MICHIGAN TECHNOLOGICAL UNIVERSITY
DEPARTMENT OF PHYSICS

PH3480 MODERN PHYSICS LABORATORY

Project #1

Franck-Hertz Experiments With Neon and Mercury Atoms

Atomic and Nuclear Physics

Quantum Mechanics

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A. PROJECT OBJECTIVES

The main purpose of this Project is to reproduce the experiments of Franck and Hertz performed in 1913. They recorded a dependence of collector current against accelerating voltage with ***repeated peaks*** in a gas-filled vacuum tube and observed corresponding ***light*** emission. Such findings demonstrate two physical phenomena encountered in collisions between electrons and atoms in a gas: ***inelastic*** scattering resulting in ***quantized*** excitation of the target atoms, and ***transitions*** from the excited states to less excited states, accompanying by ***emission*** of light. These are striking experiments: using, in a sense, a simple voltmeter they (and now you) can identify energy levels of individual atoms!

To reproduce the Franck-Hertz experiments, your job in this Project includes:

1. Measurement of the discontinuous energy change of free electrons due to inelastic collision with gas atoms and interpretation of the recorded current-voltage dependences as representing discrete energy absorption by the target atoms.
2. Observation and documentation of light emission induced by the electron excitation of such atoms.
3. Identification of the luminance phenomenon as layers with a high probability of excitation.

- As with the other Projects, your Instructor checks in the beginning of each class if ***you are ready*** for the experiments. Please, see ***Sec. C*** for the list of questions you have to answer in this ***Pre-Lab homework***. Before you start the experiments, you have to be ***familiar with theoretical*** aspects of the Project. Please, see ***Sec. B*** for references and ***Sec. D*** for a short theoretical review.

- As with any serious experiments, pay special attention to both your ***personal*** safety and the safety of the ***equipment*** (see ***Safety Notes***, ***Sec. E1*** and ***Sec. F1***).

- After reading the theory, make ***a plan for your measurements*** and decide how you should set up your experiments. ***Exploratory aspects*** of the Project help you to do some additional study of the experiment topics (see ***Sec. E2*** and ***Sec. F2***).

- Have your ***Notebook*** ready for the Project (see a link in the ***online PH3480 Syllabus***).

- After completing the experiment, ***write a Report*** as described in the PH3480 Syllabus. ***After-Lab questions*** (see ***Sec. G***) are due together with the Report but look at those ***questions right now***, so that you keep them in mind during experimenting.

B. LITERATURE

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C. PRE-LAB QUESTIONS

(The pre-lab work must be done ***at home*** and checked with your Instructor ***before*** you start the lab.)

1. Why is it important to use a monatomic gas in the Franck-Hertz experiments?
2. Explain the terms *elastic collision* and *inelastic collision*?
3. What is the first excited energy level of mercury? What accelerating voltages should we use for neon atoms?
4. Why is it necessary to apply a retarding voltage between accelerating grid and the collector?
5. Plot the expected curves of current against accelerating voltage, in the experiment with neon, showing the positions of the peak and valleys on an absolute voltage scale.

D. THEORETICAL BACKGROUND

The 1925 Nobel Prize in Physics was awarded jointly to James Franck and Gustav Hertz for "their discovery of the laws governing the impact of an electron upon an atom." Franck and Hertz performed the experiments in 1914, twelve years before the development of quantum mechanics, and it provided direct evidence for Bohr's postulates. Franck and Hertz discovered two fundamental phenomena: an "energy loss in distinct steps of ΔE = 4.89 eV for electrons passing through atomic ***mercury*** vapor" and a "light emission at the ***ultraviolet*** line, λ = 253.7 nm". The Franck-Hertz experiment turned out to be the first demonstration of the quantization of atomic energy levels: electrons scattered from atoms displayed energy loss corresponding exactly to excitation of bound state transitions. Having measured the threshold voltage at which the emission appeared, they could derive a value for Planck's constant using the Einstein relation. The agreement with the values obtained previously by Planck, Einstein, and Bohr from their theories of the blackbody spectrum, the photoelectric effect, and the hydrogen spectrum, respectively, was a striking and historic conformation of the new quantum theory.

Although the Franck-Hertz experiment is simple with clear-cut results, many subtle and interesting collision processes lie at the heart of this experiment making it sufficiently open-ended to remain challenging. Being a classic experiment, many undergraduate textbooks information about the Franck-Hertz experiment. Look at some of the references listed in the literature list above and you will have a good overview of the experiment. Many of the subtleties are also discussed in the American Journal of Physics articles.

The Franck-Hertz experiment, together with atomic spectroscopic data and the Bohr model briefly described below, inspired development of modern quantum physics. The spectrum of ***hydrogen***, which turned out to be crucial in providing the first insight into atomic structure over half a century later, was first observed by Anders *Angstrom* in Sweden in 1853. However, although a tremendous amount of scientific progress was made using spectral lines, no one had the slightest idea why atoms emitted at the frequencies they did. It was appreciated that spectra implied that atoms had *structure*. Obviously, if any pattern could be discerned in the spectral lines for an atom, that might be a clue as to the internal structure of the atom. A great deal of effort went into analyzing the spectral data from the 1860's on. Johann Balmer, a math and Latin teacher at a girls' school in Switzerland, made the main breakthrough. He decided that the most likely atom to show simple spectral patterns was the lightest (and therefore the simplest) atom, hydrogen. Angstrom had measured the four visible spectral lines to have wavelengths 656.21, 486.07, 434.01 and 410.12 nm. Balmer concentrated on just these four numbers and found that they could fit an uncomplicated equation,

$$\lambda = b\left(\frac{m^2}{m^2-4}\right) \qquad (1)$$

where b = 364.6 nm and $m \geq 3$. Eq. (1) is now known as the Balmer formula, and the series of optical lines that it fits is called the *Balmer series*, see Fig. 1. The wavelength 364.6 nm, corresponding to m $\rightarrow \infty$, is called the *series limit*. (Balmer also suggested that there would be other lines - in the infrared - corresponding to higher m, and in fact some of them had already been observed, unbeknown to Balmer. He further conjectured that the 4 could be replaced by 9, 16, 25, … and this also turned out to be true - but these lines, further into the infrared, were not detected until the early twentieth century, along with the ultraviolet lines generated by replacing the 4 by 1 and now called the *Lyman series*.)

It is instructive to write eq. (1) in terms of the reciprocal of the wavelength,

$$\frac{1}{\lambda} = \frac{4}{b}\left(\frac{1}{n^2} - \frac{1}{m^2}\right) \tag{2}$$

where n and m are integers, and $4/b$ is very close to what is now called the ***Rydberg constant*** for hydrogen R_H. = 1.097×10^7 m^{-1}. (The reciprocal wavelength is sometimes called the wave number in optics- the number of waves that fit in one unit of length. A *standard definition* of the ***wavenumber***, however, is $k = 2\pi/\lambda$.) The case of n = 1 in eq. (2) corresponds to the Lyman series, the case of n = 2 to the Balmer series, etc., as shown in Fig.1.

