

Advanced Laboratory Course, Part I

Summer Term 2005

Report on

Franck-Hertz Experiment

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18th February 2005

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1 Introduction

In 1913 James Franck and Gustav Hertz demonstrated the possibility to prove the existence of discrete energy levels in atoms by means of atomic collisional processes. Thus the Franck-Hertz experiment combines the physics of collision with the results of optical spectroscopy. Its result indicates that atoms can only absorb a discrete amount of energy, regardless the way the energy is transferred to the atom.

Using a setup similar to that of Franck and Hertz we will observe the quantized excitation of mercury atoms by means of electronic impact. We will measure the characteristic anode current and photocurrent for different sets of parameters like temperature and countervoltage. On the basis of this data we will determine the excitation voltage of the 3P level of mercury.

2 Theory

2.1 Franck-Hertz tube

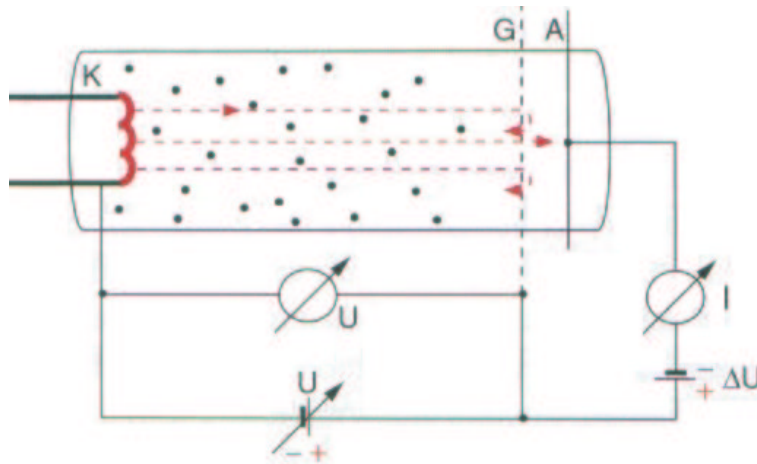


Figure 1: Franck-Hertz tube

The Franck-Hertz tube is a triode consisting of a cathode (K), an anode (A) and a grid-like electrode (G) between them. Figure 1 shows the arrangement of these components. The tube is filled with mercury vapour at low pressure (about 10^{-2} mbar). The electrons emitted from the heated cathode are accelerated between C and G by a voltage $U \equiv U_B$. Thus they receive the energy $e \cdot U_B$. The structure of the grid enables the electrons to reach the actual experimental space in great number (otherwise they all would be

captured by G). Between G and A a countervoltage $\Delta U \equiv U_G$ is applied, which means that A is charged negatively in comparison with G. Therefore only electrons with energy larger than $e \cdot U_G$ can reach the anode and cause a current signal. If there was no countervoltage applied, all electrons would reach the anode and no modulation of the current signal could be measured.

Figure 2 displays a typical measurement of the anode current as a function of the accelerating voltage. As soon as $U_B > U_G$ the current increases with rising U_B . But when it reaches a value $U_B \approx 4,9V$ (assuming $U_G \ll U_B$) it decreases, forms a minimum and increases again to $U_B \approx 2 \cdot 4,9V$, then this oscillation continues the same way. The interpretation of this observation succeeds with the assumption that electrons of about 5 eV of kinetic energy undergo inelastic collisions with the mercury atoms and thus transfer their energy to a discrete excitation level of mercury.

