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Diagnostics of Electron Temperature in Laser Produced Plasma From Iron Using Plasma X-ray Emission

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ABSTRACT

X-rays emitted from plasmas were used to calculate the temperature from the X-ray line intensity ratio. We used a Nd: YAG laser system, frequency doubled 532 nm, emitting 40 ps pulses at repetition rate 1 to 10 Hz. The energy on target was about 30 mJ corresponding to an intensity of 10^{13} Wcm^2. X-ray spectra in the range 12 - 17 Å from iron targets were detected. According to Boltzmann law, a plot of the logarithmic term versus ΔE yields a straight line with slope equal to –1/T. The plasma electron temperature determined in this way was ~ 13.18 eV for Fe.

INTRODUCTION

If thermodynamic equilibrium exists, then plasma properties, such as the relative populations of energy levels, and the distribution of the speed of the particles, can be described through the concept of temperature. In fact, thermodynamic equilibrium is rarely complete, so physicists have settled for a useful approximation, local thermodynamic equilibrium (LTE), although it may be somewhat different from region to region.

In general, the intensity of a spectral line is a function of both electron temperature and density. Such spectral lines can be very useful diagnostics of plasma electron temperature and density. However, the link between measured line intensity ratio and plasma electron temperature and density is complex and a number of issues must be examined for the diagnostics. In particular, the different processes associated with the formation of excited level populations responsible for the chosen atomic transitions must be understood well in order to extract information relative to the electron temperature and density of the plasma (Baoming Li and Hongzhi Li, 2001).

The standard spectroscopic method consists of measuring the ratio of intensities of two lines within the same series of a given charge state, ζ, such as the ratio of the Lyman-α and β lines, or the He-α and He-β lines. From the theory of atomic emission spectroscopy, the plasma temperature generally is estimated by the relative emission intensities of spectral lines. The ratio is given by the blew equation

$$\frac{P(m' \to m)}{P(m'' \to m)} = \frac{N_{\xi m'}}{N_{\xi m''}} \frac{\hbar\omega_{m' \to m}}{\hbar\omega_{m'' \to m}} \frac{A(m' \to m)}{A(m'' \to m)} \tag{1}$$

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where P(m/ —> m) and P(m// —> m) are the experimental intensities of the two lines, whose initial excited states are m/ and m//, Nζm/ and Nζm// are the densities of the initial excited states, ħωm/→m and ħωm//→m are the transitions energies, and A(m'—m) and A(m" —> m) are the transition probability corresponding Einstein coefficients.

The ratio of the intensities on the left-hand side of equation (1) is the quantity measured in the experiment; the values of the Einstein coefficients and the transition energies are found in the literature. By inserting these parameters into equation (1), one finds the ratio of the partial densities of the initial excited states, which depends on the plasma temperature and density, equation (2). If the plasma is in the LTE condition, the ratio of the densities of the two initial states is determined by the Boltzmann distribution (David Salzmann, 1998):

$$\frac{N_{\xi m^{/}}}{N_{\xi m^{//}}} = \frac{g_{\xi m^{/}}}{g_{\xi m^{//}}} \exp\left(-\frac{E_{\xi m^{/}} - E_{\xi m^{//}}}{T_E}\right) \tag{2}$$

Where g is the statistical weight of the level whose left hand, side is measured in the experiment, and whose right-hand side depends on the electron temperature. Choosing lines for which the g, A and E values and the wavelengths are known, and measuring the relative intensities, enables one to calculate T_e by the two-line method.

