Ni-like X-Ray Lasers Resonantly Photopumped by Ly-α Radiation

Joseph Nilsen
Lawrence Livermore National Laboratory, Livermore, California 94550
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This Letter proposes a new class of x-ray lasers that lase on several $4d \rightarrow 4p$ transitions ranging from 23 to 80 Å in Ni-like ions with atomic number $Z=72$ to 90 and are resonantly photopumped by Ly-α radiation from corresponding H-like ions with atomic number $(Z-21)/3$. This scheme is unique in that it consists of a family of resonant pairs working off the ground state of the laser ion. Calculations of the gain of these laser transitions in steady-state equilibrium plasmas are presented.

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In spite of the tremendous progress in the development of x-ray lasers over the last several years only two pumping mechanisms, collisional excitation and recombination, have been used to create gain and produce laser output.[1] While resonant photopumping was one of the early methods proposed for x-ray lasers,[2,3] to date it has not been observed and the shortest wavelength at which significant gain has been measured using resonant photopumping is at 2163 Å in Be-like C.[4] However, the recent demonstration of lasing at 326.5 Å in Ti suggests that resonant photopumping may be playing an important role in the Ti laser.[5] This Letter proposes a new class of x-ray lasers that lase on several $4d \rightarrow 4p$ transitions ranging from 23 to 80 Å in nickel-like ions ($Z=72$–90) and are resonantly photopumped by Ly-α radiation from hydrogenlike ions ($Z=17$–23). At high Z, there is a fortuitous resonance between the $3d \rightarrow 6f$ transition in the Ni-like ions with atomic number Z and the corresponding Ly-α lines in the H-like ions with atomic number $(Z-21)/3$. This scheme is unique in that it consists of a family of resonant pairs working off the ground state of the laser ion, unlike other resonantly photopumped schemes which consist of chance coincidences.

Figure 1 shows the basic resonant photopumping scheme, using the 54.3-Å laser line of Ca($Z=20$)-pumped Tl($Z=81$) as an example. The Ca XX Ly-α emission lines resonantly photopump an electron in the ground state to the $\overline{3d}_{5/2}6f_{7/2}(J=1)$ level of Ni-like Tl. The bar over the $3d$ state represents a single electron hole in an otherwise closed M-shell ($1s^2 2s^2 2p^6 3s^2 3p^6 3d^{10}$) configuration or Ni-like core. This transition in Ni-like Tl is the strongest $3 \rightarrow 6$ transition with an oscillator strength of 0.5. This $6f$ level decays directly to the $\overline{3d}_{5/2}4d_{5/2}(J=0)$ level, which is the upper laser state. Lasing occurs between the $4d_{5/2}$ and $4p_{3/2}$ states. The lower laser state then decays back to the ground state. Figure 1 also shows the most important kinetic rates (psec^{-1}) in Ni-like Tl which are relevant for producing gain in the 54.3-Å laser line. The radiative rates are denoted by γ^R, the collisional rates are given by γ^C, and the sum of all other radiative and collisional rates are denoted by γ. The lasing process is driven by the photoexcitation rate, $\gamma^P=0.72$ psec^{-1}, assuming a pump strength of 0.002 photon per mode, defined below in Eq. (1), for a single broad Ca pump line. For the Tl plasma an electron temperature of 2000 eV, an ion temperature of 1600 eV, and an ion density of 2.0×10^{19} ions/cm^3 is assumed.