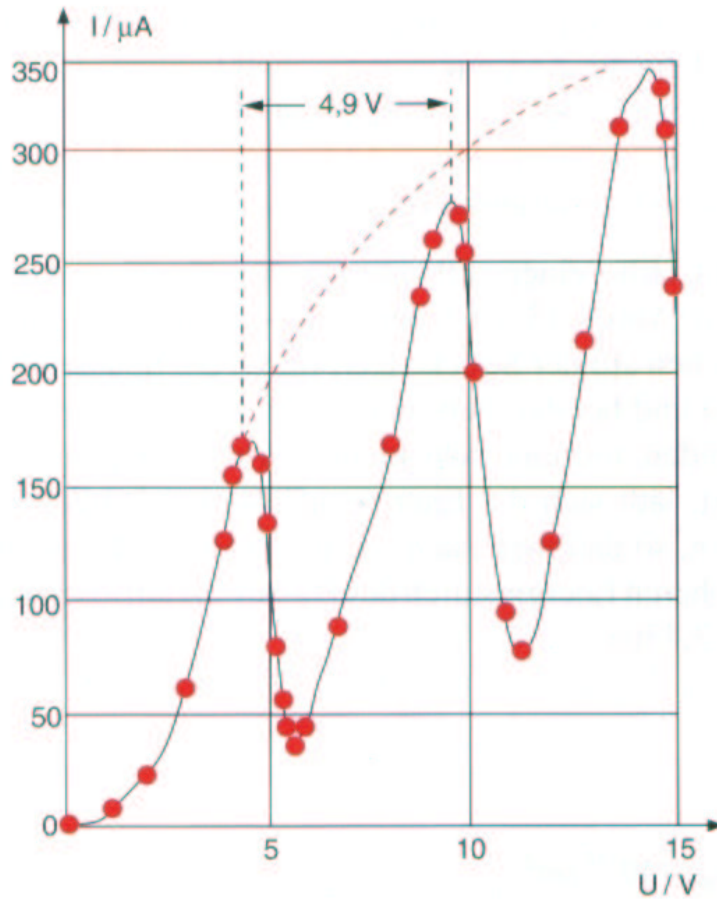


Figure 2: Anode current curve

2.2 Emission of electrons out of an heated cathode

The cathode in a vacuum tube can emit electrons if it is heated. Electrons in the conduction band of the cathode metal move freely within the band but cannot be released as they are held back by the Coulomb force of the positively charged ion grid. In order to be emitted electrons have to overcome the work function W of the order of a few eV. By means of additional thermal energy due to the heating process electrons in the high-energy tail of the Fermi distribution can be released. The share of electrons leaving the cathode is governed by the Boltzmann factor $e^{-\frac{E}{k_B T}}$. When an acceleration voltage U_B is applied dragging the electrons away from the cathode, then $E = W - eU_B$. Closer analysis of the emission process leads to the Richardson law

$$j = CT^2 e^{-\frac{W - eU_B}{k_B T}} \quad (1)$$

where C is a material constant.

Around the cathode an electron cloud forms. This negative charge density prevents the electric field built up by the acceleration voltage from reaching the cathode, which results in a characteristic run of the vacuum tube current with voltage: $I \propto U^{\frac{3}{2}}$ (Schottky-Langmuir-Formula, see also dotted line in figure 2).

2.3 The mercury atom and transitions

The mercury atom contains in total 80 electrons of which 78 are bound in filled states. In the ground state the two remaining electrons can be found in the 6s state. Their spins of $\frac{1}{2}$ each can couple to a total spin of $S = 0, 1$ leading to a singlet (multiplicity 1) and a triplet (multiplicity 3) state (see figure 3). The coupling to the total angular momentum $\vec{J}$ is determined by JJ-coupling rather than LS-coupling because mercury belongs to the heavier nuclei.

The lowest excited level is the 3P level, i.e. $L = 1$ resulting in a $J = L - S, \dots, L + S = 0, 1, 2$. According to Hund's rules for levels less than half-filled the energy is minimized so that the 3P_0 level is the lowest. Higher levels than 3P do not play a role in our experiment since the mean free path of the electrons is too short to gather a sufficient amount of kinetic energy for an excitation (see also section 4.7).

In order to calculate the probability of a transition between two atomic energy levels the Schroedinger equation coupled to the resonant light field is solved

in linear perturbation theory. It turns out that the term

$$(\vartheta_{ij}) = \int dV \varphi_i^* e z \varphi_j \quad (2)$$

called dipole matrix element, necessarily must be unequal zero. This condition implies the following optical selection rules, valid for JJ-coupling: $\Delta J = 0, \pm 1$ where $J = 0 \rightarrow J = 0$ is forbidden; and $\Delta j = 0, \pm 1$ for the first electron, $\Delta j = 0$ for all other electrons. The former rule leads to the conclusion that only the transition $^3P_1 \rightarrow ^1S_0$ is optically allowed corresponding to the intensive 253,7nm line whereas the 3P_2 and 3P_0 states are metastable and are de-excited by collisions for which the constraints of the optical selection rules are not valid.

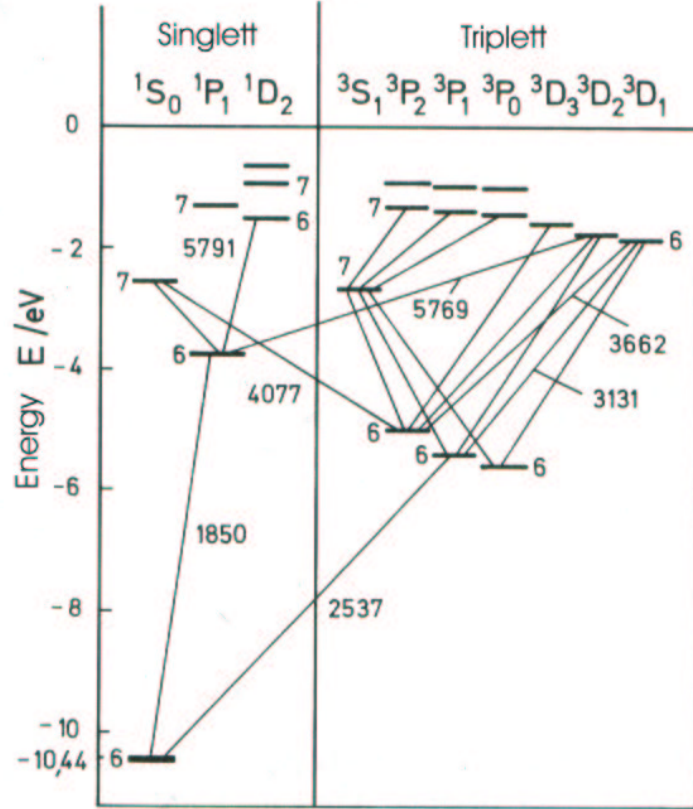


Figure 3: Termscheme of Hg

2.4 Kinetic gas theory

In kinetic gas theory atoms are considered as hard spheres, i.e. they only interact if their distance becomes smaller than the sum of their gas-kinetic radii. Therefore the area around an atom in which another atom will be scattered, defined as the cross section σ , is given by

