# The Franck-Hertz Experiment and the Ramsauer-Townsend Effect: Elastic and Inelastic Scattering of Electrons by Atoms

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These experiments measure two phenomena encountered in collisions between electrons and atoms: quantized excitation due to inelastic scattering, and ionization. The experiments also provide an opportunity to explore the thermionic emission of electrons and space charge limited current in a vacuum tube.

## I. PREPARATORY QUESTIONS

Please visit the Franck-Hertz chapter on the 8.13x website at mitx.mit.edu to review the background material for this experiment. Answer all questions found in the chapter. Work out the solutions in your laboratory notebook; submit your answers on the web site.

## II. INTRODUCTION

Franck and Hertz described the first observation of quantized excitation in 1914, one year after Bohr published his theory of the hydrogen atom with its concept of quantized energy states. They discovered that electrons moving through mercury vapor with an energy greater than or equal to a critical value near 4.9 eV can excite the 2536 Å line of the mercury spectrum. Electrons with less than the critical energy bounce elastically when they collide with mercury atoms and fail to excite any electromagnetic emission. The experiment provided crucial evidence in favor of the Bohr theory.

A version of the Franck-Hertz experiment, employing a mercury-filled vacuum tube with four electrodes made by the Leybold Company, is described in References [2, 3] to which the reader is referred for a discussion of the physical principles and the measurement objectives of the Franck-Hertz experiment.

Experiments on the related Ramsauer-Townsend effect are described in Section VII.

## III. APPARATUS

The present Junior Lab version of the experiment uses a different version of the equipment which consists of a mercury-filled triode and an oven with glass windows through which one can view the action. A power supply and control circuit built in the Junior Lab shop provides adjustable filament voltage for heating the cathode, adjustable accelerating grid voltage, and an adjustable retarding voltage. The same triode tube and power supply are used in the measurement of the ionization potential.

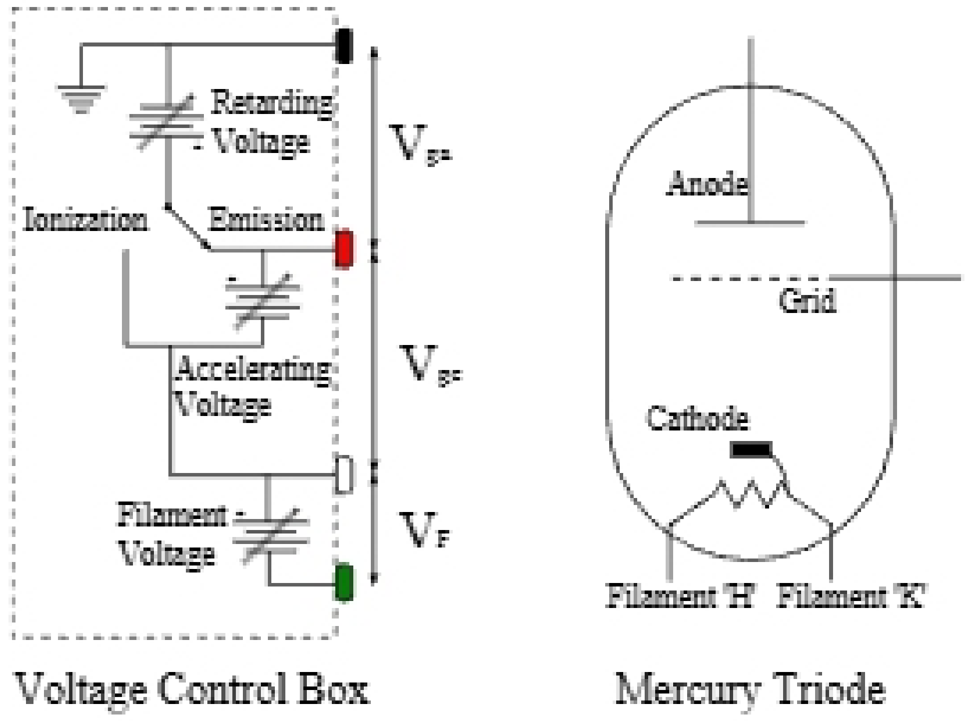


FIG. 1. Schematic illustrations of the mercury-filled triode and the voltage control box.

### III.1. Mercury Filled Triode

The experiments on the excitation and ionization of mercury atoms are carried out with a mercury-filled triode which is a sealed glass envelope containing three electrodes and a drop of mercury.[1] The experiments will be performed with the three configurations of the tube and associated circuits illustrated in Figure 1 and, in more detail, Figures 3, 4, and 7. The three electrodes are:

- a cathode which emits electrons when raised to a temperature of several hundred degrees by application of a voltage $V_F$ to a heater filament,
- a perforated grid which is set at a positive potential $V_{gc}$ relative to the cathode so that electrons emitted by the cathode are drawn toward it,
- an anode (counter electrode plate) which is connected to an ultra-sensitive Keithley electrometer for the measurement of the anode current $I_a$.

