An x-ray laser operating on 2S–2P transitions of a Ne-like ion

V. Yu. Politov and M. K. Shinkarev
All-Russian Scientific-Reserach Institute of Engineering Physics, Chelyabinsk-70, PO Box 245, Russia

(Submitted 16 September 1993)
Pis'ma Zh. Eksp. Teor. Fiz. **58**, No. 10, 794–798 (25 November 1993)

A new x-ray laser using Ne-like ions and exploiting certain features of the fine structure of these ions is discussed theoretically. The pumping is a resonant photoexcitation, which sends a 2*S* electron from the ground state into 3*P*, 4*P*, etc., excited sublevels. As a result, a 2*S* hole forms in the *L* shell. The filling of this hole by 2*P* electrons may result in lasing. Calculations of the gain coefficients on 2*S*–2*P* transitions in Ne-like Ge as a function of the pump intensity and the density of the active medium are reported for the particular example of the Mg–Ge resonant pair.

1. Resonant photoexcitation is currently regarded as one of the most promising mechanisms for pumping the active media of lasers for the x-ray range.[1] This mechanism can be used to create population inversions for transitions in the fine structure of multiply charged ions (with $\Delta n=0$) and also for transitions involving a change in the main quantum number ($\Delta n \neq 0$). Correspondingly, there is the possibility in principle of generating laser radiation with a fairly short wavelength ($\lambda < 100$ Å) at high quantum efficiencies ($\eta_q > 0.1$).

Achieving resonant pumping in practice is of course considerably more difficult than, for example, collisional pumping, which has already been demonstrated experimentally for Ne- and Ni-like ions[2,3] for several substances with large and intermediate atomic numbers *Z*. It becomes a crucial matter to select resonant pairs which have a small resonance defect and which simultaneously conform to the energy capabilities of existing apparatus. Furthermore, even if this defect is extremely small, it is necessary to solve a complicated technical problem: The converter which forms the pump line must surround the active medium of the x-ray laser to the greatest extent possible and thereby make this line highly intense. Further severe conditions are imposed on the design of the laser by reabsorption of the radiation in lines which empty the lower working level, among other factors.

For experimentally choosing among the various possible resonant schemes it is thus important to choose schemes for which these difficulties are the least onerous. One possibility is proposed in the present letter. It is based on some particular features of the discrete energy spectrum of Ne-like ions.

2. On the one hand, such ions (and also He-, Ni-, etc.-like ions) are attractive because their ground state, from which the pumping begins, is not split, and in a plasma its population can approach the maximum possible (>50%). The requirements on the pump intensity are corresponding relaxed (this point is also important for collisional schemes). On the other hand, there is the interesting possibility of

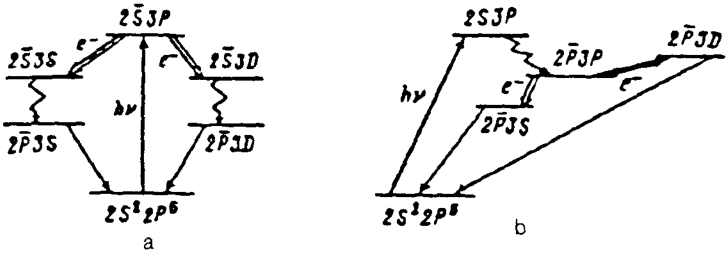


FIG. 1. Basic types of laser chains in a Ne-like ion with 2S–2P working transitions during resonant photoexcitation of a 2S electron into an $n=3$ level.

organizing a population inversion on transitions in the L shell of Ne-like ions with relatively high values of η_q through the selective excitation of a 2S electron into 3P, 4P, etc., states. Lasing chains involving two electrons arise here. Transitions of an excited electron fill the upper working state and empty the lower one, and the laser generation is due to 2P electrons which fill a $2\bar{S}$ hole (Nilsen[4] has offered a similar suggestion for an x-ray laser using Ni-like ions).

