

FRANCK-HERTZ EXPERIMENT: ELECTRON SPECTROSCOPY

(from D. W. Preston and E. R. Dietz, The Art of Experimental Physics)

Historical Note

The 1925 Nobel prize in Physics was awarded jointly to James Franck, Germany and Gustav Hertz, Germany

For their discovery of the laws governing the impact of an electron upon an atom.

Franck and Hertz performed the experiment in 1914, 12 years before the development of quantum mechanics, and it provided striking evidence that atomic energy states are quantized.

APPARATUS [Optional Apparatus in brackets]

Franck-Hertz tube

Electric oven

Variac

Franck-Hertz Power Supply

Electrometer

OBJECTIVES

To verify the quantization of atomic electron energy states of mercury atoms by observing the maxima and minima of an electron current passing through a gas of mercury atoms.

To understand how ordinary and metastable atomic electron energy states of mercury affect the transmission of electrons.

To understand how temperature affects the number density of mercury atoms, the mean free path of a transmission electron, and the kinetic energy of a transmission electron.

INTRODUCTION

The Franck-Hertz experiment, first performed in 1914, verifies that the atomic electron energy states are quantized by observing maxima and minima in transmission of electrons through mercury vapor. The variation in electron current is caused by inelastic electron scattering that excites the atomic electrons of mercury. The Franck-Hertz tube, which contains a drop of mercury, is shown in Figure 1 along with electrical connections. The tube requires the following operating voltages

Filament, f : 6.3 V ac. Operation at a lower voltage will increase the lifetime of the tube.

Space-charge grid voltage across grid G_1 and cathode k : $V_1 = 2.7$ V dc. This voltage determines the space charge about the cathode and, thus, the emission current. Some tubes do not have grid G_1 . For such tubes the voltage V_1 is omitted and the negative terminal of V_1 connects directly to k .

Accelerating voltage across grid G_2 and cathode k : $V_2 = 0-40$ V dc.

Decelerating voltage across anode A and grid G_2 : $V_3 = 1.5$ V dc. Only those electrons that arrive at G_2 with an energy greater than eV_3 will reach the anode A .

Frank Hertz

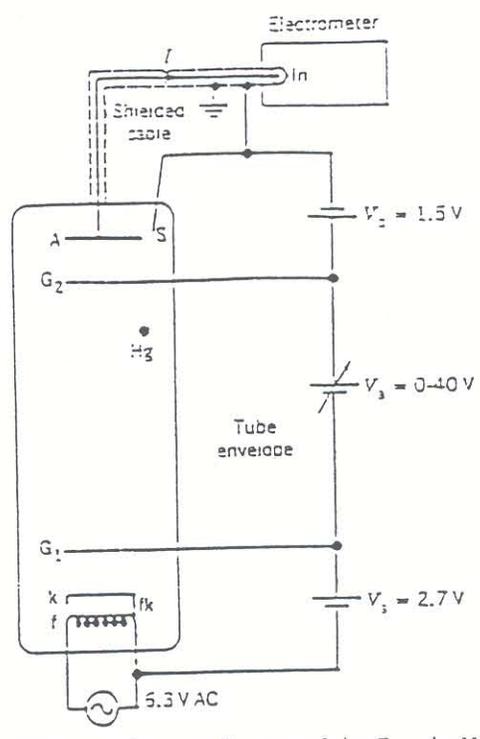


FIGURE 1 Schematic diagram of the Franck-Hertz tube with electrical connections.

Energy Levels of Mercury

A mercury atom has 80 electrons. For an atom in the ground state the K, L, M, and N shells of mercury are filled and the O and P shells have the following electrons:
 O shell: $5s^2, 5p^6, 5d^{10}$
 P shell: $6s^2$

Energy levels of mercury, which are relevant to this experiment, are shown in Figure 11.3. (See reference 4 for a discussion of the energy levels of mercury.) The energy levels are labeled with two notations:

- $n\ell$, where n is the principal quantum number and ℓ is the orbital angular momentum quantum number, designated by $s(\ell = 0)$ and $p(\ell = 1)$.
- $2S+1L_J$, where S , L , and J are the total spin quantum number, total orbital angular momentum quantum number, and total angular momentum quantum number (see reference 6).

