$$W = \sigma E^2,$$

where σ is the conductivity of the medium, as determined by the external ionization, and E is the electrical field.

A property of electron-impact excitation of rotational-vibrational levels—the proportionality of the excitation rate to the product of the electron and molecule concentrations—has as a consequence that the power radiated per unit volume of active medium in electroionization excitation increases as the square of the pressure. Thus, an increase in the working-gas pressure from the tens of Torr encountered in ordinary gas-discharge lasers to the tens of atmospheres will increase the power radiated per unit volume of active medium by a million times[1].

The use of high pressures will substantially broaden the lasing line and make it possible to generate powerful ultrashort pulses with durations down to 10^{-11}—10^{-12} sec[1,2]. The high efficiencies of electroionization lasers in the ultrashort-pulse mode (10%) is encouraging for the use of these lasers to obtain a controlled thermonuclear reaction efficient enough for power generation.

[1] Yu. V. Afanas'ev, É. M. Belenov, O. V. Bogdankevich, V. A. Danilychev, S. G. Darznek, and A. F. Suchkov, Kr. soobshch. fiz. (FIAN SSSR), No. 11, 23 (1970); N. G. Basov, É. M. Belenov, V. A. Danilychev, and A. F Suchkov, Kvantovaya élektronika, No. 3, 121 (1971); Vestn. Akad. Nauk SSSR, No. 3, 12 (1972); N. G. Basov, É. M. Belenov, V. A. Danilychev, O. M. Kerimov, I. B. Kovsh, and A. F. Suchkov. ZhETF Pis. Red. 14, 421 (1971) (JETP Lett. 14, 285 (1971)); N. G. Basov, V. A. Danilychev, O. M. Kerimov, and A. S. Podsosonnyĭ, ibid., 17, 147 (1973) [17, 102 (1973)].

[2] C. A. Fenstermacher, M. J. Nutter, W. T. Leland, J. P. Rink, K. Boyer, Bull. Amer. Phys. Soc. 16, 42 (1971); C. A. Fenstermacher, M. J. Nutter, W. T. Leland, and K. Boyer, Appl. Phys. Lett. 20, 56 (1972). K. Boyer, Los Alamos Scientific Laboratory Presentation at Japan U. S. Seminar on Laser Interaction with Matter, Kyoto, Japan, September, 1972.

[3] A. V. Eletskiĭ and B. M. Smirnov, Dokl. Akad. Nauk SSSR 190, 809 (1970) [Sov. Phys.-Dokl. 15, 109 (1970)].

[4] J. S. Levin and A. Javan, Appl. Phys. Lett. 22, 55 (1973).

[5] V. M. Andriyakhin, E. P. Velikhov, V. V. Vasil'tsev, S. S. Krasil'nikov, V. D. Pis'mennyĭ, I. V. Novobrantsev, A. T. Rakhimov, A. I. Starostin, and V. E. Khvostionov, ZhETF Pis. Red. 15, 637 (1972) [JETP Lett. 15, 451 (1972)].

[6] V. M. Andriyakhin, E. P. Velikhov, S. A. Golubev, S. S. Krasil'nikov, A. M. Prokhorov, V. D. Pis'mennyĭ, A. T. Rakhimov. ibid. 8, 346 (1968) [8, 214 (1968)]; G. G. Dolgov-Savel'ev, V. V. Kuznetsov, Yu. L. Koz'minykh, and A. M. Orishich. Zh. Prikl. Spektrosk. 12, 737 (1970).

[7] J. J. Thomson, Conduction of Electricity through Gases, v. 1, Cambridge, Cambridge Univ. Press, 1928.

[8] B. M. Koval'chuk, V. V. Kremnev, and G. A. Mesyats. Dokl. Akad. Nauk SSSR 191, 76 (1970) [Sov. Phys.-Dokl. 15, 267 (1970)].

V. I. Gol'danskiĭ and Yu. M. Kagan. Feasibility of the Nuclear-Transition γ Laser (Gaser)

The few proposals that have appeared in the literature over the past ten years concerning ways to obtain stimulated γ emission have reduced to attempts to prepare large numbers of long-lived nuclear isomers in pure or strongly enriched form and to use the Mossbauer effect.