$$\sigma = \pi(r_1 + r_2)^2 \quad (3)$$

For an ensemble of such atoms, only interacting by collisions, the ideal gas law

$$p = nk_B T \quad (4)$$

holds with n being the particle density. In a beam of N_0 atoms flying through a gas a number

$$N = N_0 e^{-n\sigma x} \quad (5)$$

will be scattered along a distance x . By definition and using equation (5) one finds for the mean free path

$$\Lambda \equiv \frac{1}{N_0} \int_0^\infty x \cdot \left| \frac{dN}{dx} \right| dx = n\sigma \cdot \int_0^\infty x e^{-n\sigma x} dx = \frac{1}{n\sigma} \quad (6)$$

The mean collision time, that is the time between the collision of two atoms, is defined as

$$\tau = \frac{\Lambda}{\bar{v}} \quad (7)$$

where $\bar{v}$ is the mean velocity.

2.5 Collisions

Electrons in the vacuum tube can interact with mercury atoms either by elastic or inelastic collisions. Since the electron mass is much lower than the mass of a mercury atom electrons hardly lose energy in elastic collisions ($\Delta E \propto 4 \frac{m_e}{m_{Hg}}$) but only change their direction. Therefore the processes we are interested in must be caused by inelastic collisions, in which a fraction of the electron energy is converted into internal, in our case excitational energy of the atom.

2.6 Two-phase system

In the Franck-Hertz tube a liquid mercury drop partially evaporates with increasing temperature. This two-phase system of liquid and vapor is described

by the Clausius-Clapeyron equation

$$\frac{dp}{dT} = \frac{\lambda}{(V_v - V_l)T} \quad (8)$$

where p is pressure, T temperature, λ the vaporisation energy and V_v and V_l the volumina of the vapor and liquid phase respectively. Further processing of this formula and inserting values for the mercury atom leads to

$$\lg p = 10,55 - \frac{3333}{T} - 0,86 \cdot \lg T \quad (9)$$

where T is given in Kelvin and p is given in Torr (1 Torr = 133,33 Pa).

2.7 Photomultiplier

A Photomultiplier is a sensitive device which converts light into a measurable electric current. Incident radiation impinges on a photocathode built of photosensitive material (mainly semiconductors) causing electrons to be emitted due to the photoelectric effect with an efficiency of up to 30%. By means of electric fields the electrons are accelerated and focused on the first dynode where their energy is transferred to the dynode material. This way 3 to 10 secondary electrons per incident electron are released which are then accelerated towards the second dynode. A potential ladder of 10 to 14 dynodes leads to a total amplification of the current by a factor of about 10^7 . The resulting pulse signal at the anode is ideally proportional in amplitude to the energy of the corresponding incident photon unless the photomultiplier is saturated. The schematic structure of a photomultiplier is given in figure 4 on page 8.

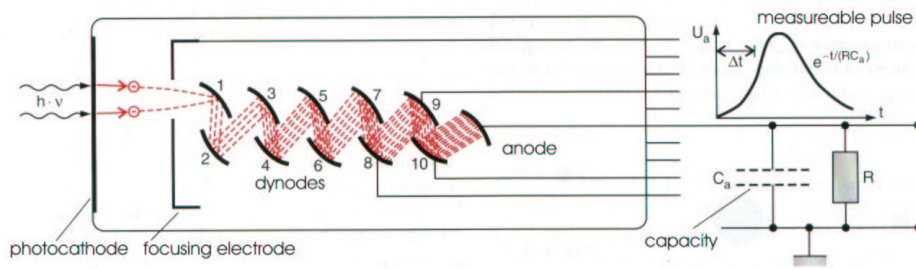


Figure 4: General structure of a photomultiplier

2.8 Interference-filter

Interference filters are based on the concept of a Fabry-Perot interferometer which consists of two plane parallel transparent elements separated by a distance d . Its basic principle is shown in Figure 5. Provided that an incident plane wave of wavelength λ is not inclined there will be constructive interference of incident and reflected waves for $\lambda = 2 \cdot \frac{nd}{m}$ where n is the refractive index of the material in the slit and $m \in \mathbf{N}$. All other wavelengths are suppressed so that the setup works as a wavelength filter. In our experiment a filter with an approximately Gaussian-shaped transmittance function centered around 254,5nm and with a FWHM of 20nm is in use.

