Atomic and nuclear physics

Atomic shell

Franck-Hertz experiment

Franck-Hertz experiment with neon - Recording and evaluation with CASSY

Description from CASSY Lab 2

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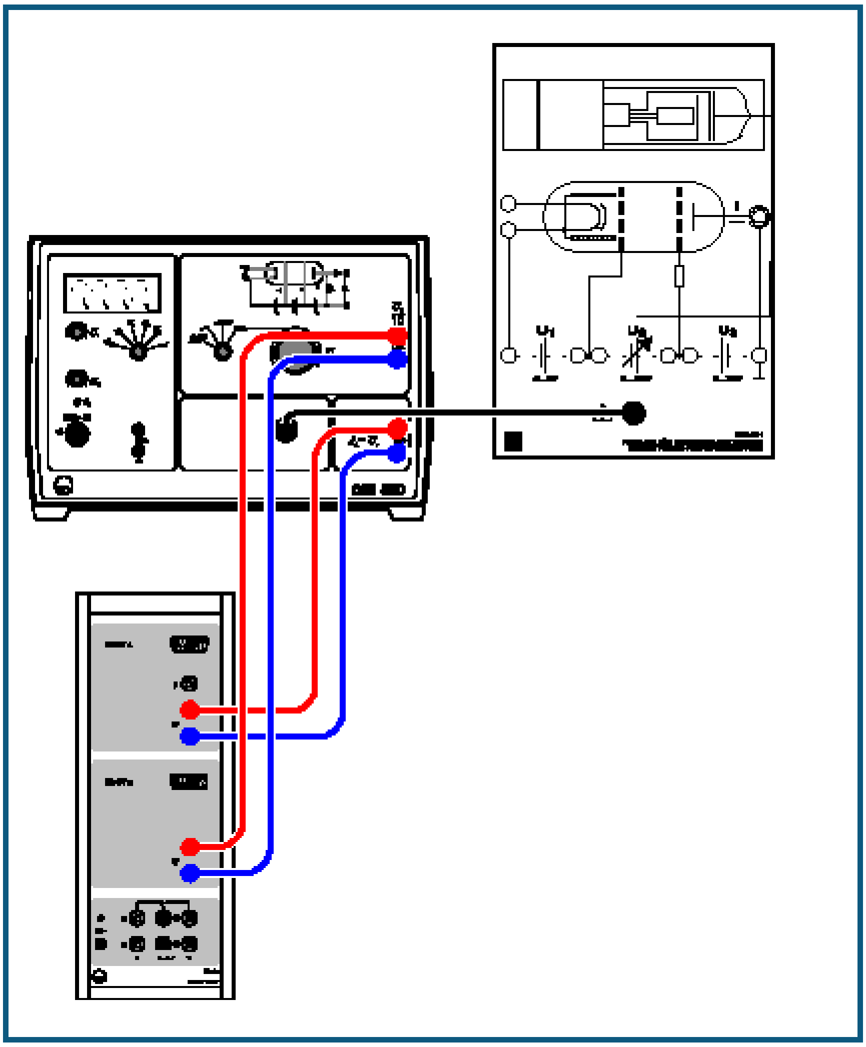
CASSY Lab 2 (2013-06-07)

