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Wavelengths of the Ni-like $4d\ {}^1S_0-4p\ {}^1P_1$ x-ray laser line

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We measure the wavelengths of the Ni-like $3d^9\,4d\ {}^1S_0-3d^9\,4p\ {}^1P_1$ x-ray laser line in several low-Z Ni-like ions ranging from Y ($Z=39$) to Cd ($Z=48$). These wavelengths are compared with optimized level calculations using a multiconfiguration Dirac-Fock code. With the help of these results, we identify this line to very high accuracy in nonlasing plasmas from As ($Z=33$) to Mo ($Z=42$). Accurate values of these wavelengths are essential for performing plasma imaging and interferometry experiments with multilayer optics that use the x-ray laser to backlight other plasmas. These results also provide important atomic data that are currently missing about the energy of the $4d\ {}^1S_0$ level in the Ni I sequence. [S1050-2947(98)50809-8]

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Accurate knowledge of the lasing wavelengths is essential for applications of laboratory x-ray lasers that rely on multilayer optics designed to work at one wavelength [1–3]. These applications include complex imaging and interferometry experiments that utilize x-ray lasers to backlight other plasmas. As an example, recent experiments [3] used an x-ray interferometer at 155 Å to measure the electron density of an exploding Se foil. The interferometer consisted of seven multilayer mirrors and beam splitters, each with a bandpass of ± 4 Å. If one wants to increase the diagnostic sensitivity, higher reflectivity components with narrower bandpasses are needed, which requires better knowledge of the x-ray laser wavelength.

Accurate knowledge of the lasing wavelengths is also important for improving our understanding of the energy level structure for the laser ion [4]. This is, in particular, true for collisionally pumped x-ray lasers where lasing occurs in Ne- and Ni-like ions that have complex level structures. In Ne- and Ni-like ions, the upper laser levels are the $2p^5\,3p\ {}^1S_0$ and $3d^9\,4d\ {}^1S_0$ states that mix with the ground states, i.e., the $2p^6\ {}^1S_0$ and $3d^{10}\ {}^1S_0$ states, due to the fact that they have the same angular momentum and parity. As a result, the energy of the upper laser level is difficult to calculate *ab initio*. For Ne-like ions, besides the observation of strong lasing on the $3p\ {}^1S_0 \rightarrow 3s\ {}^1P_1$ transition, this line is also observed in many nonlasing plasmas (see references in Ref. [5]). Therefore, in spite of the theoretical difficulty, the wealth of high-resolution experimental data has greatly improved the calculations and has resulted in excellent accuracy of the Ne-like lasing wavelengths [5].

Lasing in Ni-like ions has been more difficult to achieve and the gains have been lower compared with Ne-like lasers [6]. However, Ni-like systems are more attractive due to the higher quantum efficiency. The energy of the $3d^9\,4d$ level in Ni-like ions is more difficult to calculate *ab initio*, and transitions to and from it are also more difficult to observe, especially for low-Z materials where the $3d^8\,4l\,4l'$ states play an important role (Ni I has a ground-state occupation of $3d^8\,4s^2$ instead of $3d^{10}$). As a result, this line has only been identified in nonlasing plasmas at very low Z for Ga and Ge [7] and most attempts at constructing the energy levels for Ni-like ions do not include an experimental based value for the $3d^9\,4d\ {}^1S_0$ level [8–11]. Fortunately, x-ray laser experiments have observed the $3d^9\,4d\ {}^1S_0 \rightarrow 3d^9\,4p\ {}^1P_1$ line in many Ni-like ions from Pd ($Z=46$) to Ta ($Z=73$) [6,12–18], with saturation observed in Sm [19] and Ag [20]. (We omit the term $3d^9$ from the designation in the rest of this paper to simplify the notation).

In this paper we measure the wavelength of the $4d\ {}^1S_0 \rightarrow 4p\ {}^1P_1$ laser transition in seven ions between Y ($Z=39$) and Cd ($Z=48$) in lasing plasmas. We present results of an optimized level calculation using a multiconfiguration Dirac-Fock (MCDF) code. Using the unambiguous identification of the $4d\ {}^1S_0 \rightarrow 4p\ {}^1P_1$ line in the lasing plasma we are then able to identify this line to very high accuracy in nonlasing plasmas for most low Z ions from As ($Z=33$) to Mo ($Z=42$).