[1] Mercury is an ideal element for a study of excitation phenomena because its vapor is monatomic and its vapor pressure can be readily controlled over the range useful for this experiment by adjusting the temperature in the range from room temperature to 200°C.

In the Junior Lab apparatus, the distance from the cathode to the perforated grid is 8mm while the distance between the grid and the anode is small (of order 1mm).

All of the measurements in these experiments can be made with total tube currents (*i.e.* cathode current = anode + grid current) of 1000 nA or less. To prolong the useful life of the tube care should be taken not to exceed 1000 nA.

### III.2. Voltage Control Box

The voltage control box, built by Junior Lab staff, is used to supply the desired voltages to the mercury-filled triode. The control box functions as three variable voltage supplies, shown in Figure 1:

- the filament voltage $V_F$, which controls the temperature of the cathode
- the accelerating voltage $V_{gc}$, between the grid and the cathode
- the retarding voltage $V_{ga}$, between the grid and the anode.

The values for the voltage supplies can be measured using the "Isolated D.C. Voltmeter" outputs. These outputs are designed for use with a voltmeter that does not have any connection to the wall or ground, *i.e.* a multimeter. See Section III.4 for how to connect any of the circuit outputs to an oscilloscope.

It is wise to start each session by disassembling whatever wired-up circuit the previous users may have left. The only way to know for sure how a circuit is connected is to wire it yourself.

The control box has four circuit outputs which are color coded:

- Black is the common ground. It should be connected to the banana jack with the ground symbol near the anode connection on the oven chassis. This will establish a common ground.
- Red is connected to different points for different measurements during the experiment.
- White goes to the 'K' side of the filament, which determines the potential at the cathode. In our boxes, this is the banana jack on the right side.
- Green goes to the 'H' side of the filament, which determines the electrical power going through the filament (which has a fairly low resistance).

### III.3. Electrometer

An ultra-sensitive Keithley Model 614 electrometer is used to measure the current from anode to laboratory ground. (**Be sure to check the zero set.**) It is essential that the input cable be kept stationary during measurements. Flexing or moving even high quality cable may generate currents due to the triboelectric effect. Make current measurements as follows:

1. Turn the Model 614 on and allow one hour warm up.
2. Depress ZERO CHECK.
3. Select Volts function and the 0.2 V range. Adjust the voltage zero potentiometer with a small screwdriver to obtain a displayed reading of 0.00000. Adjustment on this range assures a proper zero on all other functions and ranges.
4. Select Current function, then appropriate units and range.
5. Apply input (be sure to use the BNC-Triaxial adapter!) and release ZERO CHECK.
6. Take measurement.

The electrometer has an analog output (2 V full scale of display) in the back of its chassis which may be connected by a coaxial cable with grounded sheath to an oscilloscope or other voltmeter. The analog output can add noise to the signal which can be decreased using a low pass filter.

### III.4. Oscilloscope Setup

In this experiment you may wish to use an oscilloscope to measure a voltage difference where neither of the measurement points are at the ground potential (most notably, the accelerating voltage). This *cannot* be done using a banana-to-BNC connector from the voltage control box isolated voltmeter output, because the oscilloscope will make a connection between the negative output and ground. As neither of the outputs are supposed to be at the ground potential, this will have adverse effects on the circuit.

Instead, a floating voltage measurement may be set up using two oscilloscope probes:

1. Check that the oscilloscope probes are 10× probes or that the probes are set to 10×. This is needed to increase the impedance of the probe-oscilloscope-ground connection and prevent the measurement from affecting the control box outputs.
2. On the oscilloscope, go to the Channel 1 menu and change the probe setting to 10× or 10:1. Do the same for Channel 2. This tells the oscilloscope you are using 10× probes.
3. Connect the probes to the voltage difference on the control box as shown in Figure 2. The probes can be connected to the actual circuit outputs or the isolated voltmeter outputs.

4. Use the math function built into the oscilloscope to subtract channel 1 from channel 2.

The math function displayed is the voltage difference. When saving data from the oscilloscope, the math function will not be saved. Make sure both channel 1 and 2 are saved so the math function can be reconstructed during analysis.

### III.5. Oven

Several sections of this experiment require the mercury filled triode be heated above room temperature to increase the mercury vapor pressure. A ceramic heating element is situated below the triode and is used to heat the apparatus. Plug the oven electrical cord into the variable AC source (variac) and the variac into the wall outlet. The variac can then be used to set the oven temperature. **WARNING:** The heater should never receive more the 75 volts AC.

