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A New Approach to Developing Gamma-ray Laser

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***Abstract*—A laser can greatly increase its power if the radiation comes from the atomic nucleus. The reason is that gamma rays, which are in the high-energy electromagnetic spectrum, come by their nature from the transition between excited to lower nuclear levels, as opposed to electromagnetic waves produced by atoms. The subject of this work is the development of a gamma laser (Graser). The first step is to excite the nuclei of certain isotopes to a higher-energy nuclear state. The excitation method used here is bombarding the nuclei with neutrons. Some isomeric nuclei, known as metastable, can remain excited for a relatively long time, which is what one is looking for. When an external source stimulates these excited nuclei, they can release their stored energy via gamma rays. The emitted gamma rays are modified to produce a coherent laser beam. This work traces the century-long achievement in the field of laser creation after numerous successful solutions and passing through the recoilless Mössbauer emission from the solid crystal lattice. However, scientists have not been able to create a Grasser due to controversial conditions. This article presents a new method, somewhat unconventional, designed to solve the so-called "Graser dilemma". This can be done by shifting the crystal lattice during the neutron bombarding. The technology has the potential to create extremely powerful lasers that can be used in various applications, including laser weapons.**

***Keywords*— gamma-ray, laser, nuclei, power.**

I. INTRODUCTION

The "laser" originates as an acronym for "Light Amplification by Stimulated Emission of Radiation.", and presents a device that emits light through a process of optical amplification on the stimulated emission of electromagnetic radiation. A gamma-ray laser "Graser" is a theoretical device that would produce a coherent beam of gamma rays, much like how a regular laser produces coherent light. Gamma rays are electromagnetic radiation of the highest energy and shortest wavelength, arising from nuclear transitions rather than electronic transitions in atoms. The difficulty of Graser development makes it a major scientific and technological challenge. This subject combines principles of quantum electronics, nuclear and optical spectroscopy, and materials science with advanced engineering techniques. The majority of proposals would use bombarding electrons or neutrons as the main pump, interacting with neutrons and generating excited states.

This work explores the theoretical and experimental principles necessary for developing a Graser. The main difference with this kind of laser is that gamma rays come from the nucleus, contrary to the familiar electromagnetic spectrum coming from electron transitions in the atom. Scientists, largely, are copying the idea from an atomic laser. Similar to how excited electrons in an atom transition to a higher energy level by absorbing a photon of energy, and vice versa emit a photon when descending to a lower energy level, energy levels exist in the nucleus of an atom, and they are responsible for the emission of high-energy photons - called gamma rays. The quest for more powerful lasers inevitably leads to exploring nuclear transitions as a basis for laser technology.

Albert Einstein's 1917 paper, 'On the Quantum Theory of Radiation,' marked the first step in the creation of a laser [1]. In this groundbreaking work, Einstein introduced the concept of stimulated emission, which later became the theoretical foundation for developing lasers. However, the first successful device came in 1953. Charles Townes and his colleagues [2], [3] at Columbia University created the first "maser" - which stands for "Microwave Amplification by Stimulated Emission of Radiation". The key point was to organize atoms to emit waves in perfect harmony, achieving coherence in space and time. They essentially turned Einstein's theoretical concept of stimulated emission into a practical reality. The next step is the first laser built by Theodore Maiman [4], [5], [6] at Hughes Research Laboratories, based on theoretical work by Charles Townes and Arthur Schawlow and the optical amplifier patented by Gordon Gould.

