Franck-Hertz-Versuch (FHV)

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Abstract

This Experiment identifies the necessary amount of energy to excited mercury and neon atoms. The experiment shows that the excitation energy is quantised as a multiple of a certain energy and is, such a proof of discrete energy levels in atoms.

1 Theoretical Foundation

According to Bohr's atom model, the electron is able to revolve in certain stable orbits around the nucleus without radiating any energy. These stable orbits are called stationary orbits and are attained at certain discrete distances from the nucleus. The stationary orbits are given by the value of their angular momentum, which is shown to be an integer multiple of Planck's reduced constant $\hbar$,

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

where $m,\ v$ and r is the mass, velocity and radius of the electron in the atom.
Furthermore, an electron is only able to move between discrete states, in which a photon with the energy,

$$E_2 - E_1 = \frac{hc}{\lambda} \ , \tag{2}$$

is emitted, where E_2 is the higher energy state and E_1 the lower, c is the speed of light and λ is the wavelength of the emitted photon. So according to Bohr; atoms can be excited, meaning the transfer of an atomic electron to a higher state, only by the addition of a discrete amount of energy to the atom. This can either be through the transfer of kinetic energy from a second particle or by the absorption of a photon with the aforementioned wavelength λ.

1.1 Energy Levels and the Excitation of Atoms

The Frank-Hertz Experiment is based on collisions between accelerated electrons and Atoms in a Gas Tube. We discern between two electron energy regimes, in the first energy regime the kinetic energy of an electron is below 4.9eV. In the second regime, the kinetic energy is above or equal to 4.9eV. The first regime is characterized by elastic collisions, in which the colliding particle maintains its kinetic energy; the atom remains unexcited. The second regime is dominated by inelastic collisions, wherein a, as explained previously, discrete amount of kinetic energy is transferred to the atom and the atom are excited.

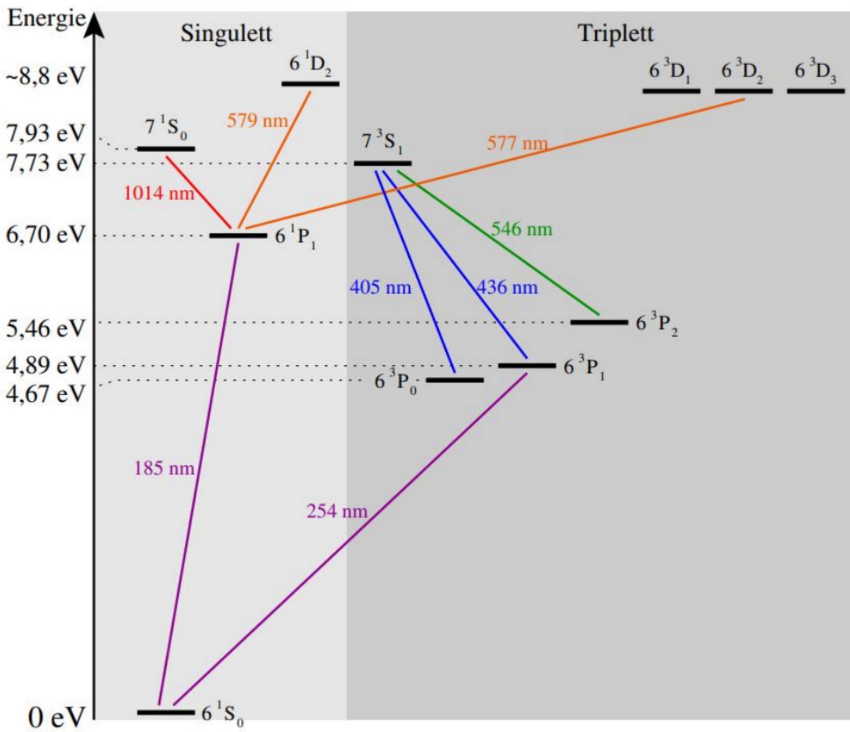


Figure 1: excitation scheme of a mercury atom

Figure 1 shows us the excitation scheme of the mercury atom. The outer electron of the mercury atom, with the principle quantum number of six, has a ground state energy of 0eV. From this state, it can be excited to two higher energy levels. Which is shown in the figure as violet lines. From these energy levels, further excitement can take place. The excited states are principally unstable, meaning after a given amount of time the atom will, in means of photon emission, return to it's ground state. The photons emitted by mercury returning to its ground state from its first excited state have the wavelength of 254nm.

