The Franck-Hertz Experiment

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Apparatus

Franck-Hertz electron tube
Control unit (power supplies and amplifier)
Oven (thermostatically-controlled)
X-y recorder (H-P)
Digital oscilloscope (Tektronix TDS 3012)

Introduction

The Bohr theory of atomic structure postulates that only certain electronic states with discrete energies are stable. In this theory the emission of electromagnetic radiation is due to the transition of the electronic state of an atom from an allowed state of higher energy to one of lower energy, the energy being carried off by a single photon of definite frequency. Absorption of radiation is by an inverse process. The success of Bohr's postulates in explaining the spectrum of the H atom and the existence of discrete spectra tend to confirm the quantized nature of electronic energy changes involved in the interaction of atoms with light. It might be argued that these observations only illustrate the quantized nature of the radiation process and not necessarily the quantization of electronic energy states. The experiment of Franck and Hertz investigates the allowed transfer of energy in the inelastic collision of an electron with a neutral gas atom.

Experiment

The apparatus consists of an electron tube containing a cathode (a thermionic source of electrons), a grid at a large distance from the cathode, and a collector plate close to the grid. The tube has been evacuated except for a small amount of liquid Hg that serves as a source of Hg vapor. In order to produce a dense enough vapor of Hg atoms so as to have an appreciable number of collisions, the tube is heated in a thermostatically-controlled oven. The cathode, heated by an electric current, emits electrons and an accelerating potential is applied between grid and cathode. The density of Hg atoms must be high enough so that the mean free path of the electrons is small compared to the grid-cathode distance, d = 8 mm. The collector plate is biased negatively with respect to the grid so as to collect only those electrons above a minimum energy. Measured currents are in the range of nanoamperes.

The necessary power supplies are all contained within the Franck-Hertz control unit. Consult the write-up that describes this control unit for the correct way to connect it to the unit containing the Franck-Hertz tube. Voltages are provided by the control unit for each of the three circuits needed. Check the apparatus provided to be sure that you recognize the components provided. When you use the control unit be sure that you understand the meaning of the controls and the connection points.

MAXIMUM VALUES:	Oven temperature	200°C
	Cathode voltage	6-8 V
	Accelerating potential	60 V

Procedure

Operate the oven initially at about 180°C. It takes on the order of 10-15 minutes to reach the final temperature and to stabilize. Turn on the control unit after your circuit has been wired and approved by your instructor. Try not to allow the tube to "fire". This will be indicated by an abrupt increase in collector current and a blue glow around the grid. If this occurs, decrease the grid potential quickly to zero. When the tube "fires", a glow discharge is set up in the tube which involves the ionization of the Hg atoms. (The first ionization energy of Hg is 10.48 eV.) The glow discharge is an interesting phenomenon in its own right.

Obtain records of the collector current as a function of accelerating potential using the *x-y* recorder or digital oscilloscope provided. Determine the excitation potential(s) of Hg, including an estimate of uncertainty in your result. Repeat your measurements at a lower temperature, i.e., about 150°C.

Questions

1) Consider the one-dimensional collision of an electron having an initial kinetic energy E_0 with a Hg atom initially at rest. The final kinetic energy of the electron is E_1, the final kinetic energy of the atom is K, and the internal excitation energy of the Hg atom is W. You can apply the laws of conservation of energy and momentum to the collisions. As part of your report,

A) calculate K/E_0 and E_1/E_0 assuming that $W = 0$ (an elastic collision) and

B) calculate the maximum value of W/E_0 if W is not equal to 0 (assume a perfectly inelastic collision).

Express your results as functions only of m/M, the ratio of the electron mass, m, to that of the Hg atom, M. (You may use the valid approximation that $m/M << 1$.) If changes in internal energy of the atom are quantized then there is a minimum change W_0. As a result, collisions for which the maximum possible value of W is less than W_0 can only be elastic. Comment on the significance of the results of your calculations of K/E_0, E_1/E_0, and W/E_0.