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Discussing the achievements of Graser's development, one has to mention many of the problems facing the Grasser study have been resolved over the years. The question of obtaining a sufficient concentration of resonant excited isomeric nuclear states for collective stimulated emission to occur turns on the broadening of the gamma-ray spectral line [7]. Of the two forms of broadening, the homogeneous broadening is the result of the lifetime of the isomeric state: the shorter the lifetime, the more broadened the line [8] - [12]. This raises the question of finding long-lived isomers. Inhomogeneous broadening comprises all mechanisms by which the homogeneously broadened line is spread over the spectrum [13]. The most familiar inhomogeneous broadening is Doppler recoil broadening from the thermal motion of molecules in the solid containing the excited isomer and recoil from gamma-ray emission, in which the emission spectrum is both shifted and broadened. The problem has been solved by Mössbauer [14] – [16]. The Mössbauer effect gave recoilless radiation exhibits a sharp line on top of the Doppler-broadened background that is only slightly shifted from the center of the background. With the inhomogeneous background removed, and reaching a sharp line, it would seem that there are conditions for gain [17] – [21]. Nevertheless, other difficulties that would degrade gain are the unexcited states that would resonantly absorb the radiation, opaque impurities, and loss in propagation through the crystal in which the active nuclei are embedded [22]. Much of the latter can be overcome by clever matrix crystal alignment [23] to exploit the transparency provided by the Borrmann effect [24], [25], [19], [20]. Another difficulty, i.e., "Graser's dilemma", is that the properties that should allow for gain and those that would allow for sufficient nuclear inversion density seem incompatible [26]. The time required to activate, separate, concentrate, and crystallize an appreciable number of excited nuclei by conventional radiochemistry is at least a few seconds. To ensure the inversion persists, the lifetime of the excited state must be considerably longer. The heating caused by neutron pumping the inversion *in situ* is incompatible with maintaining the Mössbauer effect. Heating may be reduced by two-stage neutron-gamma pumping in which neutron capture occurs in a parent-doped converter, where it generates Mössbauer radiation that is then absorbed by ground-state nuclei in the Graser [27], [28]. Two-stage pumping of multiple levels offers multiple advantages. Another approach is to use nuclear transitions driven by collective electron oscillations [29], [30]. The scheme would employ a triad of isomeric states: a long-lived storage state, in addition to an upper and lower lasing state. The storage state would be energetically close to the short-lived upper lasing state but separated by a forbidden transition involving one-quantum unit of spin angular momentum. The Graser would be enabled by a very intense optical laser to saturate the forbidden transition. A "complete" chart of nuclides likely contains a very large number of isomeric states, and the existence of such a triad seems likely, but it has yet to be found [31], [32]. Nonlinearities can result in both spatial and temporal harmonics in the near field at the nucleus, [33], [34] opening the range of possibilities for rapid transfer from the storage state to the upper lasing state using other kinds of triads involving transition energies at multiples of the optical laser quantum energy and higher multipolarities.

The first phase of Graser research, emphasizing the use of crystallized radiochemical prepared isomers, ended when the Graser dilemma and the inertia of resonance were encountered. After years of hiatus, it became apparent that these difficulties might be circumvented by the impulsive pumping of short-lived isomers, by rapid separation of isomers of intermediate lifetimes, or by artificial control of the linewidth in long-lived isomers. In the ensuing second phase, it has become apparent that (1) it is not possible to achieve gain on Doppler-broadened gamma-ray lines, i.e., the Mossbauer effect is an essential feature; (2) it is not possible to pump a Graser directly in situ since the only radiation that would not inevitably destroy the Mossbauer host cannot be generated in adequate intensity from known sources; (3) line narrowing will be extremely difficult and complicated, and there are reasons to suspect, that it may have only limited advantages. These negative conclusions of the second phase are offset, however, by hopes raised by recent rapid progress in several technologies, viz., laser-based isotope separation, atomic beam hyperfine spectroscopy, nuclear polarization, production of defect-free solids, and the generation of coherent radiation in the soft-x-ray region. Mainly Widmann's work and some others, in atomic beam hyperfine spectroscopy has demonstrated the feasibility of isomer-selective optical pumping and separation of isomers based on magnetic moments - in weak currents [35] - [37]. Optical pumping offers the hope that a population of separately pumped nuclei can be not only rapidly concentrated, implanted, and annealed but also polarized to eliminate lower-state absorption. One is convinced that an intermediate concentration step must separate the pumping and lasing stages so that the best hope for the future lies in rapid separation and careful deposition in a host. Unfortunately, properties that should enable amplification and those that would permit obtaining nuclear inversion densities sufficient for lasing are not, at present, compatible. The resonance cross section is so reduced by line broadening, in the case of long-lived transitions, that amplification is not possible; on the other hand, the intense pumping needed to invert isomers with lifetimes in the Mossbauer range may overheat, damage, or even destroy the solid that must support recoilless emission. The proposals reviewed in this article are suggestions for overcoming these difficulties.

