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X-Ray and γ-Ray Lasers

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In this talk, I would like to discuss the prospects for producing coherent electromagnetic radiation at wavelengths $\lambda < 10\text{Å}$. Since coherent radiation is most easily produced by producing a population inversion between discrete levels of a radiator, it is most natural to think of generating short wavelength coherent radiation by means of an x-ray laser (XRL) using inner-shell atomic transitions or a γ-ray laser (γRL) using transitions between discrete levels of nuclei.

Lasing action at very short wavelengths will be hard to achieve because of three difficulties not present at longer wavelengths. First, matter has a high opacity at short wavelengths. The nearest analogue to a transparent optical medium such as glass is a hot, fully stripped plasma where the opacity is due only to Compton scattering. Second, high pumping powers and pumping power densities will be required because of the higher transition energies and, in the case of x-ray lasers, very short radiative lifetimes. For example, pumping a 1Å x-ray transition will require on the order of 1 watt per atom. In the case of γ-ray lasers using long lived isomers high pumping powers may not be required, but the long lifetimes of the isomers must be compensated for by extremely narrow line widths. For example, if the lifetime is 10^3 sec then the line width must be less than .1 H_Z, which corresponds to a fractional line width $\Delta\nu/\nu$ on the order of 10^{-20}.

A third obstacle to achieving laser action at very short wavelengths is that these lasers must operate without the benefit of mirrors, due to the fact that all materials have a low reflectivity for $\lambda < 1000$ Å. In addition an XRL would operate at such a high flux level that any mirrors would be destroyed.

If a laser is to operate without mirrors then the gain down the length of the laser must be large enough to allow a traveling wave to grow by stimulated emission. In order to produce gain saturation[1] the gain in an x-ray or γ-ray laser will probably have to exceed 100 db; i.e., the small signal gain coefficient α times the length ℓ of the laser must satisfy:

$$\alpha\ell \geq 25 \quad . \tag{1}$$

For the case of an XRL using an allowed transition, Eq. (1) translates into the following threshold condition on the net inversion density $N^* \equiv N_2 - (g_2/g_1)N_1$[2]:

$$N^* \gtrsim \frac{\Delta\nu(\text{eV})}{\ell(\text{cm})} 10^{18} \text{ cm}^{-3} \tag{2}$$

where $\Delta\nu$(eV) is the width of the transition measured in electron volts. In the case of a crystalline γ-ray laser medium condition (1) becomes:

$$\ell(\text{cm}) > 10^{-4} \Delta\nu(H_Z) \tau_{spon}(\text{sec})/\lambda_{o_{\text{Å}}}^2 \tag{3}$$

where $\Delta\nu(H_Z)$ is the line width in Hertz, τ_{spon} is the spontaneous radiative lifetime and $\lambda_{o_{\text{Å}}}$ is the laser wavelength in Angstroms.

The exact inversion density required for an x-ray laser will be determined by the line width $\Delta\nu$. In cold matter this will be equal to the Auger width which for transitions of interest will be on the order 1 eV. Thus the net inversion density in cold matter must exceed $\sim 10^{18}$ cm^{-3}. In hot matter the width will be determined by the Stark effect at most densities of interest (at low densities the Doppler width will be important). In a fully stripped high Z plasma this width will be given by[3]

$$(\Delta\nu)_{Stark} \approx 30n^{2/3}\ \mathrm{eV} \qquad (4)$$

where n is the density in units of 5.10^{22} cm^{-3}. The main conclusion to be drawn from Eqs. (2) and (4) is that inversion densities much smaller than 10^{18} cm^{-3} are possible only if N^*/N is close to unity; i.e., one has a very efficient scheme for producing population inversions. I. I. Sobel'man and V. I. Vinogradov have pointed out that resonant charge exchange between ions and neutral atoms is an efficient way to populate certain ionic energy levels and have suggested that this might be a way of generating very soft coherent x-rays. It is not yet known, however, whether resonant charge exchange could be used to generate coherent radiation in the region $\lambda < 10$ Å.