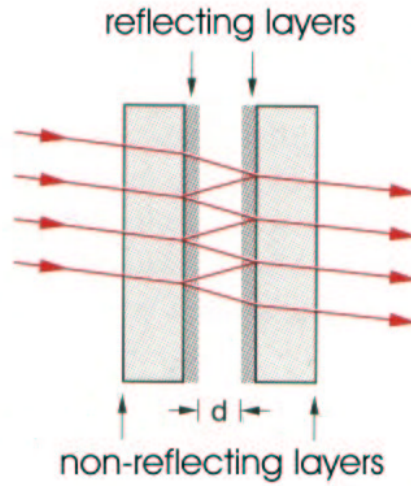


Figure 5: Principle of a Fabry-Perot interferometer

3 Setup of the experiment

Figure 6 indicates the setup of the Franck-Hertz experiment. The central element of the experiment is the Franck-Hertz tube (see section 2.1) placed in a heated oven. The temperature can be measured by a digital thermometer. The cathode is heated by an alternating voltage of 6,3 V. The maximum accelerating voltage U_B^{max} can be adjusted from 0 to 50 V. Throughout the experiment we set the value to 40 V, which turned out to be a reasonable value. We achieve a linear increase of U_B , which is connected to the X-input of the plotter, by loading a capacity C with a constant current. Opening and

closing the included switch S_1 starts and stops the measurement. After being amplified the anode current controls the Y-deviation of the analog plotter.

Furthermore there is a UV-transparent window in one side of the oven. An interference-filter selects the 254nm transition of mercury followed by a photomultiplier which converts the incident photons into a measureable current. We set the operational voltage of the photomultiplier to 300 V. After its amplification this photocurrent is connected to the Y-input of the plotter. Besides we can include a RC-device into the circuit in order to plot the differentiated photocurve.

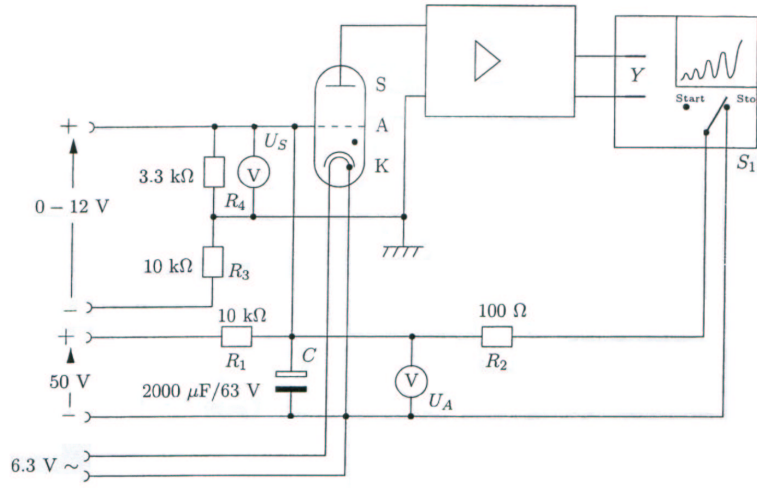


Figure 6: Setup of the experiment

4 Implementation and analysis

4.1 Proceeding

We plotted the Franck-Hertz curves for four different temperatures

$$T = 150^{\circ}\text{C}, 159^{\circ}\text{C}, 171^{\circ}\text{C}, 184^{\circ}\text{C}$$

and two different countervoltages

$$U_G = 0,5\text{V}, 1\text{V}$$

We assume the error on temperature to be $\sigma_T = 1^{\circ}\text{C}$ and the error on countervoltage to be $\sigma_{U_G} = 0,05\text{V}$.

The photocurve and its derivative were measured for all four temperatures with a constant countervoltage $U_G = 0,5V$. At $150^\circ C$ an additional photocurve was taken for $U_G = 1V$. As expected it turned out to be the same as for $U_G = 0,5V$ for the emission of light not being correlated with the deceleration of electrons behind the grid.

Furthermore we inserted a glass plate between the oven and the photomultiplier to make sure that we measure UV light indeed. As expected the photocurrent immediately broke down when shielding the beam.

For each temperature we proceeded in the following way: plot of the Franck-Hertz curves, plot of the photocurve, plot of the differentiated photocurve. Temperature was gradually increased.

4.2 Calibration

For the temperatures $T = 150^\circ C$ and $T = 159^\circ C$ a Y-scale of the plotter of $0,2 \frac{V}{cm}$ was chosen to get an adequate resolution of the curves. In order to avoid the curves to become too small we increased the Y-scale to $0,1 \frac{V}{cm}$ for the two higher temperatures. In both cases an amplifier sensibility of $0,1 \mu A$ was selected. At all temperatures the parameters for the photocurves had to be changed to 10nA amplification sensibility and a Y-scale of $0,1 \frac{V}{cm}$ and for its derivative to 1nA and to $0,05 \frac{V}{cm}$ respectively.

Throughout the experiment the X-scale of the plotter was $2 \frac{V}{cm}$. Although the X-scale was run in the calibrated mode, the actual scale did not correspond to this adjustment. This can be easily deduced from the fact that all curves are longer than 20 cm in x direction taking into account a total U_B range of 40 V. Fortunately we observed the linearly increasing U_B on an analog voltmeter and marked ticks with a distance of 10V each on the graphs. Of course this method is not very exact, but averaging over our own calibration on all eight graphs yields an acceptable result. The measured distances d between two ticks can be found in table 6.1. We calculated the arithmetic mean $\bar{d} = 5,6cm$ and standard deviation $\sigma_d = 0,2cm$. Then the actual X-scale c can be calculated by $c = \frac{10V}{\bar{d}}$ and its error σ_c by $\sigma_c = \frac{10V}{\bar{d}^2} \cdot \sigma_d$.

