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Quantum Generation of Coherent Radiation via the Molecular-Nuclear Transitions (Molecular-Nuclear Transitions)

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ABSTRACT

A quantum coherent amplification in which the production of a population inversion is not a necessary step for obtaining the active medium is discussed. The method is based on the idea of a so called molecular-nuclear transitions in a special class of diatomic and triatomic molecules in case their nuclear subsystems have near-threshold resonant states of the compound nuclei corresponding to the complete fusion of all nuclei entering into the structure of the molecule, provided the full energy of the molecule is a few kiloelectron-volts over the energy of the mentioned resonance. In this situation the molecule and the atom of the compound nucleus represent two levels of a single quantum system. Analysis of inducing quantum transitions between molecular and nuclear states of this system is carried out. The performed estimates predict that the quantum amplification of radiation (like in the lasers) is rather probable. In addition, the first experiments are reported for the process $\hbar\omega+{}^{6}\mathrm{LiD}\rightarrow{}^{8}\mathrm{Be}^{*}(2^{+}, 22.2\mathrm{MeV})+\hbar\omega+\hbar\omega$ induced by the X-rays. In these experiments, a number of high energy α-particles emitted hypothetically due to the decay of ^{8}Be was detected.

Keywords: molecular-nuclear transition, nuclear resonance, population inversion, quantum amplification

Introduction

The quantum generation of a coherent radiation (or quantum amplification) is based on the phenomenon of stimulated emission of electromagnetic radiation, the theory of which was developed by A. Einstein in (1917). The principal step in coherent radiation generation is the creation of a population inversion, and maintaining this non-equilibrium state, since the spontaneous "top-down" transitions quickly deplete the higher levels and destroy the state of inversion. Creation and maintaining of the population inversion is produced by the energy pumping. For example, in the ruby lasers, the pumping of the active medium is produced according to a three-level ($E_1< E_2< E_3$) scheme, where population inversion appears at E_2 relatively to the ground state E_1 (Maiman, 1960). Here E_i, i=1, 2, 3, denotes the energy of levels. More efficient are the four-level and more sophisticated schemes. In all cases, the pumping requires the external forcing (in the above examples, by electromagnetic radiation) and special equipment (the powerful light sources, etc.). Because of this situation the energy balance in the quantum generation of the coherent radiation is negative, and its efficiency factor is low.

New approach:

In this paper the principle of a new approach to produce the stimulated coherent radiation is discussed, which does not require energy pumping.

The essence of this method is related to the special processes taking place in certain diatomic or triatomic molecules, two examples of which are the lithium hydride enriched by the isotopes ^{6}Li and ^{2}H, i.e., the ^{6}LiD molecule, and the water molecule H_2O.

Figure 1 shows fragments of the level schemes of ^{8}Be and ^{18}Ne nuclei. From these graphs, it can be seen that the energy of the threshold E_{thr}=22.28 MeV of the disintegration of ^{8}Be into two nuclei ^{6}Li and ^{2}H (d) is very close to the energy E_{nl} of level (2^{+}, 22.2 MeV) in ^{8}Be. A similar situation takes place in ^{18}Ne: the threshold E_{thr}=4.522 MeV of the collapse of ^{18}Ne nucleus into the non-bound nuclear complex ^{16}O+p+p nearly coincides with the energy E_{nl} of the level (1^{-}, 4.52 MeV) in ^{18}Ne.

The spontaneous quantum superposition between the molecular and nuclear states under the condition of the equality of the corresponding energy values, and the identities of quantum numbers was predicted to be possible (Belyaev et al., 1996a; Belyaev et al., 1996b; Rakityansky and Dicks, 2007). However, the experiments show very low probability of the desired effect (Belyaev et al., 2001; Belyaev et al., 2006) that can be explained by the difference in the energy of the said states.