II. MATERIALS AND METHODS

A. Theoretical Formalism

a) Parameters of nuclei

The diameter of the nucleus is about 10,000 times smaller than the diameter of the atom itself. Here is shown, in Table 1, the size of nuclei and the scale of electromagnetic waves, in Table 2. As we can see γ-rays, the wavelength range starts from 0,01nm.

TABLE 1 SIZE COMPARISON FOR NUCLEI.

Unit	Symbol	Length in Meters
Meter	m	1 x 10^{0} m
Millimeter	mm	1 x 10^{-3} m
Micrometer	µm	1 x 10^{-6} m
Nanometer	nm	1 x 10^{-9} m
Picometer	pm	1 x 10^{-12} m
Femtometer	fm	1 x 10^{-15} m
Atomic Nucleus		1 x 10^{-15} m

TABLE 2 ELECTROMAGNETIC SPECTRUM ORDER.

Type of Radiation	Wavelen gtRange	Frequency Range	Coman Sources
Radio Waves	> 1 mm	< 300 GHz	Radio, TV, cell phones
Microwaves	1 mm – 1 m	300 GHz - 300 MHz	Microwave ovens, radar
Infrared	700nm-1mm	430 THz - 300 GHz	Heat lamps, remote controls
Visible Light	400nm-700nm	750 THz - 430 THz	Sun, light bulbs
Ultraviolet	10nm-400nm	30 PHz – 750 THz	Sun, black lights
X-ray	0,01nm-10nm	30 EHz – 30 PHz	X-ray machines, some stars
Gamma Rays	<0,01nm	> 30 EHz	Radioactive decay, nuclear reactions

Theoretically, there is no a low border for gamma rays. The highest energy gamma rays observed so far come from astronomical sources, like the Cygnus X-3 micro quasar. To calculate their wavelength, we can use the formula:

$$\lambda = \frac{hc}{E} \quad (1)$$

where: λ is the wavelength,
h is Planck's constant (6.626×10^{-34} Js),
c is the speed of light (3×10^{8} m/s),
E is the energy.

For a gamma ray from Cygnus X-3 with an energy of 100 TeV (100×10^{12} eV): $\lambda \approx 1.24\times10^{-20}$ meters

b) Basic formulas for Photon or γ-ray

$$h\nu = E_2 - E_1 \quad (2)$$

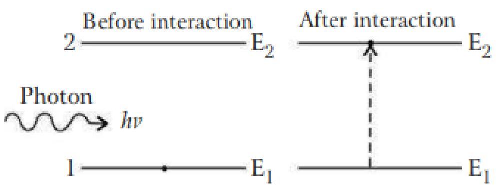

Fig. 1. Induced or stimulated absorption. Source: Physical Optics and Lasers by R.K. Agrawal

where: ν is the frequency corresponding to the energy difference.

