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PHYSICAL PROBLEMS OF X-RAY LASER, (U)

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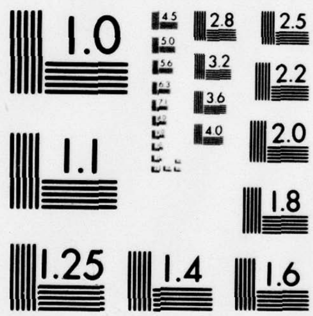
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PHYSICAL PROBLEMS OF X-RAY LASER

by

Shen Ko

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FTD -ID(RS)T-0635-79

EDITED TRANSLATION

FTD-ID(RS)T-0635-79 5 June 1979

MICROFICHE NR: FTD-79-C-000743

PHYSICAL PROBLEMS OF X-RAY LASER

By: Shen Ko

English pages: 48

Source: Chi Kvang, Number 1 and 2, 1978, pages 46-55; 56-63.

Country of origin: China
Translated by: Linguistics Systems, Inc.
F33657-78-D-0618
H. P. Lee
Requester: FTD/TQTD
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Physical Problems of X-ray Laser

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Evidently, in the 1960's soon after the discovery of laser, the study of making X-ray wave band laser has been started.[1,2] From that time on and up to date, the mechanism of X-ray laser has been, in theory, tensely and enthusiastically investigated. In recent years, experiments in this field have developed progressively. Although there has not yet been any impressive result, in theory, however, it has become possible that various specific plans concerning laser can be successfully turned into reality. And in experiment, stimulated radiation with wave length close to more than 100 angstroms has been made. As research on X-ray laser has become a more active field in laser physics, this article tries, from the viewpoint of laser physics, to review the progress that has so far been made by researchers in the field.

1. Basic Characteristics

To begin with theories, we want to try to analysize and predict all possible characteristics of using atomic inner shell electron transition X-ray laser to compare with the already known light wave band laser.

1. When entering X-ray wave band, the stimulated radiation cross-section of atom is very large. For instance, the stimulated raditation cross-section at the center of K_{a1} spectral line of copper ($\lambda = 1.54$A) is

three or four quantity levels larger than the stimulated radiation cross-section of neodymium glass with spectral line of 1.06 micron[3]. Therefore, so long as the inverse distribution of atomic inner shell electron is there, there will be great increase of X-ray laser, and this is certainly very fascinating.

2. But as we known, to a given increase coefficient, the power density of outside stimulation source is in inverse ratio to a quartic equation of laser wave length[4,5]. So to enter X-ray wave band for establishing particle number inverse distribution and having necessary increase, the stimulation source is required to have considerably high radiation power density. For instance, in order to have laser of $\lambda = 100\text{Å}$, it requires that the radiation power density of stimulation source is about 10^9 watt/cm^3; for laser of $\lambda = 10\text{Å}$, it is about 10^{13} watt/cm^3; and for laser of $\lambda = 1\text{Å}$, it is about 10^{17} watt/cm^3. Moreover, because atomic inner shell electron lacks metastable state the life of stimulating state is generally rather short. For instance, the life of high energy level corresponding to K_{a1} spectral line of copper atom is $\tau \sim 4.5 \times 10^{-15}$ second. Therefore, for stimulated radiation of outside stimulation source, it requires to have a very short leading edge time. For making atomic inner shell electron able to establish particle number inverse distribution and having a definite increase, if it uses radiation stimulation form, it requires stimulated radiation to have a very short leading edge time and very high power density simultaneously.

3. The radiationless transition of atomic inner shell electron is to

make atom have once more ionization and not a simple reduction of energy. It is different from radiationless transition in light wave band, and here exist Auger effect and Coster-Kronig effect. We now try to analysize the advantages and disadvantages of radiationless transition in X-ray laser.

If high operation energy level has large Auger width, there will be two harmful effects[6]. One is that the value of stimulated radiation cross-section σ_S will be lowered and this can be seen in the following equation:

$$\sigma_s = \frac{\lambda^2}{4\pi^2} \cdot \frac{A}{\Delta\nu} = \frac{\lambda^2 \Gamma_R}{2\pi(\Gamma_1 + \Gamma_2)} \qquad (1)$$

In the equation, λ is transition wave length, A is radiation transtion speed $(A = \Gamma_R/\hbar)$, $\Delta\nu$ is natural width $(\Delta\nu = (\Gamma_1 + \Gamma_2)/h)$, Γ_2 and Γ_1 respectively represent the total width of high and low operation energy level. The other is that for maintaining a definite vacancy number at the high operation energy level, it will surely lead to have a large pump. At high operation energy level, the change of inner shell vacancy number density N following the change of time t is:

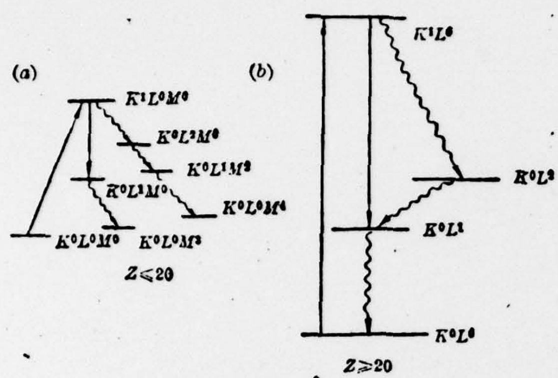
$$\frac{dN}{dt} = P - N\Gamma/\hbar$$

In the equation, P is the pump item, Γ is the total width of operation energy level , and from above equation, we have:

$$N = \hbar \frac{P}{\Gamma}(1 - e^{-\Gamma t/\hbar}) \qquad (2)$$

Obviously, it requires P following Γ to have linear increase.

However, there is also a useful aspect. Auger transition can make the terminating state selectively gather vacancy number, so Auger transition can produce particle number inverse distribution.



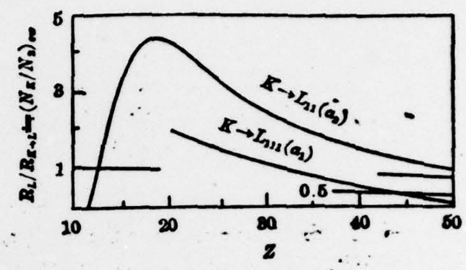


Figure 1 In the Figure, straight lines indicate radiation process, wave lines indicate radiationless process. Vacancy number is used to indicate state

Figure 2

Besides, the existence of Auger effect will limit the empoyment of some stimulation forms. For instance, to K_{a1} spectral line, generally the high operation energy level of $Z \lesssim 20$ atom has serial Auger decay, as indicated in Figure 1 (a). Consequently a movement awa' from the laser wave length takes place and the value of the movement at leas. is the natural width of K_{a1} spectral line, so the working substances made of them have no resonance absorption. But to the high operation energy level of $Z \gtrsim 20$ atom, they, through Auger decay, will be very effectively filled at low operation energy level, as indicated in Figure 1 (b). In this kind of working substances, resonance absorption will be therefore produced so as to make them difficult to reach threshold value. Evidently it will be hardly possible for $Z \gtrsim 20$ atom to use photo-ionization pump to make X-ray laser revolve[7].

4. As atomic inner shell electrons lack metastable energy level, the life of their high energy state is shorter than that of low energy state. Thus X-ray laser seems to have to belong to a type of self-terminating laser and uses pulse as a means to revolve. But people have known that the great Auger transtion rate of K_{a1}, K_{a2} specrtal lines of some atoms and the result of their producing X-ray laser have made atomic L shell enter a state of two vacancy numbers as if the original state has been removed. X-ray laser of this kind has the possibility to revolve continuously[8]. However, it is different from the condition of continuous revolving of the already known light wave band lasre. The condition that makes X-ray laser revolve continuously can be expressed as[9]:

$$\frac{\tau_{u\to l}}{\tau_l} > \frac{g_u}{g_l} \qquad (3)$$

In the equation, $\tau_{u\to l}$ is the life when inner shell electron transit from high operation energy level u to low operation energy level l, τ_l is the life of low operation energy level, g_u and g_l are the statistical weight of high and low operation energy levels. From Figure 2, it can be seen[10] that spectral lines K_{a1} and K_{a2} within the large range of Z can both possibly make continuous revolving. In Figure 2, the ratio of the total transition speed R_L of vacancy state L to the radiation decay speed $R_{K\to L}$ of vacancy state K, in stable state, can satisfy relationship: $\tau_{u\to l}/\tau_l = R_L/R_{K\to L} = N_K/N_L$. N_k and N_L are vacancy numbers of K and L shell.

What must be pointed out is that the impact of the powerful collision of Auger electron produced from the process of Auger transition upon laser process has been neglected in discussions here. In the second part of this article, we will discuss it. If we take it up now, the result of our present analysis will be otherwise.

5. Compared with already known light wave band, X-ray has very large spectral width. This is because even the ion which emits X-ray is not under any impact of its environment, and because there is radiationless transition, the width of X-ray spectral line is rather great. When X-ray laser working substance is stimulated, because of using very high power density, the heat and massive plasma can be formed. Thus Doppler width caused by ionic heat movement, Stak (Stark?) width of the quasi-static ion field, electron collision width, ionic collision width and width made by plasma turbulence must all be taken into account.

