Demonstration of Population Inversion by Resonant Photopumping in a Neon Gas Cell Irradiated by a Sodium Z Pinch

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The broadband radiation emitted from a Na Z pinch is used to photoionize Ne to the He-like ground state and radiation from the Na $1s^2$-$1s2p\ ^1P_1$ transition is used to resonantly photoexcite the Ne $1s^2$-$1s4p\ ^1P_1$ transition. Time-resolved and time-integrated spectral measurements of the Ne K-shell emission demonstrate the first population inversion driven by a Z pinch. This is the first experiment in any medium to demonstrate a soft-x-ray inversion pumped solely by resonant photoexcitation.

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Research conducted during the past ten years has demonstrated that pulsed-power drivers are capable of efficiently creating very energetic radiation sources with a variety of spectral distributions [1]. Many have suggested that these drivers can be used for applications such as creating photopumped x-ray lasers [2], imploding inertial confinement fusion capsules [3], and studying the photoionization kinetics of plasmas in intense radiation fields [4]. A serious potential problem with using pulsed-power drivers is that the powerful electrical pulse (currents of many MA and voltages of many MV) flowing within millimeters of the various "targets" may obscure the effects of the radiation drive and hopelessly complicate the execution of this class of experiment. In this Letter we show that these problems are separable and present the first unambiguous experimental demonstration of population inversion driven by a Z pinch, and the first soft-x-ray inversion pumped solely by resonant photoexcitation in any medium.

We are performing photopumping experiments using the sodium-neon resonant photoexcitation x-ray laser scheme. This scheme, which has received extensive theoretical study [5–8], employs radiation from the $1s^2$-$1s2p\ ^1P_1$ transition at 11.0027 Å in He-like Na to resonantly photoexcite the Ne $1s^2$-$1s4p\ ^1P_1$ transition at 11.0003 Å in He-like Ne. Electron and ion collisions are predicted to transfer a large fraction of the excited $4p$ singlet population to the $4d$ and $4f$ levels. The line calculated to have the highest gain is the $1s3d\ ^1D_2$-$1s4f\ ^1F_3$ transition at 231 Å. This resonance is attractive because of the excellent match between the Na and Ne resonant transitions, the intrinsic strength of the Na pump line, and the relative ease in creating a large population of Ne ions in the He-like ground state.

To produce a bright Na pump line one needs a high-density ($>10^{19}$ ions cm^{-3}), high-temperature (>300 eV) Na plasma in order to both maximize the radiation rates and ensure that a large population of Na ions are in excited He-like states. The Ne lasant plasma, however, needs to be at a lower density ($\approx 10^{18}$ ions cm^{-3}) and temperature (<100 eV) in order to both maximize the population of Ne ions in the He-like ground state and minimize collisional excitation of the lower lasing level.

In our experimental arrangement (see Fig. 1) such divergent conditions have been achieved. We create the Na plasma by imploding an array of sixteen 20-mm-long,

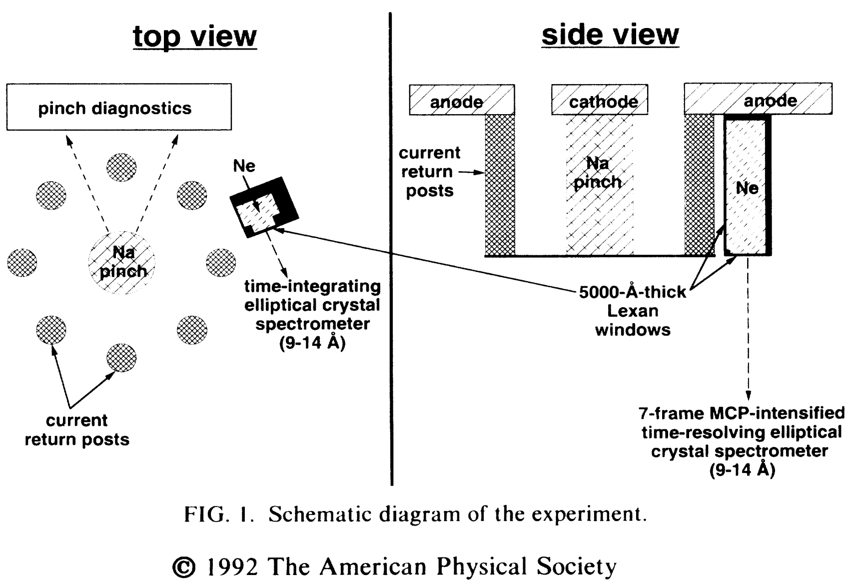

FIG. 1. Schematic diagram of the experiment.