Because of the short lifetimes of excited states in an x-ray laser medium and the very high pumping power densities needed, an x-ray laser pumping source — which might be a focussed laser beam or the x-rays produced by focussing a laser on a nearly high Z target — must be swept along the lasing medium at the speed of light, in order to minimize the pumping energy required (see Fig. 1). It can be shown that in order to pump an XRL operating at wavelengths ≤ 10 Å the pumping laser must have a power $> 10^{12}$ W and the pumping laser beam must be focussed to a spot less than 30 μm across which is then swept along the XRL. Actually 10^{12} W laser pulses of

100 psec duration are now available as a result of laser fusion research. Unfortunately, the rise time of these pulses may be too long to be useful since the lifetimes of population inversions are typically much less than 1 psec. To reconfigure existing lasers for operation in the pulse regime required would ential development of an ultra-short pulse oscillator, for use with existing amplifiers. In addition, it is clear that significant effort should be devoted to non-linear optical studies of pulse compression and sweeping. As the pulse grows shorter, the problem of self-phase modulation and pulse reshaping grows more important. Pulse compression using dispersive delay lines has been demonstrated, at low powers, in the 1 - 10 psec regime. Very short pulses, with extremely fast rise times (< 1 psec) might also be generated by stimulated scattering processes, and amplified parametrically in nonlinear elements. However, neither of these approaches is well developed for even moderately high power operation. If the problems of amplifying and sweeping a single short rise-time pulse prove insurmountable then a multiple amplifier system such as shown in Fig. 1 would have to be used.

What about γ-ray lasers? For a given energy the lifetime of a γ-ray transition will be much longer than the corresponding allowed x-ray transition, which means that the threshold inversion will be higher than that given in Eq. (2) by a factor $(\tau_{spon}/\tau_{allowed})$ where $\tau_{allowed} \gtrsim 10^{-15}\ \lambda^2_{Å}$ is the lifetime of a corresponding allowed x-ray transition. As before, the actual threshold inversion densities will be determined by the achievable line widths Δν, which for γ-ray transitions are fortunately not so strongly affected by their atomic environments. For a "vigorously" pumped γ-ray laser medium, we would have $\Delta\nu = (\Delta\nu)_{Doppler}$ where

$$\left(\frac{\Delta\nu}{\nu}\right)_{Doppler} \gtrsim 10^{-3} \left[\frac{\theta(keV)}{A}\right]^{1/2} \qquad (5)$$

where θ(keV) is the temperature of the emitting nuclei in kolovolts and A is the mass number of the nuclei. Unfortunately, at temperatures that one can realistically expect in a vigorously pumped γ-ray laser medium the gain implied by Eq. (5) would not be high enough to overcome Compton scattering. For example, assuming $\Delta\nu/\nu = 10^{-4}$ one will be able to overcome Compton scattering only if τ_{spon}^{-1} > Z E1 or 10Z M1 Weisskopf units. There are no known γ-ray transitions with $\hbar\omega$ < 200 keV which satisfy this condition. There are strong transitions at energies ∿ 15 MeV but the threshold inversion density would be unattainably high.

The conclusion to be drawn is that γRL's appear feasible at this time only if some way of substantially improving on the Doppler line width can be found. It has been pointed out by many people that one way of greatly improving on the Doppler width is to make use of the phenomenon of recoilless emission in crystals (the Mossbauer effect). Line widths as small as 10^5 Hz have in fact been demonstrated experimentally using short-lived $\tau \sim 10^{-6}$ sec isomers.[5] Unfortunately, the line width that needs to be achieved, Eq. (3), is inversely proportional to the lifetime, and this presents problems because the lifetime must be long enough to allow for preparation of a Mossbauer crystal of excited isomers. One possible method of preparation would be to excite long lived isomeric states in, for example, a nuclear reactor and then condense the excited isomeric nuclei into a crystal (see Fig. 2). If one assumes that such a process would consume at least 10 min. then one would be interested in spontaneous radiative lifetimes on the order of 10^4 sec (the difference in times being due to internal conversion). The maximum allowed line widths for such a lifetime, assuming a laser medium 1 cm long, are shown in Table I. Whether the small line widths indicated in Table I are attainable is not known. They are probably not attainable in bulk samples due to crystal imperfections and impurities.[6] It has been suggested,[7] however, that it might be possible to attain line widths approaching natural line widths in small, pure crystal whiskers. When techniques for measuring ultra-small line widths become available it will be possible to experimentally pursue this approach. The requirement on line width can, of course, be relaxed if some method of rapid "gentle" pumping can be devised. The Russian physicists Goldanskii and Letokhov have made some interesting suggestions[8,9] on how to achieve rapid gentle pumping, but none of these schemes has been shown to work in detail.

