Advanced Laboratory Course, WS 02/03
E103: Franck-Hertz-Experiment

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Contents

1 Introduction

The Franck-Hertz-Experiment, first performed by J. Franck and G.Hertz in 1913, proves that atoms can absorb energy only in discrete quanta, even when the excitation is due to collisions. Before, this fact had only been proven for optical excitation. Moreover, with the help of results of the experiment, we calculate the excitation energy of the first three excited states of mercury.

2 Theoretical Foundations

2.1 Atomic Energy States

The idea of discrete atomic energy states was first postulated by Nils Bohr for the special case of hydrogen. Bohr first only assumed this to explain the observed hydrogen spectra consisting of small lines, but this fact can today be proven with the help of quantum mechanics.
In order to undergo a transition from a state with energy E_m to a state with energy E_n, the atom must compensate the energy difference between these states, either absorbing or losing (e.g. by radiation) energy, which of course depends on which of the states has the higher energy. Of course, a transition to a higher energy state can only occur if enough energy is provided by an external source. Since the energy states have different, well defined values of energy, this is also valid for their differences, and so, the absorbed or lost energy only comes in discrete values, which are all together typical for the type of atom involved. That is why one can identify an element from its spectrum. The energy needed for excitation can be provided by photons, which is then optical excitation, or by inelastic collisions. The latter type is indispensable for the Franck-Hertz-Experiment. Of coure, energy can also be lost optically or in inelastic collisions. According to quantum mechanics, not all optical transitions are allowed, but only those which obey the selection rules, e.g. $\Delta s = 0$ or $\Delta l = 1$. For collisional transitions, there are no such limitations.
An excited atomic state is not stable. The atom will decay to its ground states after a certain amount of time, radiating energy. The quickness of the decay is caracterized by a state's lifetime. The ground state of course is stable, because there all the electrons occupy the orbitals with the lowest energies possible without violating Fermi's exclusion principle.

2.2 Collisions

In the experiment, electrons collide with mercury atoms. There are two different types of collisions, one of them is elastic collision. There, the total amount of kinetic energy is unchanged during the collision. Since the electrons are very light compared to the mercury atoms, they hardly lose energy during an elastic collision. Only their direction is changed.
The other phenomenon occuring is inelastic collision. Here, some of the kinetic energy is lost and transformed to another type of energy, for example it might be used to excite the higher energy states. Inelastic collisions slow down the electrons involved. If an electron has enough initial energy, or gains energy inbetween, it can undergo several inelastic collisions, exciting several atoms and losing energy several times.
The frequency of electronic collisions in a mercury gas can be charakterized by the free path length of the electron. It strongly depends on the pressure of the gas. The

free path is given by equation:

$$\Lambda = \frac{kT}{p\sigma} \tag{1}$$

Here σ is the cross section, giving the number of events per time divided by the incoming particle densitiy, which is an important quantity in this context. It can also be calcutated with the help of quantum mechanics, or more geometrically, under the assumption of a gaskinetic diameter d of the particles 1 and 2 involved, accordingly to:

$$\sigma = \pi \left(\frac{d_1}{2} + \frac{d_2}{2} \right)^2 \tag{2}$$

More specific, it can be stated that

$$\sigma_{Hg \to Hg} = \pi d_{Hg}^2$$

$$\sigma_{e^- \to Hg} = \pi \left(\frac{d_{Hg}}{2} \right)^2$$

If the energy of the colliding electron is very high, that is, exceeding the binding energy of some other electron belonging to the mercury atom, the mercury atom can be ionized. That means it is totally ripped of its electron. If this happens inside a Franck-Hertz-Tube, the current is rapidly increased, because ionized gas is a conductor. One has to be careful not to destroy the tube like that. The probability of ionization in the Franck-Hertz-tube is increased when the temperature decreases, because then, the density of the mercury gas also decreases, lengthening the free path length and so giving longer time for acceleration. Moreover, a higher accelerating voltage increases ionization probability.

2.3 Thermionic Emission from Solid Metal Surfaces

In metals, the electrons are bound in the electronic gas which is extended over the whole solid body. In this gas, they can move freely, but normally, they cannot leave the metal because there is a potential at the surface which cannot be easily got over. When the metal is heated up to high temperatures, a small part of the electrons gains enough kinetic energy to overcome this potential and leave the metal. If there is an electric field outside the metal, these escaped electrons can be accelerated in a certain direction. The saturated current density j_s is determined by the law of Richardson:

$$j_s = A \cdot T \cdot e^{-eU_A/kT} \tag{3}$$

A is a constant which depends on the material and of the features of its surface. For thermionic emission, it is wise to use a material which has low escape energies but does not melt easily at high temperatures.