Franck-Hertz experiment with neon

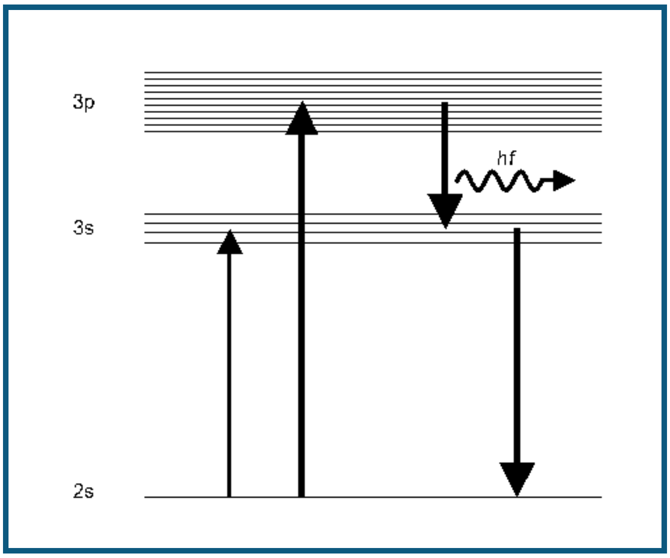


 can also be carried out with Pocket-CASSY

Experiment description

In 1914, James Franck and Gustav Hertz reported an energy loss occurring in distinct "steps" for electrons passing through mercury vapour, 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 this experiment, the energy loss of free electrons through inelastic scattering (excitation through impact) from neon atoms is investigated. Most probably the excitation occurs from the ground state to the ten 3p states, which are 18.4 eV and 19.0 eV above the ground state. The four slightly lower 3s states at 16.6 eV to 16.9 eV are less likely to be excited. The de-excitation of the 3p states to the ground state by emission of photons is only possible with a detour via the 3s states. The light emitted during this process within the visible range between red and green and can therefore be observed without any equipment.



An evacuated glass tube is filled with neon at room temperature to a gas pressure of about 10 hPa. The glass tube contains a system of four electrodes. Electrons are emitted by the hot cathode and form a charge cloud. These electrons are attracted by the driving potential U_1 between the cathode and the grid-shaped control electrode G_1 and then accelerated by the acceleration voltage U_2 in the direction of grid G_2. Between G_2 and the collector electrode, a braking voltage U_3 is applied. Only electrons with sufficient kinetic energy can reach the collector and contribute to the collector current.

In this experiment, the acceleration voltage U_2 is increased from 0 to 80 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 neon atoms 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 neon 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 neon atom. The result is a second maximum, and at greater voltages U_2 further maxima of the collector current I_A.

Equipment list

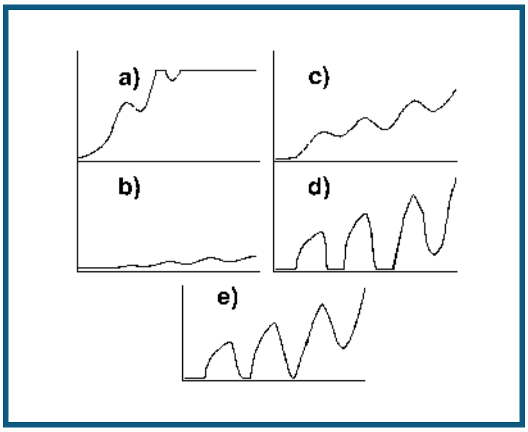
1	Sensor-CASSY	524 010 or 524 013
1	CASSY Lab 2	524 220
1	Ne Franck-Hertz tube	555 870
1	Holder with socket	555 871
1	Connecting cable for Ne-FH	555 872
1	Franck-Hertz supply unit	555 880
2	Pairs of cables, 100 cm, red and blue	501 46
1	PC with Windows XP/Vista/7/8	

Experiment setup (see drawing)

- Clamp the Ne Franck-Hertz tube in the socket on the holder and connect by means of a connection cable to the socket "Franck-Hertz tube" of the Franck-Hertz supply unit.
- Set the operating-mode switch on the Franck-Hertz supply unit to RESET.
- Connect voltage input A for the Sensor-CASSY to output U_A for the voltage proportional to the collector voltage and the voltage input B of Sensor-CASSY at output $U_2/10$ for the acceleration voltage.

Carrying out the experiment

- Load settings
- Set the driving potential U_1 = 1.5 V and the braking voltage U_3 = 5 V and record the Franck-Hertz curve in the "Ramp" operating mode. To do this, start the measurement by pressing and immediately set the operating mode switch to "Ramp". The measurement is automatically stopped after 40 s, then return the operating mode switch to RESET.



1) 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 = 80 V and the top of the Franck-Hertz curve is cut off (a):

- Reduce U_1 until the curve steepness corresponds to (c).

