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LEVEL STRUCTURE OF ^{97}Tc FROM THE DECAY OF 2.9 d ^{97}Ru

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Abstract: The level structure of ^{97}Tc has been investigated from the decay of 2.9 d ^{97}Ru. Singles γ-ray energy and intensity measurements were taken with a 42 cm^3 high-resolution Ge(Li) detector in an anti-Compton arrangement which employed a large Na(Tl) annular detector. The following new very weak γ-ray transitions were observed in the decay of ^{97}Ru: 114.34 ± 0.07, 477.7 ± 0.6, 850.1 ± 0.4 and 898.19 ± 0.15 keV. From the $\gamma\gamma$ coincidence relationships established in this work via extensive experiments employing two Ge(Li) detectors it was concluded that levels at 96.5, 215.71, 324.49, 656.82, 785.05, 855.45, 969.79 and 994.69 keV in ^{97}Tc are populated in the decay of ^{97}Ru. The population of two additional levels at 574.2 and 946.5 keV is discussed. Precision measurements of the K-shell conversion coefficients for eight transitions in ^{97}Tc were made with the aid of a Si(Li)-Ge(Li) conversion coefficient spectrometer. From the α_K value determined in this work for the 216 keV transition its multipolarity is found to be M1 with (10 ± 4 %) admixture. From log *ft* and α_K values determined in this work and from γ-ray branching ratio information J^π assignments were made for eight levels and limits placed for two remaining levels. The α_K value for the 336 keV transition in ^{95}Tc following ^{95}Ru decay was also measured and found to be $(10.4 \pm 0.5) \times 10^{-3}$, which is consistent with an M1 transition with (11 ± 9) % E2 admixture. The level structure and trends in ^{97}Tc and ^{99}Tc isotopes are examined and discussed in relation to recently published results on calculated levels in these isotopes on the basis of an extend quasiparticle-phonon coupling model for the nucleus; only moderate qualitative agreement is found.

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RADIOACTIVITY ^{97}Ru; measured E_γ, I_γ, I_{e_K}, K/L+M, α_K, $\gamma\gamma$-coin; deduced log *ft*. ^{97}Tc, deduced levels, J, π, δ. ^{95}Ru; measured K/L+M, α_K. ^{95}Tc, deduced J, π, δ. Ge(Li), Ge(Li)-NaI(Tl) anti-Compton, Si(Li)-Ge(Li) conversion electron spectrometers.

1. Introduction

The decay of ^{97}Ru was first characterized by Sullivan *et al.* ^{1}) and the first attempt to construct a decay scheme was reported by Cork *et al.* ^{2}). The decay of the 91 d ^{97m}Tc by a single M4 transition of 96.5 ± 0.1 keV was reported by Unik and Rasmussen ^{3}). By careful NaI(Tl) studies of the decay of ^{97}Ru, Cretzu *et al.* ^{4}) reported the population of ^{97}Tc levels at 96.5, 216, 325, 786 and 995 keV. Graeffe ^{5}) studied the decay of 2.9 d ^{97}Ru utilizing a small Ge(Li) detector and reported the population of levels at 97, 215, 324, 784 and 969 keV in ^{97}Tc. More recently, two groups of investi-

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gators, Hofstetter and Sugihara ^{6}) and Cook, Schellenberg and Johns ^{7}), from γ-ray studies, have reported a number of additional levels. Hofstetter and Sugihara ^{6}) reported two new levels at 560 and 856 keV. Cook *et al.* ^{7}) confirmed the assignment of the 856 keV level and assigned another level at 994 keV. However, Cook *et al.* ^{7}) have assigned a new level at 657 keV on the argument that the 560 keV γ-ray populates the isomeric state at 96.5 keV instead of the ground state as assigned by Hofstetter and Sugihara ^{6}). In a preliminary communication Jha and Bond ^{8}) have reported results on the asymmetry of the $\gamma\gamma$ cascades at 569 – 216, 460 – 324 and 645 – 324 keV.

The level sequence in ^{97}Tc has also been investigated via the ^{97}Mo(p, n) reaction by means of neutron time-of-flight experiments by Kim *et al.* ^{9}), who reported levels at 101, 213, 328, 575, 662, 785, 857, 941, 962, (987), 1050, 1134, 1202, 1234, 1268, 1376, (1407), 1517 (doublet) and 1580 keV in ^{97}Tc.

Apart from the need for clarification of the difference in the reported schemes $^{6,\,7}$) for the decay of ^{97}Ru, a detailed study of the level structure in ^{97}Tc is of considerable theoretical interest in a serious effort to understand the properties of the low-lying $\frac{5}{2}^+$, $\frac{7}{2}^+$ and $\frac{9}{2}^+$ states in nuclei with Z or N equal to 43, 45 or 47. In two recent papers [refs. $^{10,\,11}$)] we have presented a comparison of the level trends and properties for the positive-parity states in the odd-mass $^{99-105}_{\ \ \ \ \ 45}$Rh isotopes with the predictions of recent calculations of Goswami and Nalcioglu ^{12}) based on an extended quasiparticle phonon coupling scheme (EQPC). In this work we report on the decay properties of the low-lying $\frac{5}{2}^+$, $\frac{7}{2}^+$ and $\frac{9}{2}^+$ states in ^{97}Tc. Precision measurements of α_K values were used to assign J^π values and in some cases multipole mixing ratios. Furthermore, we have found evidence in support of the level assignment at 656.8 keV by Cook *et al.* ^{7}) and of an additional level at 574.2 keV. We also propose the possible population of another level at 946.5 keV. Finally, some comparisons are made between the experimental level structures of ^{97}Tc, ^{99}Tc and the theoretical level structure of ^{99}Tc based on a quasiparticle-phonon coupling model of the nucleus.

2. Experimental procedures

2.1. PREPARATION OF $^{95,\,97}$Ru SAMPLES

Sources of ^{97}Ru were produced by the ^{95}Mo(^{3}He, n) and ^{94}Mo(^{4}He, n) reactions using 15 MeV ^{3}He^{++} and 18 MeV ^{4}He^{++} beams from the Washington University cyclotron on natural molybdenum foils (18 mg/cm^{2}). In both cases beam exposures of 0.3–0.5 C were employed. The ^{97}Ru samples produced from the (^{3}He, n) reaction were used in the measurements because this method minimizes the amount of contaminating ^{103}Ru activity which is produced by the ^{100}Mo(^{4}He, n) reaction. Two or three days were allowed for the 1.7 h ^{95}Ru to decay and then the ruthenium activity was purified from the Tc isotopes which are produced in substantial yield. The radiochemical purification procedure is described below.

