Evidence of ''penetration effects'' for the 94 keV K-allowed unhindered transition in ^{169}Tm

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From the time differential angular correlation measurement of the 94-63 keV cascade in ^{169}Tm, a pure $M1$ character of the 94 keV γ ray is suggested in contrast to the 4% $E2$ admixture observed in conversion coefficient measurements. Our result indicates ''penetration effects'' on the internal conversion processes for the 94 keV transition. The observation of penetration effects for a K-allowed unhindered transition is probably the first. The magnetic moment of the 379 keV state has been remeasured, and the value [μ=(3.04±0.14)μ_N] is in close agreement with the theoretical prediction (4.5μ_N). [S0556-2813(97)03402-X]

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The level scheme of ^{169}Tm in the electron capture (EC) decay of ^{169}Yb is well established [1] (Fig. 1). The level structures of ^{169}Tm are well described by the unified model [2]. According to Mottelson and Nilsson [2], the first three excited states, viz., 8 keV $3/2^+$, 118 keV $5/2^+$, and 139 keV $7/2^+$, are members of the rotational band based on the $1/2^+$ ground state. The electromagnetic properties of the members of the $1/2^+$ ground rotational band in this highly deformed nucleus were studied earlier [3–5]. The members of the $K=7/2^-$ band are, however, not as well studied as the $K=1/2^+$ band. The $9/2^-$ state at 473 keV is the first rotational state based on the $7/2^-$ state at 379 keV. The magnetic moment of the $7/2^-$ state of this band was measured earlier. However, the only reported value of μ for this state [6] [(0.96±0.07)μ_N] is in strong disagreement with the value predicted theoretically (μ=4.5μ_N) [2]. The earlier measured value of μ for this state, using a NaI(Tl)-NaI(Tl) detector system, seems to be too low for an odd proton nucleus. The multipole mixing ratio (δ) of the 94 keV γ transition depopulating the 379 keV state was determined earlier by L-subshell ratio measurements [4,7,8]. However, to our knowledge, there was no attempt to find the value of δ(94) from angular correlation measurements.

In a recent work, Dey and Sinha [9] determined the multipole mixing ratios for the 198 and 177 keV transitions depopulating the 316 keV $7/2^+$ state from measurements of angular correlation of the 63-198 and 63-177 keV cascades in addition to the 198-118 and 177-130 keV cascades (Fig. 1). They found an almost pure $E2$ character for the 198 keV transition and an $M1+4\%$ $E2$ admixture for the 177 keV transition. For both these transitions, the results do not agree with the results of conversion electron measurements [4,7,8], which suggested an $M1+9\%$ $E2$ admixture for the 198 keV transition and an $M1+17\%$ $E2$ admixture for the 177 keV transition. The cause of the discrepancy in the results of γ-$\gamma(\theta)$ and conversion electron measurements was attributed to ''penetration effects'' on the internal conversion processes for the 198 and 177 keV transitions [9]. It would, therefore, be interesting to determine the multipole mixing ratio for the 94 keV transition from angular correlation measurements and to search for such possible penetration effects for this γ transition also. Considering the above facts, we have measured the unattenuated value of A_2, i.e., $A_2(0)$, of the 94-63 keV cascade from a time differential angular correlation experiment. Since the half-life of the intermediate state is long (46.4 nsec), a time differential measurement is required because the time-dependent quadrupole perturbation present in the source may attenuate the angular correlation within the lifetime. The magnetic moment of the 379 keV $7/2^-$ state has been remeasured by the differential perturbed angular correlation (DPAC) method using a NaI(Tl)-HPGe detector system.

For our measurement we have used a liquid source of $YbCl_3$ obtained from BRIT, Bombay. The source is taken in a small Perspex capsule of size (5×3) mm^2. The source-to-detector distances have been fixed at 7 cm.

The lifetime of the 379 keV state has been measured by the delayed coincidence (94-63 keV) method using a NaI(Tl)-HPGe system. A Bicron-made NaI(Tl) scintillator (5.1×5.1 cm^2) coupled to a Phillips XP2020 photomultiplier tube has been used to detect the 94 keV γ ray. A 10-cm^3

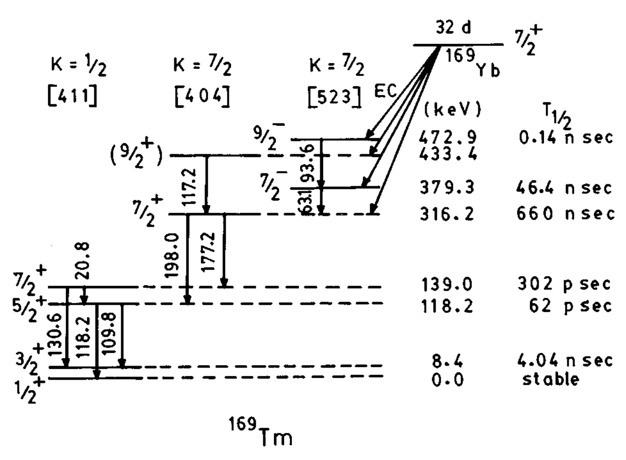

FIG. 1. Relevant portion of the decay scheme of ^{169}Yb.

