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FORBIDDEN TRANSITIONS IN THE DEFORMED Tm^{169} NUCLEUS

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Lifetimes of $(3.6 \pm 0.1) \times 10^{-8}$ sec and $(6.7 \pm 0.2) \times 10^{-7}$ sec were obtained by delayed-coincidence measurements for the 379 and 316 kev levels of Tm^{169} nucleus. The partial probabilities for eight transitions have been determined on the basis of these data and from data on the relative transition intensities from both levels and on the multipolarity ratios. For the 177-kev (E2), 177-kev (M1), 198-kev (E2), 198-kev (M1), 308-kev (E2), 240-kev (E1), and 260-kev (E1) transitions, which are forbidden with respect to the projection of the total angular momentum on the deformation axis, the delay factor comprises $10^3 - 10^4$ per unit forbiddenness, a value which differs significantly from the usual value (10 − 100). The 63-kev (E1) transition, which is forbidden with respect to the projections of the orbital and spin momenta and also with respect to the quantum number that characterizes the oscillations along the deformation axis, is five orders of magnitude less probable than that predicted by Weisskopf's estimates. However, it is in good qualitative agreement with Nilsson's calculations of the probability for deformed nuclei.

1. INTRODUCTION

MIHELICH et al.[1] measured the lifetimes of three excited states of the Tm^{169} nucleus produced by electron capture in Yb^{169}. Furthermore, in addition to the known 316-kev isomer level, long lifetimes were obtained for the 379- and 473-kev levels (4.5×10^{-8} and 0.4×10^{-6} sec respectively). Hatch and Alburger showed in a later paper[2] that, in contradiction to the result of reference 1, the lifetime of the 473-kev level was less than 3×10^{-9} sec, and confirmed the presence of an isomer state for 379 kev.

Transitions from the 316-kev and 379-kev levels are transitions between levels with different states of internal motion and, as shown by analysis, are forbidden either with respect to the projection of the angular momentum on the deformation axis, or with respect to the asymptotic quantum numbers. At the present time the relative intensities of the partial transitions from each of these two levels have been sufficiently well determined,[3] together with the mixture ratios.[4] Therefore a knowledge of the exact values of the lifetimes of the levels is quite desirable for the purpose of comparing the values of the partial probabilities of the transitions with the theory. We have measured the lifetimes for the levels with energies of 316 and 379 kev with the aid of a double scintillation spectrometer with NaI (Tl) crystals and type FEU-33 photomultipliers.

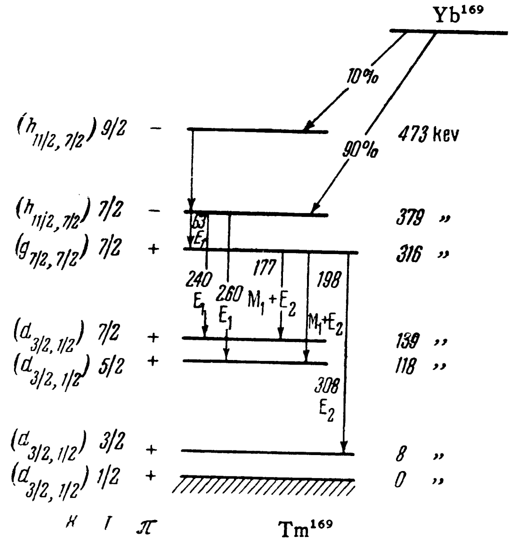

FIG. 1. $Yb^{169} - Tm^{169}$ conversion scheme.

