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An Investigation of Short-lived Isomers in the Nuclei ^{90,92}Nb, ^{99}Mo, ^{98,100,101}Tc and ^{101}Ru**

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Short-lived isomers in the nuclei ^{90,92}Nb, ^{99}Mo, ^{98,100,101}Tc and ^{101}Ru populated in photonuclear reactions were studied by pulsed beam techniques. Energy and half-life of the γ-rays deexciting the isomeric levels were measured by recording energy-time spectra. The delayed γ-rays and K X-rays were detected by means of an intrinsic Ge-detector of high resolution. From the measured intensity ratios internal conversion coefficients were determined. The multipolarities of the isomeric transitions could be deduced in most cases. A classification of the observed isomers has been tried on the basis of the obtained experimental results and most recent literature data.

1. Introduction

The nuclei investigated belong to the transitional region between spherical and deformed nuclear shapes [1, 2]. In this mass region various kinds of isomeric states are expected as described by the different nuclear models.

The shell model predicts the $(1h\,11/2^-)$ neutron state and the $(2p\,1/2^-)$ proton hole state as isomers in odd A nuclei. For spherical doubly odd nuclei one expects excited states which result from the coupling of the proton configurations $(1g\,9/2^+)$ and $(2p\,1/2^-$ or $3/2^-)$ to the neutron configurations $(2d\,5/2^+)$ and $(1g\,7/2^+)$ to positive and negative parity multiplets. Between the multiplets only γ-transitions of multipolarity $E3$ or $M4$ should be possible for the odd proton if one assumes pure shell model configurations. The detection of $E1$ or $M2$ transitions as such intermultiplet transitions offers therefore a sensitive test of the purity of the assumed configurations. Significantly hindered transitions in ^{92}Nb [3] and ^{94,96}Tc [4] have been interpreted in this way. Similar transitions should exist in ^{98}Tc and ^{100}Tc.

For the positive parity multiplets isomeric transitions may also occur as inter- or intramultiplet transitions caused by large spin differences of the states in question. Such isomers are known in the odd-odd nuclei ^{92,94}Nb and ^{94,96}Tc [5].

The doubly even Ru nuclei [6] show that vibrational excitations should be expected. From the coupling of the phonons to single particle states low energetic levels of quasiparticle phonon multiplets [7] should occur. Of special interest are transitions between such multiplets or between a multiplet and a single particle state. In this case too, deviations from the single particle character of the transitions give informations about the purity of the assumed configurations.

For a useful discussion of the isomers investigated it is necessary to know half-life, energy and multipolarity of their decays as well as the clear association to a certain nucleus. We, therefore, tried to determine experimentally all these quantities with sufficient accuracy for the γ-rays observed.

2. Experimental Procedure

2.1. Experimental Set Up

The investigations of the isomeric states were performed on-line at the bremsstrahlung beam of the Giessen

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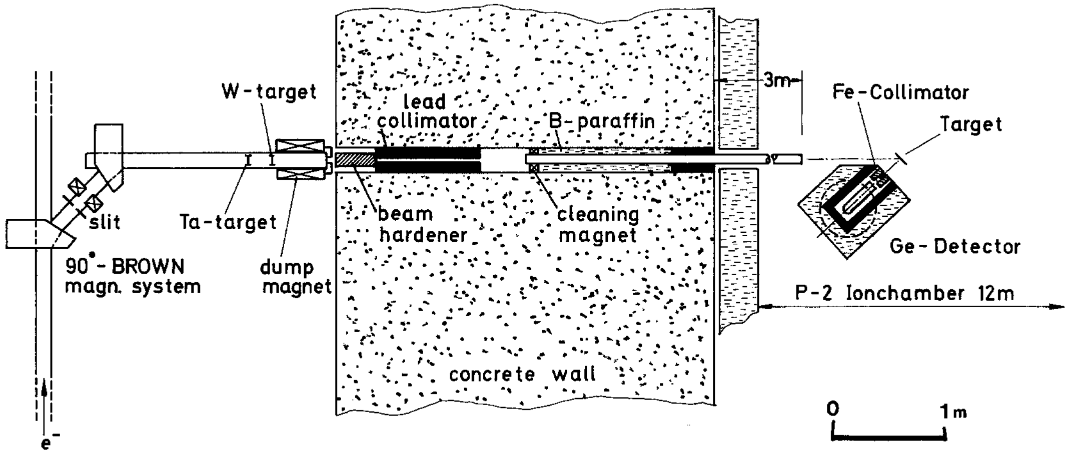

Fig. 1. Experimental set-up

electron linear accelerator ($E_{max} = 40$ MeV, pulse length 100 ns, repetition rate 800 cps) by using pulsed beam technique. Measurements with reduced endpoint energy of about 20 MeV were carried out additionally to distinguish between (γ, n)-, (γ, p)-reactions and $(\gamma, 2n)$-, (γ, pn)-reactions. Natural targets were used to obtain an over-all-view of the isomers excited in these photonuclear reactions. All other measurements were performed with enriched targets. A "Low Energy Photon" detector (LEP) with high resolution was applied to the spectroscopy of the γ-rays and characteristic K X-rays. Additional measurements were performed with a Ge(Li)-detector for the investigation of γ-lines with energies above 200 keV. Figure 1 schematically shows the experimental set-up. The events detected by the Ge-detector were analysed as to their energy and delay time (with respect to the beam trigger). The data were accumulated in a TR 86 computer to an energy-time spectrum by means of a special data reduction method.

