Superradiant Line in the Soft–X-Ray Range

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It is shown that the $2p^5 4d\,^3P_1 \rightarrow 2p^6\,^1S_0$ line of the Al^{3+} ion at a wavelength of 117.41 Å is superradiant in a dense laser-produced plasma. The measured gain in a two-plasma experiment is 17%. The gain coefficient is of the order of 10 cm^{-1} with a lower limit of 2.5 cm^{-1} and an upper limit of 22 cm^{-1}.

The possibility of producing population inversions between atomic or ionic levels of convenient energy is a key point for investigating the feasibility of an x-ray laser. Several approaches have been proposed.[1-13] Previously we suggested that the surprisingly high intensity of the almost forbidden $2p^5 4d\,^3P_1 \rightarrow 2p^6\,^1S_0$ line of the Al^{3+} ion in a dense laser plasma is due to the enhancement of the $^3P_1$ upper-level population compared with the equilibrium value expected from Boltzmann's law.[2,3] This assumption was supported by optical-thickness measurements exhibiting the large transparency of the plasma for this line, located at a wavelength of 117.41 Å, whereas the weak lines corresponding to the transitions $2p^5 4d\,^1P_1$, $^3D_1 \rightarrow 2p^6\,^1S_0$ ($\lambda = 116.46$ and 116.92 Å) were optically thick. Moreover, from time-resolved measurements in plasmas produced by 100-MW, 40-nsec Nd-laser pulses, it was concluded[14] that the 117.41-Å line exhibits an emission significantly shorter than other lines of the same ion. The possibility that a small population inversion occurs was suggested by these first results,[8,14,15] and a recombination mechanism involving autoionizing states of the Al^{3+} ion was proposed to explain the anomalous population of the $^3P_1$ level.[8,16,17] Although calculation predicted[16] that this mechanism could be effective in Ne-like ions up to $Z = 18$ (Ar^{8+}), experimental observations concern at present only the Al^{3+} ion. Recently the possible occurrence of population inversion between excited and ground states in dense hot plasmas has been discussed for the case of hydrogenic ions.[18] Here we report new experimental results leading to the conclusion that the 117.41-Å line is an actual superradiant line because it exhibits a negative absorption in the dense part of a laser plasma.

Figure 1(c) shows the special feature of the Al^{3+} lines (116.46, 116.92, and 117.41 Å wavelength) in the plasma zone under investigation. For comparison, Fig. 1(a) represents the relative intensities as observed in the low-density region of the plasma, far from the target. Similar ratios have been observed in spark discharges[19,20] showing an intensity of the $^3P_1$ line 1 order of magnitude less than that for both other lines. The radiative-transition probabilities, calculated in J_1-j coupling for the initial state and L-S coupling for the ground state $2p^6\,^1S_0$, are plotted in Fig. 1(b). These values are used because the agreement with experimental results in plasmas of low density is better than that obtained with values calculated in intermediate coupling[21] with Hartree-Fock wave functions. This fact, already mentioned,[16] seems related to an underestima-

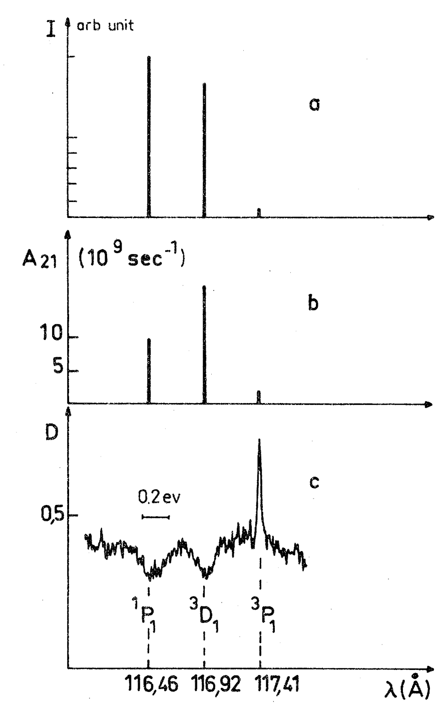

FIG. 1. $2p^5 4d \rightarrow 2p^6$ lines of the Al^{3+} ion: (a) relative intensities in plasma of low density (arbitrary units); (b) radiative-transition probabilities; (c) densitogram in the dense part of a laser-produced plasma.

tion of the spin-orbit parameter calculated by using monoconfigurational Hartree-Fock wave functions, making the intermediate coupling calculation unable to describe correctly the eigenstates in the case under investigation. In Fig. 1(c), the wide broadening (0.2 eV) of the $^1P_1$ and $^3D_1$ levels must still be noted in contrast with the narrowness of the $^3P_1$ line.

