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Spectroscopic Investigation of the Ablation Cloud of Aluminum Pellets Injected in LHD

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In order to obtain plasmas with high-ion temperatures in the Large Helical Device LHD, pellets made of different materials like aluminum and titanium are injected. Using spectroscopic measurements of lines emitted by aluminum ions at different ionization stages, the ablation cloud of the pellet is characterized assuming that the population densities of the energy levels satisfy Local Thermodynamic Equilibrium (LTE). Besides the estimation of the electron temperature and density of the plasma composing the pellet cloud, some excited level of Al^+ deviate from the LTE assumption. Many reasons which may explain such deviations have been examined.

Keywords: Aluminum pellets, ablation cloud, Spectroscopy, LTE, LHD, spectral line intensities.

1. Introduction

In magnetic fusion-oriented devices such as Tokamaks and Stellarators, solid pellets made of either hydrogen (or deuterium), or other materials such as carbon, tungsten, or titanium are injected for various purposes including fuelling, plasma control and diagnostics [1]. In the Large Helical Device (LHD), carbon (Z=6) pellets are often injected for impurity transport studies [2-4]. During the last experimental campaign, in a series of discharges, pellets made of either aluminum (Z=13) or titanium (Z=22) were injected in LHD to obtain plasmas with high-ion temperatures. Spectra in the range 300-800 nm are measured. The various lines appearing in the observed spectra have been identified by comparison with theoretical data from the NIST ADS database [5]. In the case of aluminum pellets, the identification of the numerous lines shows that singly Al^+ and doubly ionized Al^{+2} aluminum ions are the main contributors to the line emission. All the transitions used here are shown in Figs. 1 and 2. The intensities of the lines emitted by both ions are used to estimate he electron density and temperature of the plasma composing the ablation cloud of the pellet. It is assumed that Al II and Al III lines are emitted from the same cloud ("same plasma") and that their level population densities are at Local Thermodynamic Equilibrium (LTE).

The aluminum pellets used in the present study have cylindrical shapes with a length of 0.8 mm and a diameter of 0.5 mm. The speed and penetration depth of pellets are estimated to be approximately 200 m/s and 1 m respectively. The radiation emitted by the ablation cloud of the pellets is collected with optical fibers connected to a visible spectrometer and a CCD camera. From the spectroscopic measurements, the ablation duration is estimated to be ~3 ms. After total ablation of the aluminum pellet, the electron density is estimated to increase by ~4×10^{18} m^{-3}. From spectroscopic measurements, insights on atomic physical processes and characteristics of the ablation cloud can be obtained such as the electron temperature and density. Such characterization may be used to get insights on the deposition profile which is very interesting.

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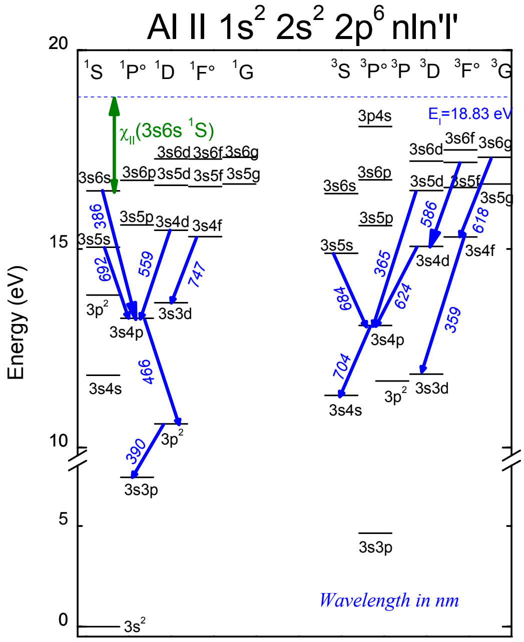

Fig.1: Partial energy diagram of Al^+ ions. Arrows show the identified Al II lines used in this study.

