

Chapter 6

Low-energy electron radical interactions - a new experiment

6.1 Introduction

A new experiment to investigate low energy electron radical interactions is introduced here. Radicals are highly reactive neutral species that are generated in plasmas and can have a great effect on the chemistry of the plasma. The interactions of radicals and neutral molecules are of interest for the modelling of industrial plasmas¹.

In this chapter the development of and preliminary results obtained with this new apparatus are described.

6.2 Apparatus design

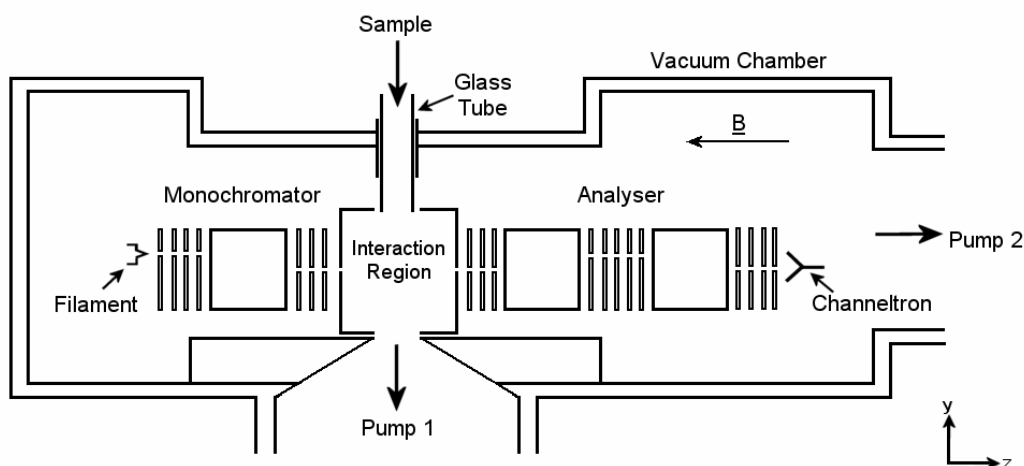


Figure 6.2.1 Schematic diagram of experimental vacuum chamber and proposed apparatus as viewed from the side.

The original design for this experiment is shown in figures 6.2.1 and 6.2.2. The apparatus was designed to allow for the generation of creation of radicals close to the interaction region. A differential pumping scheme was included in the design as it was anticipated that relatively high pressures would be required in the interaction region for the production of radicals. A trochoidal electron monochromator, TEM,

and electron analyser, based on a design by Allan,² were chosen to energy select and analyse a beam of low energy electrons. An extraction plate in the interaction region was included to pulse ions formed into a time-of-flight mass spectrometer, TOFMS, mounted perpendicular to the electron beam, figure 6.2.2.

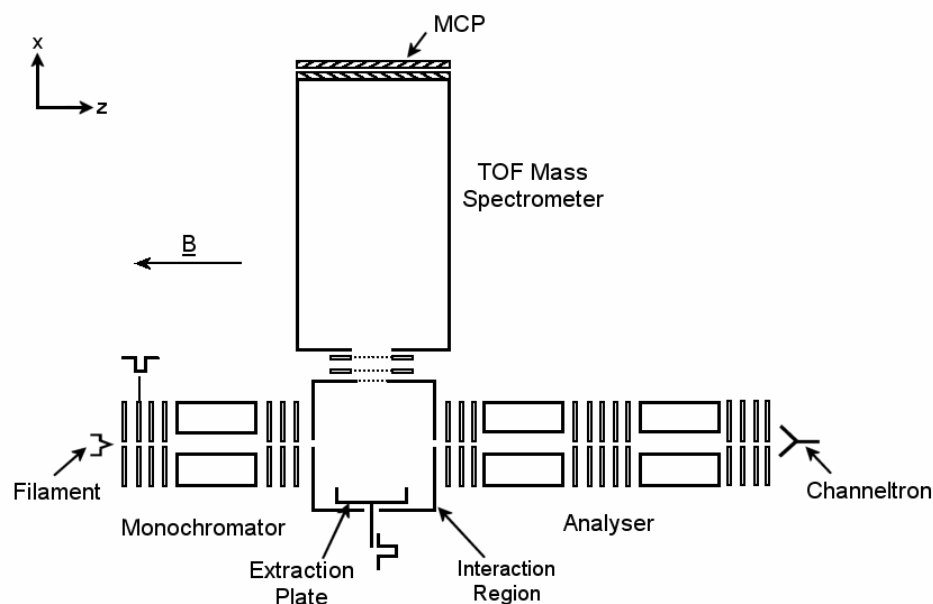


Figure 6.2.2 Schematic diagram of proposed experimental apparatus as viewed from above. Apparatus includes a trochoidal electron monochromator, electron analyser and time-of-flight mass spectrometer.