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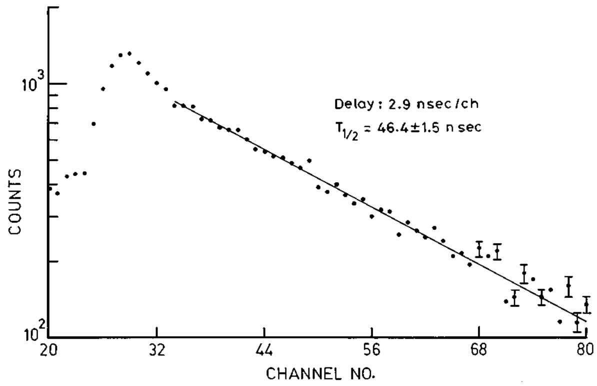

FIG. 2. Delayed coincidence spectrum of the 94-63 keV cascade of ^{169}Tm showing the lifetime of the 379 keV state.

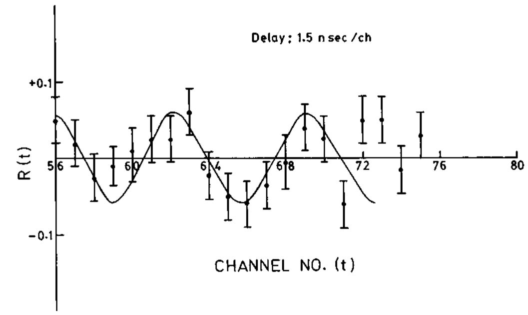

FIG. 4. Ratio $R(t)$ as a function of the time delay t, for the 94-63 keV cascade of ^{169}Tm. The solid line is the least squares fit of the experimental data points.

LEPS detector (ORTEC GLP-32340/13-P) is set to select the 63 keV γ ray. From an analysis of the lifetime curve (Fig. 2), a value of the half-life $T_{1/2}$=46.4±1.5 nsec is obtained. The present result of $T_{1/2}$ is slightly less than the value reported by Bodenstedt *et al.* [10] ($T_{1/2}$=49.8±1.5 nsec) who extracted the lifetime from a composite lifetime curve obtained for the 316 and 379 keV states in their measurement.

The time differential angular correlation for the 94-63 keV cascade has been measured using the same NaI(Tl)-HPGe system at a prompt time resolution of 23 nsec. Since the 63 keV γ transition is pure $E1$ [1,9], the theoretical value of A_4 is zero for this cascade and therefore the measurement has been performed at θ=90° and 180° to determine the value of A_2. The moving detector is alternated between these two angles every 30 min to avoid systematic uncertainties. The source is centered within 1% accuracy, and its strength is adjusted so that the true/chance coincidence rate is approximately 9:1 at the peak of the delayed curve. The background counts have been estimated from the flat random level of the time-to-amplitude converter (TAC) spectrum. Data for these two angles have been stored in two separate memory subgroups of a multichannel analyzer (MCA).

The result of the differential angular correlation measurement is shown in Fig. 3. The $A_2(t)$ values are fitted to an exponential function $A_2(t)=A_2(0)\exp(-\lambda_2 t)$, where λ_2 is called the relaxation constant. A least squares fit of the $A_2(t)$ values gives $A_2(0)=-0.060\pm0.010$ and λ_2=0.10±0.005 nsec^{-1}. After geometry correction for the detectors [11,12], the coefficient $A_2(0)$ is found to be $A_2(0)=-0.68\pm0.011$.

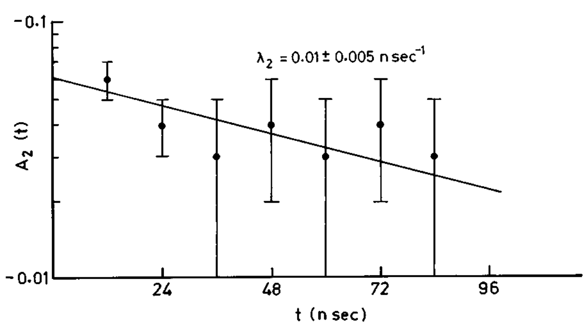

FIG. 3. Results of time differential angular correlation measurement for the 94-63 keV cascade in a liquid $YbCl_3$ source.