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If the values E_{nl} and E_{thr} are a little different, then each of these molecular-nuclear pairs can be interpreted as single two-level quantum systems where one of the quantum states corresponds to the molecule (^{6}LiD or H_2O in our case), and the other one – to the atom with the nucleus corresponding to the complete fusion of all nuclei in the atoms that constitute the molecules ^{8}Be(2^+, 22.2 MeV) or ^{18}Ne (1^-, 4.52 MeV), respectively. Important: the nuclei of these atoms should be in the excited (resonance) states, and the energy difference $\Delta E = | E_{nl} - E_{thr} |$ should not exceed the natural width of the nuclear level $\Gamma \approx 1 ... 10$ keV. In this case, there are conditions for stimulated (induced) quantum transitions between molecular and atomic states. For simplicity, in what follows, such transitions are referred as "molecular-nuclear transitions" (MNT).

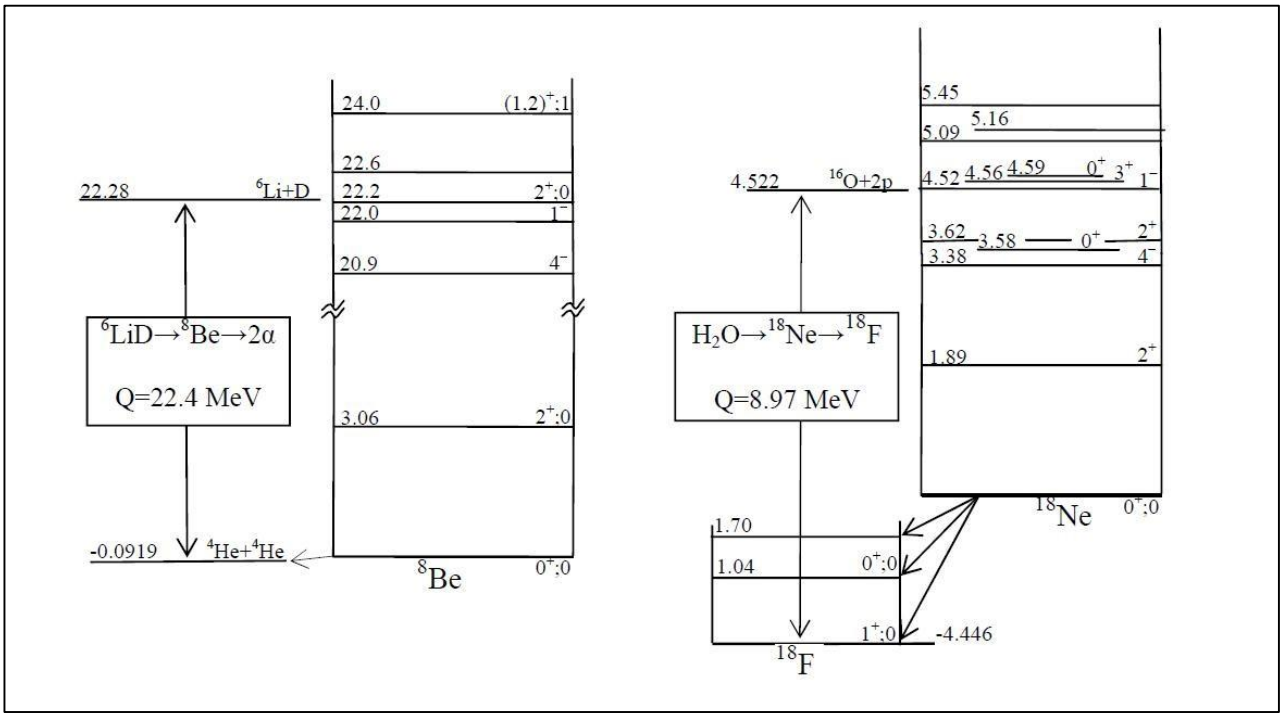

Fig. 1: Fragments of level schemes of A=8 and A=18 isobars.

The most interesting situation appears when $E_{thr}>E_{nl}$. Then each stimulated quantum transition from the molecular to the nuclear state can cause the emission of secondary photons, which are completely identical to the incident photons of electromagnetic radiation (in energy, the direction of emission, polarization), what means the quantum amplification of incident radiation, or generation of coherent radiation. The exact value of the frequency (or the energy) of the MNT is not known, so the electromagnetic radiation with a continuous spectrum covering the range of probable values of transition frequency can be applied to try to stimulate the transitions. The X-ray bremsstrahlung with the appropriate boundary energy could be the good option. It is also interesting to use a monochromatic photon source for scanning the frequency for probing the transition frequency experimentally. The first of these options is preferable at the present initial phase of study, while the second one will maybe useful for a detailed exploration of the considered effect.

