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Experiments on Resonantly Photo-Pumped X-ray Lasers

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ABSTRACT: We describe our recent effort to identify and study a promising resonantly photo-pumped X-ray laser scheme. In particular we will describe a scheme which uses the strong emission lines of a nickel-like ion to resonantly photo-pump a neon-like ion and enhance the lasing of the neon-like $3p \rightarrow 3s$ transitions.

1. INTRODUCTION

There has been a resurgence in the study of resonantly photo-pumped X-ray lasers in recent years[Elton 1990, Boehly et al 1990, Skinner 1991, Nilsen 1992]. One new idea being pursued at Lawrence Livermore National Laboratory(LLNL) is to use the strong emission lines of a nickel-like ion to resonantly photo-pump a neon-like ion and enhance the lasing of the neon-like $3p \rightarrow 3s$ transitions. Calculations suggest that there is a series of resonances between the neon-like ground state $\rightarrow \overline{2p}_{1/2}\,4d_{3/2}$ $(J = 1)$ transition in the ion with atomic number Z and the nickel-like $\overline{3d}_{5/2}\,4f_{7/2}$ $(J = 1) \rightarrow$ ground state transition in the ion with atomic number 2Z+5 for Z's from 33 to 39. An example is neon-like rubidium[Z = 37] pumped by nickel-like gold(2Z+5 = 79). We will report on the EBIT experiments which quantify these resonances and the kinetic modeling of these schemes which predicts a large enhancement for the gain of the $\overline{2p}_{1/2}\,3p_{1/2}$ $(J = 0) \rightarrow \overline{2p}_{1/2}\,3s_{1/2}$ $(J = 1)$ laser line. This is the long wavelength $0 \rightarrow 1$ line which was predicted to have the largest gain in the neon-like collisional excitation lasers but which fell short of predictions in the actual experiments.

As a next step in demonstrating a resonantly photo-pumped laser one needs a strong pump line which is both resonant with an appropriate line in the lasant material and in spatial and temporal proximity with that line. We report on a series of Nova experiments to investigate the gold-pumped rubidium scheme. These experiments use gold targets to measure the nickel-like gold pump radiation and quantify the pump strength, rubidium targets to measure the X-ray emission lines and verify the presence of neon-like rubidium ions, and layered targets of gold and rubidium to demonstrate the temporal coexistence of the gold and rubidium plasmas. The layered targets were varied to explore the impact of having a rubidium laser tamped by gold. The laser spectrum is observed in all the experiments in an attempt to verify the resonant photo-pumping mechanism.

2. LASER GAIN AND KINETICS

Figure 1 shows the basic lasing mechanism for the Au-pumped Rb laser line at 165 Å. To estimate the potential gain from photo-pumping such a system, we made an atomic model of Rb and used XRASER to calculate[Nilsen 1988] the steady state gain for a Rb plasma with an ion density of 10^{19} cm^{-3} and an electron density determined by the ionization of the Rb. The electron temperature was fixed at 1000 eV while an ion temperature of 600 eV was used. At this temperature, 44% of the Rb population is in the Ne-like sequence.

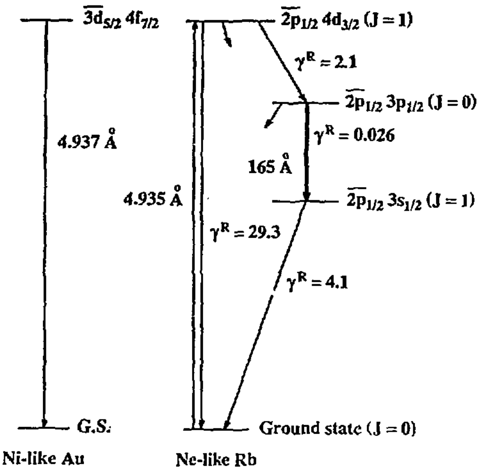

Figure 1. Ne-like Rb laser resonantly photo-pumped by Ni-like Au radiation.