A computer search through all γ-ray transitions whose energies and lifetimes are known has recently been carried out at the Livermore Laboratory to identify those transitions which might be used in a gently pumped γRL. A total of 22 candidates were found, some of the more promising of which are shown in Table II. The quantity $\zeta \equiv (\lambda^2/8\pi)\,[(1+\alpha)\,\sigma_a]^{-1}$, where α is the internal conversion coefficient and σ_a is the sum of the photoelectric absorption and Compton scattering cross-sections, is a "figure of merit" for candidate nuclei. It represents the multiple of the minimum attainable line width, viz. $(1+\alpha)/\tau_{spon}$, for which the gain is positive. Operation of a γRL at the maximum allowed line width listed in Table I would typically require a figure of merit of a few hundred. Probably only for values of ζ much larger than 1 is there a good chance of being able to achieve the threshold condition for laser action. Although the practical problems that must be overcome in order to operate a gently pumped γRL are formidable, the spectacular properties of such a laser justifies a serious effort to overcome the obstacles. Because of time-bandwidth limitations, a gently pumped γRL would emit a pulse on the order of 1 sec duration. A gently pumped γRL would therefore be a quasi-CW source of extremely monochromatic radiation. As noted earlier a gently pumped γ-ray laser would have a *frequency* definition on the order of one part in 10^{20}!

This fantastically good frequency definition would undoubtedly lead to tremendous advances in both pure and applied science. Actually even a moderately coherent source of radiation in the region $\lambda < 1$ Å would have revolutionary implications for molecular biology and materials science. One could, for example, use such a source to make 3-D holograms of biological macro-molecules in situ. It should be pointed out that x-ray lasers would not be nearly as useful for these applications because of their relatively poor coherence properties and much higher operating fluxes. In fact, x-ray lasers may only be useful because of their very short output pulses.

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TABLE I

$\hbar\omega$ (keV)	$\lambda(A^{o})$	$N^{*} = 2 \cdot 10^{22}$ cm^{-3}, $\tau_{spon} = 10^{3}$ sec Maximum $\Delta\nu$ (Hz)
10	1.2	10.
50	.25	0.3
100	.12	0.1

TABLE II

Isomer	k	λ	σ_{Max}	σ_{abs}	α	ζ	$\tau_{1/2}$	Class	Production
Co^{60m}	.059	.21	$1.8\cdot10^{5}$	120	41	37	10.7min	M3	Co^{59},100%; 18b
Se^{79m}	.096		$5\cdot10^{4}$	84	7.	112	3.9min	E3	Se^{78}, 24%;0.4b
Se^{81m}	.103	.12	$5.8\cdot10^{4}$	70	9	92	57 min	E3	Se^{80}, 49%;0.1b
Br^{77m}	.108	.15	$5.2\cdot10^{4}$	70	6	124	4.2min	E3	$Se^{77}(p,n)B^{77}$
Tc^{99m}	.143		$3\cdot10^{4}$	70	30	14	350 min	M4	Mo^{99}, β^{-} decay

TABLE II. Nuclear isomers considered most promising for production of gently pumped γRL action. The gamma energy k in Mev, the corresponding wavelength λ in Å, the approximate maximum stimulated emission cross-section possible σ_{Max} in barns, the photoelectric absorption plus Compton scattering cross sections at the transition energy σ_{abs} in barns per atom, the total internal conversion coefficient α, the figure-of-merit of the isomer. $\zeta \equiv \sigma_{Max}/(1+\alpha)\sigma_{abs}$, the excited state half-life $\tau_{1/2}$, the multipolarity of the radiative decay, and the most promising means of production of the isomer, including the fractional natural abundance and thermal neutron capture cross section (in barns) to the isomeric state of its precursor. Co^{60m}, Se^{79m} and Tc^{99m} are considered especially interesting as they are formed substantially population-inverted.

