The Franck-Hertz experiment (FHV)

1. Key words

Line spectra, series formulae, level scheme, Rydberg constant, Ritz combination principle, Planck constant, Bohr theory of the atom, quantum mechanics, electron-atom collisions, atomic excitations, light emission, fluorescent lamp.

2. Literature

1. *W. Finkelnburg,* Einführung in die Atomphysik, Springer, 1997.
2. *Bergmann-Schäfer,* Lehrbuch der Experimentalphysik, vol. VI, part 1, De-Gruyter, 1981.
3. J. *Becker, H.-J. Jodl*, Physikalisches Praktikum für Naturwissenschaftler und Ingenieure, VDI-Verlag, 1991.

3. Basics

The Franck-Hertz experiment is one of the basic experiments of atomic physics. It shows that electrons can move only on discrete orbits around the atomic nucleus and that the binding energies for the outermost electrons are of the order of magnitude eV.
When free electrons are accelerated in a voltage of several volts, they may - by inelastic collisions - excite bound electrons into higher, unoccupied orbits. According to the Bohr model only those orbits in an atom are allowed, which have an orbital angular momentum L that is an integer multiple n of $\hbar = h/2\pi$.

$$L = m \cdot v \cdot r = n \cdot \hbar. \qquad (1)$$

In this formula h means the Planck constant and m, v and r mass, velocity and radius, respectively, of the electron in the atom. In addition, Bohr postulated that electron transitions are possible only between states that have an energy corresponding to such special orbits. Hence the emission of a spectral line with frequency f is connected with a transition of an electron from an orbit with energy E_2 to an orbit with energy E_1 by

$$h \cdot f = E_2 - E_1. \qquad (2)$$

With the aid of this picture atomic spectra may be easily understood. The Franck-Hertz experiment gave a direct experimental proof of the Bohr theory.
In our experiments mercury and neon atoms are excited by electron impact. A simplified level scheme of mercury is shown in Fig. 1. The outermost electron (with principal

quantum number n= 6, i.e. in the P orbit) has – in the ground state – the energy 0 eV and can, by gaining energy (e.g. by electron impact), perform the transitions shown in the Figure. From these excited states the electron may, by emission of light (with wavelengths in nm indicated next to the transition), jump to a less excited state. Because of the selection rules for the angular momentum (which are different for electron impact and for light emission) only certain transitions are allowed:

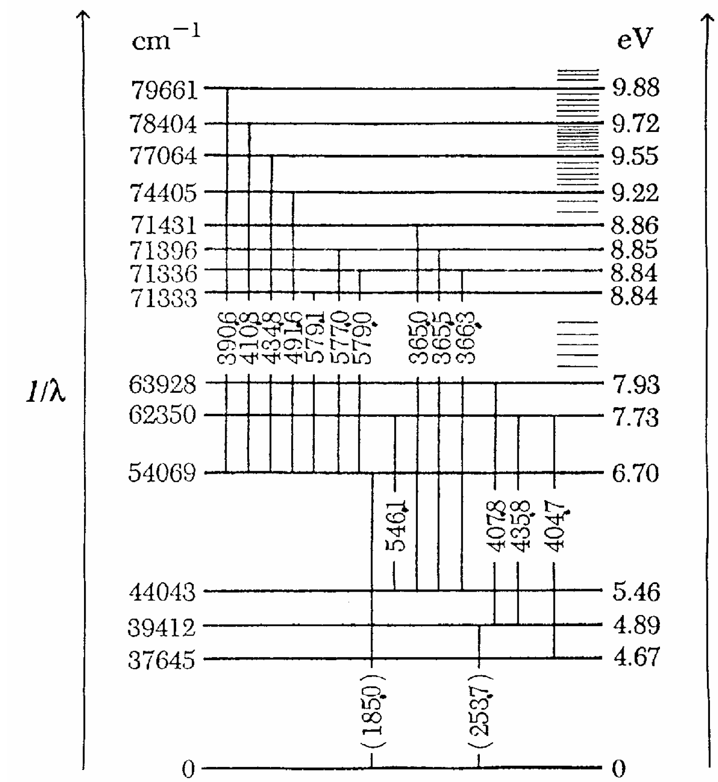

Figure 1: Level scheme of the neutral mercury atom.

