

## An educational experiment on optical phenomena associated with an electrical discharge, plasma creation and light emission

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### Abstract

The optical phenomena related to electrical discharges and to the technology of light production and material processing have been known for many decades. They have been adequately studied and widely applied. Therefore, exposure to the aforesaid optical phenomena as a learning exercise continues to impress and interest students in physics laboratories with essential learning results. With this in mind, we assembled a simple experimental apparatus which allows students to carry out experiments for the study of optical phenomena associated with electrical discharges and emission of radiation in a physics lab. A simple gas discharge flow system was utilized for observation of various coloured emissions as a function of experimental parameters, like molecular gas, discharge power, pressure and flow rate. Emission spectra were obtained using a laboratory spectrometer and emission bands were identified. Comparative spectra were also obtained with other light sources such as plasma globes and Geissler tubes of known gas composition. Distributions over vibrational states of some excited molecular states were measured and utilized to derive vibrational temperatures of vibrationally-electronically excited molecules.

### 1. Introduction

Experiments that can excite students' interest and can simultaneously act as a learning exercise for basic physical concepts are properly designed to be implemented as educational experiments. Optical phenomena and spectroscopy are important components of modern physics necessary for every student interested in the physical sciences. Basic concepts such as the definition of temperature as a parameter in the energy-level distribution of the particles in a system (e.g., the Boltzmann distribution) are also important to be understood by students in a clear and pedagogically efficient way. Excitation of species in electrical discharge experiments and subsequent emission of radiation from excited atoms or molecules, can attract the students' focus due to the impressive visual effects involved.

In this paper we propose an experiment, easily implemented in a physics laboratory, which will combine, in a visually intriguing way, the familiarization of students with modern spectroscopic equipment, the understanding of the concepts of atomic and molecular spectra, the understanding of the concept of temperature and the experimental estimation of the vibrational temperature of excited molecules.

### 2. Experimental Setup

The experimental setup was assembled by using available laboratory components. It comprises a vacuum chamber, connected to a mechanical pump, and a spectrometer. Inside the vacuum chamber are placed two self composed electrodes for the electrical discharges. DC voltage from a power supply is applied to the electrodes.

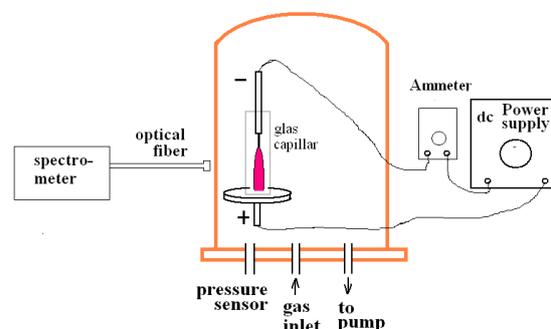


Fig. 1a: A schematic drawing of the experimental setup

The current was measured with a common digital ammeter. The light produced by the electrical discharge is measured with a compact CCD spectrom-

ter (HR2000, Ocean Optics), which is coupled with an optical fiber cable transmitting the plasma light from the target position.

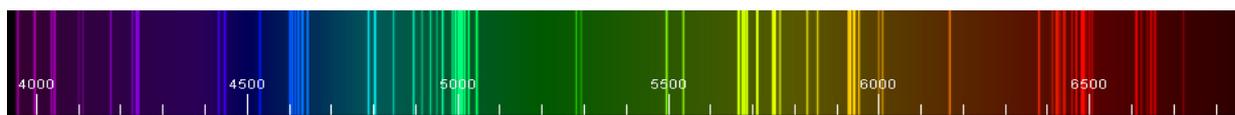


**Fig. 1b:** Photo of the experimental setup that shows the vacuum chamber, the pump, the power supply and the two spectrometers.

The pressure was measured with a simple pressure sensor (PS 2107, Pasco). Detailed measurements of spectra were also made for comparison with a laboratory table spectrometer (Andor, 303i-iDus420). The spectra were acquired and processed using appropriate software (SpectraSuite from Ocean Optics and Solis from Andor). Partial peak assignments were made using a demo versions of Plasus-SpecLine, while the graphic presentation were made using the Origin 8.0 software.