In plasma, one has to look for a level scheme that is based on closed-shell ions. Being stable configurations, closed-shell ions are the abundant charge states and their population probabilities are relatively constant for a wide range of plasma temperatures and densities. On the other hand, open-shell ions undergo rapid ionization and recombination processes. The lines from the hydrogen-like species are emitted from regions that are at a higher temperature than the lines from helium-like ions. In addition, at every given point in the plasma, the spectral lines from hydrogen-like species are emitted at different times than those from helium-like ions, according to the variation in time of the local temperature. The energy levels of the excited 2p53s and 2p53p electronic configurations are very important neon-like transitions as shown in Fig (1). These levels in plasma are excited from the ground state by electron impact with rather high probability. Population inversion occurs after the rapid spontaneous decay of the 3s electrons to the 2p closed-shell ground state (Shalom Eliezer, Kunioki Mima, 2009).

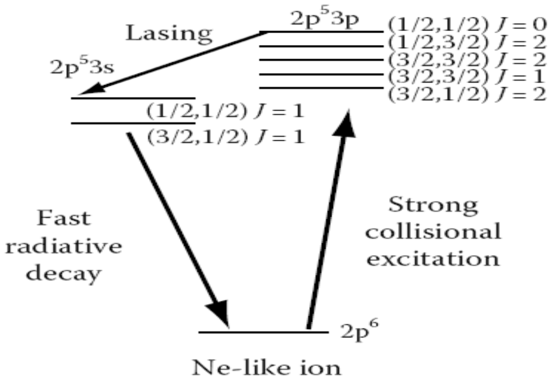

Fig. 1: Laser transition from the 2p53p to the 2p53s excited configurations.

2. The experimental Setup:

To successfully achieve the X-ray in laser-plasma experiments, a certain suitable setup has been performed with assistant of a vacuum chamber evacuated to 10^{-2} mbar to avoid absorption by air. The basic components of the laser plasma setup are shown in figure (2).

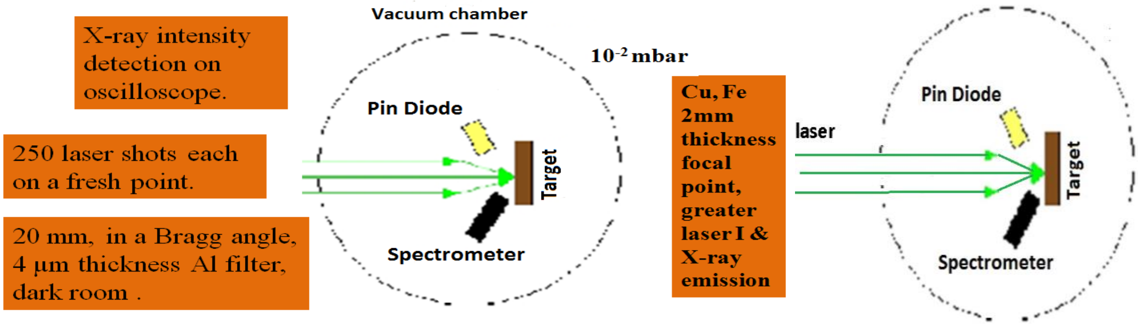

Fig. 2: Diagram of the setup used for X-ray experiments.

Q-switched Nd:YAG laser (model ND 40, spectra physics company - USA), 532 nm second harmonic, pulse energy 15 to 35 mJ, pulse width 40 ps, 2 Hz repetition rate was used in this experiment.

2.1. X-RAY Spectrometers:

The standard instrument for measuring the x-ray spectrum is the spectrometer or spectrograph. The simplest of these is the crystal spectrometer. It is based on Bragg's law, which states that if a beam of x-rays impinges on a crystal at an angle θ, only components whose wavelength satisfy the Bragg condition,

$$n_B\lambda = 2d \sin\theta \tag{3}$$

will undergo constructive interference and have an efficient specular reflection from the crystal. In equation (3), n_B is the order of the dispersion, and d is the lattice spacing of the crystal. From equation (3), it follows that the largest wavelength that is measurable by means of a given crystal is 2d. For a parallel beam of x-rays, the crystal selects only one of the wavelengths, namely the one that complies with equation (3). From a point source, however, the rays arrive at the crystal at various angles, and the crystal disperses the wavelengths according to the angles of arrival. One therefore gets the whole spectrum, see figure (3).