We are primarily interested in the case in which the 3P state is excited. This arrangement will have the highest efficiency among the entire family with $n \geqslant 3$; specifically, the efficiency will be $\sim 0.12-0.14$, depending on the value of Z. These values are close to the values of η_q for schemes with 5–4 working transitions ($\Delta n \neq 0$). Fig. 1, a and b, shows the basic lasing chains possible in this scheme. For brevity, we do not specify the components of the fine structure with different values of the total angular momentum J; we use the notation $2\bar{S}$ and $2\bar{P}$ to represent the presence of a hole in the corresponding L subshell.

What should the threshold conditions, in terms of the pump and the characteristics of the active medium, be for an effective realization of any of these chains? Despite the complexity of the spectrum of a Ne-like ion, it is a fairly simple matter to carry out some estimates, since the population of the upper working state is determined exclusively by the pump intensity and the population of the ground state under the conditions of resonant photoexcitation. Collisional processes in the level with $n=3$ and the 2S –2P working transitions have little effect, since their rates are much lower than the rate of the 2S–3P resonant decay. There are no other resonant decays from the upper state to the ground state. The generally accepted condition for the efficiency of an x-ray laser is

$$\kappa^{+} \geqslant 1. \tag{1}$$

We use the standard expression for the gain coefficient

$$\kappa^{+} = \lambda^2 A_{ul}(N_u - g_u/g_l N_l)\varphi(0)/8\pi\Delta\nu_d, \tag{2}$$

where N_u, N_l, g_u, and g_l are the densities and statistical weights of the upper and lower working states, A_{ul} is the rate of the corresponding spontaneous decay, φ (0) is the Voigt spectral function at the center of the absorption line, and $\Delta\nu_d$ is the Doppler linewidth.

Let us assume that the intensity of the pump line is characterized by a photon occupation number M. Since all other processes have only slight effects on N_u, we can assume

$$N_u \simeq 6\times 10^{23}\rho/AMC_0\, g_u/g_0, \quad N_u \gg N_l, \tag{3}$$

where C_0 is the normalized population of the ground state of the Ne-like ion, ρ is the density of the active medium in g/cm^3, and A is the atomic weight. We also express A and $\Delta\nu_d$ in terms of λ (in units of s^{-1}):[5]

$$A_{ul}=\frac{4(2\pi\hbar)^3 S_{ul}/g_u}{3\lambda^3(me\bar{Z})^2}, \quad \Delta\nu_d=\frac{4.4\times 10^7}{\lambda}\sqrt{T/A}. \tag{4}$$

Here S_{ul} is the dimensionless square of the dipole matrix element of the working transition, T is the temperature of the active medium in energy units (keV), and $\bar{Z}=Z-\chi$ is the effective atomic number, after a correction for a screening coefficient. For the 2S–2P transitions in a Ne-like ion we would have $\chi \simeq 6$.

We substitute expressions (2), (3), and (4) into condition (1), using $A\simeq 3Z$ and $g_0=1$. We set $C_0=0.5$, which is close to the maximum value attainable, and $\varphi(0)=1/\sqrt{\pi}$ (corresponding to the case of purely Doppler broadening). As a result, we find

$$\rho MS_{ul}/T^{1/2}\bar{Z}^{5/2} \geqslant 6\times 10^{-9}. \tag{5}$$

Spectroscopic calculations by the MCDF program[6] show that the value of S_{ul} for the strongest 2S–2P transitions is $\simeq 30$, and only weakly dependent on Z. For the values $\bar{Z} \simeq 30$ and $T\simeq 0.5$, characteristic of recent experiments, we have the estimate $\rho M \geqslant 7\times 10^{-7}$. With $M\sim 10^{-3}$, for example, the density of the active medium at the time of generation should be greater than 10^{-3} g/cm^3.