Table 1 shows the expected gains for the nine Ne-like Rb laser lines at four values of the Au pump line strength n_λ in photons per mode. The first four lines in the table are the most strongly photo-pumped. The line at 165.0 Å corresponds to the Ne-like Se 182 Å line; this line is seen in many of the collisionally pumped Ne-like lasers and should be strongly driven by the photo-pumping process. The line at 232.1 Å is not seen in the collisionally pumped Ne-like lasers and therefore its presence would be a strong indicator of photo-pumping, as would the weaker line at 179.6 Å . The two strongest collisionally pumped lines are at 173.5 and 176.1 Å and correspond to the Se 206 and 209 Å lines. These lines are observed in all the collisionally pumped Ne-like lasers. The line at 176.1 Å , while not directly fed by the pumped $4d_{3/2}$ state, is fed strongly by other 4d states which are populated by collisional mixing among the n = 4 manifold and would be enhanced by the photo-pumping process. The last four lines in Table 1, which involve 3p → 3s transitions with a $2p_{3/2}$ vacancy, and include the 173.5 Å line, are only modestly enhanced by the photo-pumping. Both the presence of new lines in the spectra and a dramatic change in the ratio of transitions with a $2p_{1/2}$ vacancy to transitions with a $2p_{3/2}$ vacancy should indicate the presence of photo-pumping.

3. EBIT EXPERIMENTS

The Electron Beam Ion Trap(EBIT) at Lawrence Livermore National Laboratory was used to verify the resonances[Marrs et al 1988, Levine et al 1989]. It uses a compressed, high-current electron beam to excite stationary ions confined in a small trapping volume and was specifically designed for observing the X-ray emission from highly charged ions. For these measurements the X-rays were detected with a flat crystal spectrometer operating in vacuum using either a Ge(111) or a PET(002) crystal. Measurements were done for four of the potential resonances between the Ni-like and Ne-like ions; Re/Br, Ir/Kr, Au/Rb, and Bi/Y. Figure 2 shows the calculated and measured energy difference between the Ne-like and Ni-like lines where Z is the atomic number of the Ne-like ion and 2Z+5 is the atomic number of the

Table 1. Transitions, wavelengths, and gain for a Ne-like Rb laser resonantly photo-pumped by Ni-like Au or Pt radiation

Transition	λ(Å)	Gain(cm^{-1}) for n_λ = 0.0	0.0002	0.0005	0.0010
$\overline{2p}_{1/2}\,3p_{1/2}\,(J=0) \rightarrow \overline{2p}_{1/2}\,3s_{1/2}\,(J=1)$	165.0	4.21	6.95	10.85	16.85
$\overline{2p}_{1/2}\,3p_{3/2}\,(J=2) \rightarrow \overline{2p}_{1/2}\,3s_{1/2}\,(J=1)$	176.1	6.24	7.30	8.82	11.14
$\overline{2p}_{1/2}\,3p_{3/2}\,(J=1) \rightarrow \overline{2p}_{1/2}\,3s_{1/2}\,(J=1)$	179.6	1.92	2.93	4.37	6.59
$\overline{2p}_{1/2}\,3p_{1/2}\,(J=1) \rightarrow \overline{2p}_{1/2}\,3s_{1/2}\,(J=1)$	232.1	2.42	4.68	7.89	12.83
$\overline{2p}_{1/2}\,3p_{1/2}\,(J=0) \rightarrow \overline{2p}_{3/2}\,3s_{1/2}\,(J=1)$	91.2	0.66	1.12	1.77	2.77
$\overline{2p}_{3/2}\,3p_{3/2}\,(J=0) \rightarrow \overline{2p}_{3/2}\,3s_{1/2}\,(J=1)$	141.0	1.86	2.11	2.47	3.01
$\overline{2p}_{3/2}\,3p_{3/2}\,(J=2) \rightarrow \overline{2p}_{3/2}\,3s_{1/2}\,(J=1)$	173.5	7.65	7.91	8.27	8.83
$\overline{2p}_{3/2}\,3p_{3/2}\,(J=1) \rightarrow \overline{2p}_{3/2}\,3s_{1/2}\,(J=1)$	185.2	3.91	4.02	4.18	4.43
$\overline{2p}_{3/2}\,3p_{1/2}\,(J=2) \rightarrow \overline{2p}_{3/2}\,3s_{1/2}\,(J=1)$	233.5	7.06	7.28	7.60	8.09

Ni-like ion. The calculated values using the MCDF atomic physics code of Grant et al[1980] were shifted by 1.88 eV to give excellent agreement. This is typical of the difference between theory and measurements. The best resonances, 0.9 eV, are for the Ir/Kr and Au/Rb pairs. Figure 3 shows the spectrum for the Au and Rb pair.