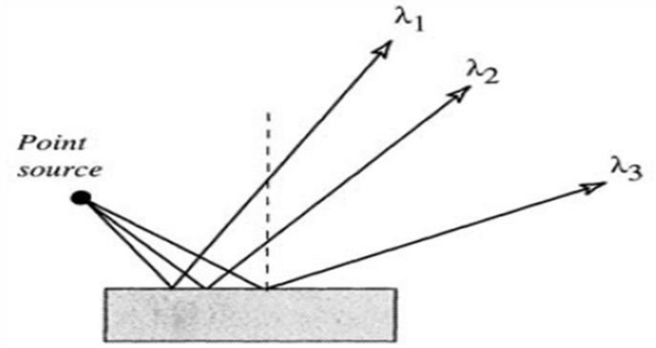

Fig. 3: The principle of flat crystal spectrometers.

Photons with the same wavelength from the various parts of the plasma impinge on the crystal at various transverse angles, and are dispersed to different transverse locations on the photographic film. Thus, the dispersion in the transverse direction-perpendicular to the spectral dispersion direction-is proportional to the intensity of the x-rays emitted from the various portions of the plasma. The crystal spectrometer therefore also gives some spatial resolution of the diagnosed plasma (Yas Al-hadith, 1995).

2.2. Procedure of X-ray experiments:

Laser beam was alignment through the optical components, and preparation of the spectrometer inside the chamber as well as loading the film inside the spectrometer in the dark room. X-ray spectra of the plasma have been recorded on photographic film (Kodak DEF) using a spectrometer with a flat RAP (Rubidium Acid Phthalate, 2d = 26.14 Å) crystal. To stop visible and UV light exposing the film, a 4 μm Al filter was used to filter the spectrometer the transmission of this filter in the KeV region. The spectrometer was placed at 20 mm from the source and filtered with a 4 μm thickness Aluminium (Al) to stop ultraviolet (UV) radiation and visible light from exposing the film.

Increasing the n order, results in increasing the Bragg angle. However, the later caused a decrease of the crystal reflectivity. Selecting a crystal with higher d will decrease the Bragg angle. Accordingly, the rays may go to hit outside the X-ray film and consequently spectrum will not be recorded. Also, the distance between the plasma plume source and the spectrometer plays an important role in the alignment of the spectrometer. Increasing the distance will give back a greater portion to loss of the definition of the present lines and instead shortening the distance allows a greater definition of the lines but on shorter ranks. After all these trickiness, it is necessary to load the spectrometer in a very dark room to protect the film from impressing or exposing by the visible radiation and therefore becoming completely black and unusable.

It is necessary to operate the laser in the focal point of the lens since in such point it’s reached the greatest intensity of the laser beam so also obtain a greatest emission of X-ray. The lens inside the vacuum chamber is ascended on a support electrical micrometric and the position of the lens in the chamber is visualized in the display that it is found on the control panel of the motion of the support.

In our case the used target were pure plates of iron metal. By the means of special manual feed-throw, inserted in the vacuum chamber, the target holder can be rotated during the experimental phase. The rotary motion comes transmitted to the support of the target and converted in a motion of the target it self. The last important step is the alignment of the beam with respect to the target inside the vacuum chamber, and the alignment of the spectrometer and the photodiode with the source. It is important to reach the greatest regime of the vacuum using the rotary vacuum pump. At this point it is possible to perform the experiment; the laser shots number to obtain the X-rays emission is equal to 250 shots for the iron.

RESULTS AND DISCUSSION

Results of laser produced plasma x-ray emission; plasma temperatures and discussion based on X-ray line intensity ratios were demonstrated. For the line ratio techniques, and for every recorded line, the corresponding wavelength, ion-like, and transition type were presented, analysed and discussed.