### 3. Nitrogen excitation and emission

A colour representation of the emission line spectrum of neutral and ionized Nitrogen excited in a electrical discharge is shown in figure 2a [3].



**Fig. 2a:** Spectrum of Nitrogen Gas Discharge: This is a colour representation of the emission line spectrum of neutral and ionized Nitrogen excited in a electrical discharge [3].

The emission spectrum generated from the electrical discharge and the subsequent relaxation of the excited Nitrogen molecules, was recorded using the HR2000, Ocean Optics spectrometer in figure 2b, where several lines of the nitrogen molecule and also ionic lines are easily visible.

#### *Estimation of the vibrational Temperature of N<sub>2</sub>*

The following procedure is used for the determination of the vibrational temperature  $T$ , using optical emission spectroscopy: The vibrational band emission intensity  $I_{ij}$  of the spectral band in the

$\Delta v = \text{constant}$  sequence for the electronic-vibrational  $i$ - $j$  transition is given [2] as:

$$I_{ij} = n_i h \nu_{ij} A_{ij} Y(\lambda) \quad (1)$$

- $n_i$  is the population of the  $i$  vibrational state
- $h$  is Planck's constant
- $\nu_{ij}$  is the  $i$ - $j$  transition frequency
- $Y(\lambda)$  is the apparatus (slit and spectral response) function
- $A_{ij}$  is the Einstein coefficient for spontaneous emission between vibrational states for the electronic-vibrational  $i$ - $j$  transition

If the populations of the vibrational levels are close to their equilibrium values, then because of the Boltzmann distribution law it is obtained, for a harmonic oscillator that is a good approximation for the vibrational levels with a low vibrational quantum number:

$$n_v = n_{\text{tot}} \exp\{-hcG(v)/kT\} \quad (2)$$

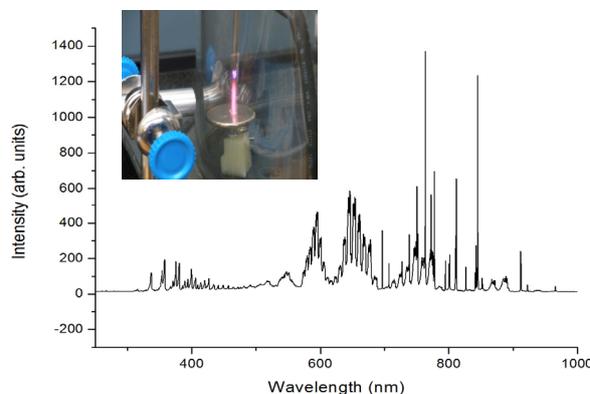
$$G(v) = hc\omega_e (v+1/2) \quad (3)$$

where

- $n_{\text{tot}}$  is the total species population
- $n_v$  is the population of the  $v$  vibrational state
- $c$  is the speed of light
- $\omega_e$  is the vibrational wavenumber of the molecular species studied
- $G(v)$  is the vibrational term value for the vibrational level  $v$
- $k$  Boltzmann's constant

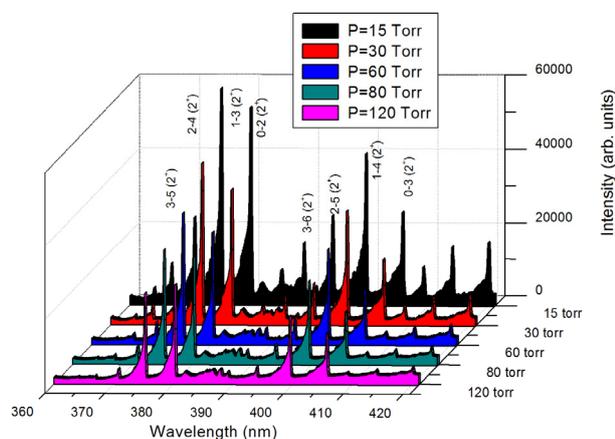
The above equations lead to the following expression for the treatment of the emission spectral data:

