

## Franck-Hertz

Equipment Franck-Hertz tube in mount, Franck-Hertz power supply, SWS, BK 2120B Scope, leads, small 15 cm ruler so apparatus dimensions can be checked

### PLEASE BE CAREFUL

The Franck-Hertz tube is quite expensive (about \$1,000). Please handle it carefully. Be sure the electron accelerating voltage  $U_2$  is set to zero while the tube is heating up and while it is cooling down. Otherwise a discharge may occur which can damage the tube. The tube should be in the oven when the power supply is turned on and should remain in the oven until the power supply has been turned off and the oven cooled to room temperature. In other words, avoid thermal shock.

## 1 Introduction

In 1913 the Danish physicist Niels Bohr postulated that the electron in the hydrogen atom could only occupy discrete energy states, and that the emission line spectrum of the hydrogen atom was due to this electron jumping from a higher energy state to a lower one with the emission of light. Further evidence that the electron energy levels of other atoms were quantized was provided in 1914 by experiments done by James Franck and Gustav Hertz. They accelerated electrons in an evacuated tube that contained mercury at a vapor pressure of about 3 kPa. (They also used other elements.) They found that the electrons collided elastically with the mercury atoms as long as the electron energy remained below 4.9 eV. If the electrons had an energy greater than 4.9 eV the electrons could lose 4.9 eV of energy in colliding with the mercury atoms. While Franck and Hertz thought they were measuring the first ionization potential of mercury, they were in fact measuring the energy of the first excited state. Their experiment showed that if the electron kinetic energy was below the energy of the first excited state of mercury, the electrons could not excite the mercury atoms. If the electron energy was equal to or greater than the energy of the first excited state of mercury the electrons could lose an amount of energy equal to that excitation energy, but not any more energy if the electron energy remained below the energy of the 2nd excited state of mercury.

Mercury has 2 electrons outside 5 completed shells. In LS coupling the ground state is  $6s^2\ ^1S_0$ . The first excited state is the  $6s6p\ ^3P_0$  state, but this is metastable as it requires  $\Delta J = 0$  for a transition to the ground state. The nearby  $^3P_1$  state, when it decays to the ground state, produces the strong intercombination line at 4.9 eV or 253.7 nm and is the transition usually referred to in a discussion of the Franck-Hertz experiment. This is the transition responsible for the operation of fluorescent lights.

More broadly, the first excited state of mercury is a triplet. There is probably some excitation of the metastable  $^3P_0$  state, which lies a little below the  $^3P_1$  state, and of the metastable  $^3P_2$  state which lies a little above the  $^3P_1$  state. Electron collisions do not obey optical selection rules.

## 2 Description of the Apparatus

The Franck-Hertz tube has cylindrical geometry. See Fig. 1. A cathode (K) is indirectly heated by a filament. The filament is heated by the voltage  $U_H$ . Close to the cathode is the control grid  $G_1$  which is kept a few volts positive with respect to the cathode by the voltage  $U_1$ . The magnitude of the electron current through the tube is largely but not completely controlled by  $U_1$ . At a relatively larger distance is the accelerating grid  $G_2$ . The voltage between  $G_1$  and  $G_2$  is  $U_2$ . With  $U_1$  fixed, the electron energy is varied by changing  $U_2$ . The voltage  $U_2$  has a range of 0-30 V, with  $G_2$  positive with respect to  $G_1$ . A short distance outside  $G_2$  is the collector or anode (A). The current to the anode is (I). The voltage between  $G_2$  and A is  $U_3$ . This is a retarding voltage of a few volts.

The tube has a small amount of liquid mercury in it. For the mercury pressure to be sufficient it is necessary to heat the tube to 170-200 deg C. There is an oven into which the tube is inserted. Inside the oven is a cylindrical copper tube to provide temperature uniformity. The Franck-Hertz tube goes inside the copper tube. A slide mechanism is provided to hold the tube and to insert the tube into the oven. A thermocouple in the form of a long thin tube sticks through a hole in the oven wall and goes all the way into a blind hole in the copper tube. *It is important that the thermocouple probe go all the way into the hole in the wall of the copper tube. See Fig. 5.* If it does not, the oven will overheat the tube and ruin it.

