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Dedicated to Professor Valentin I. Vlad's 70th Anniversary

THE GAS TEMPERATURE DETERMINATION IN THE PULSED HOLLOW CATHODE DISCHARGE

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Abstract. In this paper we deduced the gas temperature of the pulsed hollow cathode discharge in Neon from the Doppler width of the $^3P_2 – 2p^4$ Neon transition at 633.4 nm. By comparing the absorption spectral measurements on the Neon metastable atoms on $^3P_2$ level existing in a hollow cathode dc discharge performed with a diode laser and with a pulsed discharge as light source we was able to determine the line profile of the $^3P_2 – 2p^4$ Neon transition at 633.4 nm of a pulsed high voltage hollow cathode discharge and thus the gas temperature of the pulsed discharge. The dependence of the gas temperature with the applied pulsed high voltage was obtained.

Key words: absorption spectroscopy, pulsed discharge, gas temperature.

1. INTRODUCTION

Gas temperature is an important parameter for the study of discharge modeling and in plasma diagnostics processes. In this paper we deduced the gas temperature of the pulsed hollow cathode discharge in Neon from the Doppler width of the $^3P_2 – 2p^4$ Neon transition at 633.4 nm. The line profile, Doppler broadening type, of the pulsed hollow cathode discharge was obtained measuring the absorptions of the neon metastable atoms on $^3P_2$ level existing in a hollow cathode dc discharge using two spectral sources: a diode laser and the pulsed discharge as light source. The maximum absorption coefficient $\mathbf{k_0}$ of the Neon line is $k_0 = \frac{2}{\Delta\vartheta_D}\sqrt{\frac{\ln 2}{\pi}}\frac{\pi e^2}{mc}Nf$, where $\Delta\vartheta_D$ is the Doppler line broadening of the metastable atoms, e and m are the electron charge and mass, c is the light velocity and f is the oscillator strength of the $^3P_2 – 2p^4$ Neon transition at 633.4 nm. Taking into account that in both experimental cases, the maximum absorption coefficient

k_0 of the Neon line has the same value, we deduced from Mitchell and Zemanski [1] absorption formula (1), the line profile of the hollow cathode pulsed discharge light source at 633.4 nm.

$$A=\sum_{m=1}^{\infty}\frac{(-1)^{m+1}(k_0L)^m}{m!\sqrt{1+m\alpha^2}}=\frac{k_0L}{\sqrt{1+\alpha^2}}-\frac{(k_0L)^2}{2!\sqrt{1+2\alpha^2}}+\ldots \tag{1}$$

where L is the absorption length of the discharge, in our case being 2 cm and

$$\alpha=\frac{\text{Broadening of spectral source line}}{\text{Doppler line broadening of absorbing species}}. \tag{2}$$

2. EXPERIMENTAL SETUP

The experimental set up used for the absorption spectroscopy measurements with a L635P005 diode laser is presented in Fig. 1. This set up allows the measurement of the absorption of the laser light at 633.4 nm of the neon metastable atoms on $^3P_2$ level, existing in the negative light of the dc hollow cathode discharge. The width of the laser line measured with a Fabry Perot etalon with 1.6 GHz bandwidth and finesse 200 was found to be 0.15GHz corresponding to 2×10^{-4} nm.