75-μm-diam Na wires using the Saturn accelerator [9] as a Z-pinch driver. Saturn implodes the Na wire-array load with a peak current of 10 MA in an electrical pulse with a peak power of 20 TW and a 40 nsec FWHM. The total broadband radiation output from this plasma is measured to be 400 kJ in a pulse with a peak power of 10 TW and a 40 nsec FWHM. Measurements show that 90% of this radiation is emitted at energies less than 1 keV. Since the final pinch diameter is observed to be 2.5 mm (implying ion densities of 4×10^{20} cm^{-3}), we assume that the broadband radiation from this plasma can be approximated by the emission from a 89-eV blackbody (simply the blackbody equivalent temperature for the measured radiating area and power). 6 kJ of energy is typically observed to be radiated in the 11-Å Na pump line in a pulse with a peak power of 200 GW and a 20 nsec FWHM. This pulse is basically Gaussian in shape until about 25 nsec after the peak, at which time a "foot" appears that slowly decays away. Approximately 16% of the energy and power which is radiated between 1 and 3 keV appears in the 11-Å pump line. The pump linewidth has been measured [10] with a high-resolution time-integrating spectrometer and found to be approximately 20 mÅ. Calculations of this opacity broadened linewidth, based on the above-cited diameter and density and the calculated range of He-like Na fraction, result in a predicted linewidth of 10–20 mÅ. Since the ionization balance and thus the opacity of this line vary with time, a definitive measurement of the pump linewidth will require a high-resolution time-resolving spectrometer. This difficult measurement has not been made to date.

We use the broadband radiation from the Na pinch to photoionize the Ne to the He-like ionization state. The ionization balance in the Ne is dominated by the Na Z-pinch radiation field and not the Ne electron temperature. Independent simulations of these experiments by Sandia National Laboratories, the Naval Research Laboratory [11], and Lawrence Livermore National Laboratory [12] show that 53%–80% of the Ne ions are in the He-like ground state even though the Ne electron temperature is only 25–30 eV.

The target used in these experiments is located 20 mm away from the Z-pinch axis (outside the current return posts) and consists of Ne at a pressure of 10 Torr (4×10^{17} atoms cm^{-3}) contained within a "gas cell" target. The viewing and illumination windows of this target are made of free standing, 5000-Å-thick Lexan (C_{16}-$H_{14}O_3$). The illumination window which faces the Na pinch is 10 mm long and 3 mm wide. The two viewing windows which face the lasant spectrometers are circular in shape with a diameter of 6 mm. Radiation-hydrodynamic calculations predict that the Lexan illumination window is heated by the broadband radiation from the Na pinch and expands, compressing a few-hundred-micron-thick region of the Ne to densities suitable for lasing ($\approx10^{18}$ ions cm^{-3}) at the time of peak Na 11-Å pump emission. This compressed region is approximately one mean free path thick to the 11-Å pump line. Not only is this target both designed and measured to achieve suitable laser conditions, but, as discussed later, our measurements indicate that it contains no current and associated instabilities. This eliminates a major difficulty of pulsed-power driven x-ray lasers. While the present 20-mm separation facilitates a clean diagnosis and is sufficient to demonstrate population inversion, the small solid angle subtended by the sodium flashlamp can be significantly improved in future experiments. The use of more advanced targets could lead to gain in the 4-2 and 3-2 transitions which have shorter wavelengths and higher quantum efficiency.

The total broadband radiated energy and power from the Na pinch is measured with an unfiltered, thin-film resistive bolometer. The radiated energy and power above 1 keV is measured with a filtered bolometer, a time-integrating convex KAP crystal spectrometer, and an array of three absolutely calibrated, filtered x-ray diodes [13]. A twelve-frame, time-resolving, x-ray pinhole camera is used to monitor the implosion quality of the Na pinches.

The K-shell emission between 9 and 14 Å from the Ne lasant is monitored simultaneously with time-resolving and time-integrating elliptical crystal (RAP) spectrometers (see Fig. 1). The time-resolving spectrometer is located 1.2 m from the target and uses a seven-frame, microchannel-plate-intensified, x-ray framing camera as the detector [14]. The time-integrating spectrometer is located 0.35 m from the target and uses Kodak 2497 x-ray film. We insert metal tubes between the x-ray laser target and each spectrometer to guard against any Na contaminant radiation entering the line of sight of these spectrometers. The ends of these baffles are placed inside counterbored holes located at both the x-ray laser target and the entrance port of the spectrometers. To ensure that no Na contaminant radiation was observed by these lasant spectrometers, we conducted a "null" shot by replacing the Ne with N at 10 Torr. A nominal Na pinch was produced on this shot and no lines were observed on either of the lasant spectrometers.