To make these materials lase, we utilize the transient collisional excitation scheme reported recently for Ne-like Ti [21] and Ni-like Pd [18]. The scheme uses a ns pulse to preform and ionize the plasma followed by a ps pulse to heat the plasma. The experiments were performed at the COMET Laser Facility at Lawrence Livermore National Laboratory. The system is a hybrid laser based on a Ti:sapphire oscillator and regenerative amplifier tuned to 1053 nm with neodymium-doped (Nd):phosphate glass power amplifiers. The long and short pulses are generated by splitting the 800-ps pulse into two beams before the final amplifier. One beam is then sent through a delay line, maintaining the 800-ps duration, and the other is sent through a vacuum compressor, giving an $\sim$1-ps duration. In the experiments, the delay between the two pulses is 1.6 ns, and the maximum energy in the long and short pulses are each 5 J. The two beams are then combined and focused to a 70 μm$\times$12.5 mm line on to the x-ray laser targets. For the targets we used Y, Zr, Nb, Mo, Pd, Ag, and Cd slabs with thicknesses greater than 100 μm and lengths of approximately 1 cm.

The main diagnostics is an on-axis flat-field grating spectrometer coupled to a thinned backside-illuminated charge-coupled device (CCD) camera. The CCD camera has 1024×1024 pixels. A gold-coated cylindrical mirror collection optics imaged the plasma with 1:1 magnification onto a 100-μm wide entrance slit. The effective angular view was 28×20 mrad in the horizontal and vertical planes, respectively. To calibrate the spectrometer and determine the dispersion, we used well-known spectral lines in Li-like Al and O, H-like C [22], Na-like Ti, V, and Cr [22,23], Cu-like Y, Zr, Nb, and Mo [24]. The calibration is cross checked with the $3p\,^1S_0 \rightarrow 3s\,^1P_1$ lasing lines in Ne-like Ti, V, and Cr [5]. Wavelengths of these lines range from 150 to 330 Å. Given the dispersion, one CCD pixel corresponds to approximately 0.17–0.20 Å across the range of the spectrometer from 144 to 330 Å.

Our initial estimates of the wavelengths of expected laser lines were determined from previous published estimates [25], for $Z \geqslant 46$ and our own optimized level (OL) calculations, using the multiconfiguration Dirac-Fock (MCDF) atomic physics code of Grant *et al.* [26]. The OL calculation of the $4d\,^1S_0$ upper laser state included all of the $n=4$ even-parity $J=0$ states. We then did a separate extended average level (EAL) calculation of the $n=4$ odd-parity $J=1$ states and subtracted the energies to obtain the energy of the $4d\,^1S_0 \rightarrow 4p\,^1P_1$ transition. We then adjusted the calculated energies by 1.03 eV to bring the calculation of Nd into agreement with the well-measured value of this line at 79.06 Å [14]. Our best estimate of the expected wavelengths for this line is seen in Table I. It should be noted that a standard EAL calculation of all the $n=4$ levels, together with the Ni-like ground state, would give the energy of the $4d\,^1S_0$ level that was too high by about 7 eV.

In our x-ray laser experiments we observe lasing on the $4d\,^1S_0 \rightarrow 4p\,^1P_1$ transition in Ni-like Y, Zr, Nb, Mo, Pd, Ag, and Cd. The high brightness, narrow divergence, and nonlinear increase of the intensity with target length were strong evidence of lasing. An on-axis Nb spectrum of a 6-mm target showing the strong $4d\,^1S_0 \rightarrow 4p\,^1P_1$ lasing line at 203.34 Å is given in Fig. 1. The identification of the $4d\,^1S_0 \rightarrow 4p\,^1P_1$ transition is quite unambiguous because it is the only strong lasing line observed, and this same line was observed previously for many elements from Pd ($Z=46$) [18] to Ta ($Z=73$) [6]. In the modeling of low Z Ni-like ions [27], this line is also predicted to be the dominant laser line. The wavelengths of the measured lines with their uncertainties are given in Table I. The error bar given is determined by the accuracy of determining the peak of both the reference lines and the measured lines. Weak evidence of lasing on this transition had been previously reported at 204.2 Å in Ni-like Nb [28].