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

- Increase U_1 until the curve steepness corresponds to (c).
- If necessary, optimize the cathode heating as described in the Instruction Sheet for the Franck-Hertz supply unit.

2) 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 (c):

- Alternately increase first the braking voltage U_3 and then the driving potential U_1 until you obtain the curve form shown in (e).

If the minima of the Franck-Hertz curve are cut off at the bottom (d):

- Alternately reduce first the braking voltage U_3 and then the driving potential U_1 until you obtain the curve form shown in (e).

The Ne Franck-Hertz tube in the experimental example was measured using the parameters U_1 = 1.5 V and U_3 = 7.9 V.

Evaluation

The recorded curve is evaluated by drawing vertical lines (by eye) to find the distance between the subsequent maxima. In the experimental example, an average value of U_2 = 18.2 V is found. This value is much closer to the excitation energies for the 3p-levels of neon (18.4-19.0 eV) than to the energies of the 3s-levels (16.6–16.9 eV). Thus, the probability of excitation to the latter due to inelastic electron collision is significantly less.

The substructure in the measured curve shows that the excitation of the 3s-levels cannot be ignored altogether. Note that for double and multiple collisions, each combination of excitation of a 3s-level and a 3p-level occurs.

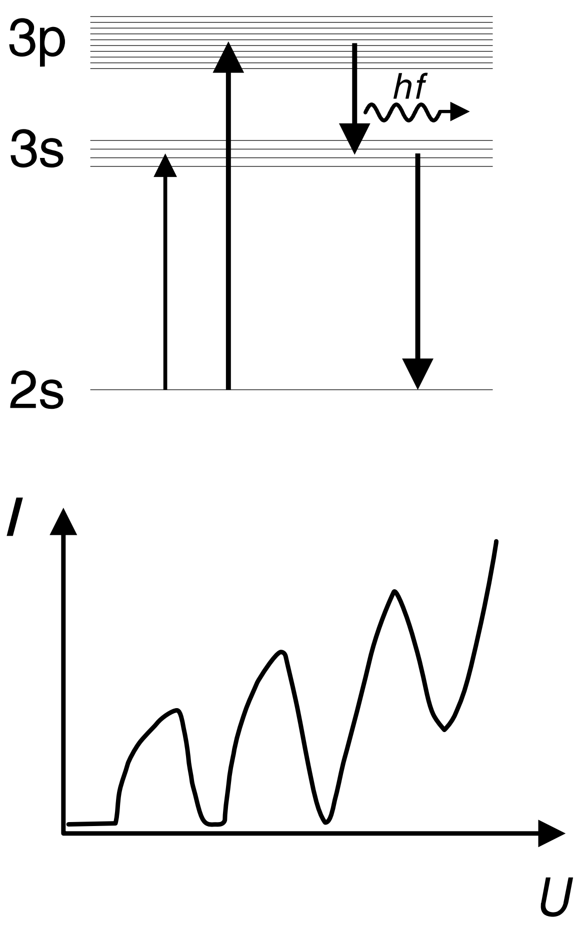
In the Ne Franck-Hertz tube, luminous zones can be observed which depend on the acceleration voltage. They directly correlate with the minima of the Franck-Hertz curve.

Franck-Hertz experiment with neon

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

Objects of the experiment

- To record a Franck-Hertz curve for neon.
- To measure the discontinuous energy emission of free electrons for inelastic collision.
- To interpret the measurement results as representing discrete energy absorption by neon atoms.
- To observe the Ne-spectral lines resulting from the electron-collision excitation of neon atoms.
- To identify the luminance phenomenon as layers with a high probability of excitation.



Top: Simplified term diagram for neon.
Bottom: The electron current flowing to the collector as a function of the acceleration voltage in the Franck-Hertz experiment with neon

Principles

As early as 1914, *James Frank* and *Gustav Hertz* discovered in the course of their investigations an “energy loss in distinct steps for electrons passing through mercury vapor”, and a corresponding emission at the ultraviolet line (λ = 254 nm) of mercury. As it is not possible to observe the light emission directly, demonstrating this phenomenon requires extensive and cumbersome experiment apparatus.