$$\ln(n_v/n_0) = hc\omega_e v/kT \quad (4)$$



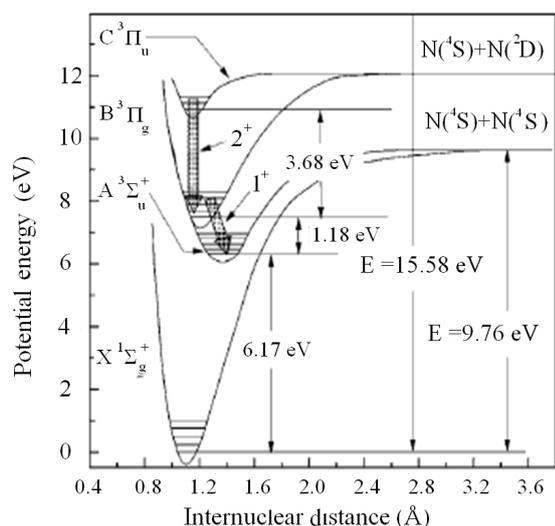
**Fig. 2b:** Emission spectrum of nitrogen N<sub>2</sub> (chamber pressure 15 torr), during an electrical discharge (dc voltage 3kV, 2.3 mA), observed with the HR2000, Ocean Optics spectrometer. Photo shows the discharge light between the two electrodes.

In order to estimate the vibrational temperature of excited nitrogen molecules, we focus our attention in this study to the second positive system of nitrogen in the region of 360 – 420 nm, which is recorded for 5 different chamber pressures (figure 3). The spectra were recorded using the Andor 303i-iDus420 for better spectral resolution.



**Fig. 3:** Emission spectra of the second positive system of nitrogen at various pressures, during an electrical discharge (dc voltage 3kV, 2.3 mA) observed with the Andor303i-iDus420spectrometer.

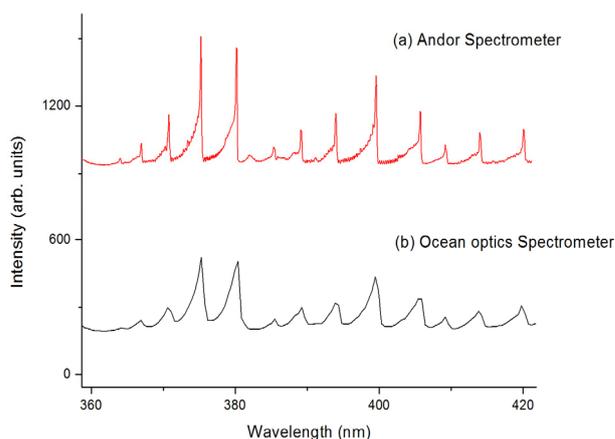
In Figure 4, the potential energy curves for  $N_2$  as modified from [1] are shown, where the relaxation path that lead to the emission lines of the second positive system ( $2^+$ ) recorded in figure 3 is schematically emphasized.



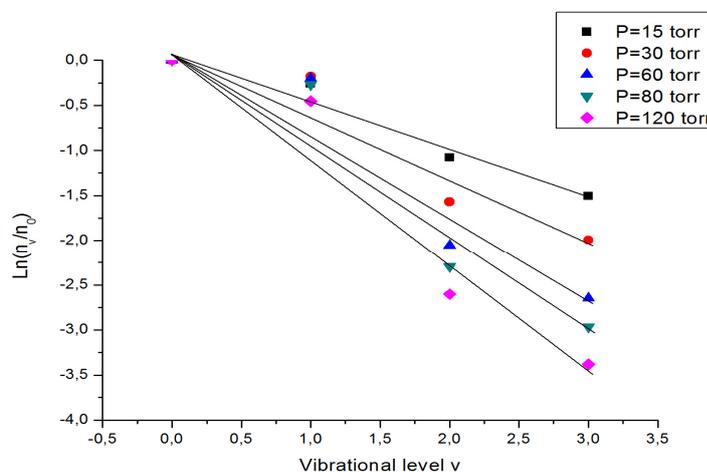
**Fig. 4:** Potential energy curves for nitrogen as modified from [1].

