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A. Carillon, F. Gadi, B. Gauthé, H. Guennou, P. Jaeglé, et al.. WAVELENGTH SCALING OF LITHIUM-LIKE RECOMBINATION SCHEME FOR X-UV GAIN PRODUCTION. Journal de Physique Colloques, 1987, 48 (C9), pp.C9-375-C9-378. 10.1051/jphyscol:1987966 . jpa-00227384

HAL Id: jpa-00227384

<https://hal.science/jpa-00227384>

Submitted on 1 Jan 1987

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WAVELENGTH SCALING OF LITHIUM-LIKE RECOMBINATION SCHEME FOR X-UV GAIN PRODUCTION

A. CARILLON, F. GADI, B. GAUTHÉ, H. GUENNOU, P. JAEGLÉ,
G. JAMELOT, A. KLISNICK, C. MÖLLER and A. SUREAU

*Laboratoire de Spectroscopie Atomique et Ionique, Bât. 350,
Université Paris-Sud, F-91405 Orsay Cedex, France
and GILM, Ecole Polytechnique, F-91128 Palaiseau Cedex, France*

RESUME. On présente des valeurs de gain obtenues tant par mesures expérimentales que par prévisions théoriques pour les transitions 3d-5f, 3d-4f et 4d-5f des ions lithiunoïdes dans des plasmas produits par laser. A la suite d'une étude détaillée du cas de l'ion Al^{10+} /1/ et en se fondant sur des prévisions obtenues par calcul pour les ions de charge plus élevée /2/, nous présentons les premiers résultats expérimentaux concernant les ions S^{13+} . En particulier, un coefficient de gain de l'ordre de 1 cm^{-1} a été mesuré pour la transition 3d-5f de S^{14} à la longueur d'onde de 65.2 Å, qui est la plus courte pour laquelle la mesure d'un gain ait jamais fait l'objet d'une publication jusqu'à ce jour. Des calculs concernant les ions K^{16+} , Ca^{17+} et Ti^{19+} sont également présentés.

ABSTRACT. Observed and predicted values of gain for 3d-5f, 3d-4f and 4d-5f transitions of lithium-like ions in laser-produced plasmas are reported. After an extensive study of the Al^{10+} case /1/ and following calculated predictions for higher-Z ions /2/ we present the first experimental results concerning the S^{13+} ion. In particular, a gain coefficient of the order of 1 cm^{-1} has been measured for the 3d-5f transition of S^{14} at the wavelength of 65.2 Å, which is the shortest for which the measurement of a gain has ever been published to day. Some calculations concerning the K^{16+} , Ca^{17+} and Ti^{19+} ions are also presented.

INTRODUCTION. Although no X-ray laser device has yet been achieved to day, the most recent progress in this field /3/ has made it sure such a feasibility. As a consequence of that, the preoccupation of searchers is no more only to increase the value of the gain-length product they obtain in their experiments, but also to look forward for future applications. Among these, the interest of biologists for shorter wavelengths comprised between 23.3 and 43.5 Å, in the so-called water-window, is now well known. In this range, since water is rather transparent to radiation while carbon is opaque, one can hope to obtain holograms of living proteins with a good contrast. That is one of the reasons why wavelength-scaling of the different schemes considered for X-ray lasing action has become an increasing preoccupation.

PRESENTATION. In this paper we shall deal with lithium-like recombination scheme, departing from the Al^{10+} case for which we have reported an amplification of spontaneous emission at 105.7 Å as early as 1978 /4/. Indeed, if one considers these ions in a rapidly cooling plasma, population inversion appears between the lower 3d level and the upper 4f (154.6 Å) and 5f levels (105.7 Å) as predicted by calculation taking into account radiative cascades and collisional transitions rates /2,5,6/. Experimental gain measurements have been performed for both transitions, in the corona, i.e., in a region of the laser-produced plasma where electronic density N_e is of the order of 10^{19} cm^{-3} . The wavelength of the laser was 1.054 μm and the pulse duration was either 600 ps or 2 ns. The laser beam was focused on the surface of a massive target by two crossed cylindrical lenses, providing a fairly homogeneous lighting along the focal line of 1 to 2 cm long. The flux linear density on the target was in the range of 0.5 to 20 GW/cm. Gain G was deduced from the enhancement of emitted intensity I_1 with plasma length l using the relation $I_1 \propto \exp(Gl)$ -1. Time-resolved experiments have shown that amplification takes place during plasma

cooling after the top of the laser pulse. Measured peak values of gain-length product are comprised between 2 and 2.5 cm^{-1} . These results have been accounted for by theoretical calculations which have shown that, in the case of aluminium, gain occurs for the 5f-3d and 4f-3d transitions in the plasma corona during the cooling and recombination phase. Calculations are performed with a collisional-radiative model used as the postprocessor of a hydrodynamical code.

Considering a higher Z element as sulphur, for which the 3d-5f and 3d-4f transitions of SXIV are situated at 65.2 and 95.5 Å, the C.R. model has been used introducing various sets of density and temperature obtained from the hydrodynamical code in the case of Al. This is made possible by the rather broad range of convenient values revealed by the code. The C.R. model gives the values of inversion density Δn and, since the expression of gain is given by:

$$G(\text{cm}^{-1}) = 3.274 \cdot 10^{-14} (\Delta n) S (M/kT_i)^{1/2}$$

where n is expressed in cm^{-3} , S is the line strength in u.a., M the atomic mass and T_i the ionic temperature in eV, one can obtain the expected value of gain in each case. Table I shows a comparison of representative results obtained for Al and S. It appears that comparable values of gain can be obtained with both elements.

