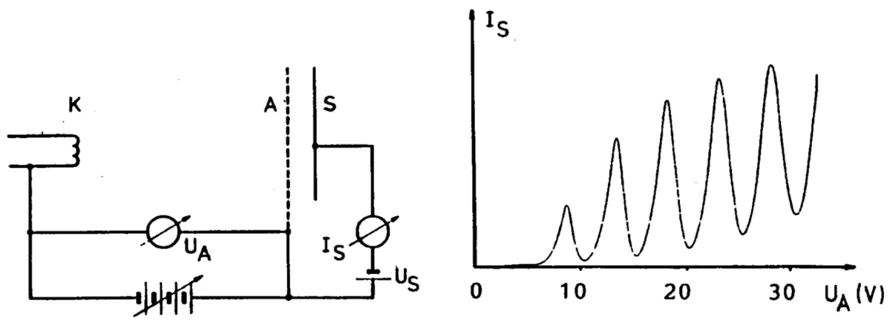
1 Basics

According to the Rutherford model, an atom consists of a positively charged core and negatively charged electrons, which orbit the core. The nucleus is very small compared to the size of the atom, but it contains almost the entire atomic mass. Since atoms themselves are not electrically charged, the positive charge of the nucleus is compensated completely by the negative charge of the electrons. The predictions of this model regarding the core were validated by scattering experiments with α-particles on metal foil. But the model could not explain the stability of atoms or the nature of the light emission (the occurrence of line/discrete spectra). According to the laws of the classical electrodynamics, the (by coulomb-interaction between core and shell of the atom) accelerated electrons should emit continuous radiation and collapse into the core due to their energy loss.

Bohr postulated, that electrons can orbit the core on trajectories of certain energies (shells) without radiating. During the transition of an electron between shells, electromagnetic radiation (light) is emitted or absorbed. The energy of the emitted photons (what´s this?) is $h\nu$, where ν is the frequency of the electromagnetic radiation. This energy corresponds to the energy difference between the shells, namely

$$\Delta E = h\nu. \tag{1}$$

The electron collision experiments, realized by Franck and Hertz in 1913, were a direct experimental confirmation of this quantum theory of the electron. They have shown, that atoms can get energetically excited by collisions with (free) electrons. The kinetic energy of the electron is transferred to the atom in energy quantums ΔE, which correspond to the characteristic excitation energy.



(a) (b)

Figure 1: (a) Setup of the experiment of Franck and Hertz (schematically) with cathode K, grid-shaped anode A, counter electrode S, counter voltage U_S (b) measuring results for $I_S(U_A)$, the locations of the minima and maxima differ in each case by a constant voltage difference of about 4.9 V.

Figure 1a shows the setup used by Franck and Hertz schematically: In an evacuated glass bulb, filled with one mercury drop, a Hg-steam pressure of some mbar is generated by external heating of a temperature of 150 °C to 200 °C. The bulb contains the electrodes K, A and S, to produce[1] free electrons and for the determination of the energy transfer by collisions with Hg-atoms. Electrons are released from the heated cathode K due to its thermal energy and accelerated by the voltage U_{A} towards the grid-shaped anode A.

The electrons collide with the Hg-atoms while traveling to the grid-shaped anode A (the mean free path of the electrons between two collisions in accordance with the Hg-steam pressure is about some µm). A part of the electrons is directly conducted to the anode grid. The other part of the electrons is braked due to a opposing field caused by the voltage U_{S} on its way to the counter electrode S, that lies behind anode A. Thus only electrons with a sufficient large kinetic energy can reach the electrode S. Figure 1b shows the current I_{S} to the counter electrode plotted versus the acceleration voltage U_{A} with a brake voltage $U_{\mathrm{S}} = 1.2\,\mathrm{V}$. If the voltage U_{A} is increased continuously from zero, the current I_{S} for $U_{\mathrm{A}} > U_{\mathrm{S}}$ will increase monotonously at first in accordance with the Hg-steam pressure and corresponding to the tube-like characteristics of the diode in the space-charge region ($I_{\mathrm{S}} \approx U_{\mathrm{A}}^{3/2}$). After an exceedance of a certain threshold voltage $U_{\mathrm{A}1}$ the current I_{S} decreases and passes minima and maxima, whose locations differ in each case by a constant voltage difference of approximately $4.9\,\mathrm{V}$, while U_{A} rises further. This behavior is explained by the type of the collisions, that the electrons suffer on the way between cathode and anode by the Hg-atoms. For voltages $U_{\mathrm{A}} < U_{\mathrm{A}1}$ all collisions are elastic, thus practically no kinetic energy is transferred because of the quite different masses of the particles brought to collision ($m_{\mathrm{Hg}}/m_e = 3.7 \times 10^5$).

The kinetic energy of the electrons, that pass the anode, is nearly equal for all electrons

$$E = e(U_{\mathrm{A}} - U_{\mathrm{K}}).$$

Where e is the elementary charge and U_{K} the contact voltage between cathode and anode (eU_{K} = difference of the electronic work function from these electrodes).