All the voltages are supplied by a single power supply unit with appropriate cables. The same power supply unit provides a thermocouple reading and amplifies the anode current. The power supply unit has voltage output terminals for the anode current I and the voltage  $U_2$  of grid  $G_2$ .

## 3 Description of the Experiment

Assume that the control grid voltage  $U_1$  and retarding voltage  $U_3$  are held constant. Electrons emitted with a thermal energy from the cathode are accelerated by the control grid voltage  $U_1$  and pass through  $G_1$  into the region between  $G_1$  and  $G_2$ . In this region the electrons are accelerated by  $U_2$  and make a number of collisions with mercury atoms. These collisions will be elastic if the electron energy is everywhere below 4.9 eV. The anode current I will increase as  $U_2$  is increased, as some of the electric field produced by  $G_2$  will leak through grid  $G_1$ . For the moment let us assume that  $U_2$  has a value such that the electron energy just before passing through  $G_2$  is just below 4.9 eV. The electrons, after passing through  $G_2$ , will have enough energy to overcome a suitable retarding potential  $U_3$  and produce the plate current I. If now  $U_2$  is raised a bit so that the electron energy is a little above 4.9 eV just before passing through  $G_2$ , some of the electrons will make inelastic collisions with mercury atoms. These electrons will have very little kinetic energy and when they pass through  $G_2$  will not have enough energy to overcome the retarding voltage  $U_3$ . The anode current will then be less even though the accelerating voltage has been increased. In other words, as  $U_2$  is increased, the anode current I decreases! When  $U_2$  is increased more, the current through the tube will start to increase once again, and the point at which electrons make inelastic collisions will move further and further from the grid  $G_2$ . But after the first inelastic collisions which leave the electrons with very little kinetic energy, they are accelerated once again, and if  $U_2$  is increased enough the electron energy is enough so they can make a second inelastic

collision just before  $G_2$ , resulting in another decrease of anode current as  $U_2$  is raised. This process can be repeated a number of times, resulting in a curve of  $I$  vs  $U_2$  shown in Fig 2. The difference in voltage between the peaks is the excitation voltage 4.9 eV.

## 4 Description of Power Supply

The front of the power supply can be divided into 4 panels which are labeled 1 through 4. See Fig. 3. Panels are labeled 1-4 by the first digit. Items within a panel are labeled in the first decimal place.

### 1. Panel 1 Tube Connection Panel

- (1.1) Female DIN socket for connecting cable from socket of Franck-Hertz tube.
- (1.2) Not used (alternative sockets for tube).
- (1.3) Not used (special interface connection).

### 2. Panel 2 Display Panel

- (2.1) DIN socket for connecting the temperature sensor.
- (2.2) Screwdriver potentiometer for setting the temperature of the electric oven. The preset value will probably be in the range 170-200 deg C. PLEASE DO NOT CHANGE THE SETTING OF THIS POTENTIOMETER WITHOUT CONSULTING THE 2ND FLOOR STAFF OR THE LAB INSTRUCTOR.
- (2.3) Potentiometer for setting the retarding voltage  $U_3$ . The voltage range is 0-10 V.
- (2.4) Potentiometer for setting the control grid voltage  $U_1$ . The voltage range is 0-5 V.
- (2.5) Selector switch for reading parameters and measured values on the digital display (2.6).
  - $\vartheta_s$  Set point temperature for oven.
  - $\vartheta$  Actual or measured temperature of oven.
  - $U_1$  Control grid voltage
  - $U_3$  Retarding voltage
  - $U_2$  Acceleration voltage
  - $I$  Collector current in nA.
- (2.6) Digital Display. Parameter displayed chosen by switch (2.5). Units are in deg C, V, or nA.  $U_3$  is a negative voltage.
- (2.7) Analog voltage out for items selected by switch (2.5). The output voltage is approximately proportional to the chosen quantity as follows.
  - $\vartheta_s$  and  $\vartheta$ : 100 deg C  $\cong$  1 V
  - $U_1$ : 1 V  $\cong$  1 V
  - $U_3$ : -1 V  $\cong$  1 V
  - $U_2$ : 10 V  $\cong$  1 V
  - $I$ : 1 nA  $\cong$  1 V.