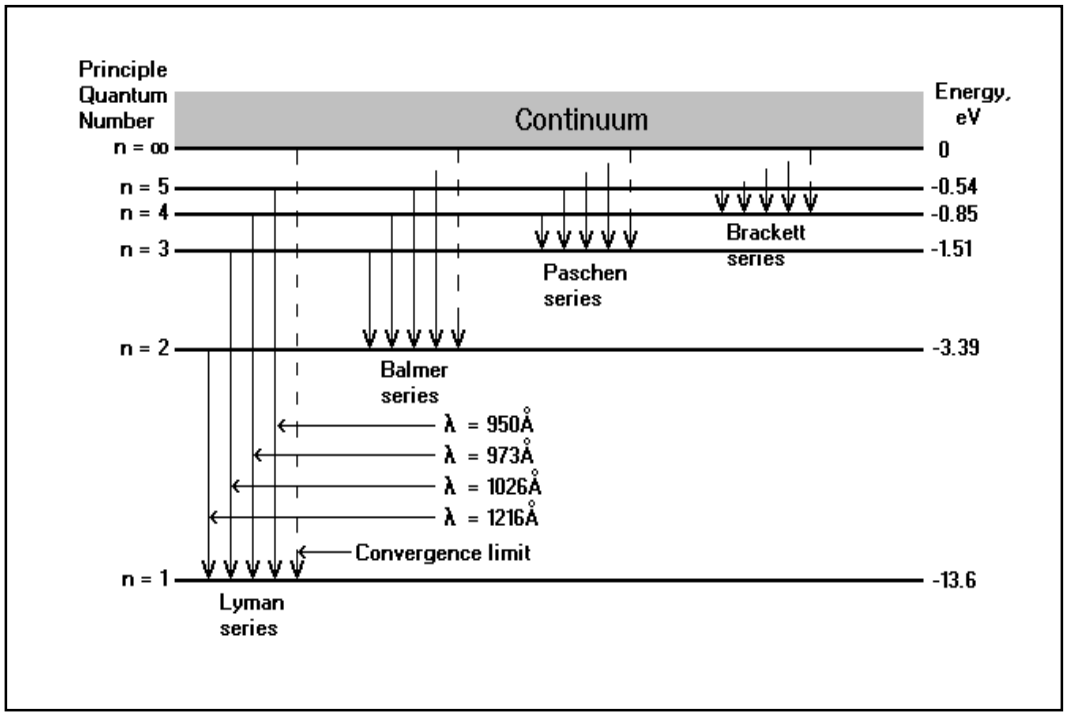

Fig. 1: Energy level diagram of the hydrogen atom.

It was Niels Bohr who in 1913 introduced his *planetary* model of the atom, together with several non-classical postulates, to account for the wavelengths present in the atomic spectrum from hydrogen gas. His ***first postulate*** was that only those orbits occur for which the *angular momentum* L_e of the electron is an integral multiple of ***Planck's*** *constant h*, i.e. $L_e = rm\mathrm{v} = nh/2\pi$, where *n* is an integer.

Using this postulate together with some relations from classical physics, Bohr showed that the energy of the electron occupying these allowed orbital states had a simple dependence on the integer *n* in a form

$$E_n = -\frac{me^4Z^2}{8\varepsilon_0^2h^2}\frac{1}{n^2} = -\frac{13.6}{n^2},\ n = 1,2,3,... \tag{3}$$

where nucleus charge Z = 1 for hydrogen and ε_0 is the permittivity. At its lowest level, with n = 1, the electron has energy E_1 = – 13.6 eV. This state is called the ***ground*** state. The higher states, with n > 1, are the ***excited*** states. The ground state energy calculated by Bohr agrees very well with the experimentally observed binding energy (or ionization energy) for hydrogen.

In classical electrodynamics, a charged particle ***radiates*** energy when it is accelerated, such as the electrons in their "planetary" orbits. Thus a classical electron would soon radiate away its energy and no longer remain in orbit. This led Bohr to his ***second postulate***, which states that an electron remaining in one of the allowed orbital states ***does not*** radiate energy, and that radiation is emitted ***only*** when an electron goes from an initial state of higher energy (n_i) to a final state of lower energy (n_f). Since the energy of the ***quantum*** of radiation emitted is $h\nu$ according to the *Einstein relation* and is also equal to the difference in energy of the two states, the second Bohr postulate then can be written as

$$h\nu = E_{nf} - E_{ni} \tag{4}$$

Combining eqs (3) and (4) then yields

$$\nu = \frac{me^4Z^2}{8\varepsilon_0^2h^3}\left(\frac{1}{n_f^2} - \frac{1}{n_i^2}\right) = \frac{13.6}{h}\left(\frac{1}{n_f^2} - \frac{1}{n_i^2}\right) \tag{5}$$

or in terms of the reciprocal wavelength $1/\lambda = \nu/c$, this is

$$\frac{1}{\lambda} = \frac{13.6}{hc}\left(\frac{1}{n_f^2} - \frac{1}{n_i^2}\right) = R_\infty\left(\frac{1}{n_f^2} - \frac{1}{n_i^2}\right) \tag{6}$$

where R_∞ is the Rydberg constant, introduced in eq. (2),

$$R_\infty = \frac{me^4}{8\varepsilon_0^2h^3c} = R_\infty = 1.097\times10^7\ \mathrm{m^{-1}} \tag{7}$$

The wavelengths of some of the hydrogen spectral lines as calculated from eq. (6) are shown in Fig. 1, and they agree well with experimental observations, confirming the predictions of the Bohr model.

It seems reasonable from the Bohr model that just as electrons may make transitions *down* from allowed higher energy states to lower ones, they may be ***excited up*** into higher energy states by *absorbing precisely* the amount of energy representing difference between the lower and higher states. This would be the other way to get direct evidence of the existence of discrete energy levels in atomic systems. Franck and Hertz showed that this was, indeed, the case in a series of experiments reported in 1913, the same year that Bohr presented his model. As seen from Fig. 1, the ***excitation energy*** of an excited state n is the energy above the ground state, $\Delta E = E_n - E_1$. For the first excited state $n = 2$, so that $\Delta E = 10.2$ eV. This energy may be provided in several ways. The atom may absorb a *photon*, as in the *photoelectric* effect experiment. Alternatively, if we *heat* the gas, atoms thermal energy could be converted, at a collision, into *excitation* energy. We may calculate the gas temperature required to provide 10.2 eV of thermal energy. Since the mean kinetic energy of an atom is $E = 3kT/2$, this temperature is about $T = 8000$ K.

Obviously, such a high temperature is not *practical* for laboratory experiments. A more convenient way is to accelerate electrons in an electric field and permit these electrons to collide with atoms in a gas transferring their energy to the atoms. If the energy of the electrons is *less* than the separation of the ground state from the first excited state, then no energy is transferred and the collisions are termed ***elastic***. If the electron energy is equal to or greater than the separation of the lowest states, then the absorbed energy is equal to the energy separation of the states, and the collision is termed ***inelastic***. The impinging electrons may be left with some of their initial energy if that energy is greater than the energy separation of the two levels. Franck and Hertz used a beam of accelerated electrons in a vacuum tube with mercury to measure such energy.

Their tube is schematically shown in Fig. 2. (Note that the first Franck-Hertz's apparatus was a simpler version of the tube seen in Fig. 2, without grid G_1. You can see a copy of that tube on the shelf above the Franck-Hertz desk.) The sealed tube contains a small amount of mercury that is vaporized by heating the tube with a surrounding furnace. A heated cathode K produces electrons by thermoemission; a perforated grid G_2 is maintained at a positive voltage U_2 with respect to a control grid G_1 located in the close proximity to the cathode; and a collector electrode A held at a small voltage U_3 (about 0.5 V) that is negative with respect to the grid G_2. Such a retarding voltage decelerates electrons after grid G_2, so that only electrons with sufficient kinetic energy can overcome the retarding potential and reach the collector A, contributing to the collector current. This current is measured by a meter I as a function of the accelerating voltage U_2.