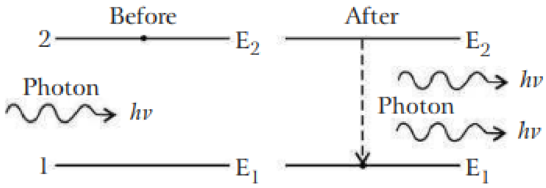

Fig. 2. Stimulated or induced emission. Source: Physical Optics and Lasers by R.K. Agrawal

c) Relation between Spontaneous and Induced Emission

$$A_{21}/B_{21} = 8\pi h\nu^3/c^3 \quad (3)$$

d) Einstein coefficients

A_{21} the probability per unit time of spontaneous emission from the energy state E_2 to the lower energy state E_1.
B_{12} the probability per unit time of induced (stimulated) absorption from E_1 to E_2.
B_{21} the probability per unit time of induced (stimulated) emission from E_2 to E_1.

e) Symmetry of Induced Processes:

$$B_{21} = B_{12} \quad (4)$$

f) Population of Energy States

The number of atoms/nuclei in each energy state is given by the Boltzmann distribution:

$$\frac{N_2}{N_1} = \exp\left(-\frac{E_2}{E_1}\right) = \exp\left(-\frac{h\nu}{Tk_B}\right) \quad (5)$$

where: N_1 and N_2 number of atoms/nuclei in states E_1 and E_2, respectively
k_B Boltzmann's constant
T absolute temperature

g) Population Inversion

The establishment of a situation in which the number of nuclei in a higher energy state is greater than that in a lower energy state is called the population inversion.

h) The total linewidth

$$\Gamma = \frac{1}{\tau} \quad (6)$$

where: Γ total linewidth (in radians per second)
τ lifetime of the excited state (in seconds)

The line-broadening factor is therefore crucial. Its maximum possible value of unity occurs only when the transition is purely radiative 2-nd to a ground state. If there are no other contributors to the line breadth, then we say that the line is "homogeneously broadened" by branching, internal conversion, and lower-state decay but is of "natural" width. In spectroscopy, linewidth is often characterized by the Full Width at Half Maximum (FWHM), which measures the width of the spectral line at half of its maximum intensity:

$$\Delta\nu = \frac{\Gamma}{2\pi} \qquad (7)$$

where: $\Delta\nu$ linewidth in hertz (Hz)

i) Doppler-recoil broadening

Because of the random thermal motion of molecules and recoil of the nucleus from photon emission, the emission spectrum is both shifted, on average by:

$$\Delta\nu = 5.32 \times 10^{-4} \frac{E'}{M} \quad \text{eV} \qquad (8)$$

$$\Gamma_D = 3.3\left(\frac{E'\mu_e}{M}\right)^{\frac{1}{2}} \quad \text{eV} \qquad (9)$$

where: $\Delta\nu$ average frequency shift.
E' photon energy in electronvolts (eV).
M mass of the emitting nucleus or molecule in atomic mass units (u)
μ_e Effective mass related to electron mass.
Γ_D Doppler linewidth.
v_{rms} Root-mean-square thermal velocity in the direction of emission.

This broadening, known succinctly as the "Doppler breadth," simplifies to:

$$\Gamma_D \approx E'\left(\frac{v_{rms}}{c}\right) \qquad (10)$$

In the optical region, the recoil shift $\Delta\nu$ is small compared with the Doppler-recoil width and can be neglected.

B. Definitions

a) Nuclear isomers

Refer to nuclei with the same number of protons and neutrons but in different energy states due to varying configurations of nucleons.

b) Metastable States

These isomers exist in excited states with relatively long half-lives (from nanoseconds to years) before decaying to lower energy states. They're denoted with an "m" (e.g., ^{99m}Tc for Technetium-99m).

c) Energy Transitions

When they decay to lower energy states, they emit gamma radiation.

d) Induced transition cross-section

For a transition between two energy levels E_1 and E_2:

$$\sigma_{12} = \frac{h\nu}{c} B_{12}, \qquad \sigma_{21} = \frac{h\nu}{c} B_{21}, \qquad (11)$$

σ_{12} cross-section for stimulated absorption.

e) Gain Medium

The induced emission cross-section helps determine the gain coefficient g of a laser medium:

$$g = N_2\sigma_{21} - N_2\sigma_{12} \qquad (12)$$

f) Recoilless transitions - The Mossbauer effect

For isomers in solids that show the Mössbauer effect, the gamma-ray emission spectrum exhibits a sharp component superimposed upon the Doppler-broadened background. Often this "recoilless" radiation is essentially of natural width, relatively intense, and only slightly, if at all, displaced from the energy of the nuclear transition. It is manifested by strong resonance absorption of radiation from excited states in one solid by ground states of the same nuclide in a second solid.