2. THE 379-kev LEVEL

Figure 1 shows the Yb^{169} decay scheme taken from reference 3, in which only the transitions of interest to us are shown. In measuring the lifetimes of the 379-kev level, we used the characteristic 51-kev x-rays that accompany K-capture of Yb^{169}, and the 63-kev γ rays in a fast-slow coincidence circuit.[5] The delay was introduced in the x-ray registering channel. In addition to the x-rays of interest to us, which accompany the K capture at the 379-kev level, the same channel registered also the x-rays that accompanied K-capture at the 473 kev level. The coincidences obtained thereby should correspond to the total lifetimes of the 379 and 473 kev levels. However, the error connected with the additional delay for capture at 473 kev is small, since the number of such captures is one-ninth of the number of captures at the measured level and furthermore, according to an estimate given in reference 2, the lifetime of the 473-kev level does not exceed 3×10^{-9}sec. This means that in measuring the lifetimes, of the order of several times 10^{-8} seconds, expected for the 379-kev level the error due to the 473-kev level does not exceed 1%.

Because of the close values of the x-ray and gamma energies (51 and 63 kev, respectively), pulses due to x-rays could be produced in the gamma channel. The number of "fast" coincidences is increased here by coincidences due to x-rays accompanying the internal conversion in 177 and 131 kev cascade transitions, as well as in those with energies of 198 and 110 kev. Actually, preliminary measurements with a double magnetic spectrometer have shown that the lifetimes of the corresponding levels of the lower rotational band (131 and 118 kev) are of the order of 10^{-9} sec and less. On the other hand, coincidences of these quanta with x-rays that accompany electron capture increase the number of delayed coincidences, owing to the long lifetime of the 316-kev level. When the lifetime of the 379-kev level is measured, these coincidences produce an additional background (on top of the random-coincidence background). This additional background is determined from the number of double coincidences in the "slow" part of the circuit by introducing long delays (0.6 to 1.1 microseconds).

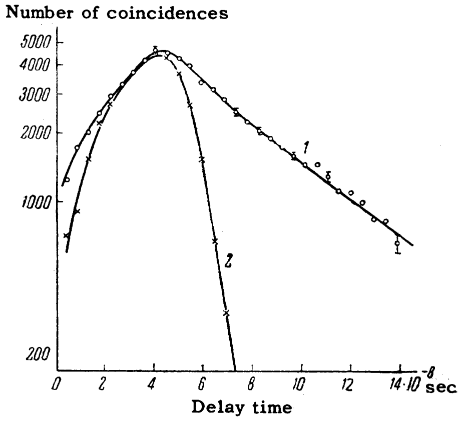

FIG. 2. Decay curve of the 379-kev state of Tm^{169}.

Figure 2 shows the coincidence curve for the 379-kev level of Tm^{169} (curve 1) and a "fast" coincidence curve obtained with a Lu^{173} source (curve 2). The half-life determined from the slope of curve 1 was found to be $T_{1/2} = (3.6 \pm 0.1) \times 10^{-8}$ sec and differs considerably from that given in reference 1 ($T_{1/2} = 4.5 \times 10^{-8}$ sec). This may be due to the inaccurate allowance for the background in that paper (the resolution time of the circuit used in reference 1 is greater than in our measurements). We indicate the magnitude of the statistical error.

3. THE 316-kev LEVEL

The lifetime of the 316-kev level was measured from the slope of the delayed-coincidence curve, with one channel registering 63-kev quanta and the other quanta with energies of 177 and 198 kev. A double-coincidence circuit was used with a resolution time of 1×10^{-7} sec. The delay was introduced in the first channel successively every 0.1 microsecond. The 2-microsecond twenty-section delay line was calibrated against an RK-2 cable. The measurement results are shown in Fig. 3. The half-life was found to be $(0.67 \pm 0.02) \times 10^{-6}$ sec, which coincided, within the limits of errors, with the result of reference 1, but which was closer to the results obtained in references 6 and 7.

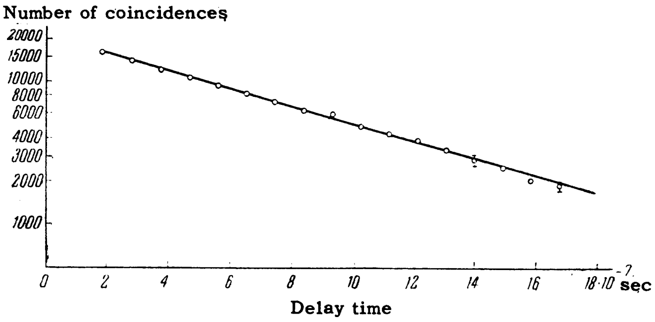

FIG. 3. Decay curve of the 316-kev state of Tm^{169}.