The natural width of X-ray spectral line is:

$$\Delta\nu_N = \frac{1}{\pi\tau_r\omega_r} \qquad (4)$$

In the equation, τ_r is the life of radiation, ω_r is X-ray fluorescent yield. For instance, for K_{a1} spectral line of sulphur (Z = 16), $\Delta\nu_N \sim 10^{14}$ hertz.

Doppler width is:

$$\Delta\nu_D = (2.3\times10^6/\lambda)(T_i/A_i)^{1/2} \qquad (5)$$

In the equation, λ is X-ray wave length and its unit is cm., T_i is ion temperature and its unit is electron volt. A_i is ion mass and its unit is atom mass unit. For instance, of K_{a1} spectral line of sulphur, $\lambda = 5.37 Å$, $A_i = 32$ because ion temperature during particle number inversion is lower than electron temperature T_e. Generally, $T_e \approx 100$ electron volt. Compared with $\Delta\nu_N$, $\Delta\nu_D$ can be overlooked here.

The width of X-ray spectral line caused by Stark effect: To inner shell electron transition and Stark width caused by quasi static ion filed is not linear. And at the same time, the screen effect of outer shell electron should be considered and its quantity level is[11]:

$$\Delta\nu_s \sim 3\times10^{-17}\frac{n_u^6}{S_e^4}Z_i^2\left(1-\frac{N_{e0}}{S_e}\right)^2 N_i^{4/3} \quad (6)$$

In the equation, n_u is the master quantum number, S_e is Steinheimer screen factor, Z_i and N_i are ionic charge and ionic density and N_{eo} is the number of outer shell screen electron. For sulphur of $Z_i = 1$ and $S_e = 10$, when it is of solid density, $\Delta\nu_s \sim 7\times10^9$ hertz.

Electron collision width is:

$$\Delta\nu_{ce} \sim 2.2\times10^{-8}\frac{n_u^4}{T_e^{1/2}S_e}\cdot\left(1-\frac{N_{e0}}{S_e}\right)^2 N_e \quad (7)$$

In the equation, N_e is electron density. For sulphur when $T_e = 100$ electron-volt and other parametres are same as above, $\Delta\nu_{ce} \sim 3\times10^{11}$ hertz.

From a comparison of the above four kinds of width, it can be seen that when photo-ionization is used to pump sulphur X-ray laser, for calculating increase, and discussing threshold value and characteristics of revolving, the suitable width is natural width.

When a collision of ion-ion is stimulated, there is an ion collision width, which approxiates:

$$\Delta\nu_{ci} \sim 10^{-6} \frac{n_u^2}{S_e^2 (V_i/A_i)^{1/2}} Z_i^2 \left(1 - \frac{N_{e0}}{S_e}\right)^2 N_i \quad (8)$$

In the equation, V_i is the relative speed of ion.

The width caused by plasma turbulence is:

$$\Delta\nu_T \sim 3.8 \times 10^{-10} \frac{n_u^6}{S_e^4} Z_i \left(1 - \frac{N_{e0}}{S_e}\right) T_e N_i \quad (9)$$

6. The vantage point in propagation loss of X-ray laser is nonresonance absorption. It includes photoionization loss, mono-photon absorption and losses caused by coherent and incoherent scattering. Among these losses, photo-ionization loss is the most serious when density is high. The cross-section of photo-ionization is[11]:

$$\sigma_{PI}(\lambda, Z_i) = \sum_{n,e} N_e(n, l) \sigma_{PI,i}(\lambda, n, l) \quad (10)$$

In the equation, $\sigma_{PI,i}$ is the partial cross-section of each electron in the assigned n and l shells and N_e is the number of electron in each shell. A simple estimation is:

$$\sigma_{PI,i} \sim 2.4 \times 10^{-27} Z_e^5 n^{-7} \lambda^{7/2} \quad (11)$$

It is almost like a ratio change of a cubic equation of laser wave length. So when there is no resonance absorption, the quantity level of monochromatic absorption coefficient is:

$$K_\nu(\mathrm{cm}^{-1}) \sim N_i \sigma_{PI} \quad (12)$$

Of course, only when increase is larger than loss, X-ray laser amplification can happen.

7. Although it has been well known that some metal films have rather high reflectivity to X-ray[12], the refractivity of most materials to X-ray is close to 1. If this is used to form X-ray resonant cavity, an optical system with a reflection angle close to 90° must be established, and this will result in a ring resonant cavity composed of a number of reflective mirrors made of metal films. At the present time, what is discussed most frequently is the Bragg diffraction phenomenon made by using X-ray on a crystal body and ring resonant cavity made of many plane reflective mirrors made of perfect crystal slices[13-15] and the output can be helped by Borrman effect[16]. These two kinds of ring resonant cavities only allow X-ray laser to pass through the cavity a few times. The life of photon is very short and the quality factor is low, so it is of no help to lower threshold value. At the same time, in adjustment and application, difficulties remain. The distribution feedback crystal resonant cavity[17], the wave conduction resonant cavity[18] and resonant cavity directly using Borrman effect[19], mentioned recently, have difficulties and problems in techniques and pump. So people think that the first X-ray laser will be a spontaneous radiation amplifier[9,20] and its output will be spontaneously radiated and amplified X-ray.

We have made a general review of the stimulated radiation cross-section when atomic inner shell electron transition radiates X-ray, radiationless transition, spectral width, propagation loss, resonant cavity structure and the strict requirements for stimulation source because of the lack of metastable energy level. Although these characteristics need further experiments to prove them, one thing, however, is clear that all these are different from the laser which has been known.

2. Proposition of Principles

In order to realize the stimulated radiation of X-ray, in recent years, many significant assumptions based on theories have been made by people in field, they, in summary, primarily concentrate on the follwoing two aspects.

(1) Proposals on Inner Shell

The proposals on inner shell aim at using inner shell transition of atom or ion to produce X-ray laser. Inner shell transition means that when the larger master quantum number shell of atom or ion contains at least one electron, transition takes place in the vacancy produced in closed shell (namely all of n tracks are filled with electron). This requires that the energy of pump source must concentrate in between some fixed energy bands and selectively remove the electrons from inner shell. This is much more complicated than the situation of atomic valence electron optical transition. Today there is some one who has suggested to use photon collision, ion collision and electron collision to produce inner shell vacancy.

1. X-ray Ionization Pump

The suggestion to use X-ray laser of X-ray ionization pump is made on the ground that the cross-section of atomic photoionization has a definite relationship with photon energy of X-ray used for stimulation. When the X-ray energy at the edge of absorption band is sufficient to ionize the atomic inner shell electron, the cross-section of inner shell electron removed away through photoionization is several quantity levels larger than the electron removed from outer shell. As a result, the distribution of atomic inner shell electron will directly enter a state of particle number inverse distribution. Up to now, three specific ways have been suggested.

First Suggestion: Under X-ray ionization pump, particle number inversion is directly formed in atomic inner shell, [2,3,9,21] and we can estimate the pump power of X-ray laser of this type. For cavityless amplification system, we can define a threshold value length l_t, and on this length, in a solid angle omega (Ω), photon number of the amplified model is larger than that of other models. At the end of l_t, still there is atomic stimulated radiation photon. If a working substance appears to be in the shape of a rod, and its diameter is d, for avoiding diffraction loss, the geometrical shape of the rod must be able to warrant Fresnel number, $N_F = d^2/l_t\lambda > 1$.

The condition of threshold value is:

$$\exp(\beta l_t) \geqslant \frac{4\pi}{\Omega} \qquad (13)$$

In the equation, the approximation of the solid angle omega is:

$$\Omega \sim \left(\frac{d}{l_t}\right)^2 \qquad (14)$$

The increase on unit length β is:

$$\beta = \sigma_s \Delta N - \sigma_a N_T \qquad (15)$$

In the equation, σ_s and σ_a are stimulated radiation cross-section and absorption cross-section, particle number inversion density, $\Delta N = N_u - (g_u/g_l) N_l$, N_T is the particle number total density of working substance. For having a positive increase, it requires:

$$\sigma_s \Delta N > \sigma_a N_T \qquad (16)$$

By combining equation (13) and (15), the vacancy density N_u^* of high operation energy level can be solved when it is of threshold value. For having power density necessary for producing laser action is $N_u^* \hbar\omega_p / \tau_u$. When the situation of K shell is supposed to be brought into discussion, $\hbar\omega_p$ is the energy at the edge of K absorption band, and τ_u is the life of K shell vacancy. The depth of X-ray penetrating working substance used for stimulation is $1/\sigma_T N_T$, σ_T is the total absorption cross-section at the edge of K absorption band. Thus, when it is of threshold value, the necessary pump power flow ϕ is:

$$\phi = \frac{N_u^* \hbar\omega_p}{\tau_u} \cdot \frac{1}{\sigma_T N_T} \cdot \frac{\sigma_T}{\sigma_p} \qquad (17)$$

In the equation, $\sigma_p < \sigma_T$, is the absorption cross-section of K energy level at frequency ω_p. When it is of threshold value, the total pump power is:

$$P = d l_t \phi \qquad (18)$$

We take sulphur (Z = 16) as working substance, for the transited X-ray at K $\rightarrow L_{III}$, $\hbar\omega = 2.31$ kilo electronvolt, the total decay speed of K shell $r^t_k = 0.57$ electronvolt, $\sigma_a = 567.6 \times 10^{-20}$ cm^2, $\sigma_e = 1.445 \times 10^{-20}$ cm^2, $\sigma_p = 10.66 \times 10^{-20}$ cm^2, and the lowest particle number inversion density $\Delta N_{min} = 0.369 \times 10^{20}$ cm^{-3}. If we take mid-value, such as taking one that is two times of the lowest particle number inversion density, then from equation (15), we can have at this time $\beta = 209.5$ cm^{-1}. If d = 10 micron, then from equation (13) and (14), ℓ_t = 490 micron. From equation (17) and (18), finally we have $\phi = 2.1 \times 10^{16}$ W/cm^2, $P = 1.02 \times 10^{12}$ watt. In experiments, such great X-ray power flow used for stimulation can be obtained by using the X-ray transformed at the high Z target from the laser radiation of an already known light wave band laser (such as neodymium glass laser). If this transformation efficiency is 30% and the efficiency of coupling X-ray radiation with working substance is 40%, it then requires a neodymium glass laser with a power flow of 5×10^{17} watt/cm^2, and also because the area of pump flow action is $l_t d \approx 10 \times 490$ micromicron^2, the neodymium glass laser is required to be able to output power of 2.5×10^{13} watt. It has no difficult now to have a neodymium glass laser with such high power.