## 3. Panel 3 Control Panel

- (3.1) Mode Switch for Acceleration Voltage  $U_2$ 
  - $/|/|/|/|$ : Fast sawtooth for oscilloscope. (Icon a bit schematic.)
  - $/|$ : Single shot slow ramp for recorder. (Icon a bit schematic.)
  - RESET: Sets  $U_2$  to 0 V.
  - MAN:  $U_2$  controlled manually by using potentiometer (3.2).
  - CASSY: type of interface not used.
- (3.2) Potentiometer for manually setting the acceleration voltage  $U_2$ . The range is 0-30 V.
- (3.3) Schematic circuit diagram of tube, voltages, and current.
- (3.4) LED's which indicate type of tube connected.
  - Hg: Briefly green when power supply switched on. Turns immediately to yellow while oven is heating up. Turns back to green when oven set-point temperature reached.
  - Ne: Green if neon tube used, which it is not.
- (3.5) Output voltage  $U$  proportional to acceleration voltage  $U_2$ .  $U = \frac{1}{10}U_2$ .

## 4. Panel 4 Collector or Anode Current Panel

- (4.1) Output voltage proportional to collector current  $I$ :  $1 \text{ V} \cong 1 \text{ nA}$ .

The back of the power supply is shown in Fig. 4. The items on the back panel are numbered 5-8.

5. (5) Socket for line voltage plug.
6. (6) Off-On switch
7. (7) Screwdriver potentiometer for setting cathode heating voltage. PLEASE DO NOT CHANGE THE SETTING.
8. (8) Sockets for connecting electric oven and copper cylinder. The two black sockets to the right supply voltage to the oven heater and should have the black plugs inserted into them. The yellow-green socket on the left should have the green grounding plug inserted and also the black plug which has a copper grounding strap connected to the copper cylinder.

## 5 Franck-Hertz Tube and Power Supply Connections

1. Refer to the previous section on the power supply. Familiarize yourself with all the items on the power supply and all the cable connections. Check that all the cables and sockets are correctly hooked up. Check that the Franck-Hertz power supply is off and that the oven is at room temperature.
2. Very carefully slide the Franck-Hertz tube out of the oven so that you can look at it. PLEASE DO NOT REMOVE THE TUBE FROM ITS SOCKET.

3. It is important that the thermocouple be fully inserted in a blind hole in the copper cylinder. Refer to Fig. 5. The copper cylinder should be fully inserted into the oven. If this is so its end will be recessed about 1/16th (2.5 mm) inch from the open end of the oven. Although not shown this way in Fig. 5, the collar on the thermocouple holder should be about 2 mm from the face of the thermocouple holder facing the oven. The distance between the closed face of the oven and the hex nut on the thermocouple holder should be about 13.6 cm. NOTE: If the thermocouple is removed from the apparatus, it is all too easy not to get it back right. The problem is that the copper cylinder is loose and not only slides in and out of the oven but it also rotates. If it rotates slightly, the blind hole for the thermocouple does not line up with the hole for the thermocouple in the wall of the oven. Then the thermocouple probe “bottoms” on the end of the copper cylinder and is not inserted in the blind hole. The temperature is misread, the oven overheats, and the tube probably ruined (BIG BUCKS).
4. Carefully slide the Franck-Hertz tube back into the oven.

## 6 Data Taking Connections and SWS Set-Up

In the experiment, the anode current  $I$  is plotted against the accelerating voltage  $U_2$  for fixed values of the control grid voltage  $U_1$  and retarding voltage  $U_3$ . The initial values of  $U_1$  and  $U_3$  are best determined by using a scope operated in the x-y mode, as then  $U_1$  and  $U_3$  can be determined in “real time.” Due to capacitance in the circuit and the short sweep times of  $U_2$  necessary for scope operation, the curve on the scope screen is distorted. The “wiggles” on the curve are not as pronounced as they actually are. The final data is taken using the SWS graph display operated in the x-y mode and at a much slower sweep speed. The relevant outputs of the Franck-Hertz power supply are connected both to the scope and the SWS interface.

