Franck-Hertz experiment for neon atoms

***Aim of the experiment** is to perform Franck-Hertz experiment for a lamp filled with neon. The intensity of current flowing in the anode circuit of the electronic lamp is measured as a function of the voltage accelerating electrons.*

***Problems:** motion of charge in electric field, conservative field, electron states of an atom, absorption and emission of radiation, kinetic theory of gases.*

***Instruments:** a neon lamp with a power supply and control panel, computer with an integrated control-measurement chart and appropriate programs.*

1. Introduction

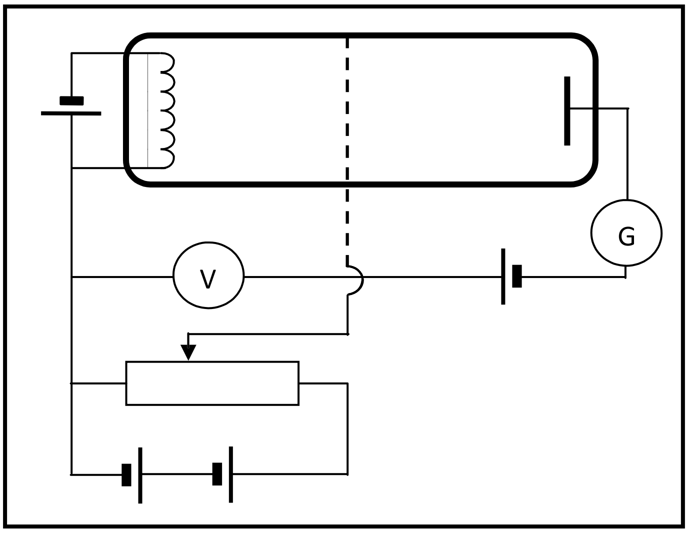

Figure. 1. Scheme of the original Franck-Hertz experiment.

The electronic lamp applied without the grid would work as a standard diode. The grid placed between the cathode and anode has a potential higher than that of the cathode (large difference) and higher than that of the anode (small difference). The voltage between the cathode and the grid accelerates the electrons to high velocities. The voltage between the grid and the anode is to stop on the grid these electrons that have low velocity in the vicinity of the grid. If there is vacuum in the tube, the lamp with the grid still acts as diode, but its conductivity is controlled by the grid potential, the higher the grid-cathode potential, the greater the current flowing through the anode. When the tube is filled with gas, the electrons can interact with its atoms. If the concentration of gas is high, the electrons continually collide with its atoms, which leads to an increase in the gas temperature, while the intensity of the current flowing through the lamp is low. A decrease in the gas pressure leads to extension of the free path of electrons and an increase in the intensity of the anode current. The electrons accelerated to high speed between the cathode and grid rather easily overcome the hindering potential behind the grid and reach the anode. On the path from the cathode to the grid, they undergo a few collisions with atoms, but because of a great difference in mass ($m_e << m_{at}$) and in velocity ($V_e >> V_{at}$) electrons practically do not exchange the kinetic energy with atoms. This motion can be compared to the rainfall of small rubber balls in the gravitational field among randomly distributed almost immovable a few hundred kilogram boulders. Although the rubber balls in this illustrating example and electrons in the lamp undergo many collisions, the speed of rubber balls (electrons) is defined by their vertical position, irrespective of the history of motion, thanks to the conservative character of the field (gravitational in the example and electric in the lamp).

If the accelerating voltage reaches the value U_g such that the product U_ge becomes equal to the difference in the energy levels of the gas atoms, then an interesting phenomenon takes place – the atoms absorb the kinetic energy of electrons and move to excited states, while electrons get stopped. As absorption is the resonance phenomenon, the electrons are divided [selected] according to their energy. The phenomenon of excitation starts at the limit voltage U_g in vicinity of the grid and takes place for voltages higher than U_g. For some substances this effect can be seen as the excitation is accompanied by emission, although the emitted radiation is not always from the visible range. By setting the grid potential to be positive with respect to anode, for the accelerating voltage close to U_g the excitation and hindering of electrons takes place in the close vicinity to the grid and the hindered electrons are captured by the grid. It is manifested as a significant decrease in the anode current as much fewer electrons reach it. With increasing value of accelerating voltage, the line at which the atoms excitation and hindering of electrons take place is shifted towards the cathode. It should be remembered that the electric field is conservative so the electron velocity and hence its kinetic energy depend only on the distance from the cathode and not on the distance passed. The shift of the excitation line away from the grid, which is visible with the naked eye if the emission takes place in the visible range, permits the electrons to accelerate and penetration through the grid. Consequently, the anode current flows and is less disturbed by the absorption acts. At the moment when the accelerating voltage reaches $2U_g$, the second excitation line appears in the close vicinity of the grid (also visible if emission takes place in the visible range), and the hindered electrons are captured. The anode current decreases and the situation is repeated in cycles with increasing accelerating voltage. The whole phenomenon is particularly striking for a neon lamp in which it is possible to see a few red excitation lines with the naked eye.