In the discussions made above, we have overlooked the process of electron collision. In fact, of low Z working substance, such as sulphur, the fluorescent yield is low, so a very large part of the pump power is consumed on the free electron produced in the process of Auger transition. These powerful electrons during the initial stage of pumping process have made collision-ionization with atomic outer shell electron. In about 10^{-15} second, there is an increase of one average ionization. So this kind of collision process will limit the life time of ion of any specific ionization. According to an estimation[7], the threshold value of pump power is basically close to the value when electron collision process is overlooked. However, in the increase of life time, the two situations are different. As indicated in Figure 3, when the lectron collision is considered, the increase of life time will be shortened. If the continuing time of particle number inversion is no more than 10^{-14}second, the result obtained will be different from the fourth point in the first section of this article.

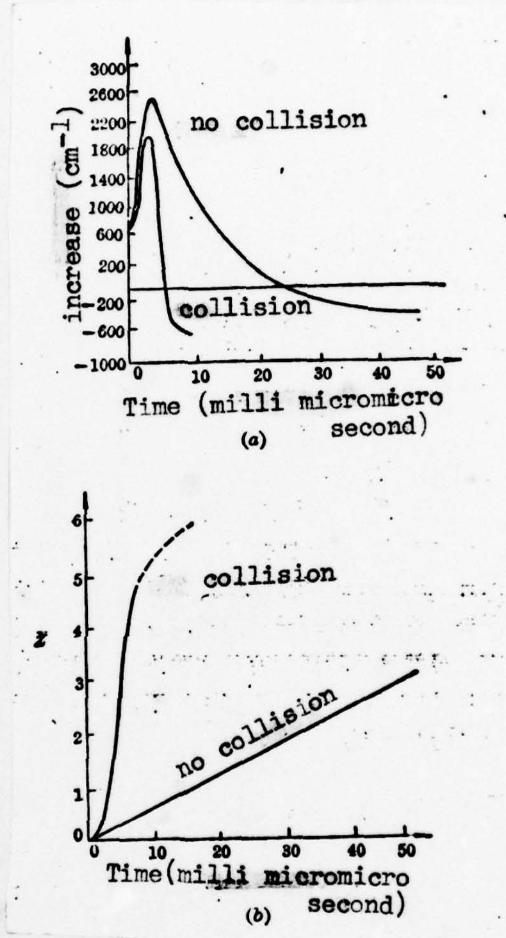


Figure 3

Second Suggestion: In the process of photoionization pumping, particle number inversion is formed through Auger decay. Taking Na for example, the neutral natrium atom under photoionization pumping will directly ionize L shell electron and directly form vacancies on L shell and then makes particle number inverse distribution between 3S - 2P (λ = 372A). These problems have been discussed in some original works[2]. Here we try to study another way of forming Na L vacancy. Na^+ which, undre photoionization pumping,has K vacancy, will produce double-vacancy on L shell because of the happening of K - LL Auger decay, and then form particle number inversion between 2P $\rightarrow$ 2S.

We can estimate the pump power of threshold value. The speed equation of particle number change of high operation energy level i is:

$$\frac{dN_i}{dt}=b_i\frac{dN_k}{dt}+\sum_j\frac{N_j}{\tau_{ij}}-\frac{N_i}{\tau_i} \quad (19)$$

In the equation, b_i is branch ratio, τ_{ij} is the inverted number of radiation transition speed from energy level j to i, τ_i is the life time of energy level i. If the energy sent forth by a known light wave band laser is Q, a laser pulse of which the pulse width is τ_L, through hard X-ray produced by a transducer of which the length is L and thickness is d, to pump Na, the speed of producing K shell vacancy is:

$$\frac{dN_k}{dt}=\eta\frac{Q}{\tau_L l d\bar{E}_k}N_{Na}\sigma_{Na} \quad (20)$$

In the equation, $\bar{E}_k$ is the average energy of hard X-ray used as pump, σ_{na} is the photoionization cross-section of K shell at $\bar{E}_k$, N_{Na} is particle density of Na, η is total transforming efficiency including transforming, penetrating and beam-splitting of hard X-ray made by laser pulse which strikes on the transducer.

There is condition of positive increase in equation (16), and the particle number inversion density at L shell is f times of the density produce by K vacancy. Combining equation (20) with (16) and considering equation (1), then when it is of threshold value, it is:

$$\frac{\lambda^2 \Gamma_1}{2\pi(\Gamma_1+\Gamma_2)} f\eta \frac{Q}{\tau_L l d \bar{E}_k} \tau_s > \frac{\sigma_s}{\sigma_{Na}} \cdot \frac{N}{N_{Na}} \tag{21}$$

In the equation, N is particle number density of material which contains Na, τ_S is the life of L shell with double-vacancy. Through solving equation (19), we have $f=0.02$[6]. If $\eta=10^{-3}$, $\lambda=375$ Å, $\Gamma_2 \ll \Gamma_1$, $\tau_s=2.5\times10^{-9}$ sec., $ld=10^{-3}$ cm^2, $\bar{E}_k=1.5$ Kev, $\sigma_s=6\times10^{-18}$ cm^2, $\sigma_{Na}\approx10^{-19}$ cm^2, then from equation (21), we have that light wave band laser sends out laser of $Q/\tau_L >$ 3×10^{11} watt.

Third Suggestion: The united pump of photo-stimulation and X-ray ionization[22]. Before producing inner shell vacancy, to use photo-frequency to stimulate atomic outer shell electron to reach a long-life stimulating state, then to use X-ray to ionize inner shell to produce vacancy, and finally particle number inversion is formed in inner shell electron, as indicated in Figure 4.

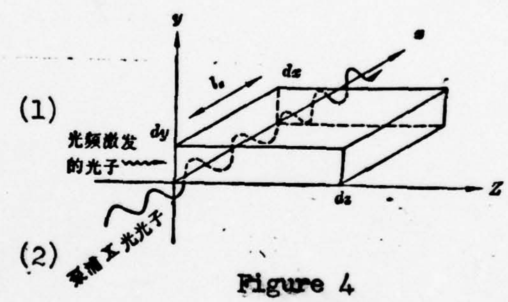


Figure 4

(1) Photo-frequency stimulated photon
(2) Pump X-ray photon

Taking Li for example, through photo-stimulation, Li atom can be made from base state $1S^2 2S$ to stimulating state $1S^2 3P$, then using X-ray of which the energy is approximately 66-70 electronvolt to ionize it and make it produce one vacancy at K shell and enter 1S3P state. Thus the impact of Auger effect can be eliminated.

If the pulse width of pump X-ray is τ_X, and its strength is the step function of time, then the number of X-ray photon attracted to the unit volume of working substance in a unit time will be $N_s(dx\,dy\,dz\,\tau_s)^{-1}$. The change of neutral Li atom following the change of time is:

$$\frac{dN_s}{dt}=\frac{N_s}{dx\,dy\,dz\,\tau_s}N_s\bar{\sigma}_{ps}l_s \qquad (22)$$

In the equation, $\bar{\sigma}_{ps}$ is cross-section of X-ray ionization, l_s is the depth of pump X-ray penetrating into working substance. By solving the above equation, we can have:

$$N_s(t)=N_s(t=0)\exp\left(-\frac{N_s\bar{\sigma}_{ps}l_s}{dx\,dy\,dz\,\tau_s}t\right) (23)$$

Lithium has $\bar{\sigma}_{ps}\simeq 6\times 10^{-18}\ cm^{2}$. If we select working substance which has $dx=2.5\times 10^{-3}$ cm, $dy=4.56\times 10^{-4}$ cm, $l_s\approx dx$, then take d_z larger than coherent length, $dz\approx 0.3$ cm. The particle number density of Li is $10^{18}cm^{-3}$, and when Li ion number, in 1S3P state, is $10^{10}cm^{-3}$, from equation (23), we can have pump X-ray photon of $N_s\sim 10^{10}$ fall on working substance within a period of $t=\tau_s$. Today X-ray photon emitted from synchrotron-circular accelerator-radiating body has already reached this stage [21,22].

Our above discussions focus on three different kinds of X-ray laser of X-ray ionization pump and respectively take sulphur, natrium and lithium three working substances for example and brieflt estimate their threshold value pump power.