The present experiment consists of photoabsorption measurements at the wavelengths of several lines lying in a small spectral range (109–120 Å). One peculiarity of such measurements in a plasma is that the plasma itself is radiating with an intensity of the same magnitude as the external radiation. As previously shown,[14,15] if the plasma is not too inhomogeneous, the absorption ratio can be defined at a given wavelength by

$$K = 1 - T, \text{ with } T = (I - I_2)/I_1, \tag{1}$$

where I_1 is the source intensity, I_2 the intensity emitted by the plasma itself, and I the total intensity when the plasma is lighted by the source. The transmission factor T is related to the frequency ν of the radiation, the half-width $\delta\nu$ of the line, the Einstein coefficient B_{12}, the populations N_1 and N_2 of both levels, and the crossed length x, by the relation

$$T = \exp[-(h\nu/c)(B_{12}/\delta\nu)(N_1 - N_2)x] \tag{2}$$

(both statistical weights are assumed to be equal to 1).

The experimental setup includes an optical system producing two plasmas from the same Nd laser, which delivers 20 J in 40 nsec. One of the two plasmas plays the role of a soft–x-ray source, while the other one is used as a sample for the photoabsorption measurements.[22] Both plasmas are produced on the same aluminum target, the separation between focusing points for the two plasmas being 0.4 mm. A soft–x-ray spectrograph is used with a 2400-grooves/mm grating. The radius of curvature is 2 m and the width of the entrance slit is 10 μm.

The main difficulty in measuring an eventual gain (or negative absorption) at a given wavelength is to obtain a large enough accuracy in intensity determinations to remove any doubt of the result. Indeed the expected gain does not exceed about 10% for a crossed length through the plasma of 0.1 mm, while the fluctuations in plasma production, as in detector response, make a larger error for an isolated wavelength. That is why we decided to measure simultaneously the intensities involved in (1) for several lines lying in the same spectral range. In taking into account the requirements of the grazing-incidence spectroscopy, we find that we must use a photographic technique; thus the results are time integrated. But the advantage is that we obtain the line-intensity ratios with a high accuracy. Then the measured transmissions are correlated with each other for all wavelengths and the possible maximum errors are lowered by limiting conditions for peculiar lines: For instance no absorption can be greater than 100%. For photographic recordings, Kodak SC5 plates, calibrated previously with synchrotron radiation, were used; thirty laser shots were recorded on each plate.

Table I gives the relative intensities of eleven lines for the "source" plasma, I_1; for the "sample" plasma, I_2; and for both plasmas when produced together, I. These values are deduced from 22 photographic plates after statistical treatment. In column T the transmission factor is given for each spectral line as deduced from the corresponding intensities according to (1). We see that the line at a wavelength of 117.41 Å is amplified since its transmission factor is larger than 1. The gain is of the order of 17%.

The purely statistical error which affects the values plotted in each intensity column of the table does not exceed 1% for the lowest values and 2% for the largest values. But a possible systematic error arises in comparing I_1 and I_2, respectively, with I because of deviations of the mean sensitivity of photographic plates used in successively recording the source spectrum, the sample spectrum, and the total spectrum. For

TABLE I. Soft–x-ray transmission, T, through a laser plasma for eleven lines. I_1 and I_2 are, respectively, the "source" intensity and the "sample" intensity.

Ion	λ (Å)	I_1	I_2	I	T	T_{min}
Al VI	109.28	0.319	0.699	0.853	0.483	0.255
Al VI	109.51	0.397	0.954	0.974	0.050	0.000
Al VI	109.84	0.431	0.974	1.000	0.060	0.000
Al VI	109.97	0.409	0.673	0.855	0.445	0.267
Al VI	113.31	0.321	0.304	0.624	0.997	0.820
Al VI	113.44	0.632	0.802	1.325	0.828	0.588
Al VI	113.62	0.333	0.307	0.633	0.979	0.804
Al VI	113.76	0.357	0.349	0.699	0.980	0.794
Al IV	117.41	0.199	0.203	0.435	1.166	1.053
Al V	118.50	0.218	0.329	0.518	0.867	0.730
Al V	118.98	0.224	0.314	0.495	0.808	0.647

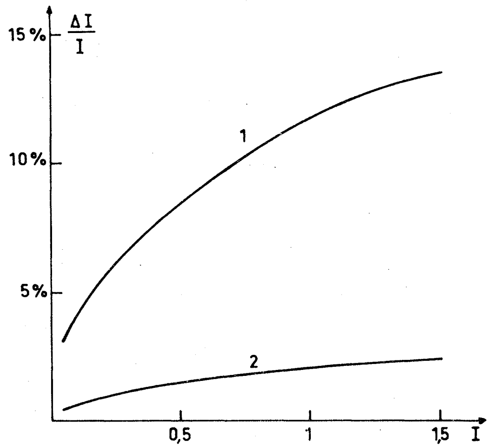

FIG. 2. Possible errors versus the intensity: I_1, curve 1; I_2, curve 2.

