Gamma-ray Laser: Some Notes

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During the last six decades, since their invention, lasers have become common-place in our society. These devices, producing highly directional light of a single wavelength, are important on their own and also as critical components of various systems. These energetic devices have applications in almost all fields of research and applications ranging from tailoring clothes to music to cookery to medicines and surgery to defence or even to cooling and trapping neutral atoms (Metcalf and Straten, 2007). Lasers made up of different materials can be as small as two microns and as large as a football field (the free electron laser - FEL). Their development has been characterised by a successive series of shorter-wavelength-lasers. The development of free-electron laser, first proposed by Madey in 1971, has significantly reduced laser wavelengths to sub-angstrom ranges. At the present state-of-the-art, lasers can emit radiations from infrared to hard X-ray regions. At the shortest wavelength, using an 8 GeV electron beam, scientists at SLAC (Stanford Linear Accelerator Centre) National Accelerator Laboratory at Stanford University have demonstrated the successful generation of laser light at 0.0634 nm, that is 63.4 pm (Emma, 2010) in a compact X-FEL device. The radiations produced are of wavelength four orders of magnitude smaller than the 694 nm produced by the first laser developed by Maiman in 1960.

X-FEL sources have also been used to pump the atomic X-ray lasers (also called raser) to achieve population inversion. In 2012, Rohringer N. *et al.* have demonstrated the generation of 1.46 nm soft X-ray laser radiations from an X-FEL pumped K_α transition in singly ionized neon plasma. These X-ray lasers (also called rasers), capable of generating powers as high as 10 GW (that is nearly ten orders of magnitude beyond conventional synchrotron sources) with a range of pulse durations from 500 to 10 fs; 1 fs or 1 femtosecond = 10^{-15} s. Such light sources are useful in high-resolution microscopy and are capable of imaging the structure and dynamics of particles at atomic size and time-scales. These light sources are now also known as fourth-generation light sources.

After developing excimer lasers in vacuum ultraviolet region, atomic rasers in soft X-ray region and FELs in hard X-ray region, one of the dreams of laser physicists has been the development of gamma-ray lasers (or grasers). These were first visualised more than five-decades ago (Vali and Vali, 1963; and Baldwin, 1981) and have been considered to be one of the two dozen most important and interesting problems in physics and astrophysics (Ginzburg, 1999).

Like electromagnetic radiations in microwaves to X-rays, gamma-rays differ from the photons in their wavelength, possessing wavelengths shorter than 0.05 nm (or 50 pm). According to the Einstein's formula, the probabilities of spontaneous (A) and stimulated (B) emissions at wavelength λ are connected through $\frac{A}{B} = \frac{8\pi h}{\lambda^3}$; *h* being the Planck's constant (Yariv 1967). It shows that for shorter wavelengths, spontaneous emission is a stronger competitor to stimulated emission.

It is a general feeling that, in principle, amplification by stimulated emission can be obtained up to all wavelengths, larger than 10 pm. Such radiations that lie in the 5 – 100 keV region would not emerge in atomic transitions rather would emerge through nuclear transitions (Baldwin, 1981; Gupta, 1991; and Rivlin, 2007). It is, therefore, grasers are also termed as nuclear gamma-ray lasers (NGL). The development of grasers in a laboratory, though attracting scientists for more than half a century, has been a fiction due to the absence of convincing data about their experimental reality. The flamboyant exciting proposals have been obscure in overcoming the real difficulties to be dealt with as the nuclear gamma radiations are quite different from the atomic and molecular transitions that are necessary for infrared to soft X-ray lasers.

Any optimistic attempt to develop gamma-ray lasers must consider the very different nature of physics involved in nuclear (gamma-ray) transitions that is not present in the atomic or molecular transitions needed for generating longer wavelengths used for lasers in other regions. In a two-level laser system amplification takes place primarily by the emission of a photon that has the right properties to cause the inverse transition from upper level to lower level in another atom or molecule. With the knowledge of known metastable state(s) in atomic (or molecular) systems, it is relatively easy to pump the atoms by the photons in the upper level to achieve the required population inversion. This does not happen in normal nuclear transitions. The population inversion by the photon absorption in atoms can further be eased by devising a three-level or four-level systems.

For achieving a population inversion in nuclear energy levels, the photon absorption is not a preferred mechanism. Furthermore, unlike the decay of upper level to lower level in atomic transitions is photon emission, the decay of a nuclear energy level to another level is not photon emission. The probability of photon emission in nuclear transition is often less than 10%. For example, a 14 keV nuclear transition in 57Fe does not normally take place by photon emission. Moreover, the small number of emitted photons do not generally have the proper energy to excite another nucleus. This is mainly due to the recoil of radiators that becomes appreciable at such high photon energy levels. Thus to pump the nuclei population to the upper level is not simple by photon irradiation processes (the probability to produce a nuclear transition by a photon incident on a sample is very small.) Photons are dominantly absorbed by electronic mechanism and not nuclear. It means that the probability of a photon incident on a sample to produce a nuclear transition rather than being absorbed by electronic transitions is less than one in a million.

