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Exploding-foil–photoionization x-ray laser

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By combining the technique of exploding foils with inner-shell photoionization, we predict that lasing can occur for x rays below 50 Å in Cu-like ions. As an example, we work out the case for Cu-like iodine (I^{24+}) which should lase on the $3d^9 4s^2 \rightarrow 3d^{10}4p$ doublet calculated at 24.565 and 26.026 Å with integrated line energies comparable to the selenium x-ray laser.

Since the first demonstration[1] of soft-x-ray amplification in laser-exploded foils, there has been much effort to achieve shorter and shorter wavelengths.[2] In broad terms, an exploding foil lases due to collisional excitations. A different means to achieve inverted populations was suggested by Duguay and Rentzepis[3] who reasoned that inner-shell photoionization of atoms from broadband x rays will produce lasing transitions. This was subsequently proved experimentally, first in Cd vapor,[4] then in Zn vapor,[5] followed by In plasma.[6] We propose to combine these two procedures to produce lasing transitions which are unattainable by either method alone.

A combined technique experiment entails a double laser beam (see Fig. 1). The first beam explodes a foil while the second beam strikes a metal to create x rays which then impinge on the created plasma. As will be seen, judicious choice of the two materials to be irradiated should allow short wavelength (< 50 Å) lasing transitions. We have investigated two particular inner-shell ionization schemes: Cd-like and Zn-like isoelectronic sequences. Both involve the photoionization of an inner d-shell electron, $4d$ and $3d$, respectively. For Cd itself, removal of a $4d$ electron from the $4d^{10}5s^2$ ground state results in Cd^+ $4d^9 5s^2\ ^2D$, which is an excited configuration of Ag-like Cd.[4] Lasing occurs to the $4d^{10}5p\ ^2P$ states which decay to the $4d^{10}5s$ ground state. However, as we go up to the Ag-like isoelectronic sequence $4f$-shell collapse sets in. It has been shown[7] that the ground state of the Cd isoelectronic sequence becomes $4d^{10}4f^2$ at Sm^{15+}. Correspondingly, the excited state of the Ag isoelectronic sequence achieved by removing a $4d$ electron is $4d^9 4f^2$. The binding energy of this configuration increases with atomic number Z faster than $n=5$ orbits and eventually at $Z \simeq 80$ it becomes the lowest excited configuration.[8] The energy of $4d^{10}5p$ becomes equal to that of $4d^9 4f^2$ at $Z \cong 75$. Thus, we calculate that the promising lasing transition to $4d^{10}5p$ never achieves a wavelength below 100 Å.

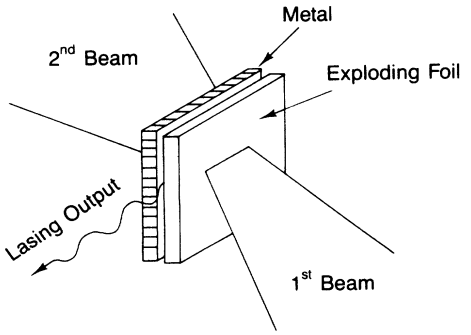

FIG. 1. Schematic representation of the exploding foil photoionization x-ray laser scheme. The metal foil is the source of the photoionizing x rays.

Since these Cd-like transitions cannot do much better than present exploding foils alone,[9] we next investigated the Zn-isoelectronic sequence. Here the physics is very favorable. A Zn-like ion will be in the $3d^{10}4s^2$ ground state which then becomes the $3d^9 4s^2$ excited state of the Cu-like ion. This will lase to the $3d^{10}4p$ levels, which decay to the $3d^{10}4s$ ground state of the Cu-like ion. Unlike the Ag-like sequence no level crossings limit the maximum photon energy achievable for increasing Z. A particularly attractive element is iodine.

We have made energy-level and transition-probability calculations for this element using the Cowan Hartree-Fock (HFR) code which includes relativistic corrections.[10] Throughout, the HFR radial integral values for electrostatic interactions were reduced by 85%, while the spin-orbit integrals were left at their HFR values. This scaling is typical of what one finds in fitting the radial integrals to observed energy levels. All our calculations are made in the configuration-average approximation.

