The Franck-Hertz Experiment  
Physics 2150 Experiment No. 9  
University of Colorado

Introduction

During the late nineteenth century, a great deal of evidence accumulated indicating that radiation was absorbed and emitted by atoms only when the radiation had certain discrete frequencies. The evidence provided by the photoelectric effect also suggested that light of a given frequency $\nu$ was transmitted in quanta, each quantum being associated with an energy $h\nu$. There was some discussion at the time as to whether this quantization was entirely a characteristic of light or whether quantization also occurred in atomic structure. In order to resolve such questions it was necessary to "look at" atoms with a probe that did not involve light. This investigation was, at least in part, the motivation for the Franck-Hertz experiment in 1914, which used electrons rather than light to explore the structure of atoms. The results of the experiment provided a strong confirmation for the Bohr theory of quantized atomic states.

The experiment consists of observing the energy losses of electrons that collide with mercury atoms. If the internal energy of an atom has a unique value so that the distribution and motion of the electrons cannot be changed, then when an atom is hit by an electron, the atom must recoil as a whole. That is, despite its fairly loose and open structure consisting of a nucleus and electrons, the atom must behave much as a rigid elastic sphere. The electron will bounce off the atom as a ping-pong ball would off a bowling ball, losing a very small fraction of its initial kinetic energy. The fraction thus lost is given by the ratio of the mass of the electron to the mass of the atom, which, in the case of a mercury atom, is about $1/(4 \times 10^5)$. Thus, even after a thousand collisions with mercury atoms, the electron will lose less than 1% of its initial energy.

Suppose that on the other hand, a moving electron were to collide with a stationary electron. It could then lose all of its energy in one collision. If an electron collides with an electron which is bound in an atomic state of definite energy and which can only make a transition to some other state of definite energy, then only if the incident electron has an energy equal to this energy difference can all of the incident electron's energy be lost in a single collision. The Franck-Hertz experiment demonstrates this type of collision and shows that such energy losses occur only for very special values of the energy of the incident electrons. These results therefore indicate that the electrons in mercury atoms can exist only in a discrete set of energy states. Furthermore, the energy of the state discovered by electron bombardment corresponds to the energy of the photons that are absorbed by mercury atoms. Thus, the results of the Franck-Hertz experiment solidly supported Bohr's suggestions as to the nature of atoms. This result is so fundamental that, even though it is now familiar, it is worthwhile to repeat the experiment and obtain a graphic display of the phenomenon.
Figure 1: Typical graph of electron current versus accelerating potential in a Klinger KA6040 Franck-Hertz tube.

Figure 2: Typical Circuit Diagram for Performing the Franck-Hertz Experiment

**Excitation Potential**

In this experiment, the voltage difference between successive maxima of electron current is measured, as indicated in Fig. 1. The experiment is performed with a vacuum tube that has three electrodes as diagramed in Fig. 2. Note that in this tube, current (electrons) is emitted by the cathode and collected by the plate. Principal accelerating electrode (the grid) is located between the other two. The plate is kept at a potential slightly lower than the accelerating grid by a 1.5 volt battery. Since the currents to be
observed are small, special arrangements have been made to eliminate the effect of leakage currents that might otherwise flow between the electrodes of the tube along the surface of the hot glass envelope of the tube. The mean free path of electrodes through the mercury vapor in the tube is small compared to the distance between emitting cathode and accelerating grid. (This can be checked by looking up the vapor pressure of mercury at the temperature at which the experiment was performed.) The conditions inside the tube are very dependent on temperature and therefore the Franck-Hertz tube is contained inside a box or oven in which the temperature can be controlled and monitored.

After the temperature-controlling circuits are turned on and the tube has reached a stable temperature, the cathode is heated so electrons will be emitted and positive DC voltage is applied between the accelerating grid, which is perforated, and the cathode. As the accelerating voltage on the grid is increased, all the electrons which are able to overcome the negative retarding potential will pass through the holes in the grid and reach the plate. This will result in a current. However, as soon as the energy of incident electrons reaches the excitation potential of the electrons in the mercury atoms, a quantum of energy will be given to the atoms and the electrons in the beam will lose enough energy that they will no longer be able to overcome the retarding potential. Consequently, they will not contribute to the current. The current will suddenly decrease and a minimum will appear on a graph of current versus accelerating potential.