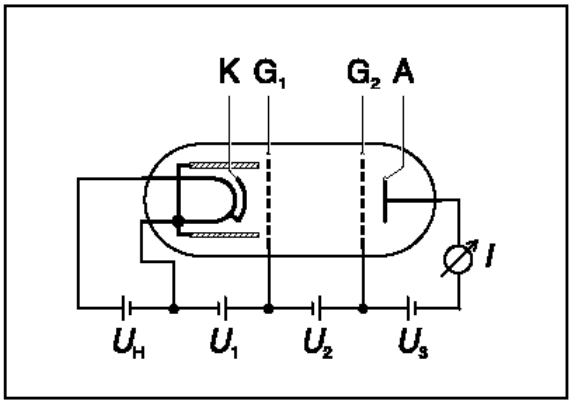

Fig. 2: Franck-Hertz tube (schematic).

The emitted electrons form a charge cloud and are attracted by the control potential U_1 between the cathode and the grid G_1. The electrons are then accelerated by voltage U_2 as they move toward the grid G_2. If their energy is less than the excitation energy ΔE, only elastic collisions will occur between the electrons and the mercury atoms. The accelerated electrons will pass through the perforated grid G_2 and will be measured at the collector. Even if the voltage U_2 is increased slowly the current I increases quite steeply: the electrons loose only ***negligible*** amounts of energy on elastic impact with the mercury atoms. Hence the electrons - part of which fly through the grid G_2 - have enough energy to overcome the retarding potential U_3. If the voltage U_2 becomes large enough to let the energy eU_2 of the colliding electron to lift an electron of the mercury atom from the ground state to the first excited state, the colliding electron looses so much energy with such an inelastic collision that it becomes unable to overcome the reverse bias U_3. This makes the collector current decrease strongly.

As U_2 is increased further, successive maxima in collector current occur with a spacing of $V = \Delta E/e$. They occur because an electron can now gain enough energy to make an inelastic collision well before reaching the grid G_2. This electron can gain additional energy to make a second inelastic collision with a second maximum in the collector current. This process will repeat as U_2 is increased, producing a series of equally spaced maxima in the measured collector current. From this spacing, Franck and Hertz calculated the energy difference between the ground state and first excited state. This permitted them to determine the frequency and wavelength of the radiation emitted by a mercury atom when it dropped from the excited to the ground state.

Why did Franck and Hertz use ***mercury*** vapor instead of hydrogen gas? The reason is that hydrogen atoms combine to form hydrogen molecules. Therefore, some of the energy lost in inelastic collisions of the electrons with a hydrogen gas would result from separating the hydrogen molecules into atoms and this would complicate the analysis of the measured collector current. A mercury gas consists of single atoms. Mercury atoms have 80 electrons (and protons) instead of the one for hydrogen since $Z = 80$ for Hg. A more detailed quantum mechanical analyses is required to account

for the energies of all these electrons. However, for the purpose of the Franck-Hertz experiment, it is sufficient to note that mercury is a transition metal and its d subshell is full, and it has an electronic configuration of the inert gas Xe plus electrons in $6s^2 5d^{10} 4f^{14}$ subshells. As for all of the transitional metals, the "outer" electrons determine many properties of mercury. For the transition metals, these are always the *s*-electrons, which have a larger mean radius than the *d*-electrons. Remember that the mean radius depends mostly on *n*; the *s*-electrons of the transition metals have a larger *n* than the *d*-electrons. For instance, Hg has two electrons in the 6*s* subshell with $n = 6$, while the rest of its 78 electrons are in subshells with $n \leq 5$. These 78 electrons bound much more strongly to the nucleus than the remaining two. Therefore, inelastic collisions of the mercury atoms with the accelerated electrons excite only these more weakly bound "outer" electrons. Correspondingly, the collector current will measure the difference between the ground and first excited state of these "outer" electrons. Fig. 3a demonstrates a diagram of the energy levels, together with possible transitions, for mercury atoms.

Since the next subshell after 4*f* and 5*d* is 6*p*, the lowest excited state for mercury is the 6^3P_0 state, which is metastable, i.e. dipole transition to the ground state is forbidden. Its lifetime is about 10^5 times that of ordinary transitions, so that these excited atoms decay only slowly allowing their number to build up to the point where most of the electron-mercury atom collisions are with them. When these mercury atoms are excited further to the next excited state, 6^3P_1, they decay immediately by emission of a 253.7-nm photon (see Fig. 3a) since the 6^3P_1 state is not metastable. Franck and Hertz detected these photons through a window in their tube. According to the ***Einstein relation*** $\Delta E = h\nu = hc/\lambda$, the wavelength $\lambda = 253.7$ nm corresponds to energy 4.89 eV, which is found to be a distance between the maxima in the dependence of the collector current as a function of the accelerating voltage. 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.

It is not easy, however, to observe directly such emission since this is the ***ultraviolet*** light outside the visible region; therefore, studying mercury requires a rather sophisticated experimental technique. (For instance, since usual glass is not transparent to such wavelength, Franck and Hertz had to use quartz instead glass.) For the inert gas ***neon***, with its ten electrons in the $1s^2 2s^2 2p^6$ subshells, the situation is different (Fig. 3b). Neon atoms may also be excited by electron impact but their emission is within the visible region between 585 nm (yellow) and 703 nm (red). The luminosity appears in layers separated by dark zones. When the accelerating voltage is increased, a drop of the collector current accompanies the appearance of a luminous layer, which can be easily observed.

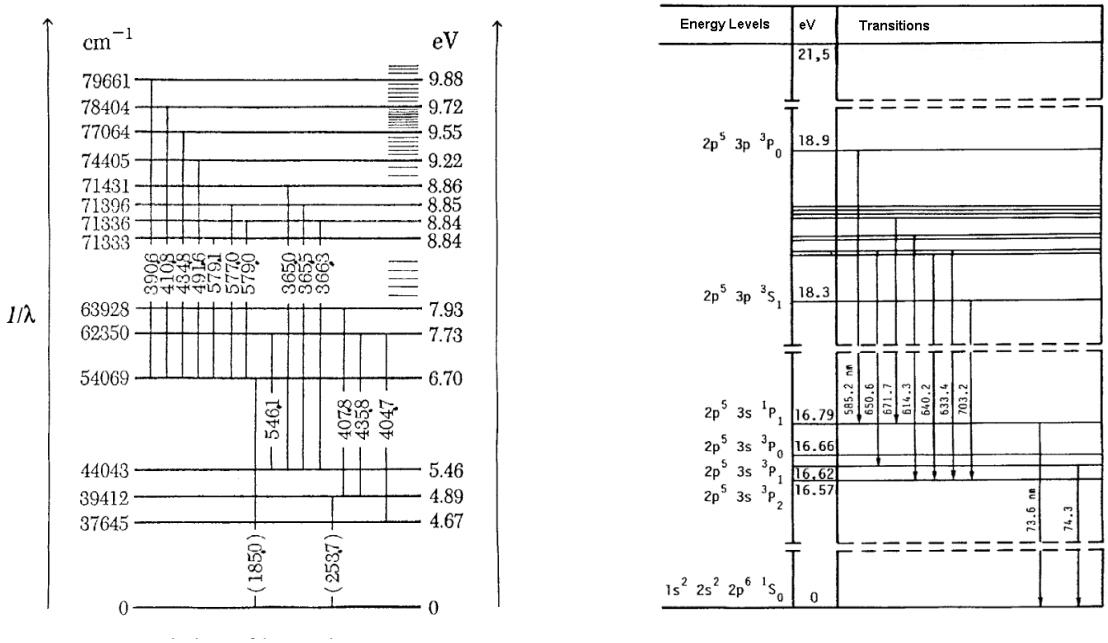

Fig. 3. Energy level diagrams for
(a) mercury atoms and (b) neon atoms.