The g factor of the 379 keV state has been measured by perturbing the angular correlation of the 94-63 keV cascade with an external magnetic field H_{appl}=14.1 kG. Here, the 94 keV γ ray is detected in the NaI(Tl) detector (5.1×5.1 cm^2) and the 63 keV γ ray in a 25% HPGe detector of Oxford-Tennelec-Nuclears (serial No. CNPGA 5.0-25195). This increases the coincidence efficiency and reduces the data taking time. Both the detectors are at a distance of 10 cm from the source. The delayed coincidence counting rates $C^{\pm}$ have been recorded at an angle of 135° between the detectors, for both up and down field directions, in a sequence of 30 min alternately. The time spectra for these two angles of the detectors have been accumulated in two memory subgroups of the MCA. In order to determine the Larmor precession frequency ω_L, the value of $R(t)$ is found for each time delay t from the expression given by

$$R(t)=2\frac{C^+-C^-}{C^++C^-}=\frac{6A_2}{4+A_2}\sin 2\omega_L t,$$

when $A_4=0$ and $\omega_L=g\mu_N H_{eff}/\hbar$, $H_{eff}=\beta H_{appl}$; β is the paramagnetic correction factor. Figure 4 shows $R(t)$ as a function of the delay time t. More than two full periods of the spin rotation have been observed. The time calibration of the TAC is determined by inserting a fixed delay with an Ortec 425A nanosecond delay unit. The magnetic field is measured accurately using a precision gaussmeter made by Walker Scientific Inc. (model No. MG-5D, resolution ±10 G in 10.000 kG range). A least squares fit to the experimental data points gives

$$\omega_L=(2.99\pm0.14)\times10^8 \text{ rad/sec.}$$

The β factor [13] for Tm ions at a temperature of 300 K is β=5.08. From the value of ω_L, the g factor of the 379 keV state of ^{169}Tm comes out to be $g=0.87\pm0.04$, corresponding to $\mu=(3.04\pm0.14)\mu_N$, using the above value of β. The sign of g has been assigned by the sense of rotation of the angular correlation.

The present value of $A_2(0)=-0.68\pm0.011$ for the 94-63 keV cascade corresponds to a pure $M1$ multipolarity for the 94 keV γ transition (δ=0), considering a spin sequence of (9/2, 7/2, 7/2) and a pure $E1$ multipolarity for the 63 keV γ ray [1]. Günther *et al.* [4] from L-subshell ratio measurements, however, reported a value of $\delta^2(94)=(3.58\pm0.16)\times10^{-2}$ (4% $E2$ admixture) for the 94 keV γ ray. Grabowski *et al.* [7] and Agnihotry *et al.* [8] also reported 4% $E2$ admixture from L-subshell ratio measurements. From the above value of δ^2, the absolute value of δ comes out to be $|\delta|=0.189\pm0.004$. For this cascade the theoretical values of A_2 are $A_2=0.048$ for $\delta=+0.19$ and $A_2=-0.188$ for $\delta=-0.19$. Our measured value of $A_2(0)$ is negative, but much lower than -0.189. Thus the value of $\delta^2(94)$ reported by Günther *et al.* [4] can be ruled out from the present measurement.

The experimental values of L-subshell ratios for the 94 keV transition, viz. $L_{\rm I}:L_{\rm II}:L_{\rm III}=1075:149:100$ [7] and $1041\pm82:166\pm13:100$ [8], indicate a mixed $M1+E2$ transition for this γ ray. The theoretical values of $L_{\rm I}:L_{\rm II}:L_{\rm III}$ are 7857:705:100 for a pure $M1$ and 12:99:100 for a pure $E2$ multipolarity [14]. The theoretical values of α_K viz., 3.11, for a pure $M1$ and 1.15 for a pure $E2$ multipolarity [7] are not sensitive enough for the determination of the $M1$ and $E2$ admixture, while the experimental value of $\alpha_K=3.3\pm0.3$ [7]. The experimental value of $\alpha_L=0.64\pm0.06$ [7] indicates that it is not a pure $M1$ transition. For pure $M1$ multipolarity the theoretical value of $\alpha_L=0.481$ and for pure $E2$ it is 2.07 [7]. From the K/L ratio $(=5.2\pm0.5)$, Grabowski *et al.* [7] suggested a 4% $E2$ admixture for the 94 keV transition, which is in satisfactory agreement with that obtained from the L-subshell ratio measurements. On the other hand, from our differential angular correlation measurement, a pure $M1$ character for the 94 keV transition has been found. The cause of this discrepancy may be attributed to the "penetration effects" on the internal conversion processes for the 94 keV transition. Because of the finite size effect of the nucleus, some conversion coefficients (particularly $M1$) deviate from the calculation of Rose *et al.* [15] in the point nucleus approximation. Nilsson and Rasmussen [16] pointed out that where transitions are allowed by K-selection rules detectable conversion coefficient anomalies may generally be found at retardations greater than 10^5–10^6 and are not found at lesser retardations. In the present case, the 94 keV transition in ^{169}Tm is retarded by only 3.7 times with respect to the Weisskopf single particle estimate and still penetration effects seem to be present. The observation of penetration effects on the conversion processes for this K-allowed $(\Delta K=0)$ unhindered transition is probably the first of its kind.

The present result of $\mu=(3.07\pm0.14)\mu_N$ for the 379 keV state is in strong disagreement with the earlier result [6] where the differential-delay-reversed-field (DDRF) method was employed. The present result of μ is closer to the value predicted theoretically ($\mu=+4.5\mu_N$ [2]) for an odd proton nucleus.

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