Thus our final result for the actual X-scale is

$$c = 1,80 \pm 0,06 \frac{V}{cm} \quad (10)$$

4.3 Features of the Franck-Hertz curves

The plotted Franck-Hertz curves distinctly show the expected sequence of minima and maxima as mentioned in section 2.1. One can recognize the following characteristics of the curves:

The curves for the higher countervoltage of 1V run below the curves for the countervoltage of 0,5V. This can be put down to the fact that the electrons need to have a higher kinetic energy behind the grid to overcome a higher countervoltage. Thus low energetic electrons cannot reach the anode, which leads to a smaller anode current.

With rising temperature the location of minima and maxima is shifted to higher voltages. Besides we recognize an offset voltage as the position of the first maximum is located at higher voltages than the expected 4,9V. We explain these phenomena by a temperature dependent contact voltage between the electrodes.

The overall amplitude of the Franck-Hertz curves decreases with rising temperature. Higher temperatures cause a higher particle density of mercury atoms, so that the mean free path of the electrons decreases (see equation (6)). Therefore more electrons are scattered between grid and anode. If the scattering angle becomes greater than $\frac{\pi}{2}$ the electrons are accelerated backwards to the grid by the countervoltage and do not contribute to the anode current anymore.

The amplitude of a single maximum increases with higher acceleration voltage U_B , because it follows the expected current voltage characteristic of a vacuum tube as depicted in figure 2. Due to statistical fluctuations and the kinetic energy distribution of the electrons the anode current in the minima remains larger than zero.

4.4 Analysis of the Franck-Hertz curves

We determined the distances x between the minima which provided the most distinct features in each Franck-Hertz curve for all sets of parameters. These values including all derived quantities mentioned in this paragraph can be found in section 6.2.1 and 6.2.2. Due to the limited accuracy in reading out the figures we assumed an individual error of σ_x .

According to $U = c \cdot x$ we arrive at the corresponding voltages. The resulting

systematic error reads

$$\sigma_U = \sqrt{c^2 \cdot \sigma_x^2 + x^2 \cdot \sigma_c^2} \quad (11)$$

For each fixed set of parameters we calculate a weighted mean

$$\bar{U} = \frac{\sum U/\sigma_U^2}{\sum 1/\sigma_U^2} \quad (12)$$

with a total systematic error

$$\sigma'_U = \sqrt{\frac{1}{\sum 1/\sigma_U^2}} \quad (13)$$

In addition to this we calculated the standard deviation of the voltages σ''_U leading us to the total error on $\bar{U}$

$$\sigma_U = \sqrt{\sigma'^2_U + \sigma''^2_U} \quad (14)$$

The following table contains our results so far:

T [°C]	U_G [V]	$\bar{U}$ [V]	$\sigma_{\bar{U}}$ [V]
150	0,5	4,90	0,23
150	1,0	4,83	0,18
159	0,5	4,90	0,15
159	1,0	4,86	0,12
171	0,5	4,89	0,18
171	1,0	4,82	0,16
184	0,5	4,72	0,17
184	1,0	4,74	0,17

Especially at the highest temperature we observe a significant decrease in $\bar{U}$. The other values include the theoretical value of $\bar{U} = 4,90V$.

Averaging all the $\bar{U}$ similar to equations number (12) and (13) we arrive at our final result for the excitation voltage U_{ex} :

$$\underline{U_{ex} = (4,83 \pm 0,06)V} \quad (15)$$

Unfortunately the theoretical value lies slightly outside the error boundaries, which might be estimated too optimistically when taking into account the inaccuracy of our calibration.

The corresponding wavelength of the optical transition is given by

$$\lambda = \frac{h \cdot c}{e \cdot U_{ex}} \quad (16)$$

with an error of

$$\sigma_\lambda = \frac{h \cdot c}{e \cdot U_{ex}^2} \sigma_{U_{ex}} \quad (17)$$

yielding $\lambda = (257 \pm 3)nm$. Again this does not quite match the theoretical value of 253,7nm.

4.5 Features of the photocurrent curves

The photocurrent curves resemble an exponential function revealing equidistant kinks in the slope. These can be recognized more easily in the differentiated curves plotted on the same sheet. The differentiated curves look like a heavily disturbed step function. Both the photocurve and its derivative decrease in amplitude with rising temperature, because the mean collision time between mercury atoms diminishes. So de-excitations preferentially take place by collisions rather than by optical transitions by virtue of their relatively long lifetimes (see also 4.7).

In order to explain the shape of the curves one has to consider two aspects. The photocurrent increases with acceleration voltage since the number of electrons and subsequently the number of excitations in the tube goes up. Moreover the kinks or steps respectively originate in the increasing number of excitations per single electron on the way from cathode to grid, e.g. if electron gather enough energy to excite two mercury atoms, twice the number of photons can be produced and so on. The voltage distance between the steps is again equal to the excitation voltage of the observed transition.