However, it is easily shown that this approach offers no promise of success. The excited-nucleus concentration needed to bring about stimulated γ emission is[1]

$$n^* = \left(\frac{E_0}{\pi\hbar c}\right)^2 \frac{\Gamma}{\Gamma_0} \frac{1+\alpha}{f\xi} \frac{1}{l(E_0)}, \qquad (1)$$

where E_0 is the energy of the γ transition, Γ_0 is the natural and Γ the actual excited-level width, α is the internal conversion coefficient, $l(E_0)$ is the free path of the resonant photons, ξ is the probability of population of the upper level on pumping ($(1+\xi)/2$ of the nuclei are initially on the upper level and $(1-\xi)/2$ on the lower level), and f is the probability of the absence of recoil when the Mössbauer transitions are used.

Since $(E_0/\pi\hbar c)^2 \approx 10^{16}$—$10^{18}$, at $E_0 \approx 10$—100 keV and $l(E_0) \approx 10^{-3}$—10^{-2} cm for medium and heavy nuclei, we have $n^* \approx (10^{19}$—$10^{20})\Gamma/\Gamma_0$ even without consideration of the multiplier $(1+\alpha)/f\xi$. This means that when the resonance line is hundreds and thousands of times broader, the necessary values of n^* are in general already outside the range of matter densities N (further compression changes nothing, since then $n^* l(E_0) = \text{const}$).

Thus, in sharp contrast to the optical region, an extreme sensitivity to any broadening of resonance lines is brought about by the increase in the energies of the transitions.

It is precisely this that dictates the use of the Mössbauer effect, because the Doppler broadening of the resonance in the presence of a recoil energy R, $\Delta_D \approx 2\sqrt{RkT}$ (or $\Delta_D \approx 2\sqrt{Rk\Theta_D}$ at $T \ll \Theta_D$, where Θ_D is the Debye temperature) is many orders greater than Γ_0 for any γ-transition time that may be of interest. In turn, use of the Mössbauer effect imposes additional limitations on the temperature of the system and on the transition energies.

Decisive among the factors that impose an upper limit on the γ-transition times suitable for the production of stimulated emission are the various possible inhomogeneous broadenings of the Mössbauer resonance line. The sources of this broadening include: 1) isomeric shift, 2) quadrupole interaction, 3) magnetic hyperfine interaction, 4) magnetic dipole-dipole interaction between nuclei, 5) temperature red shift and broadening, and 6) gravitational level shift over the thickness of the sample.

We shall not concern ourselves with broadening due to magnetic interaction because, in principle, a diamagnetic substance could be chosen and an attempt made to reduce the dipole-dipole interaction between the nuclei by means of known NMR methods.

The purely electrical interactions 1) and 2) are the principal sources of inhomogeneous broadening. Prime importance attaches to the isomeric shift, which inevitably exists in the Mössbauer effect, since two nuclear levels with different charge radii R participate in the transition (in NMR, transitions occur between HFS sublevels of the same nuclear level, so that the relative shift of the center of the HFS "comb" on different nuclei is not a factor).

For a given nuclear transition, the isomeric shift

depends, as we know, only on the density of the electrons at the nucleus, $\delta \sim |\psi(0)|^2$. In the first approximation, $|\psi(0)|^2 \sim 1/V_0$ (V_0 is the volume of the unit cell), and a local change in mass density results in a nuclear-line shift

$$\Delta E_i = (\Delta E_i)_0 \left| \frac{\Delta V_0}{V_0} \right|. \quad (2)$$

Analysis of numerous experimental results and theoretical estimates yield $(\Delta E_i)_0 \sim 10^{-7}$ eV.

Proportionality to $|\Delta V_0/V_0|$ is also characteristic for the variation of the quadrupole splitting ΔE_Q of the Mössbauer lines, which results from interaction of the quadrupole electric moments of the nuclei with the gradient of the electric field created by their own electron shells and by neighboring ions. The coefficient of proportionality obtained from experiments and theoretical estimates gives $(\Delta E_Q)_0 \sim 10^{-7}$ eV.

