Observation of lasing on the two $J = 0–1$, $3p–3s$ transitions at 26.1 and 30.4 nm in neonlike vanadium

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Received January 12, 1995

We report the first observation to our knowledge of lasing at 26.1 and 30.4 nm in neonlike vanadium ions in a recent experiment conducted on the Asterix IV iodine laser at the Max-Planck-Institut für Quantenoptik. The two lasing lines have been identified as the $3p^1S_0–3s^3P_1$ and $3p^1S_0–3s^1P_1$ transitions in neonlike vanadium ions. The transition at 26.1 nm is the first of the $3p^1S_0–3s^3P_1$ transitions in neonlike ions that has been observed to lase, and it was observed to have a higher gain than the other transition. Spatially resolved measurements showed that the lasing for this transition occurs at a position slightly farther from the target surface than for the $3p^1S_0–3s^1P_1$ one.

Since the first demonstration of high-gain soft-x-ray lasing in neonlike Se ions by use of the collisional pumping scheme,[1] lasing in neonlike ions ranging from titanium ($Z = 22$) to silver ($Z = 47$) has been demonstrated (see the references in Ref. 2). With ions of Z higher than 34, gain occurs mainly for the $3p^1D_2–3s^3P_1$ and $3p^3P_2–3s^1P_1$ transitions. The notation used is LS coupling. In jj coupling they are the $2p_{3/2}3p_{3/2}–2p_{3/2}3s_{1/2}$ and $2p_{1/2}3p_{3/2}–2p_{1/2}3s_{1/2}$, $J = 2–1$ transitions. Strong lasing on the $3p^1S_0–3s^1P_1$ transition [the $2p_{1/2}3p_{1/2}–2p_{1/2}3s_{1/2}$, $J = 0–1$ transition in jj coupling, hereafter termed the $E(0–1)$ transition[2]] in low-Z targets has been observed by application of the prepulse technique.[3–7] However, this transition's partner, i.e., the $3p^1S_0–3s^3P_1$ transition [the $2p_{1/2}3p_{1/2}–2p_{3/2}3s_{1/2}$, $J = 0–1$ transition in jj coupling, the $G(0–1)$ transition[2]], which occurs at a shorter wavelength, has never to our knowledge been observed to lase strongly. Nilsen *et al.,* using the Nova laser,[5] observed weak emissions on this line in chromium and iron in experiments at the Lawrence Livermore National Laboratory (LLNL). It was also reported that there was no evidence for gain in neonlike scandium or in vanadium ($Z = 21, 23$) even with a prepulse in the previous University of Rochester–LLNL and LLNL experiments.[3,5]

In this Letter we report what is to our knowledge the first observation of lasing on both the $E(0–1)$ and the $G(0–1)$ transitions in neonlike vanadium, with the $G(0–1)$ line lasing more strongly. We believe that this is the first observation of strong lasing on the $G(0–1)$ transition, a finding that may lead to a better understanding of the physics involved in collision-pumped x-ray lasers.

The Asterix IV[8] laser delivers as much as 800 J of energy at the fundamental wavelength of 1.315 μm with a pulse duration of 450 ps (FWHM). The spurious prepulse of the system was measured below 10^{-6} of the main pulse energy. A line focus, 3.0 cm long and 150 μm wide, is produced by a cylindrical lens array.[9] To make the prepulse, a setup similar to a previous experiment was used.[7] A pair of 17.5 cm $\times$ 9 cm mirrors with 100% reflectivity at a 60° angle of incidence was inserted into the beam path, one before and one after the final steering mirror, which deflects the beam by 60°. The delay between the main pulse and the prepulse was set to 5.23 ns. The energy ratio of the full prepulse–main pulse is deduced from the area ratio and is 15.1%, changeable by the use of calibrated filters without changing the energy of the main pulse. Typically a total energy (prepulse + main pulse + losses that are due to the edges of the prepulse mirrors) of 430 J was used.

