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FINAL REPORT

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THEORETICAL AND EXPERIMENTAL ACHIEVEMENTS IN THE FIELD OF INDUCED GAMMA EMISSION

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Abstract

A critical analysis is presented for all published to date experimental data concerning the induced gamma-emission (*IGE*) in processes $^{125m2}Te(\gamma, 2\gamma)^{125m1}Te$, $^{123m2}Te(\gamma, 2\gamma)^{123m1}Te$, and $^{119m2}Sn(\gamma, 2\gamma)^{119m1}Sn$. The co-operative model of the *IGE* phenomenon is deduced from quantum electrodynamics.

Experimental results

In 1984 we published[1] a results of experimental study regarding the *IGE* process:

$$
\begin{array}{l}
^{125m_2}Te + h\nu(109.3keV) \xrightarrow{78K} {}^{125m_1}Te + 2h\nu(109.3keV) \\
\qquad\qquad\qquad\qquad\qquad\qquad\quad \downarrow 1.48ns \\
\qquad\qquad\qquad\qquad\qquad\quad {}^{125}Te + h\nu(35.5keV)
\end{array}
\tag{1}
$$

In Ref.[1] the experimental effect is taken as:

$$\varepsilon = \frac{\Delta\Phi}{\Phi}, \tag{2}$$

where $\Delta\Phi$ is the number of gamma-quanta emitted by stimulation at the $Be^{125m2}Te$ sample temperature T_{exp}=78K, and Φ is the number of gamma-quanta spontaneously emitted at sample temperature 300K. The value ε_{exp} = 1.2±0.6% had been obtained in Ref. [1]. In order to exclude the contribution in ε_{exp} from a temperature rise of sample density we had reproduced the *IGE* process (1) in Ref.[2]. In the latter work the experimental effect is taken as:

$$\varepsilon_{exp} = \frac{\Phi_{2\gamma}}{\Phi}, \tag{3}$$

where $\Phi_{2\gamma}$ is a number of coherent pairs $2h\nu$ (109.3 keV) originated in the process (1).

Finally, in Ref.[3] we had reproduced the *IGE* process (1) using both techniques (2) and (3) . for ε_{exp}. The resulting experimental data are presented in Table 1.

Taken together References [1-3] demonstrate with confidence a reality of the *IGE* process (1). Nevertheless, by the early 1990s there was some uncertainty as to the mechanism of the *IGE* process. Hence, we undertook the experimental study regarding the *IGE* process[3]:

$$^{123m_2}Te + h\nu(88.46keV) \xrightarrow{10K} {}^{123m_1}Te + 2h\nu(88.46keV) \quad (4)$$
$$\downarrow 0.19ns$$
$$^{123}Te + h\nu(159.0keV)$$

The obtained value of ε_{exp} for process (4) together with data for reaction (1) had demonstrated[3-5] that realized *IGE* process is a collective polynuclear superradiance rather than stimulated emission of Mössbauer radiation. The corresponding theoretical equation for the effect value can be written as[3-5]:

$$\varepsilon_{theor} = \frac{2\pi N_x f_m \beta \tau_{down}}{3\mu^3(1+\alpha)(\tau_{up} + \tau_{down})}, \quad (5)$$

where N_x is a number of inversion, f_m is the Mössbauer factor, β is a branching factor, μ is the linear losses coefficient, α is an internal conversion factor, τ_{up} is the upper level life time, and τ_{down} is the lower level life time. Eqn. (5) holds[5] only when the lattice temperature (T_{exp}) is decreased to the value T_Λ wherein a de Broglie thermal wavelength for nucleus $*X$ exceeds the gamma-quantum wavelength (Λ):

$$T_{exp} \le T_\Lambda = \frac{(\hbar/\Lambda)^2}{2km_x}. \quad (6)$$

Here $\hbar$ is the Planck constant, k is the Boltzmann constant, and m_x is a mass for the $*X$ nucleus. The relationship N_x=[$*X$] was true in conditions of our experiments [1-5]. One should recognize from the data of Table 1 that Eqn. (5) of co-operative model describes within the error limits all the experimental results obtained in Ref.[1-5].

