The Franck-Hertz Experiment

The Franck-Hertz experiment, first undertaken shortly after Bohr's theory of the atom was presented, provided one of the early indications that atoms had discrete energy levels. In this experiment, electrons are accelerated and pass through mercury vapor, where they lose energy by inelastic scattering in quantized steps as they excite mercury atoms from the ground state to an excited state. This elegant experiment yielded remarkable results that were key in the early developments of quantum theory.

Introduction

In the Franck-Hertz experiment, an electron beam is produced by thermionic emission from a filament. The electrons are accelerated, pass through the vapor, and are then retarded (decelerated) by a few volts before collection at the anode. This all takes place in a tube contained within an oven that controls the tube's temperature and thus the mercury vapor density. The setup is illustrated schematically in Figure 1, and pictorially in Figure 2.

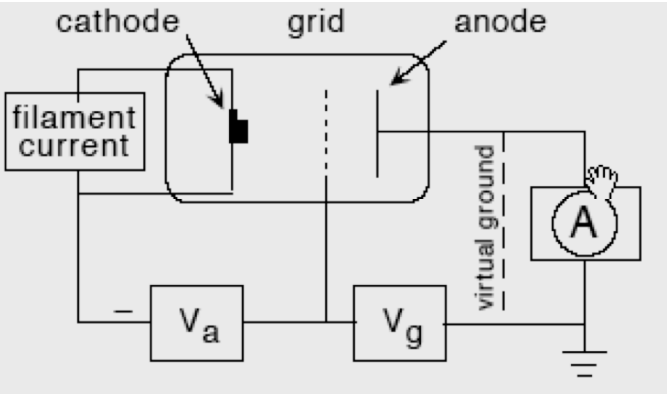

Figure 1. The Franck–Hertz tube and electrical connections. The cathode is a filament heated by the current provided from a 6.3 V supply. The voltage V_a accelerates the electrons toward the grid. A voltage, V_g slows the electrons as they travel between the grid and the anode. The current of electrons reaching the anode is measured by the picoammeter/electrometer.

Consider first what happens as the filament is heated, thus raising the average energy of conduction electrons in the metal. As the temperature increases, a greater fraction of the electrons have kinetic energy exceeding the work function of the cathode material (platinum), W_{Pt}. Some of these even reach the anode and a small current (*e.g.*, nanoamps) flows. When the accelerating voltage V_a is increased from zero, filament electrons are accelerated toward the grid and a much greater current reaches the anode. If $V_g = 0$, some of the emitted electrons reach the anode and the electron current is registered. The path of current in this circuit passes through the two power supplies, the filament, the mercury vapor in the tube, and through the ammeter. Not all the electrons make it to the anode: the "beam" really isn't a beam, and the trajectories spread out over a large range of angles. The planar geometry does improve the situation. As the accelerating voltage increases, the anode current increases because the electron trajectories are more focused, and the electrons are deflected less by scattering from the atoms of vapor in the tube. The anode current is observed to rise faster than linearly with V_a.

We now take into account electron collisions with the mercury atoms in the vapor. Elastic scattering is one channel that results in deflection of the electrons from their original trajectory. In an elastic scattering, the atom "recoils" in its ground state like a hard sphere, so the electron loses

very little energy. Inelastic scattering is also possible. In this process, kinetic energy is lost to excitation or ionization of mercury atoms. The excitation energy is $E_{ex} \approx 5$ eV, so when $(eV_a - W_{Pt}) < E_{ex}$, no such excitation is possible. For electron kinetic energy greater than E_{ex}, it is, in principle, possible for the inelastic process to occur and decrease the electron kinetic energy by about E_{ex} for each mercury atom an electron excites.

The scattering process is best represented by a cross section σ — the effective area of a mercury atom presented to the electrons as they move through a vapor. Imagine looking through the vapor with total thickness t and a number density n atoms/cm^3 from the perspective of an electron with some initial trajectory. The vapor may look partly transparent with an areal density of nt atom/cm^2 in the electron's path. The total fraction of that area taken up by mercury atoms from which the electron can scatter is σnt, a measure of the probability the electron will scatter while propagating through the vapor. In the questions, we ask you to estimate σ geometrically and find $t_{1/2}$, the thickness of vapor that would scatter electrons with 50% probability. The cross section is an effective area and depends on the nature of the interaction, initial energy, final energy and direction, and other quantum mechanical features of the process. The elastic and inelastic cross sections are generally quite different: the inelastic excitation cross section can be a resonant process with a relatively large cross section.

