Experiment 241: The Franck-Hertz Experiment

Aim

To study the inelastic scattering of electrons off atoms and thereby show that this occurs at discrete energies corresponding to quantum states of the atom.

References

1. J. Franck & G. Hertz: "Verh. Heutsch." Phys. Ges. 16, p457, (1914).
2. A. Melissinos: "Experiments in Modern Physics", Academic Press.
3. R.M. Eisberg: "Fundamentals of Modern Physics", Wiley.
4. T.B. Brown (Editor): "The Taylor Manual", Addison-Wesley.

References 2 and 4 are available in the laboratory.

Introduction

In 1914, when quantum theory was still in its infancy, James Franck and Gustav Hertz helped to validate Niels Bohr's model of the atom. The results of their famous Franck-Hertz experiment strongly supported the quantised nature of the atom where electrons may only occupy discrete bound energy states in orbit about the nucleus, as opposed to the previous solar system-like presumption of the atom.

The experiment originally involved accelerating electrons through mercury (Hg) gas. Collisions would occur between the electrons and the Hg atoms that were either elastic or inelastic. Kinetic energy is only transferred during inelastic collisions, and what the experiment indicated was that electrons were only capable of transferring a particular exact energy to the atoms in inelastic collisions implying that the excited electrons accordingly only enter into a set quantised energy level, or orbital, as the Bohr model predicted.

Today, we are performing the same experiment with argon (Ar) gas in favour of Hg as no oven is required to heat the mercury vapour.

The Franck-Hertz Tube

Our Franck-Hertz apparatus is made by Brolight Technology and consists of the argon gas-filled tube in question housed in a black container box equipped with a viewing window and a circuit diagram with connector-points corresponding to the four electrodes located inside the tube.

The first electrode at the base of the tube is the oxide-coated cathode (K) which acts as a thermal electron emitter. At the top of the tube is the plate electrode, the anode (A), that serves as the electron collector and whose current I_A you will measure. In between them lies the two accelerating grids G1 and G2. G1 sits just above the cathode and is charged positively (about $V_{\mathrm{G1K}} = 1.5$ V difference) in order to attract the free electrons up from the cathode. The potential difference V_{G2K} between K and G2 ultimately provides the total kinetic energy acquired by the electrons before they pass the grid G2.

Power supplies should be connected to the appropriate electrodes. Make sure which voltages are connected across which leads before you set anything. The voltage V_{G2K} in particular is provided by a single power box with both voltage terminals connected together in series mode, giving you the full 64 V sufficient for this experiment. Do not greatly exceed the rated voltages marked on the tube enclosure! Ask a demonstrator if you are unsure about the set-up.

The current amplifier should be connected via BNC to the anode. You are able to zero the reading by pushing in the SIGNAL button in and adjusting the dial before pushing the button out again.

Note: When you are not making measurements during the experiment, please turn the knob for the ACCELERATING VOLTAGE V_{G2K} fully anticlockwise.

Turn the cathode filament voltage to 2.7 V and the first grid voltage to 1.5 V. **Allow the argon tube to warm up for 15 minutes before beginning to take any measurements.** The filament is now emitting electrons, although they are not visible.

Looking at the circuit diagram, you will notice that the polarity of the anode voltage is reversed with respect to the other electrodes. This is the "reverse bias" voltage V_{G2A} that serves to differentiate electrons undergoing elastic from inelastic collisions by strongly rejecting the latter, as we shall see. The recommended setting is $V_{\mathrm{G2A}} = 10$ V. Combining the accelerating and retarding voltages together in the tube results in the electron potential energy distribution shown in Fig. 1.

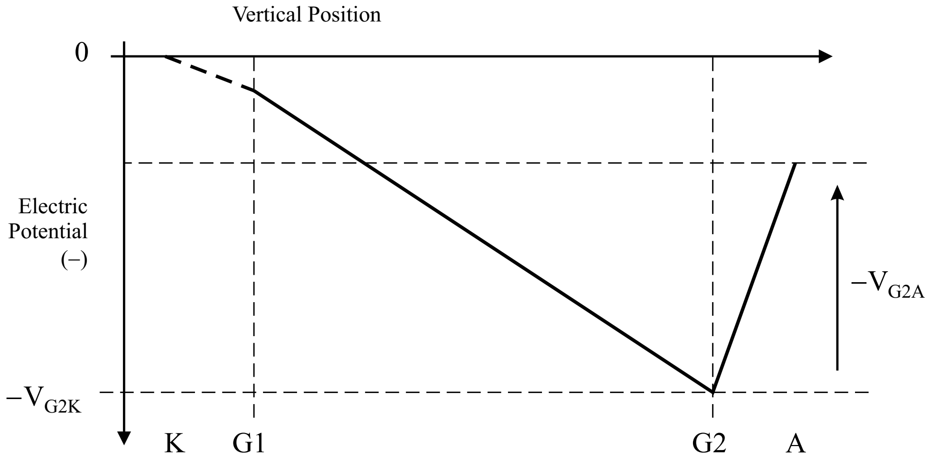

Figure 1: The negative of the electric potential inside the tube vs the vertical position inside the tube. Keep in mind that the graph shape is only intended to be approximate.

By thinking about an analogy in which ball bearings are released on a slope, only when $V_{\mathrm{G2K}} > 10$ V would you expect electrons leaving the cathode to have sufficient energy to reach the anode (after passing through the gaps in grid 2). Any electrons reaching the anode are returned to ground through the current amplifier.