This two-parameter measuring system and the electronical devices for reducing the overloading of the system induced by the γ-beam burst are described in detail elsewhere [8, 9].

The energy calibration and the determination of the relative detector efficiency were performed conventionally by using IAEA standards. The accuracy of the energy determination was ± 0.2 keV, if not stated otherwise.

2.2. Target Thickness Determination

The determination of the intensities of the different γ-lines requires an estimation of the energy dependent self-absorption in the target material. For the targets used in our measurements (≈ 100 mg/cm^2) it is possible to calculate an effective target thickness from the experimental K_α/K_β intensity ratio by solving the following formula by an iteration procedure:

$$\frac{R \cdot \mu_\alpha}{R_0 \cdot \mu_\beta} = \frac{1 - \exp(-\mu_\alpha \cdot t)}{1 - \exp(-\mu_\beta \cdot t)}$$

where are: R the experimental K_α/K_β intensity ratio corrected for the detector efficiency

R_0 the theoretical [10] K_α/K_β intensity ratio

μ_α, μ_β the mass absorption coefficients [10] $(\mu_{tot} - \mu_{coh})$ for the K_α and K_β X-rays.

t the target thickness.

The intensity I of a γ-line corrected for the detector efficiency ε and self-absorption in the target is related to the experimental value I_{exp} as

$$I = I_{exp} \cdot \frac{\mu \cdot t}{\varepsilon : (1 - \exp(-\mu t))}$$

where μ is the mass absorption coefficient for the γ-line in question.

2.3. α_K Determination

The spectroscopy of the characteristic K X-rays enables the determination of α_K coefficients from the intensity ratios of the K X-rays and corresponding γ-lines.

If I_x and I_γ are the intensities of the K X-rays and the related γ-rays, the conversion coefficient is obtained

$$\alpha_K = \frac{1}{F} \frac{I_x - C}{I_\gamma}$$

where F is the fluorescent yield [5] and C is a correction for the fluorescence of the γ-rays in the target material. C has to be considered only for identical atomic numbers of the target and the isomeric nucleus.

A suitable estimation of C [11] is

$$C = F \cdot P \cdot \sum_i I_{\gamma i} \cdot C_i$$

with

$$C_i = \int_0^{\pi/2} \left[1 - \frac{\cos\delta}{\mu_i \cdot t}(1 - \exp(-\mu_i \cdot t/\cos\delta))\right] \sin\delta \, d\delta$$

$I_{\gamma i}$ is the intensity of a γ-line, which contributes to the fluorescence in the target. The factor P is an estimate for the fraction of photoabsorption leading to K shell vacancies [10].

3. Results and Discussion

The experimental results of our measurements are summarized in Table 1. The values of the energies E, the half-lifes $T_{1/2}$ and the relative intensities I_{rel} are weighted averages of different measurements. The multipolarities L have been determined by comparing the experimental α_K and/or α_{tot} conversion coefficients with the theoretical ones [12]. The hindrance factor H describes the hindrance of the γ-transitions compared with the Moszkowski estimates [13]. The statistical factor was set to unity. The quoted errors are standard deviations.

In the following sections only those measurements shall be discussed in detail where new isomeric transitions have been detected.

3.1. ^{98}Tc *Isomer*

In the measurement with the ^{99}Ru target (Fig. 2) short-lived γ-lines of 43.5 keV and 21.8 keV were detected decaying with the same halflife as the Tc K X-rays. The weak short-lived Ru K X-rays present in the spectrum are caused only by the fluorescence of different γ-rays in the target material. Therefore it is concluded that both γ-lines arise from a Tc nucleus. The mass number 98 was determined by an alternative measurement with reduced endpoint energy of the bremsstrahlung beam using a ^{100}Ru target.
In the calculation of the intensity of the 21.8 keV γ-line the contribution of the Ru K_β X-rays has been taken into account.
During our measurements the level scheme and the isomeric decay of ^{98}Tc have been investigated by other authors [14–16], too. In contrast to Wender et al. [16] who consider the observed 21.8 keV γ-line to be a $M1$ transition to the ground state, we suppose the 91.2 keV level to be an isomeric state which decays by the 21.8 keV transition followed by the 43.5 keV line and a highly converted transition of about 26 keV

Table 1. Experimental results. E: energy, $T_{1/2}$: halflife, I_{rel}: relative intensity, L: multipolarity, H: hindrance factor

