Franck-Hertz experiment with mercury

Recording with the oscilloscope, the XY-recorder and point by point

Objects of the experiment

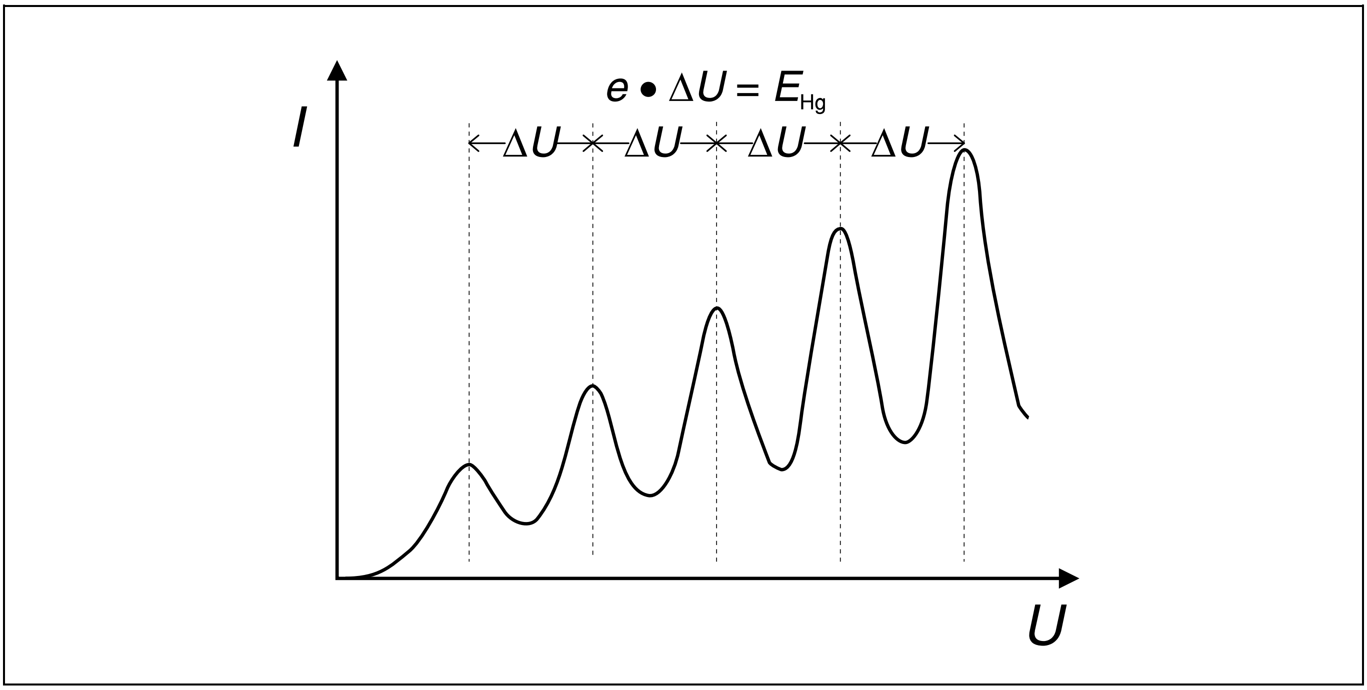
- To record a Franck-Hertz curve for mercury.
- To measure the discontinuous energy emission of free electrons for inelastic collision.
- To interpret the measurement results as representing discrete energy absorption by mercury atoms.

Principles

In 1914, *James Franck* and *Gustav Hertz* reported an energy loss occurring in distinct “steps” for electrons passing through mercury vapor, and a corresponding emission at the ultraviolet line (λ = 254 nm) of mercury. Just a few months later, *Niels Bohr* recognized this as evidence confirming his model of the atom. The Franck-Hertz experiment is thus a classic experiment for confirming quantum theory.