The 1.7 h ^{95}Ru samples were produced by the ^{92}Mo(^{4}He, n) reaction on natural molybdenum foils (18 mg/cm^{2}) using beam exposures of 0.04 C. These samples were used to prepare carrier-free Ru sources for conversion electron measurements as described below.

2.1.1. *Purification procedure for* ^{97}Ru *γ-ray sources.* The bombarded Mo foil was dissolved in 3 ml of warm 6M HNO_3 containing 2 mg of Ru(III) carrier. This solution was then diluted to 5 ml with distilled water and transferred to an all-glass still. To this 10 ml of a 5 % $KMnO_4$ solution and 25 ml of conc. H_2SO_4 were added. From this solution RuO_4 was distilled by gently heating the solution with a bunsen burner and passing a slow flow of air through the inlet at the top of the still. The RuO_4 was collected in 10 ml of 6M NaOH solution kept in an ice bath. The RuO_4 was reduced to $Ru(OH)_3$ by addition of 3 ml of ethanol to the distillate, the solution was then boiled and the $Ru(OH_3)$ formed was centrifuged. The $Ru(OH_3)$ was dissolved in 2 ml of 6M HCl and the solution was diluted with the 10 ml of H_2O. To this solution 0.2 g of powdered magnesium metal was added in small portions. The solution was boiled to coagulate the formed Ru^0 and 1 ml of 6M HCl was added to dissolve the excess magnesium metal. The Ru metal was then filtered and mounted for counting.

2.1.2. *Purification procedure for carrier-free* ^{95,97}Ru *sources.* The bombarded Mo foil was again dissolved in 3 ml of warm 6M HNO_3 without any Ru carrier, it was then diluted to 5 ml and transferred to an all-glass still. To this solution 10 ml of a 5 % $KMnO_4$ solution and 25 ml of conc. H_2SO_4 were added and RuO_4 was distilled by gently heating the solution and passing a slow flow of air through. The RuO_4 was collected in a 20 ml glass test tube containing 10 ml of H_2O and one drop of conc. HNO_3 with the test tube chilled at ice temperature. From this solution carrier-free sources were prepared either by evaporating portions of the solution to dryness or by electrodeposition on a platinum disk.

2.2. DETECTION EQUIPMENT AND METHODS OF COUNTING

For γ-ray singles counting a Ge(Li)–NaI(Tl) anti-Compton spectrometer was employed. This system consisted of a 42 cm^3 true coaxial Ge(Li) detector which was used in an anti-Compton arrangement with a 19.9 cm in diameter by 12.7 cm long annular NaI(Tl) detector. The Ge(Li) detector employed in this spectrometer had resolutions (FWHM) of 1.50 keV at 662 keV and 1.90 keV at 1332 keV. A detailed description of a similar arrangement and the method of calibration has been given elsewhere [13]).

For conversion electron counting a Si(Li) detector with 1.0 cm^2 area and 1.0 mm depletion depth was employed. This detector had a resolution (FWHM) of 4.3 keV at the 343 keV K-shell line from a ^{206}Bi source. The Si(Li) detector was used in conjunction with a 25 cm^3 Ge(Li) detector as a conversion electron spectrometer in an arrangement of reproducible geometry. Sample spectra and the calibration of this spectrometer have been discussed in some detail earlier [11]).

For γγ coincidence counting two Ge(Li) detectors with 25 cm^3 and 42 cm^3 active volumes were used in a 256 × 1024 channel two-parameter configuration which covered the energy range of 40–900 keV for both detectors. The detectors were positioned at $\approx 180°$ and at a distance of ≈ 2 cm from the source. To minimize the crystal-to-crystal Compton scattering an ≈ 1.5 cm Pb absorber was placed between the detectors. The pulse-height analysis system used has been described elsewhere [14]). The coincidence resolving times employed were ≈ 100 ns and data were accumulated for periods of ≈ 80 h at a total coincidence rate of 100–150 c/s. The random coincidence rate was determined by introducing a 60 c/s pulser in the preamplifier of the gated detector. By examining the spectrum of the γ-rays in coincidence with the pulser peak it was found that the random events did not exceed 6 % of any of the true coincidence peaks and therefore they were not subtracted from the spectra shown in the illustrations.

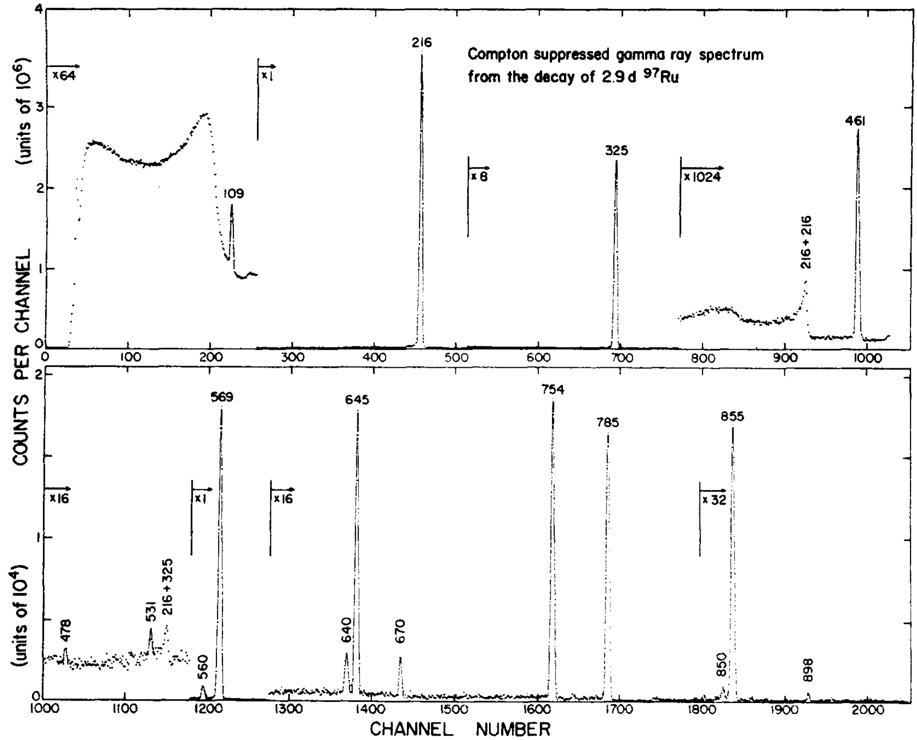

Fig. 1. A Compton-suppressed spectrum of the singles γ-rays following ^{97}Ru decay. The two peaks labeled 216+216 and 216+325 are due to random summing.