2. Ion-atom Collision Stimulation

Due to ion-atom collision, the physical process produced selectively from inner shell vacancy is that during the collision at the intersection of potential energy curves which is instantly made of double-atom and quasi-molecule, according to Pauli exclusion principle, there must be one or more electron emission, and individual atoms are thereby in inner shell stimulated state.

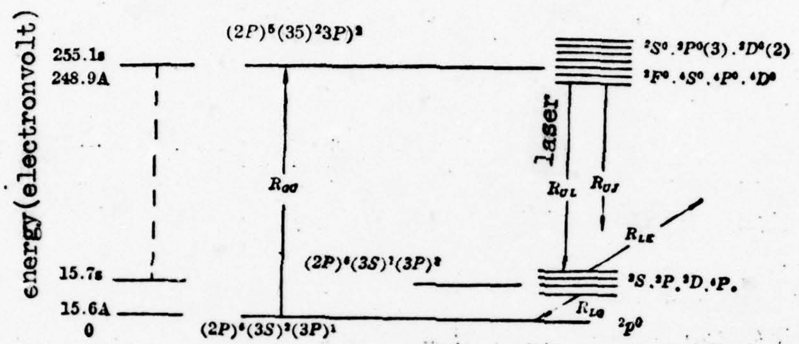


Figure 5

The structure of an ideal article-working substance would be made of an accelerated heavy ion beam and thin foil, and , in addition, there is also a proper pulse electric field. Thus the ion beam can thread its way along the longitudinal direction of the foil piece with a speed close to light velocity to attack it. While the ion is attacking the atom of the foil piece, between the inner shell energy levels of ion, atom or both, appears particle number inversion. When the X-ray produced by electron transition of high operation energy level at the point of beginning attack is passing along the longitudinal direction of the foil and comes across the inversely distributed particle formed by ion beam, it is then amplified coherently.

The elements that adequately coordinate with fiol piece and ion beam can produce X-ray laser of different wave length [23].

Because this plan of resonance collision stimulation is related to travelling wave stimulation, it can avoid the difficulty of short life of high operation energy level which can occur photoionization pump. So the article can continue to revolve.

Now taking Ar^{+5} for example, the related energy level of Ar^{+5} is what as shown in Figure 5. Using ion of medium energy to collide with Ar atom can make it become Ar^{+5} ion of which the base state is $(2P)^6(3S)^2(3P)^1$. Because of the collision of ion-ion, the $(2P)^6$ electron of Ar^{+5} can be stimulated to 3P state. When Ar^{+5} transits from $(2P)^5(3S)^2(3P)^2 \rightarrow (2P)^6(3S)^1(3P)^2$, it radiates X-ray laser. The electron which has transited to $(3P)^2$, due to Coster-Kronig effect, will radiationlessly transit to 3S. The speed of this transition is very great so the low operation energy level will be rapidly exhausted.

The threshold value condition can be expressed as:

$$N_u - \frac{g_u}{g_l} N_L \geqslant (K+1)/L\sigma, \quad (24)$$

In the equation, N_u and N_L are particle number density of high and low operation energy levels, K is absorption loss, L is the length of working substance. The threshold value can be discussed through speed process. From Figure 5, it can be seen that its speed equation is:

$$\frac{dN_u}{dt} = R_{Gu}N_G - R_{uL}N_u - \sum_j R_{uj}N_u$$
$$\frac{dN_L}{dt} = R_{uL}N_u - R_{LG}N_L - \sum_k R_{Lk}N_L \quad (25)$$

In the equation, N_G is particle number density in base state. R_{Gu} is the speed by which the particle from base state is stimulated to high energy level through ion-ion collision stimulation. It is basically determined by inner shell vacancy stimulating speed t_{ii}^{*-1}, namely

$$R_{Gu} \sim t_{ii}^{*-1} \sim 2.85 \times 10^{11} \text{秒}^{-1} \quad (26)$$

R_{uL} is the transition speed by which particles produce laser, and it is mainly determined by the stimulated radiation time $t_{s,uL}^{-1}$,

$$R_{uL} \sim t_{s,uL}^{-1} \sim 3 \times 10^{11} \text{秒}^{-1} \quad (27)$$

R_{uj} is the speed of high operation energy level particle number decay, and it is determined by radiationless transition speed t_{Au}^{-1} caused by Auger effect or Coster-Kronig effect,

$$\sum_j R_{uj} \sim t_{Au}^{-1} \sim 0.9 \times 10^{13} \text{秒}^{-1} \quad (28)$$

R_{LG} is the speed of returning from low operation energy level to base state and it is determined by radiationless transition speed $t_{Au}^{-1} = (\omega_L t_{r \cdot LG})^{-1}$,

$$R_{LG} \sim (\omega_L \times t_{r \cdot LG})^{-1}$$
$$\sim (\omega_L \times 1.52 \times 10^{-10})^{-1} \text{秒}^{-1} \quad (29)$$

In the equation, $t_{r \cdot LG}^{-1}$ is radiation transition speed, ω_L is fluorescent yield. ΣR_{Lk} is the speed by which particles at low operation energy level are stimualted to other high energy level, and it is mainly determined by the speed by which particles are stimulated to being in other state by atom-ion collision.

$$\sum_k R_{Lk} \sim t_{ei}^{*-1} \sim (7.2\times10^{-13})^{-1}\text{秒}^{-1} \quad (30)$$

Quantity levels listed in equation (26) ~ (30) all refer to Ar^{+5} ion. It can be seen through a comparison:

$$\begin{aligned}&\sum_j R_{uj} \gg R_{uL}\\&\sum_k R_{Lk} \gg R_{LG}\end{aligned} \quad (31)$$

But R_{Gu} can be substituted by the relative speed v_{ir} of ion, ion-ion collision cross-section σ_{ii}^{*} and base state ion number density N_G can be expressed as:

$$R_{Gu} = N_G \sigma_{ii}^{*} v_{ir} \quad (32)$$

When equation (31) and (32) are put into consideration, the speed equation (25) can be simplified as:

$$\begin{aligned}\frac{dN_u}{dt} &= N_G(N_G\sigma_{ii}^{*}v_{ir}) - \frac{N_u}{t_{Au}}\\ \frac{dN_L}{dt} &= \frac{N_u}{t_{s.uL}} - \frac{N_L}{t_{ei}^{*}}\end{aligned} \quad (33)$$

Particle number inversion density in balanced state is:

$$\Delta N = N_u - N_L \simeq N_G^2 \sigma_{ii}^{*} v_{ir} t_{Au} \quad (34)$$

Combining with equation (24), the specific form of threshold value condition will be:

$$N_G^2 \sigma_{ii}^{*} v_{ir} t_{Au} \geqslant (1+KL)/\sigma_{sL} \quad (35)$$

In such process, it is assumed that $g_u = g_L$.

Viewed from current ion beam technology, it is not possible to produce large enough light increase until we have an ion current which is, in energy, one-hundred times larger than what is available presently.

3. Electron Collision Stimulation

From the collision of laser plasma electron and inner shell electron, vacancy is selectively formed in inner shell. Let us examine the three energy level system as illustrated in Figure 6 [24]. We assume that energy level 1 and 2 are two inner shells which are fully filled with electron and level 3 represents all energy levels above level 2. Among these energy levels, some are fully filled with electron and some not. Using laser plasma electron collision, between energy levels of 1 → 3 and 2 → 3, there are double pumpings and in the transition from level 1 to level 2, there is X-ray laser radiated. For having particle number inversion between energy level 2 and 1, there must be rapid transition between level 3 → 2. This can be realized through Auger transition, so the threshold value power is relatively low.

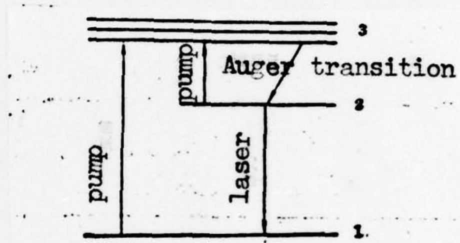


Figure 6

This is but an assumption in principle, so far there has been no specific working substance atom pointed out, and at the same time, the energy distribution of free electron is broad. In the stimulation process, the electron effect outside atomic inner shell should be definitely taken into account.

(2) In the following we shall discuss the X-ray laser which does not directly use atomic inner shell electron transition.

1. Plasma-electron Collision Produced From Laser

Using the action of high power laser and solid target, and the tunnel effect caused by laser electric field on the target will lift valency electron to conduction band to form electron plasma with solid density. These electrons at the intervals of collisions with original inner shell electron of the target and under laser electric field effect begin to store energy and form electron plasma of high energy. Then these electron plasma clash with the inner shell electron of the target and make it completely ionized. During these processes, electron states above 2P in the plasma of such high density, because of Auger effect, are expanded and overlay each other in the shape like a band. Electrons gether themselves in 2P state of lowest energy and 1S state is not expanded so it is close to electron vacuum. From an estimation of time process in the following, it can be seen that all these processes are shorter than the time of Auger transition, so particle number inverse distribution is formed between 2P-1S [25].

