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EBIT X-ray Spectroscopy Studies for Applications to Photo-Pumped X-ray Lasers

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EBIT X-ray Spectroscopy Studies for Applications to Photo-Pumped X-ray Lasers

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Introduction: Several pumping mechanisms have been suggested for x-ray lasers including collisional excitation, recombination, photo-ionization and photo-pumping [1]. The success of photo-pumping as an x-ray laser scheme hinges on sufficient overlap of the emission and absorption lines. For such a scheme to exhibit gain, the difference of the energies of the two lines must be within the line widths determined by the plasma dynamics, such as Doppler and opacity broadening. Typically, an overlap of a few parts in 10^4 is required. Due to correlation effects, high-n levels of multi-electron ions are difficult to calculate and are reliable to roughly a part in 10^3. These differences are large enough to preclude accurate predictions of successful overlaps. As a result, precise measurements of the overlaps are needed. The continued interest in photo-pumping schemes lies in its potential to improve the laser output. It also allows the excitation of lasing transitions not accessible to other mechanisms and thus to test laser kinetics from a different perspective. Figure 1 shows an example of a photo-pumped x-ray laser scheme.

We have studied several such photo-pumping schemes at the LLNL electron beam ion trap (EBIT)[2]. The Ni-like isoelectronic sequence 3d-5f and 3d-6f transitions were studied for photo-pumping by He-like ions, the Ne-like 2p-4d transitions were studied for photo-pumping by Ni-like 3d-4f transitions, and Ni-like $3d_{5/2}$-$6f_{7/2}$ transitions were studied for photo-pumping by H-like Ly-α transitions. A number of other chance coincidence pairs which do not follow an isoelectronic sequence were also studied. The data were taken with a flat-crystal vacuum spectrometer [3], a flat-crystal helium atmosphere spectrometer, or a curved-crystal spectrometer in the von Hamos geometry[4].

The advantage of EBIT over laser-produced or tokamak plasmas for such experiments is its ability to control the charge balance and the excitation process. By choosing the electron beam energy, we can select a dominant charge state. In particular, by operating below various ionization potentials, the contributions of various charge states to a spectrum can be deduced. Moreover, blends with satellite lines produced by dielectronic recombination can be avoided by proper choice of the beam energy. Thus, wavelength measurements are unambiguous, reliable, and precise.

Ni-like ions pump Ne like ions We have investigated a particular class of schemes whereby a $2p_{1/2}$-$4d_{3/2}$ transition in a Ne-like ion of atomic number Z is photo-pumped by a $3d_{5/2}$-$4f_{7/2}$ transition in a corresponding Ni-like ion of atomic number (2Z + 5) [5]. These potential resonances lie along an isoelectronic sequence. Therefore we measured a number of the transitions along the sequence to search for good overlap candidates. The theoretical predictions of the energies of these transitions, based on a multi-configuration Dirac-Fock calculation using the code of Grant et al. [6], were found to be offset by 1.88 eV from the measured values. By having observed a family of these transitions, the determined offset improves future predictive power.

A similar class of schemes exists where the $2p_{1/2}$-$4d_{3/2}$ transition in a Ne-like ion of atomic number Z is photo-pumped by the $3d_{3/2}$-$4f_{5/2}$ transition in a corresponding Ni-like ion of atomic number (2Z + 4). Here the offset was determined to be 2.86 eV and a favorable resonance was identified with Ne-like Rb pumped by Ni-like Pt at 2512 eV. The energy difference was found to be 0.4 ± 0.1 eV or 160 ppm .

He-like ions pump Ni-like ions This class of schemes also follows an isoelectronic sequence. The He-like 2^1P_1-1^1S_0 transition may pump a 3d-6f or 3d-5f transition in a Ni-like ion. Which transition depends upon the ion pair in question. For this data we also measured an offset between theory and experiment for the Ni-like transitions and found that the $3d_{5/2}$-$6f_{7/2}$ transition differed from theory by 1.60 eV, the $3d_{3/2}$-$6f_{5/2}$ transition differs from theory by 2.01 eV, the $3d_{5/2}$-$5f_{7/2}$ transition differs by 1.06 eV, and the $3d_{3/2}$-$5f_{5/2}$ transition differs by 1.29 eV[7]. The most favorable overlap was found for the He-like F 2^1P_1-1^1S_0 transition pumping the Ni-like Ag $3d_{3/2}$-$6f_{5/2}$ transition. The two lines differ by 190 ppm at 738 eV.