Local shear deformation also results in inhomogeneous variation of the quadrupole interaction. This deformation can be characterized by the change in the ratio c/a of the longitudinal to the transverse dimensions of the unit cell. We therefore have for estimates

$$\Delta E_Q \sim 10^{-7} \left| \frac{\Delta V_0}{V_0} \right| \text{eV}, \quad \Delta E_Q \sim 10^{-7} \left| \frac{\Delta (c/a)}{c/a} \right| \text{eV}. \quad (3)$$

Let us consider the role of point defects. It is known that at great distances from defects

$$\left| \frac{\Delta V_0}{V_0} \right| \approx \beta \left| \frac{\Delta V_0}{V_0} \right|_0 \left(\frac{a}{r} \right)^3, \quad (4)$$

where a is the interatomic distance and $\beta \approx 0.1$ is a numerical coefficient, We assume the value 0.1 for $|\Delta V_0/V_0|_0$. In anisotropic crystals, the same relation also obtains for Δ (c/a)/(c/a) even, significantly, in crystals of cubic symmetry. It is evident from (2)—(4) that a line broadening about equal to the natural line width, $\Delta\Gamma \approx \Gamma_0$, is reached even at a relative point-defect concentration

$$C^* \sim 10^9 \Gamma_0 \quad (5)$$

(Γ_0 is in electron-volts here and below). Hence it follows that the "critical" concentration is $C^* \sim 10^{-6}$ at an excited-level lifetime $\tau_0 \sim 1$ sec and that $C^* \sim 10^{-10}$ at $\tau_0 \sim 10^4$ sec. The difficulty of using long-lived isomers to create sources of coherent γ radiation is clear even from these figures.

Dislocations are no less dangerous from this point of view. We have for edge and screw dislocations, respectively,

$$\left| \frac{\Delta V_0}{V_0} \right| \sim 0{,}1 \frac{a}{r}, \quad \left| \frac{\Delta (c/a)}{c/a} \right| \sim 0{,}1 \frac{a}{r}. \quad (6)$$

If we now denote by η^* the "critical" dislocation (cm^{-2}) corresponding to $\Delta\Gamma \approx \Gamma_0$, we obtain from (2), (3), and (6)

$$\eta^* \sim 10^{31} \Gamma_0^2. \quad (7)$$

Thus, a low critical dislocation density $\eta^* \sim 10$ cm^{-2} corresponds even to a relatively short lifetime $\tau_0 \sim 1$ sec, and at lifetimes $\tau_0 > 10$ sec the existence of even one dislocation can no longer be permitted. On the other hand, the preparation of dislocation-free crystals or crystals with really small numbers of dislocations is an extremely difficult task, and one that itself requires much time.

An inhomogeneous line shift in specimens of finite dimensions also results from surface effects. According to existing theoretical estimates, the relative change in the interatomic distances decreases with increasing distance from the surface no more sharply than $\kappa = \kappa_0/m^3$, where m is the number of the atomic plane. From this we obtain the following estimate for the "critical" number m* of atomic planes for which the line shift $\Delta\Gamma \approx \Gamma_0$ ($\kappa \sim 0.03$): $m^* \approx 200$ for $\tau_0 \sim 1$ sec and $m^* \approx 4000$ for $\tau_0 \sim 10^4$ sec (and these values of m* are understated, partly because of the small value of κ_0 assumed here).

At the same time, it may be found that the use of thin layers is simply inevitable in virtue of the short times needed to prepare the radiators, or else necessary both to reduce heating and to eliminate the gravitational shift $\delta_{grav} = 10^{-18}$ cm^{-1} and the line broadening, which amounts to $10^{-14} - 10^{-13}$ eV/cm at $E_0 = 10-100$ keV ($\Delta\Gamma \approx \Gamma_0$ at a thickness of 0.1—1 mm for $\tau_0 \sim 1$ sec and 0.01—0.1 μm at $\tau_0 \sim 10^4$ sec).

As for the temperature red shift and the broadening of the Mössbauer lines, it must be noted at once that they could, in principle, be avoided by operating at extremely low temperatures. Otherwise, e.g., at room temperature, temperature gradients $\Delta T \sim 10^{-4}-10^{-5}$ deg at $\tau_0 \sim 1$ sec and $\Delta T \sim 10^{-8}-10^{-9}$ deg at $\tau_0 \sim 10^4$ sec would correspond to the inhomogeneous broadening $\Delta\Gamma = \Gamma_0$ for $E_0 = 10-100$ keV. At the same time, as shown by one of the authors[12], there exists a homogeneous broadening of the Mössbauer lines that amounts to $10^{-15}-10^{-13}$ eV at room temperature for $E_0 = 10-100$ keV.