3. Results

A typical singles Compton-suppressed γ-ray spectrum taken for a period of 24 h from a 2.9 d ^{97}Ru source is shown in fig. 1. This source was prepared by the ^{95}Mo (^{3}He, n)^{97}Ru reaction, it was allowed to decay for 2 d and it was then purified and counted. Spectra were recorded for 24 h each at intervals of 3 d over a period of 12 d in order to identify the γ-rays by half-life. The only contamination observed was a

TABLE 1

Energy and relative intensity of the γ-rays following ^{97}Ru decay (from singles measurements under collimated anti-Compton arrangement)

Transition	γ-ray energy (keV) [this work]	E_γ from scheme a) (keV) [this work]	γ-ray energy (keV)			Relative γ-ray intensity			
			ref. 5)	ref. 6)	ref. 7)	this work	ref. 5)	ref. 6)	ref. 7)
$3 \rightarrow 2$	108.80 *8*	108.78 *5*	108.8 *5*	108.9 *3*	108.70 *15*	0.13 *1*	0.10 *2*	0.17	0.180 *15*
$9 \rightarrow 7$	114.5 *2* b)	114.34 *7*				≦ 0.01 b)			
$2 \rightarrow 0$	215.71 *5*	215.71 *5*	215.2 *4*	215.2 *3*	215.76 *8*	100	100	100	100
$3 \rightarrow 0$	324.48 *5*	324.49 *5*	324.2 *4*	324.4 *3*	324.45 *8*	12.7 *2*	11.8 *8*	11.8	13.0 *7*
$6 \rightarrow 3$	460.59 *9*	460.56 *6*	460.2 *5*	461.3 *3*	460.60 *15*	0.15 *1*	0.12 *2*	0.125	0.150 *15*
$4 \rightarrow 1$	477.7 *6*	477.7 *6*				0.0027 *13*			
$7 \rightarrow 3$	531.1 *3*	530.96 *8*			531.2 *5*	0.0038 *8*			0.005 *1*
$5 \rightarrow 1$	560.32 *12*	560.32 *12*		560.6 *3*	560.3 *3*	0.048 *5*		0.042	0.036 *4*
$6 \rightarrow 2$	569.33 *7*	569.34 *6*	568.9 *5*	570.0 *3*	569.3 *1*	1.02 *2*	1.0 *1*	0.88	1.07 *7*
$7 \rightarrow 2$	639.73 *12*	639.74 *8*		641.5 *10*	639.5 *2*	0.010 *2*		0.008	0.0095 *10*
$9 \rightarrow 3$	645.35 *8*	645.30 *6*	644.4 *5*	646.9 *3*	645.2 *15*	0.068 *3*	0.07 *1*	0.055	0.086 *9*
$10 \rightarrow 3$	670.30 *10*	670.20 *10*			670.0 *3*	0.010 *1*			0.012 *2*
$9 \rightarrow 2$	754.03 *6*	754.08 *6*	753.8 *7*	754.2 *3*	754.05 *15*	0.087 *2*	0.08 *1*	0.070	0.092 *9*
$6 \rightarrow 0$	785.04 *6*	785.05 *6*	784.7 *7*	785.5 *3*	785.10 *15*	0.082 *2*	0.10 *2*	0.092	0.091 *9*
$8 \rightarrow 1$	850.1 *4*	850.1 *4*				0.0016 *13*			
$7 \rightarrow 0$	855.45 *8*	855.45 *8*	855.1 *8*	856.3 *3*	855.5 *2*	0.049 *1*	0.05 *2*	0.038	0.055 *6*
$10 \rightarrow 1$	898.0 *4*	898.19 *15*				0.001 *1*			
				971 *1*		< 0.0005		0.5	< 0.006

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a) Transition energy deduced from ^{97}Tc level energies given in table 4.

b) Energy and intensity determined from coincidence spectra.

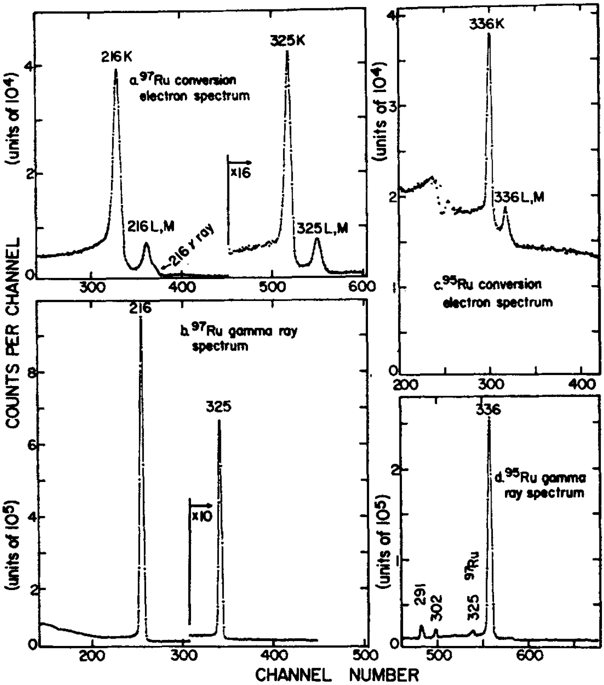

Fig. 2. Conversion electron and γ-ray spectra from ^{95,97}Ru decay taken simulteanously with a 1 $cm^2 \times 1$ mm Si(Li) electron detector and a 25 cm^3 Ge(Li) detector in the calibrated geometry of the conversion electron spectrometer. The upper parts (a) and (c) show portions of the conversion electron spectra from ^{97}Ru and ^{95}Ru decay and the lower parts (b) and (d) show the corresponding γ-ray spectra.

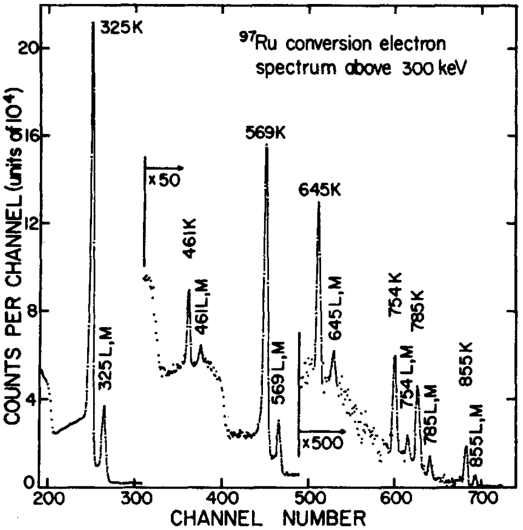

Fig. 3. A conversion electron spectrum from ^{97}Ru decay showing lines above 300 keV. This spectrum was recorded with a 1.0 $cm^2 \times 1.0$ mm Si(Li) detector for a period of 52 h.