We looked for an enhancement of the He-like Ne $1s^2$-$1s4p$ line relative to the He-like Ne $1s^2$-$1s3p$ line to demonstrate that the Na pinch photopumps the Ne plasma. The three independent kinetics calculations have shown that if an inversion exists between these two transitions (i.e., the $1s$-$4p$ line is brighter than the $1s$-$3p$ line), then at the Ne densities encountered in these experiments an inversion also exists between the $1s4f$ and $1s3d$ singlet levels. The exact magnitude of the gain, however, is uncertain. The kinetics calculations differ in the predicted He-like fraction, oscillator strengths of the pumped and laser transitions, width of the laser transition, and level of detail in modeling the excited states. Uncertainties of 10%–60% in these factors lead to the very sensitive prediction of gain varying from 0.2 to 1.5 cm^{-1}. Additional experimental uncertainties arise from the width of the 11-Å pump line at peak power and the details of the soft photoionizing spectrum.

To ensure that the enhanced emission observed in the $1s^2$-$1s4p$ line is due to resonant photopumping by the Na 11-Å pump line, we performed a second type of null shot. In this null shot the Na wire-array load was replaced with a Mg wire-array load in an attempt to generate the same broadband and general keV radiation as a Na pinch but eliminate the Na 11-Å pump line.

Figure 2(a) shows typical time-integrated and time-resolved Ne spectra from a shot with a Na pinch and a Ne-filled target. The time-integrated spectrum has been corrected for the spectrometer response [15] (using tabulated values for the film response, filter transmission, crystal reflectivity, and spectrometer geometry) and background light. In addition, the time-resolved spectra were also corrected for the gold photocathode response and the variation in gating voltage (and hence detector gain) between frames. For this shot, each gating pulse was 4 nsec wide and spaced 5 nsec apart (center to center). Since the framing camera was run at very high gain (≈ 1 kV across the microchannel plate), the bright $1s^2$-$1s2p$ line might be slightly saturated on some frames. The high gain also resulted in "noisier" time-resolved data than time-integrated data.

As can be seen from Fig. 2(a), the He-like Ne $1s^2$-$1s4p$ line is about twice as bright as the $1s^2$-$1s3p$ line, demonstrating an inversion between the $1s4p$ and $1s3p$ singlet levels. Integration of these spectra gives an intensity ratio for the $1s^2$-$1s4p$ line to the $1s^2$-$1s3p$ line of 1.7 for the time-integrated spectrum and a ratio of 2.4 at the time of peak emission of the Na 11-Å pump line. This pattern was observed on each of three Na-pumped shots. The three independent simulations predict this line ratio to be between 1.4 and 2.2 at the time of peak Na 11-Å pump emission. The spontaneous decay rate of the $1s^2$-$1s3p$ line exceeds that of the $1s^2$-$1s4p$ transition by a factor of 2.4. Even with the effects of self-absorption, population inversion is required to make the $4p$ transition twice as bright as the $3p$, as is observed here.

The excited-state density of the pumped $1s4p$ level, $N(4p)$, may be inferred from the measured power P (photons sr^{-1} sec^{-1}) of the 11-Å Ne line from $N(4p) = 4\pi P/AV$, where A is the line's decay rate (10^{12} sec^{-1}) and V is the observed Ne volume. By normalizing the absolute energy measured with the time-integrating spectrometer to the relative time history measured with the time-resolving spectrometer, we estimate that $P = 4\times10^{20}$ photons sr^{-1} sec^{-1}. The observed volume is the product of the observed window length (3 mm), the depth of penetration of the Na pump radiation into the Ne, and the depth into the Ne seen by the time-integrating instrument. The latter two quantities are inversely proportional to the line optical depth and therefore to the He-like fraction f. As a result, $N(4p)$ is proportional to f^2. If $f=0.53$ is assumed (LLNL model, Ref. [12]), we infer $N(4p) = 2.0\times10^{13}$ cm^{-3}, compared to the Ref. [12] calculation of 3.0×10^{13} cm^{-3}. However, the f of 0.8 predicted by the NRL and SNL models leads to $N(4p) = 4.5\times10^{13}$ cm^{-3}, compared to the corresponding model calculations of 5.9×10^{13} and 2.9×10^{13} cm^{-3}. Therefore, taking into account the dependence of the viewing volume on f, the measured power of the photopumped line is consistent with all three models to within 35%.

Another interesting feature of the time-resolved spectra shown in Fig. 2(a) is the general time history of the Ne K-shell lines. Note that no lines appear until frame 3 of the time-resolved data. If the ionization balance and the excitation of the Ne plasma were dominated by stray currents or by high-energy electron beams flowing in this plasma, then one would expect these lines to appear much earlier in time since this shot had a 65-nsec implosion time (the time from 10% of maximum current to stagnation). The fact that these K-shell lines follow the pinch's keV radiation pulse (and not the current pulse) indicates that both the ionization balance and the excitation of the Ne plasma are dominated by the radiation field produced by the Na pinch.