A schematic representation of the experiment is shown in Fig. 2. In a tube filled with mercury vapor electrons are ejected from a thermionic cathode and accelerated by a variable voltage between cathode and anode grid *G*. A small reverse potential (about 0.5 V) is applied between anode grid and electron collector *A*. The current into the collector electrode is measured as a function of the acceleration voltage.

Even if the voltage *U* is increased slowly the current *I* increases quite steeply; the electrons loose only negligible amounts of energy on impact with the mercury atoms. Hence the electrons - part of which fly through the anode grid - have enough energy to overcome the reverse potential. If the voltage *U* becomes large enough to let the energy $e \cdot U$ of the colliding electron near the anode be sufficiently large to lift an electron of the mercury atom from the ground state to the first excited state, the colliding electrons loose so much energy that they become unable to overcome the reverse bias. This makes the collector current decrease strongly. The same is true if the energy of the accelerated electrons is just sufficiently large to perform on their way from cathode to anode two, three or more excitation collisions.

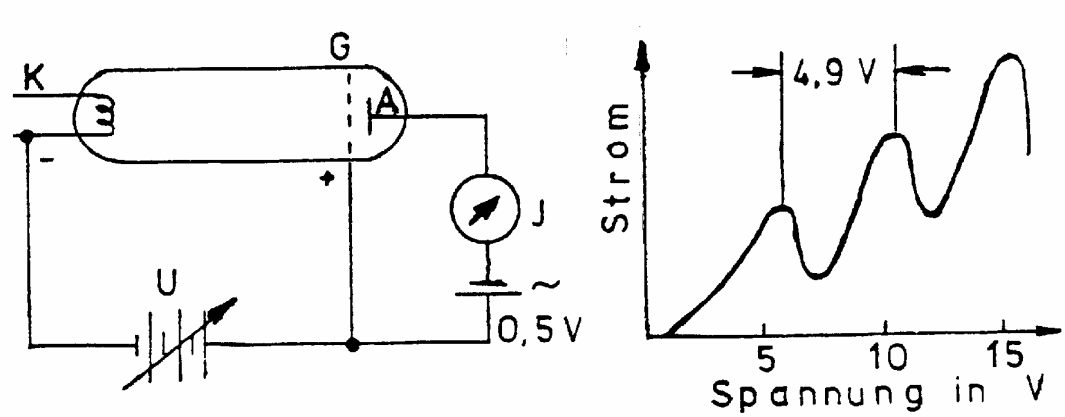

Figure 2: The Franck-Hertz experiment: a) Principle of the arrangemen; b) Current-voltage characteristic. *Strom* = current; *Spannung* = voltage.

For mercury the maximum values for the collector current are found at distances of 4.9 V; this means that the first excited state of the mercury atom lays 4.9 eV above the ground state. According to relation (2) we find (with c the speed of light)

$$\Delta E = h \cdot f = h \cdot c / \lambda . \tag{3}$$

Thus the excitation energy of 4.9 eV corresponds to a wavelength $\lambda = 253.7$ nm. Spontaneous de-excitation to the ground state should result in the emission of a photon of just that wavelength. Indeed, Franck and Hertz were able to detect during their collision experiments this spectral line in the ultraviolet region. Hence it was proven that the spectral lines have to be understood as electron transitions between discrete energy states, as it was proposed in the Bohr model.