Check that the  $U_2$  output of the power supply (3.5) is connected to both the channel 1(X) input of the scope, and, using a voltage sensor, to channel A of the interface. Check that the anode current output  $I$  of the power supply (4.1) is connected both to channel 2(Y) of the scope and, using a voltage sensor, to channel B of the SWS interface. Program SWS for the graph display with channel A on the horizontal axis and channel B on the vertical axis. Set the sampling rate to 20 Hz (the default is 10 Hz). To operate the BK scope in an x-y mode, the button marked X-Y should be in, and both the Source switch and Vertical mode switch set to X-Y. Reasonable values for the initial sensitivities of channel 1 and channel 2 would be 0.5 V/div and 2 V/div respectively. To minimize capacitance effects, the scope input switches (AC-GND-DC) for channel 1 and channel 2 should be set to DC.

## 7 Procedures

1. Franck-Hertz power supply should be off. Set switch (3.1) to RESET. This sets  $U_2$  to zero. As an extra precaution, turn knob (3.2) fully counter-clockwise. Turn  $U_1$  and  $U_3$  potentiometers fully CCW.
2. Using switch (6), turn on the Franck-Hertz power supply unit. LED (3.4) for Hg should be briefly green and then turn to yellow. Set  $U_3$  at 1.5 V.

3. Monitor the temperature while the oven heats up by turning switch (2.5) to  $\vartheta$ . You can check the set-point temperature by turning this switch to  $\vartheta_s$ .
4. In about 20 min the oven will reach the set-point temperature  $\vartheta_s$  and LED (3.4) will change from yellow to green. The temperature of the oven will overshoot by about 7 deg C and then settle down to near the set-point temperature.
5. Turn the mode switch (3.1) to the fast saw-tooth position and adjust the scope and the potentials  $U_1$  and  $U_3$  for a reasonable scope trace. You might try values for  $U_1$  and  $U_3$  between 1 and 2 volts. You want a trace that looks somewhat like Fig. 2, although on the scope you will not see such pronounced dips. If you make  $I$  too large by making  $U_1$  too large or  $U_3$  too small, you will saturate the amplifier. The peaks on the right will have flat tops. You can make  $I$  too small by making  $U_1$  too small or  $U_3$  too large. If  $U_3$  is made too large, the dips in the curve will “bottom out.” As a general procedure, set  $U_1$  and vary  $U_3$  for the best curve. Then try another value of  $U_1$ , vary  $U_3$ , and see if the results improve.

If in spite of adjustments of  $U_1$  and  $U_3$  the current  $I$  is very low, the first maximum poorly defined, and the curve rather flat, it may be necessary to decrease the oven temperature. This should be done in consultation with the 2nd floor staff and your instructor. If the temperature is reduced too much, a discharge will result which may well damage the tube. If the current  $I$  is too high (amplifier saturates) it may be necessary to increase the oven temperature.

6. When you have the kind of curve you want on the scope, set switch (2.5) so that display (2.6) shows the voltage  $U_2$ . Click REC in the left experiment set-up window and immediately turn the mode switch (3.1) to the single shot ramp so as to start a 0-30 V sweep of  $U_2$ . When the sweep is complete as shown by display (2.6), click STOP. Click auto-scale on the graph display. Click the analyze button on the graph display and use the cross hairs to measure the voltages of the peaks. Find the voltage differences between the peaks and compare to the accepted value of 4.9 V. Print out your curve. (Recall that the voltage along the horizontal axis of the graph display is  $U_2/10$ , not  $U_2$ .)
7. Looking at the scope, slowly increase  $U_1$  until the signal shows a small amount of saturation. Record the curve and print it out. Mark your print-out, showing the region of saturation.

## 8 Questions

1. Why is it better to have the cathode indirectly heated rather than directly heated?
2. When the oven temperature is too low, why is there the possibility of a discharge?
3. Why should the oven temperature not be too high?
4. Does the first peak occur at  $(U_1 + U_2) = 4.9$  V? Can you think of reasons as to why it would not?

## 9 Finishing Up

Please leave the bench as you found it. Thank you.