In Table 1 we present also the results of experimental study of the process (4) in ref.[6] and process

$$^{119m_2}Sn + h\nu(65.66keV) \xrightarrow{15-78K} {}^{119m_1}Sn + 2h\nu(65.66keV) \quad (7)$$
$$\downarrow 17.75ns$$
$$^{119}Sn + h\nu(23.87keV)$$

in Refs.[6,7].

Table 1. Comparison of theoretically calculated by formula (5) and experimentally measured ratio $\varepsilon = \Delta\Phi_\gamma/\Phi_\gamma$, where $\Delta\Phi_\gamma$ is the number of gamma-quanta emitted by stimulation at matrix temperature T_{exp}, and Φ_γ is the number of gamma-quanta emitted spontaneously at matrix temperature 300*K*.

nuclide (*X)	$^{125m2}Te$		$^{123m2}Te$		$^{119m2}Sn$	
polycrystal	*BeTe*		Mg_3TeO_6	Mg_3TeO_6 + *MgO*	*SnO*	SnO_2
T_Λ / *K*	10		6.6	6.6	3.6	3.6
Debye temperature / *K*	390		350	375	154	160
$[{}^*X]$ / 10^{18} atoms·cm^{-3}	12±5	4.9±1.5	34±7	1.0±0.2	5±1	9±3
T_{exp} / *K*	78	10	10	78	15	78
Mössbauer factor $f_m(T_{exp})$	0.10±0.02	0.108	0.18±0.01	0.13	0.0214	0.01
μ_0^{-1} / cm	0.2062	0.2062	0.1639	0.33	0.0293	0.032
$(4\pi/3)[{}^*X]\mu_0^{-3}$ / 10^{16} atoms	44±18	18±6	63±13	16±5	0.053±0.011	0.12
$\dfrac{10^{20} f_m \tau_d}{2(1+\alpha_{up})(\tau_{up}+\tau_d)}$	4.03	4.35	0.148	0.103	0.0126	0.0059
ε_{theor} / %	1.8±0.7	0.8±0.3	0.09±0.02	0.02±0.01	$7.8\cdot10^{-6}$	$7\cdot10^{-6}$
ε_{exp} / %	1.2±0.6	0.35±0.15	0.05±0.03	0.30±0.06	≤0.0012	0.02± ±0.01
reference for ε_{exp}	Skor, Dz[1], 1984	Skor, Dz[3], 1995	Skor, Dz[3], 1995	Bond. Dz[6], 1996	*ITEPh*[7], 1989	Bond, Dz[6] 1996

Co-operative effects in stimulated emission

If we use a long-lived isomer both as storage and lasing level, the stimulated emission cross section is very small because of the very weak coupling between the gamma-radiation and the nuclei. Nevertheless, if the nuclei are imbedded in a lattice, co-operative effects in the stimulated emission could enhance the amplification and thus the gain substantially.

Consider an incoming gamma-radiation with a resonant (or near-resonant) frequency. That radiation interacts with all the nuclei in the ensemble and can stimulate those nuclei which are in the excited state to emit a photon. The probability for such a process can be written as[8]:

$$P_{stim.em.}(\hat{k}\sigma,t)=\left|\left\langle n_{\hat{k}\sigma}+1,\Psi_F(\vec{r}_1,\vec{r}_2,\ldots,\vec{r}_n,\vec{r})\right|\vec{J}(\vec{r})\cdot\vec{A}_{\hat{k}\sigma}(\vec{r},t)\left|n_{\hat{k}\sigma},\Psi_I(\vec{r}_1,\vec{r}_2,\ldots,\vec{r}_n,\vec{r})\right\rangle\right|^2, \quad (2\text{-}1)$$

where $\vec{A}_{\hat{k}\sigma}(\vec{r},t)$ is the field at point $\vec{r}$ associated to the stimulating radiation with momentum $\hat{k}$ and helicity σ. For an incoming plane wave the vector potential is[9]:

$$\vec{A}_{\hat{k}\sigma}(\vec{r},t)=\vec{A}^*_{\hat{k}\sigma}\,e^{-i(\vec{k}\vec{r}-\omega t)}+\vec{A}_{\hat{k}\sigma}e^{i(\vec{k}\vec{r}-\omega t)}, \quad (2\text{-}2)$$