2) A series of peaks and valleys are observed in the measured collector current as the voltage is increased. Do these correspond to the same or to different transitions in the Hg atom?

3) How are your data affected by contact potentials? (In this experiment contact potentials are the potential differences that exist between the surfaces of two materials, e.g., electrodes, when the materials are brought into electrical contact with each other.)

4) Calculate the mean free path of the electrons in the Hg vapor at 150°C and 180°C using the kinetic theory of gases. For this calculation you will need to know the equilibrium vapor pressure of Hg at these temperatures.

5) Describe and comment on the important differences observed in the *x-y* recorder or oscilloscope displays at the highest and lowest oven temperatures. At which temperature does the collector current increase faster with increasing voltage? Why does this occur?

References

Harnwell and Livingood, *Experimental Atomic Physics*, pp. 314-319.
Melissinos, *Experiments in Modern Physics*, pp. 8-17

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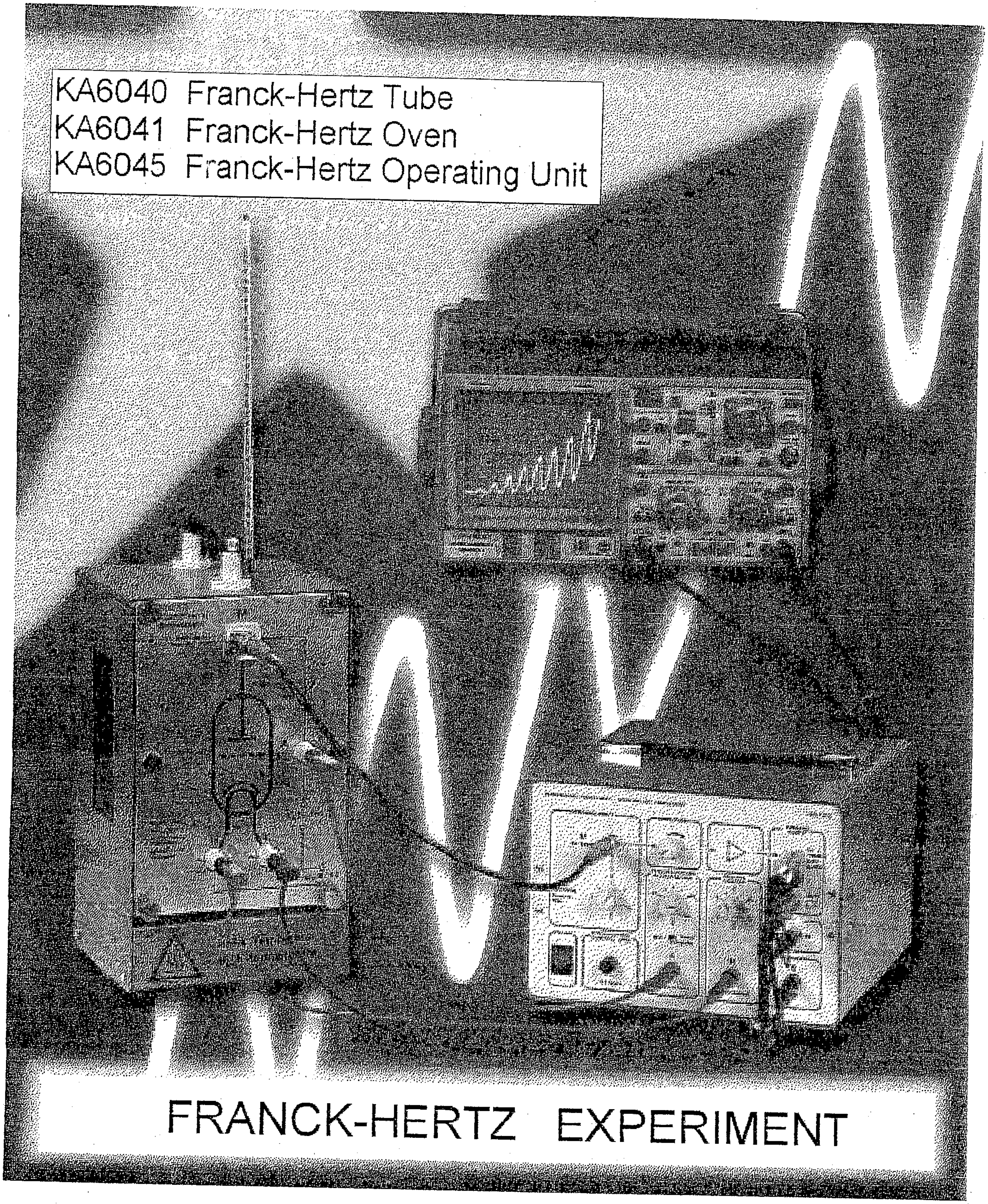