The $6f$ level also strongly feeds the $\overline{3d}_{5/2}4d_{5/2}(J=1)$ level resulting in a laser line at 62.2 Å. Other laser lines would also be present in the plasma due to collisional excitation processes, collisional mixing among the levels, as well as the $6f$ level weakly feeding other levels. All the Tl laser transitions and their wavelengths are given in Table I. The energies for these transitions were first cal-

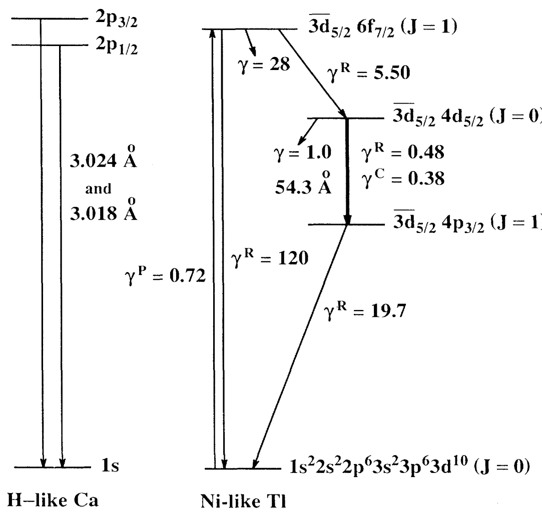

FIG. 1. Energy-level diagram showing the resonant photopumping mechanism for the 54.3-Å Ca-pumped Tl x-ray laser transition. The important kinetic rates (psec^{-1}) are shown; the radiative rates are denoted by γ^R, the collisional rates by γ^C, and the sum of all other radiative and collisional rates by γ. The lasing process is driven by the photoexcitation rate, $\gamma^P=0.72$ psec^{-1}, assuming a pump strength of 0.002 photon per mode for a single broad Ca pump line.

TABLE I. Laser transitions, wavelengths, and gain for Ni-like Tl.

Transition	λ (Å)	Gain (cm^{-1}) for $n_\lambda =$ 0.0	0.0005	0.0010	0.0020
$\overline{3d}_{3/2}4d_{3/2}(J=0) \rightarrow \overline{3d}_{3/2}4p_{1/2}(J=1)$	33.1	2.20	2.26	2.31	2.40
$\overline{3d}_{5/2}4d_{5/2}(J=0) \rightarrow \overline{3d}_{3/2}4p_{1/2}(J=1)$	42.6	0.27	0.89	1.44	2.37
$\overline{3d}_{3/2}4d_{3/2}(J=0) \rightarrow \overline{3d}_{5/2}4p_{3/2}(J=1)$	39.7	1.01	0.98	0.95	0.89
$\overline{3d}_{5/2}4d_{5/2}(J=0) \rightarrow \overline{3d}_{5/2}4p_{3/2}(J=1)$	54.3	1.24	3.51	5.53	8.97
$\overline{3d}_{5/2}4d_{5/2}(J=2) \rightarrow \overline{3d}_{5/2}4p_{3/2}(J=1)$	59.8	2.85	3.81	4.67	6.14
$\overline{3d}_{5/2}4d_{5/2}(J=1) \rightarrow \overline{3d}_{5/2}4p_{3/2}(J=1)$	62.2	2.01	5.93	9.42	15.33

culated by the author using the atomic physics code YODA.[6] These calculated energies were then lowered by 4.5 eV for transitions involving the $\overline{3d}_{3/2}4d_{3/2}(J=0)$ level to approximate the observed corrections between theory and experiment for Ni-like Eu, Yb, Ta, and W. The laser lines which involve the other $J=0$ state, such as the 54.3-Å line, will require slight modifications to account for electron correlation effects, but these have not been made because of lack of experimental data.

