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General criteria for the feasibility of nuclear gamma-laser experiment

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Abstract. **The most general conditions required for the observation of the quantum amplification of a gamma-quantum flux by excited nuclei are formulated. The region of admissible parameters for two alternative variants of the aggregate state of an amplifying medium (atoms in solids and free atoms) is found.**

Keywords: *gamma laser, amplification without inversion, amplification with hidden inversion.*

1. Introduction

Despite the differences existing between the modern concepts of the quantum amplification of a gamma-photon flux by excited nuclei as a demonstration of the feasibility of a nuclear gamma laser, it is useful to classify several common and quite obvious quantitative criteria, which must be fulfilled in any reasonable approach. Note that we are dealing with the observation of a process of 'multiplication' of gamma quanta and even a quantum avalanche rather than with the detection of individual events of stimulated emission of gamma quanta by nuclei at the level of single-quantum counting.

Two basic most popular present-day variants of a nuclear gamma-laser experiment differ from each other in the aggregate state of an amplifying medium. In the first case, active nuclei are located in a solid matrix, while in the second one, they belong to free atoms that do not interact with each other. One of the main problems that an experimenter should solve in both cases, namely, the narrowing of a gamma emission line down to its natural width is solved differently in these cases. In the first case, the conditions are created for emission of the Mössbauer zero-phonon line in a solid, while in the second case, the Doppler inhomogeneous broadening is eliminated by cooling an ensemble of free atoms by modern methods for manipulation of neutral atoms using optical lasers (see, for example, [1] and [2], respectively).

As for the classical Mössbauer variant of a gamma laser, which was proposed by Soviet and American scientists as long as forty years ago, we will not consider it here because of an 'insoluble dilemma' [1] inherent in it. The modern and probably more realistic concept of a Mössbauer gamma laser is based on the amplification without inversion (AWI) of the population of nuclear states, which appears upon resonance excitation of an atomic electron shell by an optical laser [3].

When an amplifying medium consists of deeply cooled free atoms, the amplification with hidden inversion (AHI) of the population of nuclear states is used, which appears due to the kinematic shift of absorption and emission gamma lines caused by the recoil of free nuclei upon radiative transitions [2].

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2. Quantum amplification of intrinsic spontaneous radiation by excited nuclei

Because the efficient mirrors for the gamma range are not available, we have to consider the single-pass amplification of the intrinsic spontaneous radiation by an excited nuclear medium. In the simplest case of a spatially homogeneous nuclear medium, the output density of an amplified gamma-photon flux can be written in a standard form

$$F = \frac{G-1}{\ln G} S_{\rm sp} L, \qquad (1)$$

where

$$G = \exp[(g - \chi n)L] \qquad (2)$$

is the exponential amplification during a single passage through the medium of length L;

$$g = \frac{\lambda^2}{2\pi}\left(n_2 - n_1 \frac{2J_2+1}{2J_1+1}\right)\beta \qquad (3)$$

is the gain; λ is the resonance wavelength; n_2 and n_1 are the nuclear concentrations at the upper and lower levels of the laser transition; J_2 and J_1 are the angular momenta of these levels; χ is the averaged cross section for nonresonance losses of gamma quanta on electron shells of atoms of all types; n is the total concentration of all atoms;

$$\beta = \frac{\Gamma_\gamma}{\hbar \Delta\omega_{\rm tot}} < \frac{1}{1+\alpha} \qquad (4)$$

is the ratio of the radiative linewidth Γ_γ of the transition to the total linewidth $\hbar\Delta\omega_{\text{tot}}$, which takes into account all the broadening mechanisms, including the inhomogeneous broadening, for example, Doppler broadening; α is the coefficient of internal electron conversion characterising the excess of the total natural width over the radiative linewidth Γ_γ;

$$S_{\text{sp}} = \frac{n_2}{\tau \ln 2} \frac{\beta}{1+\alpha} \frac{\Delta\Omega}{4\pi} \tag{5}$$

is the rate of spontaneous emission of gamma quanta by the unit volume of the medium to the selected modes within the solid angle $\Delta\Omega$; τ is the decay time of an excited state, taking into account the internal electron conversion.