I_2 this error is limited because no one I_2 value can exceed the corresponding I value; otherwise we would have a negative transmission. Curve 2, Fig. 2, gives the maximum possible error as a function of the intensity when taking into account this limitation. For I_1 there is no such limitation and curve 1 giving the error is deduced from the standard-deviation calculation. From these two curves and from the residual statistical error mentioned above we calculated the minimum possible values of the transmission factors, which are plotted in the last column, T_{min}, of Table I. For the 117.41-Å line the transmission factor clearly is still larger than 1 and the minimum gain is 5%. Furthermore a maximum value can be deduced in a similar way by rejecting a possible amplification for the optically thin lines at wavelengths of 113.31, 113.62, and 113.76 Å. We conclude that the 117.41-Å line exhibits a gain between 5 and 25%, the mean experimental value being 17%. Thus this line could be considered as a candidate for a future soft-x-ray laser.

By taking into account the plasma length 0.1–0.2 mm, the gain coefficient is between 2.5 and 22 cm^{-1} with a probable value around 10 cm^{-1}. With the use of this value in relation (2) the inversion density in the plasma must be

$$N_2 - N_1 = 10\frac{c}{h}\frac{\delta\nu}{\nu}\frac{1}{B_{12}}.$$

From the transition probability $A_{21} \simeq 2\times10^9$ sec^{-1} plotted in Fig. 1(b), the Einstein coefficient for absorption is $B_{12} \simeq 0.5\times10^{17}$ in cgs units for the $^3P_1$ line. In the temperature range (50–60 eV) of our plasma the Doppler broadening is $\delta\nu/\nu \simeq 10^{-4}$. Then the magnitude of the required inversion density has the value

$$N_2 - N_1 \simeq 10^{17}\ \text{cm}^{-3}.$$

This is conceivable only in plasmas having 10^{20}–10^{21} particles/cm^3. Such a high density can occur at short distances from the massive target in Nd-laser–produced plasma. This is just the plasma zone giving rise to the experimental observations reported here.

Using the 10^{17} cm^{-3} inversion density one finds that the energy stored in a "long plasma," namely a column of a lateral size of 10^{-2} cm and a length of 1 cm, is $(1.5-2)\times10^{-4}$ J. If delivered in 10 nsec, this would produce a 15–20-kW soft-x-ray superradiant pulse.

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Observation of Persistent Currents in a Saturated Superfluid Film*

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We report the first observation of a persistent flow around a closed path consisting entirely of saturated superfluid helium film in a macroscopic geometry in which the saturated vapor was in unconstrained proximity to the film.

We have observed a persistent current of saturated superfluid film in a configuration such that the *entire* flow path consisted of saturated film in intimate contact with the saturated helium vapor. This represents the first such observation under these conditions. It does not, however, represent *the* first observation of a persistent film current. Henkel, Kukich, and Reppy[1] have observed persistent currents in *unsaturated* films in porous material using the precise gyroscopic techniques developed by Reppy.[2] In those experiments a persistent current was formed by rotating the apparatus at temperatures above T_λ and then stopping the rotation slowly after cooling below T_λ.

In our own work we rediscovered the technique first used by van Alphen *et al.*[3] in their observation of the persistent flow of bulk superfluid. The technique we shall describe here is also quite similar to one reported recently by Verbeek *et al.*[4] except that our flow path contained no bulk fluid in a rouge plug and in our case the saturated vapor was in unconstrained proximity to the saturated film. Our studies were carried out from 1.16 K to 1.6 K. The basic measurement technique can be best described by reference to the schematic representation of the apparatus presented in Fig. 1. To produce a persistent saturated-film current an oscillation is induced between our coaxial-capacitor level detectors A and B. During this oscillation the film flow takes place through path L since a small electric current is applied to heater S to block that path from film flow. When the velocity of film flow through L is large, the heater S is switched off and a persistent current is trapped

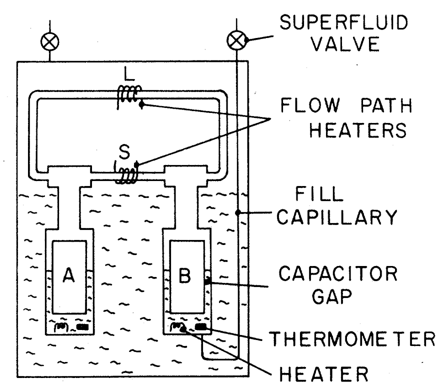

FIG. 1. Schematic representation of the persistent-current apparatus. The flow paths L and S lie in approximately the same horizontal plane but are shown vertically separated for clarity. The details of the capacitive reservoirs are given in Ref. 5. The entire detector assembly is housed in a sealed chamber which is immersed in the Dewar helium bath.