The resonance cross-sections, measured in Mössbauer spectroscopy, often are found to be far greater than the nonresonant absorption cross-section, particularly when the recoilless line is near the natural width. In nuclear isomers and Mössbauer spectroscopy, cross-sections for gamma-ray-induced transitions are key to interpreting experimental results.

g) Phonon

At their core, phonons are quantized units of lattice vibrations in crystalline solids. Think of them as the particle-like representations of sound and heat waves moving through a material at the atomic level. Just as photons are the quantized units of electromagnetic waves (light), phonons are the quantized modes of vibrations in a rigid crystal lattice.

h) Debye temperature

$$\Theta_D = \frac{\hbar\omega_D}{k_B} \qquad (13)$$

where: $\hbar$ is the reduced Planck constant,
ω_D is the Debye frequency (the maximum phonon frequency),
k_B is the Boltzmann constant.

C. The energy definitions

a) Nuclear Transition.

A nuclear transition refers to the change in energy levels within an atomic nucleus. This can involve the emission or absorption of gamma rays.

b) Displacement energy

The energy required to displace an atom from its lattice position in a crystal. While important for understanding material stability and radiation damage, it is not directly related to the lasing process in a graser.

c) Transferred Energy.

The energy difference between the initial and final nuclear states defines the energy of the emitted or absorbed gamma ray.

D. Methods

The Mössbauer effect is susceptible to thermal vibrations within the crystal lattice. When neutron-pumping is used to achieve population inversion *in situ*, the process introduces significant heating due to the interaction of neutrons with the nuclei, leading to excitations that subsequently decay and deposit energy into the lattice. This increase in temperature enhances phonon activity - essentially, the vibrations of atoms in the lattice, which can disrupt the recoil-free conditions necessary for the Mössbauer effect.

A simplified visualization to illustrate the process:

Neutron-Pumping → Nuclear Excitations → Energy Release into Lattice
↓
Increased Lattice Temperature
↓
Enhanced Phonon Activity (Vibrations)
↓
Reduction of Recoil-Free Gamma-Ray Emission (Mössbauer Effect Compromised)

The core issue is that the Mössbauer effect relies on the emitter and absorber nuclei being part of a solid lattice with minimal thermal motion to ensure recoil-free emission and absorption of gamma rays. Elevated temperatures introduce Doppler broadening and decrease the probability of recoil-free events, thus hindering the effect.

To mitigate this incompatibility, several approaches are considered:

a) Cryogenic Cooling

Implementing efficient cooling systems to maintain the lattice at low temperatures can reduce phonon interactions. Cooling the system to temperatures well below the Debye temperature of the material can help preserve the recoil-free fraction.

b) Material Selection

Choosing materials with higher Debye temperatures increases the range of temperatures over which the Mössbauer effect remains observable. Isotopes embedded in hosts with stiff lattices can sustain lower phonon activity even when some heating occurs (fig.3).

c) Pulse Techniques

Utilizing pulsed neutron sources with low-duty cycles might allow the lattice to dissipate heat between pulses, reducing overall thermal buildup