For the inert gas neon, the situation is completely different. The most probable excitation through inelastic electron collision takes place from the ground state to the ten 3p-states, which are between 18.4 eV and 19.0 eV above the ground state. The four lower 3s-states in the range from 16.6 eV and 16.9 eV are excited with a lower probability. The de-excitation of the 3p-states to the ground state with emission of a photon is only possible via the 3s-states. The light emitted in this process lies in the visible range between red and green, and can thus be observed with the naked eye.

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Apparatus

1 Franck-Hertz tube, Ne	555 870
1 Holder with socket and screen for 555 870	555 871
1 Connecting cable to Franck-Hertz tube, Ne	555 872
1 Franck-Hertz supply unit	555 88

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	

An evacuated glass tube is filled with neon at room temperature to a gas pressure of about 10 hPa. The glass tube contains a planar system of four electrodes (see Fig. 1). The grid-type control electrode G_1 is placed in close proximity to the cathode K; the acceleration grid G_2 is set up at a somewhat greater distance, and the collector electrode A is set up next to it. The cathode is heated indirectly, in order to prevent a potential differential along K.

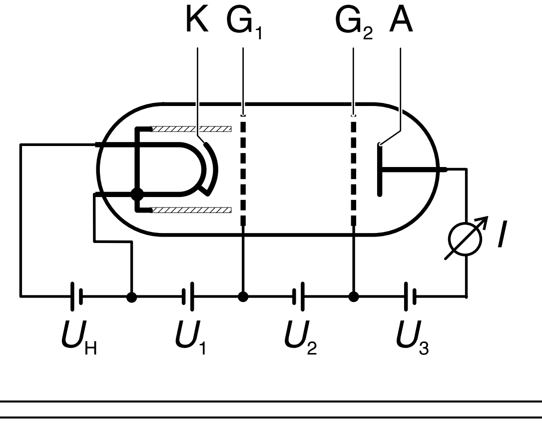
Electrons are emitted by the hot electrode and form a charge cloud. These electrons are attracted by the driving potential U_1 between the cathode and grid G_1. The emission current is practically independent of the acceleration voltage U_2 between grids G_1 and G_2, if we ignore the inevitable punch-through. 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 80 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 neon atoms 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 neon 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 neon atom. The result is a second maximum, and at greater voltages U_2 further maxima of the collector currents I_A.

At higher acceleration voltages, we can observe discrete red luminance layers between grids G_1 and G_2. A comparison with the Franck-Hertz curve shows them to be layers with a higher excitation density.

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



Preliminary remark

The complete Franck-Hertz curve can be recorded manually.

For a quick *survey,* 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 80 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 (1 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 (0.5 V/cm) and output sockets U_A to input Y (1 V/cm) of the XY-recorder.
– Set the operating-mode switch on the Franck-Hertz supply unit to RESET.
– 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.