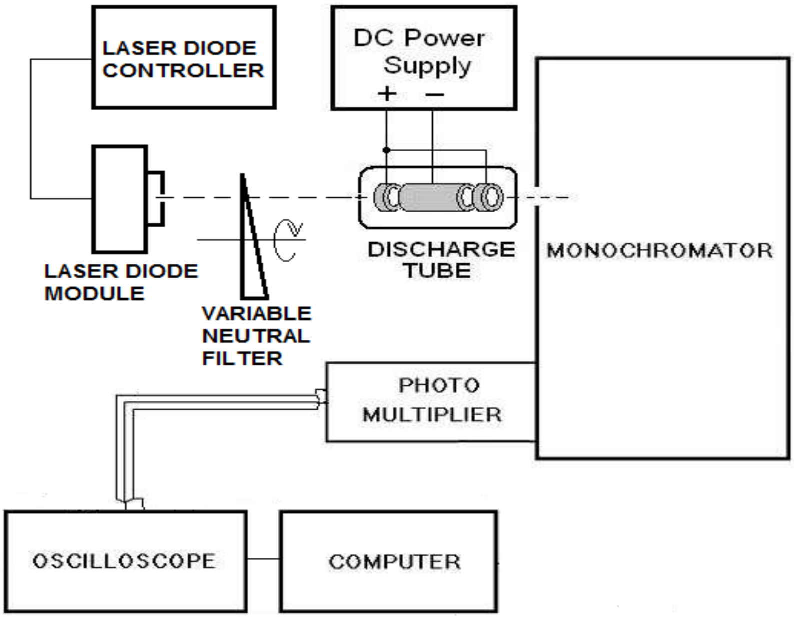

Fig. 1 – Experimental set up for the absorption spectroscopy with diode laser.

The absorption measurements were made on the Neon metastable atoms from the negative light of a dc hollow cathode discharge in Neon at 3.5 Torr working at 10 mA and 300 V. The Neon lines emitted by the discharge are Doppler broadened lines, the gas temperature being the room temperature. In this case the width of the Neon line at 633.4 nm is $\Delta\lambda_{Ne} = 4.69\times10^{-3}$ nm.

As a light source, we have considered a tunable laser source, which can be set exactly to the wavelength 633.4 nm. Thus we used as tunable source with sufficient narrow spectral band, a diode laser with a wavelength close to that required: the diode Thorlabs catalog L635P005 the nominal wavelength at 635 nm. The laser radiation spectrum consists in many longitudinal modes characteristics for the Fabry Perot resonator. In our experiment these modes were resolved and separated by Jarrell Ash monochromator with 7A/mm slit resolution (we worked with a 70 µ slit) which could separate the laser modes placed at 0.07 nm spectral distances. They were recorded (Fig. 2), matching the sweeping wavelength range of the monochromator with the temporal range of the oscilloscope.

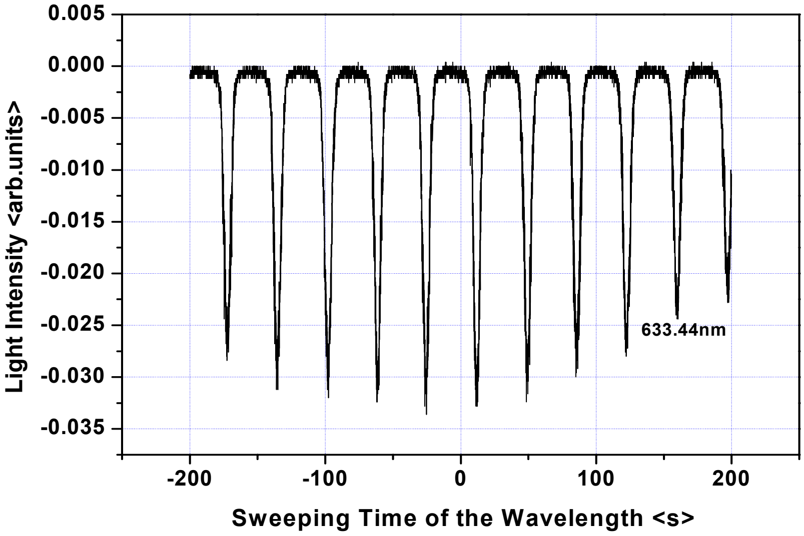

Fig. 2 – Laser modes of the diode laser working at 3.1 mW and 17.89 °C.

In order to tune one of the laser modes at the wavelength 633.4 nm, the applied power on the diode laser was swept in the range of 2.5–14 mW and the temperature was also varied in the range of 17.74–18,16 °C. Wavelength shift identification of the laser mode from 633.4 nm wavelength of Neon transition allowed us, using the catalog characteristics of diode, to reposition the diode temperature this time to 17.94 °C. Fig. 3 presents the superposition of three photomultiplier recorded signals: diode laser modes, diode laser modes passing through the discharge and the calculated $I_{Laser} + I_{Discharge}$ at 633.4 nm.