If the accelerating voltage is increased further, since the electron mean free path is small compared with the distance between cathode and grid electrons, electrons which have been slowed down in a first inelastic collision can again be accelerated; the current increases until the electrons again acquire enough energy to excite an atom and the current will then again decrease. Such a transfer of energy from an electron may take place several times as the voltage on the grid is increased; thus a series of distinct maxima and minima will be observed. In this idealized picture, each transition from maximum to minimum will occur at a sharply defined voltage. In practice, the observed transition is more gradual, mostly because of the spread in energy of electrons thermally emitted from the cathode. In the voltage range from 0 to approximately 60 V, as many as 13 minima can sometimes be observed. The difference in voltage between successive maxima corresponds to the energy difference between atomic states (in mercury, 4.89 eV, see Figure 3). The first peak will appear at a voltage different from the excitation potential by an offset voltage caused by the electrode work functions and by contact potential between the materials used to manufacture the electrodes in the tube.

In principle it should be possible to measure the excitation potentials for a series of mercury levels by this technique. However, the probability of exciting the first level is sufficiently great, compared with that of exciting higher levels, that the latter effect is masked by the former unless very special conditions exist in the tube. Therefore, these higher excitation levels are not studied in this experiment.

**Ionization Potential**

If an incident electron has sufficient energy to knock an electron free of the mercury atom, the remaining atomic system will have a positive charge. If the plate is made negative
with respect to the cathode, it cannot collect any electrons but will attract these positive ions. The electron energy at which this positive ion current starts is a measure of the ionization potential of a mercury atom. In order for such measurements to be possible, the accelerating grid must be made sufficiently positive that electrons can be accelerated from the cathode, and the plate must then be made slightly negative with respect to the cathode. Not all Franck-Hertz tubes are designed so that such arrangements are possible. Another restriction is that the measurement must be performed at a sufficiently low vapor pressure of mercury (at low temperatures). The positive ions must drift from the electrons, where they are created between the electrodes, to the plate where they are collected, without this drift being distributed by high thermal velocities of mercury atoms in the tube.

The magnitude of current which leaves the cathode depends on two factors: the temperature of the cathode and the strength of electric field between the cathode and the nearest grid. If the filament temperature is very low, then the cathode currents are limited by the cathode emission except for very small grid voltages. If the filament temperature is raised, then the emitted electrons charge the space around the cathode negatively and prevent the emission of additional electrons unless this space charge is swept out by the voltage on the grid. Under these conditions, the current space-charge limited and the current will vary as the $3/2$ power of the grid voltage.

The phenomena which occur within the Franck-Hertz tube can be quite complex. If they lead to a rapid discharge, the electrodes of the tube can be damaged. Whenever such a discharge is initiated, the grid and plate voltages must be lowered immediately.

A destructive discharge can be initiated in the tube whenever the potential of any of the electrodes is greater than the ionization potential of the mercury (or any of the impurities) in the tube. Under these conditions a variety of phenomena can occur. The ejected electrons can be further accelerated to produce more electrons and these in turn can produce more ionization. The positive ions formed can bombard the cathode, increasing its temperature and ejecting more electrons. They can also heat up the grid wires to incandescence, thus harming the tube and increasing the magnitude of the discharge current. These avalanche effects depend on the mean free path (i.e the average distance traveled by the electron after successive collisions) of the ions and electrons in the mercury vapor. The greater the mean free path, the greater the energy which can be given to the secondary ions. Thus such discharge phenomena will be most apparent at the lower mercury pressure (temperatures). At high temperatures there is a danger of damaging the insulation in the base of the tube. In addition, the vapor pressure of the mercury will become large enough that the elastic collisions of electrons with the mercury atoms will produce a significant loss of energy in the electron beam. Under such conditions the effect of the inelastic collisions (excitation) will become much less pronounced. In addition, fewer electrons will reach the collecting electrode. Finally, if the electron currents and energies become large, photoelectric effects may tend to initiate a discharge even at high mercury vapor pressures.
Procedure