The 1P_1 and 3P_1 are ordinary states, having lifetimes of about 10^{-8} s before decaying to the 1S_0 ground state by photon emission. The 3P_2 and 3P_0 are metastable states, having lifetimes of about 10^{-3} s or 10^5 times as long as an ordinary state. (See the discussion of metastable states in the "Introduction to Laser Physics.") Hence, the probability per second of an electron making a transition from either the 3P_2 or 3P_0 state to the 1S_0 ground state by photon emission is 10^5 times smaller than the transition from either the 3P_1 or 1P_1 to 1S_0 . Thus, the transitions from 3P_2 and 3P_0 to 1S_0 are *forbidden* transitions, while the transitions from 1P_1 and 3P_1 to 1S_0 are *allowed* transitions. The allowed transitions for photon emission

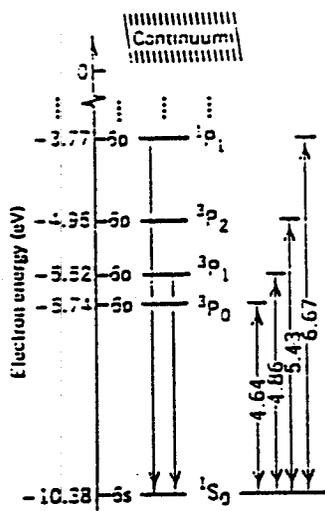


FIGURE 2 Energy levels of mercury that are relevant to this experiment. Energy level separation in electron volts is indicated on the right.

are indicated by the two arrows on the left in Figure 2, and the four arrows on the right indicate energy spacing in units of electron volts.

Direct excitation of $3P_0$, $3P_1$, $3P_2$, and $5S$ from $1S_0$ by electron impact is essentially equally probable.

Atomic Excitation by Inelastic Electron Scattering

An electron traveling from the cathode K toward the anode A has a mean free path \bar{l} (see reference 2) given by

$$\bar{l} = \frac{1}{\pi n R_0^2} \quad (\text{m}) \quad (1)$$

where $R_0 \approx 1.5 \times 10^{-10}$ m is the radius of a mercury atom and n is the number of atoms per unit volume. At the end of one mean free path the electron has gained a kinetic energy K from the electric field E :

$$K = eE\bar{l} \quad (\text{J}) \quad (2)$$

where e is the electron charge and E is the electric field established by the accelerating voltage V_a . If \bar{l} is long, then K will be large.

The number density n is very sensitive to the tube temperature; therefore \bar{l} and, hence, K are very temperature sensitive.

EXERCISE 1

What is the mean free path \bar{l} of an electron in a Franck-Hertz tube heated to 373 K? 423 K? 473 K? Assume the gas of mercury atoms behaves as an ideal gas. A table of vapor pressure of mercury and temperature may be found in the *CRC Handbook of Chemistry and Physics*.

When an electron of kinetic energy K approaches a mercury atom with $K < 4.6$ eV, the energy difference between the first excited state and the ground state, then the collision is elastic. In an elastic collision the electron loses some kinetic energy determined by the laws of conservation of momentum and kinetic energy.

EXERCISE 2

The loss of kinetic energy by an electron when it collides elastically with a mercury atom is greatest when the collision is head-on. For an elastic head-on collision with the mercury atom, assumed initially at rest, show that the change in electron energy is given by

$$\Delta K = \frac{4mM}{(m+M)^2} K_0 \quad (J) \quad (3)$$

where m and M are the masses of an electron and a mercury atom and K_0 is the initial electron energy. (See reference 3 for a discussion of a head-on, two-particle collision.) What is the fractional loss of kinetic energy by the electron for such a collision?