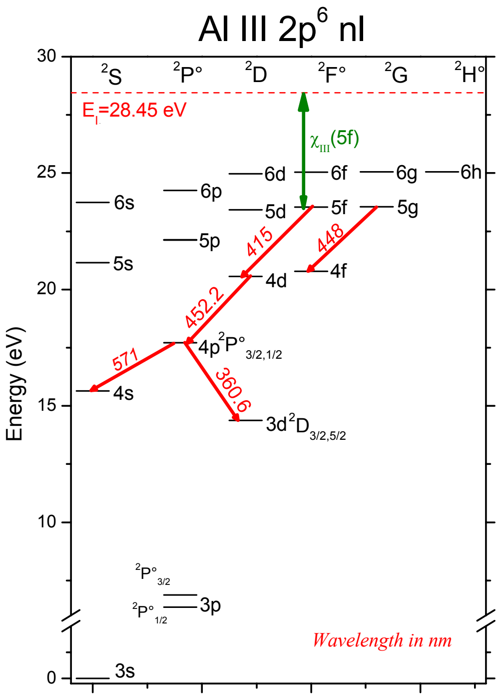

Fig.2: Partial energy diagram of Al^{2+} ions. Five transitions corresponding to four upper levels are identified (red arrows).

2. Theoretical background and Spectroscopic analysis method

The profile of each identified emission line is fitted with a Gaussian function to evaluate its intensity. In this case, a FWHM ~1.5 nm representing the instrumental function has been used. The line intensity for a transition from a level p to another level q (with a lower energy), I_{pq}, is given by:

$$I_{pq} = h\nu\ n(p)\ A(p \to q)\ V, \tag{1}$$

Where n(p) is the population density of level p, $A(p \to q)$ is the spontaneous transition probability from level p to level q, and V is the plasma volume. The volume-integrated population N(p)=n(p) V is obtained by dividing the line intensity by the photon energy hν and by the Einstein coefficient $A(p \to q)$. For almost all the identified transitions shown in Figs. 1 and 2, the values of $A(p \to q)$ are taken from NIST database [5] whereas refs [6-8] were used for only few remaining transitions. If an excited level p is in Local Thermodynamic Equilibrium, then its population density obeys the Saha-Boltzmann equation [9]:

$$\frac{N_{III}(p)}{g_{III}(p)} = \frac{1}{2g_{IV}(gr.)}\left(\frac{h^2}{2\pi mkT_e}\right)^{3/2} \times e^{\left(\frac{\chi_{III}(p)}{kT_e}\right)} \times n_e N_{IV}(gr.), \tag{2}$$

where $N_{III}(p)$, $g_{III}(p)$, and $\chi_{III}(p)$ represent the population, statistical weight and ionization potential of level p of Al^{2+} ion. The ground-state p=1 is designated by gr. According to this equation, the electron temperature is the parameter which determines the relative population distribution under LTE. If we assume that Al^{+} ions are also at LTE, then their excited level populations, $N_{II}(p)$ should satisfy:

$$\frac{N_{II}(p)}{g_{II}(p)} = \frac{1}{2g_{III}(gr.)}\left(\frac{h^2}{2\pi mkT_e}\right)^{3/2} \times e^{\left(\frac{\chi_{II}(p)}{kT_e}\right)} \times n_e N_{III}(gr.) \tag{3}$$

Furthermore under complete LTE, eq. (3) is valid for the ground state p=1. Substitution of $N_{III}(gr.) \equiv N_{III}(p=1)$, the population density of the ground-state p=1 given by eq. (2), allows to write eq. (3) as follows:

$$\frac{N_{II}(p)}{g_{II}(p)} \times \frac{2}{n_e}\left(\frac{h^2}{2\pi mkT_e}\right)^{-3/2} = \frac{1}{2g_{IV}(gr.)}\left(\frac{h^2}{2\pi mkT_e}\right)^{3/2} \times e^{\left(\frac{\chi_{III}(gr.)+\chi_{II}(p)}{kT_e}\right)} \times n_e N_{VI}(gr.) \tag{4}$$

If the ionization potential for Al^{+} levels is measured from the ionization limit of Al^{2+}, then the right-hand sides of eqs. (2) and (4) are identical.

Using a logarithmic scale, the experimental values of N(p)/g(p) for both Al^{+} and Al^{2+} ions, the population densities per unit statistical weight of the excited levels, are shown in Fig.3. In the following we designate by the term population density the ratio N(p)/g(p).