For voltages $U_{\mathrm{A}} - U_{\mathrm{K}} > U_{\mathrm{A}1} - U_{\mathrm{K}} = U_1 = 4.9\,\mathrm{V}$ inelastic collisions between electrons and Hg-atoms happen, too. Whereby the electrons emit the energy eU_1, that corresponds to the Hg-excitation energy between the ground state $6^1\mathrm{S}_0$ and the resonance level $6^2\mathrm{P}_1$. After an inelastic collision for acceleration voltages bigger than $U_{\mathrm{A}1}$, the electrons does not possess enough energy to overcome the opposing field between anode and counter electrode. This leads to the decrease of the current I_{S}, compare Fig. 1b. If the voltage U_{A} is growing further, the current I_{S} rises again, since the kinetic energy of the electrons for passing the opposing field is rising according to the increasing voltage. When the acceleration voltage U_{A} minus the contact voltage U_{K} reaches the n-fold of the excitation voltage U_1, n inelastic collisions between the electrons and the Hg-atoms happen on average. This results in the occurrence of further maxima in the current I_{S}.

Remark: With a different experimental arrangement of the Franck-Hertz-Experiment, fig. 1a, it is possible to determine other excitation energies of mercury and other atoms.

[1] Beware! Electrons cannot be produced (charge conservation)! But electrons can be released from a material, thus **free** electrons are produced.

The relaxation to the ground state of the Hg-atoms after the excitation caused by collisions is in the present experiment observed by the, as a result of the process, occurring light emission (at the anode, see 3 experimental setup). The direct transition ($\lambda = 254\,\mathrm{nm}$), according to the energy 4.9 eV,though can't be observed, since the wavelength is small.

2 Assignment of tasks

2.1 First task

The $I_\mathrm{S}(U_\mathrm{A})$–characteristic curves of a Franck-Hertz-tube at two different temperatures have to be recorded by a x-y plotter:

(a) at T_1 = approx. 175 °C for U_A = 0 V to 30 V and U_S = 0.5 V, 1.0 V, 1.5 V and 2 V

(b) at T_2 = approx. 200 °C for U_A = 0 V to 60 V and U_S = 2 V.

2.2 Second task

The results should be evaluated graphically and discussed afterwards. Determine the excitation voltage U_1 at the location of the maxima of the characteristic curves and compare it to the literature values. Discuss possible errors in the measurement.

3 Experimental setup

Figure 2 shows the circuit diagram of the present experiment. The Franck-Hertz-tube is covered by a housing with observation-windows at the side and back wall. The housing is heated by an electrical driven oven, that is connected to the AC grid (220 V) by a bimetal switch (T) and a var. autotransformer STr. Thus constant temperatures can be set in a wide range. A thermometer serves for the measurement of the temperature. The source for the acceleration voltage U_A, the counter voltage U_S and the cathode heating voltage (6.3 V) is a tube-power supply with a special control gear (shown in fig. 2 on the left beside the tube): The 0 V to 12 V output of the power supply is (gear) reduced with the potentiometer $^{10\,\mathrm{k\Omega}}/_{3.3\,\mathrm{k\Omega}}$ in proportion 4:1 for the generation of the counter voltage U_S (0 V to 3 V). The voltage output 0 V to 60 V (respectively 30 V) generates a temporally increasing voltage $U_\mathrm{A}(t)$ (charging voltage of the capacitor) when the switch S_1 is opened through the potentiometer $^{10\,\mathrm{k\Omega}}/_{2200\,\mathrm{\mu F}}$. The voltage $U_\mathrm{A}(t)$ is determined by a voltmeter and is attached to the x input of the plotter for recording the characteristic curves.

The current I_S of the tube (about 10^{-9} A to 10^{-8} A) will be measured by a DC measurement amplifier. Its output $U(I_\mathrm{S})$ (approx. 1 V) is connected to the y input of the plotter.

4 Experimentation

At first the Franck-Hertz tube must be heated. For this purpose the tube is driven by a turned on cathode heating and a var. autotransformer STr set to