	Al ¹⁰⁺		S ¹³⁺	
Ne(cm^{-3})	10^{19}		$5 \cdot 10^{19}$	
$T_i(\text{eV})$	17.4		19.1	
$G(\text{cm}^{-1})$	$4.08 \cdot 10^{-14} S \Delta n$		$4.24 \cdot 10^{-14} S \Delta n$	
	$\lambda(\text{Å})$	$G(\text{cm}^{-1})$	$\lambda(\text{Å})$	$G(\text{cm}^{-1})$
5f-3d	105.7	1.4	65.2	1.3
4f-3d	154.6	6	95.4	2.4
	154.7	8.6	95.5	3.5
4d-5f	334.2	1.1	206.3	3.1
	334.4	1.6	206.5	4.4

TABLE I

On the basis of this evaluation a study of the 5f-3d transition in sulphur, at 65.2 Å, has been undertaken. A massive planar target was used and we compared intensities emitted by plasmas of 1 and 2 cm produced by a $1.054 \mu\text{m}$ -150 J laser beam with a pulse duration of 2 ns. The 1m-grazing incidence spectrometer uses a 3,600 grooves/mm grating. An O.M.A. was used for detection. For this first experiment only time-integrated measurements were made. An example of result is shown on Fig.1. Upper curves represent the spectra emitted by both plasmas in the region of 65 Å. The strongest line is the 5f-3d at 65.2 Å, while the other one on the left side is the 5d-3p at 64.3 Å. At 65.2 Å, a sudden drop is clearly visible in the absorption curve which is represented in lower part.

A simulation has been undertaken to investigate the effects of time-integration on the observed value of gain as well as those of the experimental width. The result of this study, as it appears in Fig.2 and 3, shows that an instant gain of about 1 cm^{-1} accounts for the experimental observations.

WAVELENGTH SCALING. When scaling with higher Z-elements towards shorter wavelengths one must consider laser intensity, electronic density and electronic temperature.

In the Li-like recombination scheme, laser intensity must be sufficient for creating He-like ions. Since the presence of these ions is conditioning the inversion scheme, if Z is the atomic number of an element, the scaling will depend not on Z but on the parameter $z=Z-2$. So, with an element Z', let $z'=Z'-2$, the following relations have to be considered:

$$I'_{\text{laser}} = (z'/z)^3 I_{\text{laser}}$$

$$n'_e = (z'/z)^7 n_e$$

$$T'_e = (z'/z)^2 T_e$$

Experimental result in sulphur.
Lower part: absorption curve.

Fig. 1

Time-resolved gain at the top of the line deduced from a plasma modeling
Fig. 2

Time-integrated absorption curve
a) directly deduced from gain in Fig. 2
b) taking into account instrumental width

Fig. 3

On the basis of this scaling, departing from sulphur, a theoretical study has been undertaken concerning Ca, Ti and Cu [7]. Calculated wavelengths in Ångström of 3d-4f, 3d-5f, 4d-5f and 4f-5g transitions are the following:

	Ca ¹⁷⁺	Ti ¹⁹⁺	Cu ²⁶⁺
3d3/2-5f5/2	39.50	31.99	17.54
3d5/2-5f7/2	39.55	32.04	17.59
3d3/2-4f5/2	57.76	46.77	25.64
3d5/2-4f7/2	57.86	46.87	25.74
4d3/2-5f5/2	124.78	101.06	55.41
4f5/2-5g7/2	124.95	101.20	55.50
4d5/2-5f7/2	124.97	101.25	55.59
4f7/2-5g9/2	125.03	101.29	55.59

Extrapolated plasma parameters have been introduced into the time-dependent C.R. model. Energy levels and oscillator strengths used in the model are obtained by ab initio calculations with a modified Hartree-Fock method. Atomic dynamics includes radiative cascades and electron-ion collisions. Reduced-population densities N/g , where $g=2j+1$ is the statistical weight of the level, have been calculated as functions of temperature T_e . This was performed for different values of N_e and in each case, for various values of the parameter X which represents the proportion of He-like to Li-like ions. On Fig. 4 are presented the most characteristic results obtained for both 5f-3d and 4f-3d transitions. It appears that in all cases

significant inversion-ratio values are obtained. Due to lack of space, 5-4 transitions are not presented here although still stronger values have been observed in some cases. Thus, these results demonstrate the interesting possibilities offered by Li-like ions in X-UV laser studies.

Fig. 4

CONCLUSION. Li-like recombination scheme seems particularly appropriate for scaling towards shorter wavelengths since the need in power density for plasma production is rather moderate. An illustration of that is represented in Fig.5 where we have plotted power densities versus wavelengths for the different schemes proposed to-day. Another aspect of this study is to show up the interest of investigating also the 4-5 transitions, particularly the 4d-5f and 4f-5g, not for shorter wavelengths, but for higher gains.

Fig. 5

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