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PLASMA CONDITIONS FOR OPTIMUM GAIN IN RESONANT PHOTOEXCITATION OF STRONTIUM NEON-LIKE IONS BY ALUMINIUM RADIATION

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Résumé - On étudie sur le plan théorique et expérimental la photoexcitation résonnante des ions néonoides du strontium par le rayonnement des ions hydrogénéoides de l'aluminium. Les conditions de plasma favorisant la photoexcitation sont définies par des études en spectroscopie X et XUV. La conception des cibles est réalisée avec l'aide d'une étude de l'ablation de couches de strontium en fonction des conditions laser. L'absorption du rayonnement de l'aluminium par le strontium est démontrée dans une expérience à deux plasmas.

Abstract - Resonant photoexcitation of strontium neon-like ions by the radiation of aluminium hydrogen-like ions is studied theoretically and experimentally in laser-created plasmas. X-ray and XUV spectroscopy are used as tools to define plasma conditions where photo-pumping is efficient. The design of targets is completed by ablation studies of strontium layers under various experimental conditions. Absorption spectroscopy in a two plasma experiment demonstrates the potential usefulness of quasi-resonant photoexcitation in neon-like X-ray amplifiers.

1) Introduction

The great success achieved by Rosen, Matthews and co-workers /1-2/ at Lawrence Livermore Laboratory in the demonstration of a soft X-ray amplifier using 3p-3s transitions in neon-like selenium has confirmed the usefulness of the isoelectronic sequence of neon in X-ray laser research /3/. These results have led us to explore possible laser action in nearby-Z materials and to look for possible gain increase by external sources of pumping.

This paper presents a new population inversion scheme for X-ray laser in neon-like ions where the upper laser-level population mechanisms including electron collisional excitation and electron-ion recombination are enhanced by quasi-resonant photoexcitation proceeding from an auxiliary pump plasma. In the proposed scheme, photoexcitation takes place between the $(2s^2 2p^6)$ neon-like ground state and one of the $(2s^2 2p^5 3d)$ excited states. Then, the pumped 3d level collisionally decays towards the 3p upper-laser levels, thus increasing the inversion created by electron processes.

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II) Resonant photoexcitation of the $(1s^2 2s^2 2p^5 3d^3 D_1)$ level of neon-like strontium

1) Wavelength coincidences

Current interest exists to find high-brightness spectral lines for resonant photoexcitation /4/. We have focused our study on wavelength matching between resonance transitions of neon-like ions with Z scaling from 36 (krypton) to 42 (molybdenum) and hydrogen-like and helium-like resonance transitions of lighter elements ($11 < Z < 18$). A close matching has been found both theoretically and experimentally between the 1s-3p line of hydrogen-like aluminium (6.053 Å) and the $2s^2 2p^6 ({}^1S) - 2s^2 2p^5 3d ({}^3D)$, $J = 0-1$ transition in neon-like strontium (6.059 Å).

The SPECTRA computer package developed by R.W. Lee has been used to calculate the theoretical line profile of the aluminium 1s-3p pumping line arising from a plasma with electron density and temperature of 10^{22} cm^{-3} , 500 eV which are the typical conditions for hydrogen-like ions in our experiments. Figure 1 shows this theoretical spectrum on the same wavelength scale as the intrinsically Doppler-broadened absorption profile of the strontium line. The two lines are off-resonant by 6 mÅ. However, the Stark-broadened profile of the 1s-3p line is wide enough to produce significant intensity at 6 mÅ from aluminium line center. Furthermore, the wavelength difference can, in principle, be easily reduced by motional Doppler-shifts in a two counter-propagating plasma geometry with typical expansion velocities of $3 \cdot 10^7$ cm/s.

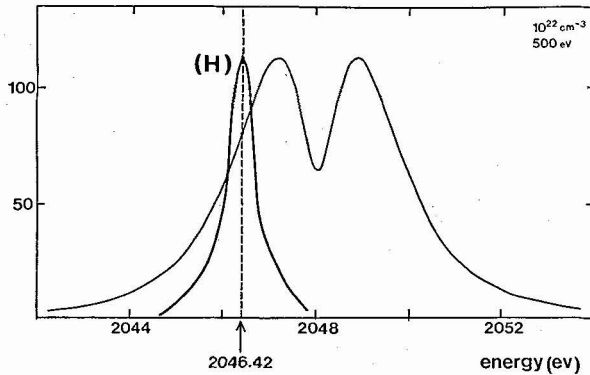


Figure 1 : Theoretical line profile of the aluminium 1s-3p line for electron density and temperature of 10^{22} cm^{-3} , 500 eV and of the $2p^6 ({}^1S) - 2p^5 3d ({}^3D)$ transition (line H) in neon-like strontium.