As follows from the above, the quantum character of excitation can be better observed for more homogeneous electric field in the area in which the electrons are accelerated. That is why lamps are often built with an additional grid close to the cathode so that the usually irregular shape of the cathode would not disturb the homogeneity of the electric field. In such lamps the electrons are accelerated between the grids.

In interpretation of results (position of minima in the I(U) plot) it should be remembered that the first minimum is shifted to the right by the distance equal to the hindering potential of the grid (potential is on the x axis) and can be to a small degree (depending on the lamp construction) shifted by a value dependent on the work of electrons needed to leave the cathode material, the so-called workfunction. That is why the result of measurement of the energy gap obtained by measurement of the distance between the subsequent minima should be charged with the relatively lowest error as the two contributions coming from the workfunction of electrons cancel out.

In an alternative measuring setup the grid current may be measured instead of the anode current. Then, instead of minima we would observe clear maxima and between the maxima the grid current would be very small.

It should be mentioned that this experiment realised by James Franck and Gustav Hertz in 1914, was meant to verify the Bohr hypothesis of the quantum character of absorption and emission of energy by atoms. It was carefully designed to provide the reliable proof of the discrete character of energy absorption by atoms, although the emission of mercury atoms (mercury vapour was used as the medium interacting with electrons) was invisible. Franck and Hertz were awarded for it with the Nobel prize in 1925.

2. Experimental setup.

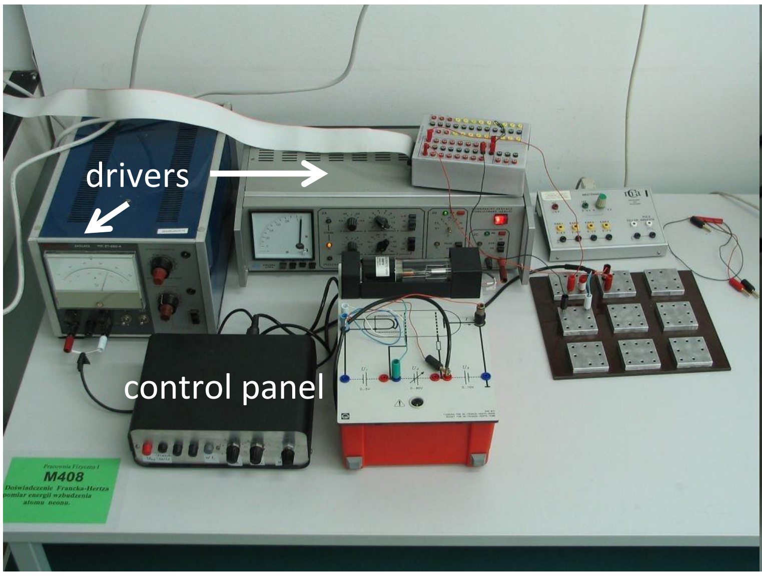

Figure 2. The measuring setup without a computer .