	Line	E [keV]	$T_{1/2}$ [μs]	$T_{1/2}$ [μs] (weighted average)	I_{rel}	α_K	Intensity ratios	L	H
^{90}Nb	K X-rays	–	–		1	–		–	–
	123	122.6±0.2	63 ±2		2.5	0.56±0.22		$E2$	120
^{92}Nb	K X-rays	–	–		1	–		–	–
	90	90.4±0.2	5.9 ±0.2		10.3	0.14±0.01		$E1$	$1.5 \cdot 10^7$
^{99}Mo	K X-rays	–	15.2 ±0.4	15.5 ±0.2	1	–		–	–
	98	97.8±0.1	15.6 ±0.2		0.95	1.45±0.27		$E2$	20
	138	137.7±0.2	0.79±0.09	0.76±0.06	1		$I_{450}/I_{138}=$	$M1$	–
	449	449.2±0.2	0.74±0.08		0.97		0.97±0.08	($M2$)	(37)
^{98}Tc	K X-rays	–	14.8 ±0.5	14.6 ±0.4	1			–	–
	22	21.8±0.2	16.4 ±2.7	from	0.036		$I_{43}/I_{22}=$	$E1+1\%\,M2$	10^7
	26	–	–	X, 43	–		5.1±0.5	($E2$)	–
	43	43.5±0.2	14.4 ±0.5		0.18			$M1$	–
^{100}Tc	K X-rays	–	8.2 ±0.7	8.2 ±0.3	1			–	–
	29	28.7±0.3	–	from	0.027		$I_{172}/I_{29}=$	$E2$	1
	172	172.3±0.3	8.2 ±0.3	X, 172	2.2		82±40	($M1$, $E2$)	–
^{101}Tc	K X-rays	–	–		1	–		–	–
	192	192.0±0.3	636 ±8		5.0	0.26±0.06		$M2$	560
^{101}Ru	K X-rays	–	16.1 ±3.9	17.5 ±0.4	1			–	–
	220	220.7±0.2	17.4 ±0.5	from	7.5		$I_{306}/I_{220}=$	$M2$	28
	306	306.6±0.3	17.7 ±0.6	220, 306	9.1		1.2±0.1	–	–