In two basic modern concepts of a nuclear gamma laser (the AWI appearing upon excitation of the electron shell of an atom by an optical laser and the AHI appearing due to the kinematic shift of the absorption and emission gamma lines caused by the recoil of free nuclei in radiative processes), a term containing the concentration n_1 of nuclei on the lower levels of the laser transition is absent in expression (3). The expression for the normalised density of a gamma-quantum flux for these most promising schemes of a gamma laser takes the form

$$\frac{F}{F^*} = \exp\left[\frac{\lambda^2}{2\pi}(1-\varepsilon)\beta n_2 L\right] - 1, \tag{6}$$

where

$$F^* \equiv \frac{\Delta\Omega}{2\lambda^2(1-\varepsilon)\tau(1+\alpha)\ln 2}; \tag{7}$$

$$\varepsilon \equiv \frac{2\pi\chi n}{\lambda^2 n_2 \beta} \tag{8}$$

is the ratio of the coefficient of nonresonance losses of photons in the medium to the gain, which is, of course, should be less than unity ($\varepsilon < 1$). The latter is possible because the cross section χ for nonresonance losses of photons is substantially lower than the square of the wavelength of gamma rays. For example, for $\hbar\omega = 10$ keV, the cross section is $\chi = 0.41 \times 10^{-22}$ cm^2 for carbon, 110×10^{-22} cm^2 for aluminium, 157×10^{-22} cm^2 for iron, 290×10^{-22} cm^2 for lead, etc. [4].

3. Threshold criterion

The inequality $\varepsilon < 1$ is in fact the threshold condition

$$\frac{n_2}{n} > \frac{2\pi\chi}{\beta\lambda^2}, \tag{9}$$

in which $n \approx 3 \times 10^{22}$ cm^{-3} for AWI in a condensed medium and $n = n_1 + n_2 \ll 3 \times 10^{22}$ cm^{-3} for AHI in free nuclei. The threshold boundaries corresponding to criterion (9) are shown in Fig. 1 by the vertical straight lines for $\chi = 3 \times 10^{-20}$ cm^2, $\beta \to 1$, and two photon energies $\hbar\omega = 10$ and 20 keV.

It follows from (9) that even in the AWI or AHI schemes, in which the concentration n_2 of excited nuclei can be assumed as low as is wished, the restriction (9) from below acts in fact, which serves as the first obvious general gamma-laser criterion.