Neon atoms may also be excited by electron impact. An excerpt from the level scheme of neon is shown in Fig. 3. Because of a higher density of states and the selection rules electron collisions preferentially excite states in the region from 18.3 to 18.9 eV. In contrast to mercury the excited neon atoms do not return directly by emission of light to the ground state. At first they spontaneously loose about 2 eV and perform transitions to states between 16.75 and 16.79 eV excitation energy. The emitted light lies in the spectral range of visible light. It contains several red and yellow spectral lines [(yellow)/585 nm – (red)/703 nm]. In the Franck-Hertz experiment this light may be observed as weak glow. We start with an acceleration voltage 0 and slowly increase this voltage. At a voltage of 19 V the electrons gain the energy necessary to excite the neon atoms just in front of the anode grid (G in Fig. 2). At this voltage, when the collector current starts to decrease, one observes a weakly glowing layer at the anode. Increasing the acceleration voltage still more shifts this layer and increases the collector current again. At an acceleration voltage of about 38 V a second glowing gas layer appears at the anode, while the first one has moved to the mid-point between cathode and anode. In this case the electrons reach already halfway between cathode and anode the energy necessary to excite the neon atoms by impact. Afterwards the electrons are accelerated again and are able to excite the neon atoms by collisions a second time, this time in front of the anode. If we increase the acceleration voltage still more, a new glowing layer appears after reaching a new maximum in the voltage-current characteristics, while the other layers move towards the cathode.

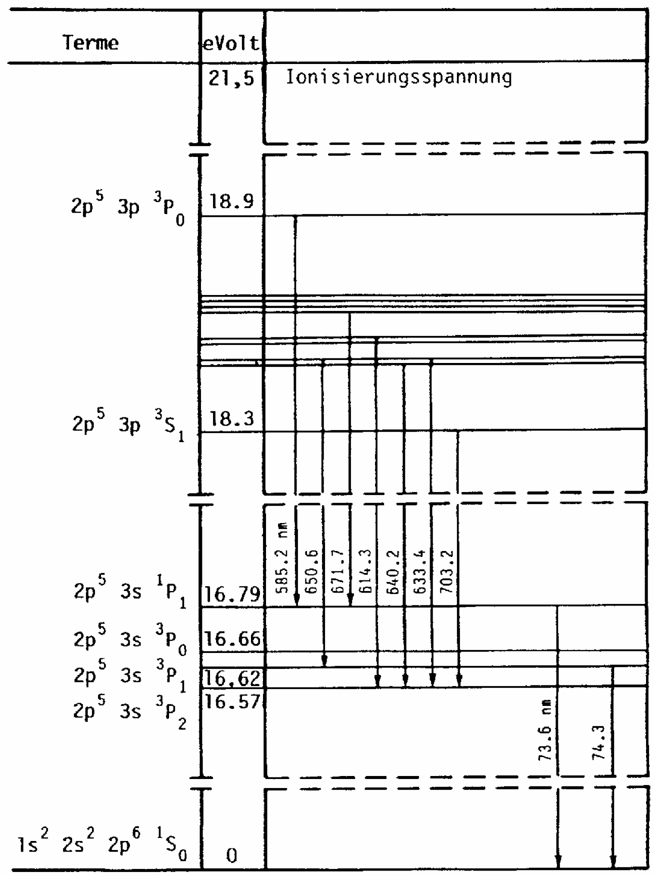

Figure 3: Level scheme for the neon atom. *Terme* = levels; *Ionisierungsspannung* = ionization voltage.

4 The Franck-Hertz experiment with mercury
4.1 Experimental arrangement

The central part of the experimental arrangement is the Franck-Hertz tube. It is positioned inside an oven. In the tube control device you will find the voltage supply for the tube and a sensitive DC current amplifier for the collector current. An oscilloscope and devices for temperature and voltage measurement complete the equipment. The circuit diagram is shown in Fig. 4. In the interior of the Franck-Hertz tube we find – from outside to inside – the following cylindrical electrodes: collecting grid A, anode grid g_2,

space-charge grid g_1, and cathode *K* (indirectly heated with the help of filament *f*). The tube also contains a drop of mercury.
The measurements are most successful at a mercury vapor pressure of about 1 – 2 kPa. In order to reach this pressure the tube has to be heated to temperatures between 170° C and 200° C. Therefore the mercury tube is placed inside an oven, whose temperature may be varied. A feedback control keeps the temperature of the oven sufficiently constant at a value that may be set with a rotary knob; you find it at the side of the oven.