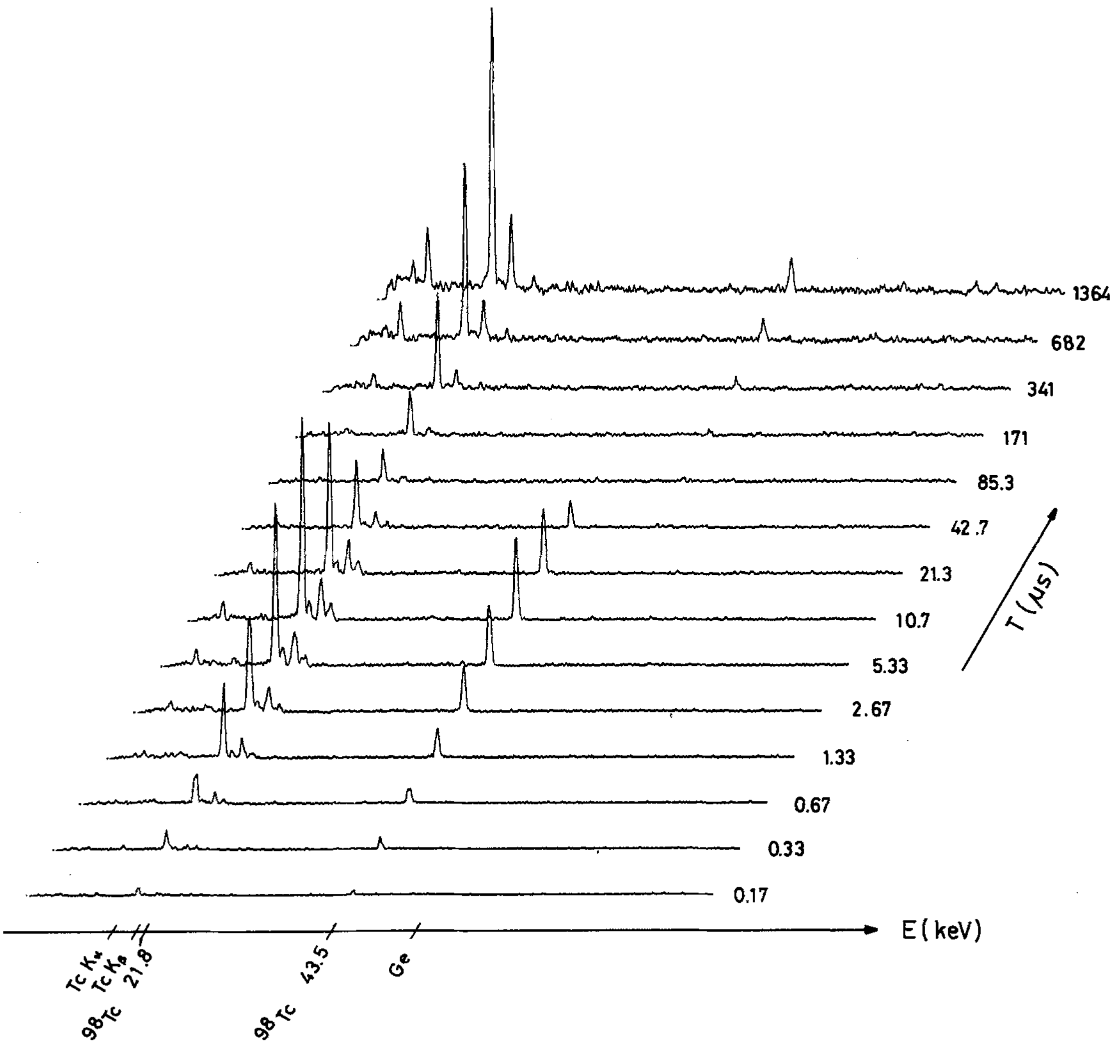

Fig. 2. Energy-time spectrum observed with the ^{99}Ru target

(Fig. 3), which could not be detected definitely. Only an indication for this transition has been observed as a very weak γ-line of about 28.5 keV with nearly suitable half-life and intensity.

Several reasons have caused this interpretation. The investigations of Finlay et al. [14] show that the 47.8 keV γ-line (Fig. 3) has neither coincidences with the 43.5 nor with the 65 keV line. This will become clear if the 91.2 keV level is accepted to be an isomeric state. Strong coincidences between the 86.6 and the 43.5 keV γ-lines and the missing of a 34 keV transition between the 104.1 and 69.7 keV levels give rise to the assumption that the 104.1, 83 and 69.7 keV levels have no lifetime of the value observed. Furthermore the good agreement of the energy values confirms a location of the 21.8 keV transition between the 91.2 and the 69.7 keV levels.

Assuming a cascade for the three γ-transitions of 21.8, 43.5 and 26 keV, their multipolarities can be estimated. The measured Tc K X-ray intensity is only in agreement with $E1$ or $M1$ multipolarity for the 21.8 keV and 43.5 keV γ-lines (Table 2). Taking into account the parities of the 69.7 keV and 91.2 keV levels as proposed by Finlay et al. [14] the 21.8 keV γ-line should be an $E1$- and the 43.5 keV γ-line a $M1$-transition. The intensity ratio of these two lines yields a $M2$ admixture of about 1% to the 21.8 keV transition. Since the non-observed 26 keV transition to the ground state should well be visible in the spectrum in the case of $E1$ and $M1$, both multipolarities can be excluded. A $M2$ transition is not in agreement with the measured Tc K X-ray intensity. Higher multipolarities ($L \geqq 3$) would only give very small contributions to the K X-rays and can, therefore, not be excluded by our measurements. Nevertheless, these multipolarities are in contradiction to the results of Finlay et al. [14]. Therefore, the 26 keV [14] transition is supposed to have $E2$ multipolarity.

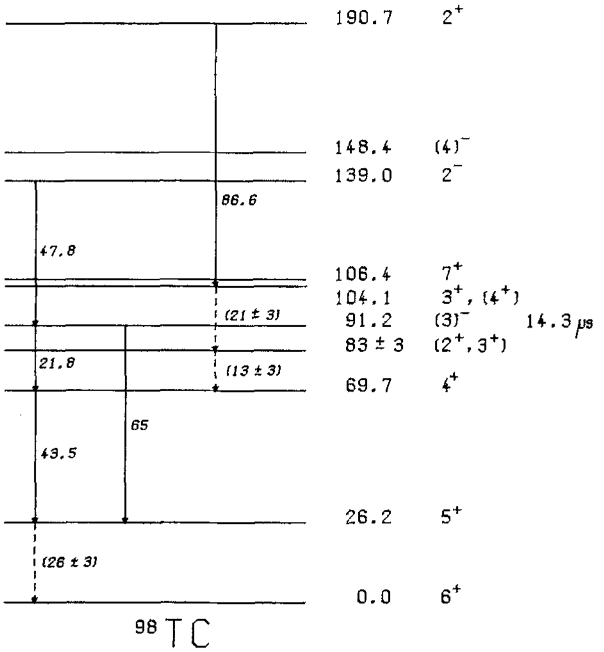

Fig. 3. Supposed level scheme of ^{98}Tc based on [14, 15, 17]. Level energies uncertain within ±3 keV with respect to the ground state

Table 2. Contributions to the Tc K X-rays normalized to the X-ray intensity. The values have been calculated from the measured intensities of the γ-lines and the theoretical conversion coefficients [12]. Three energies (23, 26, 29 keV) have been adopted for the non-observed γ-transition of about 26 keV. Their intensities have been calculated from the 43.5 keV γ-line assuming a cascade

	$E1$	$M1$	$E2$	$M2$	$E3$	$M3$	
21.8	0.21	0.54	1.2	21			±13%
23		0.47	0.10	0.42	0.00	0.11	± 9%
26		0.45	0.13	0.41	0.01	0.15	
29		0.45	0.21	0.42	0.02	0.019	
43.5	0.17	0.37	2.1				

Considering the results of [14, 15] the 91.2 keV → 69.7 keV transition is assumed to be a transition between the proton configurations ($2p\,1/2^-$) or ($2p\,3/2^-$) and ($1g\,9/2^+$). In this case the 21.8 keV line should represent a j-forbidden $E1$ transition which explains the isomerism of the 91.2 keV state. Similar transitions have been found by Cochavi et al. [3] in ^{92}Nb and by McDaniel and Snyder [4] in ^{94,96}Tc.
The detection of $E1$ and $M2$ strengths for the 21.8 keV transition in ^{98}Tc enables the estimation of configuration admixtures. This estimation is shown in Table 3 in comparison with values calculated for further Nb- and Tc nuclei.