Now let us try to estimate the time required for completing the processes mentioned above. We first estimate the time of forming electron plasma, and it is the time required for lifting valency electron in solid body from valency band to the tunnel of conduction band.[26]

$$t = \left(\frac{2mE_g}{eE}\right)^{1/2} \qquad (36)$$

In the equation, E_g is forbidden band width, E is additional laser electric field. If laser power is 10^{12} watt, focus light spot area is 30 micron^2, and the corresponding electric field stength is $E \sim 10^9$ volt/cm, then from equation (36), we know the time of this process is about 10^{-17} second. Next we estimate the time for electron plasma to store energy. Under the action of laser electric field, the energy of electron plasma is:[27]

$$\varepsilon = \frac{e^2E^2}{2m}\omega \qquad (37)$$

In the equation, ω is laser circle frequency. When laser power is what as mentioned above, this energy is about 10^3 electronvolt. Through collision, this energy can only ionize Be of low Z or inner shell electron of C target. The time needed for stimulating collision, estimated on the basis of collision cross-section and velocity, is about 10^{-15} second. The time of intervals of collision is probably same as this. Next we estimate the stimulated radiation time t_s. For $K_{\alpha 1}$ spectral line of diamond, Stark width $\Delta v_s \sim 10^{15}$ second^{-1}, spontaneous radiation time is $\tau_{sp}* \sim 2.5 \times 10^{-12}$ second, and corresponding increase coefficient $G \sim 10^4 cm^{-1}$, so $t_s \sim 3 \times 10^{-15}$ second. Lastly, about radiationless transition time, estmated according to the fluorescent yield of X-ray, for diamond, its Auger transition time is approximately 10^{-14}second. (* sp means spontaneous)

Obviously, all these process times are shorter than that of both Auger transition and spontaneous radiation.

Finally we estimate the stimulation power and evidently it is:

$$P-\left(\frac{\Delta N\Delta V}{\tau_R}\right)\hbar\omega \tag{38}$$

If $\hbar\omega - 360$ electronvolt, stimulation volume is $\Delta V \sim 3 \times 10^{-10} cm^3$, particle number density is $\Delta N \sim 10^{22} cm^{-3}$, then from equation (38), we have $P \sim 10^{11}$ watt. The power density used for stimulation is $P/\Delta V \sim 10^{20} w/cm^3$. At the present time, only neodymium glass of high power rate can meet such requirement.

In the process of compounding plasma electron collision, a particle number inversion is formed in light wave band. ~~This has been known [28]~~
This has been known[28].

2. Exchange of Atom-ion Resonance Charge

First Suggestion: Using presently available laser of high power rate to form ion plasma of which the degree of ionization is very high ($Z \sim 10$) and particle number density is very great. When the plasma thus formed begins to scatter by a movement speed v, the plasma density is reducing continuously and the collision probability $N_e\langle v\sigma_n^i\rangle$, $N_e\langle v\sigma_{n,n'}\rangle$ is also reducing. Here σ_n^i & $\sigma_{n,n'}$ are the ionization cross-section of energy level n and the transtion cross-section of energy level $n \to n'$, and N_e is electron concentration. But the radiation transition probability of energy level n is $A_n \propto n^{-4.5}$, and n is the main quantum number. So from the point when electron concentration reaches certain critical value $(N_e)_c$, the life of all $n \leqslant n_c$ energy levels is determined only by radiation process, namely

$$\begin{aligned} A_n &> (N_e)_c\langle v\sigma_n^i\rangle \\ A_n &> (N_e)_c\langle v\sigma_{n,n'}\rangle \end{aligned} \tag{39}$$

It can be hoped that in a series of $n \rightarrow n'$ transition, particle number inverse distribution will be formed.

It is possible to use the quasi resonance charge exchange produced in the process of plasma tending to neutral gas expansion, and at a certain energy level n_1, ion can selectively make very great concentration. Usually the electric charge exchange is selectively proceeded as energy level N_1 in the following equation can be satisfied.

$$\frac{R_y Z^2}{n_1^2} \geqslant I \qquad (40)$$

In the equation, R_y = 13.6 electronvolt, I is ionization potential of ion. For instance, an ion of which electric charge Z is completely ionized by laser, in the process of tending to neutral He atom gas expansion carrying out electric charge exchange, can be made into a stimulated ion of which electric charge is (Z - 1):

$$B_z + \mathrm{He}(1^2S) \longrightarrow B_{z-1}(n_1) + \mathrm{He}^+(1S) \qquad (41)$$

To make the stimulated ion B_{z-1} enter energy level ~~n~~ n_1.

Cross section of electric charge exchange is: [4]

$$\sigma \sim 10^{-16} Z^2 \ cm^2 \qquad (42)$$

This stimulation cross section is larger than any of various stimulation constructions available presently. [29]

In equation (41), the speed of energy level N_1 stimulation is:

$$q_1 = N_i N_0 \langle v\sigma \rangle$$

In the equation, N_o is neutral gas density, N_i is ion number density. If $n_1 \leqslant n_0$, then all $n \leqslant n_1$ energy levels, because of radiation transition, stay at particle number N_n. Using Seaton's series lattice $C_{n_1 n}$[30], they can be expressed as:

$$N_n = q_1 C_{n_1 n} / A_n$$

Therefore the increase coefficient is:

$$G = \frac{\lambda^2}{8\pi} N_i N_0 \sigma \alpha'_{nn'} \quad (43)$$

$$\alpha_{nn'} = n^2 A_{nn'} [C_{n_1 n}/n^2 A_n - C_{nn'}/n'^2 A_n]$$

For the transition of hydrogen-like ion, taking $N_o = 10^{18} cm^{-3}$, $N_i = 10^{17} cm^{-3}$ and for the $n = 5 - n' = 3$ transition ($\lambda \sim 100$ Å) when $n_1 = 5$ and $Z = 10$, we can have $G > 20$ cm^{-1}。

Second Suggestion: Using a focused quasi straight ion beam to enter target area. In the process of electric charge exchange, the outer shell electron of ion or atom will selectively enter stimulation ~~stae~~ state[31]. For example,

$$He^{++} + H_{1s} \longrightarrow He^{+}_{2p} + H^{+}_{1} \quad (1)$$
$$\longrightarrow He^{+}1S + \gamma(304 \text{ 埃}) + H^{+}_{1} \quad (1)\ \text{Å}$$

This is because that the cross-section $\sigma_{2p} \sim 10^{-15}$ cm^2 of He^{++} entering 2P is larger than $\sigma_{1s} \sim 10^{-17}$ cm^2. And also because the life of He^{+}_{2p} spontaneous decay is shorter by about 10^{-10} second. So the inverted ion must pass through by light velocity along the emission direction. In experiment, this can have several different forms.[32]

A system can be designed in such a way that before the ion entering target zone, a comparison of its Doppler width and homogeneous width can be overlooked. But for a solid target, the velocity split of ions in an ion beam caused by ion-ion scattering in the foil will form Doppler width and it is estimated about $\Delta\omega_D \sim 10^{12}$ second^{-1}. For a gas target, the Doppler width caused by collision of electric charge exchange should be taken into account, and it is estimated about $\Delta\omega_D \sim 10^{10}$ second^{-1}.[32]

To a solid target, the linear increase is:

$$G_m = \left[\frac{3}{4}\left(\frac{\ln 2}{\pi}\right)^{1/2}\lambda^2 \frac{\Delta\omega_s i \Delta P}{\Delta\omega_D e v_0 \Delta x \Delta y} - 2\varkappa\right] l \tag{44}$$

To a gas target

$$G_m = \left[\frac{3}{4}\left(\frac{\ln 2}{\pi}\right)^{1/2}\lambda^2 \frac{\Delta\omega_s i \Delta P}{\Delta\omega_D e v_0 \Delta x \Delta y} \cdot e^{\beta^2}(1+\mathrm{erf}\cdot\beta) - 2\varkappa\right] l \tag{45}$$

In the equation,

$$\beta = \frac{(\ln 2)^{1/2}(\gamma_a - \gamma_b)}{\Delta\omega_D}$$

$\Delta\omega_s \sim 10^{10}$ second^{-1} is radiation width, i is ion current, ΔP is a small part of the excessively produced He^+ ion in 2P state, Δx & Δy are ion beam width respectively at x and y directions, v_0 is longitudinal velocity of ion beam. γ_a and γ_b respectively represent decay speed of a and b. Loss $\varkappa = \sigma_a N_f$. For X-ray of $\lambda = 300$Å, the absorption cross-section in hydrogen $\sigma_a \sim 2.78 \times 10^{-19}$ cm^2, and for a gas target, density is 5×10^{16} cm^{-3}, so $\varkappa \sim 1.39 \times 10^{-2}$ cm^{-1}.

Let us estimate the increase. For 2P - 1S transition of He^+, $\lambda = 3 \times 10^{-6}$cm and for a solid target, if its thickness is 25 angstrom, $\Delta P = 0.1$, $\Delta x = 5.5 \times 10^{-3}$cm, $\Delta y = 10^{-2}$cm, $v_o = 9.8 \times 10^7$cm/sec., i = 30ampere, and l = 10 cm, then we have G = 1.1. For gas target, $\Delta P \simeq 0.05$, $\gamma_{ob}/\Delta\omega_b \ll 1$ hour, G~47. This is beyond the sphere of linear theory.

