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IMPACT OF OBSERVED HYPERFINE SPLITTING ON X-RAY LASER GAIN

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ABSTRACT

Line broadening mechanisms play an important role in determining the gain of X-ray laser transitions. Typically Doppler broadening is the primary mechanism which determines the linewidth of these transitions. However, we will present cases where the hyperfine effect is the dominant line broadening mechanism. Studying laser lines, which tend to have gain narrowed linewidths, enables us to observe these dramatic hyperfine effects which would be difficult to observe in opacity or Stark broadened lines. In this work we report the observation of hyperfine splitting on an X-ray laser transition and discuss how hyperfine splitting has a major impact on the laser gain. In our experiments we measure the lineshape of the $3p \rightarrow 3s$, $J = 0 \rightarrow 1$ transition in neon-like niobium and zirconium and observe a 28 mÅ splitting between the two largest hyperfine components in the niobium(Z=41) line at 145.9 Å, in good agreement with theory.[1,2] In zirconium(Z=40), no splitting is observed since the hyperfine effect is proportional to the nuclear moment, and zirconium has zero nuclear moment, as is typical for even-Z elements. The hyperfine effect is shown to effect transitions which have a $2p_{1/2}$ vacancy in the closed neon-like core much more than those with a $2p_{3/2}$ vacancy. A comparison of the neon-like niobium laser spectrum with that of zirconium shows a dramatic reduction in the relative intensity of the niobium laser lines with the $2p_{1/2}$ vacancy.[3] We also report the unusual behavior noticed recently in low-Z neon-like X-ray lasers in which ions with odd Z lase poorly, if at all, relative to ions with even Z.[4,5] The hyperfine effect is shown to have a substantial impact on the gain of the low-Z ions with odd Z and helps explain their poor performance.

PREVIOUS EXPERIMENTS

Several different experiments over the last year led us to investigate the possibility of hyperfine effects on the X-ray laser output. First, recent experiments on low-Z neon-like ions have observed lasing on the $3p \rightarrow 3s$, $J = 0 \rightarrow 1$ transition in neon-like titanium(Z=22), chromium(Z=24), iron(Z=26), and nickel(Z=28) at 326, 285, 255, and 231 Å, respectively. However, when experiments were done with scandium(Z=21), vanadium(Z=23), and manganese(Z=25) there was no obvious sign of lasing while only weak lasing was observed with cobalt(Z=27) and copper(Z=29).[4-6] Second, experiments done on neon-like zirconium(Z=40) and niobium(Z=41) observed the pair of $J = 2 \rightarrow 1$ laser lines to be very similar intensity in zirconium while in niobium the shorter wavelength line at 138.6 Å is much stronger than the other $J = 2 \rightarrow 1$ line at 140.4 Å. Also, the $J = 0 \rightarrow 1$ line in niobium is much weaker than it is in zirconium. The above experiments suggested that there was a difference between ions with even Z and odd Z. Since ions with even Z tend to have no nuclear spin while those with odd Z do have nuclear spin and therefore a nuclear moment which leads to hyperfine effects we decided to investigate this possibility in more detail.

Hyperfine splitting affects the gain of the laser line by increasing the linewidth. Since the gain is inversely proportional to linewidth the gain will decrease. If the splitting is large enough, a single line may be split into several weaker lines. For neon-like laser lines the impact of the hyperfine effect is largest for the $J = 0 \rightarrow 1$ line which dominates the spectra of the low-Z neon-like ions. We did a series of experiments to measure the lineshape of the $J = 0 \rightarrow 1$ laser line in neon-like niobium. Niobium was chosen because it has a large nuclear spin, $I = 9/2$, and a large nuclear moment, $\mu = 6.167$, its wavelength is in the range of the available high resolution spectrometer, and it has lased.[3]

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EXPERIMENTAL SETUP

Experiments were conducted at Lawrence Livermore National Laboratory (LLNL) on the Nova laser using $\lambda = 0.53$ μm. In a typical experiment the Nova laser illuminates a 125 μm thick, 3.0 cm long slab target of niobium. The above length of the target was reduced by a 16% gap in the center which results in an actual length of 2.5 cm. The pump laser beam was a 500 ps square pulse with 2.4 kJ of energy in a 120 μm wide (FWHM) by 3.6 cm long line focus, resulting in a peak intensity of 130 TW/cm^2.

