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Measurements of Line Overlap for Resonant Spoiling of X-ray Lasing Transitions

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Abstract. High-precision measurements are presented of candidate line pairs for resonant spoiling of x-ray lasing transitions in the nickellike W^{46+}, the neonlike Fe^{16+}, and the neonlike La^{47+} x-ray lasers. Our measurements were carried out with high-resolution crystal spectrometers, and a typical precision of 20–50 ppm was achieved. While most resonances appear insufficient for effective photo-spoiling, two resonance pairs are identified that provide a good overlap. These are the $4p_{1/2}\rightarrow 3d_{3/2}$ transition in nickellike W^{46+} with the $2p_{3/2}\rightarrow 1s_{1/2}$ transition in hydrogenic Al^{12+}, and the $3s_{1/2}\rightarrow 2p_{3/2}$ transition in neonlike La^{47+} with the 1^1S_0-2^1P_1 line in heliumlike Ti^{20+}.

Introduction

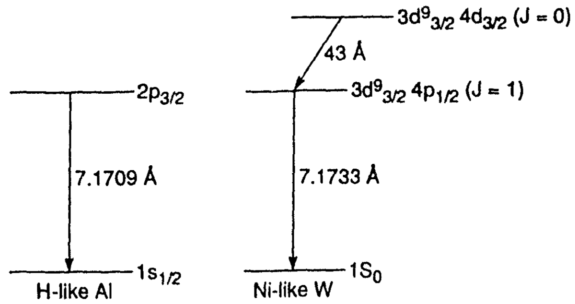
Modification of the x-ray laser kinetics by resonant photo-pumping is of practical and scientific interest. For example, resonant photo-pumping has been proposed as an efficient way to achieve lasing [1]. Conversely, resonant photo-pumping may be used to spoil lasing. This allows tailoring of the laser to yield monochromatic output that suits available x-ray optics. It can also be used to probe the laser kinetics in order to obtain a better understanding of the principles of x-ray lasing.

Photo-pumping requires resonances on the order of a few hundred parts per million (ppm). Candidate resonances must be experimentally verified, as the accuracy achieved by calculations is typically only within a range of a few parts per thousand for the multi-electron ions of interest in x-ray lasing. In the following we present measurements of candidate resonances for spoiling of x-ray laser transitions. The lasers considered are the nickellike W^{46+} laser shown to lase at 43.1 Å [2] and the neonlike Fe^{16+} laser shown to lase at 254.9, 347.6, and 388.9 Å [3]. We also investigated spoiling of a proposed neonlike La^{47+} laser, which might lase at 57, 8 and 128 Å [4]. Lasing in La^{47+} cannot yet be attained with existing facilities, but might be achieved in experiments with the planned National Ignition Facility.

Spoiling of the Nickellike W^{46+} Laser

A diagram showing the levels involved in the resonant spoiling of the nickellike W^{46+} laser is shown in Fig. 1. The 43-Å lasing transition proceeds from level $(3d_{3/2},4d_{3/2})_{J=0}$ to level $(3d_{3/2},4p_{1/2})_{J=1}$. Raising the population of the lower level will diminish or destroy the population inversion necessary for lasing and thus will spoil the 43-Å laser. This is accomplished by pumping with an appropriate line whose wavelength is nearly coincident with that of the dump transition from level $(3d_{3/2},4p_{1/2})_{J=1}$ to the $^1S_0$ ground level. The energy of the $4p_{1/2}\rightarrow 3d_{3/2}$ dump line was predicted to be 1728 eV, or 7.150 Å [5]. A candidate pump line is provided by the $2p_{3/2}\rightarrow 1s_{1/2}$ Ly-α_1 line in hydrogenic Al^{12+} at 7.1709 Å [6], as shown in Fig. 1. Other candidate pump lines are the $2p_{1/2}\rightarrow 1s_{1/2}$ Ly-α_2 line in Al^{12+} (predicted at 7.1763 Å [6]), the transition from $(2p_{1/2},3d_{3/2})_{J=1}$ to the $^1S_0$ ground level in neonlike Br^{25+} (predicted at 7.1700 Å [7]), and the transition from $(3d_{3/2},4f_{5/2})_{J=1}$ to the $^1S_0$ ground level in nickellike Er^{40+} (predicted at 7.1760 Å [8]).

FIGURE 1. Energy level diagram showing the mechanism for spoiling of the 43-Å nickel-like W^{46+} laser by resonant photo-pumping with hydrogen-like Al^{12+}. Increasing the population of the 4p level spoils a possible inversion and thus lasing between the 4p and 4d levels.



The candidate photo-pumping resonances are verified in measurements on the Livermore electron beam ion trap (EBIT). The device uses a monoenergetic electron beam to produce and excite a particular ion species of interest, and a given line can be observed free of blends with collisional or dielectronic satellites [9]. Recording spectra with the evacuated flat-crystal spectrometer described in Ref. [10], and using the Lyman-α lines of Al^{12+} as reference lines, we find 7.1733±0.0003 Å for the tungsten line. Moreover, we measured 7.1837±0.0020 Å for the wavelength of the $4f_{5/2}\rightarrow 3d_{3/2}$ transition in nickellike Er^{40+} and 7.1685±0.0002 Å for that of the $3d_{3/2}\rightarrow 2p_{1/2}$ transition in neonlike Br^{25+}. A summary of the results is given in Table I.