Estimates:

The attention to a possibility of induced MNT was paid in (Belyaev and Miller 2010) and afterward in (Belyaev and Miller 2014). Understanding that the molecular level is several kiloelectron-volts over that of the nuclear resonance, the molecular-nuclear pair was analyzed by analogy with the two-level quantum systems from the quantum optics.

In physics of the quantum amplification and lasers one uses the term “gain factor” K, describing the proportionality between the number of the incident photons, and output photons arising due to the passage of the incident photon through the active volume (medium). This value can be roughly estimated as $K = e^{gL}$, where $g=mN_A\lambda^2R$ is a so called negative absorption constant - the term introduced by (Fabricant, 1959), m is a molecular density (mol/cm^3), N_A – the Avogadro number, λ – wavelength of the resonance radiation. The value $R=W_\gamma/4(W_\gamma+\sum W_i)$ characterizes the concurrence of the different decay modes of the molecules under the influence of resonance electromagnetic wave; here W_γ is the radiation probability, and $\sum W_i$ is the sum of all other possible channels of the decay. At the energy of several kilo electron volts that is typical for the expected MNT, a main contribution to the sum $\sum W_i$ arises from the value representing the probability W_B of a breakup of the molecule due to photo-dissociation. The ratio R can be estimated by comparing matrix elements defining the

probabilities W_Y and W_B. Radial part of the matrix element defining the probability W_γ of γ-transitions with a multipolarity l is of the form:

$$M_\gamma \approx \int {}^{J_1}\Psi_{res}(r) r^l {}^{J_2}\Psi_{mol}(r) r^2 dr \quad , l = |J_1 - J_2| \tag{1}$$

where ${}^{J_1}\Psi_{res}(r)$ and ${}^{J_2}\Psi_{mol}(r)$ are wave functions of nuclear resonance and molecular state with angular moments J_1 and J_2, correspondingly.

When the difference between the energies of the molecule and nuclear resonances is in the limits of the resonance width, it is quite reasonable to expect a large overlap of the wave functions in the integrand (1). The above condition can be seen in Fig.1. The full energy of the molecule ^{6}LiD supposed to be a little over the (2^+, 0) resonance state of ^{8}Be and remains in the limits of the width of this resonance. Owing to this property the wave function of the resonance state (2^+, 0) of ^{8}Be behaves as an outgoing Coulomb wave at large distances between the ^{6}Li and D clusters; hence it is characterized by a long tail in spatial coordinates. Thus, the long distances will make a significant contribution to the integral (1). Approximating the matrix element of a transition between molecular and unbound states of the system ^{6}Li + D, one can use the formula (1), with the term ${}^{J_1}\Psi_{res}(r)$ replaced with the wave function of the system in the continuum spectrum. Due to these properties of the wave functions, the matrix element (1) will be of the similar order of magnitude as the matrix element of the break up process, or the dissociation. Hence, as a rough approximation $W_\gamma \sim W_B$, and for R the estimate is R~1/8.

Taking all this into account, estimate the value of the amplification factor K. If the difference between the two levels is $\Delta E = c/2\pi\lambda = 1$ keV, then $g \sim 4R \cdot 10^{-5}$ cm^{-1}. Figure 2 shows the values of amplification factor within a wide range of the parameter R in case of LiD solid state sample.

Thus it is clear that the gain factor $K = e^{gL}$ remains essentially over the unit within the wide range of $R << 1$, (i.e., at the values much less than our estimate of R).This fact gives the hope that our results are not very sensitive to the simplifications and assumptions used above, and that the discussed principle of quantum amplification has the real prospects.

