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Statistical Investigation of Electron Density of Laser-Air Interaction System Using Saha Relation in Local Thermodynamic Equilibrium

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Abstract: Investigating complex systems and accessing information has been of interest to researchers for years. The desired system in this research includes the investigation of the plasma resulting from the interaction of the laser with the desired substance of the research. Air is the material of choice for producing plasma in interaction with the laser. We used Nd:YAG laser for incident beam to interact with air matter. Plasma was formed by the interaction of laser with air. In the following, it is possible to check the plasma density by scanning the plasma resulting from the interaction of the laser with air. Therefore, in order to determine the electron density by the Saha method, we first need to calculate the electron temperature, which was calculated using the spectral line pair intensity ratio method of the plasma temperature equal to Kelvin. In the continuation of the research, the electron density was measured using Saha's equation.

keywords: Laser-plasma interactions, Plasma temperature and density, Laser spectroscopy, Saha equation

1 Introduction

Various lasers such as Nd:YAG, Excimer, co_2 and Microchip lasers are used for the formation of plasma according to the type of research, and the type of laser has been selected for the research according to the characteristics listed in table 1 [1-4].

In this research, we created Nd:YAG laser by setting up the laser and we used laser induced breakdown method (LIBS) to create plasma, in this method an short Q-switch pulse from a Nd:YAG laser with high energy density on the target surface is focalized. Focusing the laser on the sample causes a rapid increase in the surface temperature of the sample. In such a way, the material below the surface reaches critical temperature and pressure, leading to surface explosion. The material is absorbed by energy from the pulse of the laser, evaporation, atomized and ionized and thus plasma is formed. In this study, the Nd:YAG laser was focused on the air and the plasma produced by the interaction of the laser with the air was formed. Using a spectrograph, we recorded the spectral spectra of plasma resulting from laser interaction with air, and using the obtained spectrophotometer results, electron temperature was determined by the spectral line pairing method, and the electron density was calculated using the Saha relation.

2 Materials and method, calculations, governing equation

2.1 Local Thermodynamic Equilibrium

The thermodynamic equilibrium of the system is a state of the system in which none of the properties of the system changes with the passage of time. Complete thermodynamic equilibrium is achieved by establishing equilibrium in the four processes of kinetic equilibrium, excitation, ionization, and radiation. In such a plasma, electron and ion velocity distribution follows the Maxwell-Boltzmann distribution function and the distribution of excited states follows the Saha-Boltzmann type and photons follow the Planck energy distribution function [5]. When photons escape from the plasma in the radiation process, their energy distribution no longer follows the Planck distribution and inevitably affects the balance of electrons, ions and atoms. However, if the energy dissipated by plasma radiation is less than the energy involved in other processes and energy exchange, the condition of complete thermodynamic equilibrium (TE) is not possible, while the three processes of equilibrium-kinetic, excitation and ionization have equilibrium. are local thermodynamics and the Maxwell and Saha-Boltzmann distributions are still valid to describe the system. A new equilibrium is defined as local thermodynamic equilibrium (LTE). This equilibrium is local because it exists only in a small area of the plasma volume and the temperature will be different from one area to another in the plasma. Due to the large number of collisions in the plasma, the temperature will be the same in the whole plasma region with a good approximation, and the calculated temperature will be an average of the temperature in the whole plasma region [5].

Measurement of plasma parameters is possible only if the plasma is in local thermodynamic equilibrium. In this condition, it is assumed that the plasma has reached equilibrium and its parameters, such as its temperature and electron density, are constant and measurable [5].

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Table 1 Characteristics of lasers used in LIBS [4][6]

Features related to applications in LIBS	Repeat Rate (Hz)	pulse length (ns)	Wave-length (nm)	Laser type
Easy access to harmonic Excellent beam quality Ability to produce double tap Pump by Lamp and Diod Pump	1-20	6-15 4-8	Harmonic: Main: 1064 Second: 532 Third: 355 Forth: 255	Nd:YAG
Requires periodic gas charging Producing UV wavelengths	200	20	XeCl: 308 KrF: 248 ArF: 194	Excimer
Requires periodic gas charging	200	200	10600	CO_2
Good quality of beam and fashion Capable of producing tap to high pulse High repetition rate	1-10K	<1	1064	Microchip

2.2 Method of the intensity ratio of two lines of one element

The most important factor in plasma radiation is plasma temperature and precise determination of plasma temperature is important. Plasma temperature is often used for the same element as the size of the intensity ratios of ion-to-neutral lines or neutral lines. In the first case, line intensities are combined with equation and electron density measurement to determine plasma ionization temperature.

$$\frac{I_{i+1}}{I_i} = 2 \times \frac{(2\pi m_e k_B T)^{\frac{3}{2}}}{n_e^2} (\frac{gA}{\lambda})_{i+1} (\frac{gA}{\lambda})_i \times \exp[\frac{-(IP_I + E_{i+1} + E_i)}{k_B T}]. \quad (1)$$