KA6040 Franck-Hertz Tube
KA6041 Franck-Hertz Oven
KA6045 Franck-Hertz Operating Unit
FRANCK-HERTZ EXPERIMENT

This operating unit provides all voltages necessary for performing the Franck-Hertz experiment and contains a high-sensitivity DC amplifier for measuring the electron stream collected at the target electrode. It can be used equally well for performing the experiment with mercury vapor or with neon gas filled tubes. Using this unit considerably simplifies the experimental setup. It requires only five connections to the socket of a neon gas filled Franck-Hertz tube, or four connections to the front panel of a Franck-Hertz tube with mercury vapor. Then the associated measurement devices are connected, completing the experimental setup.

The operating unit for the Franck-Hertz experiment provides the following:

1. The accelerating voltage U_B (red jack): a regulated DC voltage continuously adjustable from 0 V to 80 V ("U_B" toggle switch in "Man" position).

2. The heater voltage U_H (green jack): a DC voltage from 4 V to 12 V for the filament of the indirectly heated oxide-coated cathode. This makes it possible to adjust the heater current from 180 to 400 mA.

3. The control voltage (brown jack): a fixed voltage of 9 V DC; required for operation of the Franck-Hertz tube with neon gas filling.

4. The reverse bias U_G: a voltage adjustable between –1.2 V and –10 V for protecting the target electrode and controlling the Franck-Hertz signal.

The unit also provides the following for displaying the Franck-Hertz signal on the oscilloscope:

5. A saw-tooth accelerating voltage U_B with a voltage level adjustable from 0 Vpp to 80 Vpp ("U_B" toggle switch in Ramp/50 Hz position). The deflection frequency is fixed at 50 Hz.

6. The necessary deflection voltage (half-wave voltage produced by half-wave rectification) for observing the Franck-Hertz curve with the oscilloscope. The amplitude of the deflection voltage is reduced to one tenth of the selected accelerating voltage (U_B/10).