	Isomeric transition			Mössbauer parameters				Photon cross sections, b		Production reaction		
Nuclide	Transition energy	Half-life	Type	Internal conversion coefficient	Recoil energy meV	Debye[b] temp. K	No-phonon fraction $f(T=0)$	Removal[c]	Resonant[d]	Type	Parent	Half-life
^{57}Fe	14.4	97.8 ns	$M1$	8.2	2.0	490	0.93	5.5(3)	1.2(6)	EC	^{57}Co	267 d
	136.5	8.7 ns	$E2$	0.14	175		0.002	1.9(1)	2.3(2)	β	^{57}Mn	1.6 m
^{67}Zn	93.3	9.3 μs	$E2$	0.89	70	327	0.024	5.9(1)	3.6(3)	EC	^{67}Ga	78 h
										β	^{67}Cu	59 h
^{73}Ge	13.3	2.75 μs	$E2$	1100	1.3	370	0.94	1.5(4)	1.2(4)	EC	^{73}As	80 d[e]
	68.3	2.9 μs	$M1$	0.8	34		0.19	1.7(2)	5.6(4)	β	^{73}Ga	49 h
^{83}Kr	9.4	147 ns	$M1$	19.6	0.57	72	0.87	8.5(3)	1.2(6)	EC	^{83}Rb	86 d
^{107}Ag[f]	93.1	44.3 s	$E3$	20	43	225	0.035	3.2(2)	4.6(2)	EC	^{107}Cd	6.7 h
^{119}Sn	23.9	17.9 ns	$M1$	5.2	2.6	210	0.81	2.6(3)	5.6(5)	EC	^{119}Sb	38 h
^{151}Eu	21.5	9.7 ns	$M1$	28.6	1.66	195	0.86		1.6(5)	EC	^{151}Gd	120 d
										β	^{151}Sm	90 y
^{155}Gd	60.0	0.19 ns	$M1+E2$	8.7	12		0.33	3.0(3)	2.3(4)	EC	^{155}Tb	5.6 d
	86.5	6.3 ns	$E1$	0.43	26	195	0.10	1.2(3)	2.2(4)	β	^{155}Eu	5.0 y
	105.3	1.2 ns	$E1$	0.26	38		0.032	7.6(2)	5.6(3)			
^{161}Dy	25.7	28.2 ns	$E1$	2.9	2.2		0.83	6.5(3)	7.9(5)	β	^{161}Tb	6.9 d
	43.8	0.8 ns	$M2$	4.3	6.4	210	0.59	1.6(3)	1.4(5)	EC	^{161}Ho	2.4 h
	74.6	3.3 ns	$E1$	0.65	19		0.22	1.9(3)	5.7(4)			
^{181}Ta	6.2	6.8 μs	$E1$	82	0.11	240	0.99	9.7(4)	7.6(5)	EC	^{181}W	121 d
	136.3	40 ps	$M1+E2$	1.8	55		0.02	5.6(2)	8.6(2)	β	^{181}Hf	42 d
^{191}Ir	82.4	4.0 ns	$M1$	10.7	19	420	0.45	2.6(3)	1.4(4)	β	^{191}Os	15.4 d
	129.4	89 ps	$M1$	2.9	47		0.14	7.8(2)	5.3(3)	EC	^{191}Pt	2.8 d
^{237}Np	59.5	68.2 ns	$E1$	1.1	8.0	200	0.50	2.8(3)	1.6(5)	β	^{237}Pu	6.8 d
										EC	^{237}U	4.5 d
											^{241}Am	460 y

Fig. 3. Lists several isotopes that emit recoilless radiation when in solid hosts. Source: Baldwin et al, (1981)

