Effect of Extranuclear Factors on the Probability of the $^{121m_2}$Te $\rightarrow^{121m_1}$Te Radioactive Decay

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Abstract—The nuclear isomer $^{121m_2}$Te was synthesized at a cyclotron by the $(d,2n)$ reaction and then incorporated into the MgO ceramic. This $\gamma$-ray source was stored either at 78 or at 298 K. The measured $\gamma$-radiation intensity ratio, $R = (\Phi_{573\text{ keV}}/\Phi_{212\text{ keV}})$, at 78 K appeared to be higher by a factor of 1.0012 ± 0.0002 than at 298 K. The temperature dependence of $R$ is caused by the low-temperature increase in the “constant” $\lambda_2$ of the $^{121m_2}$Te $\rightarrow^{121m_1}$Te decay by the internal conversion mechanism, equal to $\Delta \lambda/\lambda_2 = (0.07 ± 0.02)\%$. The same increase in the decay constant due to induced $\gamma$-ray emission, $^{121m_2}$Te $+ \gamma$ (81.79 keV) $\rightarrow^{121m_1}$Te $+ 2\gamma$ (81.79 keV), will be reached if both the size of the $^{121m_2}$Te source and the $^{121m_1}$Te concentration in it will be increased by 3 orders of magnitude, i.e., the total $^{121m_1}$Te activity should be increased by 6 orders of magnitude.

Keywords: tellurium-121, nuclear isomers, radioactive decay probability

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In 1947, Daudel [1] and Segre [2] suggested a method for affecting the constant of electron capture (EC) by a radioactive nucleus via variation of the electron density in the region of the nucleus. This approach was implemented experimentally with $^7$Be (half-life $\tau = 53$ days), with the largest reached relative change in the decay constant $\Delta \lambda/\lambda = 0.19\%$ [3]. For the strongly converted $\gamma$-transition in the isomer $^{99m}$Te ($\tau = 6.02$ h), the value of $\Delta \lambda/\lambda = 0.3\%$ was reached [4].

In principle, one more method of affecting the decay constant of $\gamma$-radioactive nuclei is possible: generation of induced $\gamma$-ray emission (IGE) in the isomer transition $^mX \rightarrow ^nX$:

$$
^mX + h\nu_{21} \rightarrow ^mX + 2h\nu_{21}$$

where

$$
\begin{align*}
\tau_2 & \quad \tau_2 \\
\tau_1 & \quad \tau_1
\end{align*}
$$

where $\tau_2$ is the lifetime of the long-lived upper level $^mX$, decaying into $^nX$ with the emission of $\gamma$-quantum M4 of energy $E_{21} = h\nu_{21}$ at the conversion coefficient $\alpha_2$; $\tau_1$ is the lifetime of the short-lived level $^mX$ decaying into $^nX$ with the emission of $\gamma$-quantum M1 of energy $E_{1g} = h\nu_{1g}$ at the conversion coefficient $\alpha_1$; $\sigma_{IGE}$ is the effective cross section of IGE (1). For many years, observation of IGE as a new physical effect was believed to be abstractly possible with short-lived nuclear isomers [5] but absolutely impossible with long-lived isomers, even taken in large amounts, because of extremely low IGE cross sections ($\sigma_{IGE} < 10^{-15}$ b). This estimate follows from the Einstein emission theory in the model of independent emitters [6]:

$$
\sigma_{IGE} = (\Lambda_2 \gamma \Gamma_\gamma (4\pi \Gamma_{tot})^{-1} = (\Lambda_2 \gamma \Gamma_\gamma (4\pi \Gamma_{tot})^{-1})f_{\delta}(T)\left[(1 + \alpha_2)\tau_2\right]^{-1}h, \tag{2}
$$

where $\Lambda_2$ is the $\gamma$-quantum wavelength, $\Gamma_\gamma$ is the partial width of the “recoilless” radiation transition, $\Gamma_{tot}$ is the total width of the spectral line, $\tau_2$ is the lifetime of the nuclear isomer, $\alpha_2$ is the coefficient of internal conversion of the $\gamma$-transition, and $f_{\delta}(T)$ is the fraction of recoilless $\gamma$-transitions (Debye–Waller factor) at the matrix temperature $T$ [7]:

$$
\delta_{\delta}(T) = \exp[-E_\delta(\hbar\theta_D)^{-1} (1 + \pi^2\tau_2^2/\theta_D^2)], \tag{3}
$$

where $\theta_D$ is the Debye temperature of the crystalline matrix, $k$ is the Boltzmann constant, and $E_\delta$ is the recoil energy of the nucleus emitting the $\gamma$-quantum.