We prepared the target by gluing and pressing a 10-μm-thick vandium foil (purity 99.8%) onto a flat metal substrate, with a flatness within 20 μm. The longest target length was 2.4 cm. Titanium, iron, and germanium slabs were also used for comparison and wavelength calibration.

An on-axis transmission grating spectrometer coupled to a thinned, back-side-illuminated CCD[10] was used for time-integrated space-resolved measurement. One-dimensional spatial resolution in the direction perpendicular to the target surface was provided by use of the sagittal focus of a toroidal mirror with a magnification of $\sim 2.6\times$. The acceptance angle of the mirror was limited to 5 mrad by a diaphragm to reduce image distortion. The spatial resolution was ~ 50 μm. A 5000-line/mm free-standing transmission grating with a 50-μm-wide slit dispersed the incident emission perpendicularly to the spatially resolved direction. The wavelength coverage was 3.4–33.2 nm, and the spectral resolution was ~ 0.1 nm. The grating has a supporting structure perpendicular to the grating bars with a period of 4 μm, which disperses the incident emission perpendicularly to the main dispersion direction. This leads to a spurious spatial structure, which has to be taken into account in the evaluation of the data.

Figure 1 shows a record of the spatially resolved spectrum for a 2.4-cm-long vanadium target. A 15% prepulse was used for this shot. The spatial direction and the dispersion direction are not exactly perpendicular to each other, and this is caused by a small angle between the grating bars and the target normal. Two very bright spots accompanied by the

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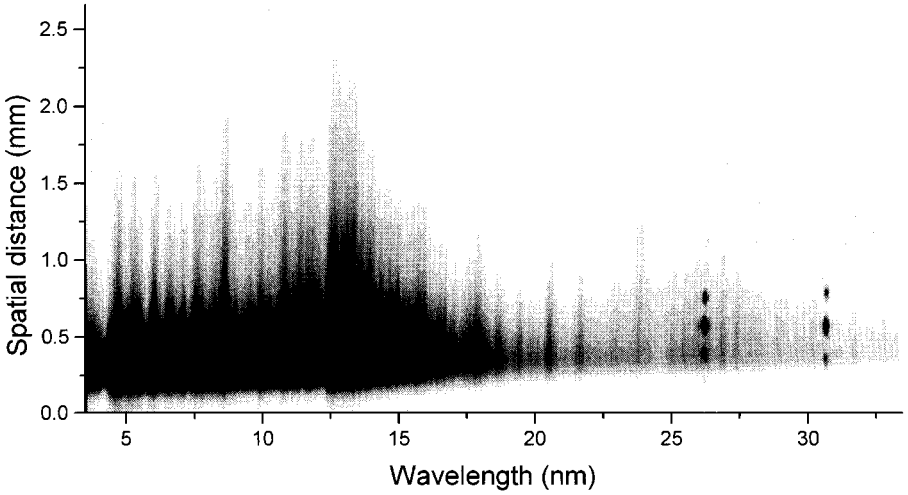

Fig. 1. Spatially resolved spectrum of a 2.4-cm vanadium target. Two very bright emissions, accompanied by diffraction resulting from the 4-μm periodical support structures of the transmission grating, are clearly seen at 26.1 and 30.4 nm. The emissions are displaced from the target surface. The scaling of the display is chosen to show the weak emission surrounding the spots, so some of the emissions are saturated.

diffraction by the 4-μm-period supporting grid are seen at positions apart from the target surface. For the emission at other wavelengths the diffraction pattern from the grating support does not appear obviously, because it is smeared by the larger source size of the nonlasing emissions. The high spectral intensity at shorter wavelengths is due to the higher sensitivity of the CCD to shorter-wavelength emissions.[10] Although the target surface is not sharply resolved because of the limited depth of focus of the imaging system, the spots seem to be well focused as a result of their small divergence. Calibrated by shots on germanium targets, which lase at 19.6, 23.2, 23.6, and 28.9 nm, the wavelengths of the two bright emissions were determined to be 26.1 and 30.4 nm. They coincide within our spectral resolution with the wavelengths of the two $G(0-1)$ and $E(0-1)$ transitions in neonlike vanadium.[2,11] The longer one is the analog of the dominating 0–1 laser observed in the other low-Z materials.[3–7]