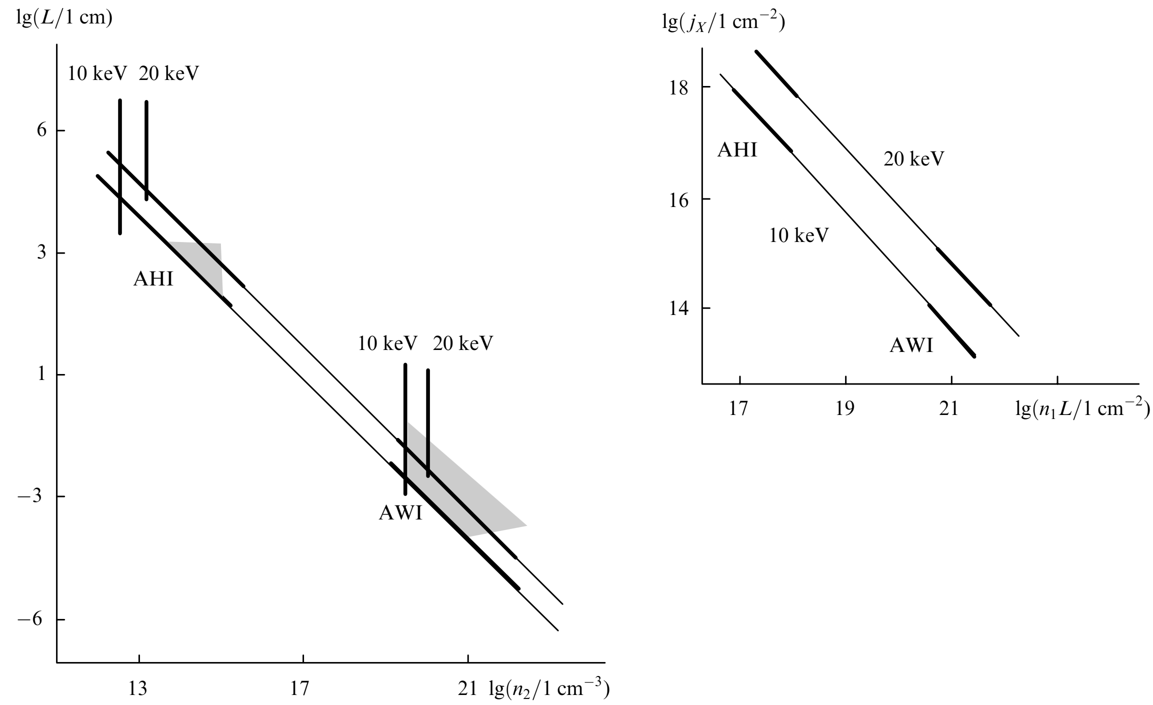

Figure 1.

4. Criterion of the minimum number of excited nuclei over the amplification length

If the exponent in (6) is substantially lower than unity, only a spontaneous photon flux is observed with the density

$$F \approx \frac{\beta n_2 L}{\tau(1+\alpha)\ln 2}\frac{\Delta\Omega}{4\pi}. \tag{10}$$

This flux is appreciably amplified when F in (6) does depend exponentially on the product $n_2 L$, i.e., when the exponent exceeds unity, and

$$n_2 L > \frac{2\pi}{\lambda^2 \beta}\frac{\ln G}{1-\varepsilon} > \frac{2\pi}{\lambda^2}\ln G, \tag{11}$$

where the second inequality corresponds to the most favourable case of $\varepsilon \ll 1$ and $\beta \to 1$.

The product $n_2 L$ is a total number of excited nuclei per square centimetre of the cross section of the amplifying medium of length L. Therefore, inequality (11) represents in fact the second general criterion of the amplification of gamma quanta, which is valid for any conceptual experimental scheme. Criterion (11) of a minimum number of excited nuclei per unit cross section of the medium of length L has the following numerical form

$$n_2 L > 4\times 10^{14}\frac{(\hbar\omega)^2}{\beta}\frac{\ln G}{1-\varepsilon} > 4\times 10^{14}(\hbar\omega)^2 \ln G, \tag{12}$$

where the photon energy $\hbar\omega$ is expressed in keV and the product $n_2 L$ is in cm^{-2}.

Here, it is useful to make some numerical estimates, assuming, for example, that $G = 12.2$ ($\ln G = 2.5$, respectively). In this case, $F/F^* = 11.2$. Let us also assume that the gamma-quantum energy is $\hbar\omega = 10$ keV and $\varepsilon \ll 1$ and $\beta \to 1$ in the most favourable case; then, $n_2 L > 10^{17}\ \text{cm}^{-2}$. This means that the required length of the amplifying medium is varied, for example, from $L = 10^{-5}$ cm for the concentration $n_2 = 10^{22}\ \text{cm}^{-3}$ up to 10 m for $n_2 = 10^{14}\ \text{cm}^{-3}$. In fact, these ultimate values correspond to two alternative variants of an amplifying nuclear medium: a condensed amplifying medium with a narrow Mössbauer line (AWI) or free nuclei in deeply cooled atomic beams (AHI).