To produce a resonantly photopumped laser one needs a strong pump line which is resonant with an appropriate line in the lasant material and which is in spatial and temporal proximity with that line. Unlike other schemes which consist of chance resonances, this scheme is unique in that it consists of a family of resonant pairs working off the ground state of the laser ion. The energy of a Ly-α line is approximately $0.75Z^2$ Ry while the energy of a hydrogenic $3l \rightarrow 6l'$ transition is approximately $0.75(Z/3)^2$ Ry. Figure 2 plots the percent deviation of the Ly-α and Ni-like ground-state $(J=0) \rightarrow \overline{3d}_{5/2}6f_{7/2}(J=1)$ transitions from $0.75(Z^*)^2$ Ry, where $Z^*=Z$ for the Ly-α lines and $Z^*=(Z-21)/3$ for the Ni-like lines. The 21 in the numerator $(Z-21)$ can be interpreted as an effective screening constant of 21 for the Ni-like transition. The solid curves are theoretical values (theory and experiment agree very well for the Ly-α lines) while the squares denote the experimental data for the Ni-like lines. Note that the Ly-α line is split into two components, the $2p_{3/2} \rightarrow 1s$ and $2p_{1/2} \rightarrow 1s$ lines. Considering the theoretical data, at $Z^*=17$ the Ni-like line approaches closely to the lower Ly-α line, crosses it by $Z^*=18$, and then tracks the Ly-α lines up to $Z^*=23$. The experimental data[7] suggest a crossing about one Z^* lower and show the Ni-like and Ly-α lines tracking almost exactly from $Z^*=19$ to 23. In most spectra, the two Ly-α lines are blended together because of the line broadening associated with Doppler and opacity effects. The FWHM (full width half maximum) Doppler width for the Ca line in a plasma with an ion temperature of 1600 eV is 1.4 mÅ while the separation between the two Ly-α lines is 5 mÅ. The actual linewidth for an optically thick pump line will be further broadened by opacity broadening. Calculations done at longer wavelength on Al targets[8] predict Ly-α radiation with brightnesses of 0.002–0.005 photon per mode and a FWHM of 8–20 mÅ. The spectral intensity I_λ of the pump line, where $I_\lambda \Delta\lambda$ is the power per unit area, is related to the modal density n_λ, in photons per mode, by

$$I_\lambda = 8\pi c \frac{hc}{\lambda^5} n_\lambda = \frac{1.497\times 10^{18}}{\lambda^5} n_\lambda \ \frac{\mathrm{W}}{\mathrm{cm^2\,m\AA}}, \qquad (1)$$

where λ is the photon wavelength in Å, c is the speed of light, and h is Planck's constant. If the resonance of Ca and Tl is considered in detail, the Ca XX Ly-α lines are calculated[9] to be at 3.018 and 3.024 Å. The Ni-like ground-state $(J=0) \rightarrow \overline{3d}_{5/2}6f_{7/2}(J=1)$ line has been measured in Ta, W, Re, Pt, Au, and Pb.[7] These values can be fitted by a straight line as described in Ref. 10. This yields a value of 3.019 Å for Ni-like Tl, which makes for an excellent resonance with Ca. Likewise, the K XIX Ly-α lines are calculated[9] to be at 3.347 and 3.352 Å while the $3d \rightarrow 6f$ Ni-like Pt line is measured[7] to be at 3.347 Å. The Ar XVIII Ly-α lines are calculated[9] to be at 3.731 and 3.737 Å while the $3d \rightarrow 6f$ Ni-like Re line is measured[7] to be at 3.734 Å. The estimated accuracy of the measured wavelengths for the Ni-like lines is 2 mÅ. The other pairs have not yet been measured but future plans are to have all these resonances confirmed using the electron-beam ion trap (EBIT)[11] at LLNL.