Figure 2 gives the traces along the spatial coordinate at 26.1 and 30.4 nm and the background close to 26.1 nm. Although the diffractions by the supporting structure influence the spatial profile, we can still see that the 26.1- and 30.4-nm transitions have maxima displaced from the target surface, whereas the background decays gradually away from the target surface. The peak positions of the 26.1- and 30.4-nm transitions are at 380 and 350 μm from the target surface, and the spatial widths are 60 μm (FWHM) for both emissions. In this measurement the target surface was assumed to correspond to the 0 crossing point obtained by extension of the straight part of the backside slope. The error was ± 50 μm. Because of the resolution limitation, detailed structure in the lasing region cannot be seen.

Line-outs along the dispersion direction are given in Fig. 3 for 2.4- and 1.2-cm target shots. They are taken at the position where the maximum of the 26.1 nm line occurs. In the 2.4-cm target case, the 26.1- and 30.4-nm transitions dominate the spectrum, whereas in the 1.2-cm shot both lines are absent. This indicates high gain but a weak source. By comparing one shot on a 2.0-cm target with this 2.4-cm one, we estimated the gain coefficients for both lines to be 3–6.5 and 1.5–3.5 cm^{-1} for the $G(0-1)$ and $E(0-1)$ lines, respectively, at their spatial maxima. The large uncertainty was due to a 0.4–0.6-cm region of nonflatness on the nominal 2.0-cm target at one end. In this shot the $G(0-1)$ and the $E(0-1)$ transitions were of similar intensity.

We have mentioned that in the University of Rochester–LLNL and LLNL experiments no gain has been observed for vanadium.[3,5] One reason for this could be the smaller prepulse (0.6%) in those experiments. This explanation is supported by the fact that titanium lased better at the $E(0-1)$ transition (32.6 nm) with a 15% prepulse than with a 1.5% prepulse in our experiment. Furthermore, the $E(0-1)$ laser in titanium was much stronger than in vanadium under similar conditions. A titanium target of only 1.2 cm gives almost one half of the intensity of the 2.4-cm vanadium target on the $E(0-1)$ transition, whereas in a 1.2-cm vanadium target all laser lines disappeared (see in Fig. 3). The $G(0-1)$ line is also absent in the 1.2-cm titanium shots. We have not shot on 2.4-cm titanium targets.

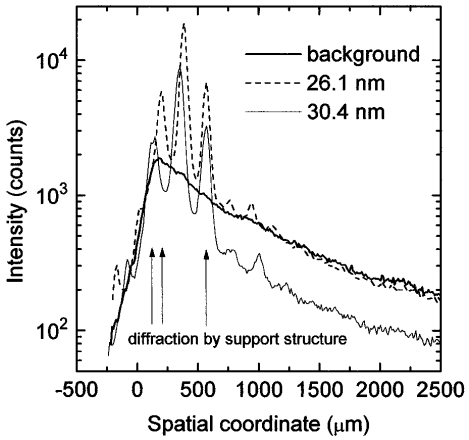

Fig. 2. Line-outs of Fig. 1 along the spatial direction at 26.1 and 30.4 nm and a background close to 26.1 nm. The 26.1- and 30.4-nm emissions show a bright peak apart from the target surface, whereas the background decays away from the target surface. The target surface is at position 0. The smooth decay at the back side of the target is due to the limited depth of focus.