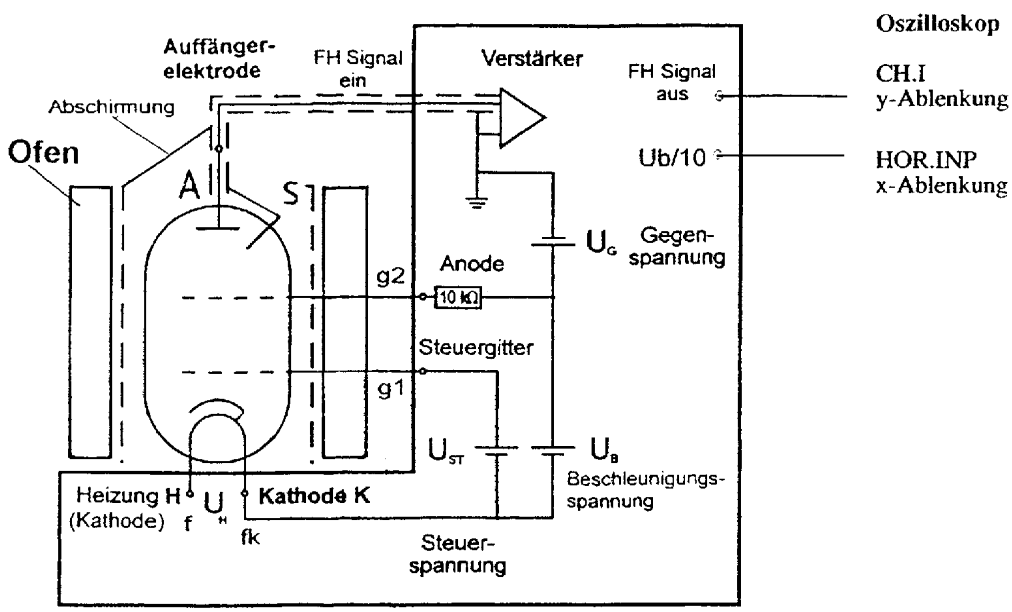

Figure 4: Circuit diagram for the Franck-Hertz tube.

4.2 Experimental task

a) Heat the oven to about 180° C.
b) Verify the Franck-Hertz diagram on the screen of the oscilloscope.
c) Find the values of the decelerating voltage U_G between anode grid and collecting grid, which give especially strong maxima and minima, when the acceleration voltage U_B is varied between 0 and 40 V.
d) Draw a sketch of this Franck-Hertz diagram in your minute book.
e) Determine mean value and error of the voltage difference between two adjacent maxima. Calculate from the excitation voltage you received the wavelength of the resulting emission line ($h = 4.136 \cdot 10^{-15}$ eV·s; $c = 2.9979 \cdot 10^{8}$ m/s).

4.3 Realization of the experiment

Assemble the wiring according to Fig. 4.

Important: Before you switch on the set-up, let the tutor check the arrangement.

4.3.1 Optimization

As soon as the oven has reached a temperature of 180° C, you may switch on the tube control. You should do so only after you have turned the control knob for the accelerating voltage to “0 V”.
At first you should try to produce a current-voltage characteristic with as many strong maxima and minima as possible. To this end you have to choose a proper set of operating voltages for the different electrodes. The possibility to change the acceleration voltage U_B within 0.01 s approximately linearly from zero to a maximum value U_{Bm} makes this task a good deal easier. The signal repetition rate is 50 Hz (cf. Fig. 5). For this mode of operation you have to throw the switch below the regulator for the voltage (on the front panel of the operating module) rightwards. With the operating module used here the voltage does not increase as linearly with time as it is shown in Fig. 5. For our measurement this, however, is not important (why??). The maximum value U_{Bm} may be set to values between 0 and 70 V.

Attention: During the experiment with the mercury tube U_{Bm} may not at all exceed 45 V! Otherwise ionization of the gas in the tube will occur!