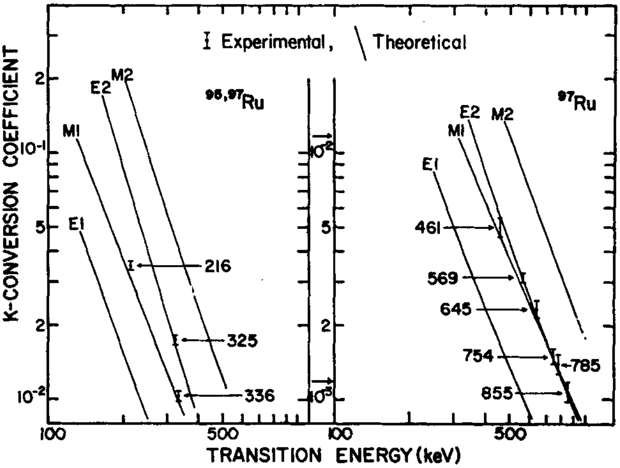

Fig. 4. A comparison for the experimental α_K values with the theoretical K-shell conversion coefficients from ref. [16]) for some of the transitions in ^{95}Tc and ^{97}Tc. Only the 336 keV transition is in ^{95}Tc.

TABLE 2

Summary of the measured K-shell conversion coefficients and K/(L+M) ratios for some transitions in ^{95}Tc and ^{97}Tc following ^{95}Ru and ^{97}Ru decay

E_γ (keV)	$\alpha_K (\times 10^{-3})$ [this work]	K/(L+M) [this work]	$\alpha_K (10^{-3})$ [ref. [5])]	K/(L+M) [ref. [5])]	Multipolarity [a]) [this work]
transition in ^{95}Tc					
336.4	10.4 *5*	6.8			M1+(11±9) % E2
transition in ^{97}Tc					
215.71	35.0 *12*	7.0	34 *3*	5.55	M1+(10±4) %E2
324.48	17.8 *8*	6.5	16 *3*	6.5	E2
460.59	5.0 *5*				M1, E2
569.33	3.14 *15*				M1, E2
645.35	2.35 *20*				M1, E2
754.03	1.51 *12*				M1, E2
785.04	1.41 *14*				M1, E2
855.45	1.08 *12*				M1, E2

[a]) Deduced by comparison with the α_K(M1) and α_K(E2) theoretical K-shell conversion coefficients of Hager and Seltzer [16]).

weak 811 keV γ-ray. At the distant geometry of the Compton-suppression system (source to detector distance of 20 cm) summing due to coincidence is negligible. However, in this system the 215.71 and 324.48 keV γ-rays are far more intense than the other γ-rays. For this reason it was necessary to use strong sources and this produced a small amount of random summing for which the ratio of random summing to singles rate is proportional to source strength and detection efficiency. This is to be

TABLE 3

Summary of the observed coincidence relationships of the γ-rays from ^{97}Ru decay

Fig.	Gate (keV)	γ-rays in the gate	γ-ray in coincidence (keV)
5b	214–217	216	109, 569, 640, 754
5c	322–328	325	461, 531, 645, 670
	458–464	461	109 [a]), 325
	559–562	560	no observed coincidence
	565–571	569	216
	639–642	640	216
	642–648	645	325
	666–672	670	325
	750–756	754	216
	783–786	785	no observed coincidence
5a	853–857	855	115

[a]) Weak coincidence.

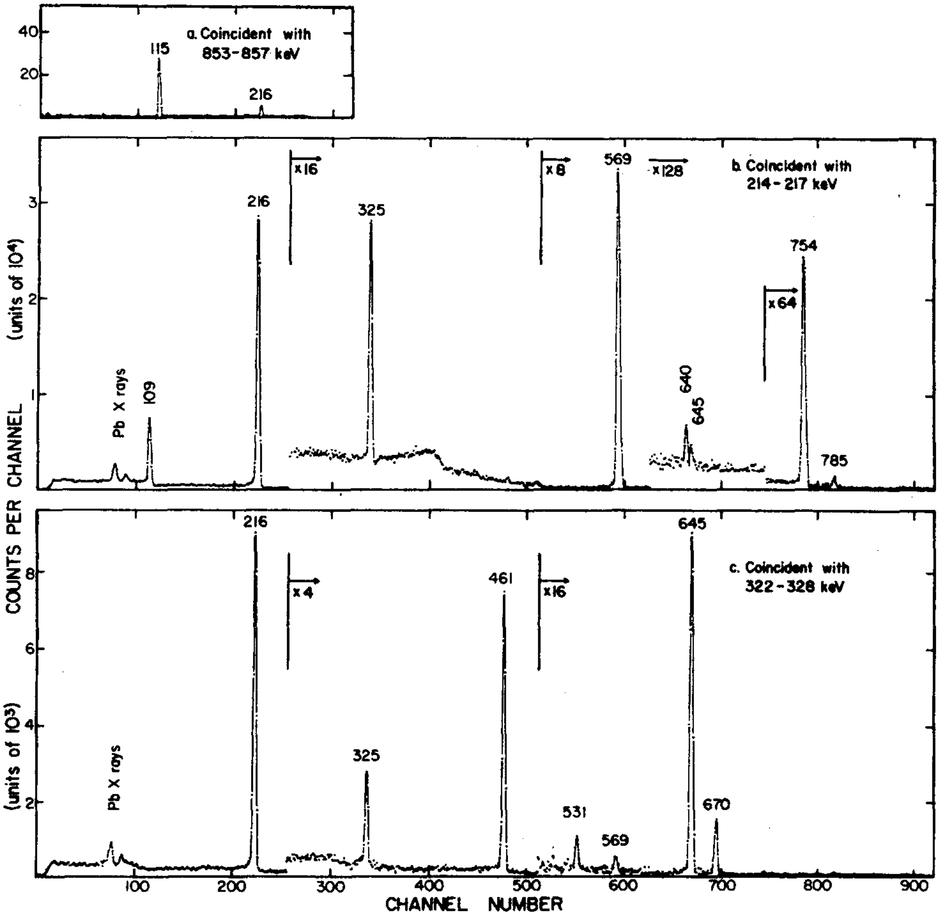

Fig. 5. Spectra of the γ-rays from ^{97}Ru decay recorded with the 42 cm^3 Ge(Li) detector in coincidence with the indicated regions in the 25 cm^3 Ge(Li) detector.

contrasted with the ratio of coincidence summing to singles rate which is proportional only to the detection efficiency.