For I^{24+} we calculated the even configurations $3d^{10}4s$, $3d^{10}4d$, $3d^9 4s^2$, and $3d^9 4p^2$ with configuration interaction (CI) between them, and the odd configurations $3d^{10}4p$ and $3d^{10}4f$ each mixed with $3d^9 4s4p$. The largest effect of CI occurs between $3d^9 4s^2$ and $3d^9 4p^2$, which allows the lasing transition $3d^9 4s^2 \rightarrow 3d^{10}4p$ shown in Fig. 2. The population of the $3d^{10}4p$ term is rapidly depleted to the $3d^{10}4s$ ground state. The slight mixture of $3d^{10}4f$ with $3d^9 4s4p$ permits some branching of $3d^9 4s^2$ to $3d^{10}4f$, but this is 40 times weaker than the desired transition. Table I gives the HFR average energies of the configurations in question and the CI radial integrals between them. In Table II and Fig. 2 we show the calculat-

TABLE I. Hartree-Fock average energies of relevant configurations of I^{24+} and CI integrals between them.

Configuration	Energy (cm^{-1})	CI integrals (cm^{-1})	Interacting configurations
1 $3d^{10}4s$	0	$R^1(ds,pp) = -13400$	1-7
2 $3d^{10}4p$	499700	$R^2(dd',ss') = -19600$	3-5
3 $3d^{10}4d$	1227900	$R^1(dd',pp) = -13900$	3-7
4 $3d^{10}4f$	1948800	$R^3(dd',pp') = -16400$	3-7
5 $3d^9 4s^2$	4434600	$R^1(ss,pp) = 175700$	5-7
6 $3d^9 4s4p$	4902500	$R^2(df,sp) = -31900$	4-6
7 $3d^9 4p^2$	5426800	$R^3(df,ps) = -30000$	4-6

ed electric dipole transitions, their transition rates and wavelengths. Since, in absence of configuration mixing, the $3d^9 4s^2 \rightarrow 3d^{10}4p$ transition disappears, we expect that the rate will be much slower than a normal dipole transition associated with a 25-Å line. Figure 2 shows this. Without this reduction of rate, it would be practically impossible to have an x-ray laser in this regime since an allowed electric dipole 25-Å line lives only ~ 2 ps.

The x-ray wavelength (λ) required to photoionize Zn-like iodine by the removal of a $3d$ electron was derived by calculating the difference in total energy between the configurations $3d^{10}4s^2$ and $3d^9 4s^2$. The corresponding wavelength is 9.4 Å.

To determine the conditions necessary to perform the double-beam iodine experiment, we have used the two-dimensional laser hydrodynamic code[11] HYRAD in nonlocal thermodynamic equilibrium. Iodine will be in the form of CsI which can be deposited very accurately on a substrate.[12] The design goal is to vary the CsI thickness and first beam intensity to produce a constant Zn-like iodine density profile for a maximum length of time and space. Calculations show that a 1000-Å layer on a substrate of 1500 Å metallic boron illuminated by 1 ns, 0.53 μm light of 5×10^{12} W/cm^2 intensity creates the desired

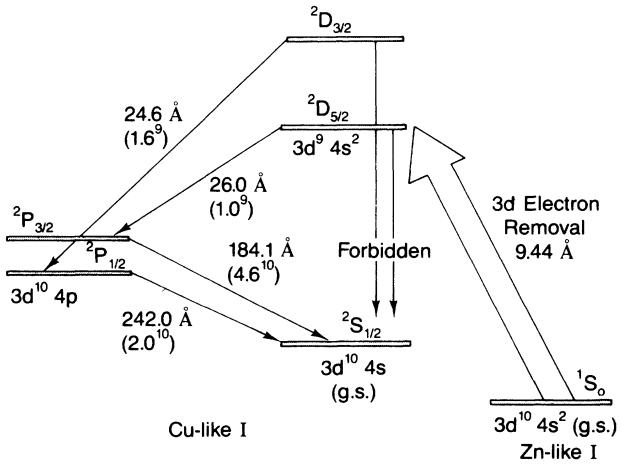

FIG. 2. Grotrian diagram for the lasing transitions. Numbers in parentheses are total radiative rates in reciprocal seconds. Notation $1.6^9 \equiv 1.6\times10^9$ is used. We do not show here the relatively weak $3d^9 rs^2 \rightarrow 3d^{10}4f$ transitions.

characteristics;[13] see Table III. The electron temperature and density 0.5 ns into the pulse are about 0.14 keV and 9×10^{20} cm^{-3}, respectively.