Figure 2(b) shows the time-integrated and time-resolved Ne spectra from the Mg-Ne null shot. For this shot the gating pulses on the time-resolving spectrometer were 8 nsec wide and spaced 5 nsec apart (center to center), resulting in some overlap between adjacent frames. The main feature to note from this spectrum is the fact that the $1s^2$-$1s4p$ line is no longer brighter than the $1s^2$-$1s3p$ line. The spectrally integrated intensity ra-

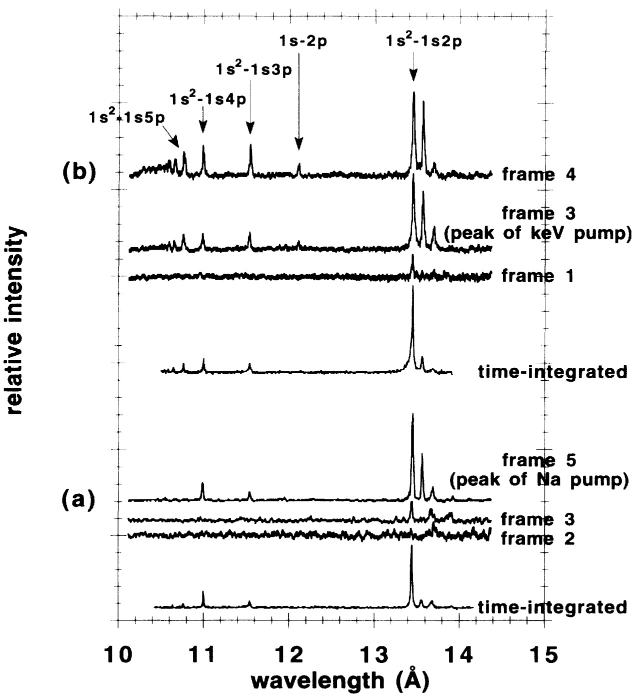

FIG. 2. Time-integrated and time-resolved Ne spectra for (a) a typical Na-pinch–Ne-target shot and (b) the Mg-pinch–Ne-target "null" shot. Time increases with increasing frame number.

tio of the $1s^2$-$1s4p$ line to the $1s^2$-$1s3p$ line is 1.0 for both the time-integrated spectrum and frame 4 of the time-resolved spectra. This observation, combined with the fact that no Na radiation was observed on the Na-N null shot, confirms our interpretation of resonant photopumping as the cause of the observed inversion between the $1s^2$-$1s4p$ and $1s^2$-$1s3p$ lines in the Na-Ne shots. Another interesting feature of the Ne spectra from the Mg-Ne shot is the relative brightness of the $1s^2$-$1s5p$, $1s^2$-$1s4p$, and $1s^2$-$1s3p$ lines. The integrated line intensities of these spectral lines are in the ratio 1.0:1.7:1.7 for the time-integrated spectrum and 1.0:1.3:1.3 for frame 4 of the time-resolved spectra. This is suggestive of recombination from H-like Ne ions in the cold, moderate-density Ne plasma. A population of H-like ions is known to exist on this shot since the H-like Ne $1s$-$2p$ resonant line is observed on frames 3–6 of the time-resolved spectra.

It is important to note that no H-like lines have ever been observed on Na-pumped shots. Moreover, the $1s^2$-$1s5p$ line is absent when a Na plasma is the pump. It can be shown that the three-body recombination rate scales as $n^{5.33}$ for the plasma conditions discussed here, where n is the principal quantum number. This scaling is deduced from a detailed balancing of collisional ionization (using the Lotz ionization formula [16]) with three-body recombination. The absence of $n=5$ radiation during the Na-pumped shots, as well as the lack of H-like lines or any recombination continuum, rules out recombination as a pump mechanism for the inversion. In contrast, the Mg-pumped shots exhibit the H-like Ne $1s$-$2p$ line and the recombination continuum, as well as a strong He-like Ne $1s^2$-$1s5p$ line, which are all characteristic of recombination. The keV lines from Mg are all of sufficient energy to ionize He-like Ne and were also emitted with 40% more power than those of Na, fully consistent with the above picture. An analysis of the (somewhat noisy) slope of the recombination continuum of the Mg shot yields an electron temperature of 30 eV, consistent with the radiation-hydrodynamic simulations of these experiments [11].

In summary, we have made time-integrated and time-resolved spectral measurements which demonstrate population inversion by resonant photopumping in the Na-Ne x-ray laser system. Success in demonstrating gain on this or other laser transitions would open the door to a class of x-ray lasers with large output energies and lasing times of several nsec or longer.

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