The energies of the more intense γ-rays from ^{97}Ru decay were determined by counting the ^{97}Ru samples simultaneously with standard sources of ^{241}Am, ^{57}Co, ^{203}Hg, ^{113}Sn, ^{137}Cs and ^{54}Mn for internal calibration. The energies of the weaker γ-rays from ^{97}Ru decay were determined from other spectra using the energies of the more intense γ-peaks for internal calibration. A quadratic function was fit to the energy calibration curves by least-squares techniques.

The relative intensities of the γ-rays were determined from full-energy peak areas using a detector efficiency curve obtained by means of calibrated sources [15]) of ^{57}Co, ^{203}Hg, ^{137}Cs, ^{54}Mn, ^{60}Co and ^{88}Y and sources with well-known relative γ-ray intensities of ^{109}Cd, ^{133}Ba, ^{180m}Hf, ^{24}Na and ^{56}Co.

The energies and relative intensities of the γ-rays from ^{97}Ru were determined from seven spectra with mixed standards and seven pure ^{97}Ru spectra. The results are given in table 1. The third column gives the γ-ray energies determined from the proposed decay scheme as differences between established levels, the energy of which was in turn obtained as a weighted average of the γ-ray energy sums leading to each level. There is excellent agreement between our γ-ray energy values and those reported by Cook *et al.* [7]). It is worthwhile to point out that the intensities of the 785 keV γ-ray reported by Graeffe [5]) and by Hofstetter and Sugihara [6]) (0.10 ± 0.02 and 0.093, respectively) are clearly too high due to coincidence summing effects. Furthermore, all of the intensity of the 971 keV γ-ray reported by Hofstetter and Sugihara [6]) is also due to coincidence summing. From our data we can place an upper limit of 0.0005 for the intensity of the 971 keV γ-ray relative to that for the 215.71 keV γ-ray taken as 100.

Typical spectra of the conversion electrons and γ-rays from the 215.71 keV and 324.48 keV transitions in ^{97}Tc and from the 336 keV transition in ^{95}Tc are shown in figs. 2a–d and were recorded simultaneously with the Ge(Li)-Si(Li) conversion-coefficient spectrometer. A spectrum of the conversion electrons from ^{97}Ru decay above 300 keV is shown in fig. 3; it was recorded with a Si(Li) detector which was calibrated for relative electron efficiency. The K-shell conversion coefficients for the higher energy transitions were determined from the relative electron intensities and relative γ-ray intensities by normalizing via the α_K value for the 324.48 keV transition, which was measured directly. The K-shell conversion coefficients and some K/(L+M+...) ratios determined in this work are summarized in table 2. The multipolarities of the various transitions in ^{97}Tc or ^{95}Tc were deduced by comparison with the theoretical values given by Hager and Seltzer [16]) as shown in fig. 4. For the 215.71 and 336.4 keV transitions estimates for the percent E2 admixtures were obtained via the relationship $\alpha_K = [\alpha_K(\mathrm{M1}) + \delta^2 \alpha_K(\mathrm{E2})]/(1+\delta^2)$.

The $\gamma\gamma$ coincidence relationships for the transitions in ^{97}Tc were established on the basis of Ge(Li)-Ge(Li) two-parameter experiments. The results are summarized in table 3 and typical spectra are shown in fig. 5a-c.

4. Construction of the decay scheme and assignment of J^π values

The proposed scheme for the decay of ^{97}Ru, from the evidence presented above, is shown in fig. 6. Table 4 gives a summary of the proposed level energies, the percent EC populations, the deduced log *ft* values, and the assigned J^π values to each proposed level. The last column of table 4 gives the level energies [9]) from the ^{97}Mo(p, n) reaction. The percent EC population was obtained as a difference of the total transition intensity depopulating and populating each level. The log *ft* values were calculated

TABLE 4

Assignment of log *ft* and J^π values to levels of ^{97}Tc

Level no.	Level energy	% EC	log *ft*	J^π	Level energy (keV) ref. [9])
0	0			$\frac{9}{2}^+$	0
1	96.5			$\frac{1}{2}^-$	101 *10*
2	215.71 *5*	87.6 *20*	5.4	$\frac{7}{2}^+$	213 *10*
3	324.49 *5*	11.1 *31*	6.2	$\frac{5}{2}^+$	328 *10*
4	574.2 *8*	0.0025 *10*	9.5	$(\frac{3}{2}^-)$	575 *10*
5	656.82 *12*	0.041 *5*	8.1	$(\frac{5}{2}^-)$	662 *9*
6	785.05 *6*	1.04 *2*	6.3	$(\frac{5}{2}^+)$	785 *9*
7	855.45 *8*	0.049 *1*	7.4	$\frac{7}{2}^+$	857 *9*
8	946.5 *2*	0.0012 *10*	8.5		941 *9*
9	969.79 *6*	0.138 *5*	6.3	$(\frac{5}{2}^+, \frac{7}{2}^+)$	962 *9*
10	994.69 *15*	0.0090 *9*	7.2	$\frac{3}{2}^+$	987 *9*