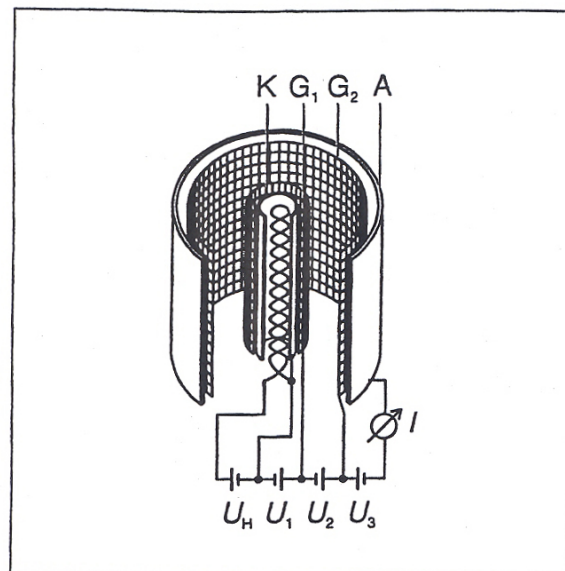


Figure 1: Schematic diagram of the mercury Franck-Hertz tube

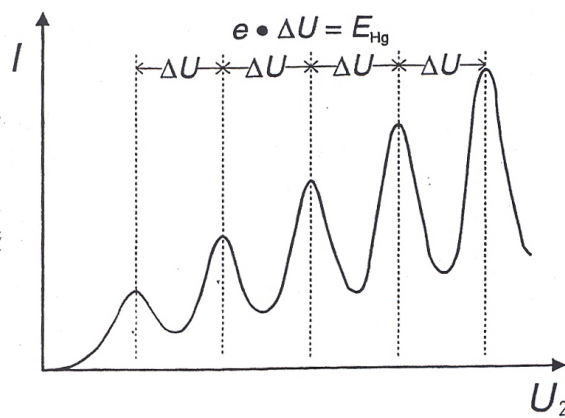


Figure 2: Anode current vs accelerating voltage

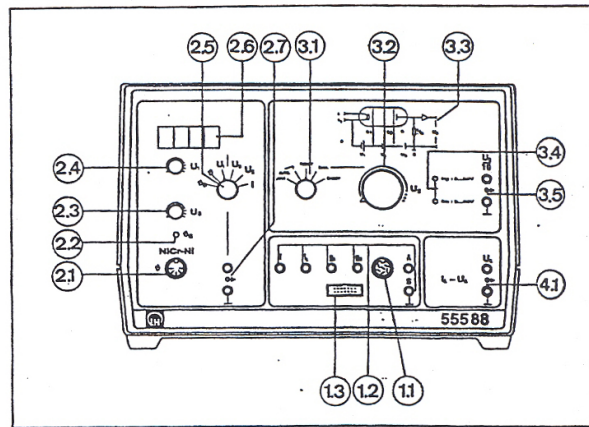


Figure 3: Back panel of power supply

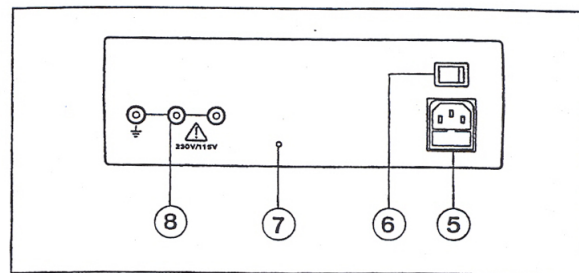


Figure 4: Front panel of power supply

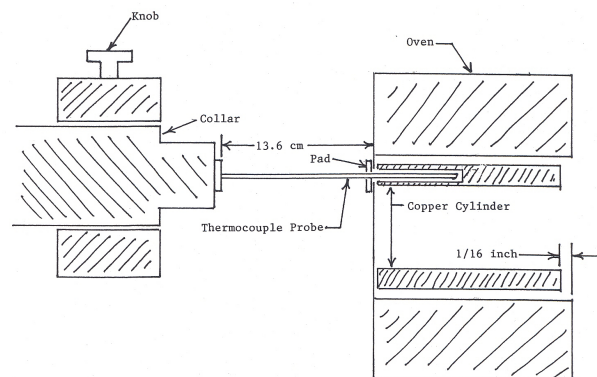


Figure 5: Oven and thermocouple assembly (not to scale)