The second beam and target material can be determined using the experimental results of Ref. 14, whose authors have experimentally measured the x-ray line emission of various metals upon laser irradiation. Now, the photoionization cross section of a $3d$ electron in Zn-like iodine near the absorption edge[15] is $\sigma_p \gtrsim 2$ Mb. For maximum efficiency, it is desirable that the ionizing photons be close to the 9.44 Å threshold. The K-shell $1s2p\ ^1P_1$-$1s^2\ ^1S_0$ transition in Mg XI, at $\lambda = 9.168$ Å was originally thought to be appropriate, but one also needs to remove the Cu-like iodine in its ground state. This is the ionic state which could quench the laser if allowed to accumulate. Unfortunately photoionizing Cu-like iodine requires a 9.14-Å photon and so the above K-shell Mg XI line is insufficient. The Al XII $1s2p \rightarrow 1s^2$ transition at 7.757 Å would do the job.[16] For large lasers of the KMS Chroma class about 0.5×10^{14} photons/J will be emitted[14] as K-shell line emission if the second beam hits Al metal with a wavelength 0.53 μm and intensity $\sim10^{14}$ W/cm^2 and pulse width $\gtrsim 700$ ps. As an example, if 2-μm Al is hit with an intensity of 6×10^{14} W/cm^2, the electron temperature and density 0.5 ns into the pulse are 3.67 keV and 6.2×10^{18} cm^{-3} in the burn region. This will be a copious x-ray emitter. We now demonstrate that even if only a tiny fraction of the emitted photons eject $3d$ electrons, the integrated lasing energy will be comparable to the original[1] selenium laser.

The strongest integrated line energy flux of the original selenium laser was[1] about 160 μJ/sr at 206 Å. With a

TABLE II. Calculated transitions between levels active in the proposed laser scheme.

Transition		A (sec^{-1})	λ (Å)
$3d^9 4s^2 \rightarrow 3d^{10}4p$	$^2D_{3/2}$-$^2P_{1/2}$	1.6×10^9	24.56
	$^2D_{5/2}$-$^2P_{3/2}$	1.0×10^9	26.03
$3d^{10}4p \rightarrow 3d^{10}4s$	$^2P_{1/2}$-$^2S_{1/2}$	2.0×10^{10}	242.02
	$^2P_{3/2}$-$^2S_{1/2}$	4.6×10^{10}	184.11
$3d^9 4s^2 \rightarrow 3d^{10}4f$	$^2D_{3/2}$-$^2F_{5/2}$	4.2×10^7	39.40
	$^2D_{5/2}$-$^2F_{7/2}$	3.8×10^7	41.08

TABLE III. Time in picoseconds (ps) into the first pulse. L_T in microns is the transverse plasma scale length for the iodine density. The longitudinal scale length is the beam line focus.

Time (ps)	$\frac{N_{\text{Ga-like}}}{N_{\text{Zn-like}}}$	$\frac{N_{\text{Cu-like}}}{N_{\text{Zn-like}}}$	$N_{\text{Zn-like}}$ (10^{18} cm^{-3})	L_T (μm)
100	3.5	0.19	1.6	8
200	0.73	0.93	16.4	27
300	0.63	1.05	9.95	50
400	0.63	1.03	7.10	77
500	0.66	0.99	6.09	98
600	0.61	1.06	5.10	120
700	0.65	1.00	4.07	140
800	0.67	0.97	3.50	160
900	0.69	0.94	3.11	183
1000	0.71	0.91	2.75	204

10-mrad divergence, this gives 10^9 photons as the total signal radiated by one of the lines. [Since the original 1985 experiments a recent report (Ref. 9) gives higher output near saturation.] If the second pulse in a photoionization x-ray laser were $\sim$300 J (characteristic of large glass lasers) then the number of photoionization photons is $0.5\times10^{14}\times300=1.5\times10^{16}$. Thus to equal the original Se signal only a tiny fraction need be captured. From Table III the calculated mean free path for photoionization at 200 ps is $\lesssim$300 μm. Thus about 1 photon in 10 along the transverse direction will be captured at time 200 ps. Allowing for unknown losses, we expect that the integrated line energies of a photoionization x-ray laser should be comparable or even higher than a collisionally inverted x-ray laser.

