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Report
for Phase 1 Basic Research on Induced Gamma Emission
to
IGIGE - International Commission on Induced Gamma Emission

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FINAL REPORT

The work at the Gamma-laser creation is of synergetic character, it having been also realised in the first phase of the Basic Research of my proposal. So for an accountable period I have worked in these directions [14-17,30]:

A) - I have analysed works and reviews in the latest papers as to this problem having in my mind to find and formulate topical general tasks connected both with the problem of
 1- photons interaction with nuclear systems [14],
 2- gamma ray lasing pumping [15].

B) - Using a quantum electrodynamics model like the Dicke's model, I have studied quantum effects in the resonant time-domain coherent interaction of the single photons with nuclear system. Nuclei are considered at the Moessbauer conditions and in three-level approximation. The aim of the investigation was [16,17,33]:

1 - to study a temporal decay and dephasing of coherent behaviour of the nuclear system;
2 - to find a good conditions for single-photon echo realization and its unusual quantum properties.

RESULTS :
A) -
1. Understanding of collective irradiation processes in many nuclear system is one of the basic questions in the Global Problem (GP) of gamma ray laser creation. In the nearest future the most important experimental results for the irradiation processes in nuclear systems can be expected at the condition of the generation which is lower than the graser's threshold. At the same time theoretical works about nuclear superfluorescence (cooperative Dicke-decay) [1-4] are performed. These Dicke-like theories are developed mainly to study cooperative Dicke pulse generation [4-6]. At this difficult situation a first experimental way is to study collective irradiation processes in the nuclear system under the threshold of pumping without Dicke's pulse generation. It is possible that such cooperative emission of correlated gamma-guanta has been already detected [7-9]. I think that since very large difficulties exist in the interpretation of these experiments, additional experimental and theoretical investigations would be performed. In order to amplify

the effect it is desirable to use new experimental possibilities, such as additional coherent microwave or optical excitation [10,11], that can reduce the threshold in 20 and more percent [2,12,13]. For description of these irradiated processes we must use namely quantum Dicke-like theory including nuclear specifics of mutual disposition of the nearest excited nuclei, their pumping, detecting parameters and etc..

A second way [14]. Although a direct production of any experimental dates in gamma region about the collective nuclei irradiation laws in the regime of Dicke pulse generation is an insoluble

problem, we could try to solve the problem by another way, instead of waiting when the pumping and heating problems of GP [3,18] will be solved. It is possible to propose the experiments which are real for experimental possibilities of our days, where the laws of the temporal collective gamma irradiation can be studied experimentally in detail. Multitude of these experiments can be realised if we will grow the media (crystals) with special concentration of atoms and its parameters so as (from the general point of view on the problem) the mathematical equations of the laser optical generation would coincide exactly with the similar equations for nuclei gamma transitions. The possibility of this mathematical similarity can be founded on the Moessbauer effect, if only the relations between wavelengths of the field generation and atomic concentration will be included in optical region also.

This experimental model will differ from the ordinary optical laser mainly by the low atomic concentration and can be realised in ordinary ruby likes crystals. Obviously this optical laser will not be the best model for the generation of optical field. It is probable that the lasers are not studied in optics in detail especially from the point of view of gamma-ray laser problems.

Why these modelling experiments can be interesting and what physical tasks of GP can be proposed for solution now ? One of the answers exists. The contemporary gamma laser's theories likes [4] are developed using the spatial averaging of nuclei parameters. As a result the theories are closed mathematically to the theories developed for optical lasers. Especially it is important to mark that in the optical region the averagings for the physical parameters of medium are performed in the small space inside volume λ^3. In this small volume ($<\lambda^3$) the coherent properties of the lasing field are formed with more efficiency at the beginning of lasing. At the same time in the gamma region wavelength is smaller with respect to interatomics distance. Moreover this situation is strengthened in the case of not total pumping of active nuclei, that will be as a rule for gamma laser. Thus the dynamics laws of coherence initiation will differ at the same physical conditions. Nevertheless now the mathematical structure of the contemporary theories stays as in optics. That is the effects of small wavelength have not yet been understood and studied sufficiently. It is not clear what physical difficulties are connected with existing simplification of the used theory, as it is difficult to examine it.

First of all, at this relation of wavelength with respect to the internuclear distance the ordinary coherent (Dicke superradiance) dynamics will be suppressed even for Moessbauer conditions of gamma laser. The second sensitive consequence will be the growth of field's fluctuations in initial stage of temporal behavior of the generation. Obviously, the role of quantum fluctuations will be more important for gamma lasing, while in optics these questions are more important near the threshold. These difficulties can be the additional reasons for the search of stable in time coherence initiation of the cooperative nuclei dynamics.

