ and $\frac{5}{2}^-$, and help one to identify this level with a $\frac{3}{2}^+$ or $\frac{5}{2}^\pm$ state observed in the (p,γ) study[19] at 1573 keV. Two new levels at 1636.9 and 1649.3 keV have been identified by evidence based on coincidences.

A level at 1676.1 keV has been identified in the present work to decay to the 580.1 keV, $\frac{3}{2}^-$, and 324.46 keV, $\frac{5}{2}^+$ states. A level at 1676 keV has been proposed in the (p,γ) study with $J^\pi = \frac{3}{2}^+$ or $\frac{5}{2}^\pm$ values.[19] In spite of their energy agreement, one should associate these levels with some hesitation since different decay modes are reported.

In the excitation range between 1692 and 2200 keV, a region in which the structure of ^{97}Tc was basically uncharted, 25 new levels have been identified with $\gamma\gamma$-coincidence evidence. These states and their decay mode are presented in Fig. 5.

IV. DISCUSSION

As was briefly outlined in the Introduction, the purpose of this work was to clarify the level scheme and decay properties of states in ^{97}Tc. The results obtained via the nonselective ($p,n\gamma$) reaction indicate the complex structure of this isotope which has been found to be characterized by a large number of low-lying states. More specifically, up to the excitation of 1580 keV, a range which has been already studied by γ spectroscopy,[18] 41 states have been located, which is twice as many as previously reported. Furthermore, the present assignment of a strong 483.6 keV γ ray in the deexcitation of the fourth excited state in ^{97}Tc helped to reject the 574.0, 807.0, 1173.0, and 1504.0 keV levels which were previously assigned[18] in relation with the 483.6 keV γ ray. No indication was found in the present study for the existence of an 849.6 keV isomeric state.[18] Finally, four levels at 832.7, 895.3, 1240.0, and 1409.7 keV tentatively proposed previously[18] were firmly established.

Above 1580 keV and up to the excitation of 2210 keV four levels in ^{97}Tc had been previously identified.[26] In the present study 28 levels were assigned in this excitation range.

Unique spin values have been proposed for 15 levels in ^{97}Tc while limits have been placed for several others by the analysis of angular distribution measurements in conjunction with any available pertinent information from the present or previous studies of ^{97}Tc. Multipole mixing ratios were also obtained for several electromagnetic transitions. For the very few transitions for which δ values had been previously determined,[23,24,25] good agreement has been observed with the present results.

Four low-lying high-spin states at 772.6, 832.7, 1126.6, and 1199.5 keV have been identified and their most probable J^π values were determined as

$\frac{13}{2}^+$, $\frac{11}{2}$, $\frac{11}{2}^+$, and $\frac{9}{2}^+$, respectively. The $\frac{13}{2}^+$ state in ^{97}Tc is located near to the 2^+ state of the even-even core, as has been observed to be the case with the other odd-A Tc isotopes for which the $\frac{13}{2}^+$ state is known.

The levels identified in ^{97}Tc are twice as many as in ^{95}Tc within the same excitation range. This increase, which seems to result from the extra residual interactions induced by the additional neutrons, should be appropriately described by the theoretical models which claim to be applicable to the odd-A Tc isotopes. Such a feature, however, is not demonstrated in the most recent theoretical calculations.[8,9]

The comparison of the present experimental results with the calculations of Bargholtz and Beshai[9] indicates a rather satisfactory agreement between experimental and theoretical δ values for transitions deexciting the first two positive and negative parity states. Application, however, of the theoretical predictions by Beshai *et al.*[25] in the selection of a unique δ value for the two transitions deexciting the second $\frac{5}{2}^+$ 785.1 keV level has not provided the value obtained in the present study. Discrepancies between theory and experiment appear also in the transitions deexciting the $\frac{9}{2}^+$ and $\frac{11}{2}^+$ states.

For most of the states identified in the present work, however, a comparison with theoretical calculations[8,9,25] is not possible since the latter provide fewer states than those experimentally observed.

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