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A CRITICAL REVIEW OF GAMMA-RAY LASER PROPOSALS*

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ABSTRACT

Laser sources generating sub-nm radiation, using recoilless nuclear transitions in solids, have been proposed for years. This review examines, from the standpoint of kinetics, many solutions (viz., narrowed line, explosive neutron pump, two-stage pump, two-step pump) that have been proposed for the basic problem: that pumping can inhibit or destroy the Mossbauer and Borrmann effects, which are essential for gain.

INTRODUCTION

This symposium of invited and contributed papers marks long-overdue recognition by the American scientific community of the enormous potentiality for coherent sub-nanometer radiation, and of the possibility that sources can be developed by exploiting unique features of nuclear transitions, of crystals, and of this particular spectral range.[1]

The probability of induced radiative transitions is derivable by an elementary theromodynamic argument which applies at any energy to any type of system or multipole order. Thus, for Mossbauer gamma-ray lines (usually, magnetic dipole or electric quadrupole) in typical solid hosts, the resonance cross sections for nuclei are identical in form with those for optical transitions, except for the Debye-Waller factor, and often exceed the photoelectric absorption cross section by several orders of magnitude [Hanna].[2] In crystals, Bragg reflections create collimated radiation-field modes with greatly reduced absorption - the Borrmann effect [Post] - but enhanced interaction with resonant nuclei at lattice sites [Hannon]. Hence, an inverted nuclear population in a cool solid should amplify; mirrors are unnecessary. The problem is to establish a population inversion without destroying the cool crystal host essential to the Mossbauer and Borrmann effects. In this paper, we examine the major proposals for pumping grasers from the standpoint of their kinetic behavior.

To excite or stimulate deexcitation of any resonant system requires time, to define the frequency of the exciting vibration and the ratio of its bandwidth to the sharpness of resonance. Thus, the stimulation cross section is time-dependent. Atoms, emitting optical lines, respond rapidly to Doppler-broadened radiation. Resonant nuclei, on the other hand, respond slowly (on a time scale comparable with the upper-state lifetime, in the range $1\ ns<T<10\ us$), because, for appreciable gain, the Mossbauer line must approach its homogeneous, natural linewidth.

UNPROMISING PROPOSALS

Early suggestions, to dope elongated crystals with radiochemically prepared long-lived nuclei ("isomers"), then cool or align the nuclear spins to increase the gain and thereby initiate lasing, were abandoned when it was realized that transitions of lifetime long enough to permit the preparation steps are inhomogenously broadened [Hanna, Hoy] to an extent that gain is impossible.

Subsequently, NMR techniques were suggested to reduce, average out or compensate three of the numerous interactions that broaden the nuclear line. They are complicated; none has been reduced to practice, despite obvious benefit to Mossbauer spectroscopy. We are not hopeful: the time needed to define the width of a narrowed line must always exceed the inverse linewidth to be achieved; even full initial inversion decays in only one half-life.

There are proposals to form highly excited compound nuclei by neutron capture; the ensuing radiative decay cascade might populate short-lived Mossbauer states. To maximize capture cross section and minimize damage to the host, the neutrons must be slow. Even then, enormous densities ($\sim 10^{22}$ cm^{-3}) and, therefore, explosive sources of neutrons are required. Neutron moderation times (and their fluctuations) exceed the lifetimes of typical Mossbauer states; thus, time-spread in the neutron pump is added to the resonant time-lag of the response of the decaying nuclei. Using the coupled Maxwell-Schroedinger equations with an appropriate time-dependence for the neutron capture rate in ^{82}Kr, we find that the 9.3-keV, 147-ns transition in ^{83}Kr has inappreciable gain unless the slow-neutron density exceeds 10^{22} cm^{-3} - but simple infinite-medium-case heat balance shows that one cannot moderate more than 5×10^{17} cm^{-3} fission neutrons (2.5 MeV) to the 40-eV ^{82}Kr capture resonance.

Another proposal would pump a three-level graser with Mossbauer radiation excited in a blanket by neutron capture. The additional kinetic delay and poor geometric efficiency (the graser filament can intercept only a small fraction of the pump radiation), dispose of this concept.