Here I is the area below the absorption line of ions and atoms, N_e is the electron density, g is the statistical weight factor, and A is the Einstein coefficient for spontaneous emission of the higher level, λ and T are the wavelength and temperature of the plasma, respectively. IP_I, E_{i+1} and E_i are the ionization potentials of the atom, the ion line excitation energy and the ionization energy of the atomic line, respectively. k_B Boltzmann constant and h is Planck constant [7]. In the second case, line intensities are combined with the Boltzmann equation to determine the temperature of the plasma excitation and the relation (2) expresses that:

$$\frac{I_1}{I_2} = \frac{g_1 A_1 \lambda_2}{g_2 A_2 \lambda_1} \exp(-\frac{E_1 - E_2}{k_B T}), \quad (2)$$

and thus, T is equal to [7, 8]:

$$T = \frac{E_1 - E_2}{k_B \ln[\frac{I_1 g_2 A_2}{I_2 g_1 A_1}]}, \quad (3)$$

where the indices 1 and 2 are related to separate lines. With an increase in energy, the difference between E_1 and E_2, accuracy in determining plasma temperature increases. This accuracy is increased by measuring the number of different pairs of lines and averaging the number of different lines. However, it is important to note that measurement accuracy is strongly dependent on factor A. Plasma temperature is one of the most important parameters in determining electron density and the concentration of plasma constituent elements [9].

2.3 Density measurement using the Saha relation

If the plasma is considered to be localized in thermodynamic equilibrium, the density of the electron can be calculated using the ratio of the intensity of different ionization states of an element, while the Saha equation is written in terms of the density ratio of the total number of two ionizing states corresponding to an element. The electron density of plasma can be calculated by considering two lines with different degrees of ionization and using the relation (4) known as the Saha equation:

$$n_e \frac{I_2}{I_1} = 2 \left(\frac{2\pi m_e}{h^2}\right)^{3/2} (kT)^{3/2} \frac{U^{II}(T)}{U^{I}(T)} e^{-E_{ion}/kT} . \quad (4)$$

In this regard m_e the mass of the electron, h is the Planck constant, k is Boltzmann's constant, E_{ion} ionization energy in electron Volts and T is plasma temperature in Kelvin.

$U^I(T)$ and $U^{II}(T)$ are the partition function with ionization of the first and second order at the plasma temperature and n^I and n^{II} are the number of photons emitted from the plasma in these states and n_e the electron density of plasma is obtained in terms of cm^{-3} [5].

3 Results and Discussion

Laser plasma was formed from Nd:YAG laser with air It is collected by the lens of light emitted from plasma and with the help of the CCD-Array Toolkit software, the plasma spectra of the air are observed in the laptop. Figure 1 shows the plasma spectra resulting from the interaction of the laser with air. In Table 2, nitrogen elements observed from the spectra of air plasma in the range of 405.99-671.77 nm are shown, and the emission lines of the spectrograph are shown in Table 3.

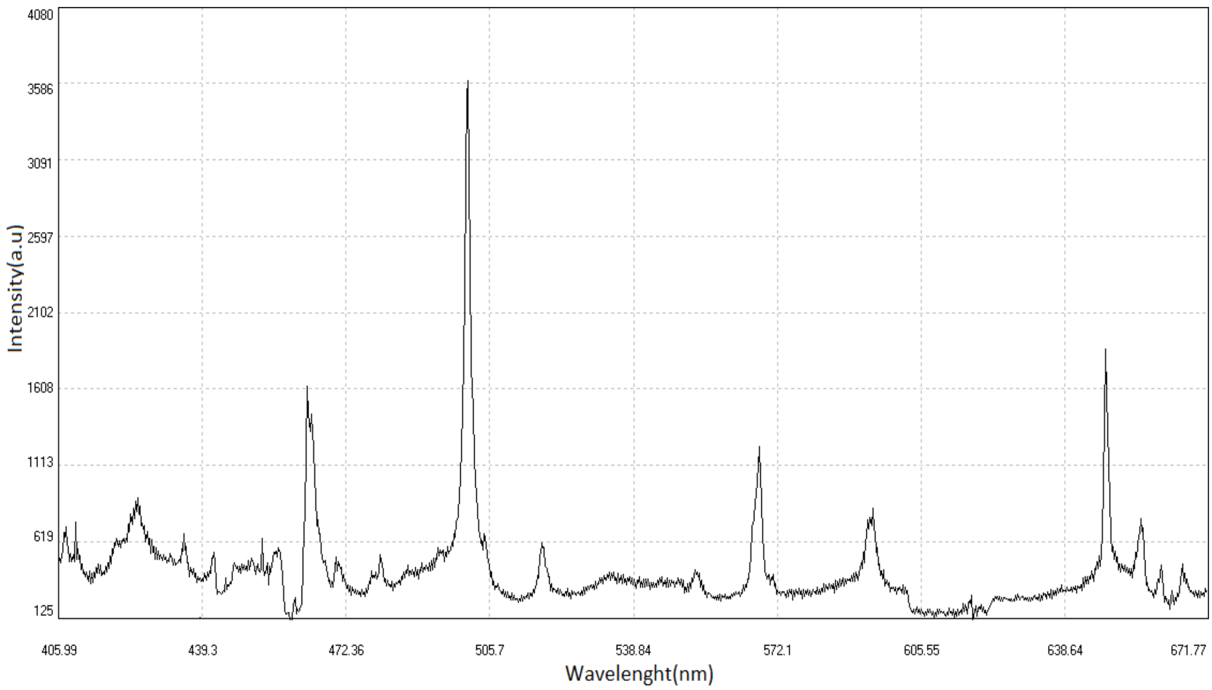

Fig.1 Spectral Spectra Plasma from Laser Interaction with Air in the range of 405.99-671.77 nm