X-ray spectra from multiple-charged ions in the range of λ~ 12.11 to 17.06 Ǻ emitted from plasma produced from iron target, were observed and identified. Spectra of the resonance lines of several Ne-like, F-like and O-like were also discussed. The Ne-like ions are important radiators from high temperature plasmas as they are strong emitters and because of the cloth-shell structure of the ground level of neon-like ions (Yas Al-hadith, 1995). They tend to be in high abundance over a wide range of temperatures; however, interest in Ne-like ions has recently increased markedly due to the success in producing X-ray lasing in Ne-like ions from LPP. The spectra are relatively uncomplicated because of the closed shell structure in comparison to nearby fluorine-like and oxygen-like, spectra and hence are useful for plasma diagnostics purposes (Yas Al-hadith, 1995). A significantly large part of the laser pulse would be absorbed by the target and consequently a high-temperature plasma could be formed. In the temperature region of k eV, plasma becomes a real source of X-rays radiation emitted from inner shell electrons. Giving that 1 eV is equal to 11600 K, the study of the plasma X-ray emission can tell a lot of information about the plasma structure and properties. This underlines the importance of the X-rays as a plasma diagnostics technique (Kruer, W.L., 1984).

In this work, X-ray set of spectra of iron was presented. The target has plate-shape of 2 mm thickness. This plate was located in the focal point of the lens, to have greatest laser intensity. A manual sideways movement was possible throughout of the experiment. Such motion is necessary because the laser, which focused to develop plasma, creates a crater on the surface of the target. The number of laser shots used to irradiate the target was 250 shots.

Development of the film carried out in a dark room by two chemical solutions, fixer and developer, gave the necessary utilization of a scanner in order to obtain a digital image of the spectra. This made the deeper study of the X-ray emission across the computer with assistant of other tools possible. A profile of the spectra across the use of two analysis programs, ImageJ and KaleidaGraph was obtained. (NIST) online databases gave more confidence in the analysis to go forward to be completed (http://physics.nist.gov/asd3). The complete analyzed spectra of Fe are shown in Figure: (4).

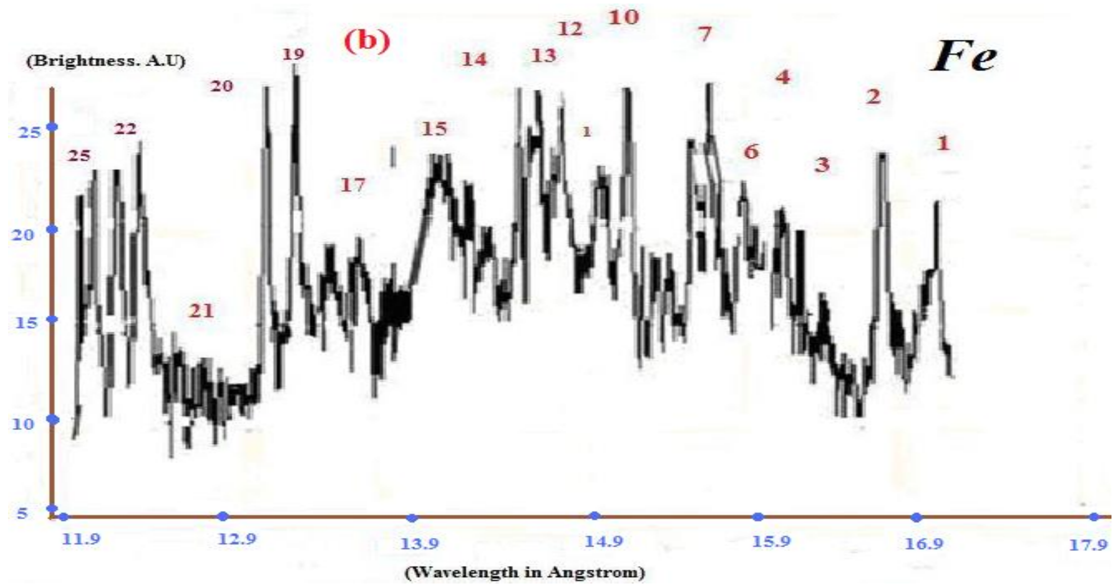

Fig. 4: a complete analysed spectrum of Fe.