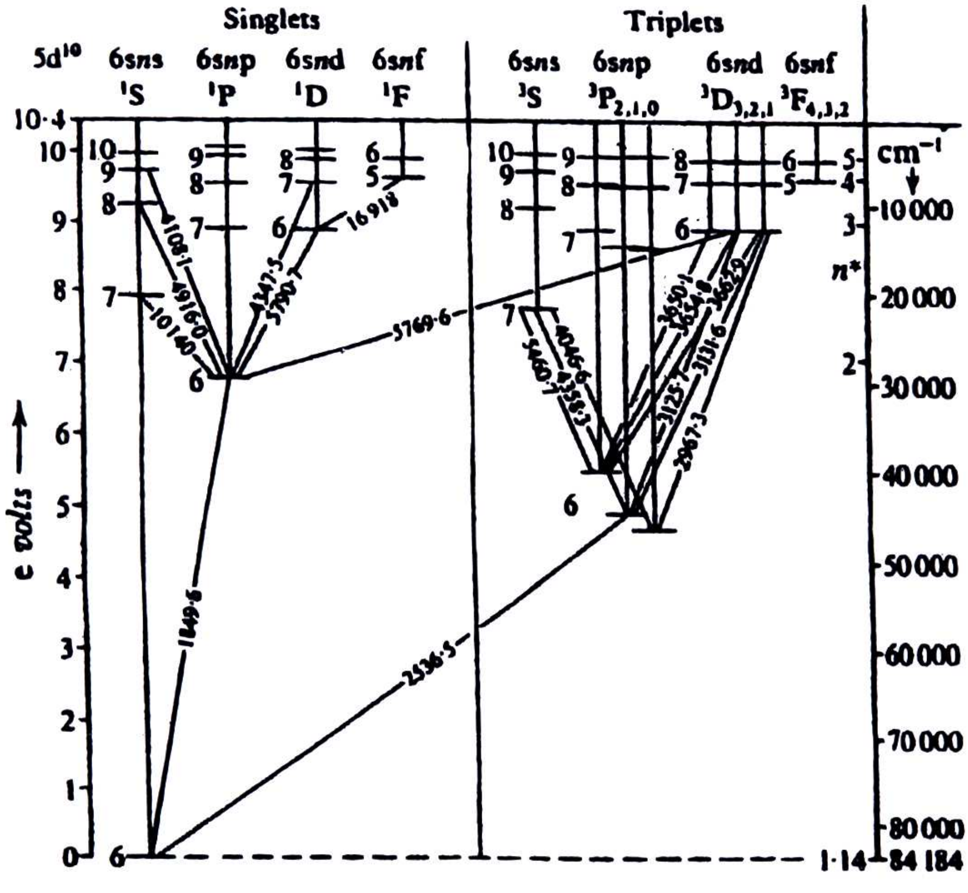
2.4 Some Features of Mercury

In the Franck-Hertz-tube, there is mercury vapor present. That is why some features of mercury will later be used during data analysis.
Mercury is a metal with atomic number Z=80. It is liquid at room temperatures. Its atomic mass has been measured as

$$m_{Hg} = 200,59u = 3,33 \cdot 10^{-22} g$$

Obviously, this exceeds the electron mass by orders of magnitudes. The gaskinetic diameter of mercury is

$$d_{Hg} = 0,44nm$$



Term diagram of Hg.

The above picture shows the energy levels of neutral mercury atoms. Allowed optical transitions are indicated by lines between the states.
The pressure of the mercury vapor inside the Franck-Hertz-tube depends on the temperature. It is described by the following equation from the scriptum:

$$\log p = 10,55 - 3333/T - 0,85 \log T \tag{4}$$

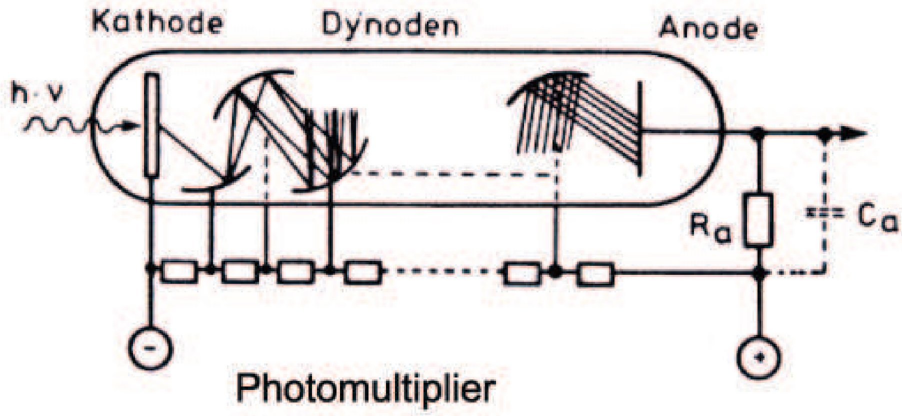
The pressure must be inserted in Torr. This equation is just another representation of the Claudius-Clapeyron-law for the special case of mercury. Generally, the Claudius-Clapeyron-law describes the relation between heat of vaporization Λ, temperature, saturated vapor pressure p_s and the volumina of the liquid and the gaseous phase (V_l,V_g):

$$\frac{\Lambda}{T} = \frac{dp_s}{dT}(V_g - V_l) \tag{5}$$

2.5 Photomultiplier

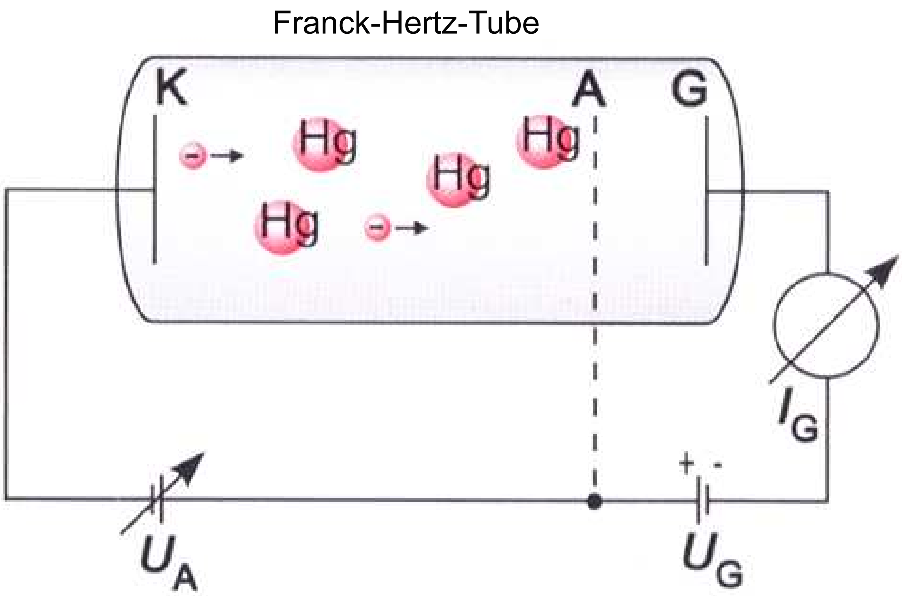
Photomultipliers are photon detectors, making use of the photoelectric effect. They are constructed out of vacuum tube with a photocathode at its front side. An incoming photon knocks an electron from the cathode. The electron is directed by an accelerating field to several dynodes which are arranged one after another.

This is accomplished with the help of a voltage divider, so that the dynodes are set at different potentials. Since the electrons have gained kinetic energy in the field, each electron produces several secondary electrons at each dynode. Like this, the electrons are multiplied. The amplified current is collected at an anode, which gives the output signal.