6.3 Theory and development

6.3.1 Electron energy selection and magnetic guidance

The trochoidal electron monochromator works on the principle of the deflection of charged particles in crossed electric and magnetic fields. A magnetic field is generated in by the experiment using a pair of Helmholtz coils mounted outside and around the experimental chamber. This magnetic field also serves to guide the electrons through the apparatus as the electrons are confined to helical motion about the magnetic field lines.

6.3.1.1 Magnetic field

The Helmholtz coils are positioned so that the z-axis of the trochoidal monochromator and electron analyser are aligned along the magnetic field direction. The coils are mounted on a support that allows the magnetic field direction to be rotated about the centre of the interaction region. Two rotations are possible about the x- and y-axes. Figure 6.3.1 shows the magnetic field strength along the z-axis of the chamber for a coil current of 500 mA, where the zero position corresponds to the centre of the interaction region and the coils are set at 10 cm from the centre.

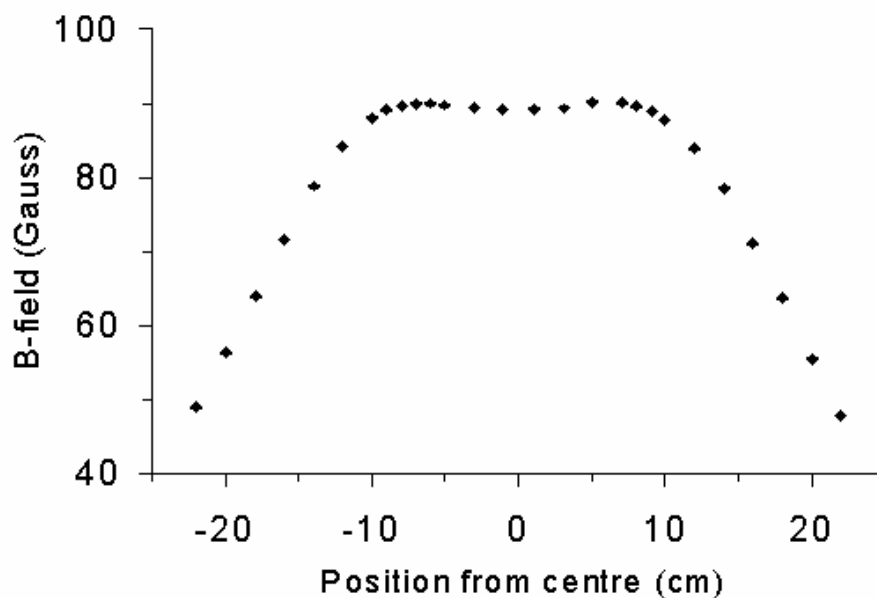


Figure 6.3.1 Graph of magnetic field against position away from the centre of the apparatus. Here the two helmholtz coils are positioned at 10 cm either side of the central position. A current of 500 mA is passed through the coils.

The magnetic field is adequately uniform over the central region of the apparatus for the operation of the monochromators. A magnetic field of up to ~100 Gauss can be applied; typically ~80 Gauss is used.

6.3.1.2 Trochoidal electron monochromator

The trochoidal electron monochromator,^{3,4} TEM, was originally developed by Stamatovic and Schulz⁴ to velocity filter a low energy beam of electrons using perpendicularly electric and magnetic fields. This technique was found to give an electron beam resolution of 0.02 eV,⁴ which improved on earlier energy selection techniques.