in which $\vec{A}^*_{\hat{k}\sigma}$ and $\vec{A}_{\hat{k}\sigma}$ are respectively related to the photon creation operator $a^+_{\hat{k}\sigma}$ and the destruction operator $a_{\hat{k}\sigma}$. Since we consider only stimulated emission we can write:

$$\vec{A}_{\hat{k}\sigma}(\vec{r},t)=a^+_{\hat{k}\sigma}\tilde{A}_{\hat{k}\sigma}(\vec{r},t). \quad (2\text{-}3)$$

The total nuclear current operator $\vec{J}(\vec{r})$ can be written as a sum of currents $\vec{j}_l(\vec{r})$ each belonging to one single nucleus. The position vector $\vec{r}$ can for each nucleus be written as a function of the position of the nuclear mass center $\vec{r}_l$ and a charge distribution vector $\vec{\rho}_l$. Then:

$$\vec{J}(\vec{r})=\sum_l\vec{j}_l(\vec{r})=\sum_l\vec{j}_l(\vec{r}_l+\vec{\rho}_l). \quad (2\text{-}4)$$

The wave functions of the initial and final state are products of single nucleus wave functions:

$$\Psi_I(\vec{r}_1,\vec{r}_2,\ldots,\vec{r}_n,\vec{r})=\prod_l\int_{|\Delta\vec{r}_l|}\varphi_l(\vec{r}_l+\vec{\xi}+\vec{\rho}_l)f(\vec{\xi})d\vec{\xi}=$$

$$=\int_{|\Delta\vec{r}|}\prod_l\varphi_l(\vec{r}_l+\vec{\xi}+\vec{\rho}_l)f(\vec{\xi})d\vec{\xi}, \quad (2\text{-}5)$$

$$\Psi_F(\vec{r}_1,\vec{r}_2,\ldots,\vec{r}_n,\vec{r})=\int_{|\Delta\vec{r}|}\prod_j\Phi_j(\vec{r}_j+\vec{\xi}+\vec{\rho}_j)f(\vec{\xi})d\vec{\xi}. \quad (2\text{-}6)$$

Here the $f(\vec{\xi})$ function presents a Heisenberg uncertainty for the spatial coordinate $\vec{r}$.

As we consider only stimulated emission, we can restrict the initial state to all nuclei which are in the exited state. The total transition amplitude is then reduced to a sum of single nucleus matrix elements. Then, for every l in the absence of any temperature gradient in a lattice following relationship is true as result of the Heisenberg uncertainty relation:

$$|\Delta\vec{r}_l| = |\Delta\vec{r}| = \sqrt{\frac{2\pi\hbar^2}{m_X k T_{lat}}}, \tag{2-7}$$

where $\hbar$ is the Planck constant, k is the Boltzman constant, m_X is a mass of radiating nucleus. T_{lat} is a lattice temperature. Now instead equation (28) of Ref.[8] we obtain following equation for total transition amplitude:

$$\mathcal{Z}_{tot}(\hat{k}\sigma,t) = \sum_l \int_{|\Delta\vec{r}|} \left\langle \Phi_l(\vec{r}_l + \vec{\xi} + \vec{\rho}_l) \middle| \vec{j}_l(\vec{r}_l + \vec{\rho}_l)\vec{A}_{\hat{k}\sigma}(\vec{r}_l + \vec{\rho}_l) \middle| \varphi_l(\vec{r}_l + \vec{\xi} + \vec{\rho}_l) \right\rangle f(\vec{\xi})d\vec{\xi}. \tag{2-8}$$