From this database, the analysis and identification details for every transition line were achieved. These include the corresponded wavelength, transition type and ion-like as listed in table (1).

Table 1: Identification details of the Fe X-ray emitted lines.

Wavelength (A^0)	Transition	Ion type
17.060	3s - 2p	Ne - like
16.7655	3s – 2p	Ne - like
16.285	3s – 2p	F - like
16.236	3s – 2p	F - like
15.977	3s – 2p	F - like
15.822	3s – 2p	F - like
15.75625	3s – 2p	F - like
15.63675	3s – 2p	Ne - like
15.441	3d – 2p	Ne - like
15.264	3d -2p	Ne - like
15.06525	3d – 2p	O - like
14.91225	3s – 2p	O - like
14.74225	3s – 2p	O - like
14.659	3s – 2p	F - like
14.221	3d – 2p	Ne - like
13.90525	3d – 2p	O - like
13.732	3d – 2p	O - like
13.5205	3d – 2p	F - like
13.36775	3d – 2p	F – like
12.6645	3d -2p	Ne – like
12.48725	4s – 2p	Ne – like

Here and from this table, the identification of the x-ray emitted from L to M ionic states resulting in very complex Fe spectra having a large variety of ionic states presented in the spectra as illustrated. The spectra are composed of three emission bands corresponding to the Ne-like, F-like and O-like transition lines. The most intense lines are due to L to M shell transitions (principal quantum numbers n = 2 to 3). So, that, in such case, line intensity ratios are a common diagnostic technique for plasma temperature estimation. Line widths are related to plasma temperature and electron density (Baoming Li and Hongzhi Li, 2001). Under this experimental condition, the most important contributors to the line width in the emitted spectra are the Doppler width and the Stark effect. Some lines recorded in the spectrum could be considered in reality as a composition of many lines. The size of the plasma x-ray source is in the order of micrometer. Thus, it is logical to use the approximation of local thermodynamic equilibrium (LTE) (Jesus Mirapeix, 1., *et al*., 2009).

The spectral information and details from table (1) exhibit the complex nature of the emission of these materials and show how difficult to use it for diagnostic. The ion-like spectra are similar along series of different atomic numbers, which facilitates spectral identification. The Ne-lines are relatively uncomplicated because of the closed shell structure in comparison to nearby fluorine-like and Oxygen-like lines and hence are useful for plasma diagnostic purposes.

From the comparisons between the achieved transitions, it was noted that characteristic groups of lines repeat themselves in the structures but in different brightness i.e. same transitions have different energies and this depends mainly on the fact that the energies of the transition levels were different. Some of these lines represent new identifications of transition types. It was also noted that different types of emission change their intensities from metal to metal. This actually came from the fact that the laser in this position excited a number of electrons equal to 19 electrons for copper and 20 electrons for iron to achieve Ne-like ions (Cu electron configuration is: 2, 8, 18, 1). This means that by lowering the atomic number no more Ne-like type of emission domination could be achieved. However, the other types like the oxygen and the Fluorine would dominate.

The method of relative intensity ratio among different ionic stages of the same atom in LTE used to obtain temperature is considered an accurate technique, because only the relative (not absolute) line intensity measurements are needed. However, some problems can rise with using line ratios as temperature diagnostic because:

(1) The transition of the quantum state populations from LTE relations leading to the line ratios having a dependence on density and temperature history of the plasma.

(2) The spectroscopic constants are very important and very sensitive; thus, the lines must be selected very carefully and correctly when the plasma temperature is needed to be calculated. Otherwise, it would lead to a great error of the temperature calculation.