The principal instruments were a time-gated, microchannel plate intensified grazing-incidence grating spectrograph(MCPIGS) and a high-resolution, grazing incidence grating spectrometer; both of these instruments observed the axial output of the X-ray laser. The MCPIGS provided angular resolution over 10 mrad near the X-ray laser axis, used a 1200 line per mm grating, and had spectral coverage of approximately 75 to 340 Å. The high-resolution, grazing incidence grating spectrometer recorded time-integrated but spatially resolved data using a Princeton Instruments camera with a backside illuminated EEV CCD. This spectrometer was centered on the laser axis with an angular acceptance of 12 mrad and had a measured spectral resolution of 20000 at 146 Å and spectral coverage of 2 Å. The angular or spatial resolution of both instruments was perpendicular to the target surface.

EXPERIMENTAL RESULTS AND ANALYSIS

Figure 1(a) shows the measured intensity(solid line) versus wavelength for the 3p → 3s, J = 0 → 1 neon-like niobium laser line at 145.9 Å. Two components are clearly visible with a separation of 28 mÅ, which is very close to the 32 mÅ prediction(dotted line) given the 7 mÅ resolution of the spectrometer. This is the shortest wavelength transition and most highly ionized plasma in which the hyperfine effect has been directly observed with the exception of some very recent accelerator experiments in hydrogen-like bismuth done at GSI Darmstadt.[7] Figure 1(b) shows the measured intensity versus wavelength for the 3p → 3s, J = 0 → 1 neon-like zirconium laser line at 150.4 Å. The zirconium laser line is now a single narrow line which is slightly gain narrowed and a hundred times brighter than the niobium line. Both experiments used the same length targets and illumination conditions as described previously. A comparison of Figs. 1(a) and 1(b) show how the increased linewidth of the niobium line reduces the gain and dramatically reduces the laser output as compared

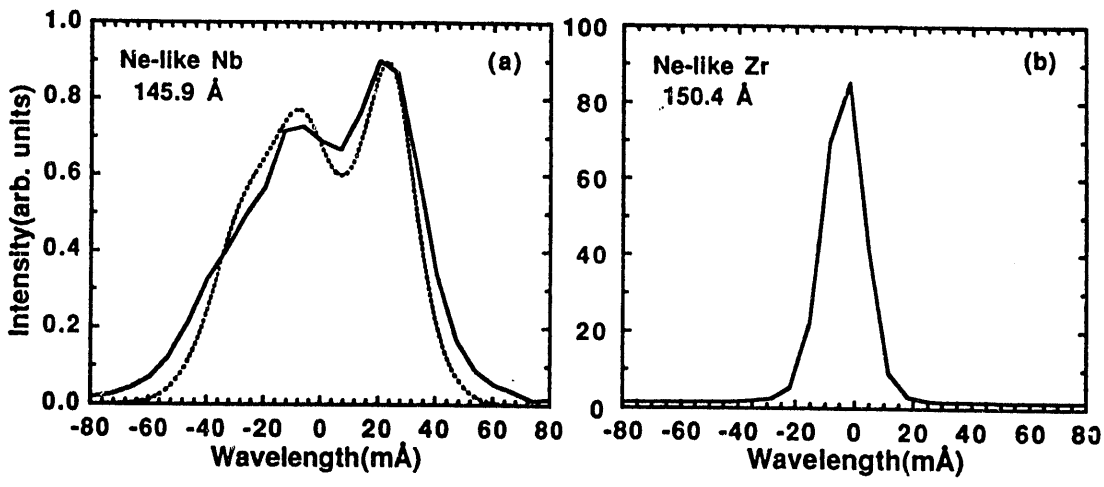

Fig. 1. Measure intensity vs wavelength around line center for the 3p → 3s, J = 0 → 1 laser line in neon-like niobium(a) at 145.9 Å and in neon-like zirconium(b) at 150.4 Å. Calculated splitting(dotted line) of 32 mÅ for niobium compares well with 28 mÅ measured splitting.

with a similar transition in zirconium, an adjacent ion which is not subject to the hyperfine effect.