The Andor spectrometer is a research equipment, not easily accessible to a students laboratory. It is thus important to compare the spectra of figure 3 with those obtained from a lower resolution but easily accessible equipment, such as the Ocean optics

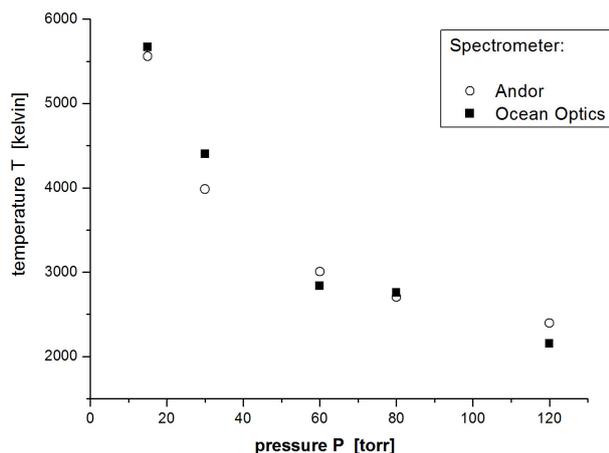
HR2000 spectrometer. Figure 5 shows the two spectra for a chamber pressure of 15 torr. It is clear that rotational details are not visible in the spectra recorded with the HR2000, but the spectrometer is sufficient for the examination of the vibrational levels. This is clearly proved in the next section, where the estimation of the vibrational temperature is proved to be similar for both spectrometers.



**Fig. 5:** Comparison of the emission spectrum of the second positive system of nitrogen (chamber pressure 15 torr) during an electrical discharge (dc voltage 3kV, 2.3 mA) observed with two spectrometers: (a) the AndorSR-303i -iDus, (b) the HR2000, Ocean Optics.



**Fig. 6:** Plot of the experimental values of  $\ln(n_v/n_0)$  as a function of the vibrational level  $v$  for 5 different chamber pressures. Spectra shown in figure 3 were used for the calculation of the populations  $n_v/n_0$ . Linear fitting of the data was used for the calculation of the slope and the estimation of the vibrational temperature from equation 4.



**Fig. 7:** Plot of the experimental vibrational temperature as determined from figure 6 vs chamber pressure.

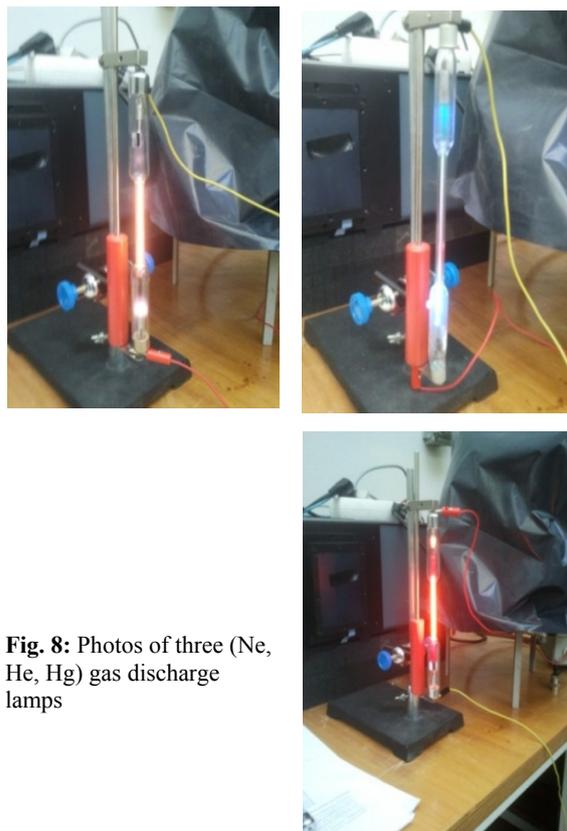
As expected from equation 4, the graphs are linear with respect to vibrational level  $v$ . Linear fitting of the data was used for the calculation of the slope  $S$  and the estimation of the vibrational temperature from equation 4. As was shown in figure 5, the vibrational band emission intensity is approximately the same if the spectra are obtained with the Ocean optics HR2000 spectrometer. This applies for all the five chamber pressures used in the figure 3. For comparison, all the calculations for the estimation of the slope  $S$  of the linear curves were repeated using data collected with the Ocean optics spectrometer. The vibrational temperatures for the 5 different chamber pressures were calculated from the slopes  $S$  using equation 4 that leads to:

$$T = hc\omega_e/kS \quad (5)$$

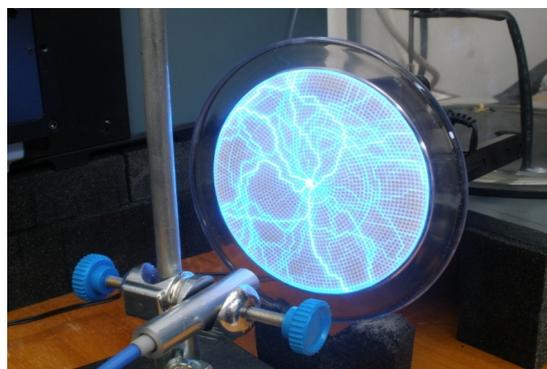
In Figure 7 the experimentally calculated vibrational temperatures are plotted as a function of the chamber pressure for both used spectrometers. It is clear that using the lower spectral resolution HR2000 spectrometer leads to insignificant differences in the estimation of the vibrational temperatures of the excited molecules, considering the simple model used for the calculations and the use of the experimental setup for educational purposes.

#### 4. Emission Spectra of other light sources

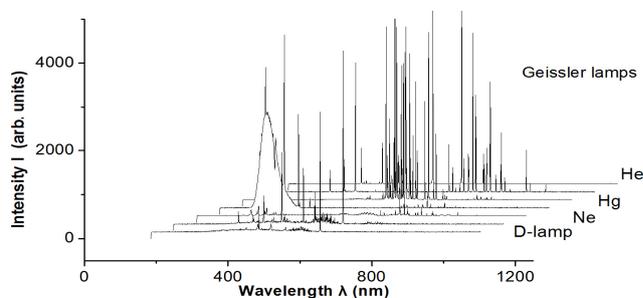
Several different light sources can be used with the proposed experimental setup, in order to intrigue the students to examine the physical mechanisms of radiation generation and the techniques of spectroscopic analysis. Several visually impressive devices are shown in figure 8 (gas discharge lamps) and 9 (magic disk lighting).



**Fig. 8:** Photos of three (Ne, He, Hg) gas discharge lamps

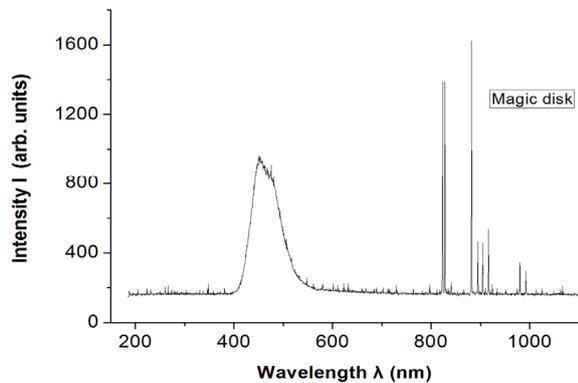


**Fig. 9:** Photo of the magic disk lighting



**Fig. 10:** Emission spectra of various gas discharge lamps (Geissler), during an electrical discharge (dc voltage 3kV, 0.5 mA) observed with the Ocean Optics spectrometer.

The spectra produced from these devices were spectroscopically analyzed using the HR2000 spectrometer. Figure 10 shows the spectra obtained from various gas discharge lamps (Geissler lamps). Figure 11 shows the spectrum obtained from the magic disk lighting shown in figure 9.



**Fig. 11:** The emission spectrum of the magic disk shown in Fig.9, observed with the Ocean Optics spectrometer.

## 5. Conclusions

This paper presents an experimental setup, easily assembled, presented as a basis for an interesting educational laboratory exercise that can facilitate understanding of light generation mechanisms on a fundamental level. In addition, students can be exposed to issues of vacuum technology, plasmas, electrical discharges, optical emission spectroscopy and data analysis techniques, which are important to most modern technological applications.

## 6. References

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