The specific increase equation (44) and (45) for X-ray laser and the threshold value condition equation (35) which is related to increase all deal with stable state. In fact, as X-ray amplifier has limited amplified band width and rapid atom decay, it produces the so-called laser "dark" (Lethargy) effect, which will make the estimated increase become low. [33]

Third Suggestion: The difficulty encountered in using the proposal of electric charge transference mentioned above is that following the mismatch of energy state between donor (atom) and acceptor (ion), the transference cross-section is reduced manifestly. But in a strong optical field, as every one knows, the transiference cross-section of nonresonance collision stimulation will be increased immensely. So there comes a proposition of uniting photon with electric charge transfering pump. [34] For instance, in the process of $H^+ + Cs \rightarrow H(2P) + Cs^+$, there is a mismatch of 0.49 electronvolt. When an optical field of 10^{10}watt/cm^2 is added, there can be a transference cross-section of 2×10^{-15}cm^2.

3. Using Double-step Stimulation of Ionic Metastable State

The process of using ionic metastable state for stimulation will be of two steps. The first step is to form metastable state of ion and the second is to make the outer shell electron of such ion enter stimulation state or an intermediate energy level. The example for discussion now is primarily focused on Li lithium ion because it has no Auger effect.

First Suggestion: The earliest assumption is that first lithium atom is changed into ion in metastable state 1S2S, then in the life time of 2P state a trigger light pulse with a suitable wave length is added and electron in 2S state is stimulated to 2P state. Between 2P-1S particle number inversion is formed.

When ion number density is befitting, the life time of Li^+ metastable energy level 2S approximately equals to 500 micro-second and the life time of 2P energy level is approximately 3.9×10^{-11} second. The wave length of $2S \rightarrow 2P$ transition $\lambda = 9562.2Å$, and the absorption cross-section is $7.3 \times 10^{-14} cm^2$.

Using cavity structure, the threshold value condition is:

$$N(2P) - \frac{g_{2P}}{g_{1S}} N(1S) \geq \frac{18.4}{\lambda^2 L} \cdot \frac{\Delta\nu}{A_{2P1S}} \ln \frac{1}{R} \quad (46)$$

In the equation, R is the reflectivity of cavity. If thevelocity extension of the moving ion beam is so insignificant that $\Delta\nu$ can be regarded as natural width. If $g_{2P} = g_{1S} = 1$, the cavity length L = 1 metre, λ =200Å, R = 1~10%, then from equation (46) we can have $N(2P) - N(1S) \geq (1.5 \sim 3) \times 10^{11} cm^{-3}$. This threshold value is relatively low.[35]

Second Suggestion: Using plasma produced from CO_2 laser as initial pump source, the incoherent soft X-ray emitted from it will selectively photoionize K shell electron of Li atom and produce metastable ion in 1s2s state. Now to tune the tunable dye laser to $1s2s^1S \rightarrow 1s2s^1P$ transition length of Li^+, and at the prefixed time, to put dye laser pulse into metastable Li^+ ion. This can bring about two different physical processes. One is that ion aborbs dye laser photon and transits to an intermediate state $1s2p^1P$ and then by stimulation or spontaneously radiates to the base state of ion. Such a process of two-step transition is called heat fluorescence (HL)[36]. The other is that the stimulated double-photon transition resonance Raman-anti-Stockes emission can also take place on a spectral line of $\lambda = 199Å$, as indicated in Figure 7. Using X-ray laser of the later mechanism and its utmost increase is[37]:

$$G_{RR}|_{max} = \frac{9\lambda^2}{2\pi}\cdot\frac{n_{mo}A}{2V_p}\exp\left(-\frac{\pi A}{4V_p}\right) \quad (47)$$

In the equation, n_{mo} is particle number density at ionic metastable energy level when dye laser is tuned, A is the spontaneous radiation speed of intermediate energy level 1s2p, $V_p = \mu_{21}E_{po}/2\hbar$, μ_{21} is double-pole lattice element of 1s2p-1s2s transition, E_{po} is laser electric field of dye laser.

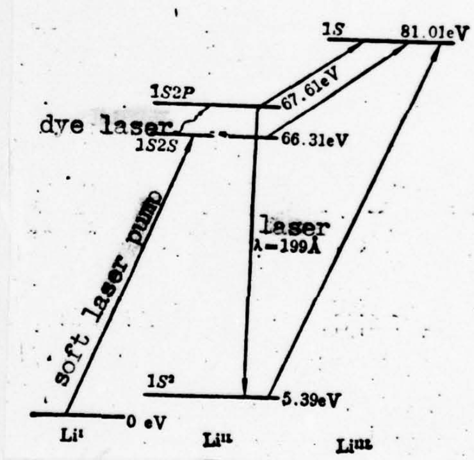


Figure 7

When dye laser strength is approximately $1.5 \times 10^5 w/cm^2$, $V_p \approx 1.1 \times 10^{11} second^{-1}$, and when initial particle number density in $1s2s^1S$ state is approximately $1.8 \times 10^{13} cm^{-3}$, from equation (47) we then have

$G_{RR}|_{max} \sim 10\ cm^{-1}$.

It will be found interesting to compare stimulated Raman scatter cross-section $\sigma_{RR}(=G_{RR}/n_{mo})$ with general stimulated radiation cross-section σ_S produced from $1s2p\,^1P$ energy level. From equation (47), we have:

$$\frac{\sigma_{RR}}{\sigma_s} \approx 36\left(\frac{\Delta\nu}{2V_s}\right)\exp\left(-\frac{\pi A}{4V_s}\right) \quad (48)$$

In the equation, $\Delta\nu$ is the transition frequence width at laser wave length, and from $\Delta\nu/2V_s \sim 1$, $V_s \gg A$, we can see that the stimulated resonance Raman scatter cross-section is clearly larger than the stimulated radiation cross-section at intermediate energy level.

Analyses indicate [37] that for making more than ~~90%~~ 95% of Li atom enter metastable state 1s2s, when the optimum primary Li atom density is $10^{14} cm^{-3}$, it requires a pump laser current of which the lifting time is 1 milli-microsecond and power density is $2.9 \times 10^9 watt/cm^2$, then it can use a soft X-ray current of medium strength. The pulse width of dye laser is required to be approximately 400 micromicrosecond, for a working substance of $0.5 \times 0.5\ cm^2$, total energy of dye laser must be 15 micro-joule.

What deserves attention is that the life time of the 1s2p metastable state of Li^+ ~~metastable state~~ is mainly determined by a combined speed of electrons in 1s2s and 1s2s state because the metastability of this state is closely related to the initial Li atom density.

In addition, using metastable energy level 2s of hydrogen-like ion O^{+7}, under the action of neodymium glass of high power and through double-photon transition, we can have X-ray laser.[38]

4. Photo-resonance Stimulation

Generally it requires that two samples exist in laser plasma and they have overlapping and strong spectral lines. One of the two samples is used as source ion and the stimulating ion of X-ray resonance emitted from it can form particle number inversion.

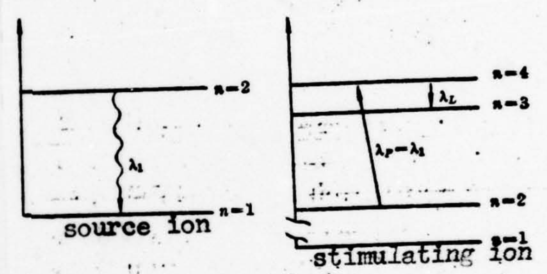


Figure 8

One arrangement includes two-step process as indicated in Figure 8. First to transfer the the working ion from base state (n = 1) to first stimulation state (n = 2), then the X-ray resonance stimulation coming from source ion make it enter high operation energy level (n = 4), and between n = 4~n = 3, particle number inversion is formed. The other arrangement is that if the source ion issues X-ray of two different kinds of wave length, and one of them can through "filter" ion filter away the X-ray of first kind of wave length and that of second kind of wave length will be used to stimulate working ion by using resonance, as indicated in Figure 10.

The specific example of first arrangement: Taking the homogeneous mixture of source ion and stimulating ion elements as target (such as C and Mg), under the shining of of neodymium glass laser, it can form plasma. In such plasma, CVl is used as source ion, which can send forth X-ray of 33.376Å and resonantly stimulate Mglll ion to form particle number inversion between states of n = 4~n = 3 and to emit X-ray of λ_L = 130Å. Through analysis,[39] the width of X-ray pulse used for stimulation should be 10^{-10} sec., and energy is approximately 10^{-2} joule. From the second arrangement, matching ion can be found. For instance, using 4s - 2p transition (λ_F = 60.375Å) of NalX as filter of BIV 2p - ls transition (λ_L= 60.314Å), it can emit laser of λ_L = 416Å.