For vanadium, assuming an ion temperature of 50 eV based on calculations, the hyperfine splitting reduces the gain coefficient of the J = 0 → 1 laser line at 304 Å by 40% as shown in Fig. 2(a) which presents gain versus wavelength around line center normalized to a gain of unity if there was no hyperfine splitting. The three hyperfine components are shown by dotted lines. Assuming vanadium has the same gain coefficient of 2.6 cm^{-1} as observed for titanium,[4,5] the hyperfine effect reduces the gain coefficient to 1.6 cm^{-1} for vanadium. For the 3.8 cm long targets tried with vanadium, this would make the vanadium fifty times weaker than the titanium. While this is still within the detectable range of the diagnostics, the hyperfine effect appears to play a major role in the non lasing of vanadium and scandium and the poor lasing of the other odd Z ions. Since the measured titanium gain was time averaged, the peak gain is no doubt larger. Therefore the relative effect of the hyperfine splitting will also be larger.

It is also interesting to calculate the impact of hyperfine splitting on other neon-like ions. The next element above niobium which has a large nuclear moment is indium(Z=49). Figure 2(b) shows the gain versus wavelength near line center for the 3p → 3s neon-like indium lines at 89.0, 89.8, and 116 Å assuming an ion temperature of 1000 eV. The first two lines are the normal pair of J = 2 → 1 lines, analogous to the selenium 206 and 209 Å lines, while the third is the J = 0 → 1 line, analogous to the selenium 182 Å line.[8] One notices a dramatic reduction in gain for the J = 0 → 1 line. For this line it may be possible to observe all three components. For the pair of J = 2 → 1 lines, the hyperfine effect is much larger for the 89.8 Å line because this is the transition with the $2p_{1/2}$ vacancy while the 89.0 Å line has the $2p_{3/2}$ vacancy. However, in preliminary experiments we have not been able to achieve lasing on any neon-like indium lines.

CONCLUSIONS

The hyperfine effect is shown to be the dominant line broadening mechanism for the 3p → 3s, J = 0 → 1 neon-like niobium laser line at 145.9 Å. We measured the lineshape of this transition and observed a 28 mÅ splitting between the two largest hyperfine components, in good agreement with theory. This is the largest hyperfine splittings ever measured on a laser transition.

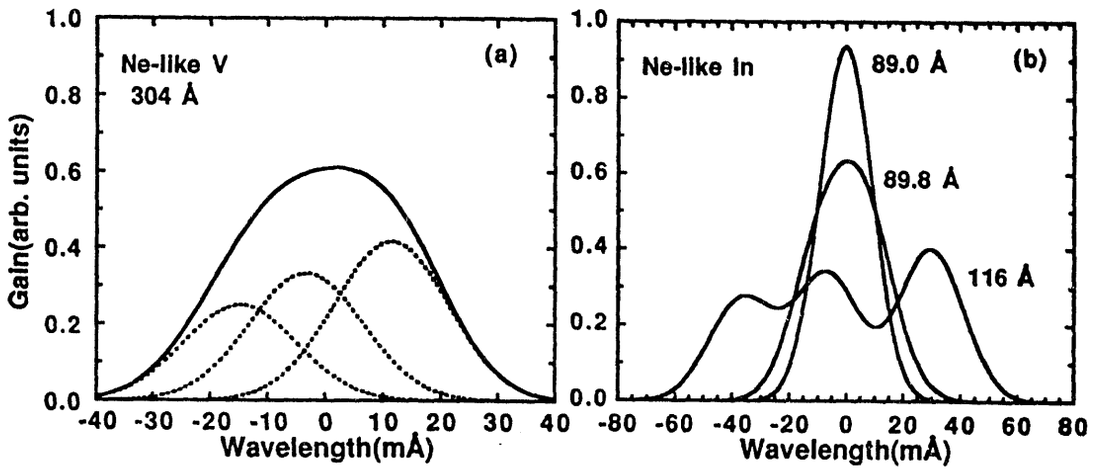

Fig. 2. Gain vs wavelength near line center for the 3p → 3s, J = 0 → 1 laser line in neon-like vanadium(a) at 304 Å and for the two J = 2 → 1 and one J = 0 → 1 laser lines in neon-like indium(b). The three hyperfine components are given by dotted lines in (a). The gain is normalized to a gain of unity if there were no hyperfine effect.

The hyperfine effect is also shown to effect transitions which have a $2p_{1/2}$ vacancy in the closed neon-like core much more than those with a $2p_{3/2}$ vacancy. A comparison of the neon-like niobium laser spectrum with that of zirconium shows a dramatic reduction in the relative intensity of the niobium laser lines with the $2p_{1/2}$ vacancy. Finally, the hyperfine effect is shown to have a substantial impact on the gain of the low-Z ions with odd Z and helps explain their poor performance.

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