In a previously evacuated glass tube, mercury atoms are held at a vapor pressure of about 15 hPa, which is kept constant by temperature control. This experiment investigates the energy loss of free electrons due to inelastic scattering, and thus due to collision excitation of mercury atoms.

The electron current flowing to the collector as a function of the acceleration voltage in the Franck-Hertz experiment with mercury (schematic representation)



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Apparatus

1 Franck-Hertz tube, Hg 555 85
1 Socket for Franck-Hertz tube,
Hg with multi-pin plug 555 861
1 Electric oven, 220 V 555 81
1 Franck-Hertz supply unit 555 88
1 Temperature sensor, NiCr-Ni 666 193

Recommended for optimizing the Franck-Hertz curve:

1 Two-channel oscilloscope 303 . . . . 575 211
2 Screened cables BNC/4 mm 575 24

Recommended for recording the Franck-Hertz curve:

1 XY-Yt recorder SR 720 . . . . 575 663
Connecting leads

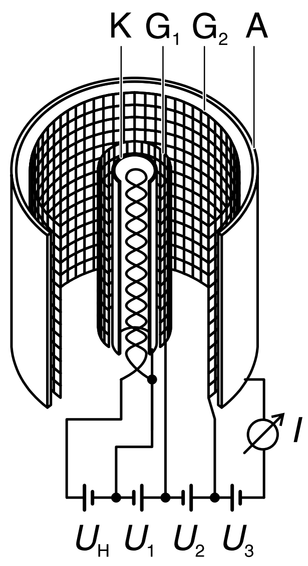


Fig. 1: Schematic diagram of the mercury Franck-Hertz tube

The glass tube contains a cylindrically symmetrical system of four electrodes (see Fig. 1). The cathode K is surrounded by a grid-type control electrode G_1 at a distance of a few tenths of a millimeter, an acceleration grid G_2 at a somewhat greater distance and finally the collector electrode A outermost. The cathode is heated indirectly, in order to prevent a potential differential along K.

Electrons are emitted by the hot electrode and form a charge cloud. These electrons are attracted by the driving potential U_1 between the cathode and grid G_1. The emission current is practically independent of the acceleration voltage U_2 between grids G_1 and G_2, if we ignore the inevitable punch-through. A braking voltage U_3 is present between grid G_2 and the collector A. Only electrons with sufficient kinetic energy can reach the collector electrode and contribute to the collector current.

In this experiment, the acceleration voltage U_2 is increased from 0 to 30 V while the driving potential U_1 and the braking voltage U_3 are held constant, and the corresponding collector current I_A is measured. This current initially increases, much as in a conventional tetrode, but reaches a maximum when the kinetic energy of the electrons closely in front of grid G_2 is just sufficient to transfer the energy required to excite the mercury atoms (E_{Hg} = 4.9 eV) through collisions. The collector current drops off dramatically, as after collision the electrons can no longer overcome the braking voltage U_3.

As the acceleration voltage U_2 increases, the electrons attain the energy level required for exciting the mercury atoms at ever greater distances from grid G_2. After collision, they are accelerated once more and, when the acceleration voltage is sufficient, again absorb so much energy from the electrical field that they can excite a mercury atom. The result is a second maximum, and at greater voltages U_2 further maxima of the collector currents I_A.

Preliminary remark

The complete Franck-Hertz curve can be recorded manually.

For a quick overview, e. g. for optimizing the experiment parameters, we recommend using a two-channel oscilloscope. However, note that at a frequency of the acceleration voltage U_2 such as is required for producing a stationary oscilloscope pattern, capacitances of the Franck-Hertz tube and the holder become significant. The current required to reverse the charge of the electrode causes a slight shift and distortion of the Franck-Hertz curve.
An XY-recorder is recommended for recording the Franck-Hertz curve.

a) Manual measurement:

– Set the operating-mode switch to MAN. and slowly increase U_2 by hand from 0 V to 30 V.
– Read voltage U_2 and current I_A from the display; use the selector switch to toggle between the two quantities for each voltage.