Criterion (12) is graphically illustrated by the lower part of Fig. 1, where the dependences of $\lg L$ on $\lg n_2$ are shown for photon energies $\hbar\omega = 10$ and 20 keV and the following values of the rest of parameters: $\beta \to 1, \varepsilon \ll 1$, $\chi = 3\times 10^{-20}\ \text{cm}^2$, $\ln G = 2.5$ and $n = 3\times 10^{22}\ \text{cm}^{-3}$ for AWI in a solid and $10^{15}\ \text{cm}^{-3}$ for AHI in free nuclei. As noted above, the vertical straight lines show the boundaries of the threshold condition (9), while the straight lines with a negative slope show the boundaries corresponding to criterion (12). The dashed parts of the diagram show conditionally the regions of admissible values of experimental parameters. One can see that these regions are limited. The refinement of the values of the parameters for specific nuclides can displace somewhat the region boundaries, the general view of the diagram remaining invariable.

5. Criterion of the minimal brightness of a pump source

In any variants of a gamma-laser experiment, the concentration of excited nuclei determined in section 3 is produced by pumping. This is also valid for the anti-Stokes experiment when the pump plays in fact the role of a trigger with the pump photon energy that is somewhat lower than the laser photon energy. In the simplest and possibly the most efficient 'two-level' X-ray ('optical') pump scheme, the energies of both photons virtually coincide.

The resonance absorption of incoherent pumping X-rays with the wavelength $\lambda_X \approx \lambda$ and the spectral density (brightness) j_X (with the dimensionality $\text{cm}^{-2}\text{s}^{-1}\ \text{Hz}^{-1} = \text{cm}^{-2}$) produces excited nuclei with the concentration

$$n_2 \approx n_1 \frac{j_X}{j^*}\left[1 - \exp\left(-\frac{\Delta t_X}{\tau}\right)\right], \tag{13}$$

where

$$j^* = \frac{2\pi}{\lambda_X^2}\frac{2J_1+1}{2J_2+1}\frac{1+\alpha}{\ln 2}; \tag{14}$$

and Δt_X is the exposure time. Expression (13) is valid for $j_X \ll j^*$ and respectively for $n_2 \ll n_1$. Upon long exposure, when $\Delta t_X \gg \tau$, we have

$$n_2 \to n_1 \frac{j_X}{j^*}, \tag{15}$$

and vice versa, upon pulsed irradiation, when $\Delta t_X \ll \tau$, we have

$$n_2 \approx n_1 \frac{j_X}{j^*}\frac{\Delta t_X}{\tau}. \tag{16}$$

Comparison of (11) with (13) gives the minimal required brightness (spectral density) of the pump radiation

$$j_X > \left(\frac{2\pi}{\lambda^2}\right)^2 \frac{\ln G}{\beta n_1 L \ln 2}\frac{1+\alpha}{1-\varepsilon}\frac{2J_1+1}{2J_2+1}\left[1 - \exp\left(-\frac{\Delta t_X}{\tau}\right)\right]^{-1}$$

$$> \left(\frac{2\pi}{\lambda^2}\right)^2 \frac{\ln G}{n_1 L \ln 2}\left[1 - \exp\left(-\frac{\Delta t_X}{\tau}\right)\right]^{-1}, \tag{17}$$

which drastically increases with the photon energy as $\sim(\hbar\omega)^4$ (in the second inequality, which corresponds to the most favourable case $\varepsilon \ll 1, \beta \to 1$, and $\alpha \ll 1$, a factor containing the ratio of the angular momenta is also omitted, which is usually of the order of unity). For pulsed pumping (16), which is most probable in experiments, we have

$$j_X > \left(\frac{2\pi}{\lambda^2}\right)^2 \frac{\ln G}{\beta n_1 L \ln 2}\frac{1+\alpha}{1-\varepsilon}\frac{2J_1+1}{2J_2+1}\frac{\tau}{\Delta t_X}$$