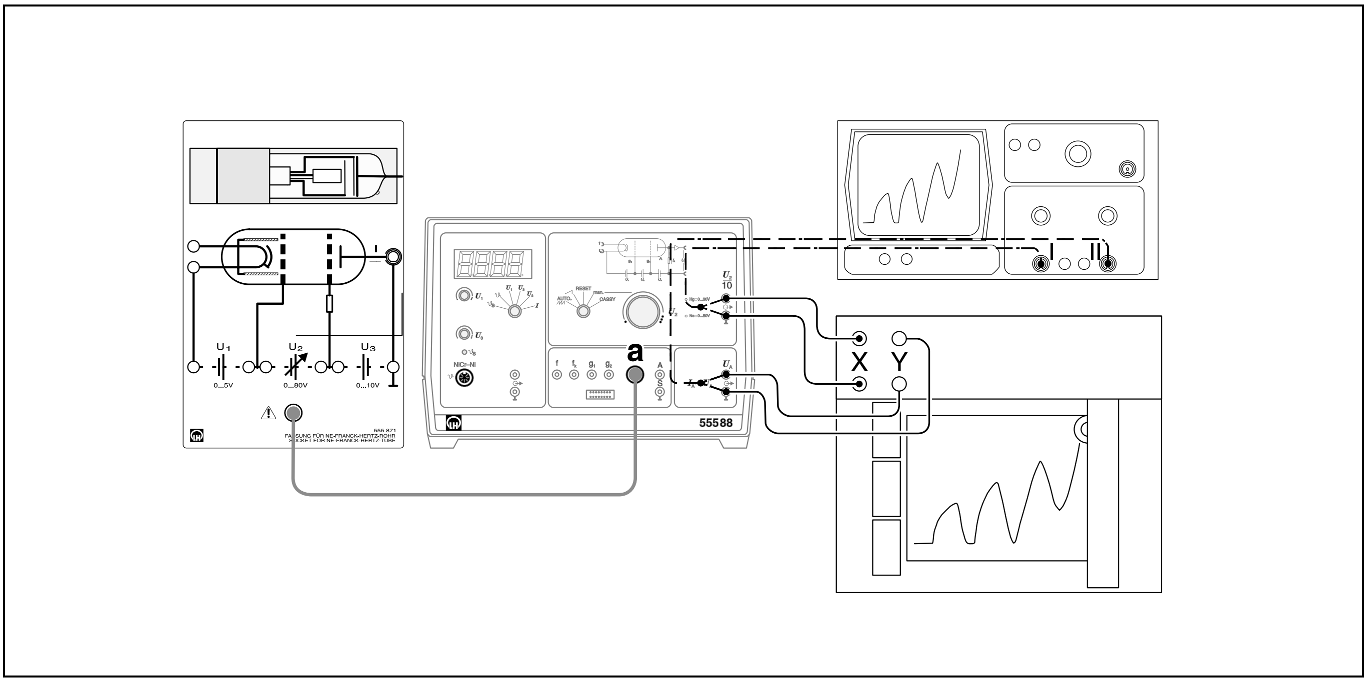


Fig. 2: Experiment setup for Franck-Hertz experiment with neon

Setup

Fig. 2 shows the experiment setup.

First:

– Insert and secure the Franck-Hertz tube in the holder and connect it to socket **(a)** on the Franck-Hertz supply unit via the connecting cable.

Optimizing the Franck-Hertz curve:

– Set the driving potential U_1 = 1.5 V and the braking voltage U_3 = 5 V and record the Franck-Hertz curve (see preliminary remark).

a) 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 = 80 V and the top of the Franck-Hertz curve is cut off (Fig. 3a):

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

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

– Increase U_1 until the curve steepness corresponds to that shown in Fig. 3c.
– If necessary, optimize the cathode heating as described in the Instruction Sheet for the Franck-Hertz supply unit.

b) 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.

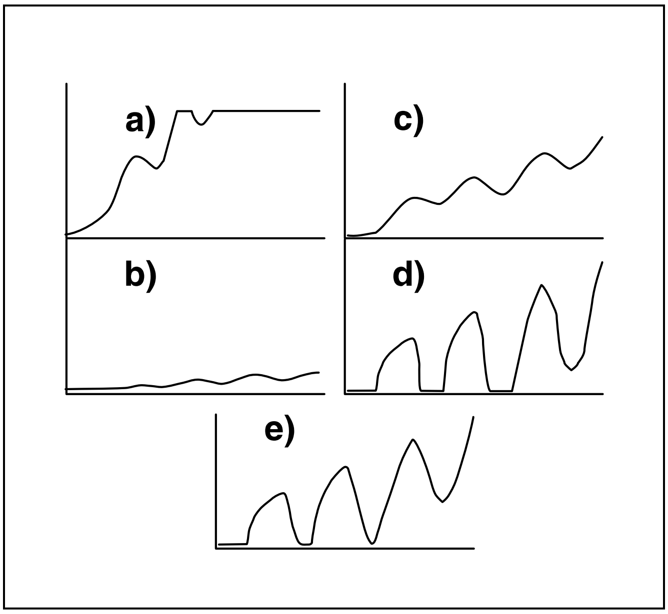
If the maxima and minima of the Franck-Hertz curve are insufficiently defined (see Fig. 3c):

– Alternately increase first the braking voltage U_3 (maximum 18 V) and then the driving potential U_1 until you obtain the curve form shown in Fig. 3e.