The differences between atomic and nuclear transition mechanisms (both for absorption as well as the emission) need to be taken into account for designing a graser. It is important to critically analyse approaches for solving the conflict of increasing the probability of photon emission; for finding the ways to get the emitted photons (or gamma-rays) to have the proper energy — Mossbauer schemes to reduce nuclear recoil in deeply cooled ensembles of free nuclei, maybe Bose-Einstein condensate; and to find efficient ways of achieving population inversion in an amplifying medium of long-lived isomers. This requires a considerable effort in this interdisciplinary problem. The search is therefore of interest due to a variety of physical disciplines and experimental approaches. At shorter wavelengths, the spontaneous emission becomes a strong competitor of stimulated emission. And therefore cooperative spontaneous emission (superradiance) provides a hope for the generation of coherent gamma-rays (Baldwin, 1981).

Simple Scale Differences

There are inherent scale differences in sizes of the radiators, the wavelengths, etc. when we compare the atomic (or optical) transitions with the nuclear transitions. Let Ra and Rn denote the size of the two radiating systems, *viz.* an atom (~10^{-9} m) and a nucleus (~10^{-14} m), respectively. The symbol D represents the distance between two neighbouring radiators (the lattice constant in a crystal); typically of the order of the size of an atom. The wave number of radiations in optical laser transitions (k_a) and in nuclear laser transitions (k_n) is of the order of 10^7 and 10^{11}, respectively. Considering the radiating systems to be harmonic oscillator at zero-point (and thus requiring Bose-Einstein condensate!) and using Heisenberg uncertainty principle, the amplitude (x) of oscillations can be related for optical systems as $k_a x_a$ to be much lesser than unity while in nuclear transitions as $k_n x_n$ of the order of unity. Thus for optical laser transitions at around 100 nm

$x \ll R \sim D \ll (1/k)$.

or

$kx \ll kR \sim kD \ll 1$.

And for nuclear gamma-ray transitions at around 10 pm,

$R \ll x \sim (1/k) \ll D$

or

$kR \ll kx \sim 1/k \ll kD$.

Since $kR \ll 1$, for optical as well as nuclear transitions, the long-wavelength approximation necessary for lasing is valid (Yariv, 1967). But kD is larger than one, and kx of the order of unity for gamma-rays describes the motion of radiating nucleus in crystal lattice tends destroying the coherence (and superradiance) between the radiations emerging from different nuclei. This also tends to reduce the coherent intensity.

There are differences in the energy domains of atomic (or optical) and nuclear (or gamma-rays) domains as well. The optical radiation energies (each photon energy of few eV) are much lesser than the atomic ionization energies (E_i), while in the case of nuclear transitions the photon energies are much greater than the atomic ionization energies. That is

$$h\nu_{optical} \ll E_i \ll h\nu_{gamma}.$$

This indicates that in case of nuclear lasers, a part of the incident energy to pump the nuclei population to corresponding upper level (usually an isomeric one) would be lost by ionization processes. In optical transitions (atomic or molecular), the recoil kinetic energy of the radiating system is much lesser than the radiative linewidth of the levels involved in the lasing transitions. However, in case of gamma rays, the recoil energy is much larger than the natural (radiative and non-radiative both) linewidth and is of the same order as the thermal energy of the crystal (Lipkin, 1987).

Consequences

1. Since the recoil kinetic energy of radiating systems is negligible for optical transitions and is crucial for nuclear transitions, the photon (electromagnetic radiation) emitted in a transition between two energy levels of an isolated nucleus is not capable to induce the inverse transition between the same two levels in other nuclei. However, in case of optical transitions, the photon emitted in a transition between two energy levels of an isolated radiator (atom or molecule) has the same frequency to induce the inverse transition between the same two levels in another radiator.

2. The ratio of natural line width of a nuclear energy level to the energy of a photon emerging in a nuclear transition is much smaller than for optical case. Thus the lineshifts which become crucial in the nuclear case tend to destroy the lasing action *(radiations are no longer monochromatic!).*

3. Unlike in atomic transitions, the photon wavelength emitted in nuclear transitions (~10pm) is shorter than the distance between nearest neighbour atoms in normal matter (1 nm). It means that there will be an appreciable phase shift in the propagation of nuclear transitions between two neighbouring radiators (nuclei). This results adversely in phase coherence.