3.2. ^{99}Mo *Isomers*

The energy-time spectrum shown in Figure 4 was accumulated in the measurement using a ^{100}Mo target. In this measurement two short-lived γ-lines were detected with energies of 97.8 keV and 137.7 keV and half-lifes of 15.4 μs and 0.76 μs respectively. A longer lived component of both γ-lines is also visible in the spectrum. This can be ascribed to the β-decay of ^{99}Nb produced by the competing (γ, p) reaction. Since no Nb K X-rays are visible in the spectrum, it can be concluded that these γ-lines are identical with the known [18] γ-transitions in ^{99}Mo (Fig. 5). The other long-lived γ-lines except the Ge-background lines, result from the β-decay of ^{99}Mo.
In a further measurement with a Ge(Li)-detector an additional γ-line of 449.2 keV decaying with the same half-life as the 137.7 keV γ-line was detected.
The multipolarity of the 97.8 keV transition could be determined by the measured α_K coefficient to $E2$. The α_K coefficient of the 137.7 keV and the 449.2 keV γ-lines could not be measured because of their weak contribution to the Mo K X-rays. Assuming a cascade

Table 3. Amplitudes of configuration admixtures estimated from the ratios of the measured and the theoretical [13] transition probabilities for j-forbidden transitions between ($\pi\,2p$ 1/2 or 3/2) and ($\pi\,1g$ 9/2) configurations. E: energy, $T_{1/2}$: halflife, L: multipolarity, H: hindrance factor, A: amplitudes of configuration admixtures

	E [keV]	L	T_H	H	A	Ref.
^{90}Nb	2.2	($M2$)	19 s	$5 \cdot 10^3$	$1 \cdot 10^{-2}$	[25]
^{92}Nb	90	$E1$ $<0.3\%\,M2$	6 μs	$2 \cdot 10^7$ $>1 \cdot 10^2$	$2 \cdot 10^{-4}$ $<1 \cdot 10^{-1}$	[3, 26]
^{94}Nb	99	($E1$)	36 ns	$1 \cdot 10^5$	$3 \cdot 10^{-3}$	[27]
^{96}Nb	326	($E1$)	<0.4 ns	$<4 \cdot 10^4$	$>5 \cdot 10^{-3}$	[28]
^{94}Tc	260 237	($E1$) ($E1$)	2.2 ns	$6 \cdot 10^4$ $>6 \cdot 10^6$	$4 \cdot 10^{-3}$ $<4 \cdot 10^{-4}$	[4]
^{96}Tc	85	($E1$)	37 ns	$5 \cdot 10^4$	$4 \cdot 10^{-3}$	[4]
^{98}Tc	22	$E1$ $1\%\,M2$	15 μs	$1 \cdot 10^7$ $1 \cdot 10^2$	$3 \cdot 10^{-4}$ $1 \cdot 10^{-1}$	[a]
^{100}Tc	223	$E1$	<200 ns	$<1 \cdot 10^7$	$>3 \cdot 10^{-4}$	[21], [a]
^{101}Tc	192	$M2$	640 μs	$6 \cdot 10^2$	$>4 \cdot 10^{-2}$	[23], [a]