2.6 Franck-Hertz-Tube

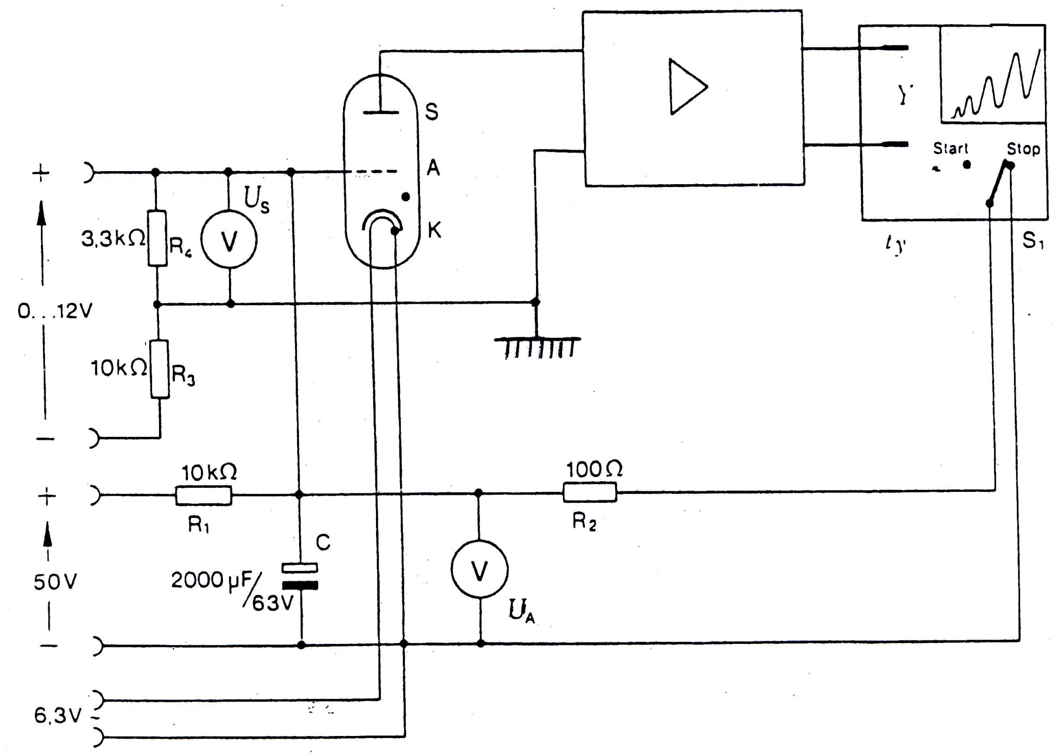
The Franck-Hertz-tube also is a vacuum tube. It contains three electrodes, the thermionic cathode, a grid-like anode and an electrode for the back voltage which finally collects the electrons. In this record, we will for simplicity call the latter one back electrode. Moreover, the tube contains a drop of mercury. That is why there is always some gaseous mercury in the tube, according to the Claudius-Clapeyron-law. The anode is set at positive potential, the back electrode must be slightly negative compared to the anode.



When the thermionic cathode is heated, electrons will escape from it. Accordingly, there will be a negative space-charge region in front of the cathode. These electrons are attracted by the anode and accelerated towards it. On their way, they gain kinetic energy whose amount depends on the anode voltage applied. The electrons can easily pass through the anode because it is a grid. Then, they must overcome the back voltage to reach the back electrode and there be detected. This is possible because before, the electrons have gained energy in the accelerating field. The more positive the anode and the less negative the back electrode, the more electrons can arrive, at least if there would not be any mercury vapor.

At low anode voltages, the electrons only undergo elastic collisions with the mercury atoms not losing any energy. But when the anode voltage is high enough, the electrons gain enough energy to excite a mercury atom in an inelastic collision. Those electrons cannot easily overcome the back voltage, and so the output current decreases. Since one electron can excite several mercury atoms, provided they have enough energy, there are typical variations in the current curve. The current starts decreasing each the anode voltage is just high enough to excite one more mercury atom, again increasing afterwards. Accordingly, the excitation energy of mercury can be calculated from the distance of the minima.

3 Experimental Setup



The above sketch shows the principal features of the experimental setup. The current from the back electrode is at first amplified and then used as Y-Input for the plotter. The X-input of the plotter is connected with the grid voltage of the anode. When starting a measurement, the capacitor is loaded, constantly increasing the grid voltage. There was also a switch which is missing in the sketch and which serves to shortcut the capacitor and quickly decrease the grid voltage. In the sketch, the back voltage is named U_S and the grid voltage U_A.
Alternatively, a photomultipier can be put in front of a UV-transparent window in the Franck-Hertz-tube and be connected with the amplifier. Then, the plotter draws the photocurrent curve. In addition, a differentiating circuit can be added just before the Y-input of the plotter.

