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ANALYSIS OF LASING TRANSITIONS IN A LASER-PRODUCED SELENIUM PLASMA

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RESUME - Des calculs de forces de collision et de taux de desexcitation radiative ont été effectués pour 8 configurations ($1s^2 2s^2 2p^6$, $2p^5 31$ et $41'$, si $1=0,1,2$ et $1'=0,1,2,3$) du selenium neonoïde (Se XXV). A partir de ces données atomiques ont été calculées les différentes populations des niveaux décrivant un plasma de selenium produit par laser en fonction de l'évolution hydrodynamique de celui-ci.

L'analyse de ces populations a permis de mettre en évidence l'existence d'inversions et de transitions "lasantes", en particulier entre les configurations $2p^5 3p$ - 3s, 4p - 3d et 4f - 3d.

ABSTRACT - We present calculations of electron impact collision strengths and spontaneous radiative decay rates for 8 neon-like selenium (Se XXV) configurations ($1s^2 2s^2 2p^6$, $2p^5 31$ and $41'$, $1 = 0, 1, 2$ and $1' = 0,1,2,3$).

From these atomic data the level populations are calculated in a laser produced selenium plasma as a function of its time-evolving hydrodynamical profile (electron temperature and density).

The analysis of these populations involves the existence of lasing transitions, especially between the $2p^5 3p$ and 3s configurations, but also between the 4p and 3d, or 4f and 3d one.

Hydrodynamical plasma conditions

According to the L.L.N.L. X-ray laser experiments /1/, we decide to study a thin Se foil (750Å deposited on 1500Å of solid CH_2: Fig.1). This target was irradiated by a single beam of a 0.53 μm laser light, with a $5\ 10^{13}$ W/cm^2, 315ps flat-topped illumination (Fig.2).

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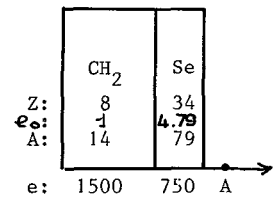

Fig.1. Se target design

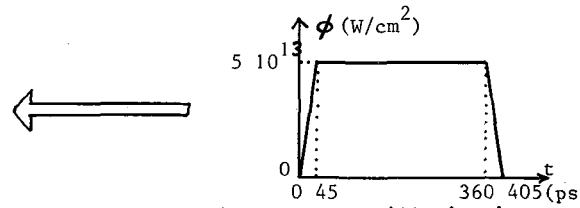

Fig.2. Laser illumination

The hydrodynamical 1-D code CHIVAS/2/, coupled with the ionization model CORINNE /3/, allows us to describe the temporal plasma evolution (Fig.3) The laser energy is supposed absorbed by inverse Bremsstrahlung and by a local deposition of 10% at the laser cut-off density. A heat-flux limiter equal to 0.05 is taken into account.