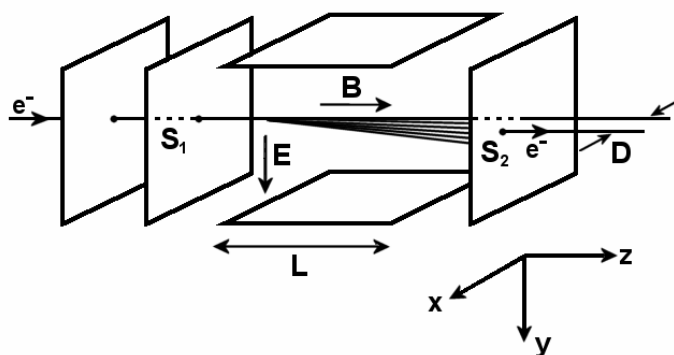


Figure 6.3.2 Schematic diagram of a trochoidal electron monochromator (redrawn from reference 4).

The dispersion region of a typical TEM, is shown in figure 6.3.2. A magnetic field is applied along the path of the incoming electron beam and an electric field is applied perpendicular to the beam by a pair of plates. In figure 6.3.2 the magnetic field is applied along the z -axis and the electric field is applied along the y -axis. The equation of motion for a charged particle within electric and magnetic fields is given by the Lorentz force, equation (6.1).

$$\frac{d\mathbf{v}}{dt} = \frac{q}{m} (\mathbf{E} + \mathbf{v} \times \mathbf{B}) \quad (6.1)$$

In this equation \mathbf{v} is the velocity of the charged particle, with mass m and charge q , and \mathbf{E} and \mathbf{B} are the electric and magnetic fields. The fields cause the particles to undergo ‘trochoidal motion’ in the x - y plane with an average drift

velocity, \mathbf{v}_d , in the x-direction. The drift velocity in the x direction is dependent on the strength of the applied fields, equation (6.2).

$$\mathbf{v}_d = \frac{\mathbf{E} \times \mathbf{B}}{B^2} = \frac{E_y}{B_z} \hat{e}_x \quad (6.2)$$

The z-component of the particles velocity is unchanged by the passage through the monochromator. Where a charged particle enters the crossed fields with a velocity of v_z in the z-direction the displacement in the x-direction, D , is proportional to the time, t , spent within the fields and therefore the length, L of the field region, (6.3).

$$D = v_d t = \frac{v_d L}{v_z} = \frac{E_y L}{B_z v_z} \quad (6.3)$$

The displacement is dependent on the initial velocity component of the charged particle in the z-direction. A slow particle is displaced more by the effects of the fields than a faster particle. Thus the electric and magnetic fields can be modified to allow only particles of a certain velocity to pass through the off-axis exit slit. Equation (6.3) can be re-written in terms of the particles kinetic energy, w in the z direction giving equation (6.4), which leads to the energy spread of the beam given in equation (6.5).

$$D = v_d L \left(\frac{m}{2w} \right)^{1/2} \quad (6.4)$$

$$\frac{\Delta w}{w} = \frac{2\Delta D}{D} \quad (6.5)$$

In this equation, ΔD is equal to the sum of the diameters of the entrance and exit slits, S_1 and S_2 , the monochromator. The full width at the base of the energy distribution of the charged particles can be determined as equation (6.6) below.

$$\Delta w = \frac{E^2 L^2 m \Delta D}{B^2 D^3} + qES_1 \quad (6.6)$$

In this equation the first term is determined from equation (6.5) and the second term is due to a potential drop across the entrance and exit slits of the monochromator, giving the particles slightly different energy depending on their position on entering the field. This equation should represent the width at the base of the energy distribution, which is generally expected to be twice that of the full width half maximum, FWHM. Stamatovic and Schulz,⁴ however, found this to be between 2.5 and 3.5 times greater than the FWHM in their monochromator.

Extra plates are included before and after the trochoidal dispersion section to focus the electron beam. Here one plate is used as a gate to pulse the electron beam as indicated in figure 6.2.2. The electron analyser works in a similar manner to the TEM, but has two crossed field regions.

6.3.2 Ion detection

6.3.2.1 Time-of-flight mass spectrometer

A Wiley-McLaren type two-field time-of-flight mass spectrometer is used in this apparatus. The spectrometer consists of two acceleration regions followed by a field free drift region. Figure 6.3.3 shows a schematic diagram of the mass spectrometer, the interaction region serves as the first acceleration region followed by a shorter second region and finally the drift region. The spectrometer is designed for second order space focusing.⁵ Each region is separated by high transmission molybdenum mesh grids, which define the boundaries of the electric fields and allow maximum transmission of ions.