[a] This work

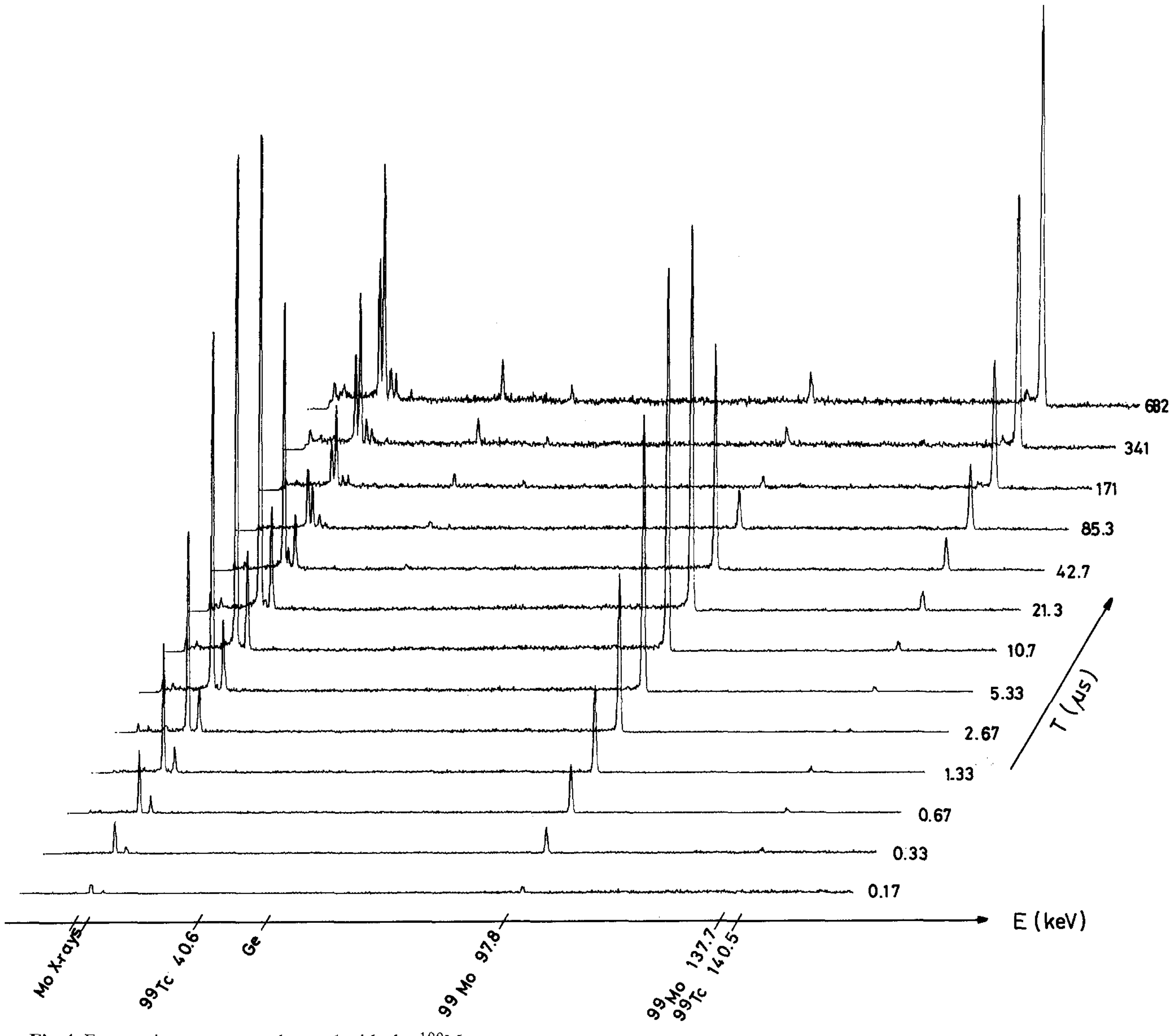

Fig. 4. Energy-time spectrum observed with the ^{100}Mo target

for these two transitions, the possible multipolarities for the 137.7 keV transition are $M1$ or $E1$ as calculated from the experimental intensity ratio of both γ-lines and the theoretical α_{tot} values. $E1$ must be excluded since the parities of the 98 keV and the 235.5 keV levels are positive [18]. The level spins for the ground state and for the 97.8 keV and 235.5 keV states are, therefore, adopted as $1/2^+$, $5/2^+$ and $7/2^+$.

There are three reasons why the 449.2 keV γ-line is supposed to be an isomeric transition from the known [18] $11/2^-$ state at 687 keV to the $7/2^+$ state at 235.5 keV. First of all both the 137.7 and the 449.2 keV γ-line decay with the same half-life, secondly the hindrance of the 449.2 keV $M2$ transition in ^{99}Mo is in good agreement with that of the $11/2^- \rightarrow 7/2^+$ $M2$ transitions in ^{101}Ru and ^{103}Ru [19], and thirdly the measured energy fits well the energy difference between these two states. The level scheme resulting from these considerations in comparison with the known [18] level and spin values of ^{99}Mo is shown in Figure 5.

A 44 keV isomeric transition supposed by McCarthy [20] has not been observed in ^{99}Mo.

3.3. ^{100}Tc *Isomer*

The ^{100}Tc levels have been populated by a (γ, p)-reaction using a ^{101}Ru target. Figure 6 shows the energy-time spectrum observed in this measurement. Three γ-lines of 172.3, 43.5 and 28.7 keV and the Tc K

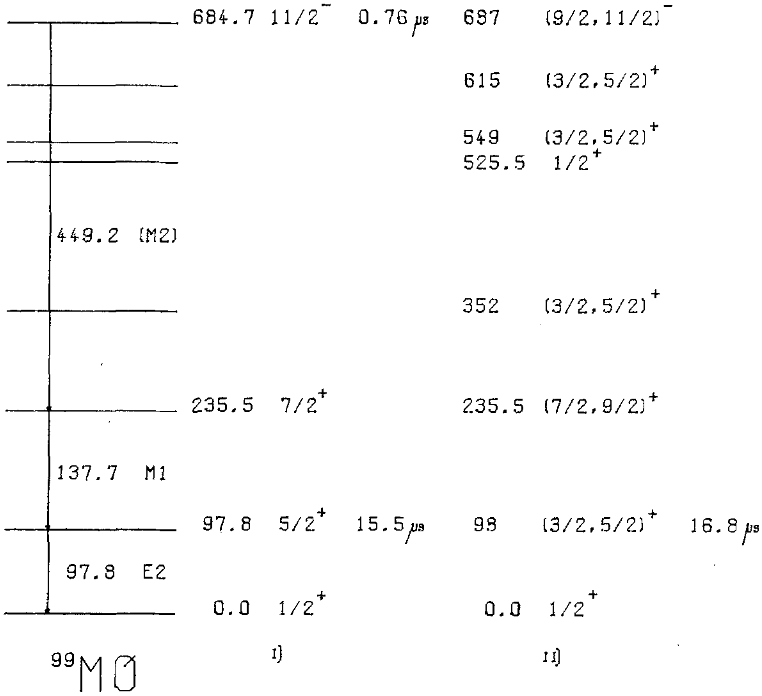

Fig. 5. Supposed level scheme of ^{99}Mo. I: this work, II: [18]