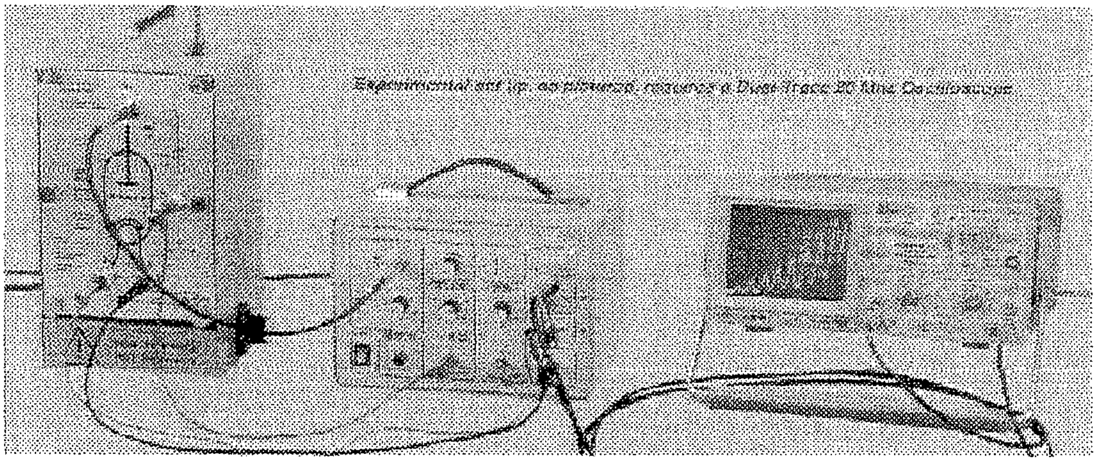
The DC amplifier consists of two cascaded operational amplifiers (OP), the first of which is wired as an electrometer amplifier. The measurement current is supplied to the non-inverting input of the first OP. The input resistance is 680 kOhm. The amplification of the Franck-Hertz signal can be adjusted using a negative feedback potentiometer ("Amplitude" control). In the second cascaded OP the signal is further amplified and inverted. The measurement voltage at the output is proportional to the target current. A measurement voltage of 1 V corresponds to an electron current of approximately 10 µA at minimum amplification ("Amplitude" knob all the way to the left), and an electron current of approximately 10 nA at maximum amplification ("Amplitude" knob all the way to the right). An ordinary commercial voltmeter with a range of 10 V can be used as a measurement instrument. It is not necessary to adjust the instrument. The measurement voltage can be loaded to 10 mA and is short-circuit protected.

Experimental Setup

Franck-Hertz Experiment with Mercury Filling

The figure below shows the experimental setup for performing the Franck-Hertz experiment with mercury filling, consisting of:

1. Franck-Hertz tube with mercury filling on front panel
2. Oven, thermostatically controlled, 110V mains (available in 220V, special order)
3. Operating unit for Franck-Hertz experiment, 110V mains (available in 220V, special order)
4. Dual-channel oscilloscope
5. X-Y recorder



Procedure:

1. Connect the various devices as shown in the figure. Do NOT connect the recorder and the oscilloscope at the same time. The oscilloscope is used first in order to adjust for a clear curve. The X-Y recorder is then used to produce a curve on paper.

Operating Unit	Socket/Tube	Oscilloscope	Recorder (alternative)	Voltmeter	Comments
PE	PE				for neon filling only
K	K/Cathode			- Input	
H	H/Heater				
A	A/Anode			+ Input	
Control Grid 9 V/10 mA	Control Grid				for neon filling only
M Signal	BNC (Tube)				
Franck-Hertz Signal Output		Ch. 1 (Y input)	Y input		
U_B/10 Output		Ch. 2 (X input)	X input		

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Preliminary Adjustments

2. Set the oven to the desired temperature (e.g., 200 °C). The data sheet supplied with the tube can be used as a guideline.
3. Before turning the unit on, turn the controls for "Heater", "Acceleration", and "Amplitude" all the way to the left stops. Set the control for "Reverse Bias" to the center position.
4. Turn the unit on with the illuminated green switch (bottom left).
5. Set the toggle switch "Man, Ramp/50 Hz" to "Ramp".
6. Connect the unit's Franck-Hertz signal output to the oscilloscope's Y input (Ch 1), and the $U_B/10$ output to the X input (Ch 2).
7. Set the oscilloscope for X-Y operation and set Ch 1 and Ch 2 for an amplification of 1 V/cm in DC mode.
8. Turn on the oscilloscope.
9. Rotate the oscilloscope's X and Y position controls to move the beam to the lower left corner of the screen.

Adjustments:

a) Now, carefully adjust the heater voltage to a value of approximately 8 V.
b) Bring the accelerating voltage to a value of approximately 40 V to 50 V.
c) Rotating the "Amplitude" control increases the amplitude of the signal. Once the oven has reached the desired temperature, one can observe the gradual appearance of the Franck-Hertz curve on the oscilloscope screen.
d) Vary the reverse bias such that a curve with well-defined minima and maxima appears.