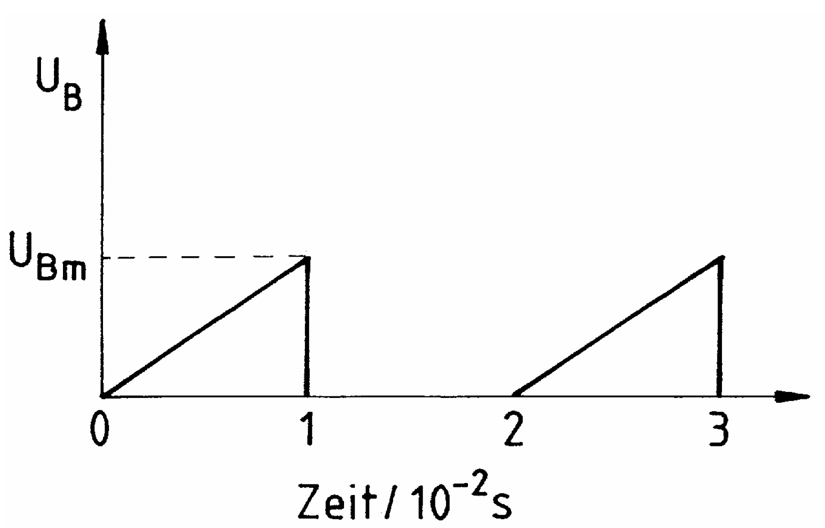

Figure 5: Time dependence of the acceleration voltage. *Zeit* = time.

Make the dependence of the collector current from the accelerating voltage visible on the oscilloscope screen. Afterwards you should be able to deduce the excitation energy. To this end the output of the measuring amplifier, which produces a voltage that is proportional to the collector current, is connected to the input "CH.I" of the oscilloscope for the y-sweep. The acceleration voltage determines the x sweep at the oscilloscope. Please connect the output "x-Ablenk." of the tube control module (which provides a voltage $0.1 \cdot U_B$) to the input "HOR. INP" of channel II at the oscilloscope. Afterwards you may switch the oscilloscope to X-Y operation. With a suitable choice of the different voltages at the electrodes of the Franck-Hertz tube, which should be taken from the data sheet at the experiment, you will produce a curve on the screen of the oscilloscope, which shows a pattern with maxima and minima, similar to that of Fig. 2b. Vary – ***with care*** – the reverse bias U_G between anode grid g_2 and collector electrode A until you see at minimum four distinct maxima.

If the vapor pressure is too low, caused by too low a tube temperature, not all of the 4.9-eV electrons will transfer their energy to mercury atoms; they can acquire higher energies and finally lead to ionization and a, highly unwanted, gas discharge. Such a discharge may be recognized by a sudden increase of the collector current. If, on the other hand, the vapor pressure is too high, which results from the tube being too hot, the electrons are scattered by elastic collisions with the mercury atoms to such an extent that the anode current remains very small for all acceleration-voltage values. The maxima and minima are no longer clearly seen or are invisible at all. Sharper extrema lead to a better determination of the distance.

The voltage difference corresponding to the distance between the maxima is the quantity that shall finally be measured. The current-voltage characteristic on the screen is suited to optimize the various tube parameters. In order to extract values for the acceleration voltage, it is mandatory to calibrate the x-sweep. For this reason the voltage difference between the maxima is determined in different way.

4.3.2 Measurement of the excitation energy

The acceleration voltage is available at the tube control module also as DC voltage and may be controlled by hand. For this the switch below the control knob has to be thrown to the leftward position and the oscilloscope has to be switched to DC mode. With the aid of a digital voltmeter the acceleration voltage may now be measured between the output jack "U_B/10" ("x-Abl.") and ground. At this output, however, only 1/10 of the real voltage is available. Using the U_B voltage regulator, you may go through the whole current-voltage curve by hand. Determine the position of the maxima and minima and measure the corresponding voltage values. State for each value also the uncertainty of the measured values.

5 The Franck-Hertz experiment with neon
5.1 The experimental arrangement

The vapor pressure of neon gas in the Franck-Hertz tube has a value of some hPa. The indirectly heated cathode, the control and anode grids, and the collector electrode are of disc shape and arranged coplanar. Control grid and anode grid have a distance of about 5 mm, both, the distance cathode - control grid and anode – collector are 2 mm. The wiring scheme is presented in Fig. 6.

