# 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. 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 electrodes for the electrical discharges. DC voltage from a power supply is applied to the electrodes. The current was measured with a common digital ammeter.

The light produced by the electrical discharge is measured with a compact CCD spectrometer (HR2000, Ocean Optics), which is coupled with an optical fiber cable transmitting the plasma light from the target position. 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. Graphic presentation were made using the Origin 8.0 software.

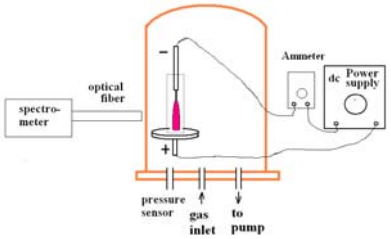


Fig. 1a: A schematic drawing of the experimental setup

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

## 2. Nitrogen excitation and emission

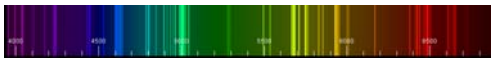

Fig. 2a: Spectrum of Nitrogen Gas Discharge: This is a colour representation of the emission line spectrum of neutral and ionized Nitrogen excited in a electrical discharge [3].

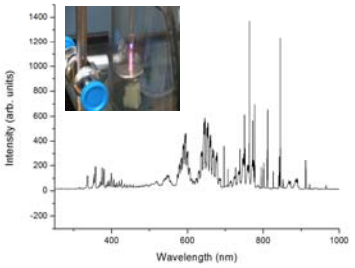


Fig. 2b: Emission spectrum of nitrogen $N_2$ (chamber pressure 15 torr), during an electrical discharge (dc voltage 3kV, 2.3 mA), observed with the HR2000, Ocean Optics spectrometer. Photo shows the discharge light between the two electrodes.

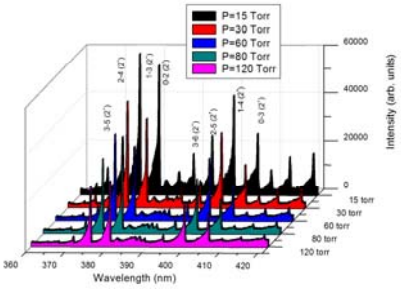


Fig. 3: Emission spectra of the second positive system of nitrogen at various pressures, during an electrical discharge (dc voltage 3kV, 2.3 mA) observed with the Andor'303i-iDus420spectrometer.

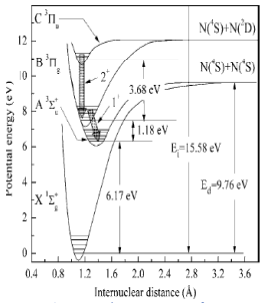


Fig. 4: Potential energy curves for nitrogen as modified from [1].

### Estimation of the vibrational Temperature of $N_2$

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

$I_{ij} = ni\ h\nu_{ij} A_{ij}\ Y(\lambda)$ (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:

$n_v = n_{tot}\ exp-[hc\omega(v)/kT]$ (2)
$G(v) = hc\omega_e (v+1/2)$ (3)
where
$n_{tot}$ 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:
$\ln(n_v/n_0) = hc\omega_e v/kT$ (4)

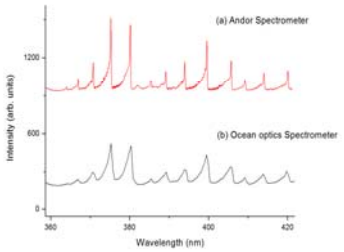


Fig. 5: Comparison of the emission spectrum of the second positive system of nitrogen (chamber pressure 15 torr) during an electrical discharge (dc voltage 3kV, 2.3 mA) observed with two spectrometers: (a) the AndorSR-303i -iDus, (b) the HR2000, Ocean Optics.

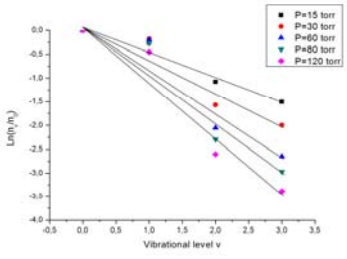


Fig. 6: Plot of the experimental values of $\ln(n_v/n_0)$ as a function of the vibrational level v for 5 chamber pressures. Spectra shown in figure 3 were used for the calculation of the populations $n_v/n_0$. Linear fitting of the data was used for the calculation of the slope and the estimation of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

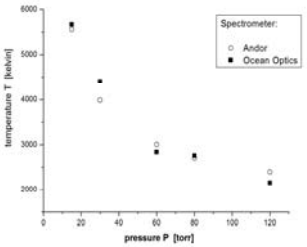


Fig. 7: Plot of the experimental vibrational temperature as determined from figure 6 vs chamber pressure. The calculations were repeated using spectra obtained with the HR2000 Ocean Optics spectrometer. As is shown the results are similar.

## 3. Emission spectra of other light sources

Fig. 8: Photos of three (Ne, He, Hg) gas discharge lamps corresponding to spectra on the Fig.3.

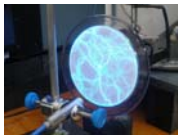

Fig. 9: Photo of the magic disk lighting

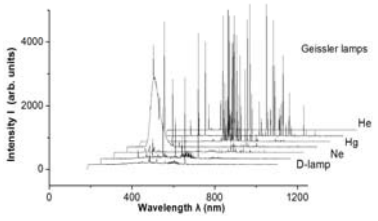


Fig. 10: Emission spectra of various gas discharge lamps (Geissler), during an electrical discharge (dc voltage 3kV, 0.5 mA) observed with the Ocean Optics spectrometer.

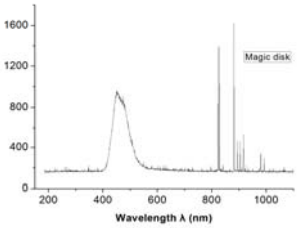


Fig. 11: The emission spectrum of the magic disk observed with the Ocean Optics spectrometer.

## 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.

## References

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