From the above considerations, we may infer the necessity of meeting the condition $n^* < N$ when long-lived levels ($\tau_0 \geq 1$ sec) are used. In fact, experiments carried out under stationary conditions with special precautionary measures have not yet produced lines narrower than $10^{-9} - 10^{-10}$ eV (Zn^{67}, Ta^{181}), which is equivalent to $\tau_0 = 10^{-6}-10^{-5}$ sec. In the record-setting experiment of[3] with the 44-second isomer Ag^{109}, the resonance line was observed to be broadened by a factor of one million, which corresponded to $\Delta\Gamma \approx 10^{-11}$ eV, in spite of exceptional measures that were taken. When it is remembered that the margin in the multiplier Γ/Γ_0 is no more than two or three orders of magnitude, we may take $\tau_0 \lesssim 10^{-1}-10^{-2}$ sec as a realistic upper limit of τ_0 for γ-laser working nuclei. A way must be found to create a population-inverted system during this short time and still preserve the possibility of bringing about the Mössbauer effect, i.e., the working system must be produced in a solid and cold form. It is natural to question the very possibility of a self-consistent choice of parameters that would satisfy such rigid mandatory conditions.

Radiative capture of neutrons is a superior way to obtain pulsed population of the upper Mössbauer level. Obviously, the inevitable heat release associated with radiative neutron capture is proportional to n* (and to the integral flux J of the pump neutrons). It would be possible to lower n* by increasing the range $l(E_0)$ of the resonant γ quanta, and hence deduce the first design feature of the γ laser: the need for strong (by a factor of 10^3-10^4) dilution of the working nuclei, which would be used in the form of impurities in a light matrix (for example, in beryllium). Further, to avoid heating by cascade nγ-capture γ quanta, it will be necessary to make the core of the laser in the form of slender needles with diameter-to-length ratios $10^{-3}-10^{-4}$ and diameters $10^{-3}-10^{-4}$ cm. Heating due to scattering of

neutrons in the matrix itself [cross section $(\sigma_s)_m$] presents no danger here if $\sigma_{n\gamma} \gg (\sigma_s)_m$. Estimates indicate that the relatively mild condition $\sigma_{n\gamma} \gtrsim 100$ b must be satisfied for this purpose.

Thus, we find that it is possible to combine the objectively available parameters with the population-inversion requirement of the γ laser without excessive overheating. This means that "head-on" pumping is possible, at least in principle, because the necessary "window" of self-consistent physical parameters exists. However, the required integral neutron fluxes over a time $t \ll \tau_0$ are enormous: $J_t \sim 10^{19}$–10^{20} cm^{-2}, i.e., on a level presently attainable only in nuclear explosions (here, of course, we refer to the pumping of many needles at once).

Nevertheless, there is hope for the development of γ lasers operating at much smaller pump-neutron fluxes. In fact, the number of active nuclei in a single laser needle should be no greater than 10^{13}–10^{14}. This suggests the idea of simultaneous excitation of the Mössbauer levels (the optimum variant is $n\gamma$ capture) and transfer of the excited nuclei to some kind of receiver. It might then be possible to collect very short-lived nuclei and to separate the overheating region, where the levels are populated, from the region of the subsequent γ emission into the bargain.