The gain per unit length of the laser will be calculated from the formula[17]

$$g=\left[\frac{4\ln2}{\pi}\right]^{1/2}\frac{1}{8\pi c}\frac{\lambda^4}{\Delta\lambda}A\left[N_U-\frac{g_U}{g_L}N_L\right], \tag{1}$$

where λ is the transition wavelength, $\Delta\lambda$ is the linewidth, A is the spontaneous transition rate and N, g are the number densities and statistical weights of the U (upper) and L (lower) lasing levels. Let ϕ be the photon flux/cm^2/ns and t the time. Then

$$N_U=\phi t\sigma_p N_{\text{Zn-like}}\leq N_{\text{Zn-like}}. \tag{2}$$

The design of the experiment requires that

$$\phi t\sigma_p=1 \tag{3}$$

for maximum g at time t. $\Delta\lambda$ will be approximated by the Doppler broadening, $\Delta\lambda_D$,

$$\Delta\lambda\approx\Delta\lambda_D=(7.7\times10^{-5})\lambda\left[\frac{T}{M}\right]^{1/2}, \tag{4}$$

where the ion temperature T is in eV and M is the atomic weight. From the computer-simulation codes, Zn-like iodine has $(T/M)^{1/2}\approx1$. Thus, for example, the 26-Å line has a gain (in cm^{-1}) of

$$g_{26.0}=(2.86\times10^{-19})\left[N_U-\frac{g_U}{g_L}N_L\right]. \tag{5}$$

TABLE IV. Ground state (g.s.) and excited state of I^{23+}. $3d$ photoionization produces the corresponding states of I^{24+}. Only $3d^94p^2\rightarrow3d^{10}4p$ does not go through the lasing transition.

	I^{23+}	I^{24+}		Goes through lasing state
Third	$3d^{10}4s4d$	$3d^94s4d$	$\rightarrow3d^94s4p$	Yes
Second	$3d^{10}4p^2$	$3d^94p^2$	$\rightarrow3d^{10}4p$	No
			$\rightarrow3d^94s4p$	Yes
First	$3d^{10}4s4p$	$3d^94s4p$	$\rightarrow3d^94s^2$	Yes
g.s.	$3d^{10}4s^2$	$3d^94s^2$	$\rightarrow3d^{10}4p$	Yes

If there is little population in N_L, then from Table III, $N_U\sim7\times10^{18}$ for over half a nanosecond, so we would expect conservatively $g\sim2$ cm^{-1} if Eq. (3) is true. An important observation is that it does not matter how much of the Zn-like iodine is in its ground state versus its low excited states. Table IV shows that the excited states must go through the lasing transition, except for branching of the second excited state $3d^94p^2\rightarrow3d^{10}4p$. Because the excited transitions go much faster than the lasing one, essentially all the $N_{\text{Zn-like}}$ present is usable. Furthermore, Eq. (3) is very easily obtained. Let E_B be the energy in joules for the second beam and let r be the separation distance of the two foils. Then[18]

$$\phi\approx(0.5\times10^{14})E_B\frac{1}{4\pi r^2}\ (\text{cm}^{-2}\text{ns}^{-1}). \tag{6}$$

By requiring Eq. (3) to be valid at time $t=0.8$ ns, then $E_B\sim140$ J, with $r=300$ μm. Experimentally we expect some line trapping of the $3d^{10}4p\rightarrow3d^{10}4s$ radiation so the actual gain in green light will be less than the 2 cm^{-1} value. This line trapping may explain the surprising results of the Zn experiment[5] where the $^2D_{5/2}$-$^2P_{3/2}$ transition lased with a large $g=2.2$ cm^{-1}, but no lasing occurred at all on the $^2D_{3/2}$-$^2P_{1/2}$ line.

In conclusion, theoretical calculations predict that by combining two well-established experimental techniques, short-wavelength (<50 Å) transitions can be amplified. This method is expected to be more efficient than the exploding beam foil alone. We gave here the iodine example which should lase at 24.5 and 26.0 Å, but clearly one can go to shorter wavelengths than these. To maintain a respectable gain coefficient (say 2 cm^{-1}) as we go to shorter lasing wavelengths, we increase N_U by going to thicker targets. This requires that the pumping laser be shorter in wavelength in order to burn through the foil. If NOVA at Lawrence Livermore National Laboratory is operated in blue (0.351 μm) light or even quadrupled light (0.261 μm), a very high energy x-ray laser can be achieved based on this scheme. As an example, Tb^{36+} will have the lasing transitions $^2D_{3/2}\rightarrow{}^2P_{1/2}$ at 12 Å and $^2D_{5/2}\rightarrow{}^2P_{3/2}$ at 13 Å with respective rates 5×10^9 and 2×10^9. The required photoionizing photon is 1.6 keV. Lastly, refraction effects will be much less severe for these short wavelengths and saturation should be attained.

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[13]These are not unqiue parameters. 300-Å CsI on 1500-Å boron requires a nanosecond pulse of 3.0×10^{12} W/cm^2 intensity at 1.06-μm wavelength. Thinner targets will decrease the expected gain.

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