

Homework 23

Franck-Hertz experiment

Franck-Hertz experiment is one of the cornerstone experiments of physics which clearly demonstrated discreteness of internal energy of an atom. The experiment was done in 1914 by German physicists James Franck and Gustav Hertz.



James Franck (1882-1964)



Gustav Hertz (1887-1975)

The idea of the experiment was simple and beautiful. If we will accelerate electrons and made them collide with gas atoms, the electrons may experience inelastic collisions resulting to the transfer of kinetic energy of the electrons to the internal energy of the gas atoms. Discreteness of the internal energy of the gas atoms means that the internal energy can be changed by fixed “portions”. We call this portion “energy quantum” and the discreet energy “quantized”. As long as the kinetic energy of the electron is less than the energy quantum the gas atom cannot absorb it and the inelastic collision cannot happen. If the electron kinetic energy is higher than the energy quantum, the inelastic collision is possible. In this case the electron loses part of its kinetic energy and slows down and the internal energy of the gas atom increases. So, as we increase acceleration of the electrons (i.e. force, applied to the electrons), we will observe that at certain values of the force, applied to the electrons, they slow down very effectively. It will look like the “friction force” experienced by the electrons depends on the accelerating force nonmonotonically.

The schematic diagram of the Franck-Hertz apparatus is shown in Figure 1.

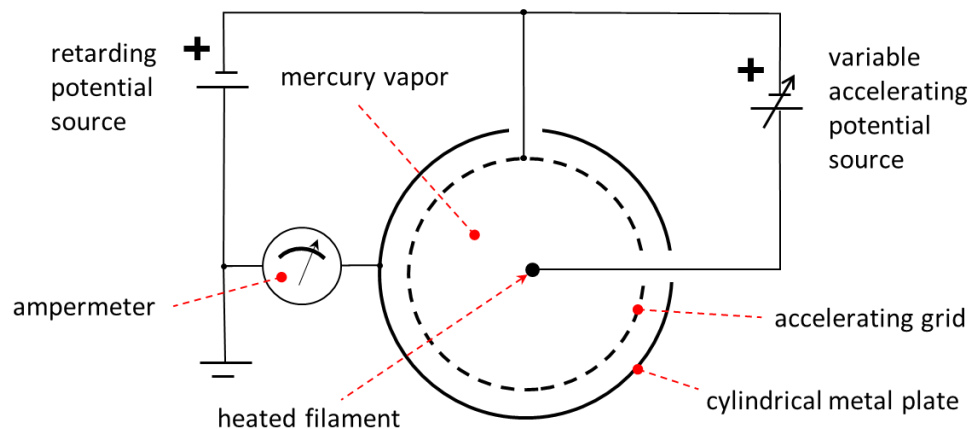


Figure 1. Franck-Hertz apparatus.

The apparatus consisted of a gas tube filled with mercury vapor, heated filament, cylindrical metal plate and an accelerating grid near the plate. The filament was heated to the temperature at which the thermally excited electrons were emitted from the filament surface, but their kinetic energy was low. The voltage applied between the grid and the filament accelerated the emitted electrons toward the cylindrical plate. A small negative potential (retarding potential) was applied to the cylindrical metal plate, so the electrons with low kinetic energy which pass through the grid would not reach the plate. The electrons moving through the gas tube toward the cylindrical plate produce the electric current which is measured by the ampermeter (Figure 1). As we increase the acceleration voltage, we expect that the electrons will move faster and the current will increase. The actual dependence of the measured electron current on the acceleration voltage is shown in Figure 2.

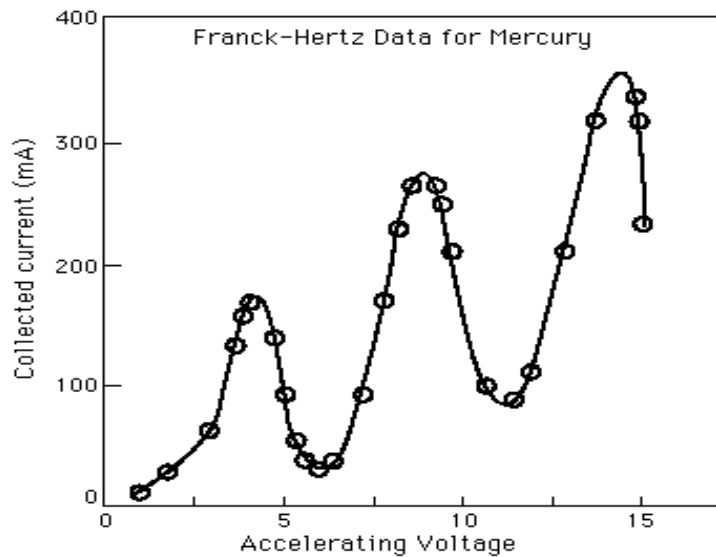


Figure 2. The electron current measured in the Franck-hertz experiment as a function of the accelerating voltage

We can see that initially, the current increases with voltage (as we expected) but near 4.9V, the current suddenly drops. This can be interpreted as the result of effective loss of the electron kinetic energy due to inelastic collision with the mercury atoms. Once the electrons just in front of the grid reached the kinetic energy equal to the energy quantum of the mercury atoms, they can effectively transfer this energy to the mercury atoms and slow down. The decelerated electrons cannot overcome the retarding potential and reach the cylindrical electrode, so the current drops sharply. As we further increase the acceleration voltage, the rest of the kinetic energy after the inelastic collision increases and it becomes possible for the electrons to overcome the retarding potential, so the current increases again. But when the accelerating potential becomes large enough for the electrons to make two separate inelastic collisions with mercury atoms, the current falls again.

So the experiment indicates that to “energy quantum” of the mercury atom corresponds to the kinetic energy of an electron accelerated by the potential difference of 4.9V. The quantum of energy is determined by the gas atom. If Franck and Hertz used not mercury vapor but other gas, the measured quantum would be different.

For this experiment Franck and Hertz were awarded with the Nobel Prize in 1925. It also should be noted that Gustav Hertz should not be confused with Heinrich Rudolph Hertz who gave his name to the frequency unit. In fact, Gustav Hertz was a nephew of Heinrich Rudolph Hertz.

Problem:

1. Calculate kinetic energy of an electron accelerated by the voltage difference of the 4.9V.
2. Show that to excite a mercury atom with the “energy quantum” E , the initial kinetic energy of the electron must have at least the value

$$K_{min} = E \left(1 + \frac{m}{M} \right), \text{ where}$$

m is the electron mass and M is the mass of the mercury atom.