4 Realization of the Experiment

During the experiment, we took different measurements, first variing the back voltage ($0,5V$,$1V$,$1,5V$,$2V$) for a fixed temperature ($163°C$) and after that, variing the temperature ($163°C$,$175°C$,$188°C$,$202°C$) for fixed back voltage. ($1V$). Accordingly, we take in total seven measurements, because one of the measurements can be used for both cases.
For each of these measurements, we also plotted the photocurrent from the photomultiplier, indicating how much UV-light was emitted from the tube. Since the photocurrent curve was always very smooth and didn't show very distinct features, we also used the differentiating circuit in order to more clearly observe where the photocurrent curve changed. This is possible, since the output of the differentiating circuit shows the changes of the inclination of the other curve.
We also tried to get better photocurrent curves by variing the photomultiplier voltage and the photocurrent amplification, but we couldn't observe any changes due to this procedure. So we decided to use the recommended voltage of $250V$ for the photomultiplier.
During the experiment, we constantly tried to optimize the settings of the x-y-Plotter. We tried to use the whole width and length of the paper, because this gives nicer pictures, and of course, it is easier to finally measure the differences between the minima of the back electrode current curve. The optimization could be done by the choice of a good amplification, and by the settings of the plotter itself, that is the choice of the magnification and of the starting point of the curve. We inserted pens of different colours in the plotter in order to be able to distinguish the different measurements.
For evaluation, it is very important to be able to fix the scale of the curves. Otherwise, we could not get any quantitative results. So we took great care to take notes on the grid voltage and the current at the end of each measurement, at the moment when the plotter reached the end of its X-axes. For all measurements, our maximum grid voltage was $40V$.
In this context, it must be noted that we didn't scale the Y-axes of the differentiated curves, since they only serve to show more clearly the changes of the photocurrent curve. The actual value of the differentiated current has no profound meaning, because it depends on the properties of the differentiating ciruit used.
In the pictures, one can see a vertical line at the end of most measurements. This has nothing to do with the actual characteristic curve, but is probably due to the fact that the plotter resets without the pen being lifted. To be sure, we verified this by observing the grid voltage. It did not change any more while the plotter drawed these vertical lines, so they cannot be due to the characteristic curves.
The temperature of the Franck-Hertz-Tube could be chosen by setting the voltage of the stove. Before starting the measurement, we had to wait until the temperature had reached its final value, because otherwise, fluctuations during the measurements would probably falsify the results.
The setting of the back voltage was controlled by a measuring instrument.
During our first measurement of the photocurrent, we once put a glass plate in front of the photomultiplier to check whether the observed photocurrent is really due to UV-light. Since normal glass is not transparent to UV-light, we expected a sudden decrease of the current down to zero. This really happened, so we were sure to measure nothing else than UV-light.
Moreover, we observed the tube during the experiment, because it can happen that the electrons ionize the mercury gas. This would cause a light flash within the tube. The thus strongly increased current could destroy the tube, so in this case, the grid voltage has to be switched of. Luckily, this did not happen to us. For the same reason, it was important to only switch on the cathode heating after the tube had

reached a temperature of at least $140°C$, because ionization is more likely at low temperatures (see chapter 2.2).

5 Analysis of the Results

All quantitative results in this section are based on the scaling of the plotted pictures. Therefore, scales have been added to them. The Y-axes has different scales for different curves, which can be distinguish by their corresponding colours. The original pictures can be found at the end of this record.

5.1 Calculation of the Excitation Energy

The back electrode current curves show several distinct minima. As explained in chapter 2.6, these minima mark the grid voltage where the electrons have gained enough energy to excite one or more mercury atoms. Because of this, the difference between the voltages corresponds to the excitation energy. The difference is therefore first measured in centimeters, which is then transformed to a voltage with the help of the scale. Since the accelerated particles are electrons, this voltage can most easily be transformed into an energy in eV.
The errors for this measurements are estimated accordingly to the precision of length measurements on the paper, or calculated with the method of Gauss. Since the seventh measurement does not show the minima clearly, we have set a greater error for it.
Moreover, the first (and in measurements at higher temperatures even the second and the third) minimum can not be located very exactly. In order to avoid big errors, these minima are simply omitted. There are enough clear minima for our calculation.
The following tables show the results of our measurements:

Measurement 1
$T = 163°C \pm 1°C$, $U_{back} = 1V \pm 0,1V$
Back Electrode & Photocurrent Curve: Black
Differentiated Photocurrent Curve: Blue
X-Scale: $40V \pm 0,2V$ are equivalent to $34cm \pm 0,1cm$.
Y-Scale Back Electrode Current: $14nA \pm 0,1nA$ are equivalent to $27,3cm \pm 0,2cm$
Y-Scale Photocurrent: $2nA \pm 0,1nA$ are equivalent to $24,8cm \pm 0,2cm$