X-rays show almost equal short-lived time distributions. As the 172.3 and 28.7 keV lines could not be observed in an alternative measurement with a ^{100}Ru target, both γ-lines are considered as transitions in ^{100}Tc. The intensity of the 43.5 keV line can mainly be ascribed to ^{98}Tc due to impurities of ^{99}Ru and ^{100}Ru (0.3% each) in the ^{101}Ru target even if contributions of two γ-lines with 43.3 and 43.7 keV (Fig. 7) observed in ^{100}Tc by Heck et al. [21] cannot quite be excluded. The intensity ratios of the measured γ-lines, however, can only be explained, if the 200.7 keV level (Fig. 7) is supposed to be the isomeric state in question. With this assumption, the multipolarities of the 28.7 and 172.2 keV lines can be determined as $E2$ and $M1$ or $E2$ respectively which is in agreement with the results of Heck et al. [21]. The measurement of the neutron transfer reaction ^{99}Tc (d, p) ^{100}Tc [22] shows that the ground state and the 172 keV level of ^{100}Tc (Fig. 7) can be referred to the neutron configuration $(\upsilon\, 1g\, 7/2)^1$. The 200 keV state, however, belongs to the excitation $(\upsilon\, 2d\, 5/2)^{-1}\, (\upsilon\, 1g\, 7/2)^2$. Therefore the 28.7 keV γ-line can be interpreted as a single neutron $E2$ transition between positive parity multiplets. Its half-life shows that collective admixtures can be neglected.

The 223 keV $E1$ transition to the ground state (Fig. 7) which should be a $(\pi\, 2p\, 1/2) \rightarrow (\pi\, 1g\, 9/2)$ intermultiplet transition could not be observed in our experiment. Probably this transition is too fast ($T_{1/2} < 0.2\,\mu$s) to be detected by our time measuring system.

4. Conclusion

Significantly hindered $E1$ and $M2$ transitions have been detected in the doubly odd nuclei ^{92}Nb and ^{98}Tc which can be interpreted as j-forbidden transitions between the negative and the positive parity multiplets described in the introduction. The admixtures to the pure shell model configurations have been estimated from the hinderance of these intermultiplet transitions. They are compared with the values derived for similar transitions in neighbouring doubly odd Nb and Tc nuclei (Table 3).

Although these estimations are only crude, it can be seen that the assumed shell model configurations are rather pure. Furthermore, the values of the admixtures are remarkably independent of the number of nucleons. However, there is an obvious difference between $E1$ and $M2$ transitions regarding the values of the admixtures. This may be caused by the fact that suitable admixtures for $M2$ (e.g. $(1f\, 5/2)$ to $(2p\, 1/2)$) can be found in the same main shell ($Z = 29$–50) whereas those for $E1$ (e.g. $(2d\, 3/2)$ to $(1g\, 9/2)$) can only be found in neighbouring shells.

In ^{100}Tc a 28.7 keV transitions has been detected as an isomeric $E2$ transition. It has been interpreted as a single neutron transition between the

$$[(\pi\, 1g\, 9/2)^3\, (\upsilon\, 2d\, 5/2)^{-1}]_{4^+}$$

and the $[(\pi\, 1g\, 9/2)^3\, (\upsilon\, 1g\, 7/2)^1]_{2^+}$ states.