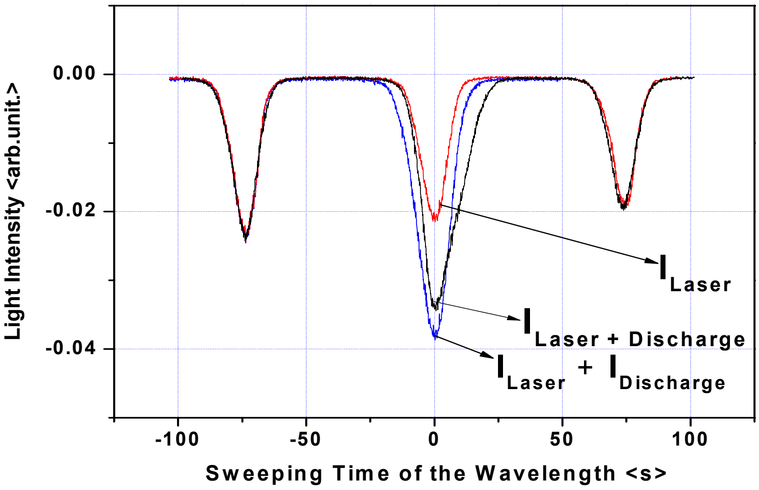

Fig. 3 – Superposition of three photomultiplier recorded signals: diode laser modes, diode laser modes passing through the discharge and the calculated $I_{Laser} + I_{Discharge}$ at 633.4 nm.

The measured absorption is defined as $A = 1 - I_t/I_0$**,** where I_0 is the intensity of the laser and I_t the total transmitted light. I_t is obtained by subtracting the emitted light of the discharge $I_{Discharge}$ from the light emitted simultaneously by the laser and the discharge $I_{Laser + Discharge}$; $I_t = I_{Laser + Discharge} - I_{Discharge}$

The measuread absorption was found to be A = **(20 ± 2)%.**

The experimental set up used for absorption measurements with the pulsed hollow cathode discharge as light source is presented in Fig. 4.

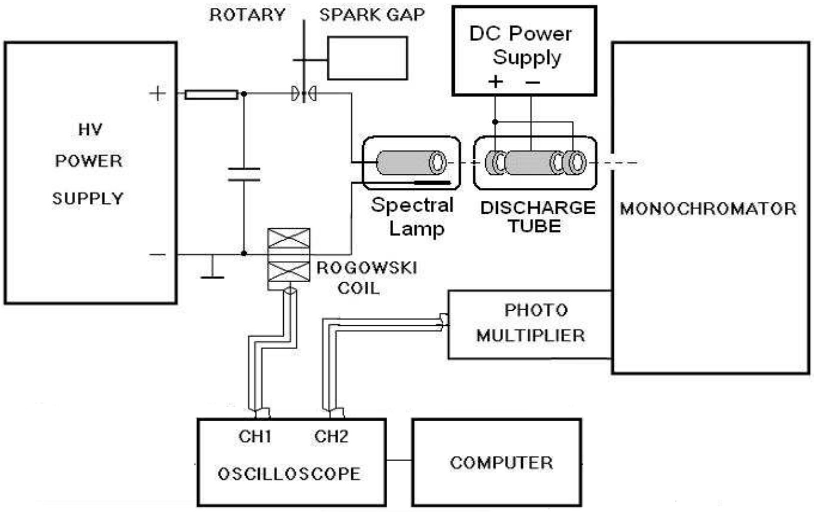

Fig. 4 – Experimental set up for the absorption spectroscopy with pulsed spectral source.

The intense pulsed light source consists of a glass chamber containing a titanium cylindrical hollow cathode (15 mm length and 3 mm diameter) and a stainless steel wire anode. High current pulses of short duration were obtained by repetitively discharging a storage capacitor C through a rotary spark gap with a commutation time below 10 ns [2].

Working at 1–5 Torr neon gas pressure, peak current pulses in the range of 20–100 A with duration of 60 ns (at half-width) were obtained (depending on the charging voltage of the main capacitor). This pulsed high current density provides a large amount of excited atoms and ions of both, the filling gas and the sputtered cathodic metal with intense emission lines [3].

The emission light of the pulsed source at 8 kV, the dc discharge light and the transmission light of the pulsed discharge through the negative glow of the dc hollow cathode discharge at the wavelength 633.4 nm are presented in Fig. 5.