These questions are possible to model and study in optical experiment, where both single optical photons can be detected and necessary atomic parameters can be realised at the special crystals. Quantitative estimations of these laser crystal which can be by the models of the perspective nuclei transitions [3] of gamma lasers can be performed, using numerous experimental dates about parameters of optical lasers [19].

2- One of the most important problems in development of gamma-laser is experimental realization of nuclear pumping of high level energy [1-3]. The optimum solution to this problem cannot be recognised stated [2]. New variants of pumping for various nuclei are being put forward. To this end, powerful energy sources, X-rays, neutron fluxes are proposed. At the same time, the pumping must not destroy very strict conditions of lasing initiation. These two important demands are in strong contrast to each other and dictate extreme conditions for gamma-laser realization, creating complex physical and experimental problems. A promising way of gamma-laser development is related to separation, in time and space, of problems of heating, pumping and lasing [18]. On this way, the extreme physical conditions must be kept during a short period of time. In this presentation, attention is drawn to the single bubble sonoluminescence effect as a new experimental possibility of creation of extreme physical state of medium satisfying conditions of pumping for nuclear gamma transitions.

The single bubble sonoluminescence effect consists in what follows. A gas bubble of 1-5 mkm diameter and surrounding liquid at the room temperature are in a field of standing ultra-sound wave. During every period of sound oscillations, the bubble first grows up manyfoldly in its size and

then, with a great speed, collapses. At the final stage of the collapse, a shock is formed inside the gas medium, propagating to the bubble center [20]. In approaching the center, its velocity grows up rapidly, becoming much higher than the speed of sound. The matter behind the shock moves to the center so fast that its following braking results in the extreme state of the matter, accompanying by short (~50 ps) pulse of light [21]. According to the published data [22], pressures in the center of the bubble attain values on the order of 1 Mbar and temperatures 0.1 MK. Physical processes inside the bubble are at present being actively investigated.

Even the temperatures obtained now in experiments allows one to consider the sonoluminescence effect as an alternative way of excitation of nuclear transition with energies on the order of
1-10 Kev. In this respect, it is interesting to try to realise single bubble sonopumping of well-studied nuclear transitions of the iron Fe(57). Thanks to small duration of light emission and
relatively large life time of excited nuclei of Fe(57), detection of gamma quanta is significantly simplified. Possibility of chemical composition control is demonstrated by existing experiments [23] in which the influence of percentage of noble-gases (Ne, Ar, Kr) purposely introduced in the bubble is investigated. At the same time it should be noted that introduction of heavy atoms into the bubble will need solution to some additional problems one of which is the choice of chemical composition optimal for nuclear pumping realization.

A curious feature of sonoluminescence consists in the fact that lowering of temperature of laboratory conditions from the room level to the freezing point significantly increases maximum collapse temperatures [24]. One of the explanations to this feature is related to variation of gas concentration in the bubble with temperature [25]. In such a case, the choice of chemical composition will be essentially dependent on temperature regime of sonoluminescence. The role of temperature is not restricted by its influence on chemical composition in the bubble. Temperature heating can contribute shock front stabilisation or its excessive smearing to the moment of collapse. Another way of control of energetic of sound energy transformation into internal degrees of freedom can be based on the use of dynamic regularities of energy transformation. In shock wave focusing, significant part of energy is consumed by ionisation and others inter-atomic and molecular processes. This influences dynamics of collapse and determines attainable maximum temperature. To increase the temperature, one can try to rapidly pump additional energy into the atomic system moving behind the shock, using contemporary broad-band femtosecond lasers.

For the effect under consideration, extreme states of matter presently attained are not limit. Attempts to obtain higher temperatures and pressures in the bubble are being continued. According to theoretical estimates [25], temperature can be increased to tens of millions degrees, for example, by increasing acoustic pressure in the sound wave to 1.4-1.5 bar while bubble dynamics in acoustic field keeps stable. Attainment of such temperatures will make it possible to perform pumping of nuclear levels at room conditions with transition energy in the range of 0.1-1 Mev.

Clearly, influence of magnetic field should be investigated in order to efficiently use the effect under consideration for pumping of nuclear transitions under conditions of high degree ionisation of atoms, first all in the sense of bubble dynamics stabilisation in the course of its collapse. The magnetic field can be generated by external stationary and in pulse sources. Spontaneous formation of strong impulse magnetic fields in the course of bubble collapse is not improbable, especially under conditions of its preliminary magnetisation.