Table 2 Nitrogen Elements Detected from Figure 1 [10]

Standard wave-length	Observed wave-length	element
409.99	409.99	NI
444.70	444.67	NII
460.71	460.62	NII
616.77	616.76	NII
648.17	648.25	NI
661.05	661.08	NII
665.65	665.63	NI

$$\frac{I_2}{I_1} = \frac{g_2 A_2}{g_1 A_1} \exp(-\frac{E_2 - E_1}{KT}),$$

$$\frac{741}{380} = \frac{4 \times 0.348}{5 \times 11.2} exp(-\frac{13.702 - 23.196}{0.86 \times 10^{-4} \times T}),$$

$$\rightarrow T = 2.5172 \times 10^4 K,$$

and for the rest of the two lines ratios are calculated as follows, the statistical results of which are given in Table 4.

In the following, the electron density is also calculated by the Saha-Boltzmann method:

$$n_e \frac{I_2}{I_1} = 2\left(\frac{2\pi m_e}{h^2}\right)^{3/2} (kT)^{3/2} \frac{U^{II}(T)}{U^I(T)} e^{-E_{ion}/kT},$$

$$2\left(\frac{2\pi m_e}{h^2}\right)^{3/2} = 6.5 \times 10^{21}, \quad k = 0.86 \times 10^{-4} \text{ eV}.$$

Table 3 Specification of Horizontal Emission Lines of Figure 1 [10]

Standard wavelength	I	element	$A_{ki} \times 10^7$	$E_k(eV)$	g
409.99	741	N I	0.348	13.702	4
444.70	380	N II	11.2	23.196	5
460.71	250	N II	3.15	21.152	3
616.77	226	N II	2.65	25.151	7
648.17	1863	N I	0.343	13.662	4
648.20	520	N II	2.58	20.409	3
661.05	458	N II	6.01	23.474	7
665.65	485	N I	0.217	13.614	2

Table 4 Calculation of temperature results with the ratio of two different lines

No	Line element (1) (wavelength)	Line element (2) (wavelength)	$T(K)$
1	NI (409.99)	NII (444.70)	2.5172×10^4
2	NI (409.99)	NII (460.71)	2.8859×10^4
3	NII (616.77)	NI (648.17)	2.8342×10^4
4	NI (648.17)	NII (661.05)	2.3641×10^4
5	NII (648.20)	NI (665.65)	2.8104×10^4
6	NII (661.05)	NI (665.65)	2.4756×10^4

Considering the relationship (4), we need the partition functions and ionization energy proportional to two lines; these parameters are obtained from library data and collected in Table 5.

Table 5 Data needed for Saha relations [10]

No	Scattering function of a single ionized element	Scattering function of a doubly ionized element	Ionization energy(eV)
1	11.38	11.63	14.5341
2	15.74	12.19	14.5341
3	15.02	12.11	14.5341
4	10.07	11.41	14.5341
5	14.69	12.07	14.5341
6	11.01	11.57	14.5341

Number (1) in table (5): For two lines N I (409.99) and N II (444.70) the Scattering function is $U^I = 11.38$ and $U^{II} = 11.63$ and its ionization energy is $E_{ion} = 14.5341$, and thus the electron density is calculated for these two lines:

$$n_e \frac{380}{741} = (6.05 \times 10^{21})(2.164)^{\frac{3}{2}} \frac{11.63}{11.38} e^{-\frac{14.5341}{2.164}},$$

$$\rightarrow n_e = 4.6619 \times 10^{19} \text{cm}^{-3}.$$

And for the rest of the lines, it is calculated as follows: the statistical results are given in Table 6.

Table 6 Results of Density Calculation with Saha Equation

No	element Once ionized (Wavelength)	element double ionized (Wavelength)	$n_e(cm^{-3})$
1	NI (409.99)	N II (444.70)	4.6619×10^{19}
2	NI (409.99)	N II (460.71)	1.5543×10^{20}
3	NI (648.17)	N II (616.77)	3.9362×10^{20}
4	NI (648.17)	N II (661.05)	6.3534×10^{19}
5	NI (665.65)	N II (648.20)	4.2609×10^{19}
6	NI (665.65)	N II (661.05)	2.2682×10^{19}

4 Conclusion

In this research, the values of temperature and electron density for plasma produced by laser interaction with air have been calculated. To determine the electron temperature, spectral line pairing method was used. Considering the results of temperature calculations from Table 4, the value 2.6479×10^4 was determined for the electron temperature and Saha equation was used to calculate the electron density and by means of the results of the calculations of electron density from table (6) the value of $2.5914 \times 10^{20}\ cm^{-3}$ for the electron density was obtained.

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