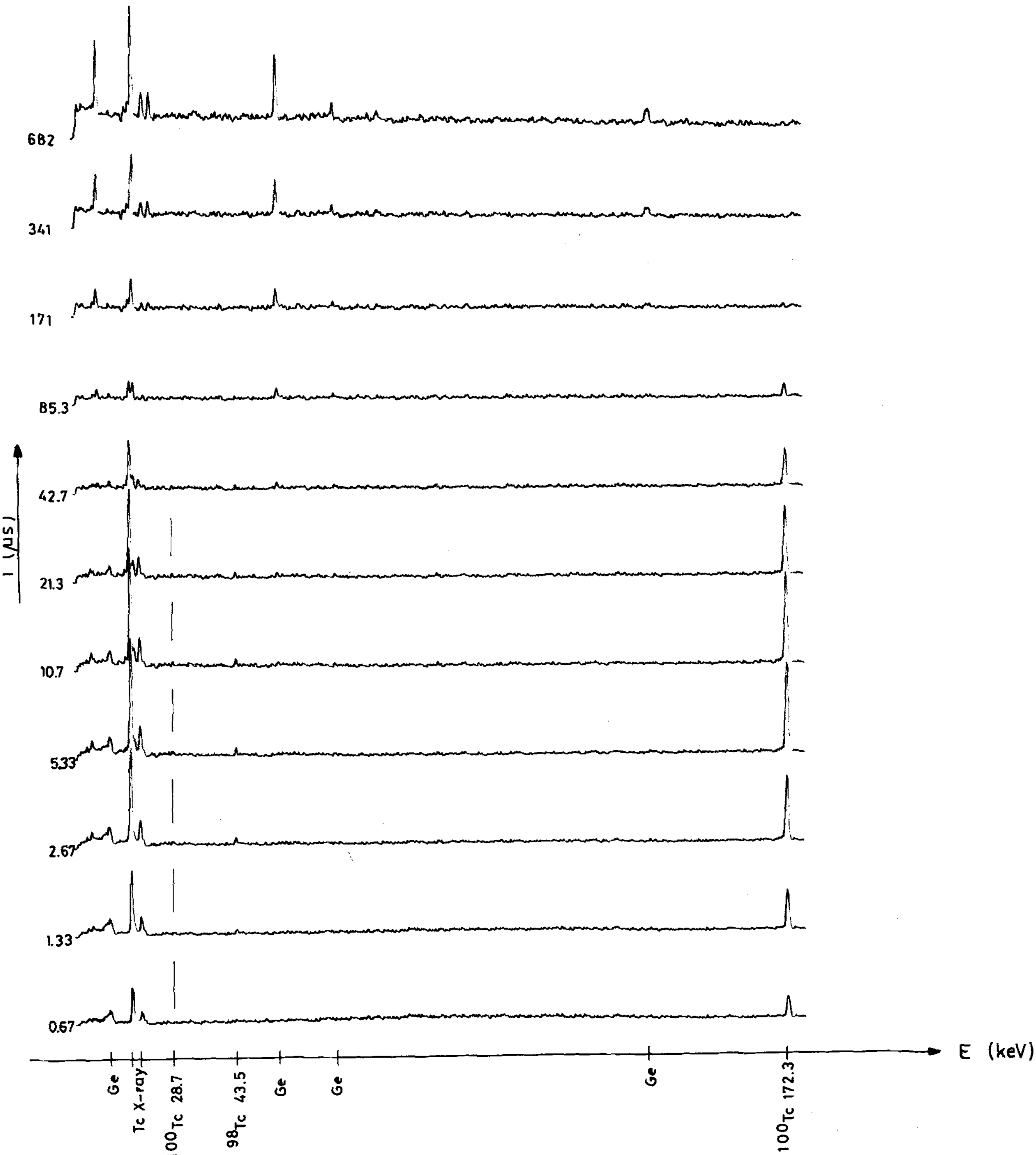

Fig. 6. Energy-time spectrum observed with the ^{101}Ru target

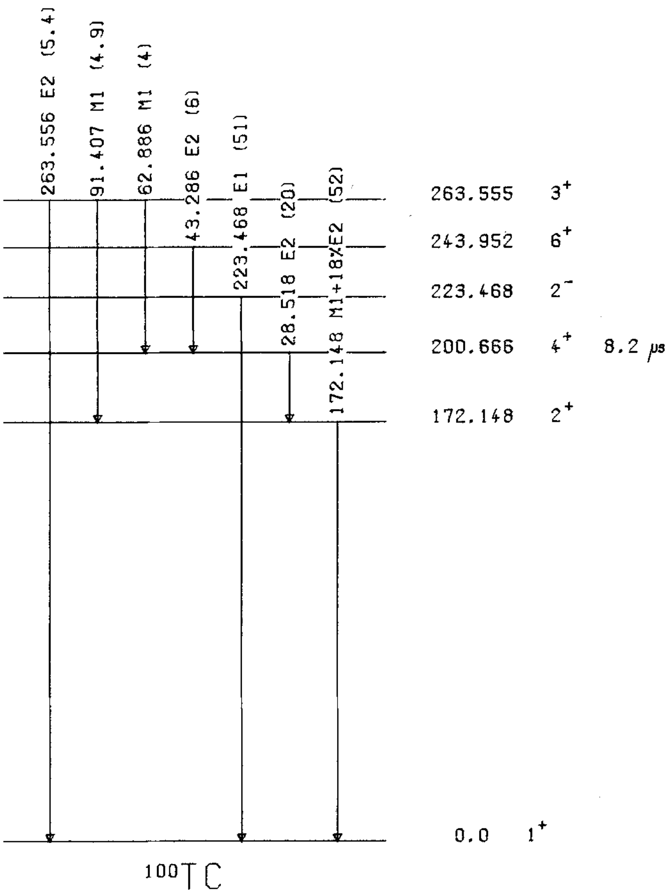

Fig. 7. Level scheme of ^{100}Tc from [21] reduced to levels below 264 keV

In ^{99}Mo a second isomeric state (besides the known 98 keV level) has been found which is supposed to be the (ν 1 h 11/2) shell model state.

The spherical shell model seems to describe the investigated isomers sufficiently.

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