FH - Franck-Hertz Experiment

Do this first — turn on the oven!

The mains power switch on the Franck-Hertz tube oven unit must be switched on as soon as you come into the lab to allow the oven sufficient time to reach its operating temperature. **Use an oven Temperature dial setting of 7**.

- **The Franck-Hertz tube power supply must not be switched on until the tube is hot and the demonstrator has checked the circuit.**

Introductory Theory

In 1914, the German physicists James Franck and Gustav Hertz (a nephew of Heinrich Hertz, who discovered electromagnetic waves) produced experimental evidence for the existence of quantized energy levels in atoms by studying the collisions of electrons with atoms in a gaseous vapour. This confirmed the results that had previously been obtained by looking at the discrete spectral lines that are emitted by a gas when it is excited thermally. They received a Nobel prize for their experiment in 1925.

An experimental arrangement similar to that used by Franck and Hertz is shown in the figure:

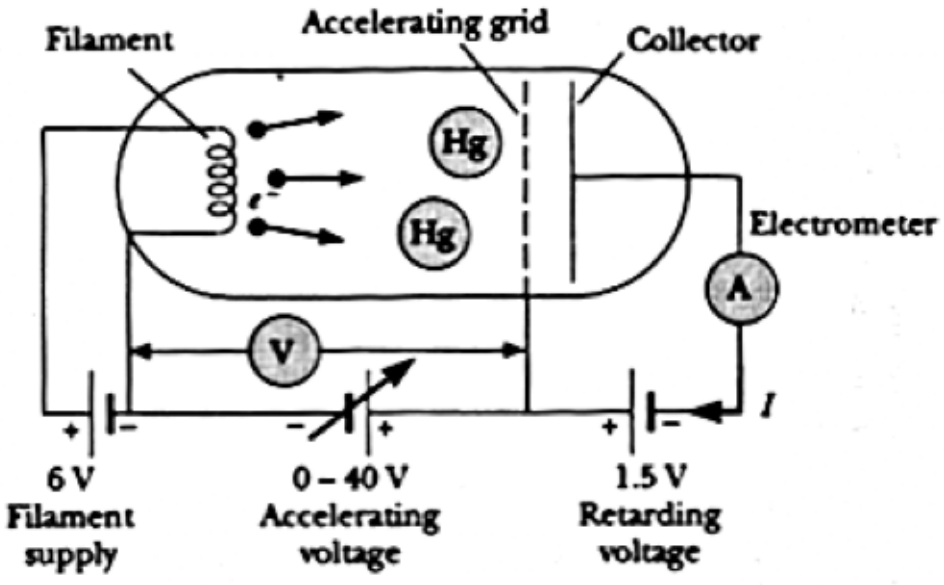

Figure 1: Schematic of apparatus similar to that used by Franck and Hertz.

Electrons are emitted from a hot filament (cathode), and then accelerated by the positive potential on the accelerating grid (0-40V). Most of the electrons pass through the grid, consisting of wire mesh, and then feel the effects of a decelerating voltage (typically 1.5 V) between the grid and the collector plate. If the electrons have an energy greater than 1.5 eV after passing through the grid

they will have enough energy to reach the collector and be registered as current in an extremely sensitive ammeter (electrometer). A voltmeter measures the accelerating voltageV. The experiment consists of measuring the current I in the ammeter as a function of V .

The accelerating electrons pass through a region containing mercury (Hg) vapour (a monatomic gas). At low accelerating voltages (below about 5V), the electrons do not have enough energy to excite the atom from its ground state to its first excited state. So perfectly elastic collisions occur between the electrons and the Hg atoms in which the sum of the kinetic energies of the electron and atom are conserved. Because the Hg atom is vastly more massive than the electron, the electron transfers almost no kinetic energy to the electron in a collision, and so "bounces off" with little energy loss. Even after multiple collisions, the electron reaches the grid with a kinetic energy of e times the accelerating voltage V, and will reach the collector if the accelerating voltage is greater than 1.5V. When V is modestly increased, more electrons reach the collector and the current I in the ammeter increases (see figure 2).