When switching off the light in the laboratory we observed thin layers of bluish light parallel to the grid in the Franck-Hertz tube. According to our explanations so far the number of layers as well as the intensity of the blue light increased with rising acceleration voltage.

4.6 Analysis of the photocurrent curves

Analysing the photocurrent curves we used our own calibration (see section 4.2). As the steps in the differentiated photocurrent curve are not vertical we decided to measure the distances between the middles of the rising slopes. We only used well defined steps without artefacts and too heavy noise

perturbations. The results can be found in table 6.3 on page 22. Due to the numerous sources of inaccuracy we estimate a systematic error on the distance measurements of $\sigma_x = 0,2cm$. Again we calculate the corresponding voltage $U = c \cdot x$ and its error σ_U according to equation (11). Using equations (12), (13) and (14) we arrive at

$$\underline{U_{ex} = (5,0 \pm 0,2)V} \quad (18)$$

Keeping in mind the limited accuracy this result matches the theoretical value and agrees with the outcome of the analysis of the Franck-Hertz curves.

4.7 Calculation of mean free path and collision time

We will now calculate the mean free path of an electron with a kinetic energy of 5 eV at a temperature of $171^\circ C \equiv 444,15K$. According to equation (9) the pressure p in the tube is

$$p = 10^{10,55 - \frac{3333}{T} - 0,85 \cdot \lg T} \approx 832,16Pa \quad (19)$$

The cross section for the excitation of the triplet P-levels of mercury can be read out from Figure 7 on page 16: $\sigma(^3P_0) = 1\pi a^2$, $\sigma(^3P_1) = 2,5\pi a^2$ and $\sigma(^3P_2) = 0$ with $a \equiv$ Bohr's radius yielding

$$\sigma_{tot} = 3,5\pi a^2 \approx 3,092 \cdot 10^{-20}m^2 \quad (20)$$

Making use of the ideal gas law $p = nk_B T$ we arrive at the mean free path

$$\Lambda = \frac{1}{n \cdot \sigma_{tot}} = \frac{k_B T}{\sigma_{tot} p} \approx 238,1\mu m \quad (21)$$

So the 5 eV electron will excite a 6P-triplet level by collision and as a consequence lose its kinetic energy before it is able to gather enough energy for an excitation of a higher level. Therefore the assumption is justified that higher energy levels than the 6^3P -level can be neglected.

In order to calculate the time between the collision of two mercury atoms we refer to the gas-kinetic cross section of mercury atoms given by

$$\sigma_{Hg \rightarrow Hg} = \pi \cdot \left(\frac{d_{Hg}}{2} + \frac{d_{Hg}}{2} \right)^2 = \pi d_{Hg}^2 \approx 6,08 \cdot 10^{-19}m^2 \quad (22)$$

where $d_{Hg} = 0,44nm$, the gas-kinetic diameter, was given in the scriptum.

Considering the Maxwell-Boltzmann distribution the mean velocity of mercury atoms in the gas at temperature T is

$$\bar{v} = \sqrt{\frac{8k_B T}{\pi m_{Hg}}} \approx 216,5 \frac{m}{s} \quad (23)$$

where $m_{Hg} = 200,59u$ with u being the atomic mass unit. Finally the collision time is

$$\tau = \frac{\Lambda}{\bar{v}} = \frac{1}{\bar{v} \cdot n \cdot \sigma_{Hg \rightarrow Hg}} = \frac{k_B \cdot T}{\bar{v} \cdot p \cdot \sigma_{Hg \rightarrow Hg}} \approx 55,9 ns \quad (24)$$

Regarding the fact that the lifetime of the optical transition $^3P_1 \rightarrow ^1S_0$ (117 ns) is more than twice as great as the determined time between two collisions τ , a lot of atoms will most likely deexcite by collision than by emission of a photon.

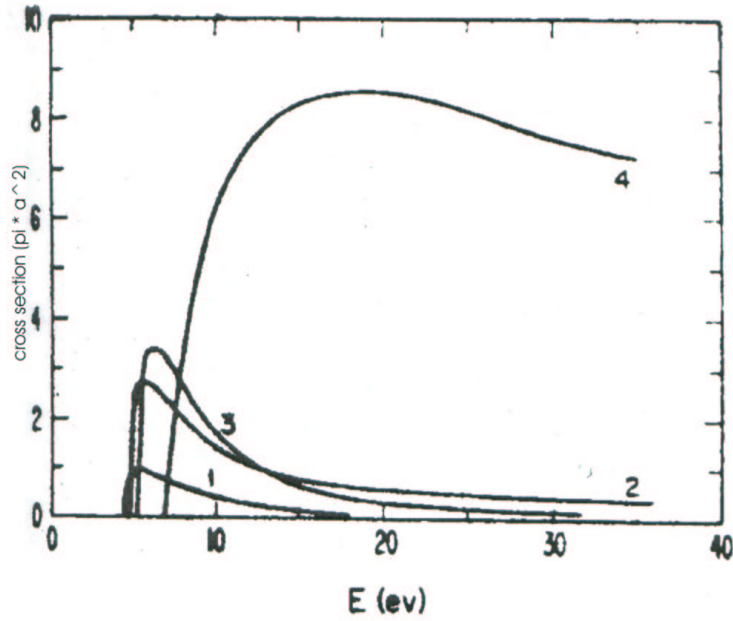


Figure 7: Total cross section for the excitation by electron impact. Curve 1: $6^1S_0 \rightarrow 6^3P_0$ excitation. Curve 2: $6^1S_0 \rightarrow 6^3P_1$ excitation. Curve 3: $6^1S_0 \rightarrow 6^3P_2$ excitation. Curve 4: $6^1S_0 \rightarrow 6^1P_1$ excitation.