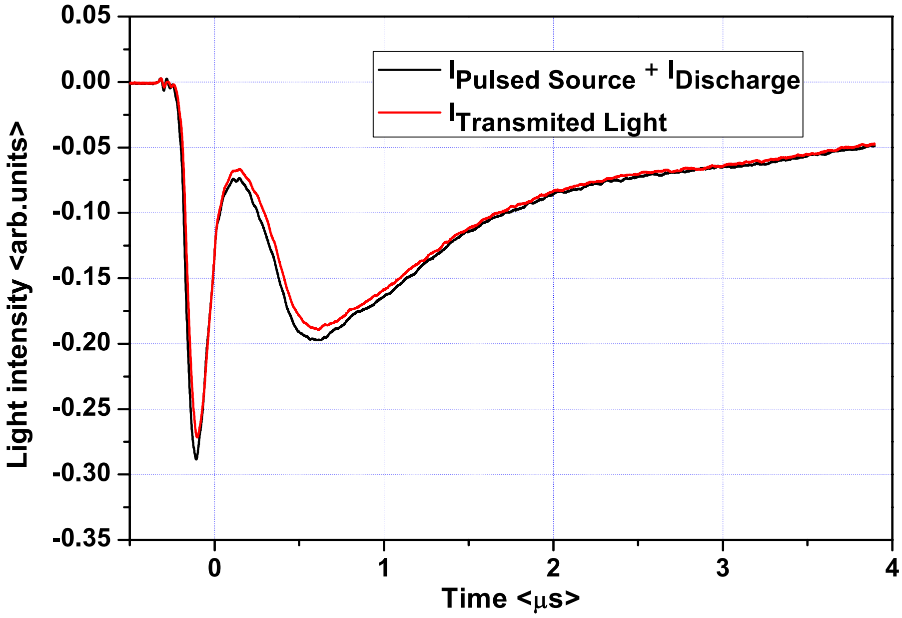

Fig. 5 – The $I_{Pulsed\ source} + I_{Discharge}$ emission light at wavelength 633.4 nm and $I_{Transmission}$ through the negative glow of the dc hollow cathode discharge; the pulsed source working at 8kV.

The measured absorption $A = 1 - I_t/I_0$, where I_0 is the intensity of the pulsed source at 8kV applied voltage and $I_t = I_{Discharge+Pulsed\ Source} - I_{Discharge}$ was found to be (5.6 ± 0.3)%. We made similar measurements for different applied voltages on the pulsed source. The results are presented in the table below.

Table 1

The measured absorptions for different voltages applied on the pulsed light source

Applied voltage on the pulsed source (kV)	Measured Absorption (%±3%)
4	11
5	8.1
6	7.7
7	6.4
8	5.6

3. RESULTS AND DISCUSSIONS

Starting from equation (1) we have to find the roots for two scenarios:

I. $$f(x)=\sum_{m=1}^{\infty}\frac{(-1)^{m+1}x^{m}}{m!\sqrt{1+m\alpha^{2}}}-A=0,\quad x=(k_0L),$$

and

I. $$f(x)=\sum_{m=1}^{\infty}\frac{(-1)^{m+1}(k_0L)^{m}}{m!\sqrt{1+mx^{2}}}-A=0,\quad x=\alpha.$$

The derivative of *f(x)* can be defined analytically; therefore for both cases we have used a New-Raphson method with derivative. Because the global convergence properties of this algorithm are known to be poor, we have used a combination of bisection and Newton-Raphson methods. Calculations have been performed for any *m* in a few numbers of iterations and with very high accuracy.
The root of the first scenarios was found to be k_0L = 0.22332743, where

$$\alpha=\frac{\text{Broadening of the laser line}}{\text{Doppler broadening of absorbing Neon metastable atoms in the dc discharge}}=$$

$$=\frac{2\times10^{-4}\,\text{nm}}{4.69\times10^{-3}\,\text{nm}}=0.042$$

and A, the measured absorption with diode laser as spectral source, is 0.20 ± 0.02. For k_0L = 0.22332743, the dependence $f(\alpha)$ for different A values (scenarios II) is presented in the Fig. 6. One can see that real roots α exist for a limited range of A values only.