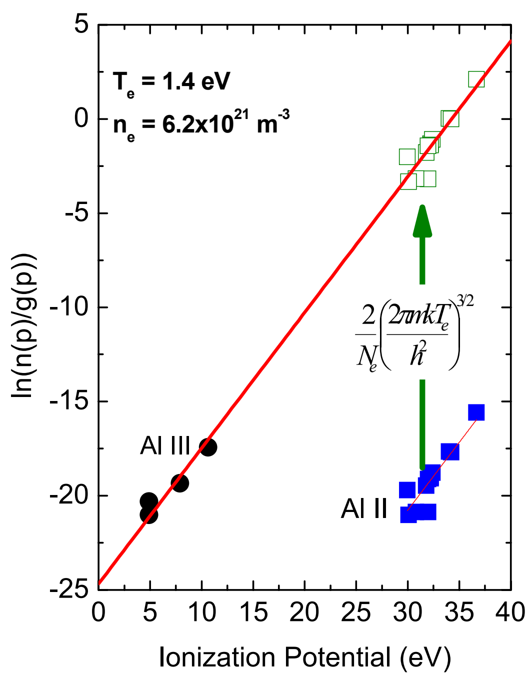

Fig.3: Comparison of experimental and theoretical volume-integrated population densities of excited levels of Al^{+} and Al^{2+} ions.

The population densities of Al^{2+} levels (full circles) and those of Al^{+} (full squares) are fitted using respectively eqs. (2) and (4) (i.e. Saha-Boltzmann). The fitting curves are two parallel lines whose slope gives the electron temperature (1.4 eV here) of the emission layer. The open squares represent the population densities of Al^{+} levels multiplied by a constant factor such that they lie on the same fitting line as for the population densities of Al^{2+} levels. This constant factor, determined simultaneously with the other fitting parameters (e.g. slopes), is given by:

$$\frac{2}{n_e}\left(\frac{2\pi mkT_e}{h^2}\right)^{3/2}. \qquad (5)$$

The electron density n_e of the ablation cloud is then estimated from (5) using the electron temperature derived from the slope of the fitting line.

3. Results and discussion

This spectroscopic technique has been applied to the different frames (times) of an LHD discharge following the injection of an aluminum pellet to obtain the temporal evolution of both the electron temperature and density of the ablation cloud. This is illustrated in Fig. 4 for the LHD discharge #83198 over a time period corresponding approximately to the duration of the ablation process. If the electron temperature is almost constant remaining between 1.2 and 1.8 eV, according to the upper panel of Fig. 4, the electron density varies almost over two orders of magnitude. However, these preliminary values of the electron density have to be checked using other methods. Stark broadening of VUV lines emitted by these ionized aluminum ions will be used to determine the electron density and compare it to the one obtained using the above spectroscopic method described earlier.

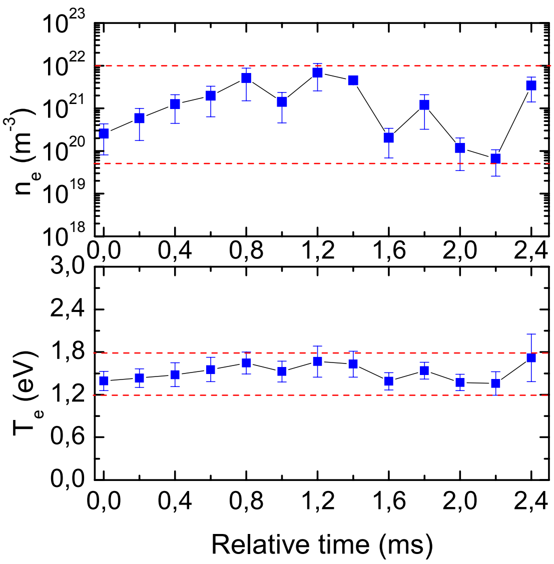

Fig. 4 : temporal evolution of the spectroscopically determined electron density and temperature of the ablation cloud.

Furthermore, close examination of the fit of the population densities of Al^{+} levels, shows that some of them are deviating from the LTE assumption as it is illustrated in Fig. 5 (obtained by zooming Fig.3). Numbers in this figure represent the ratio of the theoretical (at LTE) to the experimental values of the population densities of Al^{+} levels. It can be seen from this figure that the experimental population density of the upper level of the 358 nm line is more than 5 times lower than the corresponding theoretical value calculated at LTE. On the other side, for the 386 nm line, it is the experimental value of the upper level which is higher than the calculated value by a factor of more than 3.