4. ANALYSIS OF THE EXPERIMENTAL RESULTS

From the data on the relative intensities of the 177, 198, and 308 kev γ lines, as well as on the 63, 240, and 260 kev lines, as given in the paper by Hatch, Boehm, et al.,[3] it is easy to obtain the partial times for these transitions, using the formula

$$\tau_{i\gamma} = (\tau_{\exp} / I_{i\gamma}) \sum_{k=1}^{n} I_{k\gamma} (1 + \alpha_k),$$

where $\tau_{i\gamma}$ is the partial time of the γ transition, $I_{i\gamma}$ the relative intensity of the γ line, α_k is the internal conversion coefficient, $\tau_{\exp}$ is the experimental lifetime of the level, and n is the number of discharge channels for the level.

The sixth column of Table I gives the partial lifetimes $(\tau_\gamma)_{\exp}$ for the 316 and 379 kev levels.

TABLE I

Level energy, kev	Transition energy, kev	Type of transition	Relative intensity of γ line	α_{tot}	$(\tau_\gamma)_{exp}$, sec	$(\tau_\gamma)_W$, sec	$F=(\tau_\gamma)_W/(\tau_\gamma)_{exp}$
316	177	$E2$	5.6	0.54	$2.9\cdot10^{-5}$	$8.3\cdot10^{-8}$	$2.9\cdot10^{-3}$
	177	$M1$	25	0.37	$6.4\cdot10^{-6}$	$5.8\cdot10^{-12}$	$0.9\cdot10^{-6}$
	198	$E2$	4.6	0.45	$3.5\cdot10^{-5}$	$4.8\cdot10^{-8}$	$1.4\cdot10^{-3}$
	198	$M1$	46	0.83	$3.5\cdot10^{-6}$	$4.1\cdot10^{-12}$	$1.2\cdot19^{-6}$
	308	$E2$	18	0.05	$9.0\cdot10^{-6}$	$5.2\cdot10^{-9}$	$0.58\cdot10^{-3}$
379	63	$E1$	65	0.9	$1.1\cdot10^{-7}$	$1.2\cdot10^{-12}$	$1.1\cdot10^{-5}$
	240	$E1$	1	0.03	$6.4\cdot10^{-6}$	$2.2\cdot10^{-14}$	$0.34\cdot10^{-8}$
	260	$E1$	8	0.03	$7.8\cdot10^{-7}$	$1.8\cdot10^{-14}$	$2.3\cdot10^{-8}$

The multipolarity data for 177 and 198 kev transitions were graciously supplied by V. M. Kel'man and V. A. Romanov.[4] The 177 and 196 kev transitions are mixed transitions of type M1 + E2, with the E2 admixture amounting to 18% in the former and 9% in the latter.

The conversion coefficients for the K and L shells were taken from the tables of Sliv and Band.[8] For the M + N shells we assumed a value of $0.3\,\alpha_L$, where α_L is the conversion coefficient on the L shell. The theoretical value $(\tau_\gamma)_W$ was calculated by the Weisskopf formulas.[9] The last column of the table gives the F-factor that characterizes the slowing down of the transition, relative to that predicted by Weisskopf's formulas.

It is seen from the table that the electric quadrupole transitions are slowed down by approximately three orders, and the magnetic dipole transitions by approximately six orders of magnitude. The 240 and 260 kev electric dipole transitions are slowed down by ~ 8 orders, and the 63-kev transition by ~ 5 orders.