b) Representation on the oscilloscope:

– Connect output sockets U_2/10 to channel II (0.5 V/DIV) and output sockets U_A to channel I (2 V/DIV) of the oscilloscope. Operate the oscilloscope in XY-mode.
– Set the operating-mode switch on the Franck-Hertz supply unit to ”Sawtooth”.
– Set the Y-position so that the top section of the curve is displayed completely.

c) Recording with the XY-recorder:

– Connect output sockets U_2/10 to input X (0.2 V/cm CAL) and output sockets U_A to input Y (1 V/cm CAL) of the XY-recorder.
– Set the operating-mode switch on the Franck-Hertz supply unit to RESET.

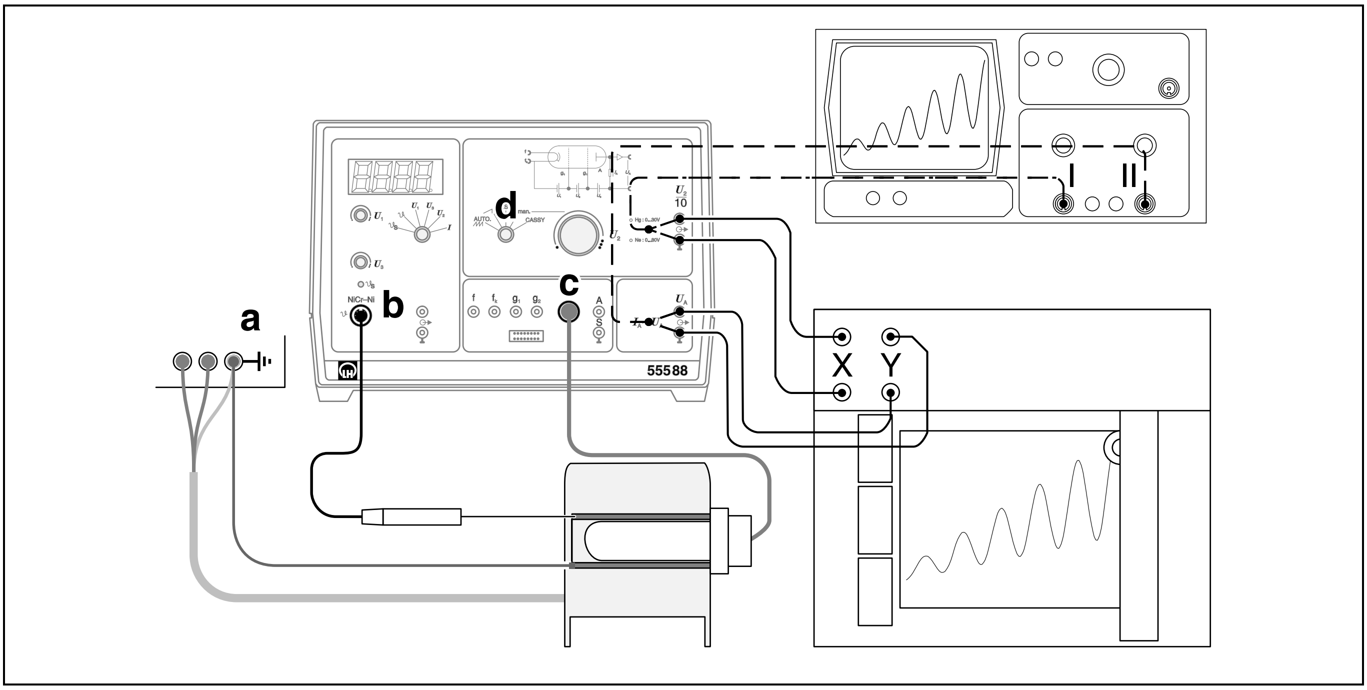


Fig. 2: Experiment setup for the Franck-Hertz experiment with mercury

- Adjust the zero-point of the recorder in the X and Y direction and mark this point by briefly lowering the recorder pen onto the paper.
- To record the curve, set operating-mode switch to “Ramp” and lower the recorder pen.
- When you have completed recording, raise the pen and switch to RESET.