Table I. Comparison of measured and predicted wavelengths of candidate photo resonances in the Ni-like W^{46+} and Ne-like Fe^{16+} and La^{47+} lasers (in Å). Lines used as reference standards are denoted by (*).

Laser	Upper Level	Ion	Theory	Experiment
W^{46+}	$3d_{3/2},4p_{1/2}$(J=1)	W^{46+}	7.150 [Ref.5]	7.1733(3)
	$3d_{5/2},4f_{7/2}$(J=1)	Er^{40+}	7.1760 [Ref.8]	7.1830(20)
	$2p_{1/2},3d_{3/2}$(J=1)	Br^{25+}	7.1700 [Ref.7]	7.1685(2)
	$2p_{3/2}$(J=3/2)	Al^{12+}	7.17091 [Ref.6]	7.17091(*)
	$2p_{1/2}$(J=1/2)	Al^{12+}	7.17632 [Ref.6]	7.17632(*)
Fe^{16+}	$2p_{1/2},3s_{1/2}$(J=1)	Fe^{16+}	16.797 [Ref.7]	16.772(3)
	$1s_{1/2},2p_{3/2}$(J=1)	F^{7+}	16.8064 [Ref.11]	16.8064(*)
La^{47+}	$2p_{3/2},3s_{1/2}$(J=1)	La^{47+}	2.61001 [Ref.13]	2.61015(10)
	$2p_{3/2},3s_{1/2}$(J=2)	La^{47+}	2.61330 [Ref.13]	2.61330(5)
	$1s_{1/2},2p_{3/2}$(J=1)	Ti^{20+}	2.61040 [Ref.11]	2.61040(*)

The measured location of the candidate pump lines relative to the measured position of the $4p_{1/2} \rightarrow 3d_{3/2}$ dump transition in tungsten is shown schematically in Fig. 2. The best resonance is found with the $2p_{3/2} \rightarrow 1s_{1/2}$ Ly-α_1 line in hydrogenic Al^{12+}. The two lines differ by 2.4±0.3 mÅ or 335 ppm. Figure 2 also gives a schematic overview of the predicted locations of the various lines. A comparison of the predicted and measured locations illustrates the unequivocal need for precise measurements of candidate resonances.

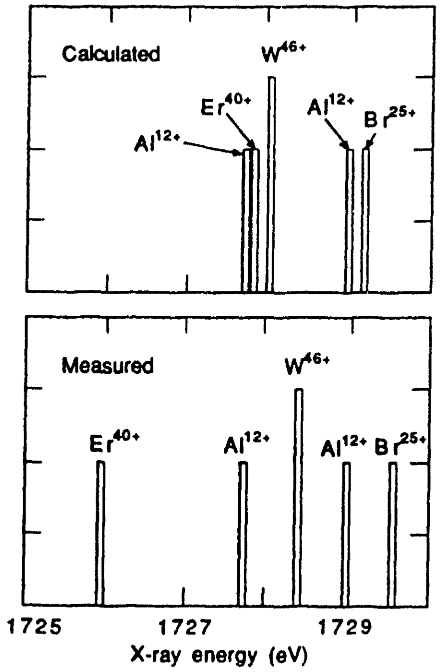


Figure 2. Comparison of predicted and measured location of the 3d-4p transition in nickel-like W^{46+} and of various candidate resonant photo-pumping transitions.

Spoiling of the Neonlike Fe^{16+} Laser

A diagram showing the levels involved in the resonant spoiling of the neonlike Fe^{16+} laser is shown in Fig. 3. Resonant photo-pumping of the $2p_{1/2}$–$3s_{1/2}$ transition in neonlike iron at 16.772 Å enhances the population of the $(2p_{1/2},3s_{1/2})_{J=1}$ level, which is the lower level for several 3p→3s lasing transitions, including the 255-Å lasing line observed to dominate lasing in neonlike iron [3]. A candidate pump line is given by the 1^1S_0–2^1P_1 line in heliumlike F^{7+}.

The candidate photo-pumping resonance is again verified in measurements on the EBIT facility. Using the wavelengths of the 1^1S_0–2^1P_1 and 1^1S_0–2^3S_1 lines calculated by Drake [11], (16.8064 and 17.1528 Å, respectively) to calibrate the measurements, we find 16.772±0.003 Å for the $2p_{1/2}$–$3s_{1/2}$ line in neonlike iron Fe^{16+}. The separation between it and the heliumlike F^{7+} resonance line is 35±3 mÅ, or 2,000 ppm.