SCHEMATIC X-RAY LASER AND ASSOCIATED PUMPING SYSTEM

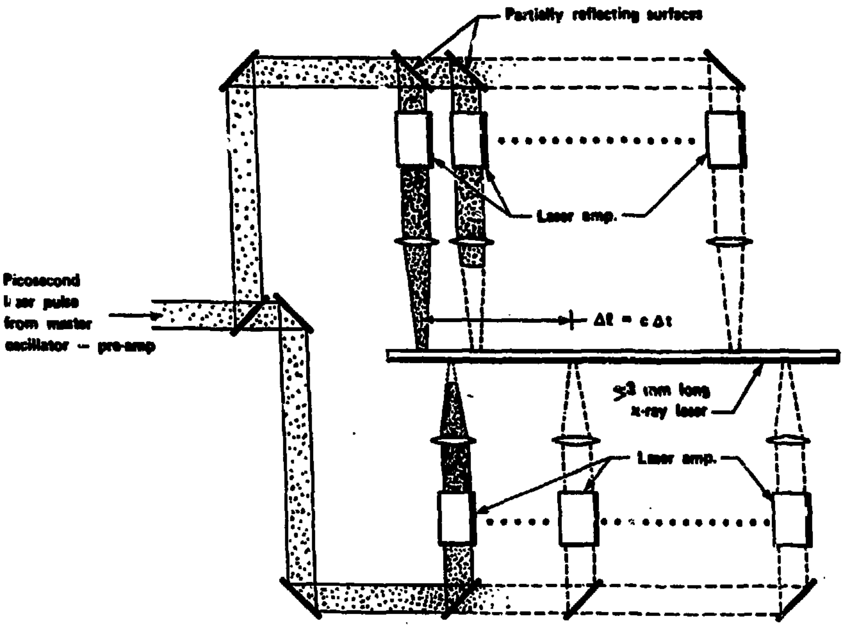
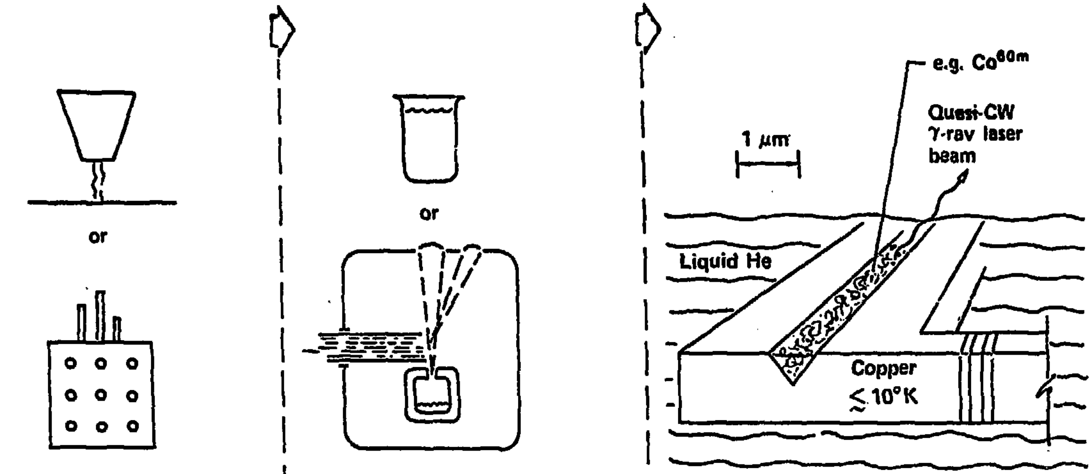


Figure 1

GENTLY PUMPED γ-RAY LASERS



Preparation of long-lived nuclear isomeric state species in particle accelerators or nuclear reactors

Rapid separation of nuclear isomers from parent and sister nuclei, e.g. via radiochemical or photophysical techniques

Purified nuclear isomeric material, deposited in microscopically homogeneous fashion in supercooled, leveled, acoustically isolated heat sink

Figure 2

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