### III.6. Grounding

The electrometer and oscilloscope make connections between the negative input from the BNC cable and the ground of the electrical outlet. To prevent ground loops from affecting the experiment, **the voltage control box, electrometer, and oscilloscope must all share the same ground.** This is done by plugging all three boxes into the same wall circuit. The electrical outlets in lab are labeled with numbers indicating which circuit each outlet is on.

## IV. THERMIONIC EMISSION OF ELECTRONS AND SPACE CHARGE LIMITED CURRENT

Consider first the situation in the tube connected as shown in Figure 3. At room temperature the vapor pressure of the mercury is so low that the mean free path of electrons emitted by the cathode is large compared to the dimensions of the tube (~8 mm). When the cathode is heated by the filament, it emits electrons in a process called thermionic emission. In thermionic emission, electrons near the top of the Fermi distribution in the metal penetrate the potential barrier at the surface and escape. The kinetic energies of the emitted electrons roughly follow a Maxwell-Boltzmann distribution with a mean energy $E_0$ near $kT$, where $T$ is the cathode temperature. In the steady state, with the grid at a positive potential relative to the cathode, the emitted electrons form a cloud of negative charge over the surface of the cathode. This cloud changes the local electric field, suppressing electron emission by forcing lower energy electrons back to the cathode. This condition is known as space charge limited current. The physics of thermionic emission and space charge limited current is discussed in [2] for a tube with ideal cylindrical geometry. Our tube, designed for other purposes, has a different geometry that does not lend itself to a "clean" experiment in thermionic emission. Nevertheless the qualitative characteristics of space-charge limited current can be observed with it.

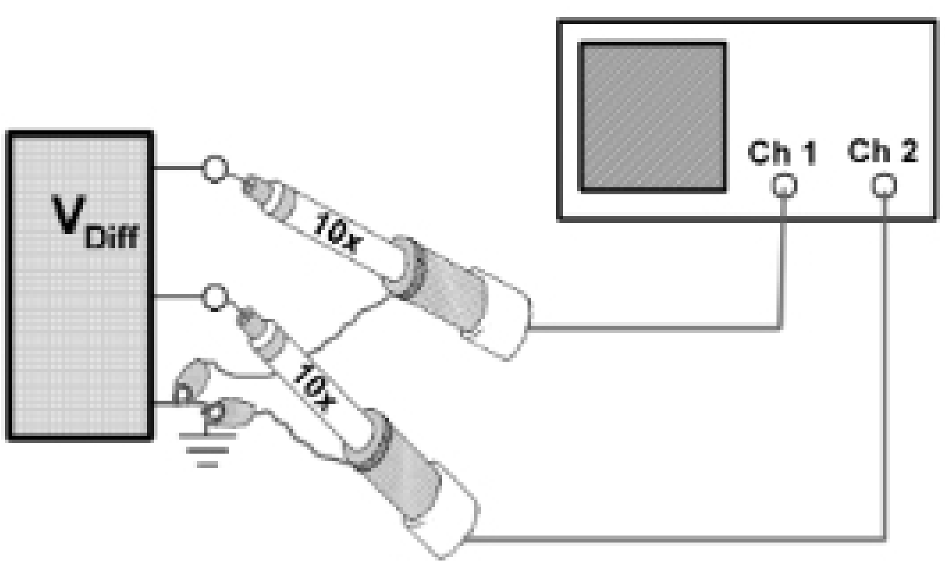


FIG. 2. The setup necessary to measure a floating voltage from the voltage control box with an oscilloscope.

The first part of the experiment is an exploration of the dependence of the total tube current on two quantities: (1) the filament voltage which controls the temperature of the cathode and thus the emitted current density and (2) the accelerating potential between the electron emitting cathode and the grid. You will find a filament voltage which will be used throughout the rest of the experiment. The measurements are made at room temperature ($20-25°$C).

### IV.1. Procedure for Exploring Thermionic Emission

1. Connect the tube as shown in Figure 3. Set the toggle switch to 'emission'. Set the filament voltage $V_F$ and the retarding voltage $V_{ga}$ to their lowest values (~ 1.2 V and 0 V, respectively).

2. In order to measure the TOTAL tube current, the grid and anode currents should be summed at the electrometer input with coaxial cables and a BNC 'T' connector. Use a two-prong banana plug-to-BNC adapter at the grid terminal on the triode tube, taking care as to which side of the banana plug adapter is connected to the grid's banana jack.

3. Set the accelerating voltage $V_{gc}$ to its highest voltage, about 60V. The retarding voltage control should still be at $V_{ga} = 0$. Increase $V_F$ in small steps until the total current is between 100 and 1000 nA. Tabulate and plot the total current (grid + anode) $I_{ag}$ versus $V_F$ as you proceed.

4. Set $V_F$ at a value for which $I_{ag}$ is in the range 100 – 1000 nA when $V_{gc} \approx 60$ V. Allow several minutes for the current to stabilize to ensure the current will