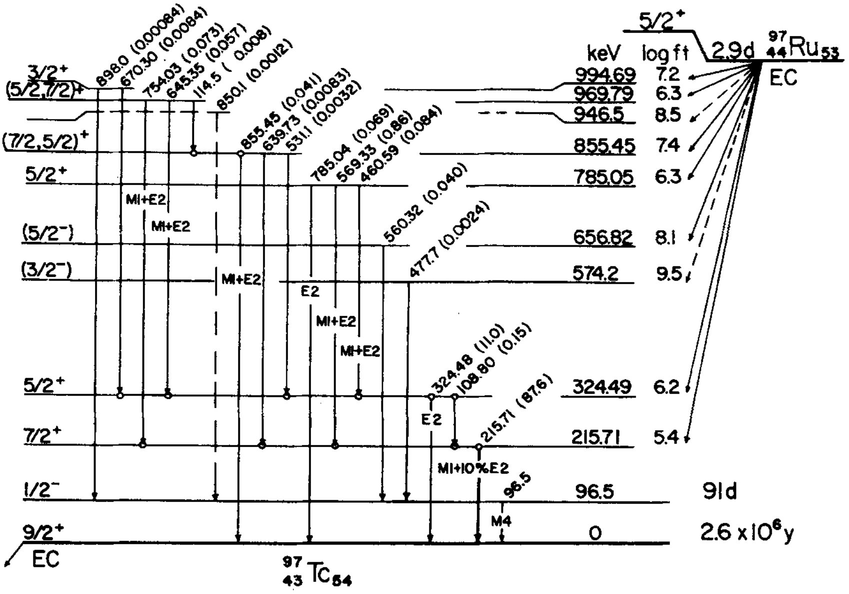

Fig. 6. Proposed scheme for the decay of ^{97}Ru to levels in ^{97}Tc. The energies are given in keV and the intensities in parentheses are expressed per 100 decays.

using the nomograms in pp. 573 and 574 of ref. 17). A value of 1.06 MeV for Q_{EC} was used in the calculations of log *ft* values and was obtained from a simple average of the calculated values of Garvey *et al.* 18), Mattauch *et al.* 19), and Everling 20). It should be pointed out that the log *ft* values of the levels at 946.5, 969.70 and 994.69 keV are particularly sensitive to possible errors in the Q_{EC}. The arguments supporting the proposed decay scheme and J^{π} assignments are summarized below.

The ground state of ^{97}Ru can be assumed as $\frac{5}{2}^{+}$ in analogy to those of ^{99}Ru and ^{101}Ru which have been determined directly by ESR measurements 17).

The ground state and 96.5 keV 91 d *metastable state.* The ground state and metastable state at 96.5 keV in ^{97}Tc have been assigned as $\frac{9}{2}^{+}$ and $\frac{1}{2}^{-}$ from the conversion-electron studies of Unik and Rasmussen 3) who assigned an M4 character to the 96.5 keV transition from K/L/M and K/L conversion electron intensity ratios and from comparison of the experimental transition probability to the estimates of Moszkowski [ref. 21)] and of Goldhaber and Sunyar 22). Both of these levels have also been seen in the ^{97}Mo(p, n) reaction studies of Kim *et al.* 9).

The 215.71 keV *level.* The highest intensity γ-ray at 215.71 keV is assigned to populate the $\frac{9}{2}^{+}$ ground state directly on the basis of the observed level at 213 ± 10 keV in the ^{97}Mo(p, n) reaction 9).

This level is assigned as $\frac{7}{2}^{+}$ on the basis of the $\mathrm{M1} + (10 \pm 4)\,\%$ E2 multipole admixture determined in this work for the 215.71 keV transition (see table 2) and from the strong EC population (log *ft* = 5.4) from the $\frac{5}{2}^{+}$ ground state of ^{97}Ru.

The 324.49 keV *level.* This level is well established on the basis of the following evidence: (i) the observed coincidence between the 108.80 and 215.71 keV γ-rays (see fig. 5b), (ii) no observed coincidence between the proposed crossover transition of 324.48 keV and the 215.71 keV γ-rays, and (iii) the reported level at 328 ± 10 keV from the ^{97}Mo(p, n) reaction 9).

The 324.49 keV level has been assigned as a $\frac{5}{2}^{+}$, since the 324.48 keV transition to the $\frac{9}{2}^{+}$ ground state is a pure E2 (see table 2) and the EC decay to this level is indicative of an allowed transition (log *ft* = 6.3). In further support of this assignment, is the apparent M1 + E2 multipolarity of the 108.80 keV transition calculated from the conversion electron work of Cork *et al.* 2) and the relative γ-ray intensities determined in this work.

The 574.2 *and* 656.82 keV *levels.* These levels are proposed from the fact that the weak 477.7 and 560.32 keV γ-rays were not observed in any coincidences and therefore probably populate either the ground state or isomeric state. The population of the isomeric state is favored since levels at 575 ± 10 and 662 ± 9 keV were observed in the ^{97}Mo(p, n) reaction 9).

The 574.2 and 656.82 keV levels are most likely $\frac{3}{2}^{-}$ and $\frac{5}{2}^{-}$, respectively, as deduced from the apparent first-forbidden character of β-decay to these levels. In further support of this assignment the analogous states 23) in ^{99}Tc occur at 366.4 and 528.9 keV above the $\frac{1}{2}^{-}$ isomeric state, respectively. From nuclear systematics 17, 24) in the odd-mass $Z = 43$, 45 and 47 isotopes, the $\frac{3}{2}^{-}$, $\frac{5}{2}^{-}$ doublet in ^{97}Tc would be expected to lie somewhat higher in energy above the $\frac{1}{2}^-$ state as suggested above.

The 785.05 keV *level.* The assignment of this level is based on the observed coincidences between the 460.59 and 324.48 keV γ-rays and the 569.33 keV γ-ray with the 215.71 keV γ-ray (fig. 5b, c). This is further supported by the observed 785.04 keV γ-ray assigned as the crossover transition to the ground state with excellent energy agreement. A level at 785±9 keV was also seen in the ^{97}Mo(p, n) reaction [9]).

The transitions of 460.59, 569.33 and 785.04 keV are all M1 and/or E2 in character (see table 2). The branching ratios for the decay of this level to the $\frac{9}{2}^+$(g.s.), $\frac{7}{2}^+$ (215.71 keV) and $\frac{5}{2}^+$ (324.49 keV) levels are 0.08 : 1 : 0.15. This evidence, together with a log *ft* of 6.3, strongly suggests a $\frac{5}{2}^+$ assignment for this level.

The 855.45 keV *level.* This level is firmly established from the observed coincidence between the 639.73 and 215.71 keV γ-rays and between the 531.1 and 324.48 keV γ-rays (fig. 5b, c). This assignment is further supported by the assignment of the 855.45 keV γ-ray as the crossover transition to ground state with excellent energy agreement. A level at 857±9 keV was also seen in the ^{97}Mo(p, n) reaction [9]).

The M1 and/or E2 character of the 855.45 keV transition to the $\frac{9}{2}^+$ ground state establishes a positive-parity assignment (see table 2). The 531.1 and 855.45 keV transitions to the $\frac{5}{2}^+$ (324.49 keV) and $\frac{9}{2}^+$ ground state respectively, eliminate possible assignments of $\frac{3}{2}^+$ and $\frac{11}{2}^+$. The log *ft* value of this level is 7.4. This evidence suggests a $\frac{7}{2}^+$ assignment, although $\frac{5}{2}^+$ cannot be excluded. The $\frac{9}{2}^+$ assignment can be eliminated since the log *ft* from the $\frac{5}{2}^+$ parent to a $\frac{9}{2}^+$ level would be second-forbidden.