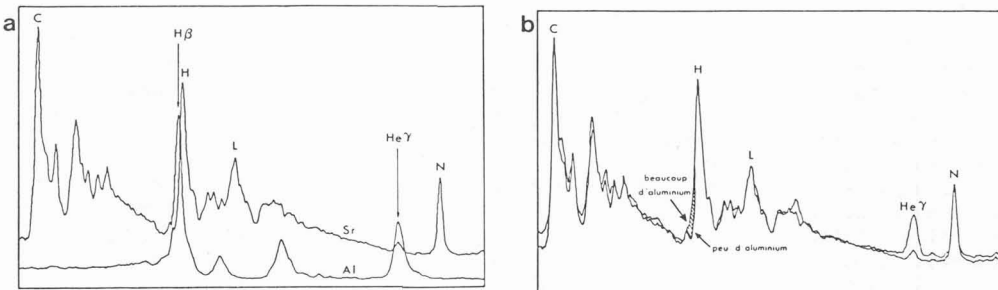


Figure 2 : a) Experimental spectra of pure aluminium and strontium targets. Aluminium impurities give us standards for wavelength calibration in strontium. The measured wavelength difference is smaller than the FWHM of the aluminium line.
 b) Experimental spectrum of a deposit of strontium on aluminium. The aluminium and strontium lines are barely resolved.

Experimental data obtained with pure aluminium and strontium targets and deposits of strontium on aluminium at laser intensities in the 10^{14} W/cm² range and 600 ps duration, 0.53 μ m laser wavelength are in good agreement with theory : the measured 5.2 to 6.3 mÅ wavelength difference is smaller than the 9.2 mÅ experimental full-width at half maximum (FWHM) of the hydrogen-like line (see Fig.2a). As a result, the aluminium and strontium lines are unresolved in the spectrum shown in Fig. 2b.

2) Calculation of the pumping rate

In evaluating the practicability of the matched-line scheme, one must first be concerned with the photoexcitation photon flux which can be obtained with the source plasma. The pumping rate per strontium ion in the neon-like ground state is /5/ :

$$P_{lu} = 1/2 g_u/g_l A_{ul} n_p$$

where g_u and g_l are the statistical weights of the levels $2s^2 2p^5 3d(3D_1)$ and $2s^2 2p^6$, respectively, and A_{ul} is the spontaneous decay rate of the corresponding transition. The number of photons per mode, n_p , has been deduced from the intensity produced by the 1s-3p aluminium pumping line at the frequency of the strontium pumped-line. This pump brightness has been computed using the SPECTRA code coupled to the collisional-radiative RATION code to calculate the population of the 3p level. Figure 3 shows the pumping rate as a function of electron density in the aluminium pump-plasma for three electron temperatures.

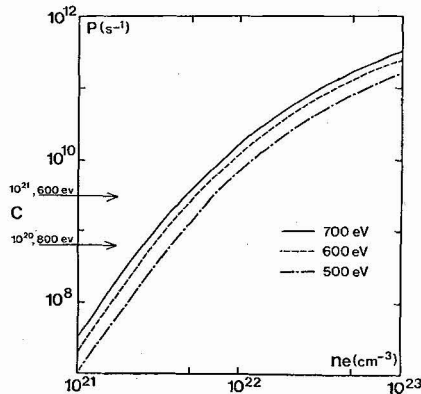


Figure 3 : Photoexcitation pumping rate as a function of electron density in the aluminium source plasma for three electron temperatures. The collisional excitation rate coefficient for the $2p^0-2p^2 3d$ transition is also shown for two different conditions of the strontium plasma.

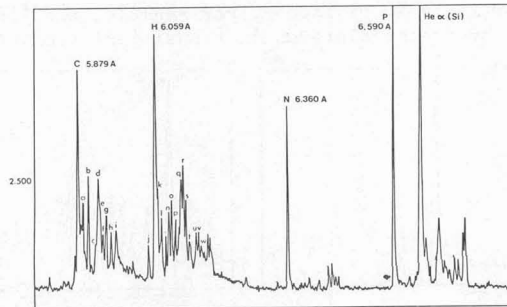


Figure 4 : Densitogram of strontium neon- and sodium-like transitions around 6 Å showing the strong features H,C,N and P together with silicon lines wavelength standards.