In the spectrum of Zr, one additional line at 271.05 ± 0.30 Å was seen in some of the experiments. Like the $4d\,^1S_0 \rightarrow 4p\,^1P_1$ lasing line, it also has a relatively narrow divergence. We believe it to be the $4f\ ^1P_1 \rightarrow 4d\,^1P_1$ transition, which lases due to the self-photopumping occurring on the $4f\ ^1P_1 \rightarrow 3d\,^1S_0$ resonance transition. In Mo this line is calculated to have $\frac{2}{3}$ of the gain on the $4d\,^1S_0 \rightarrow 4p\,^1P_1$ line [27]. It is the analog of the $3d\,^1P_1 \rightarrow 3p\,^1P_1$ lasing line that has been observed in Ne-like S [29], Ar [16], and Ti [30]. According to the predicted energy of the $4d\,^1P_1$ level in [9] and the measured energy of the $4f\ ^1P_1$ level [31], this line should be at about 270.9 Å in Zr.

Using the modest resolution measurements and the unambiguous identification of the $4d\,^1S_0 \rightarrow 4p\,^1P_1$ transition in lasing plasmas, we were able to identify this line in nonlasing plasmas from As to Mo. The experiments were described previously [7–9,11,32] and they used either a vacuum spark or a laser-produced plasma for the source with corresponding uncertainties in the wavelength measurement of 0.005 and 0.015 Å. In the analysis, we used the same spectra used in a previous work on Ni-like As [10], Br [8,32], and Rb to Mo ($Z=37-42$) [8,9]. In the previous analysis, the correct identification of the $4d\,^1S_0 \rightarrow 4p\,^1P_1$ line is problematic due to the difficulty in calculating the energy of the $4d\,^1S_0$ level. As an example, the most recent analysis [9] would predict the $4d\,^1S_0 \rightarrow 4p\,^1P_1$ line at 232.35 Å in Y, while it is now observed at 240.11 Å in the x-ray laser plasma and at 240.135

TABLE I. Wavelengths (in Å) of the $4d\,^1S_0 \rightarrow 4p\,^1P_1$ transition in Ni-like ions with $Z=31-60$. The uncertainties in the last digits are given in parentheses.

Z	OL prediction	Laser measurement	Nonlaser measurement
31			840.950(5)[a]
32			642.974(5)[a]
33			519.437(5)
34			435.1(4)[b]
35			374.174(5)
36			328.35(20)[b]
37			292.490(5)
38			263.71(15)[b]
39	240.2	240.11(30)	240.135(15)
40	220.0	220.20(30)	220.290(15)
41	202.9	203.34(30)	203.480(15)
42	188.3	188.95(30)	188.930(15)
43	175.5		
44	165.2		
45	155.3		
46	146.5	146.79(15)	
47	138.6	138.92(15)	
48	131.4	131.66(15)	
49	124.9		
50	119.0		
51	113.6		
52	108.7		
53	103.9		
54	99.65		
55	95.64		
56	91.90		
57	88.40		
58	85.10		
59	82.00		
60	79.06		

[a]From Ref. [7].

[b]Interpolated values.

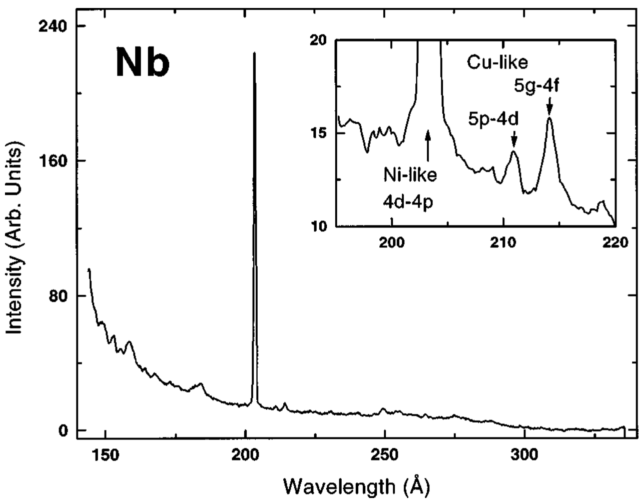

FIG. 1. An on-axis spectrum of a 6-mm Nb target showing the strong $4d\,^1S_0 \rightarrow 4p\,^1P_1$ lasing line at 203.34 Å. The inset shows the Cu-like Nb $5p$-$4d$ and $5g$-$4f$ lines at 210.843 and 214.284 Å.