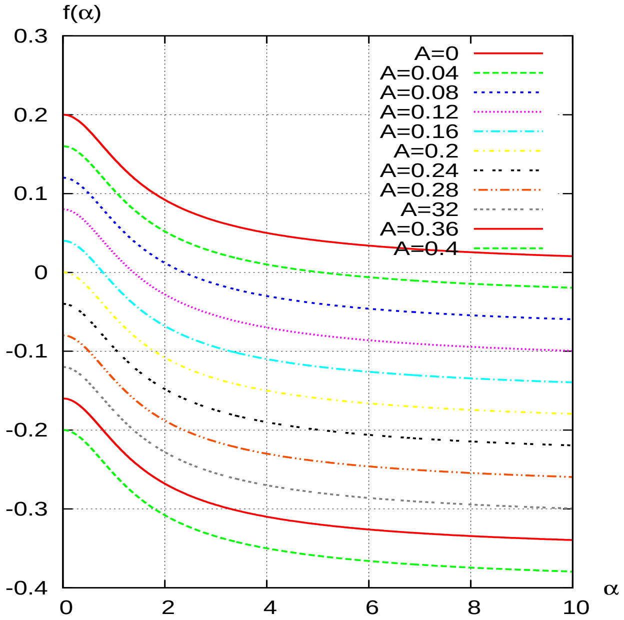

Fig. 6 – The dependence f(α) for different A values.

The calculated values of α, the roots of the scenarios II for different values of *A* are presented in Table 2.

Table 2

Calculated values of α for different given A values

A	**k_0L**	**α**
0.024	0.22332	8.55241
0.032	0.22332	6.37874
0.04	0.22332	5.06616
0.048	0.22332	4.18397
0.056	0.22332	3.54753
0.064	0.22332	3.06449
0.072	0.22332	2.68351
0.08	0.22332	2.37373
0.088	0.22332	2.11549
0.096	0.22332	1.89561
0.104	0.22332	1.70492
0.112	0.22332	1.53678
0.12	0.22332	1.38626
0.128	0.22332	1.24954
0.136	0.22332	1.12355
0.144	0.22332	1.00571

Table 2 (continued)

0.152	0.22332	0.89371
0.16	0.22332	0.78527
0.168	0.22332	0.67784
0.176	0.22332	0.56801
0.184	0.22332	0.45008
0.192	0.22332	0.31042

From Table 2, related to our experiments, we can easily deduced that for the same k_0L the emission lines of the pulsed hollow cathode discharge powered at different voltages have different line profile, α being

$$\alpha = \frac{\text{Broadening of the pulsed spectral source line}}{\text{Doppler broadening of absorbing Neon metastable atoms in the dc discharge}}$$

The line broadening of the pulsed spectral source is also of Doppler type and is given by the formula $\Delta\lambda_D = \sqrt{\frac{8kT\ln 2}{mc^2}}\lambda_0$. Thus, α becomes $\alpha = (T_{pulsed\,source}/T_{discharge})^{1/2}$. Assuming that the gas temperature of the dc discharge is at the room temperature we succeed to determine the gas temperature of the pulsed hollow cathode discharge. The results are presented in Table 3.

Table 3

The measured absorptions, α and the gas temperatures for different voltages applied on the pulsed light source

Applied voltage on the pulsed source (kV)	Measured Absorption (%±3%)	α (calculated)	T_{gas} of the pulsed source (K)
4	11	1.53678	708
5	8.1	2.3737	1689
6	7.7	2.4437	1791
7	6.4	3.06449	2817
8	5.6	3.5475	3775

4. CONCLUSIONS

The determination of the gas temperature of the high voltage pulsed hollow cathode discharge performed in this paper, opens the possibility to use this kind of discharges as spectral source for absorption measurements with temporal resolution. We demonstrate that the gas temperatures of these discharges and thus the profile of spectral emission lines are dependent on the applied voltages.

As shown in absorption formula (1), significant absorption is obtained with α = 1 or less, which implies that the source spectral emission lines must to be narrower or comparable to gas absorption. That is why a pulsed discharge with controlled profile of the spectral emission lines, by adjusting the applied voltage, is particularly suitable for absorption measurements in the spatial or temporal afterglow plasma.

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