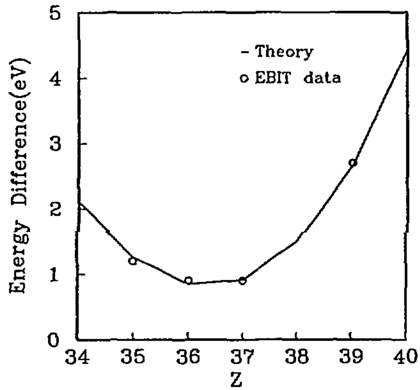

Figure 2. Energy difference between Ne-like $\overline{2p}_{1/2}\,4d_{3/2}(J=1)$ and Ni-like $\overline{3d}_{5/2}\,4f_{7/2}(J=1)$ lines.

For the other Ni-like 4f $\rightarrow$ 3d line there is an excellent resonance of 0.4 eV ± 0.1 eV for one pair of ions, the Ni-like Pt $\overline{3d}_{3/2}\,4f_{5/2}(J=1) \rightarrow$ ground state transition at 2511.9 eV and the Ne-like Rb $\overline{2p}_{1/2}\,4d_{3/2}(J=1) \rightarrow$ ground state transition at 2512.3 eV.

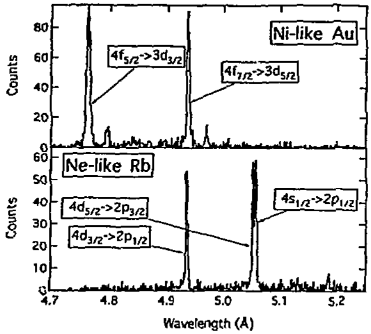

Figure 3. Gold and rubidium spectra shows excellent resonance at 4.935 Å .

4. NOVA EXPERIMENTS

Experiments were conducted on the Nova laser at LLNL using $\lambda = 0.53$ μm. Two beams of the Nova II laser illuminated simultaneously each side of a Rb, Au, or Au/Rb foil. The Rb(or Au) foil consisted of 100 μg/cm^2 of RbCl(or Au) deposited on a 24 μg/cm^2 lexan substrate. The Au/Rb foil had 50 μg/cm^2 of Au, then 50 μg/cm^2 of RbCl, deposited on the 24 μg/cm^2 lexan substrate. The targets were 2-cm long(with a 16% gap in the middle) and were mounted on aluminum stadia. Each beam of the Nova laser had a 500 ps square pulse which was focused to a line 120 μm wide (FWHM) by 2.4 cm long. For a drive pulse with total intensity 4×10^{14} W/cm^2, this corresponds to 2400 J per beam illuminating each side of the target.

The diagnostic instruments included a time-gated, microchannel-plate-intensified grazing-incidence grating spectrograph(MCPIGS) and a streaked flat field spectrograph(SFFS); both of these instruments observed the axial output of the X-ray laser. The MCPIGS provided angular coverage over ± 4.7 mrad about the X-ray laser axis, while the SFFS looked at only one surface of the foil with an angular acceptance of 0 - 10 mrad with respect to that surface. The angular resolution of both instruments was perpendicular to the target surface. Off-axis, a streaked X-ray crystal spectrograph(Keanetech) was used with a KAP crystal to observe the 4.3 - 7.2 Å radiation which originates with the n = 3 and 4 → n = 2 emission lines from the Ne-like Rb and nearby sequences and from the n = 4 → n = 3 emission lines of Ni-like Au and nearby sequences. Two time-integrated crystal X-ray spectrographs(Henways), located at ± 30° to the X-ray laser axis, observed the 3 - 8 Å emission. A second MCPIGS spectrometer was located off-axis to observe the strong emission lines from the plasma in the lasing wavelength region and thereby provide an important check of lasing.