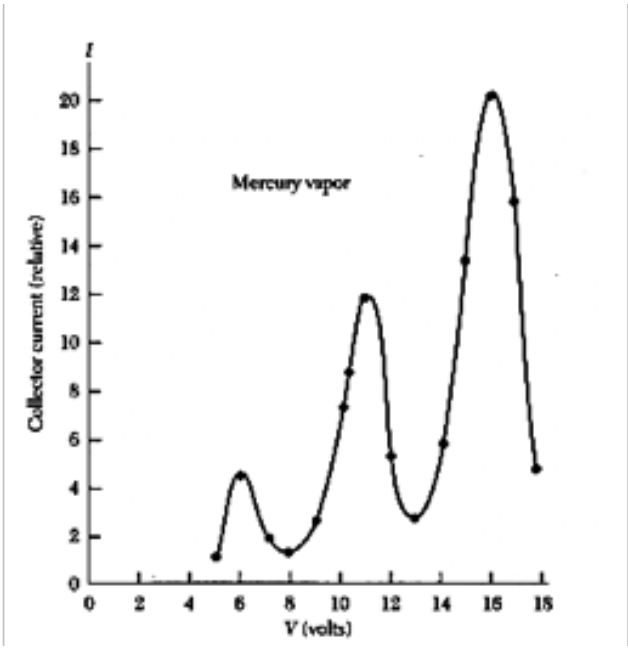

Figure 2: Collector current vs accelerating voltage

However, as the accelerating voltage is increased above about 5V, there is a sudden drop in the current (see the figure). As the accelerating voltage continues to increase above 5V, the current increases again, but suddenly drops again above 10V. Franck and Hertz first interpreted this behaviour of the current with voltage as the onset of ionization of the Hg atom; that is, an atomic electron is given enough energy to remove it from the Hg atom, leaving the atom ionized. They later realized that the Hg atom was actually being excited to its first excited state. The difference between the energy of the ground state and the first excited state in a Hg atom is 4.88 eV. As long as the kinetic energy of the accelerating electron is below 4.88 eV, no energy can be transferred to a Hg atom in a collision because not enough energy is available to excite it from its ground state to its first excited state, and perfectly elastic collisions occur in which the electron loses essentially no energy. If the electron gains at least 4.88 eV of kinetic energy from the accelerating potential, it can transfer 4.88 eV to an electron in a Hg atom, promoting it to the first excited state. This is an inelastic collision. An electron that has lost energy in an inelastic collision then has too little energy (after it passes the grid) to reach the collector and the current drops.

The first current drop occurs when the grid voltage is increased to a point where the electrons reach the first excitation energy of Hg at the grid; these electrons can lose all their energy in an inelastic

collision with a Hg atom and so are unable to “climb" the 1.5V potential hill to reach the collector. When the accelerating voltage is increased further, the inelastic collision region moves progressively closer to the filament, and the electrons that are stopped in an inelastic collision are re-accelerated in the region between the collision and the grid, thus reaching the collector and causing another rise in the current. Another dip in the current occurs when V has been increased sufficiently for an electron to undergo two inelastic collisions: an electron excites a Hg atom half way between the filament and the grid, and then is accelerated sufficiently to excite a second Hg atom at the grid, again losing its energy and being unable to climb the hill and reach the collector. Further excitations take place with increasing grid voltage, giving rise to a series of equally spaced maxima and minima in the I-V curve.

The first peak does not actually occur at 4.88 eV but at a higher energy because of the difference in the work functions (the amount of energy to liberate an electron from a metal) ϕ_K and ϕ_A for the different metals used as cathode and anode. The filament is required to be a good electron emitter and so has a low work function. The collector has a high work function. The accelerating potential experienced by the electron is actually V + (ϕ_A - ϕ_K). There are other highly excited states in Hg that could also be excited in an inelastic collision, but the probability of exciting them is much smaller than that for the first excited state, and so they are more difficult to observe.

The Franck-Hertz experiment convincingly proved the quantization of atomic electron energy levels. The bombarding electron's kinetic energy can change only by certain discrete amounts determined by the atomic energy levels of the mercury atom. Franck and Hertz even carefully observed radiation emitted from the Hg vapour region. They found no radiation was emitted when the electron's kinetic energy was below about 5 V, but as soon as the current dropped, indicating excitation of Hg, an emission line of wavelength 253.7 nm (ultraviolet) was observed. Because glass does not transmit ultraviolet radiation, they had to construct a quartz apparatus.

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Oh wait... we’ve already said this. I guess it bears repeating.

Overview of experiment

In this experiment we will reproduce the Franck-Hertz experiment using a sensitive apparatus which contains mercury vapour as in the original experiment. The electrons collide elastically with the mercury atoms in the vapour unless they have exactly the right energy to excite the valence (outermost) electron in the mercury atom from the 6 1s0 orbital (its lowest energy state) to the 6 3p1 orbital.

- **Exercise**: when the excited valence electron returns to its ground state, a photon corresponding to ultraviolet radiation with a wavelength of 253.7 nm is emitted. Determine the excitation energy of the electron (show your working).

  A four electrode evacuated tube is employed, having an indirectly heated cathode. A small amount of liquid mercury is present in the bottom of the tube, and by heating the whole tube, a mercury

vapour consisting of single mercury atoms can be produced. The vapour pressure is temperature dependent. A pressure of about 15mm of Hg is required, and the entire tube must be maintained at a temperature of about 180 ˚C to achieve this. If the vapour pressure is too low, there will be too few mercury atoms for the electrons to scatter from and the Franck-Hertz effect will not be observable; also, excitations of the mercury atoms to higher energy levels can occur because an electron may not collide with a mercury atom at the point in the tube at which it has the right energy to cause the transition from the 6 1s0 orbital to the 6 3p1 orbital. If the vapour pressure is too high, the mean free path of the electrons is reduced by too much to give an observable plate current, and the thermal agitation of the mercury atoms due to the high temperature necessary to produce the vapour pressure would also be troublesome.