Setup

Fig. 2 shows the experiment setup.

First:

- Make sure the Franck-Hertz supply unit is switched off.
- Connect the heating oven via the 4-mm safety sockets **(a)** on the rear of the supply unit.
- Additionally, connect the copper lead of the copper sleeve with 4-mm plug to the green-yellow safety socket (to screen the Franck-Hertz tube from interference fields).
- Insert the DIN plug of the temperature sensor in socket **(b)** of the supply unit and the DIN plug of the Franck-Hertz tube in socket **(c)**.

Heating:

Note:
If the thermal contact of the temperature sensor is poor, the measured oven temperature will be too low, resulting in overheating of the tube.

- Insert the temperature sensor in the corresponding blind hole of the heating oven as far as it will go and slide the Franck-Hertz tube with copper sleeve into the oven.
- Turn the operating-mode switch **(d)** to RESET and switch on the supply unit (after a few seconds, the LED indicator for mercury (Hg) changes from green to red).
- Check the default setting ϑ_S = 180 °C and wait until the operating temperature is reached (LED indicator changes from red to green; the temperature ϑ first reaches a maximum, and then declines to the final value).

If the indicator in the display flashes:

- There is a mistake in the setup for temperature measurement (see the Instruction Sheet).

Optimizing the Franck-Hertz curve:

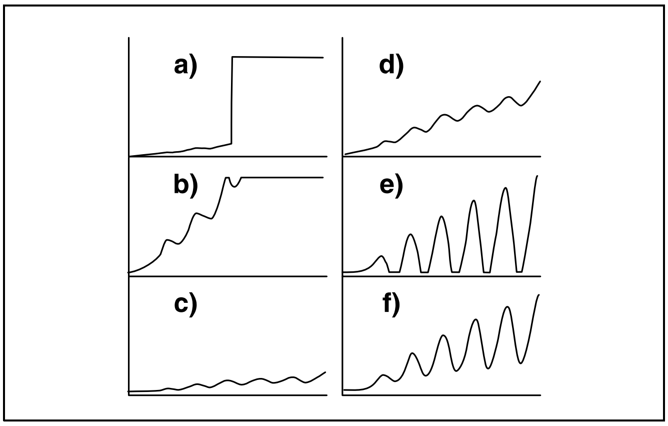
- Set the driving potential U_1 = 1.5 V and the braking voltage U_3 = 1.5 V and record the Franck-Hertz curve (see preliminary remark).

a) Optimizing ϑ

If the Franck-Hertz curve rises abruptly (see Fig. 3 a) and you can see a gas discharge in the Franck-Hertz tube through the insertion opening of the oven (blue glow):

- Immediately turn the operating-mode switch to RESET and wait until the setup reaches the operating temperature.
- If necessary, raise the set value ϑ_S using the screwdriver potentiometer (e.g. by 5 °C) and wait a few minutes until the system settles into the new thermal equilibrium.

Fig. 3: Overview for optimizing the Franck-Hertz curves by selecting the correct parameters ϑ, U_1 and U_3.



b) Optimizing U_1:

A higher driving potential U_1 results in a greater electron emission current.

If the Franck-Hertz curve rises too steeply, i.e. the overdrive limit of the current measuring amplifier is reached at values below U_2 = 30 V and the top of the Franck-Hertz curve is cut off (Fig. 3b):

– Reduce U_1 until the curve steepness corresponds to that shown in Fig. 3d.

If the Franck-Hertz curve is too flat, i.e. the collector current I_A remains below 5 nA in all areas (see Fig. 3c):

– Increase U_1 (max. 4.8 V) until the curve steepness corresponds to that shown in Fig. 3d.