3) Comparison of the collisional and photoexcitation rates

This radiative-pumping scheme will be efficient if the photoexcitation rate $F_{\ell_{lu}}$ is at least equal to the corresponding electron collisional rate coefficient $C_{\ell_{lu}}$. At an electron density and temperature of 10^{20} cm^{-3} , 800 eV (respectively 10^{21} cm^{-3} , 600 eV) for the strontium plasma, $C_{\ell_{lu}} = 6.52 \cdot 10^8 \text{ s}^{-1}$ ($C_{\ell_{lu}} = 3.04 \cdot 10^9 \text{ s}^{-1}$) which is 10 times (2 times) lower than the photo-pumping rate provided by an aluminium plasma of 10^{22} cm^{-3} , 500 eV.

The arrows on Fig. 3 show the values of $C_{\ell_{lu}}$ for the strontium plasma mentioned above and make easier the comparison with $F_{\ell_{lu}}$ for various conditions of the aluminium plasma. It results that the present $F_{\ell_{lu}}$ method of resonant photoexcitation will be very useful, in a properly prepared strontium-aluminium system, to enhance by a factor larger than 10 the inversion generated by collisional excitation. This may be confirmed experimentally by an increase of the intensity of the $2s^2 2p^6 - 2s^2 2p^5 3d(^3D_1)$ X-ray line and of the XUV $3s-3p$ lasing transitions if the collisional coupling between the $3d$ and $3p$ levels is strong enough.

III) Spectroscopy of strontium

1) X-ray spectroscopy of neon-like and sodium-like ions

X-ray spectroscopy is a valuable tool to determine plasma conditions. A typical spectrogram obtained with a target consisting of a strontium deposit on silicon (for wavelength calibration) at a laser intensity of $2 \cdot 10^{14} \text{ W/cm}^2$ and $0.53 \mu\text{m}$ wavelength is shown in Fig. 4. When compared to earlier observations [6], the spectral resolution is clearly improved. This enables to get a detailed identification of the sodium-like satellite lines accompanying the four neon-like lines labelled C, H, N, and P corresponding to the $2s^2 2p^6 - 2s^2 2p^5 3d$ and $2s^2 2p^6 - 2s^2 2p^5 3s$ transitions.

Ab initio calculations have been made using the relativistic parametric potential method [7]. The RELAC code yielded the level energies and the oscillator strengths of several excited levels of sodium-like ions pertaining to the configurations $2s^2 2p^6 3s$, $-3p$, $-3d$, $2s^2 2p^5 3s^2$, $-3s3p$, $-3s3d$, $-3p^2$, $-3p3d$, $-3d^2$ and $2s2p^6 3s^2$, $-3p^2$, $-3d^2$, $-3s3d$, $-3s3p$, $3p-3d$. Synthetic spectra are reproduced in Fig. 5a for sodium-like lines close to the C line and in Fig. 5b for sodium-like lines close to the H line to show directly the comparison between experiment and theory. In order to take into account the finite instrumental width of our apparatus, we convoluted the theoretical line intensities with Gaussian profiles of 7 m\AA FWHM. The population ratio of ground states of sodium- and neon-like ions were calculated using Saha-equilibrium with $T = 800 \text{ eV}$ and $n_e = 10^{20} \text{ cm}^{-3}$. Owing to the simplicity of this assumption, the agreement is outstanding both on the wavelength position of lines and on their relative intensities. Discrepancies in line positions are well within 2 m\AA corresponding to uncertainties in wavelength calibration. The broad feature on the long-wavelength side of H and C are satellite lines with one spectator electron in the orbitals 4ℓ or higher. For example, the line labelled ℓ in Fig. 5b involves a $4s$ spectator electron in transitions from $2p^5 3d 4s$ to $2p^6 4s$.

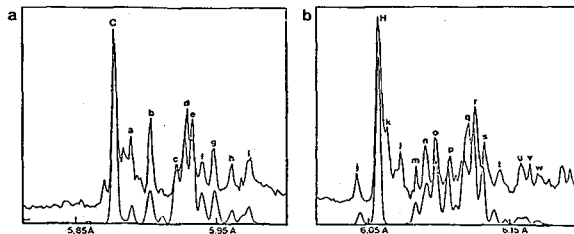


Figure 5 : a) Sodium-like satellite lines in the vicinity of the C line.
 b) Sodium-like satellite lines in the vicinity of the H line.
 The population ratio of neon-/sodium-like ionization stages is given by Saha equilibrium at 10^{20} cm^{-3} and 800 eV.