$$> \left(\frac{2\pi}{\lambda^2}\right)^2 \frac{\ln G}{n_1 L \ln 2}\frac{\tau}{\Delta t_X}, \tag{18}$$

or in the numerical form (the photon energy is expressed in keV),

$$j_X > 2.4 \times 10^{29} (\hbar\omega)^4 \frac{\ln G}{\beta n_1 L} \frac{1+\alpha}{1-\varepsilon} \frac{2J_1+1}{2J_2+1} \frac{\tau}{\Delta t_X}$$

$$> 2.4 \times 10^{29} (\hbar\omega)^4 \frac{\ln G}{n_1 L} \frac{\tau}{\Delta t_X}. \quad (19)$$

Thus, for the example considered above with $\Delta t_X/\tau = 0.1$, we obtain $j_X > 6 \times 10^{16}$ cm^{-2} for $n_1 L = 10^{18}$ cm^{-2} (AHI) and $j_X > 2 \times 10^{13}$ cm^{-2} for $n_1 L = 3 \times 10^{21}$ cm^{-2} (AWI). The inset in Fig. 1 illustrates criterion (18) for the favourable case $\beta \to 1, \varepsilon \ll 1, \alpha \ll 1$, as well as for $\Delta t_X/\tau = 0.1$, and $\ln G = 2.5$ by neglecting angular momenta.

To make comparison with standard X-ray sources, which are characterised by the number of quanta emitted from a square millimetre of a source per second within the frequency band equal to 10^{-3} of the emission frequency and to the solid angle equal to a square milliradian, it is reasonable to present the above estimates of j_X in these units. For $\hbar\omega = 10$ keV, these estimates are $\sim 10^{30}$ and $\sim 10^{27}$ photon mm^{-2} s^{-1} mrad^{-2}, respectively. These very high values only approach the peak characteristics of relativistic X-ray sources of a new generation [for example, free-electron X-ray lasers with linear accelerators SBLC and TESLA at HASYLAB/DESY (Hamburg) and SLAC (Stanford)].

6. Criteria for the perturbation (damage) of an amplifying medium by the pump

Along with the production of the required concentration of excited nuclei, the pump also exerts an adverse effect on the amplifying medium. This effect consists mainly in the perturbation and even a complete violation of Mössbauer conditions in experiments with condensed media, or in a decrease in the concentration of excited nuclei due to their removing from a deeply cooled atomic beam in experiments with free nuclei.

In the case of a condensed medium, it is useful to estimate the energy dissipated in the medium during pumping. Let us assume that the emission band $\Delta\omega_X/(2\pi)$ of an X-ray pump source exceeds the broadened resonance absorption line of nuclei by a factor of $\xi > 1$:

$$\frac{\Delta\omega_X}{2\pi} = \xi \frac{\ln 2}{\beta\tau}. \quad (20)$$

Then, the penetration depth of pump radiation into the condensed medium will be different for different parts of this band.

The radiation resonant with the nuclear absorption will penetrate to the depth

$$\delta_n = \left(\frac{\lambda^2}{2\pi} \frac{2J_2+1}{2J_1+1} \beta n_1 + \chi n\right)^{-1} = \frac{2\pi}{\lambda^2 \beta n_1} \frac{2J_1+1}{2J_2+1}$$

$$\times \left(1 + \varepsilon \frac{2J_1+1}{2J_2+1} \frac{n_2}{n_1}\right)^{-1} \approx \frac{2\pi}{\lambda^2 \beta n_1} \frac{2J_1+1}{2J_2+1}, \quad (21)$$

where the latter approximate equality corresponds to a favourable case with $\varepsilon \ll 1$ and $n_2/n_1 < 1$, i.e., the penetration depth δ_n of resonance emission is mainly determined by the nuclear absorption (for example, $\delta_n \approx 10^{-5}$ cm for $\hbar\omega_X = 10$ keV and $n_1 = 3 \times 10^{21}$ cm^{-3}).