H-like ions pump Ne-like and Ni-like ions The collection of possible lasant-pump pairs in this group do not follow an isoelectronic sequence but are chance coincidences between the H-like Ly-α line and various transitions in a number of Ne-like ions. The pairs we have studied to date are Ne and Fe [8], Na and Co [9], and Mg and Ge [10]. The H-like Ne Ly-α and $2p_{1/2}$-$4d_{3/2}$ Ne-like Fe transitions differ by 600 ppm at 1022 eV, the H-like Ly-α Na and $2s_{1/2}$-$4p_{3/2}$ Ne-like Co transitions differ by 100 ppm at 1237 eV, and the H-like Ly-α Mg and $2s_{1/2}$-$3p_{1/2}$ Ne-like Ge transitions differ by 340 ppm at 1472 eV. Figure 2 shows an example of the spectra of Na and Co elucidating the overlap.

A measurement was also done on the H-like Al and Ni-like Er pair. The H-like Al Ly-a and $3d_{3/2}$-$4f_{5/2}$ Ni-like Er transitions differ by 1000 ppm at 1726 eV [11].

An additional class of Ly-α pumped schemes uses a H-like ion of atomic number Z and the $3d_{5/2}$-$6f_{7/2}$ Ni-like transition in ions of atomic number (3Z + 21) [12]. The best candidate was determined to be H-like Ca pumping Ni-like Tl. The Ca Ly-α and Ni-like Tl $3d_{5/2}$-$6f_{7/2}$ transitions differ by 260 ppm at 4108 eV.

He-like ions pump Ne-like ions This collection of possible lasant-pump pairs does not follow an isoelectronic sequence. The pairs we have studied to date include Ar and Y [13] and Mg and Cu [8]. The He-like Ar 2^1P_1-1^1S_0 and Ne-like Y $3p_{1/2}$-$5d_{3/2}$ transitions differ by 150 ppm at 3140 eV and the He-like Mg 2^3P_1-1^1S_0 and Ne-like Cu $2p_{3/2}$-$4d_{5/2}$ transitions differ by 200 ppm at 1343 eV. Figure 3 shows an example of the spectra of Mg and Cu.

Conclusion Several of the above pairs are good candidates for photo-pumping. For example, if the appropriate plasma conditions could be prepared, the Pt-Rb scheme described above would lase on a transition of about 165 Å. The Ar-Y scheme would lase on a transition near 155 Å, and the Mg-Cu scheme would lase near 235 Å.

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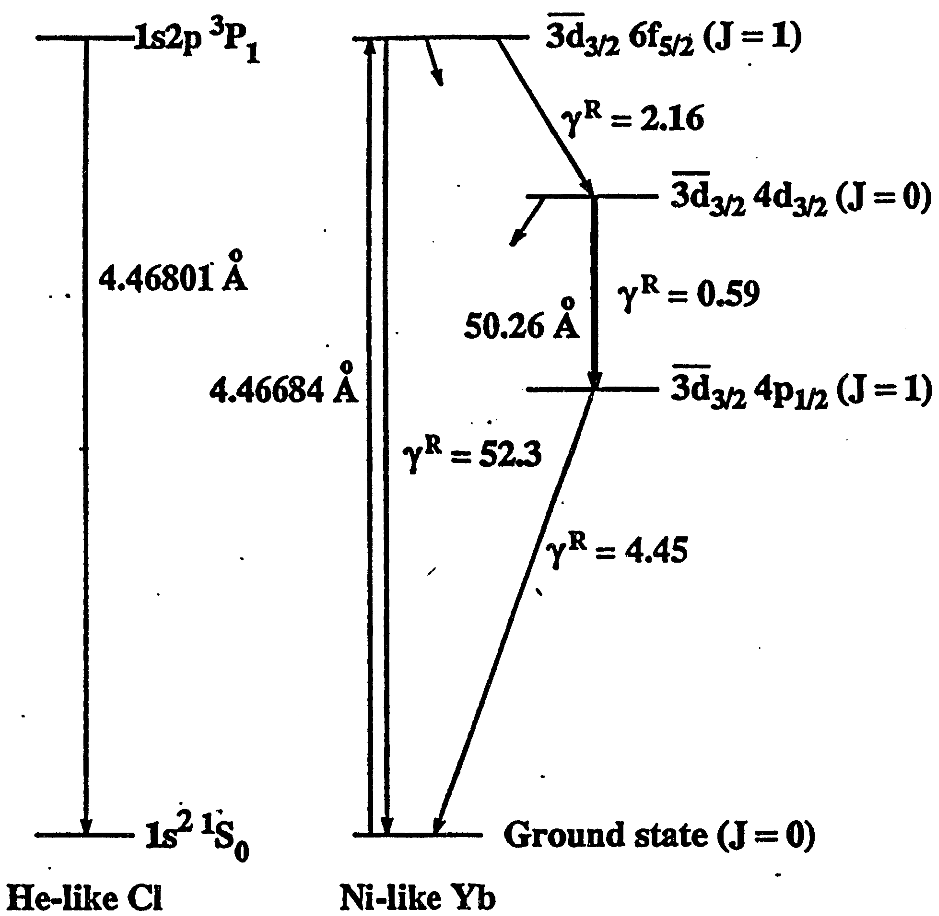

Figures 1: Level diagrams demonstrating an example laser scheme. Transition rates are indicated γ^R and are in units of $psec^{-1}$. The bar over the 3d indicates a vacancy in the closed M shell.