The times-of-flight of ions are measured from the application of the extraction pulse to the extraction plate to their detection at a set of multi-channel

plates, MCP, mounted at the end of the drift region. The voltages on the mass spectrometer are reversible so both positive and negative ion mass spectra can be recorded.

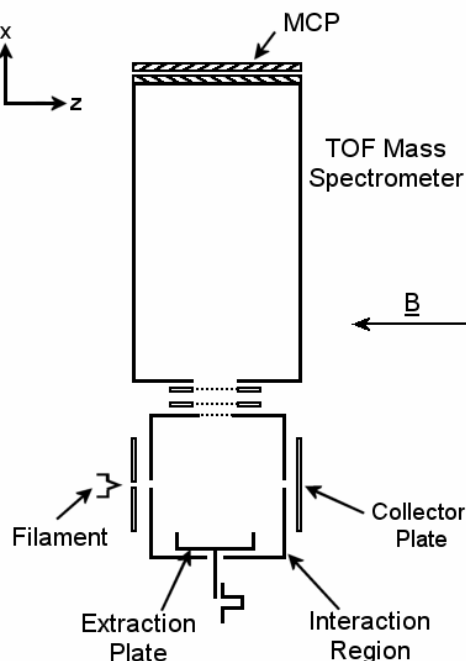


Figure 6.3.3 Apparatus used for testing of TOFMS. Simple electron gun with collector plate, ions are extracted/pushed into tofms by plate.

6.3.2.2 Preliminary tests of TOFMS

The initial tests of this spectrometer were carried out with a simplified apparatus, shown in figure 6.3.3. Here the electrons were supplied by a basic pulsed electron gun, this comprised of a filament mounted behind a plate with an aperture of ~ 1 mm. The voltage applied to the electron beam was pulsed to ‘switch off’ the beam when the ion extraction pulse was applied. A collector plate was mounted on the opposite side of the interaction region to monitor the current of electron passing through the interaction region.

Time-of-flight spectra were recorded for the electron ionisation of the background gas in the chamber and converted to a mass scale. The data were collected by an online computer with a time-to-digital converter, TDC, card. Figure

6.3.4 shows a mass spectrum of background gas in the chamber and an enlarged section is shown in figure 6.3.5. The constituents of air were observed in the spectrum and there is also evidence of long chain hydrocarbon fragments, most likely from the diffusion pumps oil. The mass resolution of the spectrometer was measured to be ~ 200 .

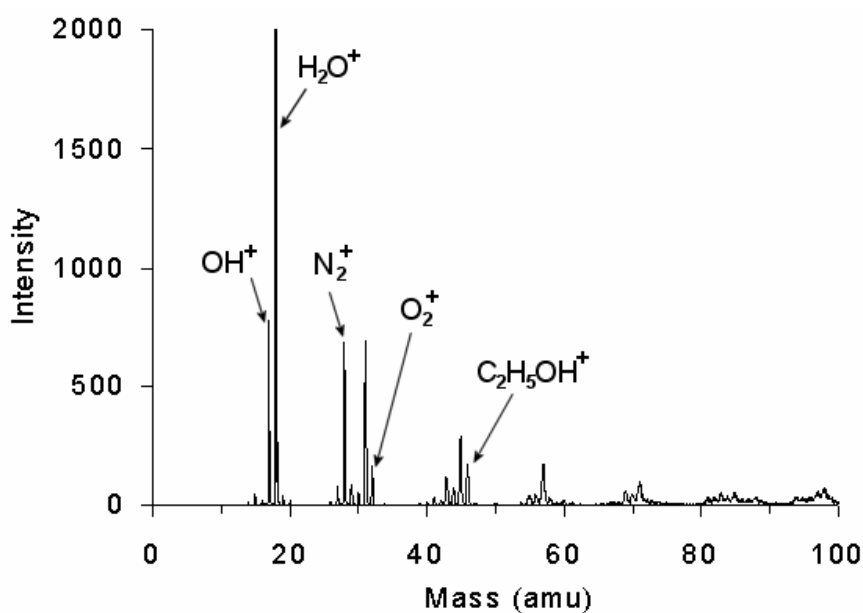


Figure 6.3.4 Mass spectrum for chamber background gas, using above configuration.