As an electron passes through the vapor, it gains energy in the accelerating field produced by V_a. At the point where the electron's energy exceeds E_{ex}, inelastic scattering becomes possible, and the electron scatters with a short scattering length and loses almost all of its kinetic energy so that the process begins again. Thus multiple inelastic scatterings are possible as an electron moves from cathode to grid.

The final energy of electrons that reach the grid is the initial energy, eV_a, minus energy lost in scatterings. A small retarding voltage between the grid and anode deflects electrons with energy less than $eV_g + W_{Cu}$, where W_{Cu} is the work function of the anode. This energy is a few eV. Electrons with greater energy reach the anode and the electron current is registered by the ammeter. For electrons that lose total energy ΔE by scattering, the requirement for detection (reaching the anode) is $\Delta E < e\left(V_a - V_g - \Delta W\right)$, where ΔW, the "contact potential", is the difference of work functions of the cathode and anode. The anode current is therefore a measure of the integral number of electrons that satisfy this inequality. These raw data must be analyzed to determine the electron energy loss spectrum and extract E_{ex}.

Reading

Scattering and cross section are covered in Marion's Classical Mechanics text.
The Franck-Hertz experiment is described in detail in Melissinos I, pp. 8-17.

The Apparatus

The Franck-Hertz tube is contained within an oven, which is a metal box with a thermostatically controlled heater and terminals for connections to the tube. A thermometer can be inserted through a hole in the top of the oven.

The tube has a parallel system of electrodes in order to produce a fairly uniform electric field. The distance between the filament/cathode and the perforated grid is much larger than the mean free path of electrons through the mercury vapor under normal operating conditions. A platinum ribbon with a small barium-oxide spot serves as a direct heated cathode. An electrode connected with the cathode limits the current and suppresses secondary and reflected electrons, making the electric field more uniform. In order to avoid current leakage along the hot glass wall of the tube, a protective ceramic ring is fused in the glass as a feed-through to the counter electrode. The tube is evacuated and coated inside with a "getter" which absorbs traces of air that leaked in during the manufacturing process and over the lifetime of the tube.

Power supplies are provided for the accelerating and grid voltages, and a separate supply is provided for the filament current. The anode current should be read with either a Keithley model 610 Electrometer or a picoammeter. Other voltages should be monitored with DVMs.

Before making any connections, be sure you understand the circuit. To aid in understanding, trace the closed circuit that electrons take from the cathodes through the power supplies and electrometer and back to the cathode. (Also see the first question.)

Take care in making the connections that the signal cable is grounded correctly. The "virtual ground" represents the effective electrical potential of the ammeter in the circuit. The ammeter has a low impedance, and all the anode current flows through it.

You'll discover that the apparatus seems very sensitive to your presence! This is because the small currents detected represent very small amounts of charge flowing, amounts of charge that can be significantly affected by stray capacitance including your own, which is about 100 pf.

Getting Started

We use a Franck-Hertz tube and control unit pictured in the figure below. First take data varying the voltage manually with the toggle switch set to "Man", and don't hook up the oscilloscope.

You should begin by familiarizing yourself with the apparatus, its operation, and the nature of electron emission from the filament. As you hook up wires, make sure you understand the circuit through which currents flow by tracing the path of electrons from the filament through the

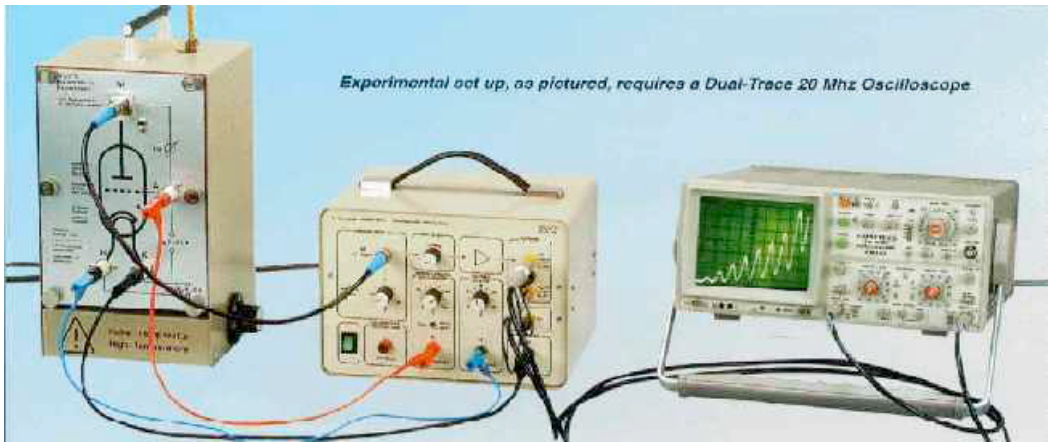

Figure 2 – Experimental setup with oscilloscope.