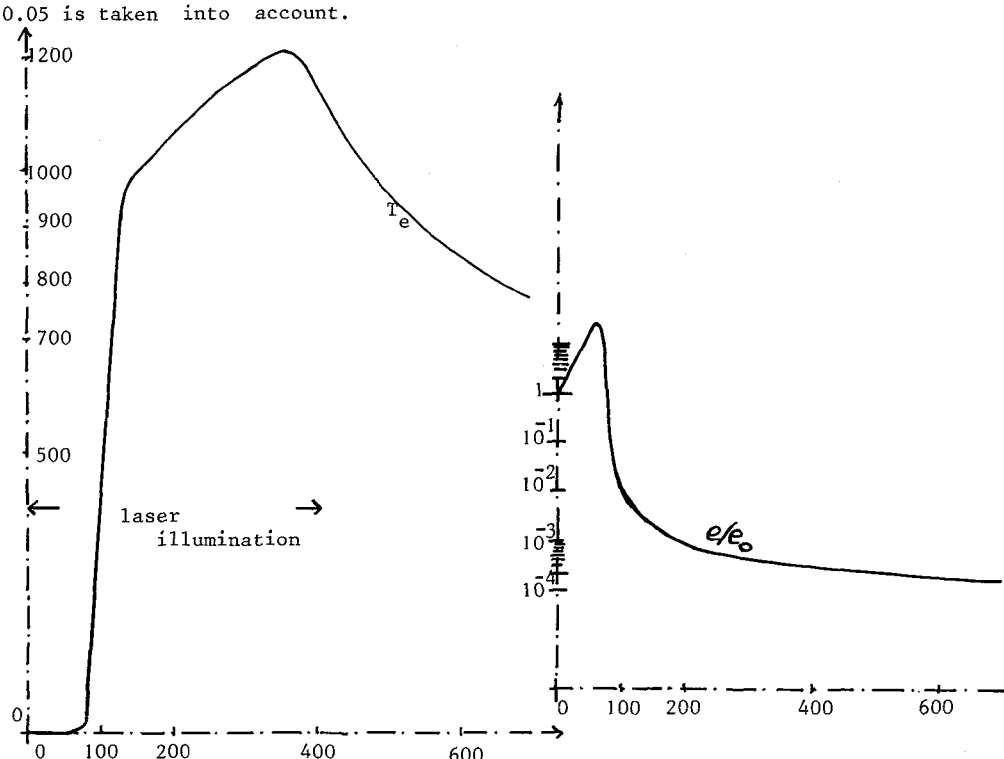

Fig.3. Electron temperature Te(ev) and compression factor e/e_0 versus time t (ps)

Atomic structure calculations

An atomic model of highly ionized selenium has been constructed. It includes the six most relevant configurations of Se XXV : the ground state $1s^2 2s^2 2p^6$ and the n = 3 -n = 4 configurations $1s^2 2s^2 2p^5 31$ and 4 l' (for l=0, 1,2 and l' = 0,1,2,3), which represent 65 levels in LSJ coupling. The excited

levels above 4f through n=9 are consolidated by principal quantum numbers. This plasma model is completed by the ground states of the other ionization stages, consolidated by seven n-levels.

The 328 various states are coupled by electron collisional excitation and de-excitation, spontaneous radiative decay, collisional ionization and three-body, radiative or dielectronic recombination.

The main atomic problem becomes the determination of configuration interaction wawefunctions and energies from which can be deduced the different needed parameters. The energy levels, statistical weights and spontaneous radiative probabilities are calculated in LSJ coupling by the SUPERSTRUCTURE computer code /4/ which derives from a relativistic modified Thomas-Fermi statistical potential approximation and assumes wavefunctions as linear combinations of Slater determinants, developed on a basis of the four monoelectronic orbitals s, p, d and f. The scaling parameters of the potential are obtained by a minimization procedure based upon some selected neonlike configurations : $1s^2 2s^2 2p^6$ and $2p^5 31$ (1=0,1,2).

$$\lambda_s = 1.1727$$
$$\lambda_p = 1.0873$$
$$\lambda_d = \lambda_f = 1.0963$$

The scattering problem was carried out in a distorted wave approximation using the computer package SUPERSTRUCTURE + DW + JJOM /5/, an electron-collision cross-section program which calculates collision strengths, in fine-structure coupling, versus incident electron energy (here, 160 Rydbergs). The contribution to these strengths from high partial waves ($l > 20$) is taken into account in a Coulomb-Bethe approximation. The main collision strengths at 160 Rydbergs (Ω), radiative probabilities (A, in s^{-1}) and wavelengths (λ in Å) are represented on Fig.4.

All the hydrodynamical and atomic data that we calculate in the first part of this analysis are then introduced in the LIMEIL computer code LASIX /6/.

This program first determines the temporal evolution of the plasma : the average charge $\bar{Z}$, the rates r(z) of the different existent ions (where z is the nuclear charge of the studied ion) , and the electron density n_e (Fig.5).

After the end of the laser illumination , the average nuclear charge $\bar{Z}$ may be considered as constant :

$$\bar{Z} = 25.70$$

and four ionization degrees prevail in the plasma :

z = 28 (N) - z = 27 (O) - z = 26 (F) - z = 25 (Ne)

with a predominance of the oxygenlike and fluorinelike ions , which explains the importance that the different recombination processes take in the determination of