Variants of the transplantation type require pickoff of Mössbauer nuclei from the surfaces of neutron-bombarded samples using the $n\gamma$ capture recoil energy. In the bombardment of highly dispersed (~100 m^2/g) systems, even when only 1% of the bombarded volume is filled (in the form dust), 1 cm^3 contains 10^{19}–10^{20} nuclei that are ready to escape from the surface upon $n\gamma$ capture. About 10^{15} excited nuclei can be obtained by bombarding 1–10 cm^3 of such a dust even at $J_t \approx 10^{15}$ cm^{-2} when $\sigma_{n\gamma} = 10^{-21}$–$10^{-20}$ cm^2—a number sufficient to bring about stimulated γ emission. The emitting Mössbauer atoms might, for example, be collected quickly by converting them into oxide molecules (in an oxygen atmosphere) and expelling them in supersonic jets, or by ionization and focusing with an electric field. In the variants considered, therefore, the working body of the laser (needle, thin film, etc.) has already been formed from short-lived Mössbauer emitters, perhaps also with dilution by light nuclei. We should note that the production of integral fluxes on these scales during times $t \ll \tau_0$ on the order of 10^{-6} sec is even now quite feasible, even though such neutron sources do not yet exist. Special plasma sources that generate neutrons in a thermonuclear reaction, e.g., sources of the "plasma focus" type, may prove to be the optimum. The question as to selection of the isotope that is optimal with respect to the entire aggregate of requirements remains open. At the moment, we do not know all of the necessary characteristics, and the so-called isomer ratio in particular, for any of the appropriate transitions. This lends urgency to the performance of special nuclear-spectroscopy studies.

Basic conclusions. 1) The development of a gaser for long-lived ($\tau > 10^{-1}$–10^{-2} sec) nuclear levels as proposed earlier is rendered unrealistic by inhomogeneous broadening of the resonant-transition line by defects—at least without the incorporation of ideas based on artificial line narrowing.

2) A pulsed variant of population of excited levels with lifetimes much smaller than 10^{-2} sec seems realistic.

3) Only transitions for which the Mössbauer effect occurs can be used.

4) Radiative neutron capture is the optimum pumping variant.

5) It is shown that stringent requirements regarding overheating of the working crystal can, in principle, be met by strong dilution of the working nuclei in a light matrix and by making the body of the laser in the form of slender needles. However, the required pulsed neutron flux is on the scale of 10^{19}–10^{20} n/cm^2, which can now be attained only from nuclear explosions.

6) The required pump-neutron integral fluxes can be lowered by many orders of magnitude by exciting and separating the excited nuclei simultaneously, e.g., by using the recoil of the nuclei and a branched target surface.

[1] V. I. Gol'danskiĭ and Yu. M. Kagan, Zh. Eksp. Teor. Fiz. 64, 90 (1973) [Sov. Phys.-JETP 37, 48 (1973)].
[2] Yu. M. Kagan, Zh. Eksp. Teor. Fiz. 47, 366 (1964) [Sov. Phys.-JETP 20, 243 (1965)].
[3] G. E. Bizina, A. G. Beda, N. A. Burgov, and A. V. Davydov, Zh. Eksp. Teor. Fiz. 45, 1408 (1963) [Sov. Phys.-JETP 18, 973 (1964)].

Yu. A. Il'inskiĭ and R. V. Khokhlov. The Possibility of Observing Stimulated γ Radiation.

The question as to the possible use of long-lived isomers for the development of γ lasers was first posed back in the early 1960's (see[1] and others). This question was answered in the affirmative in the first papers. Later, however, apparently insurmountable difficulties made their appearance, with the result that no serious experimental work on the γ laser has been done in recent years. Now interest in the γ laser has been revived by a quick succession of developments in various branches of physics[2,3]. The present paper is devoted to ways to solve the problem of observing stimulated γ emission by the use of long-lived isomers.

If there is a column of matter of length l, in which some of the nuclei are in an excited state, γ quanta will be emitted from the end of the column at an intensity

$$I = I_0 G,$$

where

$$G = \frac{\exp[(\beta-\delta)l-1]}{(\beta-\delta)l};$$

here I_0 is the spontaneous-emission intensity of a slender column, β is the gain due to stimulated emission, and δ is the absorption coefficient.

In the range of atomic weights around 100, which includes most isomer transitions for γ quanta with energies E from 1 to 200 keV, absorption is determined basically by the photoeffect and decreases with energy as $E^{-7/2}$. Under normal conditions in pure substances, $\delta = 10^3$ cm^{-1} for E = 10 keV, and $\delta = 5$ cm^{-1} at E = 200 keV. The amplification is determined by

$$\beta = \pi\lambda^2 f \frac{1}{\Gamma\tau} \frac{1}{1+\alpha} N,$$