Minima	$d[cm]$	$\Delta d[cm]$	$U[V]$	$\Delta U[V]$
3-2	4,2	0,1	4,94	0,12
4-3	4,1	0,1	4,82	0,12
5-4	4,1	0,1	4,82	0,12
6-5	4,15	0,1	4,88	0,12

Measurement 2
$T = 163°C \pm 1°C$, $U_{back} = 0,5V \pm 0,1V$
Back electrode & Photocurrent Curve: Red
Differentiated Photocurrent Curve: Green
X-Scale: $40V \pm 0,2V$ are equivalent to $34cm \pm 0,1cm$.
Y-Scale Back Electrode Current: $18nA \pm 0,1nA$ are equivalent to $23,7cm \pm 0,2cm$
Y-Scale Photocurrent: $1,9nA \pm 0,1nA$ are equivalent to $26,7cm \pm 0,2cm$

Minima	$d[cm]$	$\Delta d[cm]$	$U[V]$	$\Delta U[V]$
3-2	4,1	0,1	4,82	0,12
4-3	4,2	0,1	4,94	0,12
5-4	4,1	0,1	4,82	0,12
6-5	4,15	0,1	4,88	0,12

Measurement 3

$T = 163°C \pm 1°C$, $U_{back} = 1,5V \pm 0,1V$
Back electrode & Photocurrent Curve: Black
Differentiated Photocurrent Curve: Blue
X-Scale: $40V \pm 0,2V$ are equivalent to $34cm \pm 0,1cm$.
Y-Scale Back Electrode Current: $12nA \pm 0,1nA$ are equivalent to $20,5cm \pm 0,2cm$
Y-Scale Photocurrent: $1,8nA \pm 0,1nA$ are equivalent to $23cm \pm 0,2cm$

Minima	$d[cm]$	$\Delta d[cm]$	$U[V]$	$\Delta U[V]$
3-2	4,1	0,1	4,82	0,12
4-3	4,15	0,1	4,88	0,12
5-4	4,05	0,1	4,77	0,12
6-5	4,15	0,1	4,88	0,12

Measurement 4

$T = 163°C \pm 1°C$, $U_{back} = 2V \pm 0,1V$
Back electrode & Photocurrent Curve: Red
Differentiated Photocurrent Curve: Green
X-Scale: $40V \pm 0,2V$ are equivalent to $34cm \pm 0,1cm$.
Y-Scale Back Electrode Current: $10nA \pm 0,1nA$ are equivalent to $20,3cm \pm 0,2cm$
Y-Scale Photocurrent: $1,2nA \pm 0,1nA$ are equivalent to $21,2cm \pm 0,2cm$

Minima	$d[cm]$	$\Delta d[cm]$	$U[V]$	$\Delta U[V]$
3-2	4,1	0,1	4,82	0,12
4-3	4,05	0,1	4,77	0,12
5-4	4,05	0,1	4,77	0,12
6-5	4,1	0,1	4,82	0,12

Measurement 5

$T = 175°C \pm 1°C$, $U_{back} = 1V \pm 0,1V$
Back electrode & Photocurrent Curve: Black
X-Scale: $40V \pm 0,2V$ are equivalent to $33,9cm \pm 0,1cm$.
Y-Scale Back Electrode Current: $7nA \pm 0,1nA$ are equivalent to $24,8cm \pm 0,2cm$
Y-Scale Photocurrent: $1,1nA \pm 0,1nA$ are equivalent to $16,2cm \pm 0,2cm$

Minima	$d[cm]$	$\Delta d[cm]$	$U[V]$	$\Delta U[V]$
3-2	4,1	0,1	4,84	0,12
4-3	4,0	0,1	4,72	0,12
5-4	3,9	0,1	4,60	0,12
6-5	3,95	0,1	4,66	0,12

Measurement 6

$T = 188°C \pm 1°C$, $U_{back} = 1V \pm 0,1V$
Back electrode & Photocurrent Curve: Green
X-Scale: $40V \pm 0,2V$ are equivalent to $33,9cm \pm 0,1cm$.
Y-Scale Back Electrode Current: $3,5nA \pm 0,1nA$ are equivalent to $8,0cm \pm 0,2cm$
Y-Scale Photocurrent: $0,7nA \pm 0,1nA$ are equivalent to $9,2cm \pm 0,2cm$

Minima	$d[cm]$	$\Delta d[cm]$	$U[V]$	$\Delta U[V]$
4-3	3,95	0,1	4,66	0,12
5-4	3,9	0,1	4,6	0,12
6-5	3,9	0,1	4,60	0,12