If the Franck-Hertz curve is flat even after increasing U_1:

– Reduce the set value ϑ_S for the oven temperature using the screwdriver potentiometer.

c) Optimizing U_3:

A greater braking voltage U_3 causes better-defined maxima and minima of the Franck-Hertz curve; at the same time, however, the total collector current is reduced.

If the maxima and minima of the Franck-Hertz curve are insufficiently defined (see Fig. 3d):

– Alternately increase first the braking voltage U_3 (maximum 4.5 V) and then the driving potential U_1 until you obtain the curve form shown in Fig. 3f.

If the minima of the Franck-Hertz curve are cut off at the bottom (see Fig. 3e):

– Alternately reduce first the braking voltage U_3 (maximum 4.5 V) and then the driving potential U_1 until you obtain the curve form shown in Fig. 3f.

Carrying out the experiment

– Record the Franck-Hertz curve (see preliminary remark).
– To better demonstrate the first maxima, you can increase the sensitivity of the Y-input and repeat the recording process.

Measuring example and evaluation

U_1 = 1.58 V

U_3 = 3.95 V

ϑ_S = 180 °C

In Fig. 4, the average of the intervals between the successive maxima gives us the value

ΔU_2 = 5.1 V.

This corresponds to an energy transfer of

ΔE = 5.1 eV

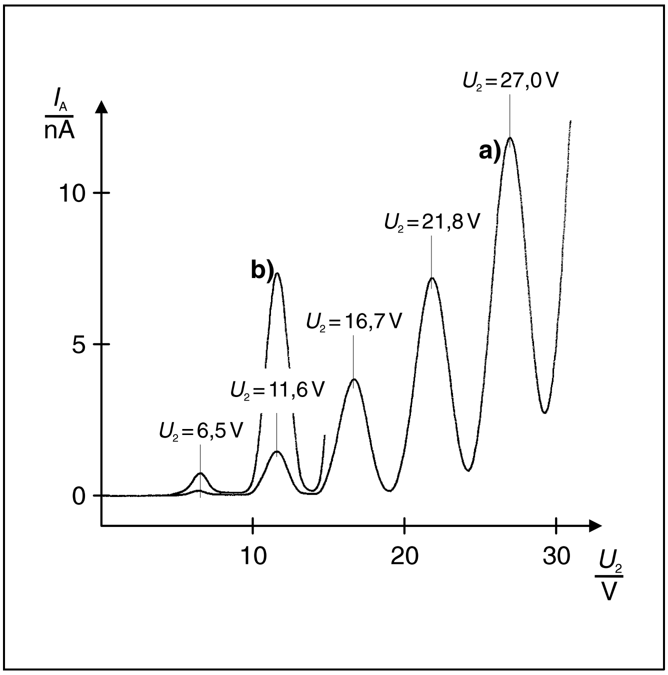


Fig. 4: a) Franck-Hertz curve of mercury (recorded with XY-recorder)
b) Curve section, with ordinate enlarged five times

We can compare this value with the literature value

E_{Hg} = 4.9 eV

for the transition energy of the mercury atoms from the ground state $^1S_0$ to the first $^3P_1$ state.

The kinetic energy of the electrons at grid G_2 can be calculated as

$E_{kin} = (U_1 + U_2)$

On the basis of this, we would expect the first maximum of the collector current at $U_1 + U_2$ = 4.9 V. In fact, the first maximum is not registered until $U_1 + U_2$ = 8.1 V. The difference between the two values is the effective contact potential between cathode K and grid G_2.

Supplementary information

A number of factors influence the effective contact potential. The most important of these deserve mention here.

The actual contact potential is caused by the different work of emission of the cathode and grid materials. The emission properties of the mixed-oxide cathode and the gas charge resp. the mercury coating of the grid play an important role here.

The electrons emitted by the hot cathode have an initial velocity which depends on the temperature of the cathode.