Since neon atoms have a higher density of states and because of the selection rules, electron *inelastic* collisions preferentially excite states in the region between 18.3 and 18.9 eV, to the ten 3*p*-states, as seen in Fig. 3b. Neon electrons are excited from the ground state and 3*p* levels (transitions ${}^1S_0 \rightarrow {}^3P_0$ and ${}^3S_1$). The four lower 3s-states in the range from 16.6 eV and 16.9 eV are excited with a lower probability. In contrast to mercury the excited neon atoms do not return directly by emission of light to the ground state. The de-excitation of the 3*p*-states to the ground state with emission of a photon is only possible via the 3*s*-states. Therefore, at first they spontaneously loose about 2 eV and then perform transitions to states between 16.75 and 16.79 eV excitation energy emitting visible light observed with the naked eye.

In the experiments with neon, this light may be observed as weak glow. As the accelerating voltage U_2 is increased, the collector current is also increased until, at about 19 V, the electrons gain the energy necessary to excite the neon atoms. Now the collector current starts to decrease since inelastic electron-atom collisions occur right at the grid and the electron's remaining energy is too small for overcoming the retarding potential. Simultaneously, a weak reddish glowing layer appears at the grid indicating light emission. As the accelerating voltage is increased further, this glowing layer shifts, together with an increase in the collector current. At an accelerating voltage of about 38 V, a second glowing layer appears at the grid, while the first one has moved to the mid-point between G_1 and G_2. It means that the

electrons now have a sufficient energy to excite the neon atoms in this area of the tube. Afterwards the same electrons are accelerated again being able to excite the neon atoms by collisions a second time, but this time in front of the grid G_2. As the accelerating voltage is increased more, a new glowing layer appears after reaching a new maximum in the voltage-current dependence, while the other layers move towards the grid G_2.

E. SETTING UP THE EXPERIMENT WITH NEON ATOMS

E1. SAFETY NOTES

A Franck-Hertz supply unit, a tube holder with socket and screen, and a tube, similar to that shown in Fig. 2, are used for the experiment. The tube, Model # 555 870, is made by Leybold Didactic Company, Hürth, Germany. This is an evacuated glass tube filled with neon at room temperature to a gas pressure of about 5 torr (or about 0.006 atm). The distances between the tube planar electrodes are as follows: about 2mm between the cathode K and control grid G_1, 5 mm between the grids G_1 and G_2, and 2 mm between the accelerating grid G_2 and current collector A. The cathode is heated indirectly (by the voltage U_H), in order to prevent a potential difference along the cathode.

The supply unit allows you to select the operating parameters including the collector current by the ***parameter*** selector. You use only U_1, U_2, U_3, and I for the neon tube. The parameters values are shown in the supply unit's digital display (the parameters units are V and nA).

The ***mode*** selector has five positions (from left clockwise): for fast sawtooth signal to oscilloscope; for a signal to recorder; RESET to reset instantaneously, if needed, acceleration voltage to 0 V, MAN for the manual setting of U_2, together with the large centrally located potentiometer, see ***Sec. E4.4***, and CASSY, which allows connecting to a computer.

The standard default setting of the tube should be inside the following ranges:

- Heating voltage U_H = 6.3 V (current approx. 200 mA) (see also two last notes!)
- Control voltage between the cathode and control grid $U_1 = 0 \div 5$ V
- Accelerating voltage between the grids $U_2 = 0 \div 80$ V
- Retarding voltage between the accelerating grid and collector $U_3 = 0 \div 10$ V

The digital display of the supply unit shows corresponding settings in °C (for mercury only), V or nA units depending on the selector switch.

The next five safety notes are of a ***great importance*** for your experiment: please, read them carefully!

1. ***Do not turn on the supply*** unit if the tube is not insert and secure into the holder!
2. When inserting the tube into the holder, be careful: the danger of implosion exists for the tube if it is dropped or banged against other objects since the internal pressure in this low-pressure tube is only about 100 Pa (or 0.75 torr)!
3. If during experiments with light emission (see ***Sec. E4.5***) luminescence layers appear outside the region between the grids, reduce the accelerating voltage U_2 and the control voltage U_1.

4. If during optimizing of the Franck-Hertz curve $I(U_2)$ you cannot adjust it to examples of ***Fig. 5*** in ***Sec. E3*** and a bright luminance is seen between the grids at a too low control potential U_1, the collector current is ***too high***. Decrease the cathode temperature by reducing the applied voltage U_H using the screwdriver potentiometer in the rear panel of the supply unit (down to 5.9 V or as required).

5. If the maxima in the $I(U_2)$ curve are barely noticeable (see ***Sec. E3*** and ***Fig. 5***) and no luminance layers are seen between the grids even at a high control potential U_1, the collector current is ***too low***. Increase the cathode temperature by increasing the applied voltage U_H using the screwdriver potentiometer of the rear panel of the supply unit (up to 6.7 V or as required).

E2. EXPLORATORY NOTES FOR NEON TUBE

In these experiments, you are in charge of ***four*** parameters to look over: U_H, U_1, U_2, and U_3. You should explore the effects of these parameters on the observed Franck-Hertz curves $I(U_2)$ and its features.

1. The ***voltage U_H*** controls the temperature of a cathode and therefore the total number of emitted electrons. The cathode is heated by a filament and emits electrons when its temperature is high enough. Such a process is called thermionic emission: electrons near the top of the Fermi distribution in the metal penetrate the potential at the surface and escape into gas. The kinetic energy distribution of the emitted electrons is rather close to the Maxwell-Boltzmann distribution, with a mean energy near kT_c, where T_c is the cathode temperature. ***Why and how changes in T_c*** (through U_H) ***influence the curve $I(U_2)$ and light emission you are going to study***?