The 946.5 keV *level.* This level is suggested from the lack of any observed coincidences with the 850.1 keV γ-ray. This indicates that the 850.1 keV γ-ray probably populates the ground state or the isomeric state, with the latter being favored on the basis of a 941±9 keV level which was observed in the ^{97}Mo(p, n) reaction [9]).

No J^π assignment can be made from the present evidence.

The 969.79 keV *level.* This level is well established on the basis of the observed coincidence between the 645.35 and 324.48 keV γ-rays and between the 754.03 and 215.71 keV γ-rays (fig. 5c, b). This is further supported by the observed coincidence (fig. 5a) between the 855.45 keV γ-ray and a 114.5 keV γ-ray with a good energy agreement. A level at 962±9 keV was also observed in the ^{97}Mo(p, n) reaction [9]).

The M1 and/or E2 character of the 645.35 and 754.03 keV transitions (see table 2) establish the parity of the 969.79 keV level as positive. The log *ft* value of 6.3 from the $\frac{5}{2}^+$ ^{97}Ru parent eliminates a $\frac{9}{2}^+$ assignment to this level. The absence of a transition to the $\frac{9}{2}^+$ makes a $\frac{7}{2}^+$ assignment rather unlikely. The branching ratio of this level to the $\frac{7}{2}^+$(215.71 keV) and $\frac{5}{2}^+$ (324.49 keV) levels is 1.3 : 1 which strongly favors a $\frac{5}{2}^+$ assignment over $\frac{3}{2}^+$. This assignment is further supported by the 114.5 keV transition to the $\frac{7}{2}^+$ state at 855.45 keV and the log *ft* of 6.3. However, a $\frac{7}{2}^+$ assignment of this level cannot be completely excluded.

The 994.69 keV *level.* This level is assigned on the basis of an observed coincidence between the 670.30 and 324.48 keV γ-rays (fig. 5c). In addition, an 898.0 keV γ-ray is in good agreement with the energy difference between the 994.69 and 96.5

keV level. A level at 987±9 keV was also seen in the ^{97}Mo(p, n) reaction 9).

Since this level de-excites only to the $\frac{5}{2}^+$ and $\frac{1}{2}^-$ levels at 324.49 and 96.5 keV respectively, and has a log $ft = 7.2$, a $\frac{3}{2}^+$ assignment is proposed.

Jha and Bond 8), from preliminary $\gamma\gamma$ coincidence anisotropy measurements, have reported probable level J^π assignments of the ground state ($\frac{9}{2}^+$), 215 keV ($\frac{7}{2}^+$), 324 keV ($\frac{5}{2}^+$) and 784 keV ($\frac{5}{2}^+$, $\frac{7}{2}^+$) which are consistent with the J^π assignments to these levels from this work.

The decay scheme of ^{97}Ru proposed in this work is in good agreement with that from the recent work of Cook *et al.* 7) with the addition of levels at 574.2 and 946.5 keV. However, from the conversion electron coefficients and K/L+M ratios determined in this work, the present J^π assignments of $\frac{5}{2}^+$ and $\frac{7}{2}^+$ ($\frac{5}{2}^+$) for the 785.05 and 855.46 keV levels, respectively, are in disagreement with the assignments of ($\frac{5}{2}^-$, $\frac{7}{2}^-$) and $\frac{7}{2}^-$ made by Cook *et al.* 7) for these levels. The above J^π assignments together with the $(\frac{5}{2}, \frac{7}{2})^+$ assignment for the 969.79 keV level from this work remove some of the ambiguities in the J^π values reported by Hofstetter and Sugihara 6).

5. Discussion

The low-lying negative-parity states of $\frac{3}{2}^-$ and $\frac{5}{2}^-$ that consistently occur 17) in the odd-mass isotopes of Tc, Rh and Ag have been described by Kisslinger and Sorensen [ref. 25)] in terms of the $p_{\frac{1}{2}}$ quasiparticle coupling to the 2^+ phonon state of the doubly even core. This description of these states has been supported by the experimental work of Black *et al.* 26) on the $\frac{3}{2}^-$ and $\frac{5}{2}^-$ state of ^{103}Rh. Black *et al.* 26) have shown that the B(E2) values of the $\frac{3}{2}^- \to \frac{1}{2}^-$ and $\frac{5}{2}^- \to \frac{1}{2}^-$ transitions are equal within experimental error to those of the $2^+ \to 0^+$ transitions in the neighboring doubly even nuclei of ^{102}Ru and ^{104}Pd. Black *et al.* 26) have found that the $B(\mathrm{E2})_{\mathrm{exp}}/B(\mathrm{E2})_{\mathrm{s.p.}} \approx 40$ for the $\frac{3}{2}^-, \frac{5}{2}^- \to \frac{1}{2}^-$ transitions and that $B(\mathrm{M1})_{\mathrm{exp}}/B(\mathrm{M1})_{\mathrm{s.p.}} \approx 0.22$ for the $\frac{3}{2}^- \to \frac{1}{2}^-$ transition.

In analogy to the negative-parity states one might expect that the low-lying positive-parity states would be formed by the coupling of a $g_{\frac{9}{2}}$ quasiparticle to a 2^+ phonon to generate a quintet of states with $\frac{5}{2}^+ \leqq J^\pi \leqq \frac{13}{2}^+$. However, the calculation of Kisslinger and Sorensen 25) based on the quasiparticle-phonon coupling model were unable to reproduce the experimentally observed low-lying positive-parity states.