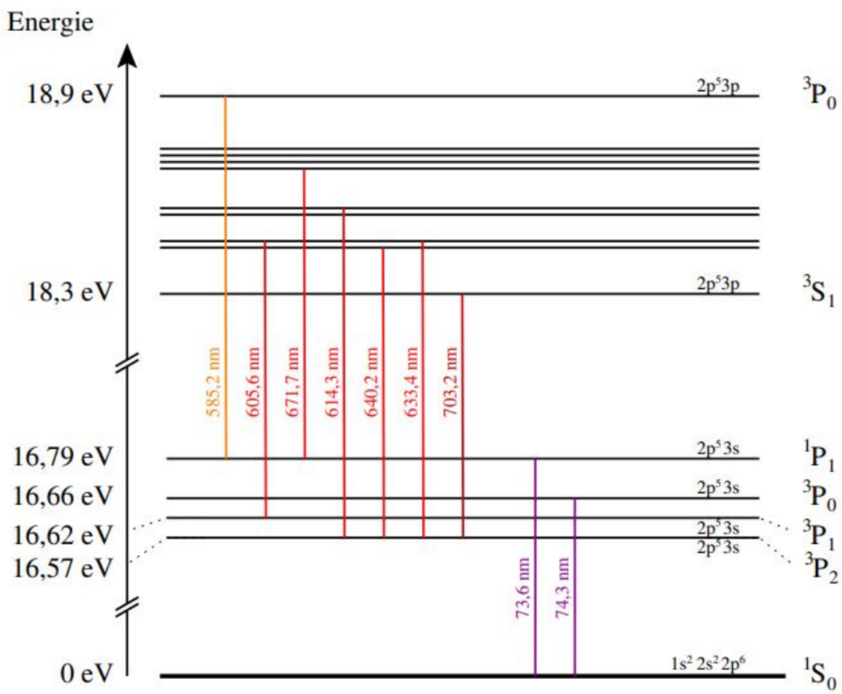


Figure 2: excitation scheme of a neon atom

Figure 2 shows the excitation scheme of a neon atom. Notably, neon atoms are excited to an energy level of between $18,3$eV and $18,9$eV through electron collisions. The return to ground state is characterized by the emission of two photons via an intermediate energy level between $16,57$eV and $16,79$eV. The photons from the first photon emission have wavelengths within the visible spectrum, namely between a yellow 585nm and a red 703nm. The neon atoms can be excited from an electron energy of 19eV.

1.2 Characteristic Voltage-Current Curves

The Frank-Hertz experiment outputs characteristic voltage-current curves, whereby the current is proportional to the amount of electrons reaching the Anode, we plot the current against the accelerating voltage and see the characteristic curve of the atomic gas. An example of one of these Plots is shown in figure 3. The curves can be interpreted as follows, as the voltage changes electron gain energy faster and reach excitation energy sooner after atom excitement electrons don't have enough energy to reach the anode so the current sinks. the increasing voltage means, that one electron is accelerated ever faster and reaches excitement energy multiple times, and the process is repeated. Resulting in the wave form of the curve.

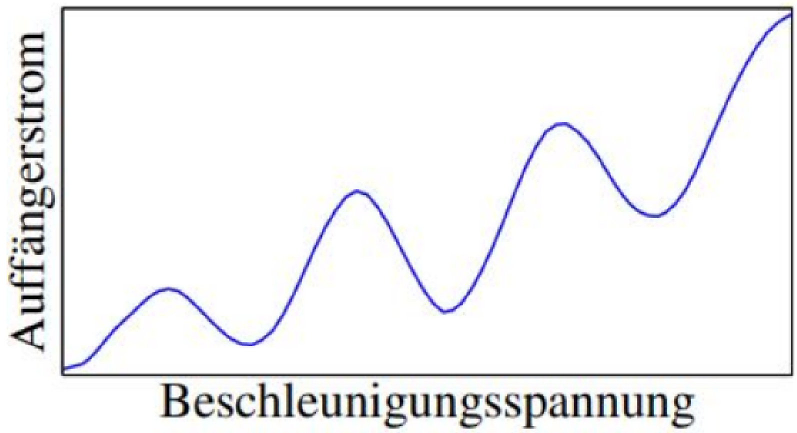
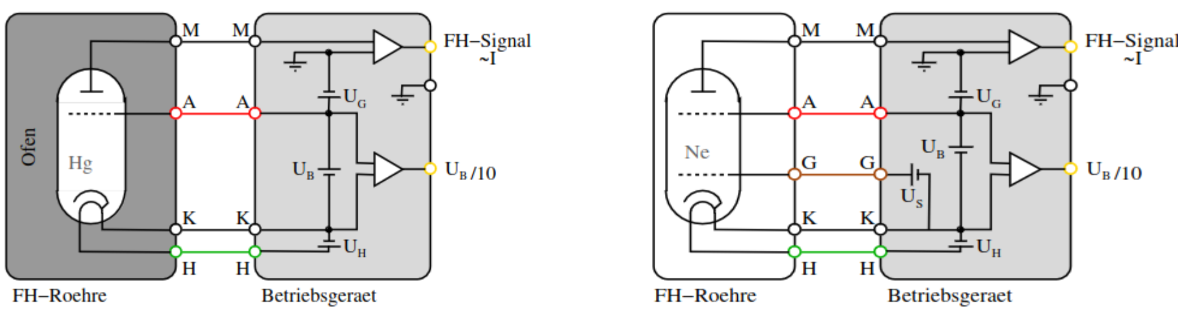