2) XUV spectroscopy

Figure 6 shows an XUV spectrum generated by focusing the laser on a massive strontium rod. The laser wavelength was again $0.53 \mu\text{m}$ and the intensity on the target was about 10^{14} W/cm^2 . The strongest features have been unambiguously identified as magnesium-like and sodium-like transitions in agreement with previous results /8/. Unfortunately, second- and third-order diffraction from the grating complicate the identification of weak lines in the range 150-170 Å where neon-like lines are anticipated from RELAC calculations.

IV) Absorption of aluminium radiation in a two plasma experiment

The purpose of this experiment was to produce, with a variable optical delay, a strontium plasma with an electron density of the order of 10^{20} cm^{-3} and an aluminium plasma emitting mainly hydrogen-like lines in a high electron density region to favor Stark broadening. The aluminium thickness was optimized to provide maximum absorption of aluminium by strontium and the thickness of the strontium layer had to be small enough to be completely ablated during the laser shot. So, a detailed study of the ablated strontium thickness as a function of laser intensity has been first carried out.

1) Ablation of multilayered targets

The targets consisted of a deposit of strontium fluoride on a silicon substrate. The thickness of strontium fluoride could vary from 430 to 2000 Å. We used only one laser beam of $1.06 \mu\text{m}$ radiation and 600 ps pulses. The intensity on the target was in the range $5 \cdot 10^{13}$ to 10^{14} W/cm^2 . Spectral and temporal resolution were provided by a concave PET crystal coupled to a streak camera.

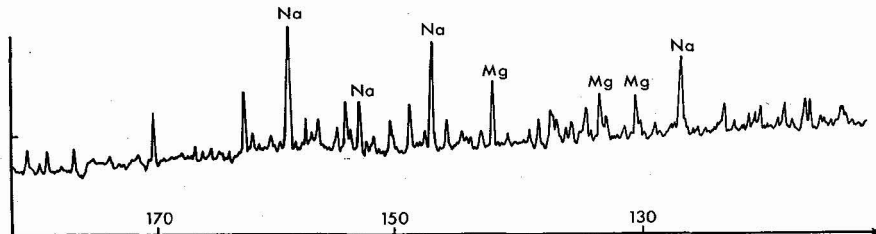


Figure 6 : XUV spectrum of a strontium target irradiated at $0.53 \mu\text{m}$, 10^{14} W/cm^2 . Magnesium-like and sodium-like lines are unambiguously identified.

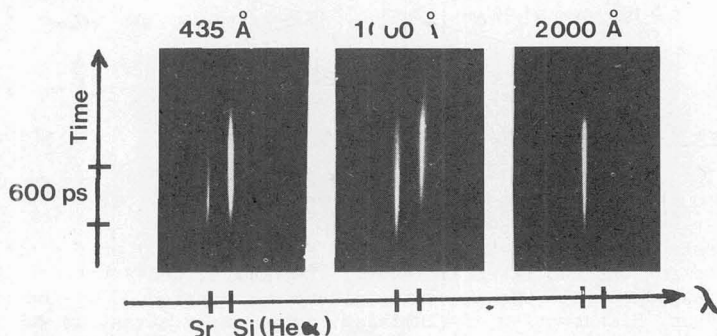


Figure 7 : Streaked spectra showing the time delay and the duration of emission for strontium-silicon targets as a function of strontium thickness.

The emission of the strontium P line (6.591 Å) and of the $1s^{21}S-1s2p^1P$ line of helium-like silicon (6.648 Å) were recorded as a function of time and for three different strontium thickness (435, 1000, 2000 Å) as shown in Figure 7. The time delay between silicon and strontium emission as well as the duration of strontium emission clearly increase with the strontium thickness. Comparison is made in Figure 8 with the predictions of a 1D hydrocode including atomic physics using the average atom model. Experiment and code results agree qualitatively, both for the delay and for the duration of strontium emission.

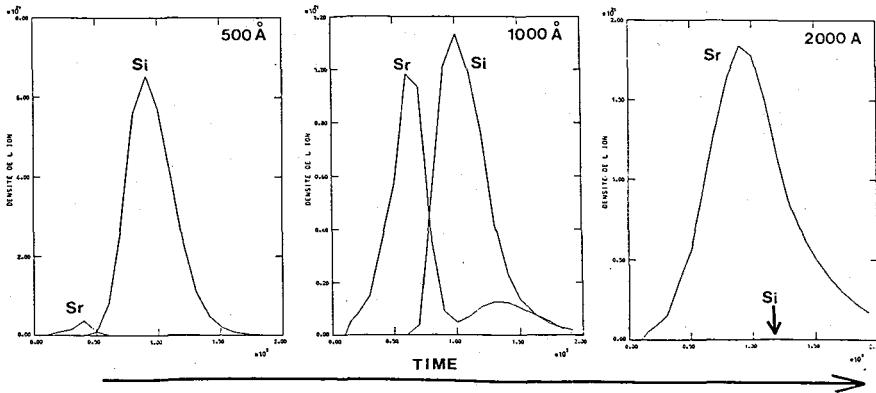


Figure 8 : Code simulation of streak profiles of strontium and silicon emissions at 5.10^{13} W/cm² for three strontium thickness.