Å in the nonlasing plasma. Furthermore, interpolation with the aid of Ga and Ge data [7], we found the previous identification of the $4d\,^1S_0 \rightarrow 4p\,^1P_1$ line at 393.824 and 341.752 Å in Se and Br [32] was incorrect. The Br line is now identified at 374.174 Å, a change of over 30 Å, and the Se line is predicted at 435.1 Å by interpolation. Even the Ge line was originally identified at 748 Å [33] before its reidentification 10 years later at 642 Å [7]. These problems just point out the great difficulty of measuring and identifying this line. Finally, with the identification of the $4d\,^1S_0 \rightarrow 4p\,^1P_1$ line, one can now also identify the $4d\,^1S_0 \rightarrow 4p\,^3D_1$ line branching from the same $4d\,^1S_0$ level in As, Br, and Y at 525.350, 380.520, and 247.402 Å. This further verified the correctness of the identification of these lines. In Table I, we include the measurements of the $4d\,^1S_0 \rightarrow 4p\,^1P_1$ line for Ga to Mo in the nonlasing plasma. For Se, Kr, and Sr, the wavelengths are interpolated using the measured values of the adjacent Z's and are included in Table I with larger error bars.

In Table I, the listed OL calculation is compared with that of Ref. [25], which is optimized for the then existing data of lasing plasma for Eu, Yb, and Ta ($Z=63,70,73$) [25]. The present OL calculation is found to have better agreement with the measurement for Pd, Ag, and Cd, which are calculated at 146.5, 138.6, and 131.4 Å while measured at 146.79, 138.92, and 131.66 Å. The values in Ref. [25] are correspondingly 148.10, 139.92, and 132.56 Å. For Sn ($Z=50$), when lasing was demonstrated, the wavelength was measured to be 119.6$\pm$0.5 Å [15]. But other measurements gave values of 119.1 [34], 119.2$\pm$0.2 [35], and 119.3$\pm$0.1 Å [36], which are closer to our calculated value of 119.0 Å than to the one of 119.87 Å from Ref. [25]. For higher $Z>54$, agreement between the two sets of calculations becomes better with differences less than 0.5 Å.

It is useful to compare our measurement with those previous measurements in lasing plasmas. For Mo, our measurement of 188.95 Å verifies the identification of the 189.1 Å line in a previous experiment [37]. For Nb, we measured 203.34 Å, while it was reported at 204.2 Å in an x-ray laser

TABLE II. Comparison of calculated and measured wavelengths of the $4d\,^1S_0 \rightarrow 4p\,^1P_1$ transition for Ni-like Ag; wavelengths in angular brackets are predicted. The uncertainties in the last digits are given in parentheses.

Wavelength (Å)	Reference
138.92(15)	This work
143	[13]
139.95(15)	[35]
138.9(1)	[36]
⟨138.6⟩	This work
⟨139.92⟩	[25]
⟨137.76⟩	[10]

experiment [28] in which the line was rather weak. For Ag, there are a number of measurements and calculations that we compare in Table II. When lasing was first demonstrated in Ag, the $4d\,^1S_0 \rightarrow 4p\,^1P_1$ line was measured at 143 Å [13]. Another group then measured it at 139.95 Å [35], and later revised it to 138.9 Å [36], which is in good agreement with our value of 138.92 Å. While the experimental data spans an $\sim$4 Å range, the theoretical values span an $\sim$2 Å range. For Te, La, and Ce ($Z=52,57,58$), the wavelengths were measured [13] at 111, 89, and 86 Å, which have a 1–2 Å difference from our OL calculation as seen in Table I. Given the large difference of $\sim$4 Å for Ag from the same paper, these wavelengths may have considerable uncertainties. For Nd, the wavelength was first measured at 79.7 Å [12], 0.64 Å away from the higher-resolution measurement of 79.06 Å [14], which is the benchmark of our OL calculation. For Xe ($Z=54$), the lasing line was measured at 100 Å [16], in agreement with our OL calculation within 0.4 Å.

In conclusion, we have measured the wavelength of the $4d\,^1S_0 \rightarrow 4p\,^1P_1$ x-ray laser line in many low-Z Ni-like ions from Y to Cd. Using the MCDF code we have estimated the wavelength of this laser line for all elements from 39 to 60. Using the unambiguous identification of this line in the x-ray laser plasma we were then able to identify this line in many low-Z Ni-like ions from As to Mo with very high resolution. Since lasing in Ni-like x-ray lasers for $Z<65$ is completely dominated by this transition, these measurements provide invaluable data in identifying this laser line under weak lasing conditions for future experiments. It also provides precise knowledge of the wavelength for constructing complex interferometers and other complex experiments that require multilayer optics and use x-ray lasers as a source to study other plasmas.

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