Figure 3: characteristic curve of Frank-Hertz experiment

2 Experiment setup & Results

The core part of the experiments are two Franck-Hertz tubes filled with mercury and neon, whose experimental setup is shown in figures 4a and 4b. The experiments are fairly similar, so we will first go through the basic measurements and then outline the unique part of both tubes.

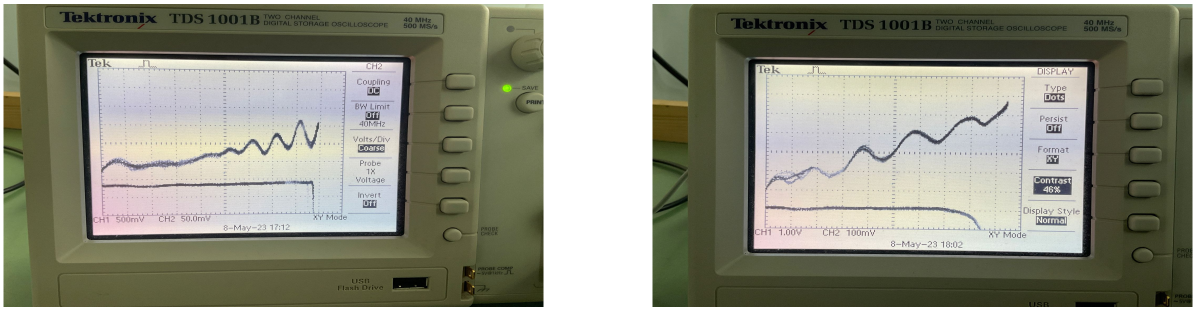


(a) Franck-Hertz tube filled with mercury.

(b) Franck-Hertz tube filled with neon.

Figure 4: Experimental setup for the Franck-Hertz experiment [1].

A Franck-Hertz tube consists of a cathode (K), an anode (A) and a metal mesh grid (M). Electrons emitted from the hot furnace (H) are produced with a heating voltage, U_H, accelerated from the cathode to the anode with an acceleration voltage, U_B, and then filtered using a counter voltage, U_G.
Additionally, we tap the voltage signals U_B (only a $U_B/10$) and the voltage at the mesh-grid, which is proportional to our collector current, and deliver it to an oscilloscope which is set to XY-Mode.
For a set of optimized voltage values $\{U_H,\ U_{Bm},\ U_G\}$, a periodic acceleration voltage with a frequency of 50 Hz and a maximum of U_{Bm}, we can reproduce the characteristic Franck-Hertz voltage-current lines with at least eight local extrema.



(a) Characteristic curve for Franck-Hertz tube filled with mercury.

(b) Characteristic curve for Franck-Hertz tube filled with neon.

Figure 5: Pictures of characteristic $U_B - I_M$ curves on the oscilloscope.

After, we set the acceleration voltage back to DC-mode and measure these extrema with a digital multi meter. The difference between the neighboring maxima and minima will tell us what the excitation energy and what the frequency of the emitted wavelength is.
In the first experiment with mercury, the best measurement environment is given when the 1 kPa to 2 kPa, which is why the Franc-Hertz tube with mercury is placed in an oven where we can set the temperature between 180 °C and 200 °C. Not ideal steam pressure conditions will either lead to sudden rises in gas discharge, leading to sudden peaks in current, or large scattering of the electrons, leading to very small current.
In the second experiment with neon, we don't need to heat the Franck-Hertz tube, but we need to measure the wavelength of the emitted light after excitation, because the excited electron does not immediately fall back into its ground state. For this purpose, we use a handheld spectroscope, since the emitted light is in the visible light spectrum.