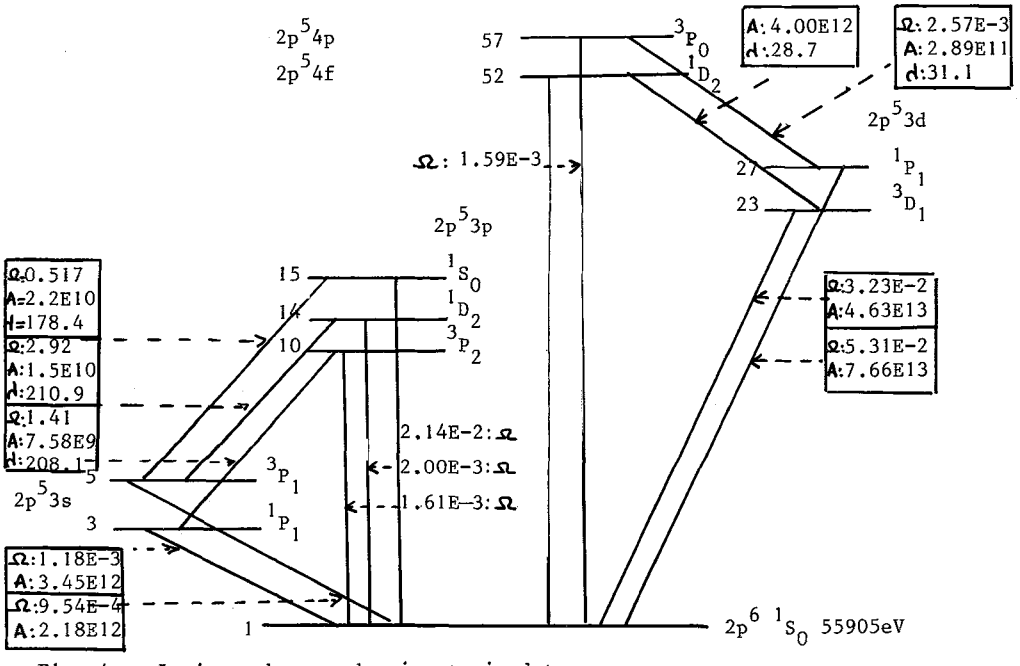

Fig. 4 . Lasing scheme and main atomic data

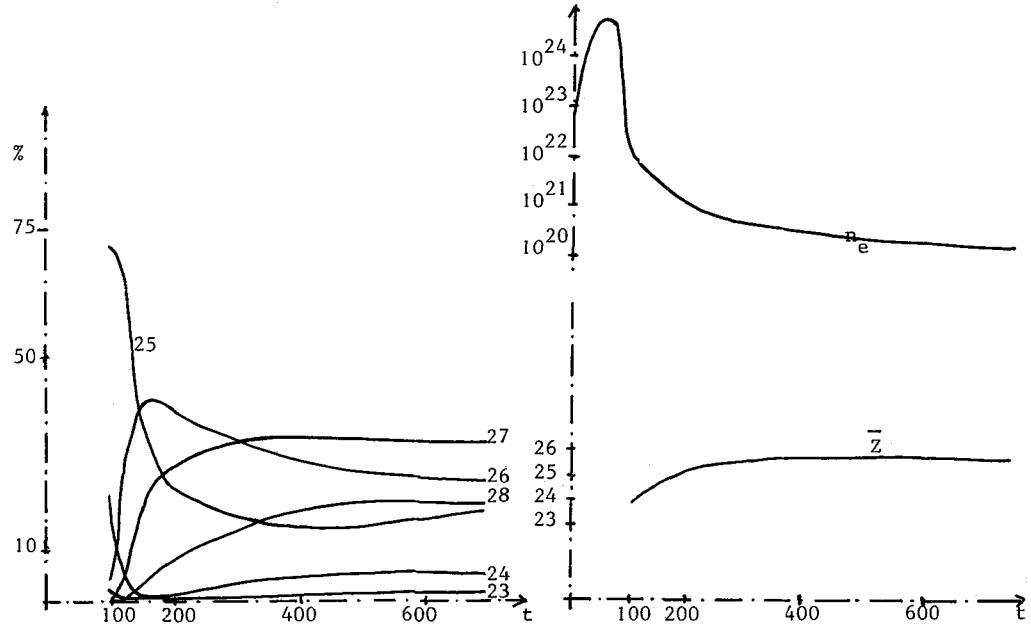

Fig. 5 . Temporal evolution of the different nuclear charges in the selenium plasma and of the electron density n_e (cm^{-3}) versus time t (ps).

the ionization balance and of the detailed level populations .

Then , LASIX solves the set of coupled equations :

$$\frac{dP_i}{dt} = -P_i \left(\sum_{j<i} (A_{ij} + n_e C^d_{ij}) + n_e \sum_{j>i} C^e_{ij} + X \right) + \sum_{j>i} P_j (A_{ji} + n_e C^d_{ji}) + n_e \sum_{j<i} C^e_{ji} + Y$$

where X and Y represent the contribution of the ionization-recombination processes in the population and depopulation of the ith level (P_i) . C_{ij} is the collisional excitation (e) (or de-excitation (d)) rate coefficient .