wires, ammeter, *etc*. Do not apply voltages with the tube cold, because mercury may have condensed on the electrodes and could short out and damage parts of the tube. Start by hooking up the filament current supply and the accelerating voltage. Connect the ammeter to the anode/collector, and use a jumper wire to short out the grid-anode gap (*i.e.*, $V_g = 0$). It's useful to set the ammeter so that it can measure positive or negative current; for example, set the meter to read "center zero." Start with $V_a = 0$, and turn up the filament current until you see a dim orange glow in the tube. Observe the anode current as you vary the filament current. What's happening?

With the filament current set to produce a visible orange glow—not a bright blue-white glow—begin to increase V_a to about 40–60 V. Note (record) the current collected on the anode as a function of accelerating voltage. You can do this as a function of the filament current. Be careful that the tube does not go into continuous discharge mode, characterized by the bright blue-white glow. It if does, lower the accelerating voltage 10 V or more so that it stops.

The vapor pressure of mercury is a strong function of temperature; it is given by the Clausius-Clapeyron equation and tabulated in the CRC handbook. The temperature of the cabinet should be adjusted to 180ºC ± 5ºC. It takes about 20 minutes to reach equilibrium after the temperature setting is changed. Set the sensitivity of the measuring amplifier at 10^{-9} A, the retarding potential at 1.5 V and raise the acceleration potential to 50 volts. Now, slowly increase the current in the cathode until the ammeter reads 10^{-9} A. Run the accelerating voltage down to about 15 V and then bring it back up slowly, checking that the ammeter does not go off scale. If it does, lower the filament and repeat. The filament will respond very slowly to any changes, so allow at least 30 seconds for it to stabilize before making new measurements.

At this stage, the apparatus is ready for taking measurements. Experience shows that it's best to start at the highest accelerating voltage and take measurements with decreasing V_a voltages. Increase (or decrease) V_a very slowly. It may be helpful to change the ammeter scale for lower voltage readings.

Things to measure

The measurements are straightforward: anode current vs. accelerating voltage. You will find that the apparatus is quite sensitive to your own capacitance. If you move near the set up, the current changes, sometimes wildly. You will need to learn where to stand or sit so that this effect is minimized.

Once you have taken the data, a plot of current *vs.* voltage will reveal both the rise of anode current with voltage and the dips corresponding to the inelastic scattering resonances. You will need to determine the positions of the resonances. This is a challenging analysis problem since what you have are dips on a changing background. You should try to fit the data to a reasonable model—for example, the exponentially rising emission with the observed number of (negative) gaussian dips with width and centroid as free parameters. What free parameters characterize the rising exponential?
The contact potential is the difference between the work functions of the cathode and anote, since they are oppositely directed in the electric field, that is, the electric field has to work against the cathode potential but is helped in the case of the anode. Thus we should expect that the voltage to the first peak will be greater than the average peak to peak voltage, due to the contact potential. The contact potential can be calculated as the average peak to peak voltage subtracted from the first peak voltage.

If a neon tube is available, repeat for neon.

Questions

1. Students often have trouble understanding the electrons' path through the circuit that includes the tube, and expect charge to build up at various places. Charge build-up in fact does occur, but not much. To make this clear, estimate the capacitance of the tube and the magnitude of charge build-up. Compare this to the amount of current that flows around the closed circuit during a measurement.

2. The mean free path of electrons propagating in a gas is given by

$$\lambda^{-1} = \sigma n$$

where σ is the total cross section summed for all processes, elastic and inelastic, and n is the number density of the mercury. The number density can be found using the tables for mercury vapor pressure in the CRC handbook. Assume that the elastic scattering cross section is the area of a disk with the radius of a mercury atom. Find the mean free path and $t_{1/2}$ for the vapor at 180ºC. Compare this to the size of the Franck-Hertz tube, and explain what is different in the case of elastic scattering.

3. Why is the retarding voltage needed to observe the Franck-Hertz effect?

4. Should you use the positions of the peaks or of the valleys to determine the excitation en-

ergy? Or both? Explain.

5. Why are the peaks and valleys smeared out rather than sharp?

6. How would increasing the temperature affect your observations? Would there be a higher or lower background current? Sharper or less sharp peaks? More peaks?

7. How would molecular contaminants in the tube affect your results?

8. Look up the spectrum for mercury to see if there is a spectral line(or lines) whose wavelength(energy) corresponds to the energy differences you measured for mercury.