Part I: Measurement of First Excitation Potential of Mercury

Consult the detailed operating instruction notes posted with the experimental apparatus regarding turning on the experiment and adjusting the controls. For this part of the experiment, the positive side of the 1.5 V bias battery, which supplies the retarding potential, must be connected to the grid (point #1 in Figure 2). The oven containing the Franck-Hertz tube should then be turned on and allowed to come to the equilibrium at temperature of about 155-170°C. The filament supply and the accelerating voltage supply are then turned on with controls set to zero. The nanometer and protection circuit may then be turned on. The purpose of the protection circuit is primarily to keep the current in the Franck-Hertz tube below about 2.5 nanoamperes to prevent it from being burned out. If the current exceeds 2.5 nanoamps, a relay will be tripped which will disconnect the accelerating potential. A pushbutton switch is provided on the front of the box containing the protection circuit so that the relay can be reset after having been tripped. The protection circuit also provides an output voltage proportional to the current in the tube; this voltage is connected to the vertical input of a storage display oscilloscope and is a measure of plate current.

In this part of the experiment, the oscilloscope display controls should be set so that the full range of electron current is displayed as a function of accelerating potential which will vary from 0 to about 50 volts.

As the accelerating potential is increased slowly, one obtains a plot similar to the one given in Fig. 1 on the oscilloscope. Make a sketch of the trace observed and list the voltage locations of the peaks before computing differences. Include both the labeled sketch and a table of peak voltages. From the differences between maxima on this plot, determine the first excitation potential of mercury. At least three different traces should be measured in order to obtain sufficient data. Also determine the offset voltage (the difference between the voltage at which the first peak appears and the average peak-to-peak spacing). Voltage measurements taken from the meter will generally be more accurate than those taken from the oscilloscope.

Part II: Measurement of Ionization Potential of Mercury

With the same apparatus, one can perform an additional experiment with only a minor modification. This experiment was not a part of the original Franck-Hertz experiment. In this part of the experiment the ionization potential is measured. The ionization potential is the energy required to remove the least tightly bound electron from the atom.

Move the positive lead of the 1.5 V bias battery from the grid terminal to the cathode terminal (point #1 to point #2 in Fig. 2). When connected in this way, electrons leaving the cathode cannot reach the plate. When the accelerating potential is large enough that electrons have enough energy to ionize mercury atoms, the positive ions formed between
the grid and the plate will be collected by the plate and will appear as a current of sign opposite to the electron current observed in Part I.

Unplug the oven and begin making measurements after the temperature falls to about 110° C. Make suitable adjustments of the oscilloscope controls for vertical sensitivity and position. For better accuracy in this part of this experiment the gain of both horizontal and vertical amplifiers can be increased. Recommended settings are posted with the apparatus.

Note that a change will occur in the plate current as the tube cools. A very sharp increase will be observed in ion current which is due to an avalanche of the ejected electrons ionizing more atoms, with the electrons produced ionizing still more atoms, and so on; this avalanche does not necessarily occur as soon as the ionization threshold is crossed. If the mercury vapor is too dense, the ions can recombine with electrons before reaching the anode, thus masking the effect until complete breakdown sets in.

Set the accelerating potential to zero. Then increase it slowly (and uniformly) while watching the oscilloscope trace. Increase the voltage until the trace has made a definite downward departure from the horizontal. Repeat this process a few times such that you can clearly identify a point where the ion current begins. **Record this value of accelerating voltage for ten different temperatures from 55° C ≤ t ≤ 110° C. Subtract from these values the offset voltage measured in Part I to obtain a set of individual determinations of the ionization potential for Mercury.**

**From the data decide whether the ionization potential is temperature dependent.** (Can you use a statistical technique to determine the *correlation* between ionization potential and temperature, to determine dependence/independence?) Sketch one of the traces you observe. Then do a statistical analysis to determine your average value of ionization potential and compare with the accepted value of 10.38 eV as given in Fig. 3.

![Figure 3: A Considerably Simplified Energy Level Diagram for Mercury](image)