The rest of the pump spectrum lies outside the nuclear resonance absorption, and the penetration depth of this radiation is

$$\delta \approx (\chi n)^{-1}. \quad (22)$$

For example, $\delta \approx 10^{-3}$ cm for typical values of $\chi = 3 \times 10^{-20}$ cm^2 and $n = 3 \times 10^{22}$ cm^{-3}.

If the coefficient ξ noticeably exceeds unity, then the main part of the dissipation energy is absorbed by atomic electrons in a solid, and the volume density of the pump energy scattered in a solid is

$$w \approx \hbar\omega_X j_X \frac{\Delta\omega_X}{2\pi} \frac{\xi - 1}{\xi} \chi n \Delta t_X$$

$$= \hbar\omega_X \left(\frac{2\pi}{\lambda^2}\right)^2 \frac{\chi \ln G}{\beta^2 L} \frac{2J_1+1}{2J_2+1} \frac{n}{n_1} \frac{1+\alpha}{1-\varepsilon} (\xi - 1), \quad (23)$$

or in the numerical form,

$$w \approx 2.7 \times 10^{10} (\hbar\omega_X)^5 \frac{\chi \ln G}{\beta^2 L} \frac{2J_1+1}{2J_2+1} \frac{n}{n_1} \frac{1+\alpha}{1-\varepsilon} (\xi - 1), \quad (24)$$

where w is expressed in kJ cm^{-3} and $\hbar\omega_X$ is in keV. Relation (24) shows that w very strongly depends on the pump quantum energy. Thus, the density of scattered energy changes from $w \sim 3$ kJ cm^{-3} if $\xi = 1.5$ and $n_1 L = 10^{18}$ cm^{-2} to $w \approx 10$ J cm^{-3} if $n_1 = 0.1$ n and $L = 0.1$ cm (for $\hbar\omega_X = 10$ keV, $\alpha \ll 1, \varepsilon \ll 1, \beta \to 1$, the factor of angular momenta being omitted). We can try to decrease this estimate by setting $\xi \to 1$; however, it is unlikely that such a perfect coincidence of the pump and nuclear resonance spectra can be achieved in real experiments.

Assuming that the pump energy with the volume density w is mainly scattered due to photoeffect involving atomic electrons in a solid, we can estimate the ratio of the number of ions being produced to a total number of atom in the solid by dividing expression (23) by $n\hbar\omega_X$ (we assume that each pump photon produces single ionisation):

$$\frac{n_i}{n} \approx \left(\frac{2\pi}{\lambda^2}\right)^2 \frac{\chi \ln G}{n_1 \beta^2 L} \frac{2J_1+1}{2J_2+1} \frac{1+\alpha}{1-\varepsilon} (\xi - 1), \quad (25)$$

or in the numerical form,

$$\frac{n_i}{n} \approx 1.7 \times 10^{29} (\hbar\omega_X)^4 \frac{\chi \ln G}{n_1 \beta^2 L} \frac{2J_1+1}{2J_2+1} \frac{1+\alpha}{1-\varepsilon} (\xi - 1), \quad (26)$$

where the photon energy is measured in keV. For example, for $\hbar\omega_X = 10$ keV, $\chi = 3 \times 10^{-20}$ cm^2, $n_1 = 3 \times 10^{21}$ cm^{-3}, $\ln G = 2.5$, we obtain $n_i/n \approx 10^{-7}$ for $L = 0.1$ cm and $n_i/n \approx 10^{-4}$ for $L = 10^{-4}$ cm. These values represent lower estimates because high-energy electrons produced by gamma quanta in photoeffect are capable of ionising atoms.

In addition, one should take into account that both pump gamma quanta and fast electrons produced in photoeffect cause a strong damage of the crystal lattice.