Measurement 7
$T = 202°C \pm 1°C$, $U_{back} = 1V \pm 0,1V$
Back electrode & Photocurrent Curve: Red
X-Scale: $40V \pm 0,2V$ are equivalent to $33,9cm \pm 0,1cm$.
Y-Scale Back Electrode Current: $1,1nA \pm 0,1nA$ are equivalent to $7,6cm \pm 0,2cm$
Y-Scale Photocurrent: $0,2nA \pm 0,1nA$ are equivalent to $1,4cm \pm 0,2cm$

Minima	$d[cm]$	$\Delta d[cm]$	$U[V]$	$\Delta U[V]$
5-4	3,7	0,2	4,35	0,24

From these values, we calculate the mean value of the voltage, taking into account the errors. That means, the voltage obtained from measurement 7 with an error which is twice as big as the errors of the other measurements only contributes half as much as the other calculated voltages.
Like this, we get:

$$\bar{U} = 4,78V \pm 0,12V$$

From this, it directly follows:

$$\bar{E}_{excitation} = 4,78eV \pm 0,12eV$$

In most books, we find that this value should be $4,9eV$ for the Franck-Hertz-experiment. This would just be included in our error bar, so our result seems sensible. When consulting the instructions for the experiment, we find more detailed information about the energy levels of Hg:
$1S0$ at $0,00eV$ (ground level)
$3P0$ at $4,67eV$
$3P1$ at $4,89eV$
$3P2$ at $5,46eV$
It meets the eye that our result lies just in the middle between the first and the second excited state. Making the assumption that all three P-states are equally frequently excited, the result should be $5eV$, which is the mean excitation energy of these states. Then, the deviation of the theoretical and the measured value would not be covered any more by the error bars.

5.2 Calculation of the Wavelength

Now, we calculate the wavelength belonging to the excitation energy. It should be in the UV-region because we experimentally verified, as described in chapter 4, that the emitted light must be UV-light. Using

$$4,78eV = 7,66 \cdot 10^{-19}J$$

and

$$\lambda = \frac{h \cdot c}{E}$$

we get:

$$\lambda = 259nm \pm 6,5nm$$

The error here is also calculated with the Gaussian method. The wavelength is indeed in the UV-region, fulfilling our expections.
Nevertheless, it must be clearly underlined that this calculation does not make too much sense, because it uses the measured excitation energy for collisions. The optical transitions $1S0 \rightarrow 3P0$ and $1S0 \rightarrow 3P2$ are forbidden and therefore do not contribute to the UV-light! So the calculation can only be an estimation of the real wavelength, but deviations will probably be small, since the energy of the allowed

transition lies near the mean energy of all three levels.
We can theoretically calculate the wavelength, using the above mentionned energy of $4,89eV$ for the allowed optical transition. This gives:

$$\lambda_{theoretical} = 253,6nm$$

5.3 Correlations of Back Electrode Current and Photocurrent

Unfortunately, the bends in the photocurrent curve are hardly visible. Comparing these curves with their corresponding differentiated curves, one can more or less guess where the bends are. The maxima and minima of the differentiated curve coincide with the turning points of the photocurrent curve. These features can be roughly recognized in our plots, but for a precise discussion of possible differences to our theoretical expectations, the bends of the photocurrent curve are too indistinct. All we can clearly see is that the maxima and minima of the differentiated curves lie somewhere in the middle between a maximum and minimum of the back electrode current curve. Then, the turning points of the photocurrent curve should be there, too, as expected.
Now we want to shortly explain how we think the relations between the different curves should be. In order to emit UV-light, the mercury atoms must be first excited by the electrons. When the back electrode current curve reaches its first maximum, the first electrons have just gained enough energy to achieve this, so there, the first mercury atoms get excited. Accordingly, the photocurrent should start there. In our plots, the first maximum is not very marked either and cannot precisely be located, but it seems like this is true, at least roughly. While the back electrode current decreases to its first minimum, more and more electrons gain enough energy for excitation, and so, the photocurrent should rise quickly. Then, on the back electrode current's way to its next maximum, it is true that the electrons gain energy, but not enough for a second ionization. But it must not be forgotten that, then the electrode current start increasing after the minimum, the number of excitations still rises. At this point, the grid voltage is only able to overcome the loss to an extent which enables more electrons to reach the back electrode. That is why the photocurrent still rises there. Unfortunately we cannot decide if there is a point in the curve where virtually all electrons undergo one inelastic collision. At this point, the photocurrent should stay constant until the next maximum of the back electrode current is reached. When looking at our curves, is seems that this is never the case. Nevertheless, the point in question must at least be approached, since there are turning points in the photocurrent curve.