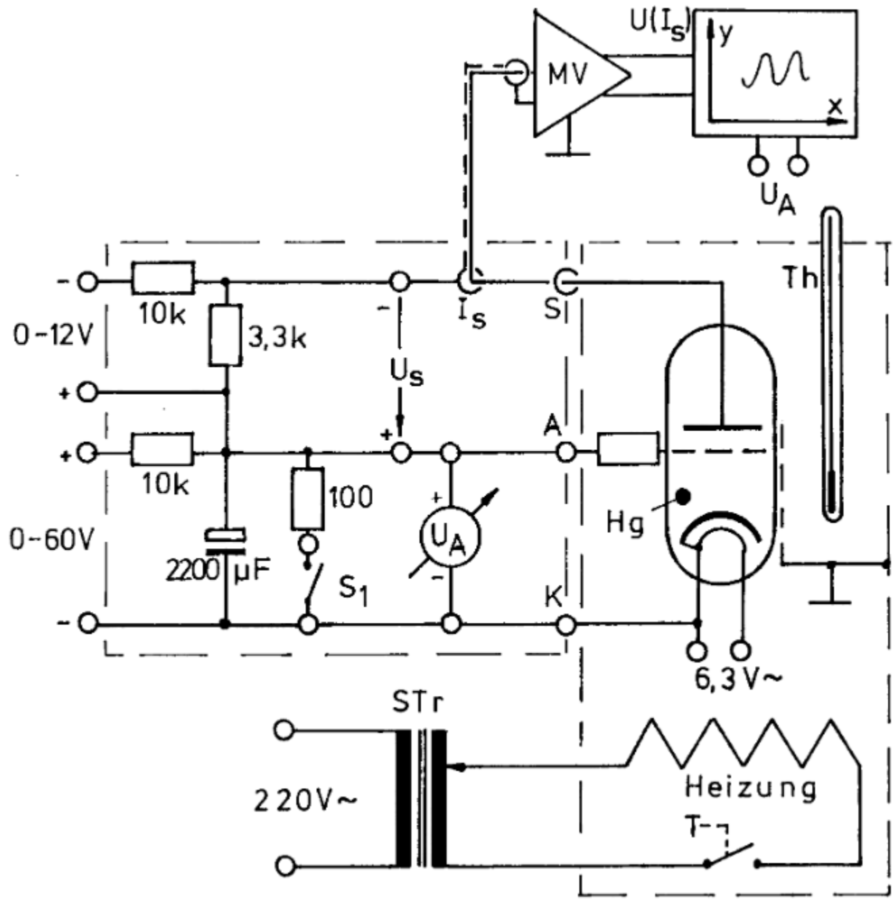


Figure 2: Circuit diagram of the Franck-Hertz experiment, with the potentiometer, the switch S_1, a voltmeter U_A on the left, the Franck-Hertz tube (elektrodes S, A and K) and a thermometer Th on the rigth, a x-y plotter on the top and a cathode heating (Heizung) with a var. autotransformer STr on the bottom.

approx. 200 V. The bimetal thermostat on the side wall of the oven is set to approx. 175 °C. When the tube reaches a temperature of approx. 160 °C, the transformer is set back to 140 V. If necessary the bimetal thermostat is set to the desired temperature. The remaining setup is connected in accordance with the circuit diagram, fig. 2. The mass connections of the amplifier and the housing also need to be connected. Before you start the recording of the characteristic curves, become familiar with the handling of the amplifier and the plotter.

For recording the characteristic curves at about 175 °C the following settings are necessary:

Measurement amplifier range:	10^{-8} A
Plotter, y input:	$0.1\,\mathrm{V\,cm^{-1}}$ var.: = ca. $30\,\mathrm{mV\,cm^{-1}}$
Plotter, x input:	$1\,\mathrm{V\,cm^{-1}}$ cal.

The 4 characteristic curves for all counter voltages U_S should be plotted together, if possible, after a test (start and end via opening and closing of S_1), into only one diagram.
For recording the characteristic curves at about 200 °C the following adjustments need to be performed:

Measurement amplifier range:	10^{-9} A
Plotter, y input:	$0.1\,\mathrm{V\,cm^{-1}}$ var.: = ca. $30\,\mathrm{mV\,cm^{-1}}$
Plotter, x input:	$10\,\mathrm{V\,cm^{-1}}$ var.: = ca. $2\,\mathrm{V\,cm^{-1}}$

Remark: If the tube is driven at about 200 °C, the characteristic curve in the range of $U_\mathrm{A} < 60\,\mathrm{V}$ should exhibit approx. 10 maxima and minima. For smaller temperatures, the ignition voltage for the corona discharge of the tube (what's this?) is below 60 V. Thus a corresponding smaller range for U_A needs to be chosen. A recording of the characteristic curve during the corona discharge is not useful for this experiment. The beginning of the corona discharge can be recognized by a stage in the characteristic curve of the tube and by light emission of the Hg-atoms around the cathode. At the same time it causes a rise of the anode current. The protective resistor (directly at the anode grid, see fig. 2) limits the current and prevents the destruction of the cathode respectively increasing its service life.

5 Evaluation

The characteristic curves need to be labeled (scale and zero points of the axes, specification of the respective brake voltage as curve parameter). The maxima of the curves should be identified/labeled and their spacings should be determined. The mean values of the spacings of the maxima, as well as the standard deviations have to be to determined separately for both temperatures T_1 and T_2. The results need to be compared to the literature value. Discuss the course of the characteristic curves and possible errors in the measurement.

6 Questions for Self-checking

- Interpret the course of the $I_\mathrm{S}(U_\mathrm{A})$ characteristic curve (fig. 1b).
- Why does the current I_S in the minima does not go back to zero?
- Why a counter voltage U_S is used?
- Which impact does the temperature of the Franck-Hertz tube have on the current I_S?
- Which kind of excitation takes place in the Hg-atom?
- Which wavelength does light, emitted by the Hg-atom after excitation caused by collisions, have? How does one prove it?