5 Summary

Our results for the excitation voltage of the 3P level of mercury are in relatively good agreement with the expected value within the framework of measurement accuracy. The analysis of the Franck-Hertz and photocurrent curves are in principle both suitable for precise measurement, but in our case were limited because of poor calibration. Therefore it would have been appropriate to put more emphasis on determining the features of the plotter. Besides the quality of the differentiated photocurrent curves suffered from the heavy noise (also in a literal sense), which we were not able to overcome.

6 Appendix

6.1 Table of data - calibration

number	d [cm]	number	d [cm]
1	5,3	17	5,4
2	5,6	18	5,7
3	5,8	19	5,5
4	5,5	20	5,5
5	5,4	21	5,6
6	5,6	22	5,5
7	5,9	23	5,8
8	5,4	24	5,4
9	5,6	25	5,4
10	5,5	26	5,8
11	5,8	27	5,7
12	5,3	28	5,4
13	5,4	29	5,3
14	5,8	30	5,8
15	5,8	31	5,9
16	5,3	32	5,3

Table 1: Distance d between 10V tics

6.2 Tables of data - Franck-Hertz curves

6.2.1 Databasis

In the column 'minima' the minima are indicated whose distance is given in the corresponding row.

The remark 'np' indicates that no accurate measurement could be performed.

	T [°C]	U_G [V]	minima	x [cm]	σ_x [cm]	U [V]	σ_U [V]
1	150	0,50	1 - 2	2,50	0,20	4,50	0,39
2	150	0,50	2 - 3	2,70	0,15	4,86	0,31
3	150	0,50	3 - 4	2,70	0,10	4,86	0,24
4	150	0,50	4 - 5	2,80	0,10	5,04	0,25
5	150	0,50	5 - 6	2,70	0,10	4,86	0,24
6	150	0,50	6 - 7	2,80	0,10	5,04	0,25

Table 2: Data at T = 150°C and $U_G = 0,50V$

	T [°C]	U_G [V]	minima	x [cm]	σ_x [cm]	U [V]	σ_U [V]
7	150	1,00	1 - 2	2,50	0,20	4,50	0,39
8	150	1,00	2 - 3	2,70	0,15	4,86	0,31
9	150	1,00	3 - 4	2,70	0,10	4,86	0,24
10	150	1,00	4 - 5	2,70	0,10	4,86	0,24
11	150	1,00	5 - 6	2,70	0,10	4,86	0,24
12	150	1,00	6 - 7	2,70	0,10	4,86	0,24

Table 3: Data at T = 150°C and $U_G = 1,00V$

	T [°C]	U_G [V]	minima	x [cm]	σ_x [cm]	U [V]	σ_U [V]
13	159	0,50	1 - 2	np	np	np	np
14	159	0,50	2 - 3	2,70	0,20	4,86	0,39
15	159	0,50	3 - 4	2,70	0,15	4,86	0,31
16	159	0,50	4 - 5	2,70	0,10	4,86	0,24
17	159	0,50	5 - 6	2,70	0,10	4,86	0,24
18	159	0,50	6 - 7	2,80	0,10	5,04	0,25

Table 4: Data at T = 159°C and $U_G = 0,50V$

	T [°C]	U_G [V]	minima	x [cm]	σ_x [cm]	U [V]	σ_U [V]
19	159	1,00	1 - 2	np	np	np	np
20	159	1,00	2 - 3	2,70	0,20	4,86	0,39
21	159	1,00	3 - 4	2,70	0,15	4,86	0,31
22	159	1,00	4 - 5	2,70	0,10	4,86	0,24
23	159	1,00	5 - 6	2,70	0,10	4,86	0,24
24	159	1,00	6 - 7	2,70	0,10	4,86	0,24

Table 5: Data at T = 159°C and $U_G = 1,00V$

	T [°C]	U_G [V]	minima	x [cm]	σ_x [cm]	U [V]	σ_U [V]
25	171	0,50	1 - 2	np	np	np	np
26	171	0,50	2 - 3	2,60	0,20	4,68	0,39
27	171	0,50	3 - 4	2,70	0,15	4,86	0,31
28	171	0,50	4 - 5	2,70	0,10	4,86	0,24
29	171	0,50	5 - 6	2,70	0,10	4,86	0,24
30	171	0,50	6 - 7	2,80	0,10	5,04	0,25