From your answer to Exercise 2 it should be clear that the loss of electron energy due to a single elastic collision is negligibly small. The probability of an inelastic collision occurring is large when the electron's energy equals the energy difference between an excited state and the ground state of the mercury atom, that is, 4.6, 4.9, 5.4, and 6.7 eV (see Figure 2). At some distance $d1 \pm \Delta d$ from the cathode, the kinetic energy K of the electron will equal 4.6 eV and the first inelastic collision occurs. The inelastic collisions occurring in this distance range of $d1 \pm \Delta d$ populates the 3P_0 metastable state of the mercury atoms in this distance range. The electrons that later enter the shell will collide elastically with the mercury atoms in the 3P_0 state; hence these electrons pass through the shell with negligible energy loss. At some larger distance d_2 , these same electrons will have a kinetic energy of $\epsilon = 4.9$ eV and they collide inelastically with mercury atoms in the ground state. The 3P_1 state decays to the 1S_0 state after about 10^{-8} s by photon emission, and then the atoms is ready for another inelastic collision; that is, the atoms in this shell continuously convert electron kinetic energy to radiant energy. If the accelerating voltage V_a is high enough, this process may be repeated at intervals $d\epsilon_1, d\epsilon_2, \dots$. Note that these are the distances of travel required for the electron to gain a certain energy.

What effect do these inelastic collisions have on the current measured by the electrometer in Figure 1? The decelerating voltage V_r is about 1.5V and as V_a is increased from 0V, a current is first observed when V_a exceeds 1.5V and the observed current will increase as V_a increases until $V_a=4.9$ V. When $V_a=4.9$ V the electrons lose energy from inelastic collisions; hence, they no longer have enough energy to overcome the 1.5V decelerating voltage and the observed current decreases. (With $V_a=4.9$ V, $d\epsilon$ is approximately the distance from the cathode to the grid.) As V_a is increased from 4.9V the current will again increase until $V_a=9.8$ V, which corresponds to a second distance of $d2\epsilon \pm \Delta d$ from the cathode where inelastic collisions which populate the 3P_1 state occur. Thus, when $V_a = n \times 4.9$ V, $n = 1, 2, 3, \dots$, there is a decrease in current. A curve of expected current I versus accelerating voltage V_a is sketched in Figure 3. Each peak represents the onset of inelastic collisions that populate the 3P_1 state. The first peak does not occur at 4.9V because of the contact potential difference between cathode and anode. Contact potential difference is discussed in reference 1.

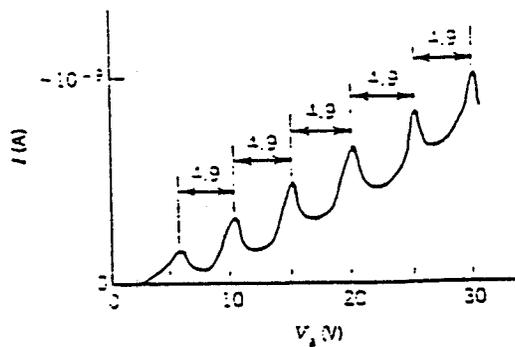


FIGURE 11.4 Electrometer current as a function of the accelerating voltage V_a .

Electrometer

Electrometers are extremely sensitive electronic instruments designed to measure both (+) and (-) currents and voltages. A function switch permits the selection of current or voltage mode. A range selector switch allows voltage measurements from about $1 \mu V$ to $1 V$ and current measurements from about $1 pA$ to $1 mA$. The output of the electrometer ranges from 0 to plus or minus a few volts for an input ranging from 0 to full scale.

The output current of the Franck-Hertz tube ranges from 0 to about $-10^{-9} A$ as the accelerating voltage varies from 0 to $+30 V$ (voltage of G_2 relative to k).