3. To check these estimates, we developed a kinetic model for a Ne-like ion. The model includes 37 J-split Ne-like states with $n=2$ and 3, unsplit states with $n=4$–10, and several states of ions with approximately the same charge (O-, F-, Na-, etc.-like). In practice, the procedure is one of simply entering calculated MCDF information—line strengths, dipole transitions, and total ionization potentials of states— into the database of the TARAN program,[7] written for modeling the kinetics of an ion of an arbitrary type. As the object of the modeling we selected germanium, with $Z=32$. In the course of a search for resonant pairs it was found that one of the lines of the Ne-like 2S–3P doublet of this element, with $\lambda=8.423$ Å, agrees very well with the $Ly\alpha$ line of H-like Mg ($\lambda=8.4246$ Å). This agreement is supported by both theoretical[8] and experimental[9] data.

From the standpoint of designing an experiment, this pair is an extremely fortunate find. In the first place, the energy required for forming the pumping line in a magnesium converter is estimated to be quite moderate. The ion composition in Mg shifts in the direction of H-like ions at a temperature of only $T\sim 0.5$ keV. Second, the maximum density of Ne-like Ge ions corresponds to roughly the same temperature, as can be seen from Fig. 2, which is a plot of $C_0(T)$ for two densities, $\rho=5\times 10^{-4}$ and 5×10^{-3} g/cm^3. The approximate agreement of the optimum temperatures for the converter and for the active medium raises the hope that it will be possible to realize

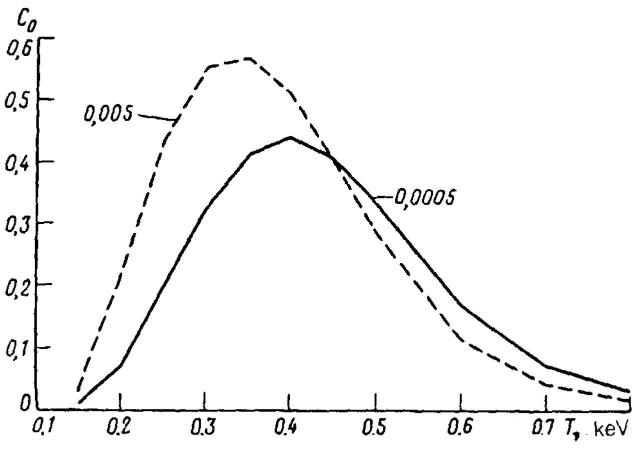
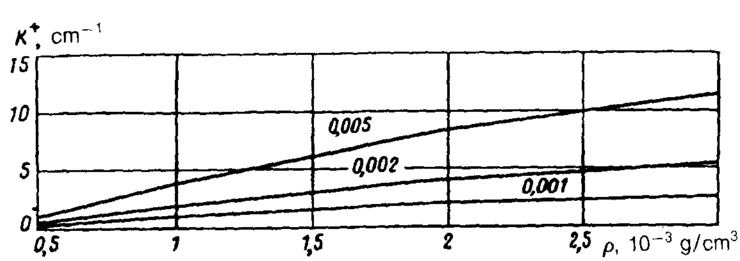


FIG. 2. Theoretical temperature dependence of the population of the ground state of the Ne-like Ge ion for two densities of the active medium. Solid curve—$\rho = 5 \times 10^{-4}$; dashed curve—5×10^{-3} g/cm^3.

a simple design for the x-ray laser, in the form of a two-layer plane target illuminated by an intense optical-range laser. At the time of generation, the Mg and Ge layers will presumably be in a plasma corona, in which there is a rapid equalization of temperatures by electron thermal conductivity.

Dielectronic recombination causes a significant shift of the optimum density of Ne-like Ge ions toward higher temperatures T. According to the data of Ref. 10, the coefficient of the dielectronic recombination which couples the ground states of the Ne- and Na-like ions is $\alpha_{DR} \simeq 10^{-11}$ cm ^{3}/s at $T = 0.3 - 0.5$ keV and $Z = 32$. The corresponding rate $N_e \alpha_{DR}$ is roughly eight times the rate of photorecombination under these conditions (N_e is the density of free electrons). This circumstance was taken into account in the kinetic calculations.