Table 6: Data at T = 171°C and $U_G = 0,50V$

	T [°C]	U_G [V]	minima	x [cm]	σ_x [cm]	U [V]	σ_U [V]
31	171	1,00	1 - 2	np	np	np	np
32	171	1,00	2 - 3	2,60	0,20	4,68	0,39
33	171	1,00	3 - 4	2,60	0,15	4,68	0,31
34	171	1,00	4 - 5	2,70	0,10	4,86	0,24
35	171	1,00	5 - 6	2,70	0,10	4,86	0,24
36	171	1,00	6 - 7	2,70	0,10	4,86	0,24

Table 7: Data at T = 171°C and $U_G = 1,00V$

	T [°C]	U_G [V]	minima	x [cm]	σ_x [cm]	U [V]	σ_U [V]
37	184	0,50	1 - 2	np	np	np	np
38	184	0,50	2 - 3	np	np	np	np
39	184	0,50	3 - 4	2,60	0,20	4,68	0,39
40	184	0,50	4 - 5	2,70	0,15	4,86	0,31
41	184	0,50	5 - 6	2,60	0,10	4,68	0,24
42	184	0,50	6 - 7	2,60	0,10	4,68	0,24

Table 8: Data at T = 184°C and $U_G = 0,50V$

	T [°C]	U_G [V]	minima	x [cm]	σ_x [cm]	U [V]	σ_U [V]
43	184	1,00	1 - 2	np	np	np	np
44	184	1,00	2 - 3	np	np	np	np
45	184	1,00	3 - 4	2,60	0,20	4,68	0,39
46	184	1,00	4 - 5	2,60	0,15	4,68	0,31
47	184	1,00	5 - 6	2,70	0,10	4,86	0,24
48	184	1,00	6 - 7	2,60	0,10	4,68	0,24

Table 9: Data at T = 184°C and $U_G = 1,00$

6.2.2 Interim results

basis table	$\overline{U}$ [V]	$\sigma'_{\overline{U}}$ [V]	$\sigma''_{\overline{U}}$	$\sigma_{\overline{U}}$
1	4,90	0,11	0,20	0,23
2	4,83	0,11	0,15	0,18
3	4,90	0,12	0,08	0,15
4	4,86	0,12	0,00	0,12
5	4,89	0,12	0,13	0,18
6	4,82	0,12	0,10	0,16
7	4,72	0,14	0,09	0,17
8	4,74	0,14	0,09	0,17

Table 10: Interim results calculated on the basis of the tables in section 6.2.1 as described in section 4.4.

6.3 Table of data - photocurrent curves

	T [°C]	x [cm]	σ_x [cm]	U [V]	σ_U [V]
1	150	2,9	0,2	5,22	0,40
2	150	2,8	0,2	5,04	0,40
3	159	2,8	0,2	5,04	0,40
4	159	2,8	0,2	5,04	0,40
5	159	2,7	0,2	4,86	0,39
6	159	2,9	0,2	5,22	0,40
7	171	2,7	0,2	4,86	0,39
8	171	2,8	0,2	5,04	0,40
9	171	2,7	0,2	4,86	0,39
10	184	2,7	0,2	4,86	0,39
11	184	2,7	0,2	4,86	0,39

Table 11: Measured distances between two steps in the differentiated photocurrent curves as described in section 4.6.

6.4 Legend concerning the original plots

- Franck-Hertz curves
 - Sheet **1**: $T = 150^{\circ}\text{C}$; black line $\equiv (U_G = 0,5\text{V})$;
green line $\equiv (U_G = 1\text{V})$
 - Sheet **2**: $T = 159^{\circ}\text{C}$; black line $\equiv (U_G = 0,5\text{V})$;
green line $\equiv (U_G = 1\text{V})$
 - Sheet **3**: $T = 171^{\circ}\text{C}$; black line $\equiv (U_G = 0,5\text{V})$;
green line $\equiv (U_G = 1\text{V})$
 - Sheet **4**: $T = 184^{\circ}\text{C}$; black line $\equiv (U_G = 0,5\text{V})$;
green line $\equiv (U_G = 1\text{V})$
- Photocurrent curves
 - Sheet **5**: $T = 150^{\circ}\text{C}$; black line $\equiv$ photocurrent curve;
thick black line $\equiv$ differentiated photocurrent curve
 - Sheet **6**: $T = 159^{\circ}\text{C}$; black line $\equiv$ photocurrent curve;
thick black line $\equiv$ differentiated photocurrent curve
 - Sheet **7**: $T = 171^{\circ}\text{C}$; black line $\equiv$ photocurrent curve;
thick black line $\equiv$ differentiated photocurrent curve
 - Sheet **8**: $T = 184^{\circ}\text{C}$; black line $\equiv$ photocurrent curve;
thick black line $\equiv$ differentiated photocurrent curve

References

- [1] Haken, Wolf: *Atom- und Quantenphysik*, edition 8, Springer-Verlag (2004)
- [2] Demtroeder: *Experimentalphysik 2*, edition 1, Springer-Verlag (1995)
- [3] Demtroeder: *Experimentalphysik 3*, edition 2, Springer-Verlag (2000)
- [4] *Advanced Laboratory Scriptum*, University Bonn (2005)

This report contains several figures which are taken from the following sources:

Figure 1, 2 and 4 were taken from [3].

Figure 3 was taken from [1].

Figure 5 was taken from [2].

Figure 6 and 7 were taken from [4].