In order to calculate the electron temperature from a line ratio, a careful selection of emission lines must be made. The line ratio of the selected transitions must be insensitive to intensity variations to be applied for the determination of temperature (Jesus Mirapeix, 1., 2009). Using equations (1 and 2) of line intensity ratios method, the statistical weight of the level (g), the transition probability Einstein coefficient (A) and the transitions energies (E) can be obtained from the handbooks of the spectroscopic constants, chemistry and physics. For plasma temperature calculation, a number of Fe spectral lines were selected as listed in table (2).

Table 2: the logarithmic term of Iron lines used for relative intensities ratio of the x-ray lines.

$Ln\left(\dfrac{\dfrac{N_{\varepsilon m^-}}{N_{\varepsilon m^{--}}}}{\dfrac{g_{\varepsilon m^-}}{g_{\varepsilon m^{--}}}}\right)$	$E_{m^-} - E_{m^{--}}$ **(KeV)**
100	0.88
72	0.9
45	1.01
30	1.12
10	1.25

From table (2) and, assuming a Boltzmann distribution in the populations, a plot of the logarithmic term versus ΔE yields, a straight line whose slope, S, is equal to –1/T. The calculated results showed that for a given spectrum, a plot of the function taken with unsuitable spectroscopic constants yielded a straight line that both the linearity and the correlative coefficient were bad. In this research, a set of spectroscopic constants of six atomic iron lines, which are suitable to construct a plot function, was recommended. Some of the crucial factors to obtaining a good plot are accurate line intensities, accurate transition probabilities, and well spaced upper levels. The further apart the extremes of the upper level values, the easier defining the slope of the line (Silver, E. *et al*., 2004). The linear relation of the x-ray line parameters is shown in Figure (5).

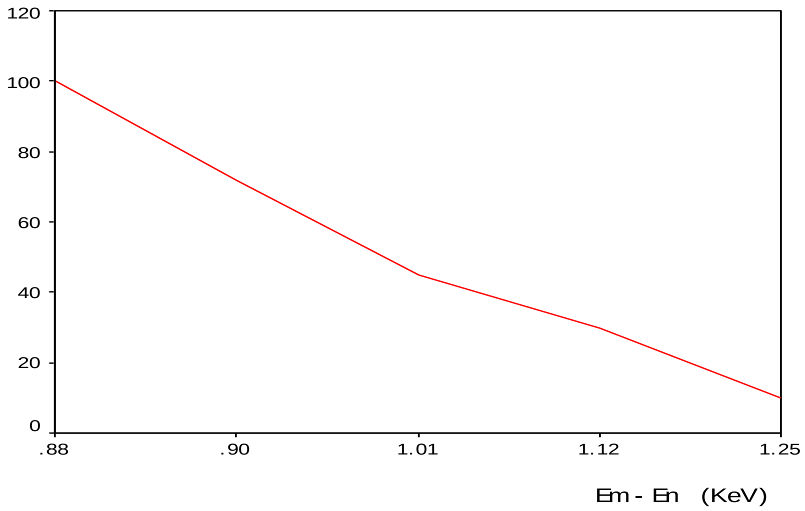

Fig. 5: The experiment linear relationship between the logarithmic term on Y axis and ΔE term on X axis for iron.

From the above Figure, the experiment linear relationship between the logarithmic term on Y axis and ΔE term on X axis for iron, and from the slope of the line in a plasma temperature for Fe target of 250 eV was determined. Te = 250 eV

This temperature value looks high enough for the ionization of the inner shell of the elements. However, it was apparently not high enough to produce the highly-charged stages of ionization from k shell, or may be, the duration of the plasma was not long enough.

Conclusions:

From the obtained results one can conclude that

1- Characteristic groups of lines from the same element, repeat themselves in the structures but with different intensities.

2- In order to calculate the electron temperature from a line intensity ratio, a careful selection of emission lines and corresponding spectroscopic constants must be made.

3- During the used laser intensity, the temperature of Fe was 250 eV in the X-ray regime.

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