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

– Alternately reduce first the braking voltage U_3 (maximum 18 V) and then the driving potential U_1 until you obtain the curve form shown in Fig. 3e.

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



Carrying out the experiment

a) Franck-Hertz curve:

– Record the Franck-Hertz curve (see preliminary remark).

b) Light emission:

– Set the operating mode switch to MAN.
– Optimize the acceleration voltage U_2 until you can clearly see a red-yellow luminance zone between grids G_1 and G_2.
– Additionally, find the optimum acceleration voltages for two or three luminance zones and log these values.

Measuring example and evaluation

a) Franck-Hertz curve:

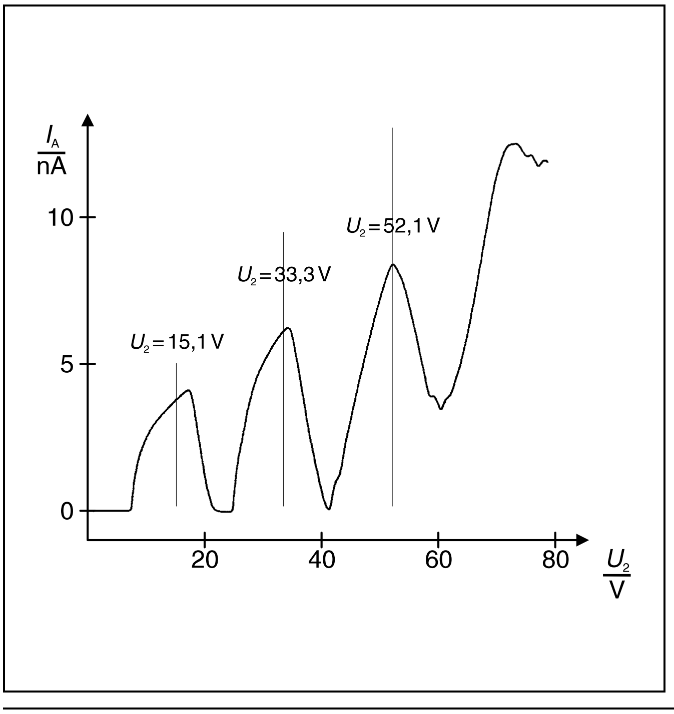
U_1 = 2.06 V

U_3 = 7.94 V

The distance between the vertical lines (these were placed by eye on the main points of the maxima) has an average value of ΔU_2 = 18.5 V. This value is much closer to the excitation energies for the 3p-levels of neon (18.4 – 19.0 eV) than to the energies of the 3s-levels (16.6 – 16.9 eV). Thus, the probability of excitation to the latter due to inelastic electron collision is significantly less.

The substructure in the measured curve shows that the excitation of the 3s-levels cannot be ignored altogether. Note that for double and multiple collisions, each combination of excitation of a 3s-level and a 3p-level occurs.

Fig. 4: Franck-Hertz curve for neon (recorded using an XY-recorder)



b) Light emission:

U_1 = 2.06 V

U_3 = 7.94 V

The luminance layers are zones of high excitation density. They can be compared directly with the minima of the Franck-Hertz curve. Their spacing corresponds to an acceleration voltage U_2 = 19 V. Therefore, an additional luminance layer is generated each time U_2 is increased by approx. 19 V (see table 1).

Table 1: Number *n* of the luminance zones in relation to the acceleration voltage U_2

n	U_2
1	30 V
2	48 V
3	68 V

Supplementary information

The emitted neon spectral lines can be observed easily e.g. with the school spectroscope (467 112) when the acceleration voltage U_2 is set to the maximum value.