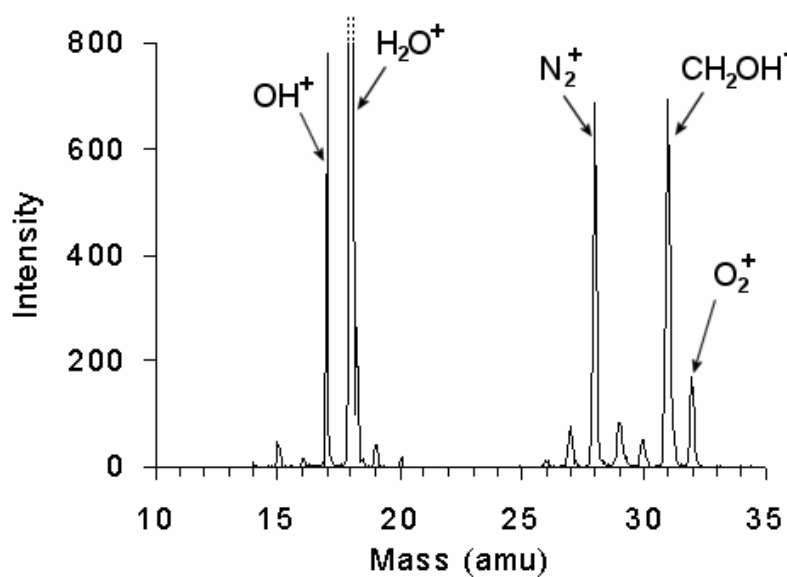


Figure 6.3.5 Mass spectrum for chamber background gas, using above configuration.

6.3.3 Radical production

Radicals are to be produced with a microwave discharge in a glass tube, which enters the chamber and delivers the gas sample directly to the interaction region. Radicals have not yet been investigated.

6.4 Preliminary tests for electron-molecule interactions

At the time of writing the apparatus is being tested with the standard molecules SF₆ and CCl₄. The experimental configuration for these test is shown in figure 6.4.1. The trochoidal monochromator provides the electron beam and ions are detected with the TOFMS. A collector plate is used to monitor the current of electrons passing through the interaction region. The pulsing of the electron gun and the extraction plate were set up so that the electron beam is ‘off’ when the ion extraction pulse is applied. This is done so that there are no electrons in the interaction region when the ion extraction pulse is applied. Most recently the collector plate has been replaced by a series of lenses and a Faraday cup to collect the electrons.

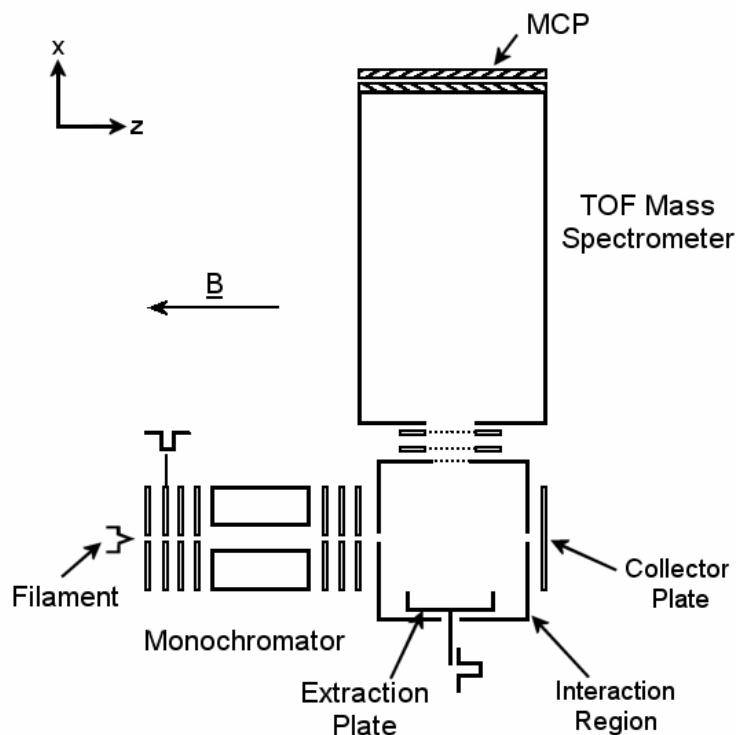


Figure 6.4.1 Experimental apparatus used for preliminary tests.