Connecting the Circuit to the Franck-Hertz Tube

Turn off all voltages and then connect the circuit and filament power supply to the Franck-Hertz tube. NEVER APPLY VOLTAGES TO THE TUBE UNLESS IT IS IN THE OVEN AT THE DESIRED TEMPERATURE. To do otherwise could burn out the tube, and it is expensive. After connecting the circuits to the tube, then:

1. Attach the thermocouple to the tube (approximately centered on the anode), place the metal shield around the tube and connect it to ground (this will reduce ac pickup), and then insert the tube into the oven as deeply as possible.
2. Plug the oven into the variac and experiment with the oven temperature as a function of voltage. You want to determine the variac setting(s) required to bring the tube-oven system to the desired temperature as quickly as possible. The voltages to the tube may be applied after a stable operating temperature is reached.

With the anode connected to the electrometer as shown in Figure 1 vary the anode voltage to op-amp 1 from 0 to $30 V$, recording appropriate currents and voltages in your notebook. Also measure the temperature periodically and adjust the oven voltage as required to maintain a reasonably constant temperature.

Analyze the data, interpreting it in terms of the theory discussed in the Introduction.

EXERCISE 3

The cathode at temperature T emits electrons with a distribution of speeds. The average kinetic energy \bar{K} of the electrons is

$$\bar{K} = 2kT \quad (\text{J})$$

where k is the Boltzmann constant and T is the absolute temperature. Assuming that T is 2500 K, what effect will \bar{K} have on your measured excitation potentials? What effect will the distribution of speeds of the electrons have on the sharpness of the peaks?

EXERCISE 4

What effect would contact potential have on peak spacing? What peak positions would be affected by contact potential?

REFERENCES

1. R. Eisberg and R. Resnick, *Quantum Physics of Atoms, Molecules, Solids, Nuclei, and Particles*, 2d ed., Wiley, New York, 1985. Contact potential is discussed on pages 407-408, and the Franck-Hertz experiment is briefly discussed on pages 107-110.
2. D. Halliday and R. Resnick, *Physics*, Part I, 3d ed., Wiley, New York, 1978. Mean free path is discussed on pages 522-524.
3. K. Rossberg, *A First Course in Analytical Mechanics*, Wiley, New York, 1983. Collision of two particles is discussed on pages 157-160.
4. L. Loeb, *Atomic Structure*, Wiley, New York, 1938. An older book which you may find in the library. A good discussion of the Franck-Hertz experiment appears on pages 249-254. The energy levels of mercury are discussed on pages 256-264.
5. E. Leybold, Manufacturer's description of the Franck-Hertz tube. This is a discussion of the Franck-Hertz tube, which should be available from your instructor.
6. R. Eisberg, *Fundamentals of Modern Physics*, Wiley, New York, 1961. LS coupling is discussed on pages 428-441.

FRANCK-HERTZ EXPERIMENT

S. KENDALL

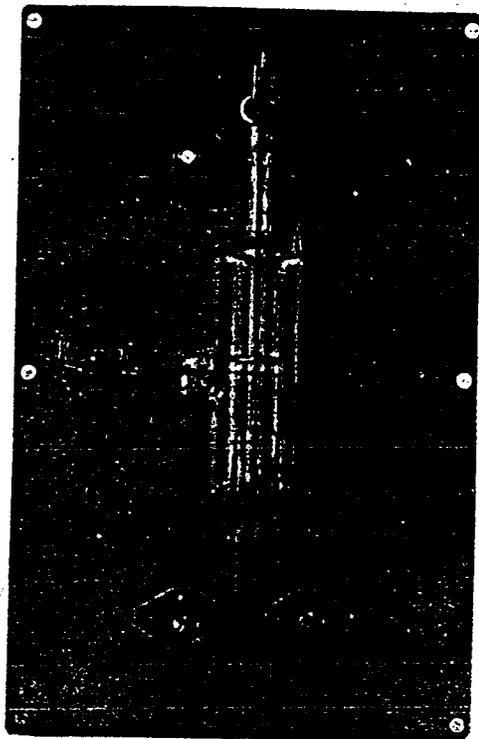
The Franck-Hertz experiment (1913; Nobel Prize 1926) with the well-defined periodic and equidistant maxima and minima of the collector electrode current when exciting the mercury resonance line at 253.7 nm wavelength, is undoubtedly one of the most impressive experiments to demonstrate and verify the quantum theory. This experiment provides direct proof for the truth of the concepts of quantum theory.