In a previous paper 11) we have made comparisons between the experimental level structure of the odd-mass Rh isotopes and the predictions of the extended quasiparticle-phonon coupling model of Goswami and Nalcioglu 12). These authors, using the measured value of the quadrupole moment of the first 2^+ state of ^{104}Ru to evaluate the quadrupole interaction matrix, have been qualitatively successful in explaining the occurrence of the low-lying positive-parity states. Goswami and Nalcioglu 12) have also calculated the level structure of $^{99}_{43}$Tc, which is compared in fig. 7 to the experimental structure of $^{97}_{43}$Tc and $^{99}_{43}$Tc; again, only qualitative agreement is achieved. One possible discrepancy in the calculations of Goswami and Nalcioglu for

^{99}Tc is that they used the measured quadrupole moment of the first 2^+ state in ^{104}Ru, which is substantially larger than that of the 2^+ state in ^{98}Mo. This can be inferred from the B(E2; $2^+ \rightarrow 0^+$) values [27] of ^{98}Mo and ^{104}Ru which are $(2.66 \pm 0.30) \times 10^{-49}$ cm^4 and $(9.28 \pm 0.68) \times 10^{-49}$ cm^4, respectively. Since the quadrupole moment for the 2^+ state is related to the B(E2) value one would expect a smaller quadrupole moment for the 2^+ state of ^{98}Mo when compared to that of ^{104}Ru.

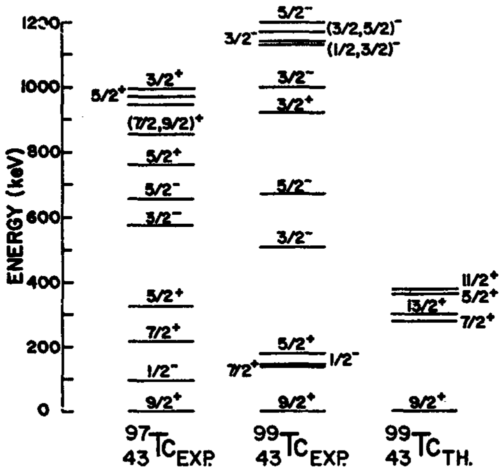

Fig. 7. Experimental level structure of ^{97}Tc (this work) and ^{99}Tc ([ref. [23]]) from the decay of ^{97}Ru and ^{99}Mo, compared to the extended quasiparticle-phonon coupling calculations of Goswami and Nalcioglu [12] (denoted by TH) on the level structure of ^{99}Tc.

If the low-lying $\frac{7}{2}^+$ and $\frac{5}{2}^+$ states were formed by the coupling of the $g_{\frac{9}{2}}$ quasiparticle to the 2^+ phonon state of the doubly even core one would expect an enhancement in the collective nature of these states. This appears to be the case, since from the K-shell conversion coefficients measured in this work, the deduced multipolarities for the $\frac{7}{2}^+ \rightarrow \frac{9}{2}^+$ transition in ^{95}Tc and in ^{97}Tc are M1 + (11 ± 9) % E2 and M1 + + (10 ± 4) % E2, respectively. This is also true in ^{99}Tc where the multipolarity for the $\frac{7}{2}^+ \rightarrow \frac{9}{2}^+$ transition is M1 + (7 ± 3) % E2 [ref. [23]].

Since B(E2) values have not been measured for the positive-parity states in the odd-mass Tc, Rh or Ag isotopes, in a previous paper [11] we have made comparisons of the E2 admixture in the $\frac{3}{2}^- \rightarrow \frac{1}{2}^-$ transitions in the odd-mass Rh and Ag isotopes and found them to be of the same magnitude as those in the $\frac{7}{2}^+ \rightarrow \frac{9}{2}^+$ transitions. From this it may be inferred that the low-lying $\frac{7}{2}^+$ and most probably the $\frac{5}{2}^+$ states would be analogous to the $\frac{3}{2}^-$ and $\frac{5}{2}^-$ with regard to the participation of the phonon-coupled $g_{\frac{9}{2}}$ quasiparticles in the description of these states.

References

1) W. H. Sullivan, N. R. Sleight and E. M. Gladrow, Phys. Rev. **70** (1946) 778
2) J. M. Cork, M. K. Brice, J. C. Schmid and R. G. Helmer, Phys. Rev. **100** (1955) 188

3) J. P. Unik and J. O. Rasmussen, Phys. Rev. **115** (1959) 1687
4) V. T. Cretzu, K. Hohmuth, G. Winter and J. Schintlmeister, Ann. der. Phys. **17** (1966) 1
5) G. Graeffe, Nucl. Phys. **A127** (1969) 65
6) K. J. Hofstetter and T. T. Sugihara, Nucl. Phys. **A140** (1970) 658
7) W. B. Cook, L. Schellenberg and M. W. Johns, Can. J. Phys. **48** (1970) 217
8) S. Jha and P. D. Bond, Bull. Am. Phys. Soc. **13** (1968) 583
9) H. J. Kim, R. L. Robinson, C. H. Johnson and S. Raman, Nucl. Phys. **A142** (1970) 35
10) M. E. Phelps and D. G. Sarantites, Nucl. Phys. **A135** (1969) 116
11) M. E. Phelps and D. G. Sarantites, Nucl. Phys. **A159** (1970) 113
12) A. Goswami and O. Nalcioglu, Phys. Lett. **B26** (1968) 353
13) M. E. Phelps, D. G. Sarantites and W. G. Winn, Nucl. Phys. **A149** (1970) 647
14) W. G. Winn and D. G. Sarantites, Nucl. Instr. **66** (1968) 61
15) H. Houtermans, International Atomic Energy Agency, Vienna, Jan. 1970
16) R. S. Hager and E. C. Seltzer, Nucl. Data **A4** (1968) 1
17) C. M. Lederer, J. M. Hollander and I. Perlman, Table of isotopes, sixth ed. (Wiley, New York, 1967)
18) G. T. Garvey, W. J. Gerace, R. L. Jaffe, I. Talmi and I. Kelson, Rev. Mod. Phys. **41** (1969) S1
19) J. H. E. Mattauch, W. Thiele and A. H. Wapstra, Nucl. Phys. **67** (1965) 1
20) F. Everling, Nucl. Phys. **36** (1962) 228
21) S. A. Moszkowski, in Alpha-, beta- and gamma-ray spectroscopy, ed. K. Siegbahn (Interscience, New York, 1955) ch. XIII
22) M. Goldhaber and A. W. Sunyar, Phys. Rev. **83** (1951) 906
23) C. W. E. Van Eijk, B. Van Nooyen, F. Schuette, S. M. Brahmavar, J. H. Hamilton and J. J. Pinajion, Nucl. Phys. **A121** (1968) 440
24) M. E. Phelps, Ph. D. thesis, Washington University, St. Louis, Missouri (1971) unpublished
25) L. S. Kisslinger and R. A. Sorensen, Rev. Mod. Phys. **35** (1963) 53
26) J. L. Black, W. J. Caelli and R. B. Watson, Nucl. Phys. **A125** (1969) 545
27) P. H. Stelson, Nucl. Data **A1** (1965) 21