2. After the electrons are emitted, the control grid G_1, which is under the positive ***potential U_1***, attracts them and they form a negatively charged cloud located between the cathode and grid G_1. The higher U_1 the denser the cloud. Such a cloud contributes to an additional field inside the tube that suppresses electron emission and creates a steady state distribution of charges in the cloud. As soon as some electrons from the cloud are able to cross the grid G_1 and moved further from the grid by the accelerating voltage U_2, more electrons are emitted from the cathode to keep the cloud at its steady state. The collector current resulted from such a steady state condition is called the "space charge limited current". ***What effect has the value of U_2 on the curve $I(U_2)$? On the number of maxima observed?***

3. The ***retarding voltage U_3*** between the grid G_2 and collector controls the energy threshold of electrons able to reach the collector after collisions with atoms: the higher U_3 the more distinctive are maxima and minima of the curve $I(U_2)$ but the smaller the collector current I. ***Why is that? What is the connection between the voltages U_1 and U_3?***

4. The ***accelerating voltage U_2*** between the two grids defines the curve $I(U_2)$. ***What is the connection between U_2 and the other parameters?***

Unlike in experiments with the mercury atoms, you cannot change the gas pressure in the neon tube. It means that the ***mean free path*** of electrons, which is also one of

the main important parameters of the experiment, remains constant. During manufacturing, a neon gas pressure is made of about 5 torr, and this is turned out to be an optimal pressure. ***But what does it mean, optimal?***

If the gas pressure and, hence, the density of the neon atoms are too high, the mean free path of emitted electrons is short compared with all tube dimensions, including the wire diameter of the grids. The electrons collide elastically with neon atoms moving along the electric field lines, which "connect" the cathode and grids, so that the electron trajectory jitter along the electric field lines. Regardless of their energy the electrons are mostly intercepted by the grids since most of the field line end there. As a result, the collector current remains very small, the maxima and minima are no longer clearly seen or are invisible at all.

If, on the other hand, the vapor pressure (and the gas density) is so low that that the mean free path is large compared with all dimensions, the grids do not intercept the electrons and they can acquire energies high enough for exciting neon atoms. But such events take place rather rare since the collision rate is low. Although the collector current is high, no maximum is observed. On the other hand, the electrons with high energies can cause the ionization of neon atoms starting a dangerous gas discharge. Such a discharge may be recognized by a sudden increase of the collector current.

When the mean free path is optimal the situation is quite different. An electron, just emitted, can undergo many elastic collisions but they do not affect electron's energy too much; at the same time, the electron gains more and more energy, enough to overcome the retarding potential and contribute to the current. Finally, after the first elastic collision electron lost so much energy that it cannot reach the collector. Thus, the first decrease in $I(U_2)$ curve occurs.

E3. SETUP FOR NEON EXPERIMENTS

As described below, you start with a quick ***survey*** of the experimental setup using a two-channel oscilloscope. After ***optimizing*** the experiment parameters, record manually the complete Franck-Hertz curve, with as many maxima as possible. Observe the light emission after electron impact excitation in the space between the grids. Note that a new glowing layer appears after each new maximum. Compare your results with example given in ***Sec. E5***.

Fig. 4 shows the setup for the Franck-Hertz experiment. Details for the setup are described below.

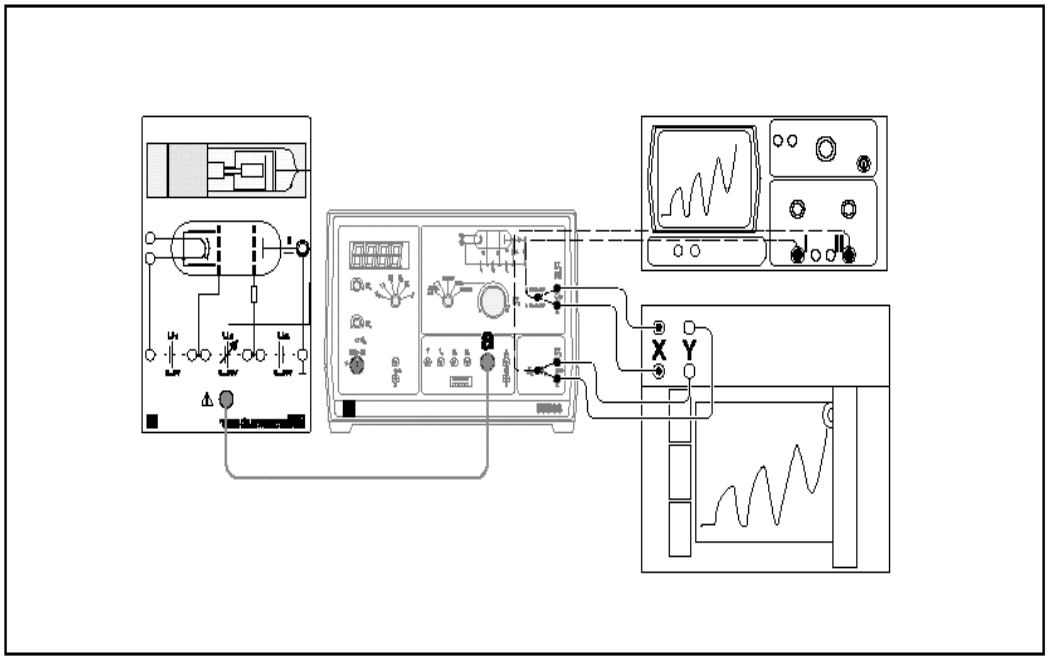

Fig. 4: Experiment setup for Franck-Hertz Neon experiments (don't use the recorder shown).

E3.1. Procedure for Setup

1) Insert and secure the Franck-Hertz tube into its holder.
2) Connect the holder and the supply unit with a 7-pin cable as shown in Fig. 4.
3) Connect output sockets of the supply unit to an XY oscilloscope, the U_2-socket to the X-channel and the U_A–socket to the Y-channel. Check that the scope scales are 1 V/Div and 2 V/Div for the X- and Y-channels, respectively. Note that U_A is proportional to the collector current I, with a scale of 1 V ≈ 1 nA.
4) Set the mode selector knob of the Franck-Hertz supply unit to "sawtooth". The accelerating voltage U_2 will be applied the tube automatically as a sawtooth sweeping signal from 0 V to a set value of U_2 (up to 80 V).
5) Turn on the supply unit. A ***green*** LED should indicate the neon tube recognition. The tube is ready for experiment after about ***one minute*** of cathode warm-up.
6) Using the parameter selector knob, digital display and corresponding potentiometers, set the control voltage U_1 to 1.5 V and the retarding voltage U_3 to 5.0 V. Observe the Franck-Hertz curve on the oscilloscope. Set the Y-position so that the top section of the curve is displayed completely.

E4. PROCEDURE FOR CARRYING OUT NEON EXPERIMENTS

Before performing further measurements, you should optimize the Franck-Hertz curve to observe as many strong maxima and minima as possible. This can be reached by a proper choice of several operating voltages, U_1, U_3 and U_H, to the "best" values.

E4.1. Optimizing U_1 and U_H

1) A higher control potential U_1 results in a greater electron emission current. Therefore, if the Franck-Hertz curve rises too steeply so that an overdrive limit of the current amplifier is reached at $U_2 < 80$ V and the top of the Franck-Hertz curve is cut off (as in Fig. 5a), ***reduce*** U_1 until the curve steepness corresponds to that shown in Fig. 5c.

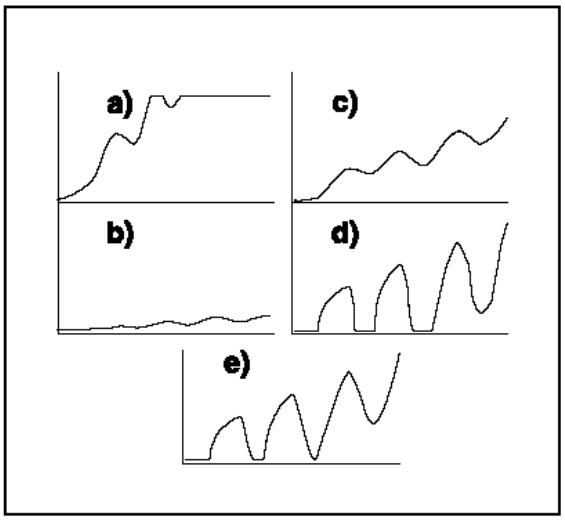

Fig. 5. Overview of the optimizing procedure for parameters U_1 and U_3.