KA6040 - Franck-Hertz tube filled with mercury is a three-electrode tube with indirectly heated oxide-coated cathode, grid-form anode and collector electrode. The electrodes are arranged in plane-parallel manner. The distance between the cathode and the anode (8mm) is large compared with the mean free path length in the mercury vapor atmosphere (at 180° C) in order to ensure a high collision probability. On the other hand, the separation between the anode and the collector electrode is small.

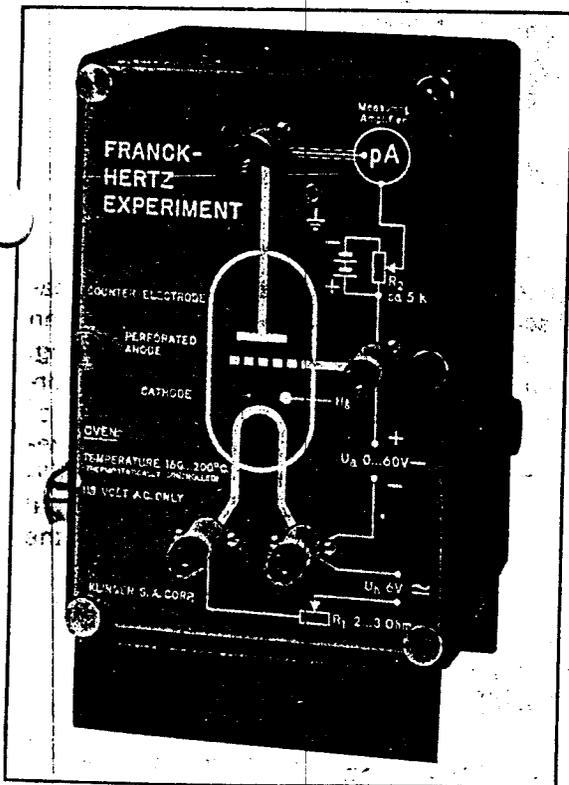
The envelope wall between the anode and the collector electrode carries a vacuum-proof sealed-in protective ring made of sintered carborundum, to prevent leakage currents via the ionically conducting hot glass wall. The tube contains a drop of highly purified mercury.

This new Franck-Hertz tube is not interchangeable with any other tube type formerly supplied for the same application. Tube KA6040 is supplied already mounted inside the thermostatically-controlled oven and contains the necessary resistors.

As an additional feature, the tube can be repaired when the filament burns out, provided the glass form is returned intact. This repair can be made at approximately two-thirds the original purchase price.



KA6040 - Franck-Hertz Tube
(mounted on front panel)



KA6041 - Heating oven consists of a steel-plate cabinet heated with chrome-nickel spirals mounted in a ceramic former on the floor of the oven. The power consumption is 400 Watts. A rheostat which can be adjusted from the exterior serves for setting and stabilizing the oven temperature. The spiral heater and the bimetal contact are electrically shielded with a wire net so that the measurements are not disturbed by the switching surges of the heating oven.

Ordering Data:

KA6040 - Franck-Hertz tube, mercury filled, for observation of quantum transitions due to electron collisions with mercury atoms.

KA6041 - Thermostatically-controlled oven for tube KA6040.

KA6040R - Repair of the Franck-Hertz tube KA6040. Only tubes with burned out filaments can be repaired by us. All orders for KA6040R must be accompanied by the defective tube.

KA6042 - Voltage divider, a potentiometer mounted on stand, regulated by a knob with provision to clamp a 1.5 volt flashlight battery.

KA6043 - Set of leads with plugs and special coaxial cable.

KH2235 - Thermometer, range -10° to +200°C.

KA6045 - Operating unit for Franck-Hertz experiment (combination power supply and DC amplifier).

The above set of equipment for the Franck-Hertz experiment is suitable for student laboratory work and is most dependable. As an amplifier and current indicator any other instrument can be used.

ATOMIC PHYSICS