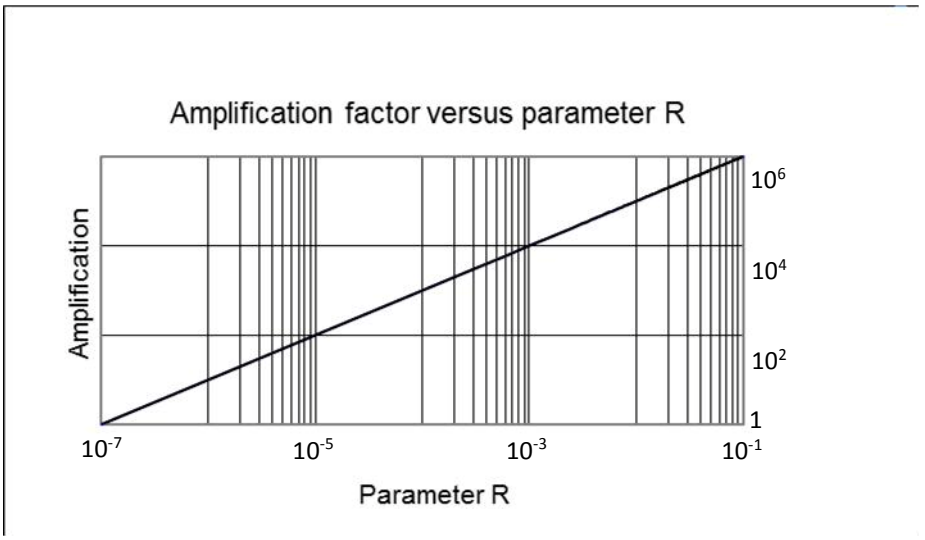

Fig. 2: Quantum amplification versus parameter R for LiD solid state sample.

Experiments:

The feasibility of the above method of quantum amplification of electromagnetic radiation (or generating coherent radiation) depends primarily on the validity of the hypothesis of the actual molecular nuclear quantum transitions and on the efficiency of a significant acceleration of MNT by the resonant electromagnetic radiation. In what follows, there are summarized the results of experiments on the observation MNT in the γ + LiD → ^{8}Be* reaction. Nuclear resonance ^{8}Be* disintegrates mainly by a channel ^{8}Be*→ 2α with the alpha-particle energies E_α=11.2 MeV each.

The alpha-particles move away along the same line but in opposite directions due to the conservation of momentum. These characteristics of the decay imply that the most efficient way of detecting the MNT events would be to look for alpha-alpha coincidences.

In the present work, the track detectors of light charged particles, namely, CR-39 (plastic, based on the organic polymer compound *allyldiglycol carbonate,* ADC) were used. The experiments were conducted in the assembly of the type of "multi-layer sandwich": detector-sample-detector. This assembly was exposed to the X-ray radiation and then the detectors were developed and it was planned that alpha-tracks would be identified in the method of "space filtration", i.e., if the coordinates of a pair of tracks in two vis-à-vis detector layers

coincide, then they were recognized as the searched for event of induced MNT: $\gamma + LiD + {}^{8}Be^{*}(2^{+}, 22.2\ MeV) \rightarrow \gamma + \gamma' + \alpha + \alpha$.

In this equation, the symbols γ designate the primary quanta, whereas γ' is the secondary ones −resulting due to the induced quantum transition to the (2^{+}, 22.2 MeV) level of the $^{8}Be^{*}$.As was said above, the both γ- quanta are identical.

The prepared LiD powder was purchased from Sigma-Aldrich Corporation, USA. The isotopic enrichment was only in the deuterium (98%), and the lithium was of the natural isotopic concentration (7.59% of ^{6}Li).

The powder was placed in a sandwich configuration with CR-39 detectors, and this was assembled in a container for the X-ray exposure as indicated in Fig. 3.

The samples were irradiated by the X-rays generated by a XYLON Y.TU 225-D02 tube. The tube was operated at the anode voltage of 100 kV for 112 hours at 30 mA, the emitted radiation had a 40^{0} dispersion cone, the focus size on the tungsten anode was 5.5 mm, and a 0.8 mm Be filter constituted the x-ray tube window.