2) If, on the other hand, the curve is too flat, i.e. the collector current remains below 5 nA over the whole range of U_2 (see Fig. 5b), ***increase*** U_1 until the curve steepness corresponds to that shown in Fig. 5c.

3) If you cannot reproduce Fig. 5c, ***optimize*** the cathode heating voltage U_H as described in **Sec. E1**, Safety Notes.

E4.2. Optimizing U_3

1) A greater retarding voltage U_3 causes better-defined maxima and minima of the Franck-Hertz curve; at the same time, however, the total collector current is reduced. Therefore, if the maxima and minima of the curve are insufficiently defined (as seen in Fig. 5c), alternately ***increase*** first the retarding voltage U_3 (maximum 18 V) and then the control potential U_1 until you obtain the curve form shown in Fig. 5e.

2) If the minima of the Franck-Hertz curve are cut off at the bottom (as seen in Fig. 5d), alternately ***reduce*** first the retarding voltage U_3 and then the control potential U_1 until you obtain a curve similar to that shown in Fig. 5e.

E4.3. Studying the Franck-Hertz Neon Curve with Oscilloscope

1) Draw a sketch of the optimized curve seen on the oscilloscope screen in your Notebook and estimate the positions of each maximum in V. (It is necessary to calibrate the oscilloscope channels beforehand.)
2) Change slightly the parameters optimized in ***Sec. E4.2*** and repeat 1).
3) Determine mean value and error of the voltage difference between two adjacent maxima using data from 1) and 2). Estimate the experimental uncertainties.
4) Calculate from the obtained excitation voltage the wavelength of the expected emission line.

Keep in mind, however, that at a frequency of the accelerating voltage U_2, such as is required for producing a stationary oscilloscope pattern the capacitance of the tube and holder becomes significant. The current required to reverse the charge of the electrode causes a slight shift and distortion of the Franck-Hertz curve.

E4.4. Manual Measurements of the Franck-Hertz Neon Curve

1) Set the mode selector knob to MAN and slowly increase U_2 by hand from 0 V to 80 V.
2) Read and write down voltage U_2 and current I from the display; using the parameter selector knob to toggle between the two quantities for each voltage.
3) Estimate the experimental uncertainties.
4) Using Excel, plot the dependence $I(U_2)$, include error bars obtained in 3), and compare the manual curve with the oscilloscope curve.

E4.5. Light Emission of Neon Tube

1) Set the mode selector knob to MAN.
2) Optimize the accelerating voltage U_2 until you can clearly see the first red-yellow luminance zone between grids G_1 and G_2.
3) Increasing the accelerating voltage, find the best values of U_2 for two or three luminance zones and log these values in you Notebook. Compare your results with the example shown below in ***Sec. E5***.
4) Finally, take two pictures of the luminance layers you consider to be the most representative of the experiment (those that even Drs Franck and Hertz would be proud of).

Note: Examples shown in ***Sec. E5*** below are given only for comparison. Since each tube has slightly different dimensions, the corresponding absolute value of the voltage U_2 might vary from tube to tube. At the same time, the distance between the voltage maxima should be practically identical for each tube.

E5. MEASURING EXAMPLES

E5.1. Franck-Hertz Neon Curve

The curve in Fig. 6 is obtained at U_1 = 2.06 V and U_3 = 7.94 V. The distance between the vertical lines (these were placed by eye) has an average value of ΔU_2 = 18.5 V. This value is much closer to the excitation energies for the 3*p*-levels (18.4 ÷ 19.0 eV), which is therefore much more probable, than to the energies of the 3*s*-levels (16.6 ÷ 16.9 eV).

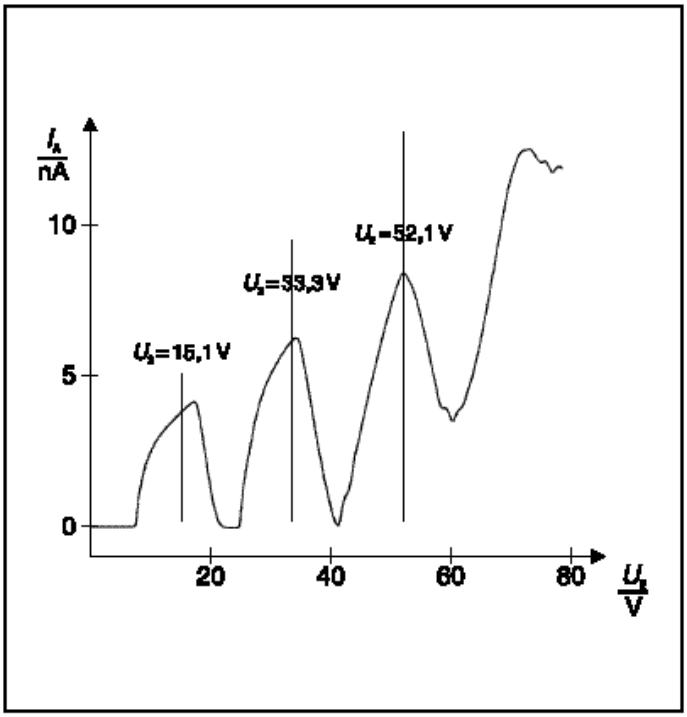

Fig. 6. Franck-Hertz curve for neon (obtained with an XY-recorder)

The substructure in the measured curve shows that the excitation of the 3s-levels cannot be ignored altogether. Note that for double collisions (the second peak) and multiple collisions, each combination of excitation of a 3*s*-level and a 3*p*-level occurs.

E5.2. Neon Light Emission

The light emission is obtained at U_1 = 2.06 V and U_3 = 7.94 V and observed as the luminance layers that are zones of high excitation density. They can be compared directly with the minima of the Franck-Hertz curve. Their spacing corresponds to an accelerating voltage of about U_2 = 19 V. Therefore, an additional luminance layer is generated each time U_2 is increased by approximately 19 V (see Table 1).

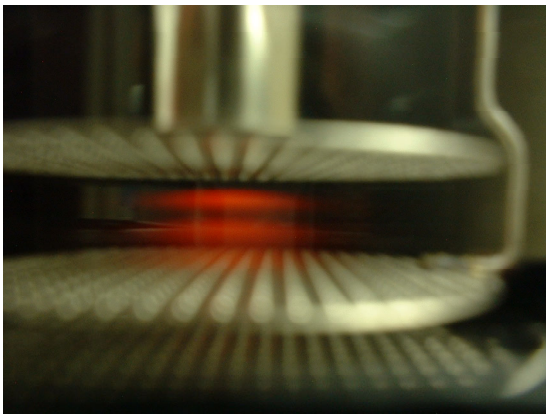

Fig. 7a. Two luminance layers of neon tube emission.