By increasing the accelerating voltage to a value of approximately 80 V and slightly changing the other parameters (including the oven temperature if necessary), one can observe the Franck-Hertz curve on the oscilloscope screen, which proceeds from the bottom left to the top right and shows up to 13 pronounced maxima or minima (Fig. 2). The accelerating voltage must not be increased so far that an independent discharge occurs in the tube, since collision ionization disrupts the curve.

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The method described is a general adjustment procedure. Since Franck-Hertz tubes are manufactured by hand, the optimal parameters vary widely from tube to tube. The data sheet delivered with the tube provides a guideline for good values.

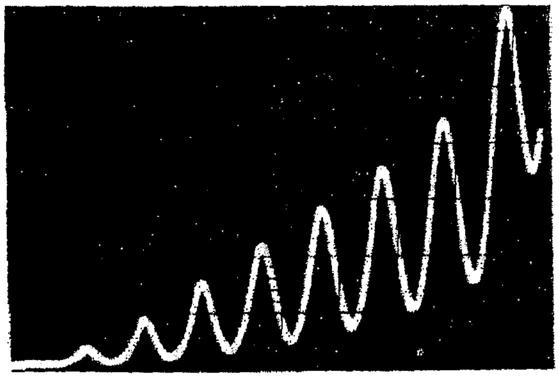

Fig. 2 Oscilloscope image of the Franck-Hertz curve

Precise Analysis of the Franck-Hertz Curve:

The precise analysis of the Franck-Hertz curve additionally uses an X-Y recorder and a digital voltmeter. It is not absolutely necessary to measure the absolute value of the thermionic current for this purpose. You should first set up a Franck-Hertz curve on the oscilloscope screen that has well-defined maxima and minima.

Procedure:

a) Set the "Man/Ramp 50 Hz" toggle switch to "Man".
b) Rotate the control for the accelerating voltage to the left stop (U_B = 0V).
c) Also connect the digital voltmeter to the unit's "A" and "K" jacks.
d) By rotating the control for the accelerating voltage to the right stop, you can measure a maximum accelerating voltage of approximately 80 V. Afterwards, rotate the U_B control back to the left stop.
e) Remove the measurement cables from the oscilloscope's X and Y inputs and replace them with 4 mm cables connected to the corresponding inputs of the X-Y recorder.
f) Turn the X-Y recorder on and set both its axes to an amplification of 1 V/cm.

Note: The accelerating voltage at the signal output (recorder signal) is reduced by a factor of 10. However, the digital voltmeter measures the full accelerating voltage between the "A" and "K" connections.

g) You can now vary the amplification at the recorder so as to obtain a Franck-Hertz curve that fills the sheet of paper.

h) You can now record a Franck-Hertz curve (Fig. 3) by slowly and steadily raising the accelerating voltage U_B, and determine the exact positions of the maxima and minima with the digital voltmeter.

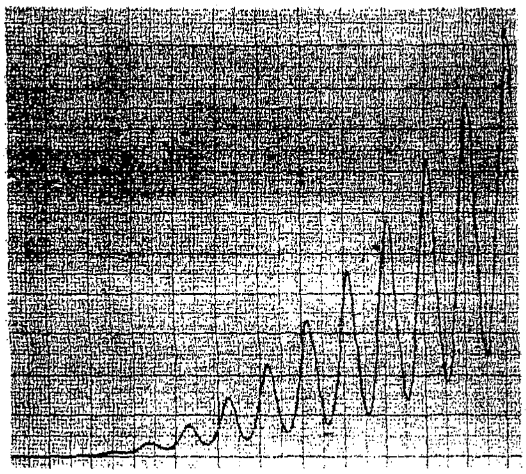

Fig. 3 Recorder image of the Franck-Hertz curve

Franck-Hertz Experiment with Neon Filling

In addition to the connections reproduced in Fig. 1, the control electrode for the neon Franck-Hertz tube must also be connected to the corresponding jack on the unit. Setup follows the same sequence as in the case of the mercury Franck-Hertz curve; however, only three maxima are possible here.

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