Equipment

- “Franck-Hertz tube oven” — holds the vacuum tube containing the mercury and an oven to heat the vacuum tube and vaporize the mercury
- “Franck-Hertz tube power supply” — provides voltages for the vacuum tube bias, the heating element, cathode and anode. The anode voltage is adjustable.
- “Electrometer” D.C. Current unit — the third bread-box size apparatus holds control and monitoring equipment.
- DC voltmeter to monitor over temperature
- DC voltmeter to measure anode to cathode voltage difference

◆ **The tube must not be taken out of the oven at any stage.**

The following voltages are supplied by the power unit:

1. 6.3 volts dc applied between the terminals marked 6.3 V.D.C. and CATHODE in order to heat the cathode to cause thermionic emission of electrons.
2. 0 - 4 volts variable dc between the terminals BIAS and CATHODE, varied using the BIAS knob. This bias voltage is applied to a grid around the cathode - this in NOT the accelerating grid, but another grid close to the cathode which is used to maximize the number of electrons emitted by the cathode.
3. 0 - 28 volts variable dc between accelerating grid (the terminal ANODE in this apparatus) and CATHODE. There are three settings for the potential applied between the accelerating grid and the cathode: HIGH, LOW and SWEEP. In SWEEP mode, the voltage is automatically increased at a slow rate. In the HIGH and LOW modes, the voltage can be controlled using the knob marked H.V. It is necessary to start on the LOW mode and then switch to the HIGH mode to achieve the full range of voltages.
4. There is a retarding potential of 1 volt between the collector and accelerating grid.

The power supply also incorporates a 33,000 ohm resistor in series with the cathode to limit the current in the event of a gas discharge occurring. This will occur if the potential difference between the cathode and anode is sufficiently high to strip the valence electron from the mercury atoms (ionization).

Experiment

Connect the circuits as shown in the diagram provided with the apparatus and have a demonstrator check your ciruit.

Monitor the temperature of the tube using the copper-constantan thermocouple output. The thermocouple produces a voltage that is proportional to the temperature in the oven. On the card on the lab bench is a tabulation of the voltage against temperature. At room temperature the thermocouple

outputs about 6.5 mV. At operating temperature it outputs about 7.3 mV.

Switch on the electrometer (sensitive ammeter), set it to the least sensitive range and adjust the zero. Note: when first turned on, the needle on the electrometer will flick fully to the right. After a few seconds, it should return to zero. If not, switch off the electrometer and ask the demonstrator for help.

Before switching on the power unit (and thus the cathode heater), the controls should be set with the bias voltage knob at its mid position and the high voltage off. This means that there is no potential difference between the cathode and the accelerating grid (anode).

- **Warning**:
  The potential difference between anode and cathode should not be allowed to exceed 28 volts. If this does occur, ionization by collision may easily set in. This is evidenced by a sharp increase in the collector current and if this is noticed the anode potential should be reduced to zero immediately.

Set the electrometer to its least sensitive setting and then set the accelerating grid voltage to SWEEP mode. Watch the collector current shown by the electrometer as the accelerating grid voltage sweeps up from zero to 28V (the electrometer setting should be adjusted according to the current). Observe the peaks and dips in the collector current.

Measure the collector current as a function of the accelerating grid (ANODE) voltage. Do this by varying the ANODE voltage from 0 to 28V in 1 volt steps in manual (i.e. low and high) mode and noting the collector current at each step. From a graph of the data, go back and make more sensitive measurements to determine the exact position of each of the peaks.

Questions

1. Determine the excitation energy of the mercury atoms by measuring the spacing between successive peaks in the current. Give an average value with an associated error.
   - Note: the accepted value of the excitation energy in the Franck-Hertz experiment is 4.89 eV. However, the value measured in a particular apparatus depends crucially on the vapour pressure of the mercury, which is temperature dependent, and the distance between the accelerating grid and the collector. Hanne (G.F. Hanne, What really happens in the Franck-Hertz experiment with mercury? , American Journal of Physics 56 (1988) 696-700) reports that the excitation energy for a vapour pressure times accelerating grid to collector distance of 4 mbar cm is 5.15 eV, for 20 mbar cm it is 4.9 eV, and for 100 mbar cm it is 4.8 eV.
2. Explain why the collector current becomes small if the tube is overheated.
3. A certain minimum energy called the work function is required to extract an electron from a metal. The work function of the anode is higher than that of the cathode, resulting in a contact potential difference between the anode and cathode. Its effect is to shift the entire current versus voltage curve (but not the difference between successive peaks). Estimate the contact potential difference.
4. If time permits, investigate the effect of lowering the temperature of the oven. Allow at least fifteen minutes for the oven to come to thermal equilibrium once the oven temperature is changed.