The estimated values of w, which vary from tens to thousands joules per cubic centimetre, and estimates of the percent of ionised lattice atoms and of other damage factors are too large to be taken into account in solving the question about the use of such pumping in experiments requiring the maintenance of subtle Mössbauer conditions, because the estimated density of scattered energy corresponds to the heating of crystals up to thousands kelvins (taking into account that the volume heat capacity is ~ 1 J cm^{-3} K^{-1}). Moreover, the crystal homogeneity will be distorted due to all these negative perturbations.

In the case of AHI in free nuclei, an amplifying medium is not heated upon pumping because the medium is transparent. The negative influence of the pump radiation consists in the removing ('knocking out') of atoms from a monokinetic group of atoms in a cooled beam upon the interaction of pump photons with atomic electrons. It seems that this process is mainly determined by photoeffect. The ions and electrons produced in this process can be removed from the atomic beam by a weak transverse electric field. Therefore, we should estimate the relation between the number of nuclei excited by the pump and the number of atoms removed by the pump. The concentration of these atoms is estimated as

$$n_{\rm out} \approx n_1 \chi j_X \frac{\Delta\omega_X}{2\pi} \Delta t_X. \qquad (27)$$

Then, the ratio of $n_{\rm out}$ to the concentration n_2 (16) of excited nuclei is

$$\frac{n_{\rm out}}{n_2} \approx \frac{n_2}{n} \xi \varepsilon \frac{2J_1+1}{2J_2+1}(1+\alpha). \qquad (28)$$

One can see that $n_{\rm out}/n_2 \ll 1$ for any reasonable relations between the parameters because the conditions $n_2/n \simeq n_2/n_1 \ll 1$ and $\varepsilon \ll 1$ are fulfilled, i.e., the loss of atoms caused by the negative influence of the pump on the amplifying medium consisting of free atoms in the AHI scheme is relatively small.

7. Comments on the anti-Stokes scheme of a gamma-laser experiment with isomeric nuclei

The source of energy of gamma rays in both 'two-level' AWI and AHI schemes is the pump only, which has a very low efficiency tending in fact to zero. Therefore, it is quite attractive to attempt to use the intranuclear energy of long-lived isomers in gamma-laser experiments (see [5–12] and other works). However, this attempt encounters with an internal contradiction.

If we are dealing with isomeric nuclei, whose long lifetime is caused by a large difference between the angular momenta of the metastable ($J_{\rm m}$) and the ground ($J_{\rm g}$) states (spin isomers), this contradiction consists in the fact that in the anti-Stokes process this difference cannot be combined with the requirement of a small difference between the angular momenta $J_{\rm m}$ and $J_{\rm t}$ of the levels of the trigger transition and between the angular momenta $J_{\rm t}$ and $J_{\rm g}$ of the laser-transition levels, because both these transitions should be fast.

It is possible that this contradiction could be solved by using nuclei with a strictly forbidden isomeric transition between the levels with $J_{\rm m} = 0$ and $J_{\rm g} = 0$ and fast trigger and laser transitions, for example, through the trigger level with $J_t = 1$, when the corresponding differences between the angular momenta do not exceed unity. However, a proper isomer of this type has not been proposed so far, although nuclei with $J_m = 0$ and $J_g = 0$ are known ($^{16}_{8}$O, $^{40}_{20}$Ca, $^{72}_{32}$Ge, $^{90}_{40}$Zr, etc.)