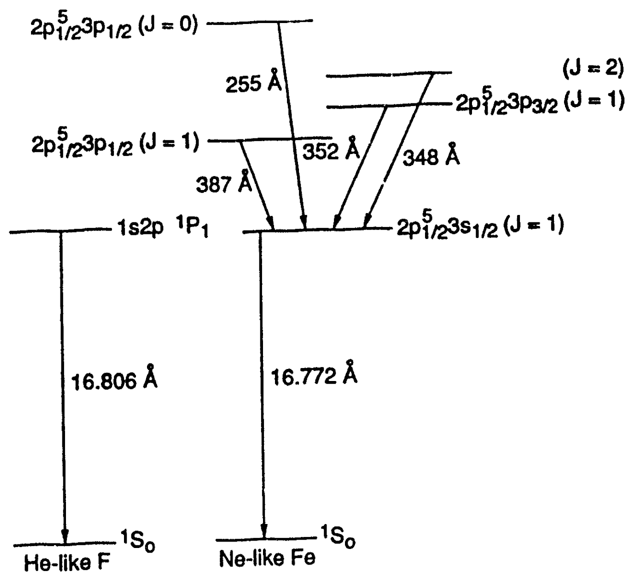


Figure 3. Energy level diagram showing the mechanism for spoiling of lasing in neonlike Fe^{16+} by resonant photo-pumping of the $2p_{1/2}$-$3s_{1/2}$ transition by the 1^1S_0 - 2^1P_1 transition in heliumlike F^{7+}. Increasing the population of the 3s level spoils a possible inversion and thus lasing between the 3s and 3p levels.

Spoiling of the Neonlike La^{47+} Laser

The highest-Z neonlike laser demonstrated so far is neonlike Ag^{37+} with lasing lines at 100 Å [12]. This experiment was carried out on the NOVA laser facility and appears to represent the upper limit of Z that can be made to lase with existing facilities. As a result, a neonlike La^{47+} laser has not yet been demonstrated. Such a laser would, however, be feasible with the planned National Ignition Faciliy. If successful, lasing between the levels $(2p_{1/2},3p_{3/2})_{J=2}$ and $(2p_{1/2},3s_{1/2})_{J=1}$ and between the levels $(2p_{3/2},3p_{1/2})_{J=2}$ and $(2p_{3/2},3s_{1/2})_{J=1}$ would result in lines at 58.3±2 and 128.2±0.8 Å, as inferred from high-resolution measurements of the 2p-3p and 2p-3s transitions [4]. Lasing would also be expected at 57 Å between the levels $(2p_{3/2},3p_{3/2})_{J=2}$ and $(2p_{3/2},3s_{1/2})_{J=1}$ as well as between other levels.

Resonant photo-pumping of the $2p_{3/2}$–$3s_{1/2}$ transition with the 1s2p $^1P_1 \rightarrow 1s^2\ ^1S_0$ transition in heliumlike Ti^{20+} could be used to spoil lasing transitions involving the $(2p_{3/2},3s_{1/2})_{J=1}$ dump level. Drake [11] predicted the wavelength of the 1^1S_0-2^1P_1 line in heliumlike Ti^{20+} to be 2.6104 Å, while Ivanova and Gulov [13] predicted the wavelength of the transition from $(2p_{3/2},3s_{1/2})_{J=1}$ to the $^1S_0$ ground level in neonlike La^{47+} to be 2.6100 Å.

The candidate photo-pumping resonance is verified in measurements on the Princeton Large Torus (PLT) tokamak using a Johann-type Bragg-crystal spectrometer [14]. Using 2.61040 Å for the 1^1S_0-2^1P_1 line in titanium to calibrate the spectrum, we find 2.61015±0.00010 Å for the wavelength of the transition from $(2p_{3/2},3s_{1/2})_{J=1}$ to the $^1S_0$ ground level in neonlike lathanum La^{47+}. We find 2.61330±0.00005 Å for the neighboring transition from the $(2p_{3/2},3s_{1/2})_{J=2}$ level to ground.

Discussion

Among the candidate resonances investigated only two are found that are sufficiently good to allow photo-pumping. The first is the resonance between the $2p_{3/2}\rightarrow 1s_{1/2}$ Ly-α_1 line in hydrogenic Al^{12+} and the $4p_{1/2}\rightarrow 3d_{3/2}$ transition in nickellike W^{46+}. The two lines differ by 335 ppm, which approximately equals the Doppler broadening of the aluminum line in a 500-eV plasma. Moreover, the tungsten line differs only 420 ppm from the $2p_{1/2}\rightarrow 1s_{1/2}$ Ly-α_2 line in hydrogenic Al^{12+}, and the Ly-α_2 line may also contribute to pumping the nickel-like transition, especially as the two Ly-α components blend into a sinigle line in optically thick plasmas. The fact that the tungsten line lies between the Ly-α lines is especially important in cases where plasma motion shifts the wavelength of the tungsten line (or that of the aluminum lines). Such a shift would improve the resonance, regardless of the relative direction of the motion.

The second, good resonance is found between the $3s_{1/2}\rightarrow 2p_{3/2}$ line in neonlike lathanum La^{47+} and the $2p_{3/2}\rightarrow 1s_{1/2}$ line in heliumlike Ti^{20+}. The two lines differ by only 96 ppm, representing an excellent resonance for photo-pumping provided a neonlike lathanum La^{47+} laser were achieved with the National Ignition Facility or a similar laser facility with the more intensity and energy than currently available.

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