Part 1 Anode Current

Turn the ACCELERATION voltage V_{G2K} to a minimum. Turn the current amplifier to the 10^{-12} range (1pA resolution).

Monitor an increase in V_{G2K} on the power supply whilst watching the current level on the amplifier display. Notice that the current signal remains constant at zero for a long range and then abruptly increases once passed a certain point, as shown in Fig. 2.

(1) Plot a *quick* graph of current signal I_A vs V_{G2K} for V_{G2K} from 0 to 20 V. Determine V'_{G2K}, the approximate voltage at which electrons begin to flow.

You should find that V'_{G2K} is greater than 10 V. Electrons do not reach the anode unless the anode is significantly more positive than the cathode. This is because they are made of different metals with different work functions.

In a metal, the valence electrons are not bound to the metallic ions. They can move freely throughout the metal, like a (Fermi) "sea" of electrons that fills a box to a certain height. The work function (ϕ) is the

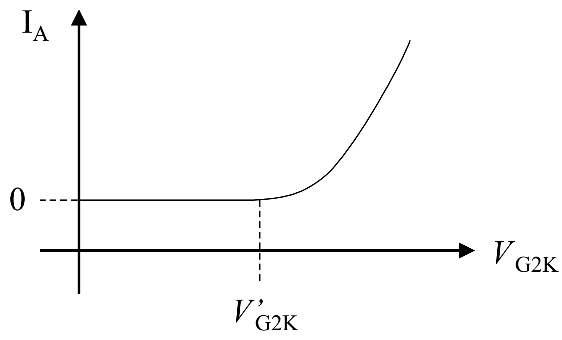

Figure 2: Anode current I_A vs small acceleration voltage V_{G2K}.

minimum energy required to move an electron from the sea's surface to somewhere far from the metal (on a molecular scale). This is the same work function you may have experience with from the photoelectric effect.

If there is a way for the electrons to travel, a few electrons will shift between two metals of different ϕ (from cathode to anode). This occurs until the two Fermi seas (Fermi levels) are equalised. Thus, a contact potential is developed between the metals,

$$\Delta V = \phi_1 - \phi_2$$

In other words, there is an electric field between the cathode and counter-electrode which repels incoming electrons from the latter. To combat this effect, a dc voltage is applied between them to reverse (eliminate) the electric field.

Part 2 Excitation by Inelastic Electron Scattering

Returning to your graph, if you increase V_{G2K} beyond 20 V you will observe an interesting phenomenon. The current I_A continues to increase initially, but then levels out before dropping after a certain point.

The drop occurs when, in the vicinity of the second grid G2 where the electrons achieve maximum speed, the kinetic energy of the fastest electrons becomes equal to the energy required to excite the Ar atom to one of its excited states, ψ'. Inelastic collisions between electrons and Ar atoms then leave the impacting electrons stationary. The targeted atoms, initially in ψ, will enter state ψ'. The stationary electrons now have insufficient energy to reach the anode, so the current begins to decrease.

(2) Plot a graph of I_A vs V_{G2K} for V_{G2K} from 0 to 64 V (the power supply limit). You should find that there is a pattern of repeated peaks and troughs. Try to take the graph promptly as the current levels *may* tend to drift up and down slowly over several minutes causing frustration.

Depending on the day, and the voltage you have set the cathode to, the number of electrons emitted may vary. Set the amplifier sensitivity higher, between 10^{-11} and 10^{-9}, such that the accuracy is high, but that the current reading does not saturate at the highest acceleration voltage levels.

Add more data points to your graph until you can accurately identify the voltage of each peak. Measure the spacing between each neighbouring peak and give an uncertainty estimate. It is this value that is most important. You may want to measure the trough positions as well to be even more accurate.

The spacings should be equal within experimental error. This suggests that the collisions only excite the atom to the ψ' state, even though the Ar atom has more than one excited state. The second trough corresponds to a single electron exciting two different atoms to ψ' en route to grid 2, the third trough by excitement of three different atoms, and so on.

(3) With reference to the potential energy curve in Fig. 1, explain what happens to electrons as they move from cathode to anode, when V_{G2K} equals the voltage at the second trough.

(4) Obtain a mean spacing between the peaks (or troughs) with error estimate (in eV). From this, find the wavelength λ and hence the wavenumber $(1/\lambda)$ in cm^{-1}. Compare with the values given in *Atomic Energy Levels vol. I* by C.E. Moore (available in the laboratory). Identify the excited state.

The first peak should occur at a voltage greater than the peak-to-peak voltage. As explained earlier, V_{G2K} is the maximum kinetic energy of the electrons plus some extra energy required to overcome work functions.

(5) By comparing the voltage of your first peak with the peak-to-peak voltage, deduce the voltage that must be subtracted from V_{G2K} to obtain the maximum kinetic energy reached by the electrons.

Questions

As well as providing a graph for each part of the experiment, concisely answer the following:

1. Why is it important to perform the experiment with a monatomic gas (eg. Hg, Ne)?
2. Explain how elastic and inelastic collisions occur with respect to the acceleration voltages used in parts 1 and 2.
3. Your graph in part 2 should show a series of peaks and troughs. As mentioned before, troughs occur because electrons lose discrete amounts of energy through inelastic collisions. So surely we would expect sharply-defined voltages at the transitions from peak to trough. In practice, this is not observed. Please explain.

List of Equipment

1. Franck-Hertz tube.
2. Variable power supplies, including on duel supply in series mode.
3. Current amplifier.
4. Connecting leads.

This version: M. Anderson, 15 December 2014