5.4 Dependencies on the Back Voltage

Measurements 1 to 4 are done with different back voltages and a constant temperature (for more Details see chapter 5.1).This enables us to examine the influence of the back voltage on the curves. To do this, we compare the maximum back electrode currents for a grid voltage of $40V$. Moreover, we have measured the depth of the fifth minimum (that is, the difference of the forth maximum and the fifth minimum) in order to compare these data, too. We chose the fifth minimum because it is very marked in each measurement. We obtained the following results:

Measurement	$U_{back}[V]$	$I_{max}[nA]$	$d_{depth}[nA]$	$\Delta d_{depth}[nA]$
2	0,5	18	1,4	0,10
1	1	14	3,0	0,31
3	1,5	12	3,4	0,30
4	2	10	3,6	0,36

At first, it meets the eye that the maximum back electrode current decreases with increasing back voltage. This can easily be explained, because the electrons must have enough energy to overcome the back voltage in order to reach the back electrode. The higher the back voltage, the more difficult this is, and the lesser electrons arrive.
Secondly, the minima are the deeper, the higher the back voltage is. This has a very similar reason to the decreasing maximum current. When an electron loses energy by exciting a mercury atom, it will be more difficult for it to finally overcome the back voltage and reach the back electrode. That is why exciting electrons are more efficiently stopped by higher back voltages.

5.5 Dependencies on the Temperature

Measurements 1 and 5 to 7 are done with different temperatures and fixed back voltage. This enables us to compare the dependency of the back electrode current and the photocurrent on the temperature.
For comparison of the back electrode currents, we have not chosen the current for a grid voltage of $40V$, but the height of the fifth maximum, since for higher temperatures, the curves are a bit shifted to the right.

Measurement	$T[°C]$	$I_{backelectrode}[nA]$	I_{photo}
1	163	11,4	2
5	175	7,0	1,1
6	188	2,4	0,7
7	202	2,3	0,2

As one can see, the back electrode current decrease with higher temperatures. The maxima and minima get more and more indistinct, but this is clear because due to the lower currents, all variations have to take place in a smaller current interval. This is probably due to the higher particle density.
Similarly, the photocurrent also dramatically decreases with higher temperatures. This is also due to the higher particle density. At higher temperatures, the probabilty of collisions is increased, perhaps it gets more and more likely that the mercury atoms will lose their excitation energy in inelastic collisions, and therefore cannot radiate energy any more.
Moreover, regarding the results of chapter 5.1, it meets the eye that the differences between the minima slightly decrease with higher temperatures. This could be just an accident, but it might also be that, due the to higher density, the excitation of the 3P0-state gets more likely relatively to the other states, because it has the lowest energy. When the particle density is high, one can imagine that the electron undergoes an inelasic collision right after reaching this energy, having no time to accelerate to the slightly higher energies of the other states.

5.6 Free Path and Life Time

In order to calculate the pressure in Torr inside the Franck-Hertz-tube, we use equation (4).We set the Temperature as $T = 163°C$, because this value was often used during the experiment. We get:

$$p = 4,59Torr = 611,9Pa$$

Equation (1) gives the free path of an electron at this pressure:

$$\Lambda_{e^- \to Hg} = 6,47 \cdot 10^{-5} m$$

One can also calculate the free path for the collision of two Hg-atoms like that, one must only pay attention to the fact that then another cross section must be used (see chapter 2.2). We get:

$$\Lambda_{Hg \to Hg} = 1,62 \cdot 10^{-5} m$$

The mean velocity of the mercury atoms due to the temperature is given by:

$$\bar{v} = \sqrt{\frac{8kT}{\pi m_{Hg}}} \tag{6}$$

Accordingly, the mean velocity is:

$$\bar{v}_{Hg} = 214,56 m/s$$

From this follows the time between two collision:

$$\tau = \frac{\Lambda}{\bar{v}} = 75,4 ns$$

Since this is shorter than the life time for the optical transition $3P1 \to 1S0$, which is $117ns$, most atoms will probably undergo collisions before losing their excitation energy by emission of radiation. Some of them probably will thus lose their energy in the collision and not be able to emit radiation any more.

6 Sources

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