2.1 Franck-Hertz tube with mercury

Optimizing the measurement parameters in AC-mode to

- $U_H = 8.02 \pm 0.47$ V,
- $U_G = 1.25 \pm 0.47$ V and
- $T = 185 \pm 2$,

we can produce the Franck-Hertz-Curve in figure 4a. We can then measure the voltage points of the extrema with a digital multimeter. The measurement data of the minima and maxima is depicted in table 1.

Table 1: Measurements of the voltage extrema for mercury. The uncertainty is given by a systematic uncertainty by the digital multimeter.

U_B^{min} [V]	U_B^{max} [V]
27.9 ± 0.5	25.6 ± 0.5
33.1 ± 0.5	31.4 ± 0.5
38.1 ± 0.5	35.5 ± 0.5
42.7 ± 0.5	40.7 ± 0.5

We can then use equation (2), which gives us the exciting energy of mercury,

$$E_{min} = 4.9 \pm 0.5 \text{ eV}$$
$$E_{max} = 5.0 \pm 0.8 \text{ eV}$$

where we used

$$u(E) = \sqrt{u_{SYS}^2 + u_{STD}^2} \tag{3}$$

to determine the uncertainty. At last, we can use the weighted mean average to determine the mean exciting energy of mercury and the wavelength of the emitted photon,

$$\Delta E_{exp} = 4.961 \pm 0.448 \text{ eV} \tag{4}$$
$$\lambda_{exp} = 249.894 \pm 22.556 \text{ nm} \tag{5}$$

where we used the Gaussian propagation law,

$$u(\lambda) = \frac{hc}{E^2}\Delta E \tag{6}$$

to determine the uncertainty of the wavelength.
The experimental results are well within range of uncertainty with the literature values,

$$\Delta E_{lit} = 4.9\,\text{eV}, \tag{7}$$
$$\lambda_{lit} = 253.02\,\text{nm}, \tag{8}$$

and therefore satisfactory.

2.1.1 Franck-Hertz tube with neon

We can again optimize the measurement parameters in AC-mode to

- $U_H = 4.27 \pm 0.47$ V and,
- $U_G = 6.94 \pm 0.47$ V,

and produce the Franck-Hertz-Curve in figure 5b.
With the same procedure as with mercury, we can again determine the voltage extrema, see table 2,

Table 2: Measurements of the voltage extrema for neon.

U_B^{min} [V]	U_B^{max} [V]
20.0 ± 0.5	
37.4 ± 0.5	25.5 ± 0.5
56.6 ± 0.5	45.3 ± 0.5
63.9 ± 0.5	80.0 ± 0.5

and the mean excitation energy of the neon atom.

$$E_{min} = 19.200 \pm 0.761 \text{ eV}$$
$$E_{max} = 20.000 \pm 2.613 \text{ eV}$$
$$E_{mean} = 19.263 \pm 0.731 \text{ eV}$$

The excitation energy of mercury leads to the following wavelength, $\lambda = 64.365 \pm 2.442$ nm, which is the wavelength of ultraviolet light. However, the excitation energy does not equal the wavelength of the released photon, because the transitions from excited state to ground state to is not allowed in the scheme of neon. We can find the photon energy with a hand held spectroscope, which shows two distinct lines at roughly, $\lambda \approx 590\,\mathrm{nm}$ and $\lambda \approx 630\,\mathrm{nm}$, which equals to $\Delta E = 2.10\,\mathrm{eV}$ and $\Delta E = 1.97\,\mathrm{eV}$ respectively. These values are really close to the literature and therefor satisfactory.

3 Short Questions

1. **What are elastic and inelastic collisions?**
   Elastic and inelastic collisions describe the interaction of two particles with one another. Fundamentally, elastic collisions are characterized in their conservation of both momentum and energy. In other words, if particles collide elastically, their total kinetic energy before and after the collision remain the same. In contrast, an inelastic collision only requires the conservation of momentum, this allows for the loss of kinetic energy. Through processes such as deformation, energy is transformed into heat or potential energy. In the case of the Franck-Hertz experiment, the kinetic energy of an electron is lost exciting a mercury atom.

2. **Why can electrons with energy smaller than** $4.9\,\mathrm{eV}$ **only go through elastic collisions with an atom?**
   In case of mercury, electrons with energy smaller than $4.9\,\mathrm{eV}$ can not excite electrons in the shell of a mercury atom, therefor energy is conserved and electrons collide elastically with the mercury atom.