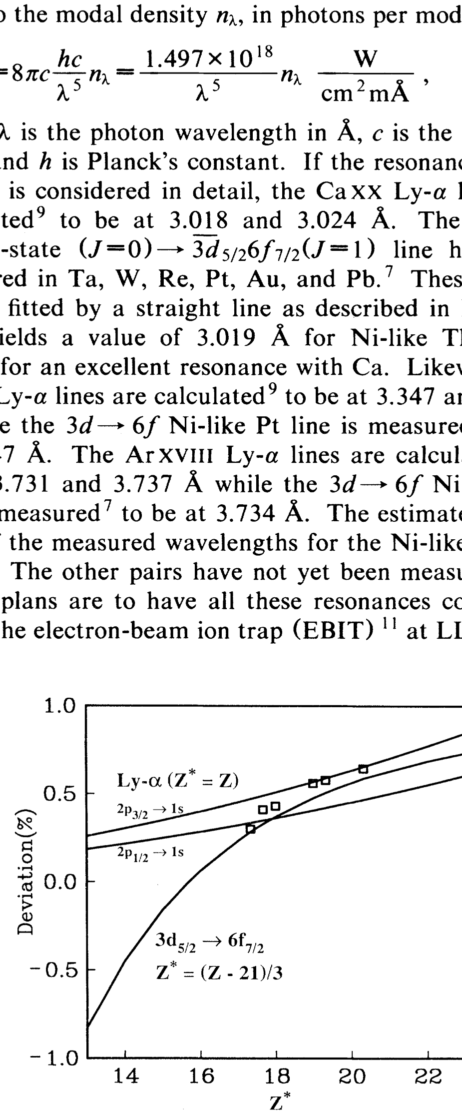

FIG. 2. Percent deviation of the Ly-α and Ni-like $3d_{5/2} \rightarrow 6f_{7/2}$ lines from $0.75(Z^*)^2$ Ry vs Z^*. The solid curves are theoretical values while the boxes denote the experimental data for the Ni-like lines. Note that the Ly-α line is split into two components, the $2p_{3/2} \rightarrow 1s$ and $2p_{1/2} \rightarrow 1s$ lines.

The ability to produce the pump and lasant ions has been demonstrated in the laboratory using laser-produced plasmas. In spectroscopic studies of Cl and Ti, Ly-α and He-α lines[12] have been generated in plasmas with the KMS Chroma laser at 0.53 μm with intensities varying from 0.08×10^{16} to 1.1×10^{16} W/cm^2. The Ly-α line of Ar has also been seen using a dense plasma focus.[13] Likewise, laser-produced Ni-like plasmas have been produced and made to lase.[14]

In terms of creating the correct ionization balance in the Ni-like plasma, another advantage of this scheme is that the strong Ly-α and He-α lines have sufficient energy to photoionize Cu-like ions to Ni-like ions but they do not have enough energy to photoionize the ground state of Ni-like ions to Co-like ions. This facilitates making a large population of Ni-like ions without the fear of overionizing.

To estimate what gain might be achieved in Ni-like Tl by resonant photopumping, an atomic model of Tl was constructed using the atomic physics package YODA.[6] YODA was used to calculate energy levels, oscillator strengths, and collision strengths for the $n=3$ Co-like Tl states, the $n=3$–6 Ni-like Tl states, and the $n=4$ Cu-like states. These were combined with simple hydrogenic data for the Rydberg states and the other nearby sequences. Using this atomic model as input, several steady-state XRASER calculations[15] were done assuming there was a strong Ca Ly-α line available to pump the Ni-like Tl ground-state to $\overline{3d}_{5/2}6f_{7/2}(J=1)$ transition. For the purpose of these calculations the two Ly-α lines are considered as a single broad line with a spectral intensity determined by n_λ. The photoexcitation rate γ^P from the Ni-like Tl ground state to the $\overline{3d}_{5/2}6f_{7/2}(J=1)$ level is calculated by multiplying $3n_\lambda$ by the spontaneous emission rate for that transition, with the factor of 3 being the ratio of degeneracies for the two levels. The calculations were done with a Tl ion density of 2.0×10^{19} ions/cm^3 and an electron density determined by the ionization of the Tl. The electron temperature was fixed at 2000 eV while an ion temperature of 1600 eV was used. At this temperature, in the absence of the Ca pump line, 26% of the Tl population was in the Ni-like sequence, with 11% or 2.2×10^{18} ions/cm^3 in the Ni-like ground state. The electron density was 1.04×10^{21} electrons/cm^3. Steady-state calculations were done under these conditions for several values of the Ca pump line n_λ from 0 to 0.002 photon per mode. In Table I are shown the gains for the six Ni-like Tl laser lines at four values of the Ca pump line. The two strongest lines at 54.3 and 62.2 Å have maximum gains of 9 and 15 cm^{-1}. The shortest-wavelength line at 33.1 Å, which is analogous to the dominant line observed to lase in laser-driven Ni-like plasmas of nearby ions, is relatively unaffected by this pumping mechanism and would be expected to lase weakly in comparison to the other two lines. Another advantage of this scheme is that the analog to the 62.2-Å line has been observed to lase in Ni-like Ta and W.[14] Therefore it will be much easier to observe the photopumping process on the 62.2-Å line as it should lase in the absence of the Ca pump and so the use of the Ca pump will increase an already finite exponential gain.