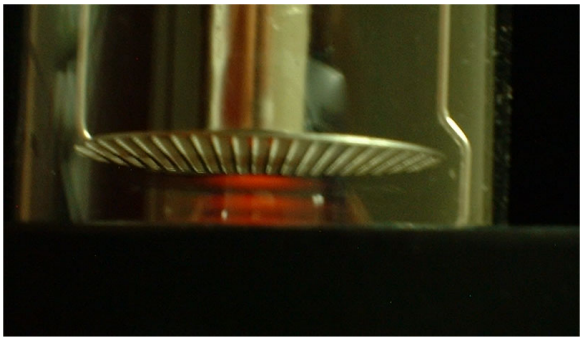

Fig. 7b. Three luminance layers of neon tube emission.

Fig. 7c. Three luminance layers at higher magnification.

Table 1: Number of luminance zones as a function of the accelerating voltage U_2 (example)

Number of zones	U_2, V
1	30
2	48
3	68

In summary, Table 2 shows typical parameters for setting a neon tube. Please, reproduce the Table 2 in your Report and fill out your best setting of the experiment to compare them with measurements done by the others.

Table 2. Typical setting parameters of a neon tube

Typical Ne tube setting		Your setting
U_H, V	6.3	
U_1, V	3.0	
U_2 (1st max.), V	18	
U_2 (2nd max.), V	36	
U_3, V	– 8.0	

Please disassemble the wiring at the end of the experiment!

F. SETTING UP THE EXPERIMENT WITH MERCURY ATOMS

F1. SAFETY NOTES

A Franck-Hertz supply unit, a copper tube for holding the mercury tube, similar to that shown in Fig. 2, and an electric furnace are used for the experiment. The tube, Model # 555 85, is made by Leybold Didactic Company, Hürth, Germany. The tube is an evacuated glass tube filled with mercury; unlike the neon tube, the mercury tube has cylindrical electrodes, the same as in the neon tube. You can see several drops of mercury inside the tube at room temperature. By heating the tube in the furnace to a temperature between 170°C and 200°C, the mercury vapor pressure can reach optimal values between 1 and 2 kPa (or between 7.5 and 15 torr). Like in the neon tube, the cathode of the mercury tube is also heated indirectly.

The main difference between mercury and neon tubes is that the mercury tube (a) needs external heating and (b) it operates at much lower accelerating voltage U_2.

The supply unit allows you to select the operating parameters including the collector current by the ***parameter*** selector. Additionally to the same parameters you have used for the neon tube, there are two more parameters: the setting temperature of the furnace, θ_s, and real temperature, θ, as measured by the NiCr-Ni sensor (thermocouple). The parameters values are shown in the supply unit's digital display (the parameters units are V, °C and nA).

The ***mode*** selector has five positions (from left clockwise): for fast sawtooth signal to oscilloscope; for a signal to recorder; RESET to reset instantaneously, if needed, acceleration voltage to 0 V, MAN for the manual setting of U_2, together with the large centrally located potentiometer, see ***Sec. E4.4***, and CASSY, which allows connecting to a computer.

The standard default setting of the tube should be inside the following ranges:

- Temperature of the electric furnace $T = 140 \div 210$°C (preset $T = 180$°C)
- Heating voltage $U_H = 6.3$ V (current approx. 200 mA)
- Control voltage between the cathode and control grid $U_1 = 0 \div 5.0$ V
- Accelerating voltage between the grids $U_2 = 0 \div 30$ V
- Retarding voltage between the grid and collector $U_3 = 0 \div 10$ V
- The digital display of the supply unit shows corresponding settings in °C, V or nA units depending on the selector switch.

The next seven safety notes are of a ***great importance*** for your experiment: please, read them carefully!

1. ***Do not turn on the supply unit*** if the tube is not inserted and secured in the holder with a cupper cylinder and if the electric furnace is not connected to the rear panel of the supply unit!

2. When inserting the tube into the holder, be careful: the danger of implosion exists for the tube if it is dropped or banged against other objects since this is a low-pressure tube!
3. Be sure that the copper cylinder for the tube is grounded to the yellow green safety socket.
4. Be sure that the temperature sensor is inserted all the way into the corresponding blind hole of the copper cylinder; otherwise the tube can be overheated. ***Never*** exceed 200°C as higher temperatures literally melt the tube! ***Never*** leave the tube in the hot furnace after finishing experiment since metal and glass parts of the tube can deteriorate the vacuum because of outgassing! ***Never*** apply voltages to the tube unless it is in the oven at a high enough temperature! To do otherwise could ***burn out*** the tube (metallic mercury can short out the tube electrodes! ***Never*** exceed 30 V for the accelerating voltage U_2! A higher voltage can start ionization of the gas by collision leading to dangerous discharge inside the tube.
5. If you observe a ***blinking*** display of the supply unit during an operation, it might indicate one of the following ***errors*** in the temperature measuring setup:
    a) A problem in the temperature sensor connection (bad or no connection).
    b) The temperature sensor is not inserted into the blind hole of the copper cylinder. Blinking starts several minutes after the supply unit is turned on.
    c) The temperature sensor has fallen out of the blind hole of the copper cylinder after the operating temperature has been reached. Blinking starts a few seconds after the sensor falls out.
6. If the oven temperature, by some reason, is higher than the typical temperature range, the mercury vapor pressure and consequently the collision rate become too high. As a result, the collector current considerably reduced.
7. If the oven temperature, by some reason, is not high enough (lower than the typical temperature range), gas discharge can occur as indicated by an abrupt jump of the collector current and blue luminance in the tube. In this case,

IMMEDIATELY:

Set the acceleration voltage U_2 to 0 V by placing the mode selector to RESET. Contact your Instructor: you might need to change the oven temperature setting from the default 180°C.

F2. EXPLORATORY NOTES FOR MERCURY TUBE

In these experiments, you are in charge of ***six*** parameters to look over: T_s (that is the setting temperature of the furnace, or θ_s), T (that is the real measured temperature, or θ), U_H, U_1, U_2, and U_3. You should explore the effects of these parameters on the observed Franck-Hertz curves $I(U_2)$ and its features.

1. The ***voltage U_H*** controls the temperature of a cathode and therefore the total number of emitted electrons. The cathode is heated by a filament and emits electrons when its temperature is high enough. Such a process is called thermionic emission: electrons near the top of the Fermi distribution in the metal penetrate the potential at the surface and escape into gas. The kinetic energy distribution of the emitted electrons is rather close to the Maxwell-Boltzmann distribution, with a mean energy near kT_c, where T_c is the cathode temperature. ***Why and how changes in T_c*** (through U_H) ***influence the curve $I(U_2)$ and light emission you are going to study***?

2. After the electrons are emitted, the control grid G_1, which is under the positive ***potential U_1***, attracts them and they form a negatively charged cloud located between the cathode and grid G_1. The higher U_1 the denser the cloud. Such a cloud contributes to an additional field inside the tube that suppresses electron emission and creates a steady state distribution of charges in the cloud. As soon as some electrons from the cloud are able to cross the grid G_1 and moved further from the grid by the accelerating voltage U_2, more electrons are emitted from the cathode to keep the cloud at its steady state. The collector current resulted from such a steady state condition is called the "space charge limited current". ***What effect has the value of U_2 on the curve $I(U_2)$? On the number of maxima observed?***

3. The ***retarding voltage U_3*** between the grid G_2 and collector controls the energy threshold of electrons able to reach the collector after collisions with atoms: the higher U_3 the more distinctive are maxima and minima of the curve $I(U_2)$ but the smaller the collector current I. ***Why is that? What is the connection between the voltages U_1 and U_3?***

4. The ***accelerating voltage U_2*** between the two grids defines the curve $I(U_2)$. ***What is the connection between U_2 and the other parameters?***

5. Unlike in experiments with the neon atoms, you can change the gas pressure in the mercury tube by heating it in the furnace. Such heating evaporates mercury droplets seen at room temperature and produced mercury vapor inside the tube. You need to choose the best temperature, so that the ***mean free path*** of electrons that depends on the vapor density is optimal. As before for the neon case, as explained in ***Sec. E2***, the optimal mean free path allows you to obtained the best Franck-Hertz curve. Check the relationship between the temperatures θ and θ_s. Is there any ***difference*** between them? If so, is the difference the same when you ***change*** temperature by 10°C? How and why does temperature affects ***features*** of the Franck-Hertz curve?