The difference of the angular momenta of the states in metastable nuclei having structural isomers is of minor importance because the structural isomerism is caused by the fact that the metastable and ground states belong to two different potential wells, which are separated by a barrier and correspond to two different structures of a nucleus (for example, the actinide family). In this case, it is necessary to overcome this internal barrier or tunnelling should occur for emission of a gamma quantum from the metastable state. However, the possibility of tunnelling caused by an external triggering is not obvious. In addition, a spontaneous fission of a nucleus can be a competing process if a total external potential barrier of a deformed metastable nucleus is lower than the barrier between the wells. Although it was predicted theoretically that the total external barrier in nuclei with the isotopic number $A < 200$ exceeds the internal barrier between the wells (which is necessary, as noted above, for emission of a gamma quantum from a metastable level), this prediction has not been confirmed experimentally so far. Note also that it is interesting to study trigger processes in structural isomers initiated by other factors (apart from gamma quanta), for example, neutrons.

Therefore, the possibility of using the nuclear isomerism (including the so-called K isomers, whose study requires apparently the extension of a scope of proper nuclei apart from the most popular at present $^{178}_{72}$Hf) in gamma-laser experiments is not obvious at present and requires a comprehensive analysis. Thus, only the 'two-level' scheme of gamma-laser experiments is sufficiently actual so far despite its extremely low energy efficiency.

8. Conclusions

The analysis of the general properties of a nuclear gamma-laser experiment has shown that both variants considered above that involve the use of amplifying media in different aggregate states (crystals or free atoms) require the overcoming of substantial difficulties. The problems common for both variants are:

(i) the necessity of obtaining a sufficiently large number of excited nuclei per unit cross section of an extended amplifying medium (more than 10^{17} cm^{-2});

(ii) the necessity of having a pump X-ray source with an extremely high brightness;

(iii) the limited region of parameters for which successful experiments can be expected (in particular, the gamma-quantum energy cannot exceed tens of kiloelectronvolts because of a sharp increase in the pump intensity with the quantum energy).

In addition, the possibility of using long-lived isomers in experiments as nuclei for amplification is not obvious at present and requires further study.

Each of the versions involves their own specific problems. The most important problems are:

(i) in experiments with crystals, the latter are subjected to an extremely high damage load produced by the pump radiation, which can cast doubt on the possibility of maintaining the required experimental conditions (for example, emission of the Mössbauer zero-phonon line);

(ii) in experiments with a medium consisting of free atoms, it is necessary to form and maintain a threadlike deeply cooled atomic ensemble of a considerable extension amounting to a few tens of metres.

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References

1. Baldwin G.C., Solem J.C. *Rev. Mod. Phys.,* **69**, 1085 (1997).
2. Rivlin L.A. *Kvantovaya Elektron.,* **27**, 189 (1999) [*Quantum Electron.,* **29**, 467 (1999)].
3. Kocharovskaya O. *Hyperfine Interactions,* **107**, 187 (1997).
4. *Beta i gamma-spektroskopiya* (Betha and Gamma Spectroscopy), Ed. Sigban K. (Moscow: Gos. Izd. Fiz.-Mat. Lit., 1959).
5. Baklanov E.B., Chebotaev V.P. *Pis'ma Zh. Eksp. Teor. Fiz.,* **21**, 286 (1975).
6. Baklanov E.B., Chebotaev V.P. *Kvantovaya Elektron.,* **3**, 634 (1976) [*Sov. J. Quantum Electron.,* **6**, 345 (1976)].
7. Rivlin L.A. *Kvantovaya Elektron.,* **4**, 676 (1977) [*Sov. J. Quantum Electron.,* **7**, 380 (1977)].
8. Arad B., Eliezer S., Paiss Y. *Phys. Lett. A,* **74**, 395 (1979).
9. Ishkhanov B.S., Piskarev I.M. *Yad. Fiz.*, **32**, 593 (1980).
10. Becker W., Schlicher R.R., Scully M.O. *Phys. Lett. A,* **106**, 441 (1984).
11. Eliezer S., Martinez-Val J.M., Paiss J., Velarde G. *Kvantovaya Elektron.,* **22**, 1140 (1995) [*Quantum Electron.,* **25**, 1106 (1995)].
12. Eliezer S., et al. *Laser Phys.,* **5**, 323 (1995).