Under condition $f(\vec{\xi}) = \delta(\vec{\xi})$ our equations (2-5), (2-6), (2-8) coincides with equations (26), (27), (28) of Ref.[8]. Instead of equation (29) in Ref.[8] the total transition amplitude becomes equal:

$$\mathcal{Z}_{tot}(\hat{k}\sigma,t) = \int_{|\Delta\vec{r}|} \sum_l \left\langle \Phi(\vec{\rho} + \vec{\xi}) \middle| \vec{j}(\vec{\rho})\vec{A}_{\hat{k}\sigma}(\vec{r}_l + \vec{\rho},t)T(-\vec{r}_l) \middle| \varphi(\vec{\rho} + \vec{\xi}) \right\rangle f(\vec{\xi})d\vec{\xi} =$$

$$= \sum_l \left\langle \Phi(\vec{\rho}) \middle| \vec{j}(\vec{\rho}) \cdot \int_{|\Delta\vec{r}|} \vec{A}_{\hat{k}\sigma}(\vec{r} + \vec{\rho},t)T(-\vec{r}_l - \vec{\xi})f(\vec{\xi})d\vec{\xi} \middle| \varphi(\vec{\rho}) \right\rangle, \tag{2-9}$$

where:

$$\int_{|\Delta\vec{r}|} \vec{A}_{\hat{k}\sigma}(\vec{r}_l + \vec{\rho},t)T(-\vec{r}_l - \vec{\xi})f(\vec{\xi})d\vec{\xi} = \vec{A}_{\hat{k}\sigma}(\rho,t) \int_{|\Delta\vec{r}|} e^{-2ik(\vec{r}_l + \vec{\xi})} f(\vec{\xi})d\vec{\xi}. \tag{2-10}$$

The total transition probability for stimulated emission can thus be written as:

$$P_{stim.em.}(\hat{k}\sigma, T_{lat}, t) = |\ldots|^2 \sum_{j,l} \int_{|\Delta\vec{r}|} e^{-2i\vec{k}(\vec{r}_l - \vec{r}_j + \vec{\xi})} f(\vec{\xi})d\vec{\xi}, \tag{2-11}$$

where:

$$|\ldots|^2 = \left| \left\langle \Phi(\vec{\rho}) \middle| \vec{J}(\vec{\rho}) \cdot \vec{A}(\vec{\rho},t) \middle| \varphi(\vec{\rho}) \right\rangle \right|^2 = \hbar\omega_{res} A_{21} \frac{f_m(T_{lat})\beta\hbar\Gamma_{up}\hbar\Gamma_{tot}}{4(1+\alpha)\left[(E_{21} - \hbar\omega)^2 + \frac{1}{4}(\hbar\Gamma_{tot})\right]}. \tag{2-12}$$

Here β is a branching factor, α is an interval conversion factor, f_m is the Mössbauer factor, Γ_{up} is a line width of the upper level, Γ_{tot} is the total line width, A_{21} is the Einstein coefficient, $\hbar\omega_{res} = E_{21}$ is the energy of electromagnetic transition.

Under condition $|\Delta\vec{r}| << |\vec{k}|^{-1}$ there are both situations outlined by equations (32)-(36) of Ref. [8]. However, under opposite condition $|\Delta\vec{r}| \geq |\vec{k}|^{-1}$ we get:

$$\sum_{j,l} \int_{|\Delta\vec{r}|} e^{-2i\vec{k}(\vec{r}_l - \vec{r}_j + \vec{\xi})} f(\vec{\xi})d\vec{\xi} = \kappa(T_{lat}) \sum_{j,l} 1 = (N')^2 \kappa(T_{lat}), \tag{2-13}$$

where:

$$N' = [N] l_x l_y l_z, \tag{2-14}$$

$$l_j = Min(L_j, \mu_j^{-1}), \tag{2-15}$$

$$\kappa(T_{lat}) = \begin{cases} 1, & if \quad T_{lat} \le T_\Lambda \\ (T_\Lambda / T_{lat})^{0.5}, & if \quad T_{lat} > T_\Lambda, \end{cases} \tag{2-16}$$

$$T_\Lambda = \frac{(\hbar / \Lambda_{21})^2}{2km_X}, \tag{2-17}$$

L_j is the sample length along j-axis, μ_j is the absorption coefficient along j-axis, and Eqn. (2-17) is the same as Eqn. (6). Now one might see that equations (2-11) - (2-17) under condition $|\Delta\vec{r}| \ge |\vec{k}|^{-1}$ coincides completely with basic equation (5).

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