Electron Impact Ionization of N\textsubscript{2}

Introduction

Ionization of any atom or molecule by electron impact is a process of fundamental importance whether one is studying the stellar and planetary atmospheres, the interiors of fusion reactors, or electrical discharges through gases such as lightning, neon signs, and fluorescent lamps. Most mass spectrometers depend on electron impact to ionize the sample under analysis. Electrical discharges through gases are of such importance to industry that there is at least one annual conference devoted to the topic each year in North America (Gaseous Electronics Conference).

Electron impact ionization can be described in general by the reaction:

$$e + X \rightarrow X^+ + e^- + e^-$$

where X is any atom, molecule or cluster. The reaction will not take place unless the impacting electron's kinetic energy exceeds the binding energy of the electron to X. Once this minimum ionization energy (or threshold) is reached, the reaction occurs with increasing likelihood until a maximum is reached, and falls slowly afterwards. A plot of ion yield versus electron impact energy is known as an ionization efficiency curve, or the ionization cross section – see Figures 1 and 2.

In this demonstration, you will measure the threshold or minimum ionization potential for molecular nitrogen using two different methods.

![Figure 1: Compilation of absolute cross section data for electron impact ionization of N\textsubscript{2}.](image1)

![Figure 2: Close-up view of electron impact ionization yield near threshold.](image2)
Description

A commercial nitrogen gas filled type 884 triode is used - also known as a ‘thyatron’. Even though we live in the age of nano-scale solid state devices, large thyratrons remain the best means for switching large currents in excess of $10^5$ A, typically encountered in fusion experiments, or electrical discharge incinerators. The pressure inside the 884 triode is about 1 torr. Referring to the wiring diagram in Figure 3, the triode has four elements. A tungsten filament (a) for heating the tungsten cathode (b). The cathode serves as the source of electrons (see thermionic emission). There is a plate (d) to collect the electrons or ions, and a grid (c) between the plate and cathode. Be sure to carefully examine the tube and identify its parts. The real triode has cylindrical geometry, with the filament lying along the axis, inside a 2 mm diameter tube which is the cathode. The grid is a wire spiral, and the plate is a larger tube about 7 mm in diameter which surrounds the previous parts.

This arrangement for producing electrons is known as an ‘indirectly heated’ cathode. Electrons are also being emitted by the hot tungsten wire, and it too can be used as a source, known as a ‘directly heated’ cathode.

Procedure

Connect the circuit depicted in Figure 3. Before connecting the 0-20 V DC power supply, make sure it is current regulated to 250 mA maximum. Notice the grid and plate are connected together, making the triode a diode.

The plate current is measured as the voltage across the plate and cathode is increased, to a maximum of 20 V. The ammeter should be set to the 200 mA range. When the plate voltage $V_p$ is increased to the ionizing potential of the gas, the plate current increases sharply. The initial increase in plate current with $V_p$ prior to ionization is predicted by the Child-Langmuir Law, or the 3/2 power law. The law states that the plate current $I_p$ is proportional to the 3/2 power of the plate voltage, namely:

$$I_p \propto V_p^{3/2}$$  \hspace{1cm} (1)

for a space charge limited current between the cathode and the plate. If a plot of $I_p^{2/3}$ versus $Vp$ were made, a straight line would be obtained. One could plot this for the experiment to try and verify the
Alternatively by taking the logarithmic form of Eqn (1) one could try and determine if the power is really 3/2, to within error bars. Use both methods and comment on their relative accuracy. What do you observe to happen near the ionizing potential? Determine the ionizing potential for the gas from your observations. How does it compare to the accepted value of 15.58 eV?

**Figure 4.** Wiring diagram for the ion collection method of determining the minimum ionization potential.

Connect the circuit depicted in Figure 4. This method is more sensitive as we will now be collecting ions at the plate rather than a torrent of electron current. The plate is biased 3 V negative with respect to the cathode. The plate current is now measured as the grid voltage $V_g$ is increased up to 20 V. The plate will never receive any electrons because of its bias, regardless of the grid potential. Draw a diagram showing the potential and kinetic energy of electrons at various points between the cathode and the plate and explain the last feature.

As the grid potential $V_g$ is increased past the ionizing potential of the gas, the electrons have sufficient kinetic energy to ionize the molecules and hence cause a positive ion current at the plate. Set the ammeter on the 100 or 200 micro-amp range to measure $I_p$. A plot of $I_p$ versus $V_g$ should be made to determine the ionizing potential of the gas. The onset is not sharp, but can be determined by extrapolating the nearly linear part of the curve above 16 V to the abscissa. Discuss any discrepancies you find with the accepted ionization energy.

**Figure 5:** Photoelectron spectrum of N$_2$ for $h\nu = 21.218$ eV.

Figure 5 is an energy-resolved photoelectron spectrum showing the 3 lowest ionic states of N$_2^+$, $^2\Sigma_g^+$, $^2\Pi_u$, $^2\Sigma_u^+$. The two $\Sigma$ states have similar internuclear separations to that of the ground molecular state. Consequently, due to the Franck-Condon principle, most of the photoelectron yield is
in ground ($\nu = 0$) vibrational level – with a small amount in the first vibrational state ($\nu = 1$). In contrast, the $^3\Pi_u$ state, whose $\nu = 0$ energy is at 16.69 eV, has many vibrational levels excited.

Do you find any evidence of an increase in ion yield at the onset on these ionic states (see also Figure 2)? How might you best plot and process your data to search for such evidence?

Questions

What is the advantage of an indirectly heated cathode source?

1st Method - Is there a plate current $I_p$ for zero $V_p$? Explain. Why is there such an increase in $I_p$ at the ionization potential?

2nd Method - At zero $V_g$ there is a measurable plate current in the nanoamp range. Explain. Why is the onset broad? How may this set up be used as a vacuum gauge for measuring pressure? Using a sketch, show what region in the triode the collected ions originate from at various grid voltages.

Show the derivation for the Child-Langmuir Law for parallel planes. What are the assumptions of the Child-Langmuir Law? Do they apply in this case?

References

Field F.H. and Franklin J.L. *Electron Impact Phenomena*
Melissinos A.C. *Experiments in Modern Physics*
Spangenberg K.R. *Vacuum Tubes*

Apparatus

RCA 884 Thyratron
Thyratron base with 6.3 V AC filament supply Voltmeter
Ammeter
Microammeter (Keithley Model 480)
0-20 V DC Power supply
Two 1.5 V dry cells