3. **Why can an electron only transfer small amounts of energy through elastic collision with an atom?**
   The mass of an electron is much smaller than of an atom, therefore the kinetic energy transfer is much smaller.

4. **How does the through inelastic collision, excited atom return back to its ground state?**
   After excitation into a higher discrete energy state, the electron can return into its ground state by magnetic dipole and electric quadrupole transition. A photon is emitted in exchange.

5. **What is the difference between an excitation of an atom through quanta of light and electrons?**
   In order to excite an Atom the energy of the Photon is required to have the wavelength corresponding to the relative energy level of the excited state. In comparison, Electrons will excite Atoms if their kinetic energy is larger than the relative energy of the excited state.

6. **Why do we need counter voltage between the anode and the collector electrode?** The counter current exists to stop electrons under a certain energy level reaching the anode. Without the counter current it would be impossible to discern electrons, that have and have not excited an atom, as all electron, irrespective of energy level would reach the anode an be "counted".

7. **Compare the working principle of the Franck-Hertz-Tube with a fluorescent lamp, and try to understand the fluorescent lamp with its principle circuit in figure 6. Why are they called fluorescent lamp?**

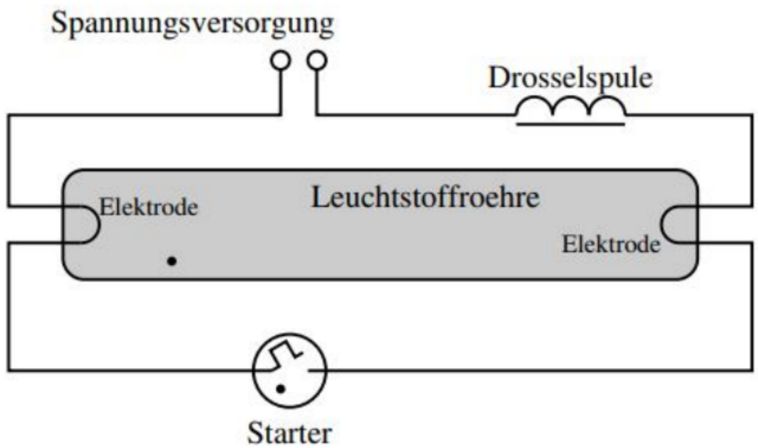


Figure 6: basic circuit of a fluorescent lamp

A fluorescent lamp also works by exciting mercury atoms, for example. In comparison, to the Frank-Hertz experiment the goal is to produce light, thus there is no breaking current and the mercury gas denser in order to produce more radiation. We also note the existence of a fluorescent coating, that makes use of fluorescence, the absorption of one wavelength of light and then emitting light of different wavelengths to return to ground state, as the radiation produced by mercury is ultraviolet and not within the visible spectrum.

8. **What is the difference to an X-ray tube?**
   To produce X-rays (Gamma-Radiation). Electrons are accelerating by many Kilovolts and collide into a heavy metal target. The Atoms in the target are then excited and produce X-rays, as the goal of an X-ray tube is produce X-rays a vacuum is used instead of gas in order to prevent premature energy loss of the electrons.

4 Error Analysis

4.1 Systematic uncertainty of digital multimeter

The uncertainty of the digital multimeter is given as follows [2], [3],

$$u_{SYS}(U) = \sqrt{\left(\frac{A\% \cdot U}{\sqrt{3}}\right)^2 + (B^2 + 1) \cdot \left(\frac{C}{\sqrt{3}}\right)^2} \,. \tag{9}$$

For both experiments we measured in the 20 V range, so the parameters are

- A = 0.5,
- B = 8 and,
- $C = 0.1\,\mathrm{V}$.

4.2 Weighted mean average

The statistical uncertainty of measurements with the same expected outcome is given by the weighted mean average [2],

$$\overline{x} = \frac{\sum_i w_i \cdot x_i}{\sum_i w_i}, \tag{10}$$

and its uncertainty is given by

$$u(\overline{x}) = \max\{u_{int}, u_{ext}\}, \tag{11}$$

where

$$u_{int} = \frac{1}{\sqrt{\sum_i w_i}} \text{ and,} \tag{12}$$

$$u_{ext} = \sqrt{\frac{\sum_i w_i \cdot (x_i - \overline{x})^2}{(n-1) \cdot \sum_i w_i}}\ . \tag{13}$$

5 Literature

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