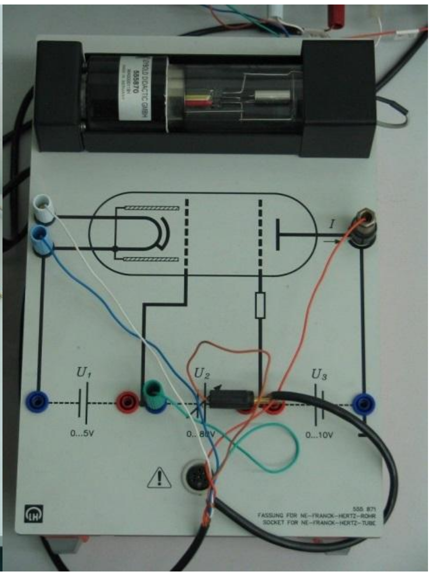

Figure 3. The lamp and the scheme of connections

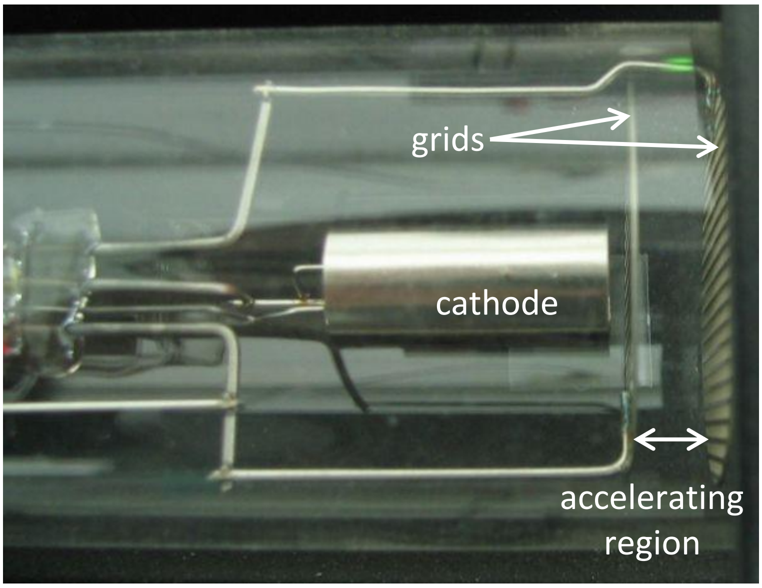

Figure 4. The lamp tube with electrodes.

Figure 5. Visible neon emission in the excitation regions .

3. The experiment.

In the measuring setup, the accelerating voltage of the maximum value of about 80 V is supplied through the RC circuit of the time constant near 100 s. Because of the slow increase of the voltage in the lamp, it is possible to follow easily the changes in the anode current measured as a drop in the voltage on the resistor connected in series in the anode circuit. Possible changes in the experiment caused by its modifications will be explained under the tab “Informacje” [information].

Stop the supply of accelerating voltage by pressing up the red button on the control panel of the lamp. In the computer program choose the tab “Pomiar” [measurement]. The two upper plots show the time changes in the accelerating voltage and anode current. The third plot shows the changes in the anode current intensity as a function of the accelerating voltage. When the red button is pressed up, the accelerating voltage and anode current intensity are close to zero.

Press down the red button on the control panel and click the “Start” box in the program. The accelerating voltage supplied through the RC circuit slowly increases from zero to about 80 V. Observe the changes in the anode current intensity. By the click on “Stop” the measurement stops. Subsequent click on “Start” in the program erases the data and the next recording starts (remember to press up and then press down the red button on the control panel).

In the dark or under cover protecting from external light, observe the region between the grids (Fig. 4) when the accelerating voltage increases. Try to note the appearance of red bands of shining neon moving gradually from one grid to another. At the maximum voltage you should be able to observe the image similar to that shown in Fig. 5.

Record one typical run of I(U) and after stopping the measurement by the click on “Stop” go to the tab “Analiza” [analysis]. You can enlarge the plot by marking a certain area with two cursors. The enlarged plot permits easy reading of the positions of the minima of the anodic current intensity on the axis of voltage. Moreover, you can try to straighten up the I(U) dependence by dividing the measured anode current intensity values by the hypothetical values of the current I_0, that would flow through the lamp without the gas inside. The latter values you will obtain assuming that the increase in voltage on the grid cause a linear increase in the intensity of the anode current and that between the minima the lamp behaves as a vacuum lamp. By using appropriate knob controls you can fit a line to the I(U) sections between the minima and observe on the second graph the behaviour of I/I_0 as a function of the accelerating voltage. In this representation the changes in the relative depth of the minima are better visible. Remember that because of the hindering potential and workfunction, the line $I_0(U)$ does not have to come through the starting point of the system of coordinates.

In all parts of the program, the key “Kopiuj” [copy] permits copying the relevant plots to the Clipboard in the Window system, which means that they can be copied to the report from the experiment. The WMF format ensures a small size of the files and a possibility to scale the figures.

The computer desktop contains a shortcut to the IrfanView program that can be used for simple bitmap image processing, e.g. of the whole computer window screenshot obtained by pressing Alt-PrintScreen.

4. Final remarks.

Besides the main result presented in the form of I(U) plot and description of the observation of lamp work, the report should give answers to the following questions.

1. What is the optimum (for best observation of the phenomenon) free path length of an electron? In which way the optimum gas pressure should be selected?
2. Why the minima in I(U) occur in regular distances? For the first four excitation regions calculate the velocities of the electrons that have reached the excitation regions with no energy loss. What was the velocity of the electrons that caused the excitation?
3. What is the energy of excitation of a neon atom? Is the wavelength corresponding to this energy in agreement with the red colour of the emitted light? Give the reasons for the disagreement and name two groups of instruments in which neon emission is employed.
4. What determines the width of the minima? Why the relative depth of subsequent minima decreases?
5. What is the velocity of electrons at which neon atoms get excited? The electron mass is 9.1×10^{-31} kg, while its charge is 1.6×10^{-19} C.
6. Evaluate the validity of the assumption of weak exchange of kinetic energy between electrons and neon atoms. Calculate the velocity that a static neon atom gets as a result of central collision with an electron travelling at the velocity calculated in task 5. The ratio of neon to electron masses is close to 40000. Make use of the principle of energy and momentum conservation.