Once the irradiation was completed the CR-39 track detectors were recovered in a glove box to ensure that natural α-sources would be limited, and they were etched using a 6.25mol/l solution of NaOH for 8 hours at a temperature of 70°C. These detectors were then analyzed using an optic microscope, and digital photos were taken of significant tracks. These tracks were measured using Adobe Photoshop, and the energies of α -particles that left these tracks were determined based on the track color and diameter. In this instance the LiD-powder layers were too thick to observe both α-particles that would be produced in disintegration of ^{8}Be from the MNT.A track was considered to be formed by the ^{8}Be disintegration if the track was due to a particle with an energy greater than that of the main natural α-sources: 4.78MeV(Ra-226); 5.49MeV (Rn-222), 6.0MeV (Po-218), 7.68MeV (Po-214), 5.3MeV (Po-210),4.783MeV ($n_{th}+{}^{6}Li$); here the energy of α-particles are indicated, indicated also the energy of α-particles from $n + {}^{6}Li$ reaction, giving the α-background in the presence of thermal neutrons.

As a further measure the X-ray spectrum was modeled throughout the sample in order to find out a correlation between the energy of the X-rays available and the yield of the MNT rate. An investigation into the effect of the X-ray spectrum on the presumably MNT rate has not produced conclusive results.

At the end of the experiment 88 tracks were altogether determined to have been formed as a result of the MNT. This indicates that the reaction lifetime is 3.6×10^{17} years per nuclear pair – indicating that the presence of X-rays increased the reaction rate relatively to the spontaneous transitions compared to 10^{19} years suggested in (Belyaev et al., 2006). Thus we can make the tentative conclusion on the observation of the induced molecular-nuclear quantum transition. Note that this optimistic conclusion should be treated with a caution because the events were identified only by the energy of particles over that exists in the natural background. In subsequent experiments the paired alpha - alpha coincidences will be selected that should give unambiguous testing.

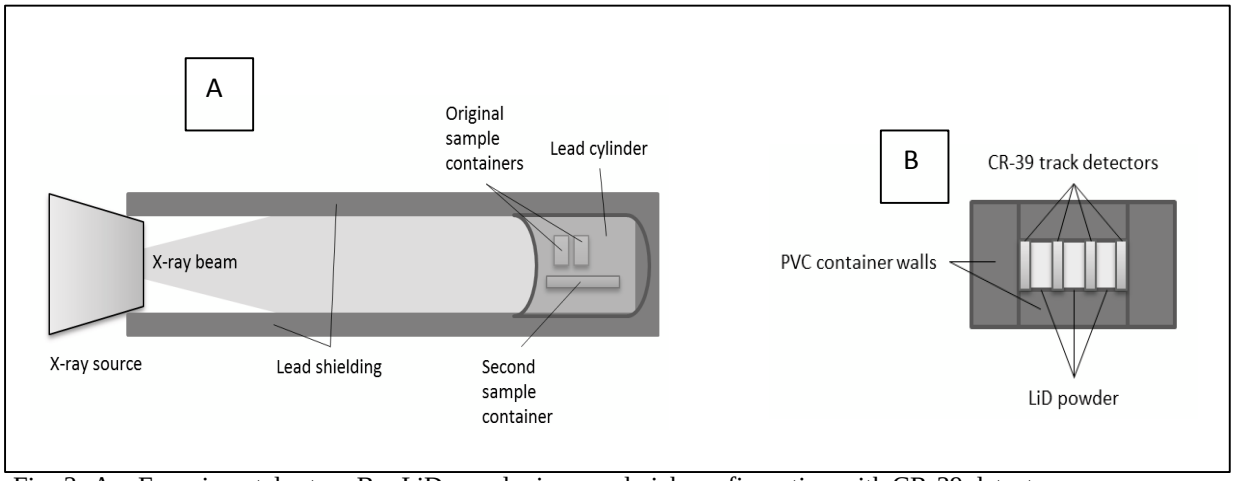

Fig. 3: A – Experimental setup, B – LiD powder in a sandwich configuration with CR-39 detectors.

Conclusion:

The possibility of quantum amplification and generation of the electromagnetic radiation based on the induced molecular-nuclear transitions is considered. As previously indicated, these properties take place in lithium hydride molecules enriched in ^{6}Li and ^{2}H isotopes (molecule ^{6}LiD). The discussed type of quantum amplification does not require the energy pumping of the inverse population state. Estimates for the probability

of molecular nuclear transitions in the system $\hbar\omega + {}^{6}LiD \rightarrow {}^{8}Be^{*} + 2\hbar\omega \rightarrow 2\alpha$ are given, and preliminary results of the first experiments on the observation of α-particles from the above reaction are presented.

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