We conclude with the results of some calculations of the gain coefficients for the $2S$–$2P$ transitions as a function of ρ and M (Fig. 3, a and b) at the optimum temperature of a germanium plasma for the existence of Ne-like ions, $T = 0.4$ keV. These results show that in the interval $\rho = 5 \times 10^{-4} - 5 \times 10^{-3}$ g/cm^3 the lasing chains in Fig. 1b would be preferable. The largest values of κ^+ are found for the two transitions $[2\bar{S}_{1/2} 3P_{1/2}(J=1)]$–$[2\bar{P}_{1/2} 3P_{1/2}(J=1)]$ and $[2\bar{S}_{1/2} 3P_{1/2}(J=1)]$–$[2\bar{P}_{3/2} 3P_{1/2}(J=2)]$, with $\lambda = 77$ and 62 Å. The corresponding values of the parameter ρM turn out to be significantly higher than (5). This difference is attributed to a rigorous incorporation of all the main channels for the decay and filling of the upper and lower working states in the kinetic model. Nevertheless, we predict fairly large values, $\kappa^+ \geqslant 4$ cm^{-1}, and completely reasonable pump intensities, $M \sim 0.002 - 0.005$, and $\rho \sim 2 \times 10^{-3}$ g/cm^3. We hope that this circumstance, along with the novelty of this new scheme and the possible advantages in terms of target design, will attract interest to a corresponding experimental study.



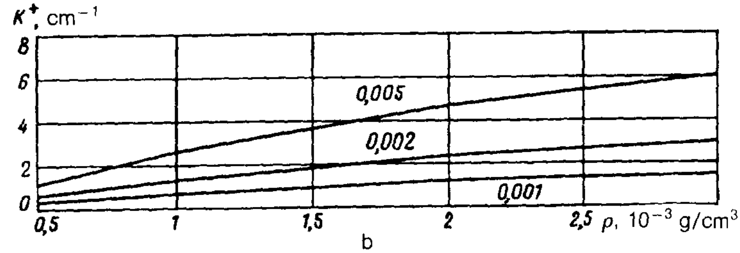


FIG. 3. Theoretical gain coefficients on two transitions as a function of the density of the active medium at $T=$ 0.4 keV. a: The transition $[2\bar{S}_{1/2}3P_{1/2}\ (1)]$–$[2\bar{P}_{3/2}3P_{1/2}\ (2)]$. b: $2\bar{S}_{1/2}3P_{1/2}$–$2\bar{P}_{1/2}3P_{1/2}\ (1)$. The curves are labeled with the value of the photon occupation number in the pumping line, M.

[1] J. Nilsen, J. L. Porter *et al.*, *Third International Colloquium on X-ray Lasers* (Schliersee, Germany, May 18–22, 1992).
[2] M. D. Rosen, P. L. Hagelstein, D. L. Matthews *et al.*, Phys. Rev. Lett. **54**, 106 (1985).
[3] B. J. MacGowan, S. Maxon, P. L. Hagelstein *et al.*, Phys. Rev. Lett. **59**, 2157 (1987).
[4] J. Nilsen, Opt. Commun. **72**, 371 (1989).
[5] I. I. Sobel'man, *Introduction to the Theory of Atomic Spectra* (Pergamon, Oxford, 1972).
[6] I. P. Grant, B. J. McKenzie *et al.*, Comp. Phys. Commun. **21**, 207 (1980).
[7] V. Yu. Politov, V. A. Lykov, and M. K. Shinkarev, Preprint 39, VNIITF, 1993.
[8] L. A. Vaĭnshteĭn and U. I. Safronova, Preprint, Institute of Spectroscopy, Academy of Sciences of the USSR, 1985.
[9] P. G. Burkhalter, D. J. Nagel, and R. D. Cowan, Phys. Rev. A **11**, 782 (1975).
[10] S. Dalhed, J. Nilsen, and P. Hagelstein, Phys. Rev. A **33**, 264 (1986).

Translated by D. Parsons