In closing it should be noted that both the gamma laser creation and the problem of sonopumping is of synergetic character. They require taking into account coordinated course of many physical processes in a wide range of variation of temporal and spatial scales. Their solution can be found only by using theoretical description based on models of macro and micro levels.

B) -

At present in the development of the gamma ray laser problem we see special interest to find new variants for realisation of dynamic coherent interaction of gamma region irradiation with nuclear resonant systems [11,26]. This tasks must be connected with the solution of the general physical problem of the interaction of quantum fields with systems contain of many particles. Indeed, first of all in the nearest future we can expect realisation of graser lasing for the regime with a small number of coherent photons, it is most probably that at these physical conditions the quantum peculiarities of

the creation and decay of the lasing photons coherence can play very important role. Why can the quantum nature of the weak fields be important in the gamma lasing ? Which quantum properties can be expected and exploited in the weak laser generation? At the beginning of the pulse laser irradiation the field contains a small number of lasing photons and quantum properties of the field present the main source of the lasing fluctuations. At the following evolution these fluctuations can increase essentially, so the quantum nature of the Weak Pulsed Quantum (WPG-) fields would determine the temporal properties and fluctuations of the macroscopic intensive fields. This effect takes place at the pulse generation in the Dicke optical superradiance and induced Raman effects [27,28]. With respect to optical region in gamma region the energy of photon is very large so the roles of the quantum properties of the WPQ- fields will be more significant.

Some additional answers we can also obtain using the achievements of Quantum Optics, where the quantum effects of the fields with a small number of photons are studied very intensively, and a number of interesting physical results have been already obtained. Here I stress one of them. It was found, that very great (unusual for classical physics) correlations (or great coherent properties) in the quantum fields can been realised. Especially it was examined experimentally for special states of two- and three-photons fields [29.30]. The nature of these great correlations has a fundamental causal, so the correlations are of interest also for the understanding of the foundation of the Quantum Theory. It can be that special dynamics connected with these great correlation behaviour. The deep understanding of the properties of the correlations can be also important in the solution of some practical problems. Since the searches of the ways to amplify the coherence in collective nuclear dynamics is one of the primary problems in graser dynamics, so the using of great quantum correlations for the amplification of the gamma ray lasing would be a tempting way of the investigations.

The study of the temporal coherent and quantum behavior is interesting both for the gamma-ray laser problem and for the more general point of view, for the understanding of the quantum interaction's nature, namely quantum theory can reflect more fundamental unusual quantum laws than the classical theory in the macroscopic temporal tasks [31]. The fundamental property of quantum field connected with the formation of the interrupted (collapsed) behavior in the continuent evolution. These tasks are connected also with the temporal quantum properties at the creation and decay of great quantum correlations in nuclear system. Many of these properties can be realised in the effect of single photon echo [32] and its several modifications.

1- Developing the S-matrix approach [32] the new exact analytical solution of Single Photon (gamma quantum, SP-) echo amplitude has been obtained [33]. The solution gives the possibility of a cooperative nuclear excitation decay at the transition 2-1, if initially the photon was absorbed at the transition 1-3. The coherence can be transferred at the transition 3-2 by spontaneous one particle decay. Any additional homogeneous broadening at the transition 3-2 will suppress the nuclear coherence decay at the transition 2-1. The nature of the effect was determined by the same quantum fluctuations. All conditions of the cooperative decay are studying in the case if photon wavelength is smaller with respect to medium size. Then the collective decay will be strengthened at a phase matching, that is the falling photon resonanced to 1-3 transition and emitting photons at 3-2 and 2-1 transitions propagate along the same direction as the falling photon.

2- New variant of SP-echo in three level medium was proposed and theoretically analysed [16,17,33]. This is the single photon realization of modifying variant for a stimulated photon echo [34,35]. It is important, that amplitude with comparison to the first result [32] can be more large and conditions for the observation of nuclear coherent behavior are more good. This SP-echo will be generated at the following conditions. The falling on the medium photon is resonant with the nuclear transition 1-2 and propagates along two optical paths with some mutual temporal delay. Then additional laser pulse reads out the collective nuclear single particle excitation at the transition 2-3, where SP-echo can be generated. SP-echo will be generated as a signal of simultaneous diffraction at small temporal delay.