It results from this that the maximum strontium thickness ablated by a 600 ps laser pulse of 10^{14} W/cm² intensity is close to 1000 Å. For the intensity we used in our absorption experiments, namely 5.10^{13} W/cm², the maximum ablated thickness is roughly 780 Å. We have kept this value for the absorption targets.

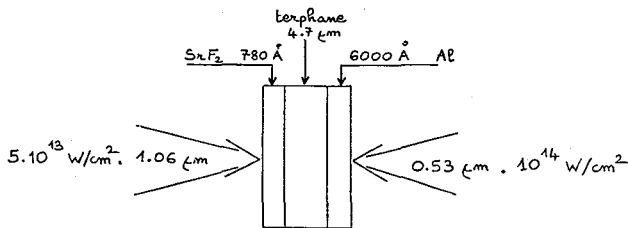


Figure 9 : Geometry of the target for quasi-resonant X-ray absorption.

2) Quasi-resonant X-ray absorption

The geometry of the targets is shown in Figure 9. A 4.7 μm plastic foil acts as a substrate for the two material layers. The optical delay between the two laser beams was adjusted so that the aluminium plasma was created 300 ps before the strontium plasma. Reabsorption of aluminium radiation by strontium was varied by changing the distance between the focal spots on the two sides of the target. Figure 10 shows a bilorentzian analysis of the red and blue halfwidths of the aluminium 1s-3p line as a function of the position on the film in two experimental configurations where absorption is suppressed (Fig. 10b) or favored (Fig. 10c).

Spatial resolution was provided by a 100 μm slit ; increasing positions on the film correspond to increasing distances from the target plane.

On Figure 10c, the red half-width (spectrally on the strontium side) is clearly smaller than the blue half-width which takes similar values with and without reabsorption. These results qualitatively show the absorption of the aluminium line on the merging spectral region of the strontium line.

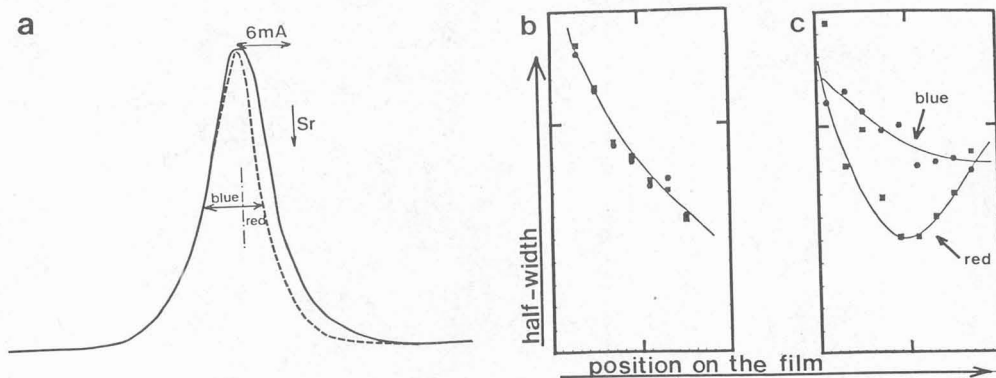


Figure 10 : a) Experimental spectra of the 1s-3p line of aluminium with reabsorption (dashed line) and without reabsorption (solid line). The position of the strontium H line is also shown.
 b) Red (squares) and blue (circles) halfwidths of the aluminium line reabsorbed by strontium as a function of position along the laser axis. This case is without reabsorption (solid curve in a).
 c) with reabsorption (dashed curve in a).

V) Conclusion

We have studied the feasibility of a resonant photoexcitation scheme ensuring the enhancement of gain in collisional excitation population mechanism of lasing levels in neon-like strontium. The approximate value of the photo-pumping flux which can be obtained with the aluminium source plasma has been calculated and we have evaluated the plasma conditions which must be produced in the strontium plasma to favor photo-pumping. Finally, absorption of aluminium radiation by strontium on a two plasma experiment has been demonstrated.

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