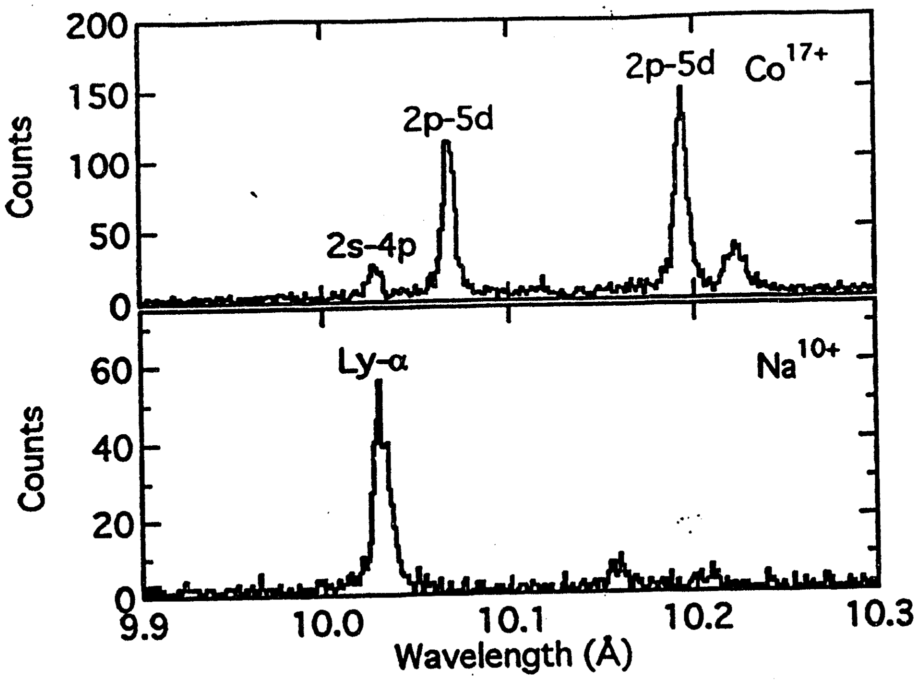

Figure 2: The spectra of H-like Na and Ne-like Co elucidating the potential overlap.

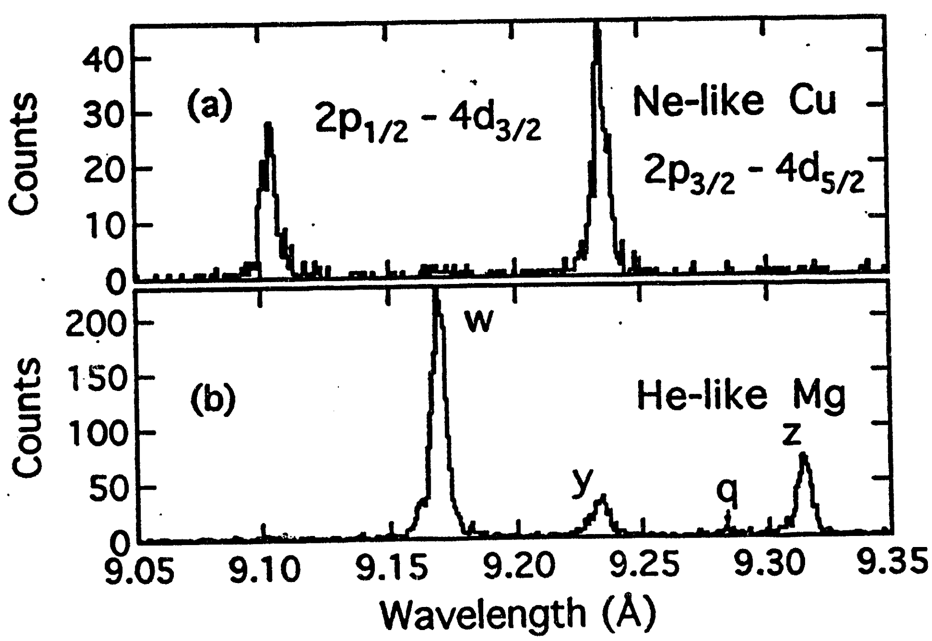

Figure 3: The spectra of He-like Mg and Ne-like Cu elucidating the potential overlap.

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