New property of the echo signal will be induced by the quantum decay of the nuclear excitation. Namely the quantum reduction of the wave function connected with phasing relaxation will simultaneously destroy collective property of nuclear population in second level. This effect are analysed at the time delay interaction of the photon with resonant nuclei using the following Hamiltonian:

$$H = H_a + H_f + V, H_a = \sum_{j=1}^{N}\sum_{n=1}^{3}\left[E_n^j + \delta E_n^j(t)\right]\tilde{\hat{P}}_{nn}^j, H_f = \int_{-\infty}^{\infty} d^3k \hbar\omega_k \hat{a}_k^+ \hat{a}_k, \qquad (1)$$

$$V = \hbar\sum_{j=1}^{N}\sum_{n\rangle m}^{3}\int_{-\infty}^{\infty} d^3k\{\hat{P}_{mn}^j \hat{a}_k\, g_{mn}^j(k)e^{ikr} + \hat{P}_{nm}^j \hat{a}_k^+\, g_{nm}^j(k)e^{-ikr}\}.$$

Nuclei operators: $\hat{P}^{j}_{m}=\left|n_j\right\rangle\left\langle m_j\right|$, g^{j}_{nm} (k)- the constants of the interaction. The functions $\delta E^{j}_{n}(t)$ model the influence of random processes determining the irreversible behavior of the system. The Moessbauer nuclei are considered at three level approximation with energies $E^{j}_{3} > E^{j}_{2} > E^{j}_{1}$. The transition |1>↔|2> is a gamma transition, the frequency |2>↔|3> is an optical transition.

The gamma photon propagates to the medium at the regime of time-delay interaction [32,33] along two different spatial directions k_1 and k_2, as it can be done at Moessbaur diffraction [36,37]. The photon is resonanced with the transition |1>↔|2> of nuclei. Before the interaction the total wave function is:

$$|\Psi_{in}(-\infty)\rangle = \frac{1}{\sqrt{2}}\int_{-\infty}^{\infty} d^3k\left[F(k-k_1)e^{-i\omega_k\tau} + F(k-k_2)\right]\hat{a}^{+}_{k}|0\rangle \otimes \prod_{J} \otimes |1_j\rangle \qquad (2)$$

The coherent interaction leads to the formation of singlenuclear collective excitation in a form of the spatial grating described by the density matrix [33] :

$$\hat{\rho}_a(t) = |\Psi_a(t)\rangle\langle\Psi_a(t)| = \hat{\rho}_{a,a}(t) + \hat{\rho}_{a,22}(t), \hat{\rho}_{a,a}(t) = \sum_{i}^{N} \sum_{\neq j'}^{N} \beta^{*}_{j'}(t)\,\hat{P}^{j}_{21}\,\hat{P}_{V}\,\hat{P}^{j'}_{12},$$

$$\hat{\rho}_{a,22}(t) = \sum_{j=1}^{N} \hat{P}^{j}_{22} \left|\beta_j(t)\right|^2 \hat{\rho}_V(j); \hat{\rho}_V(j) = \prod_{n\neq j}^{N} \oplus|1_n\rangle\langle 1_n| \oplus |0\rangle\langle 0|;.|0B>= \prod_{n}^{N} \oplus|1_n> \oplus.|0>.(3)$$

Density matrix (3) will transform into the diagonal form $(\hat{\rho}_a(t) \rightarrow \hat{\rho}_{a,22}(t))$, as irreversible processes of phase relaxation will be realised. This transformation is performed at the time T_r (time of collapse) which is determined by the phase memory time T_2. According to the existing quantum mechanics interpretation the transformation is connected with the instantaneous collapse of the wave function at some random moment of time. Thus the spatial delocalized wave function will transform into the new physical state where the excitation will be localized at the one of the nuclei. At present the reasons of the collapse are connected only with the destruction of coherent behavior of the wave function. At the same time any mechanisms of this collapse are unknown. Thus the favourable situation for study of this fundamental quantum collapse phenomenon appears at the single photon field interaction, where the quantum properties are shown considerably.

This temporal picture of the quantum collapse can be detected experimentally, if the excited spatial grating in nuclei system will be read out by the additional field. The more favourable case will be if the frequency of the additional field is resonanced with the optical transition |2>↔|3>. When the grating lives, the additional field will leads to the scattering field, or the single photon echo (the more favourable case for the detection) propagating only in a certain spatial direction in accordance with phase matching $k=k_s+k_2-k_1$ and at the fixed moment of time.When the collapse will destroy the nuclei excited grating this phase matching will destroy instantaneously, so the echo signal or the scattering field will disappear. By the realization of this interaction in different moments of time we will have the method of the visualisation of the temporal properties of spatial collapse in delocalized quantum nuclei system.

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