5. EXPERIMENTAL RESULTS

Initial experiments, done for a variety of laser irradiation conditions(1 - 4×10^{14} W/cm^2), indicated that the highest intensities were required to produce the Ni-like Au pump lines while the Ne-like Rb lased well over the whole range of intensities on the 173 and 176 Å collisionally pumped laser lines. To show the simultaneous production of the Ne-like Rb and Ni-like Au, subsequent experiments used an intensity of 4×10^{14} W/cm^2 for the 2 cm long targets of Rb, Au, and Au/Rb described above. The Keanetech and Henway crystal spectrometers verified the production of the Ne-like Rb and Ni-like Au. Figure 4 shows a snapshot in time of the Au and Rb X-ray spectra from the Keanetech spectrometer on separate Au and Rb foils. The spectra are a time integral of the data from 200 to 300 ps where zero is the beginning of the optical drive pulse. All the major 3 → 2 lines in Ne-like Rb[6.2 - 7.0 Å] are observed as well as the 4d → 2p lines[4.94, 5.05 Å]. Some strong F-like Rb 3d → 2p lines[6.05 Å] are also seen. In addition, the He-α line of Cl at 4.444 Å is observed and serves as an important reference line. The Au target produced a nice 4 → 3 Ni-like spectrum with many strong lines between 4.7 and 5.1 Å in the region of the 4.935 Å Ne-like Rb line.

The SFFS and MCPIGS spectrometers showed the Rb targets lasing well on the 173 and 176 Å Ne-like Rb laser lines, another indicator of a strong Ne-like Rb population. The MCPIGS spectrometer observed the Au lase at 35.6 Å in Ni-like Au, an indicator of a strong Ni-like Au population.

For a typical Au/Rb target, Figure 5 shows the time snapshot of the X-ray spectra from the Keanetech spectrometer. One now sees both the strong 4 → 3 Ni-like Au lines and the strong 3 → 2 Ne-like Rb lines. This indicates that we can produce the pump and lasant ions simultaneously in a single plasma. The SFFS and MCPIGS spectrometers also showed lasing on the 173 and 176 Å Ne-like Rb laser lines. This is a very important indicator that the plasma conditions are adequate to allow laser propagation in a Rb target tamped with another material, Au in this case. No enhanced lasing due to the resonant photo-pumping could be verified in this experiment.

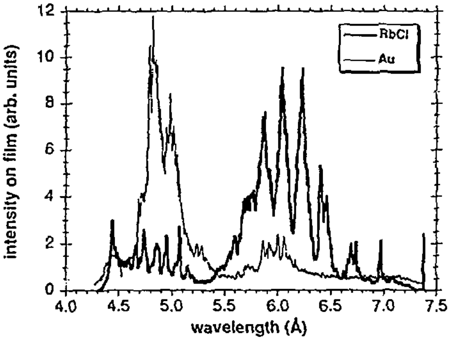

Figure 4. Keanetech X-ray spectra of RbCl and Au plasmas.

6. CONCLUSIONS

We have theoretically identified a series of resonances between the neon-like ground state → $\overline{2p}_{1/2}\,4d_{3/2}$ (J = 1) transition in the ion with atomic number Z and the nickel-like $\overline{3d}_{5/2}\,4f_{7/2}$ (J = 1) → ground state transition in the ion with atomic number 2Z+5 for Z's from 33 to 39. Four of these resonances have been verified on EBIT. Modeling of the gain for the Au-pumped Rb laser has been done. Initial Nova experiments with targets of Au, Rb, and Au/Rb have shown that we can produce a strong Ni-like Au pump line at 4.937 Å simultaneous with the Ne-like Rb line at 4.935 Å which we are trying to resonantly photo-pump.

EBIT experiments have also confirmed an even closer resonance between the neon-like ground state → $\overline{2p}_{1/2}\,4d_{3/2}$ (J = 1) transition in rubidium and the nickel-like $\overline{3d}_{3/2}\,4f_{5/2}$ (J = 1) → ground state transition in platinum. New experiments are underway with the Pt/Rb combination to try to increase the pump

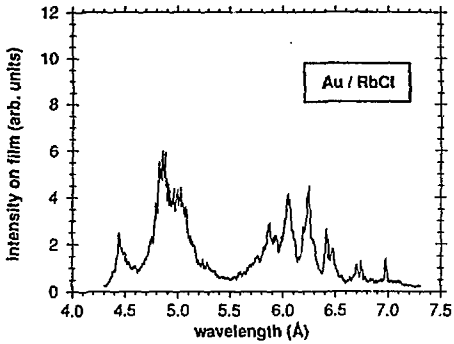

Figure 5. Keanetech X-ray spectrum of the Au/RbCl plasma.

strength and demonstrate the resonantly photo-pumped X-ray laser.

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