III. RESULTS AND DISCUSSION

The present work proposes a combination of neutron beams for the excitation of metastable nuclei
in the correct crystal lattice to ensure recoil-free Mössbauer emission and, by ensuring such emission, prevent the broadening of the resonant nuclear line, which is crucial for maintaining coherence. However, the challenge lies in selecting the right metastable nuclei and creating the ideal crystal environment. The choice of Europium-151 (^{151}Eu) can offer the conditions we need (fig.3). The half-life of ^{151}Eu is approximately $4.62{\times}10^{18}$ years. This incredibly long half-life means that ^{151}Eu is nearly stable. ^{151}Eu is a compelling choice when delving into the Mössbauer effect and the pursuit of coherent gamma emission. Its nuclear properties make it suitable for emitting and absorbing gammarays without recoil, which is .essential for maintaining the sharp resonance lines one strives for. The 21.5 keV nuclear transition of ^{151}Eu has relatively low energy, which facilitates the Mössbauer effect at accessible temperatures. By embedding ^{151}Eu atoms into a carefully selected crystal lattice, one can minimize the recoil during gamma emission and absorption. The lattice acts as a collective mass that absorbs the recoil momentum, preserving the energy precision needed for coherence. One of the intriguing challenges with ^{151}Eu is its natural abundance and isotopic purity. Since Europium naturally occurs as two stable isotopes - ^{151}Eu and ^{153}Eu - enriching samples with a higher concentration of ^{151}Eu can enhance the effectiveness of one‘s experimental setup. Isotopic enrichment ensures that a larger proportion of the nuclei participate in the Mössbauer resonance, improving the overall efficiency of recoilless emission.

Creating the appropriate crystal lattice is another hurdle. The lattice must be capable of absorbing the recoil energy completely, which often requires ultra-low temperatures to minimize lattice vibrations - phonons - that can disrupt the process. Quantum engineering at this scale pushes the boundaries of materials science. The choice of host lattice is also crucial. The crystal structure must not only accommodate Europium ions but also possess suitable vibrational properties to suppress phonon interactions that could broaden the resonance line. For our case, the compound E u_2 Ca F_2 (Europium Calcium Fluoride) has been chosen. It is known for its interesting lattice dynamics and structural phase transitions. It can exist in multiple phases, including cubic, trigonal, and monoclinic, depending on temperature and pressure. The cubic phase is particularly stable at ambient conditions, which might be beneficial for maintaining a consistent crystal lattice. $\mathrm{E}u_2\mathrm{Ca}F_2$, on the other hand, has a fluorite structure, which is a face-centered cubic (fcc) lattice. This structure is known for its high transparency and low phonon energy, which are advantageous for optical applications. The incorporation of Europium into the $\mathrm{Ca}F_2$ lattice can introduce new optical properties, making it my choice for gamma-ray laser.

In exploring the excitation of nuclei with neutrons to produce gamma rays, one is treading a fine line between effectively stimulating the desired nuclear transitions and inadvertently damaging the crystal lattice. The "border of overheating the crystal" refers to the threshold at which neutron irradiation begins to disrupt the crystal structure and undermines the conditions necessary for recoilless emission. When neutrons interact with a crystal lattice, they can transfer significant energy to the atoms within the material.

The key point in the present work is the suggestion that even if the transferred energy exceeds the displacement energy of the atoms, under the right combination of circumstances, the Graser can be achieved:

- Estimating the displacement energy of atoms in E u_2 Ca F_2 involves considering the individual contributions of Fluorine, Calcium, and Europium ions within the crystal lattice. I use the computational method of density functional theory (DFT) to provide quantum mechanical modeling of atomic interactions at finite temperatures and estimate:

Fluorine Ions: ~25–40 eV
Calcium Ions: ~30–50 eV
Europium Ions: ~50–80 eV

- The common estimation to avoid overheating the crystal, usually essential to optimize the neutron flux and energy, is not helping in our case. Usually for neutron energy, one uses thermal or cold neutrons (with energies in the meV = 10^{-3} eV range) to reduce the risk of displacing lattice atoms.
- One knows lower-energy neutrons may have a lower probability of inducing the desired nuclear transitions. However, flux density should be limited the neutron flux minimizes the number of interactions that could lead to lattice damage. It's a balance between enough interactions to excite the nuclei and prevent excessive collisions that harm the lattice.
- Additionally, irradiation time should be shorter to reduce cumulative damage. Pulsed neutron sources should deliver neutrons in bursts, allowing the lattice to dissipate energy between pulses. Pulsed neutron sources with low-duty cycles allow lattices to dissipate heat between pulses, reducing overall thermal buildup.
- Low-temperature operations should further reduce lattice vibrations, enhancing the Mössbauer effect.