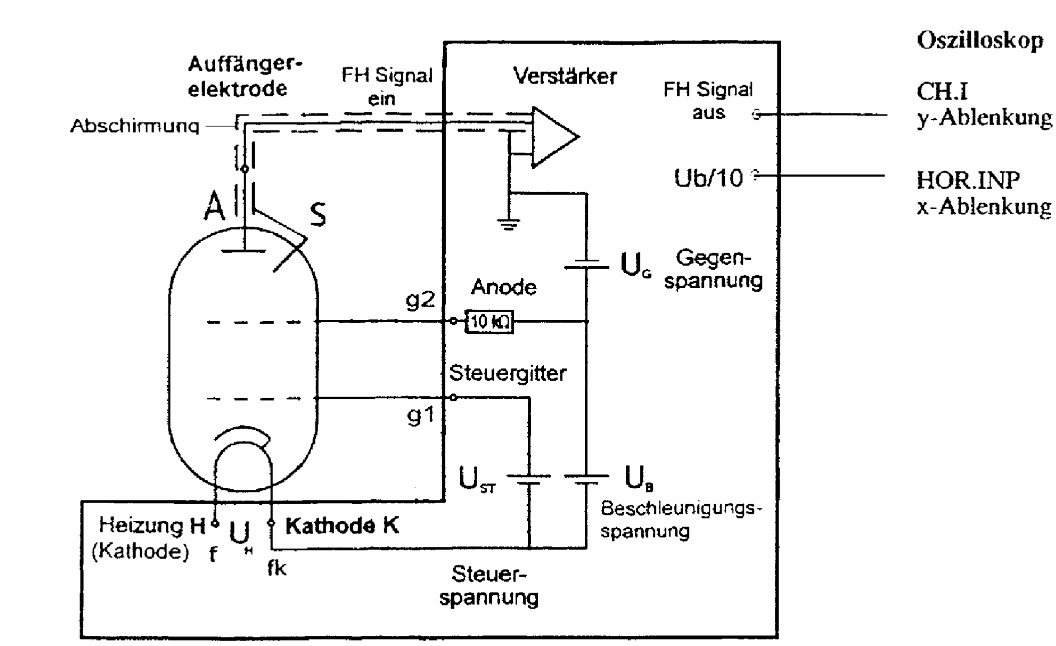

Figure 6: Experimental arrangement for neon.

5.2 Experimental task

a)..d)
Heating the tube is not necessary. Follow the instructions b) to e) of chapter 4.2.

e) Measure the wavelength of the emitted light with the aid of a pocket spectroscope.

5.3 Realization of the experiment

Please optimize the working conditions under periodic variation of the acceleration voltage, as described in chapter 4.3.1. Afterwards you should measure with oscilloscope and voltmeter the position of maxima and minima of the Franck-Hertz curve and state the experimental uncertainties. Observe the light emission after electron impact excitation in the space between the grids. After each new maximum a new glowing layer appears.

pears. In order to determine the spectral lines with the pocket spectrometer, you have to strongly suppress the scattered light from the surroundings.

Please disassemble the wiring at the end of the experiment!

5. Questions

a) Explain the terms *elastic collision* and *inelastic collision*?
b) Why is an electron at energies below 4.9 eV only able to perform elastic collisions?
c) Why is the energy an electron can transfer to an atom low in elastic collisions?
d) How does an atom excited by an inelastic collision dispose itself of the acquired energy?
e) What is the difference between the excitation of an atom by electrons and by light quanta?
f) Why is it necessary to apply a deceleration voltage between collector electrode and anode grid?
g) Compare the functionality of a Franck-Hertz tube with that of a fluorescent lamp and try to understand this lamp with the help of the schematic sketch. Why are these lamps called fluorescent lamps? [cf. Bergmann-Schäfer, Lehrbuch der Experimentalphysik, vol. III (Optik)]
h) What is the difference to an x-ray tube?

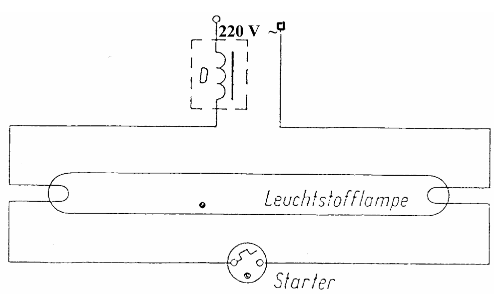

Figure 7: Scheme of a fluorescent lamp. *Leuchtstofflampe* = fluorescent lamp.