4. The phase coherence is also likely to be destroyed because the wavelengths of emitted gamma-rays are of the same order of magnitude as the amplitude of thermal or zero-point motion in normal matter (kx~1 for nuclear transitions.)

5. The emission of a photon is the most dominant mechanism for the decay of upper level to a lower level of isolated atoms or molecules. But in case of nuclear transitions, the most dominant mechanism for the decay of an upper nuclear level to a lower nuclear level in isolated nuclei is the internal conversion that is ejection of an atomic electron and not the photon emission.

6. In atomic or molecular transitions the most dominant mechanism for the absorption of photons emitted by electrons is absorption by bound electrons. These absorptions are instrumental in exciting the atoms from a lower level to a desired upper level for producing a state of population inversion in the matter. In case of nuclear transitions, the dominant absorption mechanism of the gamma-ray photons emitted by the nucleons is still the absorption by the electrons. Therefore the gamma-rays emitted in nuclear transitions cannot induce other nuclear transitions. *(The consequences given in points 5 and 6 are due to radiation-less transitions!)*

Problems in Developing a Graser

The basic problems in achieving lasing in nuclear transitions are due to the recoil shift and internal conversion. The recoil shift changes the energy of emitted gamma-rays by the nucleons in the isolated radiator (nucleus) by a large amount to the extent that the emitted photon becomes useless for the purpose of exciting the other nucleus. And thus the emitted photon lost to stimulate another nucleus necessary for the stimulated emission and the amplification. On the other hand, the internal conversion takes most of the energy of emitted photon for further absorption. In addition to these two problems, the fact that the gamma-ray wavelengths are short compared to the interatomic spacing (lattice constant of a crystal) which destroys the phenomenon of super radiance necessary for coherence in the nuclear case.

Any radiator that emits a photon must recoil with a momentum equal and opposite to the photon momentum. This recoil brings a change in the energy of the photon which is known as recoil shift. This recoil shift is negligible in case of optical transitions but for nuclear transitions, the recoil shift is often larger than the natural width of the nuclear energy levels, as noted earlier. This loss in the energy of emitted photons may be minimized by using the Mossbauer effect, in which the atom making the transition (nuclear) is bound in a crystal and the recoil momentum is distributed in all radiators present in the whole crystal with negligible energy loss. This, however, depends on the energy of gamma-ray, temperature and crystal properties. These conditions heavily restrict the choice of medium in which graser transitions can be obtained.

As noted earlier that the energy of a nuclear transition is much greater than the ionization energy of the atom, it is, therefore, possible for the transition between two nuclear levels to take place with the energy emitted by ejecting an atomic electron (internal conversion) rather than in the form of a photon. In fact, in 57Fe nuclei, the probability of ejection of the atomic electron rather than a photon is only about 10%. The energy loss due to the internal conversion may only be eliminated by using the Bormann effect (or superradiance). It explains an anomalous increase in the intensity of X-rays (and possibly the radiations for the interest of grasers) through a perfect crystal when the electric field of the radiations approaches to zero amplitude at the crystal planes to minimize the absorption by the atoms (or to minimize the energy loss due to internal conversion).

In view of the exploitation of both the Mossbauer and Bormann effects in a crystal for graser medium, almost all nuclei have been searched for potential candidates for developing a graser but this needs further technological advancements in nuclear spectroscopy.

There is another problem with the pumping transitions. The radiations that are to be used to pump the nuclear population to an upper level must have higher energy than the lasing transition. The pumping then may populate the levels, *pumping levels*, higher to the upper level. Then there must be a radiation cascade from such pumping levels to the upper level. Thus creating a population inversion in the upper nuclear level in a sample is similar to *funnelling*. This upper level will then lase into the lower level. Yet the probability of absorbing photons by the desired nuclear transition (nuclear cross-sections) are much smaller than the probabilities for the photoelectric and Compton effects. In typical cases, it is as small as 10^{-8}. This indicates that there could be an enormous waste of energy in the pumping process. This would necessarily require an efficient mechanism for disposing of this waste without excessively heating the sample. The funnelling of upper level from the higher pumping energy levels may also heat the sample. The Mossbauer and Bormann effects are very sensitive to the temperature and any excessive heat can destroy these effects. In this situation, one may envisage an isomeric storage level — that may have lifetimes as large as few days or more. Such storage levels need to be very close to the upper level that can lead to giving the desired graser output by decaying to a suitable lower level so that only a little amount of energy would be needed to create a population inversion without bringing any crystal defects that can destroy the Mossbauer and Bormann effects. However, no isomers having such properties are known.

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