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

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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 $\hbar = h/2\pi$.

$$L = m \cdot v \cdot r = n \cdot \hbar. \tag{1}$$

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

$$h \cdot f = E_2 - E_1. \tag{2}$$

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:

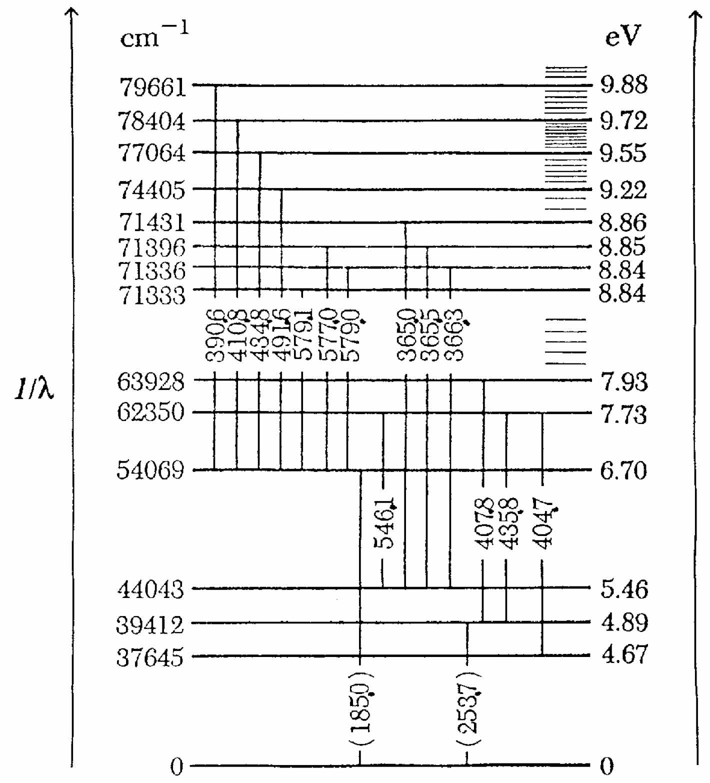

Figure 1: Level scheme of the neutral mercury atom.

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.

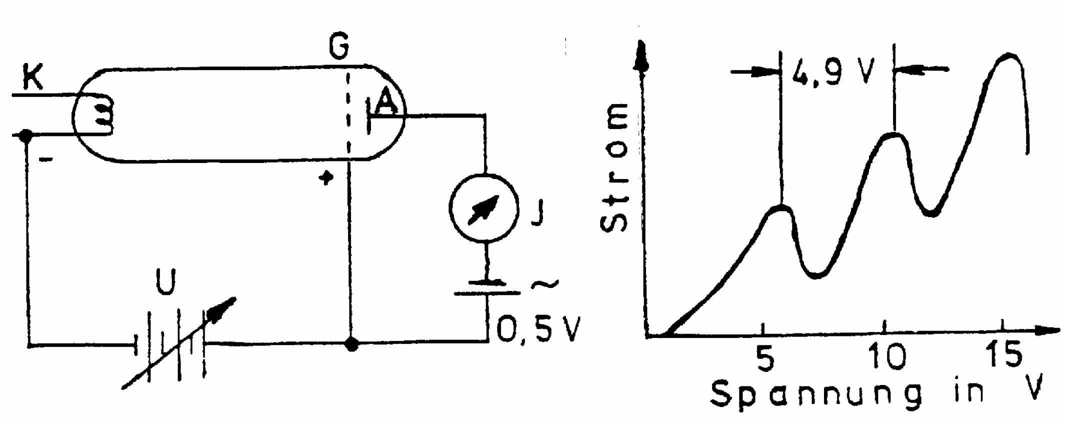

Figure 2: The Franck-Hertz experiment: a) Principle of the arrangemen; b) Current-voltage characteristic. *Strom* = current; *Spannung* = voltage.

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 λ = 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.

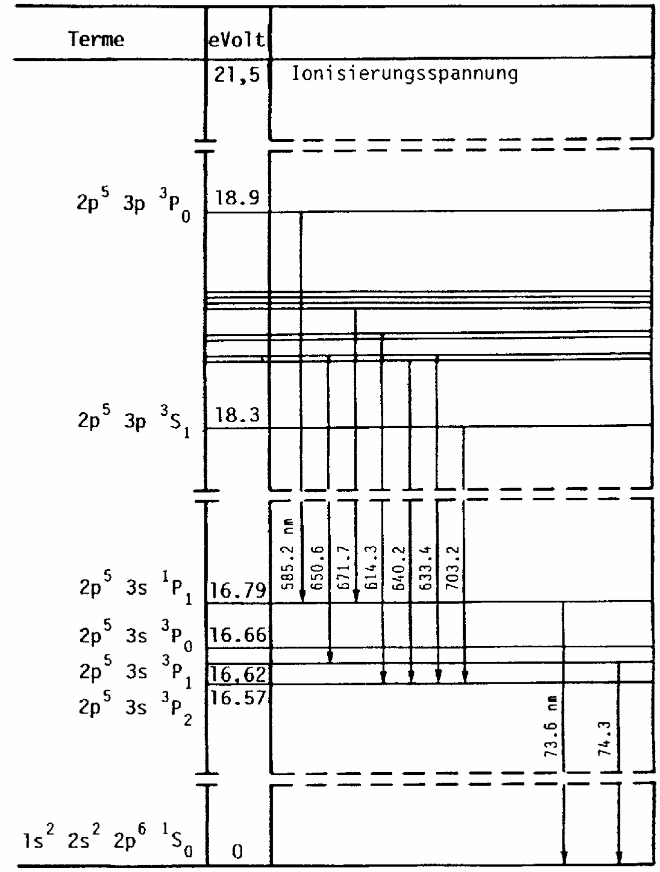

Figure 3: Level scheme for the neon atom. *Terme* = levels; *Ionisierungsspannung* = ionization voltage.