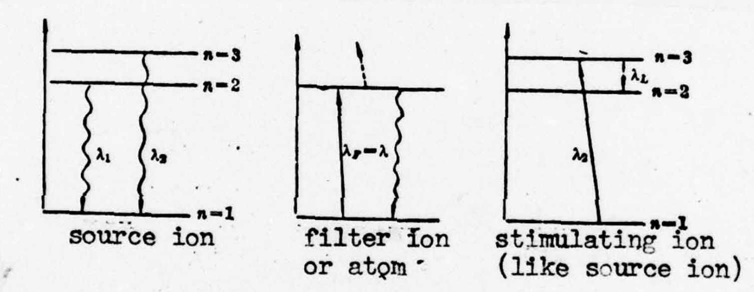


Figure 9

5. To Establish Particle Number Inverse Distribution According to Velocity Difference of Ion Movement[40]

Let plasma make heat expansion in vacuum, and under the action of electric field, ion is accelerated to a velocity which is in direct ratio to charge-to-mass ratio. Those ions which are in a state higher than high operation energy level, during a period of relaxation because of collision with other ions, can reach velocity v' and stay at high operation energy level. But the ions at low operation energy level maintain their original velocity v_0. When the decay speed of spontaneous radiation is larger than collision speed, the stimulation of high operation energy level is slow. So in the period of high operation energy level relaxation t_d, in the space there is an "inverse sheath" of which the thickness $l = (v' - v)t_d$. For ions of which Z is approximately less than 4, t_d is approximately 10^{-9} second and for plasma of which the ion velocity is approximately larger than 10^8 cm/second, l is larger than 1 cm.

For Doppler width and the super radiation of an end reflection mirror with a reflectivity of R = 0, the threshold value can be expressed as:

$$L\left(N_u \frac{g_l}{g_u} - N_l\right) = \frac{8\pi \Delta\nu_D \tau}{(\pi \ln 2)^{1/2}\lambda^2\phi} \quad (49)$$

In the equation, ϕ is branch ratio, τ is average radiation life time of laser transition. When $\lambda = 10^{-5}$cm, $\tau = 10^{-9}$ second, $\Delta\nu_D = 10^9$ hertz, L = 1 cm and $\phi = 0.5$, from equation (49), we can have particle number density is larger than or equal to $2.3 \times 10^{12} cm^{-3}$.

The possible transitions are: $2s2p^3P^o - 2s3d^3D$ ($\lambda = 459.5$A) of C^{3+} and $2s^2S - 4p^2P^o$ ($\lambda = 244.9$A) of C^{4+}.

6. Transition Between Isoelectronic Sequence Ion Energy Levels

The outer shell electron transition of isoelectronic sequence ion can produce X-ray and this has been well known in spectroscopy. For producing X-ray laser, people have tried to utilize the similarity in energy level of isoelectronic sequence ion and using laser transition of light frequency band as basis to seek suitable ion.[41] For instance, N_e^{3+} ion has observed laser of 2358Å, and the corresponding transition is 3p - 3s. The life time of 3p energy level is 20 times longer than that of 3s energy level. On this basis, the corresponding 3p - 3s transition of isoelectronic sequence ion U^{85+} should be able to produce laser of 11Å, and the life time of its high operation energy level 3p is accordingly 20 times longer than 3s.

The ionic transitions under the action of laser, which have been observed at light frequency band, are: $np \to ns$; $(n+1)s \to np$; $(n+1)p \to nd$ and they all can be used as basis for seeking suitable isoelectronic sequency ion. The forming of ion of definite ionizability can make stripping ionization of neutral atoms by using high power laser.

The suggestions mentioned above are certainly not all those made by interested people. X-ray laser produced by stimulated Compton-Wu Youxun (Wu Yu-hsun) emission and the coherent X-ray obtained by using high degree harmonic technique of non-linear optics all have had specific estimation. Most of these suggestions, although they have to wait for puting into practice, through discussions like what we have done, will greatly help to make X-ray laser and the possible mechanism become clearer and clearer. Moreover, new suggestions are to emerge unceasingly.

3. Fundamental Experiments

The experiment work in X-ray laser started in the 1970's. In a short period of 5 to 6 years, people have from different aspects tried in their experiments to observe X-ray emitted from stimulated emission. Here are some experiments which have captured great attention.

1. In 1972, Kepros and others announced the result in their laser experiments.[42] They use output power of 15 kilo-megawatt, and neodymium glass laser pulse of which the maintaining time is approximately equal to 20 milli-microsecond, through a cylinderical lens of which the focal distance is 4 cm, to focus into a thin and long beam of 1 cm, and then they use this beam to stimulate the transparent thin film working substance which contains copper sulphide and which is held by microthin glass plyer. From experiments they found that when they put X-ray sensitive negatives at the points of 30 cm and 110 cm on the extended focal line respectively, there were sensitive spots of which the diameter is 0.2 millimeter. Evidently the spots are made by X-ray with good calibrating ability. From experiments, they also found that the strength of laser used for stimulation and the density of copper sulphide all have definite threshold value. From the X-ray decay rate acquired from the study of Fe, Ni, Al and others, they calculate that the X-ray emitted there is K_a spectral line of copper and its wave length is 1.54Å. Therefore they announced that they had found X-ray laser.

It is obvious that these experiments carry the primary idea that plasma produced by laser can fly past by light velocity and produce vacancy at inner shell of Cu atom.

Following the announcement of their experiments, came a wave of **heated** argument. Schawlow thought that in theory their way of conducting experiment is correct[5] and there is some redundance in experiments of other people[43-45]. But some others in experiment as well as theory completely deny the result of their experiment[25,46-49]. The theoretic basis for denying their experiment result is just like what we have discussed in Section one of Second Suggestion in the second part of this article[25]. In order to pump K_a laser of Cu, the pump power they used is too low and the lifting time is too long. From experiment we know that it will finally result in failure to use electronic computer to check X-ray of this kind.

Four years later, Kepros and other tried to repeat such experiment[50,51], but up to date, they have not yet suggested any basic criterion for X-ray of stimulated radiation (such as light spectral line becomes narrow, good coherency and others).

2. In 1974, Jaeglé and other tried to use neodymium glass laser of 40 milli-microsecond and 100 megawatt to attack aluminium target, and they found that the soft X-ray of Al^{3+} ionic $(2p)^5(4d)^3p_1 \rightarrow (2p)^6{}'S_0$ transition and with a wave length of 117.41Å was produced from particle number inverse distribution[52-54]. Of soft X-ray used in experiments, light grid of spectrography is 2400 line/mm, curvature radius is 2 meters and seam width is 10 micron. The penetration rate T of plasma which emits soft X-ray of 117.41Å was measured in experiment, and it is used to estimate increase. The process of measuring penetration rate is to divide neodymium glass laser pulse into two

beams, which after a relative delay are focused on two aluminium targets, then use 117.41Å soft X-ray, of which the strength emitted from plasma (1) is I_1, as probe to investigate the aborption and increase of plasma (2). The strength of plasma (2) when there is no shine of 117.41Å soft X-ray is I_2 (λ= 117.41Å). But under the shine of the 117.41Å soft X-ray from plasma (1), if the strength of 117.41Å soft X-ray is I, then we can have penetration rate $T = (I - I_2)/I_1$ and absorption $K = 1-T$.

From experiment it is discovered that T is larger than I and K is less than 0, this means that plasma (2) is in negative aborption state and the average value of net increase is 17%. The inferred increase coefficient $G = 10cm^{-1}$, then it can be calculated that particle number inversion density is about $10^{17}cm^{-3}$.

The stimulation construction can be explained as follows: Aluminium target under the action of laser becomes into Al^{3+} ion, and after being compounded with electron, it becomes into:

$$Al^{4+}(2s^2 2p^{5\,2}P^0) + e^- \longrightarrow$$
$$Al^{3+}(2s2p^6 np^3P^0)$$

Al^{+3} ion comes into collision again with electron and it is stimulated into

$$Al^{3+}(2s2p^6 np^3P^0) + e \longrightarrow$$
$$Al^{3+}(2s^2 2p^5 4d'^3P^0) + e^-$$

To such an experiment result, the challenge has recently become more and more[55-58].

3. In 1976, Dewhurst and others tried to use neodymium glass laser to ionize C atom completely. Through collision and compounding of laser plasma electron, and between energy levels n = 3 and n = 2 (a spectral line of Balmer series) of CVI ion, particle number inversion is formed, and then there is an increase of which the wave length is 182Å.

Experiment requires that the plasma which has been completely ionized should be quickly expanded and cooled down. For this purpose, carbon fibre of which the diametre is 5.3 micron is used and it is radiated by neodymium glass laser in vacuum. The arrangement of experiment is that the carbon fibre is vertically supported over the focal point of neodymium glass laser and keeps a distance of 12 cm from the opening crack of the 2-meter incidence type light grid spectrograph. The laser is an ordinary neodymium glass laser and the laser pulse emitted by is 0.5 joule and pulse width is 140 micromicrosecond, but in experiment only 150 milli-joule is actually used.

When the experiment is being proceeded, it uses a front laser pulse of which the pulse width is 100 micromicrosecond to smash the carbon fiber, then the front laser pulse interacts with the master laser pulse to form crowded plasma. To speculate the emerging of particle number inversion is by way of observing the relative strength of the spectral line of CVI Lyman series. The result of experiment shows that the particle number inversion in alpha spectral line transition of Balmer series begins to be established at about 900 micromicrosecond behind the front laser pulse. The radius of plasma is about 150 micron, particle number inversion density is close or equal to

$3 \times 10^{14} cm^{-3}$ and the product of the increase and length along the carbon fibre axis is GL~2%. Upon this basis, if we want to have GL~10, then it requires neodymium glass laser energy of 100 ~~joulr~~ joule.

Previously, Irons and others tried to make such kind of experiment, but because the ion density is too low, they did not succeed in having the usual light increase.