Figure 6.4.2 shows the mass spectrum of SF_6 and CCl_4 . The negative ion peaks of Cl^- , SF_5^- and SF_6^- are observed in the spectrum. The mass resolution is lower in this spectrum as compared with the spectrum in section 6.3.2.2 because the extraction voltages are lower. Figure 6.4.3 shows the counts of Cl^- as the monochromator float voltage is varied. The variation of the voltage changes the energy of electrons entering the interaction region. The installation of the Faraday cup for this measurement removed the noise due to scattered electrons, but the resolution is still poor.

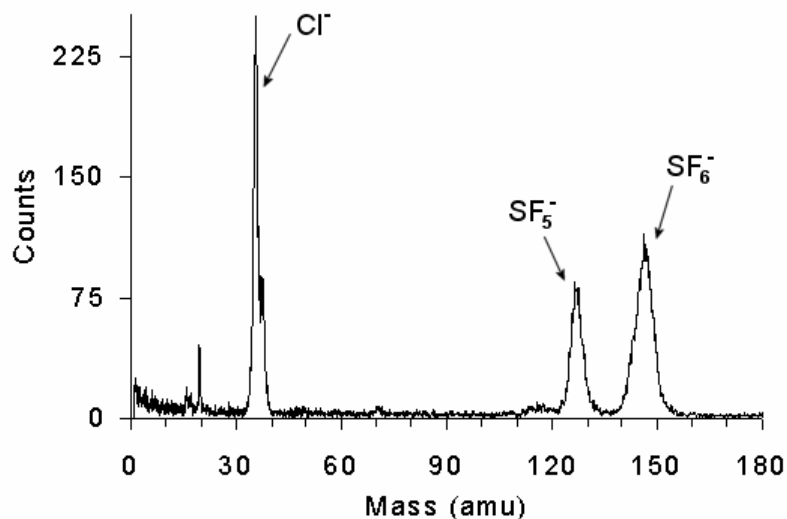


Figure 6.4.2 Electron attachment mass spectrum for SF₆ and CCl₄.

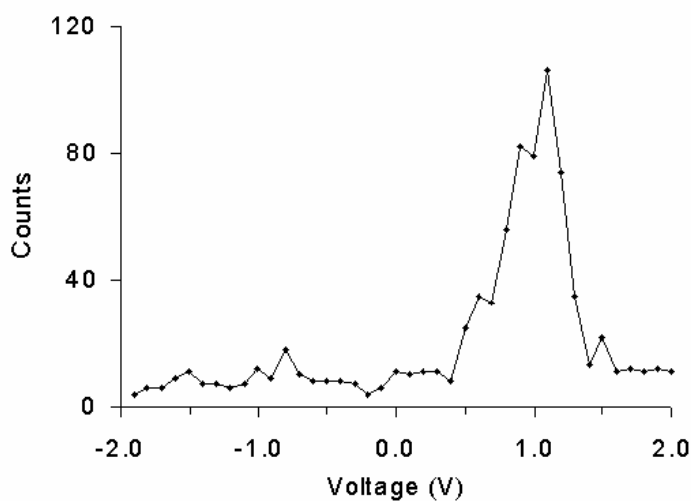


Figure 6.4.3 Scan for the collection of Cl⁻ for the dissociative electron attachment of CCl₄.

6.5 Conclusions and future development

There was not enough time for the investigation radicals. The preliminary tests, however, are encouraging and show that the measurement of electron-radical interactions should be possible using this technique.

6.6 References

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- ³ Grill V., Drexel H., Sailer W., Lezius M., Märk T.D., *Int. J. Mass Spectrom.* **205** (2001) 209
- ⁴ Stamatovic A., Schulz G.J., *Rev. Sci. Instrum.* **41** (1970) 423
- ⁵ Eland J.H.D., *Meas. Sci. Technol.* **4** (1993) 1522