One might eliminate lower-state resonance absorption in a four-level scheme by polarizing the nuclei to be pumped. For example, in ^{161}Dy, line x-rays from a Ra target might invert a 75-keV m = -3/2 upper laser state with respect to substates of the 24-keV, I = -5/2 lower laser state via a 103-keV transition from an m = -7/2 ground state. High magnetic field and very low temperature are required; the necessary high pump power (not all the x-ray lines will be resonant) would inevitably overheat the Mossbauer medium.

Optically pumping the respective states into extreme hyperfine sublevels of opposite sign could also eliminate initial terminal-state resonance absorption. However, optical pumping is too slow to polarize the previously excited states before they have decayed.

TWO-STEP PUMPING

The best proposal for reducing pumping power is to incorporate a "storage isomer" into a host, then, with a small additional amount of energy, induce transfer to a level that can lase. Its feasibility depends upon:

1) Finding a nuclide with a short-lived level only slightly higher than the storage level. One known pair of nuclear states is separated by only 73 eV--if others exist, how do we find them [Martin, Strottman, Dietrich, Gove, Haight, Collins, Yaakobi]?

2) Producing and separating enough active isomer from other nuclear reaction products. This problem is soluble, at least in particular cases [Dyer].

3) Devising a rapid and efficient transfer process. Transfer by resonant radiation (the essence of Mossbauer spectroscopy!) is clearly feasible - but is it fast enough, and how do we generate it, or is there a better way [Solem, Rinker, Biedenharn, Reiss, Wender]? To enhance its rate of absorption by what will probably be a higher-multipole transition, the active nuclei in the graser host should be disposed in layers, so as to form a superlattice, spaced to enable Bragg reflections of the transfer radiation at the same angle as the radiation to be stimulated.

Assuming that nearly complete inversion can be established by interlevel transfer while preserving host integrity, Dicke superradiance[3] in Borrmann channels [Feld] provides an efficient, fast mechanism for creating a multi-beam coherent output pulse. Table I illustrates the kinetics for a hypothetical case, computed using relations derived by Feld[4] and explained in his paper. Note the high ratio of in-beam to off-beam radiation; also, that less than 10^{14} active nuclei need be created in the transfer step to generate a pulse carrying several megawatts of peak power. Whether it is possible to implant them into the host material, cubic boron nitride (an artificial crystal of exceptionally high Debye temperature) and then transfer from 40-h ^{133m}Ba to invert the 8-ns Mossbauer level is, of course, unknown.

TABLE I: SUPERRADIANCE OF ^{133}Ba IN BORAZON

Nuclide	Host
^{133}Ba	Cubic BN
Storage level, 40-h, 288 keV	Debye temp. 1700
Upper laser level, 8-ns, 12.3 keV	Bragg mode 222
Lower laser level, 10.7-y, 0 keV	

Performance			
Length, mm	5	10	20
Diameter, um	0.80	1.13	1.60
Active nuclei (times 10^{13})	2.4	5.0	10.4
Peak Power, Mw	17.2	35.9	75.1
Pulse Width, ns	0.68	0.67	0.65
Energy Ratio, on/off axis, times 10^9	3.9	7.7	15.0

CONCLUSIONS

To summarize, although solving the interdisciplinary problem of stimulating recoilless nuclear transitions will not be easy, the expected performance and many potential applications of a superradiant graser featuring anomalous emission of Mossbauer radiation into Borrmann modes from nuclei excited by gentle but fast transfer from a long-lived storage isomer, probably distributed to form a superlattice, justify a coordinated research program featuring identification of suitable nuclides, development of methods for preparing and incorporating pure storage isomer in appropriate single-crystal hosts of suitable geometry, and for rapid interlevel transfer that will not inhibit the Mossbauer and Borrmann effects.

REFERENCES

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1. G. C. Baldwin, J. C. Solem, V. I. Gol'danskii, Rev.Mod. Phys. 53, 687 (1981).
2. Bracketed names refer, by first author, to other papers in this symposium.
3. R. H. Dicke, Phys. Rev. 93, 99 (1954); J. H. Terhune, G. C. Baldwin, Phys. Rev. Lett. 14, 589 (1965).
4. J. C. MacGillivray, M. S. Feld, Phys. Rev. A14, 1163 (1976).