The long lifetime of the 316-kev level was attributed in reference 10 to forbiddenness with respect to the quantum number K, which represents the projection of the spin of the nucleus on its prolate axis. Actually, as can be seen from the decay scheme of Tm^{169} in Fig. 1, transitions with energies 177, 198, and 308 kev correspond to a change in K by three units (from $7/2$ to $1/2$). According to the classification introduced by Alaga et al.[11] the degree of forbiddenness is characterized by a number $\nu = \Delta K - L$, where L is the multipolarity. Thus, $\nu = 1$ for electric quadrupole transitions from the 316-kev level, and $\nu = 2$ for magnetic dipole transitions. From the data in Table I it is seen that the unit of forbiddenness corresponds, for this level, to a slowing down by approximately three orders.

Since $K = 7/2$ for the 379-kev level, 240 and 260 kev, γ transitions to the levels with $K = 1/2$ are also slowed down because of K-forbiddenness. For these transitions, one unit of forbiddenness causes a slowing down by ~ 4 orders. Usually one unit of forbiddenness with respect to the quantum number K reduces the transition probability by a factor of 10 — 100.[11] In the case of Tm^{169}, however, this probability is decreased by a factor of 1000 — 10,000. This may be connected with the peculiarity of the Tm^{169} ground-state band, for which $K = 1/2$.

As to the 63-kev transition, as can be seen from the decay scheme, it is not forbidden with respect to the projection of the angular momentum. Nevertheless, the probability of this transition is reduced by 5 orders. The cause of this effect must be sought in possible forbiddenness with respect to other quantum numbers, which characterize the motion of the nucleons in strongly deformed nuclei, which include also the Tm^{169} nucleus with a deformation parameter of ~ 0.28.[12] These quantum numbers are as follows:[13] N — principal oscillator quantum number, n_z — quantum number of the nucleon oscillations along the prolate axis, and also Ω, Λ, and Σ — quantum numbers that represent the projections of the total, orbital, and spin angular momenta of the particle on the prolate axis of the nucleus.

As follows from Fig. 1 and Nilsson's paper,[13] the quantum numbers, Ω, Λ, Σ, N, and n_z should be assigned the values $7/2$, 4, $-1/2$, 4, and 0 respectively for the 316-kev level and $7/2$, 3, $1/2$, 5, and 2 respectively for the 379-kev level.

TABLE II

$\Delta\Omega = \Omega_f - \Omega_i$	$\Delta\Lambda = \Lambda_f - \Lambda_i$	$\Delta\Sigma = \Sigma_f - \Sigma_i$	$\Delta N = N_f - N_i$	$\Delta n_z = n_f - n_i$
0	1	—1	—1	—2
$\pm(L-1)$	$\pm(L-1)$	0	$L, (L-2), \ldots, -L$	±1
0	0	0	±1	—1

*The index f denotes the 316-kev level, while i denotes the 379-kev level.

The upper row of Table II gives the change in the quantum numbers due to a 63-kev γ transition, while the lower line gives the selection rules obtained by Voĭkhanskiĭ[14] for E1 transitions. It is seen from the table that the 63-kev transition is forbidden with respect to the quantum numbers Λ, Σ, and n_z (one unit of forbiddenness with respect to each of these quantum numbers).

As shown in reference 14, a one-unit forbiddenness decreases the transition probability by a factor of 10 — 100, which indeed takes place in our case. On the other hand, for a 63-kev transition that is allowed with respect to the quantum number K, the probability can be calculated from the Nilsson formulas [see Eqs. (29) and (35) of reference 13]. The calculation yields $(\tau_\gamma)_N = 2.3 \times 10^{-8}$ sec, which agrees[14] with the experimental value to a degree that is usual for such cases, namely $(\tau_\gamma)_N/(\tau_\gamma)_{exp} = 0.21$.

Thus, the slowing down of the 63-kev transition is connected with forbiddenness with respect to the asymptotic quantum numbers, and the long lifetime of the 379-kev level is explained by simultaneous action of K-forbiddenness for the 240 and 260-kev transitions and forbiddenness with respect to the numbers Λ, Σ, and n_z for the 63-kev transition.

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