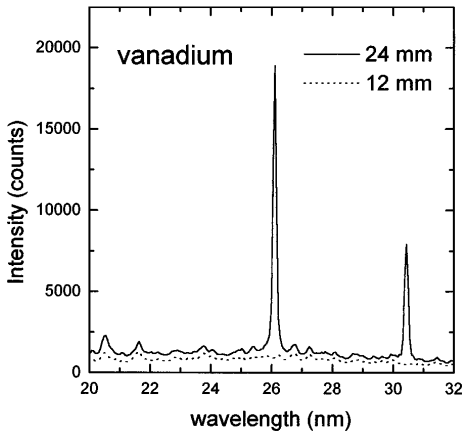

Fig. 3. Line-outs at the spatial maximum of the 26.1-nm emission for a 2.4- and a 1.2-cm target. The 26.1- and the 30.4-nm line emissions dominate the 2.4-cm target spectrum and are absent in the 1.2-cm one.

For comparison, we measured the gain for the $G(0-1)$ and $E(0-1)$ transitions in iron, an even-Z element, with a 1.5% prepulse. The gain was 2.3 cm^{-1} on the $G(0-1)$ line (20.5 nm), much lower than the gain of 4.1 cm^{-1} on the $E(0-1)$ transition (25.5 nm). The maximum of the $G(0-1)$ transition is ~ 30 μm farther from the target than that of the $E(0-1)$.

Two arguments may help us to explain our observation of the lasing on the $G(0-1)$ transition in vanadium and why it can be stronger than the $E(0-1)$ line. First, the emission oscillator strength of the $G(0-1)$ transition, as calculated, e.g., in Ref. 2, just peaks at $Z = 22$. Therefore scandium, titanium, vanadium, and chromium should be favorable for showing gain on this transition. Second, the hyperfine splitting of the lower level of the $E(0-1)$ laser, i.e., the $3s^1P_1$ state, may also be important. The hyperfine splitting is usually important only in odd-Z elements.[12] This splitting reduces the gain of the laser line by effectively increasing the line width. We note that the $G(0-1)$ transition shares the upper level, i.e., the $3p^1S_0$ state, with the $E(0-1)$ transition. Before one of them saturates and without hyperfine splitting, one can roughly estimate the ratio of their gain coefficients by assuming a similar population inversion for them; it is $g_G/g_E \approx (f_G/f_E)(\lambda_G/\lambda_E)$. Here g is the gain coefficient, f is the emission oscillator strength, and λ is the lasing wavelength.[2] For vanadium, titanium, and iron this ratio is 0.49, 0.47, and 0.48, respectively. However, in vanadium it may be considerably modified by the hyperfine splitting. At an ion temperature of 50 eV a 40% gain reduction on the $E(0-1)$ line is estimated[12] for vanadium, resulting in a new gain ratio of $g_G/g_E \approx 0.83$.

By the above arguments, it is also expected that it will be possible to see the $G(0-1)$ line lase in titanium and chromium with long targets, but more weakly than the $E(0-1)$ line, as we have observed in iron. More interestingly, it is possible to see the $G(0-1)$ line lase just as strongly as or even more strongly than the $E(0-1)$ line also in scandium and manganese (which have odd Z's), as we have observed for vanadium. In our laboratory a further experiment with these targets is being planned, in which a time-resolved measurement is also proposed.

In summary, we have observed lasing on the two $J = 0-1$ transitions, i.e., $G(0-1)$ and $E(0-1)$, at 26.1 and 30.4 nm in neonlike vanadium ions. Their peak emission occurred at somewhat different distances from the target surface, with the $E(0-1)$ line being emitted closer. We estimated the gain to be 1.5–3.5 cm^{-1} for the $E(0-1)$ and 3–6.5 cm^{-1} for the $G(0-1)$ line.

The authors thank the Asterix facilities crew for providing support for the experiments. A profitable discussion with Joseph Nilsen is acknowledged. Yuelin Li was supported by the Alexander von Humboldt Foundation. He thanks S. Witkowski and R. Sigel for their hospitality. Georg Pretzler was supported by the European Union Programm "HCM" CT920015. This research was supported in part by the Commission of the European Communities in the framework of the Association Euratom/Max-Planck-Institut für Plasmaphysik.

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