Contrary to these predictions, direct experiments have shown that the IGE events do occur under definite conditions in M4 transitions of long-lived nuclear
where \( T_{\text{exp}} \) is the temperature of the crystalline matrix; \( x, y, z \) are the linear dimensions of the matrix containing \( m_2X \); \( A_{21} = \left[ \tau_2(1 + \alpha_2) \right]^{-1} \) is the Einstein coefficient for the spontaneous decay \( m_2X \rightarrow m_1X \). The IGE yields predicted by formula (5) are compared in Table 1 with the experimentally measured values:

$$
\varepsilon_{\text{exp}}(T_{\text{exp}}) = \frac{\Phi_{\gamma}(T_{\text{exp}}) - \Phi_{\gamma}(300 K)}{\Phi_{\gamma}(300 K)} = \frac{\Phi_{2\gamma}(T_{\text{exp}})}{\Phi_{\gamma}(300 K)} - \Phi_{\gamma}(300 K),
$$

(6)

where \( \Phi_{\gamma}(T) \) is the flux of \( \gamma \)-quanta \( h\nu_{21} \) from the \( m_2X \)-containing matrix with temperature \( T \); \( \Phi_{2\gamma}(T) \) is the flux of coherent pairs \( 2h\nu_{21} \) from the same matrix.

It follows from Eq. (5) that IGE (1) by the cooperative mechanism:

$$
\varepsilon_{\text{theor}}(T_{\text{exp}}) = \frac{(4\pi/3)^{[m_2X]}[A_{21}\beta_{\text{die}}/(\tau_1 + \tau_2)]_{\text{min}}(x, \mu_{21}^{-1})}{\text{min}(y, \mu_{21}^{-1})_{\text{min}}(z, \mu_{21}^{-1})},
$$

(5)

Despite negative prediction following from formulas (2) and (3) that, for all the four nuclides \( m_2X \), the cross section \( \sigma_{\text{IGE}} \) does not exceed \( 10^{-37} \text{ cm}^2 \), and the linear loss coefficient \( (\mu_{21}) \) is no lower than \( 10^{-10} \text{ cm}^{-1} \). Therefore, even at the maximum possible concentration \( [m_2X] = 10^{22} \text{ cm}^{-3} \), the overall amplification coefficient \( (a) \) for IGE in a solid matrix containing \( m_2X \) is always negative:

$$
a = \sigma_{\text{IGE}}[m_2X] - \mu_{21} \leq 10^{-15} \text{ cm}^{-1} - 10^{-10} \text{ cm}^{-1} < 0.
$$

(4)

isomers \( ^{125m_2}X \) [8–12], \( ^{123m_2}X \) [13, 14], and \( ^{119m_2}Sn \) [15]. The numerical parameters of transitions (1) with which the experiments were performed are given in Table 1.

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$$

(4)

Despite negative prediction following from formula (4), induced emission (1) was observed in [8–10] and was reproduced in another laboratory [11, 12]. Thus, there is no doubt in the occurrence of IGE with long-lived nuclear isomers. However, instead of one-particle (with respect to the number of participating \( m_2X \) nuclei) mechanism (1), it is necessary to assume [10] a cooperative mechanism of nuclear superemission, admissible in the running wave model within the framework of nonstationary optics [21]. For IGE, the cooperative model [10, 22, 23] gives the following theoretical value of the relative yield \( \varepsilon \):

$$
\varepsilon_{\text{theor}}(T_{\text{exp}}) = \frac{(4\pi/3)^{[m_2X]}[A_{21}\beta_{\text{die}}/(\tau_1 + \tau_2)]_{\text{min}}(x, \mu_{21}^{-1})}{\text{min}(y, \mu_{21}^{-1})_{\text{min}}(z, \mu_{21}^{-1})} = \frac{(4\pi/3)^{[m_2X]}[A_{21}(T_{\text{exp}})]_{\text{min}}(x, \mu_{21}^{-1})}{\text{min}(y, \mu_{21}^{-1})_{\text{min}}(z, \mu_{21}^{-1})},
$$

(5)

where \( T_{\text{exp}} \) is the temperature of the crystalline matrix; \( x, y, z \) are the linear dimensions of the matrix containing \( m_2X \); \( A_{21} = [\tau_2(1 + \alpha_2)]^{-1} \) is the Einstein coefficient for the spontaneous decay \( m_2X \rightarrow m_1X \). The IGE yields predicted by formula (5) are compared in Table 1 with the experimentally measured values:

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where \( \Phi_{\gamma}(T) \) is the flux of \( \gamma \)-quanta \( h\nu_{21} \) from the \( m_2X \)-containing matrix with temperature \( T \); \( \Phi_{2\gamma}(T) \) is the flux of coherent pairs \( 2h\nu_{21} \) from the same matrix.