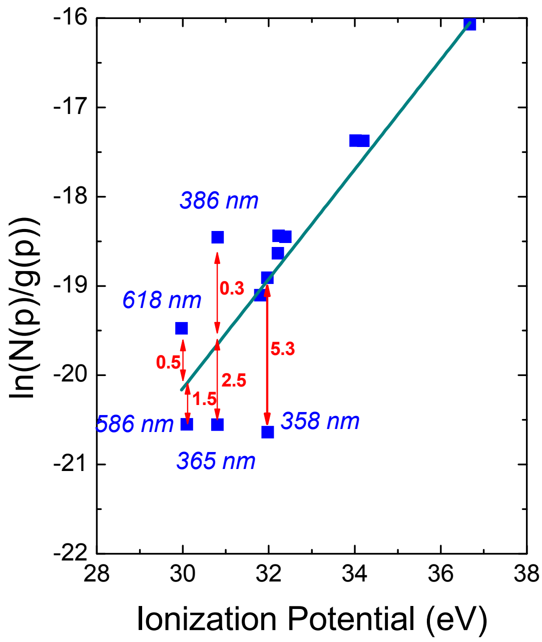

Fig. 5: Deviations from LTE for some excited levels of the Al^{+} ion following the pellet injection in LHD.

Several reasons which may be responsible for such deviations from LTE have been investigated. The first one is the validity of the LTE approximation itself. Since the deviations concern upper levels having principal quantum numbers higher than the other upper levels which satisfy the LTE assumption, we rule out the non validity of this assumption. In addition, radiation absorption effect does not seem to be important and has been ruled out. If the validity of the LTE assumption is confirmed and if we attribute these deviations from LTE to uncertainties or inaccuracies in the values of the transition probabilities then we can recommend new values. For instance for the 618 nm transition, the recommended value is that given by ref. 8. However, we have still to check carefully the previously mentioned possible reasons of such deviations such as radiation absorption effect, uncertainties in the measured intensities. Also, one has also to consider that the Al^{+} and Al^{2+} ions may emit from two regions of the ablation cloud which may not necessarily have the same plasma parameters (electron density and temperature). A more extensive study is planned by considering other discharges where aluminum pellets were injected.

4. Conclusion

A spectroscopic technique to estimate simultaneously the electron temperature and density of the ablation cloud of a solid pellet injected in LHD has been presented. This technique requires the measurements of the intensities of several lines emitted by at least two ions with successive ionization stages of the element constituting the pellet (aluminium in this case) and assumes that the emission comes from the same part of the ablation cloud and that the excited levels of the ions satisfy the Saha-Boltzmann equation, i.e. are at Local Thermodynamic Equilibrium LTE. The temporal evolutions of both the electron temperature and density of the aluminium pellet ablation cloud have been estimated even though confidence is missing concerning the electron density determination and another independent method such as Stark broadening should be applied to check the validity of the obtained values. Furthermore, deviations from the LTE assumption have been observed for some upper levels of some lines emitted by Al^+.

References

[1] B. Pégourié, Plasma Phys. Control. Fusion **49**, R87 (2007).
[2] H. Nozato *et al*., Phys. Plasma **11**, 1920 (2004).
[3] H. Nozato *et al*., Rev. Sci. InstrumFF**76**, 073503 (2005).
[4] H. Nozato *et al*., Phys. Plasma **13**, 092502 (2006).
[5] Yu. Ralchenko *et al*, NIST Atomic Spectra Database (version 3.1.2) (http://physics.nist.gov/asd3)
[6] V. Vujnović *et al*, A&A 388, 704 (2002); T. Chang and R. Wang, Phys. Rev. A **36,** 3535 (1987)
[7] The atomic line list version 2.04 (Peter Van hoof): http://www.pa.uky.edu/~peter/atomic/
[8] R. Payling and P. Larking, "Optical emission lines of the elements", ed. John Wiley & Sons (2000).
[9] T. Fujimoto, "Plasma Spectroscopy", Oxford University Press, Oxford, 2004.