F3. SET UP FOR MERCURY EXPERIMENTS

In general, the setup for the mercury tube is quite similar to that of the neon tube, ***Sec. E3***, except that you don't need the tube holder, shown in Fig. 4. Put it aside since you will use instead a copper holder-shield for the mercury tube.

F3.1. Procedure for Setup

1) Insert and secure the Franck-Hertz mercury tube into the copper cylindrical tube.
2) Insert the cupper tube, together with the mercury tube, into the electric furnace. Ground the copper tube to the yellow-green safety socket located in the rear panel of the supply unit using the lead connected to the copper tube.
3) Connect the cable of the electric furnace to the double socket located in the rear panel of the supply unit.
4) Insert the measuring tip of the temperature sensor in the blind hole of the copper tube and connect its cable to the socket "NiCr-Ni" of the supply unit.
5) Connect the mercury tube and the supply unit with a 7-pin cable.
6) Connect output sockets of the supply unit to an XY oscilloscope, the U_2-socket to the X-channel and the U_A–socket to the Y-channel. Check that the scope scales are 1 V/Div and 2 V/Div for the X- and Y-channels, respectively. Note that U_A is proportional to the collector current I, with a scale of 1 V ≈ 1 nA (or 10^9 : 1).
7) Set the mode selector knob of the Franck-Hertz supply unit to "sawtooth". The accelerating voltage U_2 will be applied the tube automatically as a sawtooth sweeping signal from 0 V to a set value of U_2 (up to 30 V).
8) Turn on the supply unit. A ***green*** LED should indicate the mercury tube recognition; it turns red several seconds later when the furnace is heating up. It becomes ***green again*** after about 10 to 15 min. indicating that temperature is in the set range and the system is ready for experiments. If the digital display starts blinking during warm-up period or later, check the temperature measuring setup (see Safety Notes, ***Sec. F1***).
9) A curve on the oscilloscope screen can appear, with a sharp drop and a transitional part, which indicate a small current caused by discharge of the system equivalent capacitance (of cables, leads, etc.).
10) Using the parameter selector, digital display and corresponding potentiometers, set the retarding voltage U_3 to 1.5 V. The curve on the oscilloscope should remain the same. Slowly increase the control voltage U_1 to 1.5 V and observe the change the curve into a typical Franck-Hertz curve. Set the Y-position so that the top section of the curve is displayed completely.

F4. PROCEDURE FOR CARRYING OUT MERCURY EXPERIMENTS

Similar to the neon tube procedure, you should optimize the same operating parameters of the mercury tube to observe as many strong maxima and minima in the Franck-Hertz curve as possible, as described in ***Sec. E4.1***. The only difference is that now you have one extra parameter, temperature, so that you might need to repeat the optimization after each change in the oven temperature T.

Start with the preset temperature, T = 180°C, and optimize the operating parameters following procedure in ***Sec. E4.1*** and Fig. 5, until you get a Franck-Hertz curve with well-distinguishable maxima and minima. Remember that, unlike the neon tube, the mercury tube can tolerate a much ***lower*** accelerating voltage, so that keep $U_2 < 40$ V at any optimization. If you are unable to observe a good curve, increase or decrease the temperature by 10°C and optimize the parameters. Then follow procedures described below in ***Sec. F4.1*** and ***Sec. F4.2.*** Change the temperature by ±5°C and repeat the whole measurement procedure again for a new temperature. Compare the results for the two temperatures.

F4.1. Studying the Franck-Hertz Mercury Curve with Oscilloscope

1) Draw a sketch of the optimized curve seen on the oscilloscope screen in your Notebook and estimate the positions of each maximum in V. (If necessary, calibrate the oscilloscope channels.)
2) Change slightly the optimized parameters and repeat 1).
3) Estimate the experimental uncertainties. Determine mean value and error of the voltage difference between two adjacent maxima using data from 1) and 2).
4) Calculate from the obtained excitation voltage the wavelength of the expected emission line.

F4.2. Manual Measurements of the Franck-Hertz mercury curve

1) Set the mode selector knob to MAN and slowly increase U_2 by hand from 0 V to 30 V.
2) Read and write down voltage U_2 and current I from the display; using the parameter selector knob to toggle between the two quantities for each voltage.
3) Estimate the experimental uncertainties.
4) Using Excel, plot the dependence $I(U_2)$, include error bars obtained in 3), and compare the manual curve with the oscilloscope curve.

In summary, Table 3 shows ***typical*** parameters for setting a mercury tube. Please, reproduce the Table 3 in your Report and ***fill out*** your best setting of the experiments with two different temperatures to compare them with measurements done by the others.

Table 3. Typical setting parameters of a mercury tube

Typical mercury tube setting		Your setting #1	Your setting #2
U_H, V	6.3		
U_1, V	1.5		
U_2 (1st max.), V	6.0		
U_2 (2nd max.), V	10.9		
U_3, V	–1.5		
T, °C	180	T, °C:	T, °C:

Please disassemble the wiring at the end of the experiment!

G. REPORT AND AFTER-LAB QUESTIONS

In your Report on the Franck-Hertz experiments, include a discussion section as required by the PH3480 Syllabus to explain main features and findings of your experiments.

Additionally, answer the ***following questions***:

1. Why the light emission from neon tube and maxima in the Franck-Hertz curve were so important that Franck and Hertz were awarded the Nobel Prize?
2. What physical process is responsible for observed light emission?
3. Why is it important to heat the cathode of a Franck-Hertz tube indirectly?
4. According to basic classical mechanics, when an electron collides elastically with a mercury atom, what will happen to the atom? To the electron? Should we expect the gas to heat up greatly? (***Hint***: their masses are very different: $m_e \approx 6\times10^{-4}$ u and $M_{Hg} \approx 200$ u. Why is it important for these questions?)
5. Why is an electron at kinetic energies below 4.9 eV in mercury gas and below 18.5 eV in neon gas only able to perform elastic collisions?
6. What is the maximum amount of energy that an electron can impart to a gas atom with which it collides, for:
    a. 4.0-eV electron and mercury atom?
    b. 6.0-eV electron and mercury atom?
    c. 18.0-eV electron and neon atom?
    d. 20-eV electron and neon atom?
7. How does an atom excited by an inelastic collision dispose itself of the acquired energy?
8. What is the difference between the excitation of an atom by electrons and by light quanta?
9. It is known that the ionization potential of mercury atoms is about 10.5 eV and of neon atoms 21.6 eV. Why is it possible to apply a greater accelerating voltage U_2 (such that you can observe the second and third peaks) during your Franck-Hertz experiments without ionization the gas and without gas discharge?
10. What is the difference between a Franck-Hertz tube and an X-ray tube?