4. Resonant Cavity

It has been well known that for various lasers, a good resonant cavity will help to prolong the photon life time, reduce threshold value and to improve the directionality and coherency of output beam. Because of the presence of resonant cavity, it has become possible to further develop laser techniques, such as Q tuning technique, cavity dumping technique and lock simulation technique. Therefore, to seek suitable resonant cavity for X-ray laser has become a natural hope of the people. Some suggestions in theory which have been made include:

1. Ring Resonant Cavity

Some crystal face of perfect crystal can have very high reflectivity to Bragg reflection of X-ray with definite wave length, so to use this kind of crystal to make plane reflective mirrow has been suggested. Due to the fact that Bragg reflection angle to X-ray with definite wave length is invariable, so an ideal cavity must be a ring resonant cavity made of many crystal flakes [13-15]. The tunable cavity, as illustrated in Figure 10, is a better one recommended by many. The arrangement of six crystals is $M_1 \| M_4$, $M_2 \| M_5$, $M_3 \| M_6$, and the light track is a plane polygon. Its output can be made by the help of Borrman crystal M_7 and some stimulating material of stimulated radiating X-ray can be imxed with M_7 crystal.

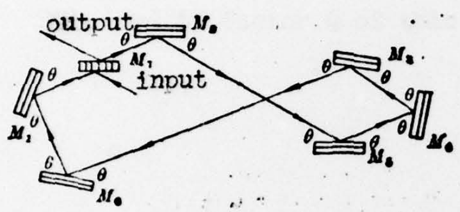


Figure 10

The quality factor Q of this resonant cavity is:

$$Q = \frac{2\pi L}{\lambda}\left(1-\prod_{i=1}^{7} R_i\right)^{-1} \quad (50)$$

In the equation, L is the light distance of X-ray in the cavity, R_i is Bragg reflectivity of crystals of i number. If $R_1 \sim R_6$ are all close to 1, $R_7 \simeq 50\%$, and when $\lambda \simeq 10^{-8}$ cm, $L \simeq 5$ cm, $Q \simeq 6 \times 10^9$. The spectral width of resonant cavity $\Delta\lambda$ then is:

$$\Delta\lambda = \frac{\lambda}{Q} \simeq 1.7 \times 10^{-18} \text{ cm} \quad (51)$$

And the life time of photon in the cavity is:

$$\tau = \frac{Q}{\omega} \simeq 3 \times 10^{-10} \text{ second} \quad (52)$$

During this period of time, the X-ray beam passes through a distance of $C\tau \simeq 10$ cm, and the gap delta-lambda ($\delta\lambda$) between two neighbouring spectral lines is:

$$\delta\lambda = \frac{\lambda^2}{L} \simeq 2 \times 10^{-17} \text{ cm} \quad (53)$$

But the spectral line width of eigen X-ray is $\Delta\lambda_x \simeq 10^{-12}$ cm, so it can include many longitudinal molds.

2. Resonant Cavity of Distribution Feedback Type

If the crystal face of the crystal working substance is used as reflective mirror, then because the fact that the change of electron density in the crystal is periodic, the radiation wavelength of the eigen X-ray can together with crystal lattice constant d(hkl) satisfy the condition of $d=\lambda/2$ or $d=\lambda$, and between the advancing wave and back wave of X-ray a backward Bragg coupling is produced. So feedback is suggested [17].

It could be considered to use the antinode of the standing wave of an X-ray laser to magnify atoms and the node to absorb atoms subsequently reducing X-ray absorption.

Let us estimate the possibility of this cavity. If the complex amplitude of incident X-ray is A_1, Bragg scattering can be produced on (hkl) crystal face. This can be regarded as scattering caused by the ups and downs of the refracting power on (hkl) plane direction. Thus the coupling equation of incident light and scattering light is:

$$\frac{dA_i}{dr_i} = K_{is} A_s \exp\{i[\vec{k}_i - \vec{k}_s - \vec{G}(hkl)]\cdot\vec{r}\}$$
$$\frac{dA_s}{dr_i} = K_{si} A_i \exp\{-i[\vec{k}_i - \vec{k}_s - \vec{G}(hkl)]\cdot\vec{r}\} \qquad (54)$$

In the equation, A_s is the amplitude of scattered light, $\vec{k}_1$ and $\vec{k}_s$ are wave vector of incident light and scattered light $\vec{G}(hkl)$ is the inverse vector which is perpendicular to (hkl). The coupling coefficient K_{is} is in direct ratio to the amplitude a_G of refracting power that is modulated along $\vec{G}(hkl)$:

$$n(\vec{r}) = \sum_{G(hkl)} a_G \exp(i\vec{G}\cdot\vec{r}) \qquad (55)$$

Obviously, at what direction there is a change of refracting power, and at that direction the X-ray feedback can be suggested.

It is easy to prove for the scintillating zinc-ite crystal of gallium phosphide, that at (111) direction the change of refracting power is:

$$\Delta n_{(111)}(\vec{r}) = -\frac{N_0 e^2}{\sqrt{2}\,\omega^2 m \varepsilon_0} \cdot \cos\left[\frac{2\pi\sqrt{3}}{a_0}\left(\xi - \frac{a_0}{8\sqrt{3}}\right)\right] \quad (56)$$

In the equation, ξ is the distance along (111) direction, a_0 is the size of unit chief cell, N_0 is the electron density of unit volume. So the period of modulation of refracting power is $d_{111} = a_0/\sqrt{3}$, and the condition of producing Bragg feedback at (111) direction is:

$$d_{111} = \frac{a_0}{\sqrt{3}} = \frac{\lambda}{2} \quad (57)$$

This can warrant that X-ray only propagates back and forth along (111) direction and produces coupling and not scatters along ($\bar{1}1\bar{1}$), ($\bar{1}\bar{1}1$) and ($\bar{1}\bar{1}1$) direction.

3. Resonant Cavity of Wave Conduction Type

Recently in experiments, X-ray wave conduction has been realized, and on this basis, a resonant cavity of wave conduction type can be suugested. Taking zeolite crystal for example, it can explain the principles of the structure of a cavity of this kind.[18] Zeolite crystal is an aluminum-silcate crystal, also it is called molecular sieve. It has thin holes of which the smallest diameter is 3~12Å and it also has periodicity. So X-ray working substance of gas state or plasma state can be put into it. Because the refracting power in the thin hole is high (n = 1), so the refracting power of the alumin-silcate on both sides of the hole to X-ray is $1 \sim n \simeq 4 \times 10^{-5}$.

So X-ray can be conducted out through the thin hole. In the cross-section of the thin hole because of the changes of periodicity, Bragg reflection of X-ray is produced and distribution feedback is formed.

Obviously, in order to have a strong feedback, it requires that the half wave length of X-ray must be an integral multiple of the diameter of hole. Because there is zeolite with various structural parameters, the requirement can be satisfied through a selection. For soft X-ray, this is easy to be done.

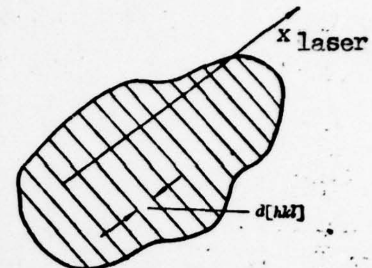


Figure 11

4. Resonant Cavity of Borrman Effect

In a perfect crystal, under the condtion of Bragg diffraction, and when the crystal is of a proper thickness, there can happen coherent gradual increase of two X-ray waves. When the crystal temperature $T \ll \Theta_D$ (Θ_D is Debye temperature), absorption is greatly reduced (the absorption coefficient of X-ray is reduced by 20~100 times). Such extraordinary penetration effect has great sensitivity to Bragg diffraction angle, and the X-ray which propagates in an unusual penetration region, can maintain a polarization state unchanged[19]. So the X-ray laser that is supposed to be formed can be forced to limit its propagation in a fixed region, then the direction of propagation, polarization state and the action of wave length are all put under control. This supposition is produced in the discussion of γ-ray laser.

5. Conclusions

In this article, we tried from theories to analysize the characteristcs of X-ray laser; the propositions of making X-ray laser; experiment results; and several forms of X-ray laser resonant cavity which can possibly be used in the future. However, we see that the results of theoretical analysis and various propositions need more experiments to prove their validity. Theories and experiments should all go deeper. At the same time, we notice that the heated arguments over experiment results and theoretic analyses are really unique in the history of laser development.

In the 1950's, those who tried to discuss and predict the possibility of having X-ray laser seem to have recognized that it might be difficult to push the principle of stimulated radiation toward a much shorter wave length (such as X-ray and γ-ray) [61]. During this period, there were some doubts. Through efforts of many years, however, our knowledge on the subject has been substantialized. Now we all believe that X-ray laser and γ ray laser can be successfully manufactured and even glass laser and Fermi laser have already been put into consideration.

The significance of developing short-wave laser is obvious. From the past more than ten years, we have recognized that the emergence of laser has provided a powerful instrument for us to investugate the nature and to improve the nature. X-ray laser, because it has a much shoter wave length and greater penetrating ability, can accomplish what cannot be done before. For example, the application of X-ray laser to holography has made us abble to see molecules. X-ray laser can focus on a single atom, and this is a great convenience for us to understand the micro-world. To optics, biophysics, analysis of crystal structure, solid spectrum and the new field at the juncture of solid physics and non-limear X-ray optics, X-ray laser can all be applied. Moreover, in space communication, precise measurement, micro-working technique and national defence, X-ray laser has its potential.

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