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Cryogenic cooling of the systems to maintain the lattice at low temperatures will reduce phonon interactions. Cooling the system to temperatures well below the Debye temperature of the material will help preserve the recoil-free fraction.

- Exploring external influences such as magnetic and electric fields might offer additional control over the nuclear states of ^{151}Eu. Hyperfine interactions can split the nucleus energy levels, allowing for more precise tuning of the resonance conditions. This added control could be an instrument for additional rising energy and achieving coherence.

One needs energy in the range of keV or MeV to achieve the necessary nuclear transitions and coherence. When discussing Grasers on the base of ^{151}Eu, the energy levels are typically in the keV range. This range is achievable for our case, for instance, the 21.5 keV nuclear transition for ^{151}Eu is a good example of energy levels involved in gamma-ray applications. However, the Graser dilemma is still present, i.e. the neutron beam energy ~22 keV is significantly higher than the displacement threshold energy 50–80 eV. This means that a single neutron with this energy has more than enough energy to displace an atom from its lattice site.

The new method invented here to develop Graser and overthrow Graser's dilemma is "to burn the lattice." One must stop worrying about damaging the crystal lattice but sacrifice it and consider it a temporary consumable. The "burn" symbolically means that one should leave a high-energy neutron (for example, 22 keV) to destroy/burn the lattice, simultaneously exciting the metastable nuclei (in this case ^{151}Eu). Furthermore, to ensure the continued existence of the Grasser body, a mechanism for moving and constantly feeding a new crystal lattice at the same location where the beam of nuclei hits the lattice must be added. The creation of an excited state, population inversion, and emission of coherent waves will be possible by means of a pulsed beam and only for the exact location and moment. At the next moment, this will happen with the new part of the incoming crystal. Precise adjustments of location and time are mandatory for the process to have an effect.

IV. Conclusions

The quest for a gamma-ray laser resembles that for controlled nuclear fusion in many ways. Neither goal seems to forego any fundamental principle, both offer enormous rewards for success, both present challenging problems in many disciplines, and both have been maddeningly elusive, and both have been pursued for many years. In each, just when one approach has failed, another concept emerges, and the search is renewed. The nuclei that will play an important role in fusion are known; in Graser, where nuclear parameters play a much more important role, there are still no clear candidates.

The theoretical calculations and consideration of the present work suggest the possible development of Graser. It is on the base of the metastable isotope of ^{151}Eu embedded in the crystal lattice as Eu_2CaF_2, a chemical compound that subsequently guarantees recoil-free Mössbauer scattering and prevents the broadening of the Doppler recoil and, in turn, ensures coherence of the laser beam. However, to make Graser possible, one should optimize the neutron flux and energy. On the first impression, the bombarding neutron flux mustn't exceed energy up to 80 eV, which is the low border of displacement energy for ^{151}Eu, to prevent overheating and damage. On other hand, energies in the area of 80 eV could not be enough to excite the nucleus and create the "population inversion" desired for a coherent beam. The solution is that one can use the energy of the neutron flux at approximately 21.5 keV desired to excite the nuclei and produce a laser beam, however, at the price of destroying the crystal lattice. This new method of "burning and constantly feeding with new crystal", with embedded metastable nuclei circumvents the Grasser dilemma and practically opens a new way to develop Grasser.

It doesn't matter that the model seems expensive, destroying the hard-to-produce lattice with rare metastable isotopes is quite a waste, but Graser's achievement seems possible. Further research could reduce the heavy losses by finding other chemical elements and/or reducing the lattice burn-up rate.

Using Grasers with energies in this range for defensive purposes could revolutionize areas such as advanced shielding and energy transfer systems.

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