An important limitation on the thickness of the Tl laser is absorption of the Ly-α pump line by the Tl and radiation trapping. Assuming $n_\lambda=0.002$, the Tl resonance line being pumped has an absorption coefficient of 92 cm^{-1}, indicating that a 100-μm-thick laser would be approximately 1 mean free path thick to the pump radiation. The Ni-like Tl ground-state to $\overline{3d}_{5/2}4p_{3/2}(J=1)$ transition, which is responsible for radiation-trapping effects that can lower the gain in the laser lines, has an absorption coefficient of 97 cm^{-1}, and places similar limitations on the thickness of the laser.

Similar laser performance would be expected from the other Ni-like ions in the presence of the appropriate Ly-α pump lines. Table II gives the wavelengths for the analogous laser lines of the other Ni-like ions from hafnium to thorium which can be resonantly photopumped in the same manner as Ca-pumped Tl. Of the six laser lines shown for each ion only two, the analogs to the Tl 54.3- and 62.2-Å lines, would be expected to dominate the spectra if the laser is strongly photopumped.

In conclusion, a new class of x-ray lasers has been proposed which consists of a Ni-like ion with atomic number Z being resonantly photopumped from the ground state to the $\overline{3d}_{5/2}6f_{7/2}(J=1)$ state by the Ly-α lines of a H-like ion with atomic number $(Z-21)/3$. Experimental data indicate a good resonance between the Ni-like transitions and the Ly-α pump lines and suggest that gain on several $4d\rightarrow4p$ Ni-like transitions ranging from 23 to 80 Å may be observed for seven pairs of Ni-like and H-

TABLE II. Laser wavelengths for Ni-like ions.

Transition	λ (Å) for Z = 72	75	78	81	84	87	90
$\overline{3d}_{3/2}4d_{3/2}(J=0)\rightarrow\overline{3d}_{3/2}4p_{1/2}(J=1)$	46.6	41.6	37.1	33.1	29.4	26.2	23.3
$\overline{3d}_{5/2}4d_{5/2}(J=0)\rightarrow\overline{3d}_{3/2}4p_{1/2}(J=1)$	60.3	53.7	47.8	42.6	37.9	33.8	30.0
$\overline{3d}_{3/2}4d_{3/2}(J=0)\rightarrow\overline{3d}_{5/2}4p_{3/2}(J=1)$	52.7	47.9	43.6	39.7	36.2	33.0	30.1
$\overline{3d}_{5/2}4d_{5/2}(J=0)\rightarrow\overline{3d}_{5/2}4p_{3/2}(J=1)$	70.8	64.7	59.2	54.3	49.9	46.0	42.4
$\overline{3d}_{5/2}4d_{5/2}(J=2)\rightarrow\overline{3d}_{5/2}4p_{3/2}(J=1)$	76.6	70.4	64.9	59.8	55.2	51.0	47.2
$\overline{3d}_{5/2}4d_{5/2}(J=1)\rightarrow\overline{3d}_{5/2}4p_{3/2}(J=1)$	79.8	73.3	67.5	62.2	57.4	53.0	48.9

like ions. By modifying the existing design of collisionally pumped Ni-like lasers it is quite possible that this new laser will be demonstrated in the near future.

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