The formulation of these rate coefficients is classical :
C_{ij} is a function of the collisional strength Ω_{ji} :

$$C^d_{ij} = 8.015\ 10^{-8} \Omega_{ji} / g_i\ T_e^{-1/2} \quad (cm^3 s^{-1}; eV)$$

g_i being the statistical weigth of the ith level , while collisional ionization and radiative recombination rate coefficients derive from semi-empirical formulae (Lotz /7/ and Seaton /8/) . The dielectronic recombination rate coefficient has been previously determined (/9/) .

The calculated populations can be represented per unit statistical weigth to show the existence of the classical inversions 3p - 3s but also of 4 - 3 one (Fig. 6) . The gain coefficient for these lasing transitions is supposed to be given , if Doppler broadening is the main source of line broadening , by :

$$\alpha = 1.437\ 10^{-7}\ T_e^{-1/2} \lambda^3_{ij}\ A_{ij}\ g_i \left(\frac{P_i}{g_i} - \frac{P_j}{g_j} \right) \qquad (cm^{-1}, \text{ Fig. 7})$$

Analysis and conclusion

The short-wavelength transitions (with change of principal quantum number) present , in such described hydrodynamical plasma conditions , gains never exceeding 0.1 cm^{-1} and therefore are not interesting as X-ray laser possibilities . In fact , the main result of this study is the restitution of the Livermore X-ray experiments' conclusions : as far as the 3p-3s transitions in neonlike selenium are concerned , the highest gains must be expected for the J = 2 to J = 1 lines (at 206 Å and 210 Å) while the J = 0 to J = 1 transition(at 183 Å) presents a lower gain (0.25 cm^{-1}) .

In summary , it seems that , to calculate correct gains in laser-produced plasmas , it should be necessary to do accurate evaluations of dielectronic recombination rate coefficients and collision strengths and to use time-dependent models .

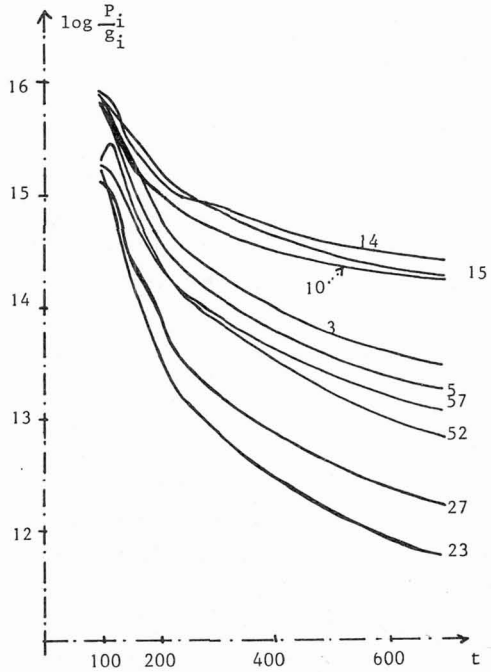

Fig. 6 . Relative level populations per unit statistical weigth (cm^{-3}) versus time (ps)

(numbers 5,3,10,14,15,23,27,52 and 57 refer to Fig.4)

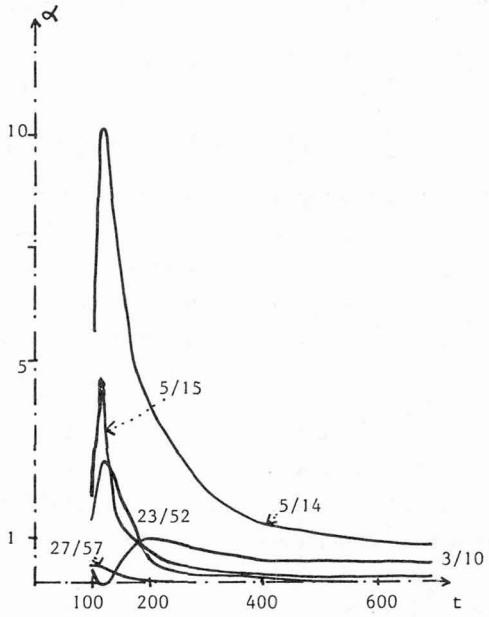

Fig. 7 . Gain coefficients (cm^{-1}) versus time (ps)

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