Rice University
Physics 332

THE FRANCK-HERTZ EXPERIMENT

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I. Introduction

By the early part of the twentieth century it was clear that isolated atoms absorb and emit electromagnetic radiation at characteristic frequencies. Bohr's atomic model suggested that this was due to an inherent quantization of the allowed energies of atomic electrons. Given these ideas, it is reasonable to ask if other modes of energy transfer would also exhibit quantization. This was the question posed, and answered, by James Franck and Gustav Hertz (not Heinrich Hertz, of electromagnetic fame) in 1914.

Franck and Hertz bombarded isolated atoms with electrons and showed that the electrons lost discrete amounts of energy characteristic of each element. Further, they were able to show that electron bombardment at an appropriate energy led to optical emission at the known spectral frequency corresponding to that energy. Their results could be interpreted within the Bohr model as demonstrating excitation of one of the discrete energy levels, followed by a transition back to the ground state with emission of light. This is obviously a classic experiment, in the sense of being of key importance, but the adjective is otherwise unfortunate in that the experiment provided strong evidence against classical mechanics and in favor of the nascent quantum mechanics.

In our laboratory we will repeat Franck and Hertz's energy-loss observations, using mercury, and try to interpret the data in the context of modern atomic physics. We will not attempt the spectroscopic measurements, since the emissions are weak and in the extreme ultraviolet portion of the spectrum.

II. Theoretical considerations

It is well known that electrons can be boiled out of a hot metal filament. By applying a positive potential between the filament and a nearby electrode one can give the electrons any desired kinetic energy. If the electron subsequently hits a gas atom it may transfer energy to the atom. In this experiment we seek to measure that energy transfer. Because of the large mass difference between the electron and any atom, collisions which do not excite internal motions in the atom result in very small changes in electron energy. The energy loss we observe, therefore, is essentially a measure of the energy changes internal to the atom.

To a first approximation, the experiment can be understood by examining the idealized sketch in Fig. 1. Electrons are accelerated toward a grid through a sealed bulb containing a small amount of mercury. If the accelerating voltage is large enough, and there is no loss of energy in collisions, most electrons will pass through the grid and continue up the retarding gradient to the collector electrode. The current meter measures this flow of electrons. Alternatively, electrons which have made an inelastic collision and reach the grid with small kinetic energy will be captured there, rather than at the collector. If we measure the collector current as a function of grid-filament voltage we can infer the probability of an inelastic collision as a function of electron energy.

With this geometry and our assumption of quantized atomic energy levels we should expect to see several dips in the collector current as we increase the accelerating voltage. Ignoring the retarding potential for the moment, the first dip will occur when electrons reach the grid with just enough energy to excite a mercury atom. The next dip will occur at twice this voltage, since an electron can then lose its energy midway from filament to grid and then be accelerated enough to collide again near the grid. At still higher voltages there can be additional collisions leading to

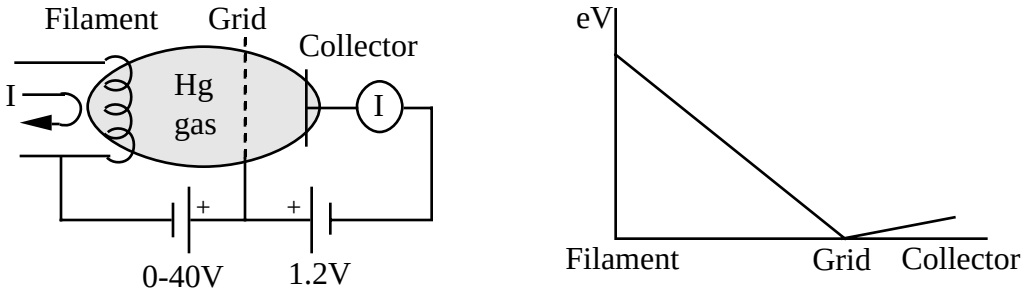

Fig. 1 The drawing on the left shows the geometry and voltages used for the Franck-Hertz experiment. The graph shows the mechanical potential energy of an electron as a function of position within the tube. Note that both accelerating and retarding regions are present.

more dips. The important point is that the whole array of equally-spaced dips will be due to the lowest energy transition that the electron can excite. In this picture, the only effect of the retarding potential is to shift the whole pattern to higher voltages.

If there were only one transition, this would be the whole story. Actually, though, mercury is a multi-electron atom with a complicated excitation spectrum and electron impact is a violent process. As a result there are several competing processes, and the energy loss observed may not reflect the energy difference between the ground state and the first excited state of atomic mercury. You should refer to the attached reprint for a complete discussion of this issue. Figures 4 and 7 are particularly informative.

Several non-atomic factors also complicate the simple picture. First, electron impact can ionize the atom, as well as induce the intra-atomic transitions we have discussed so far. The free electron produced by the ionization event can then be accelerated and ionize another atom, eventually leading to creation of a conducting plasma in the tube. This causes a large increase in the collector current and, for the Hg vapor, a visible blue glow in the tube. The exact accelerating voltage at which breakdown occurs depends on the tube geometry, gas density and electron current, as well as the type of gas present. Once the gas has broken down the electrons are in a conducting medium and we can no longer interpret the collector current as a measure of the collision probability.

A more modest difficulty arises from other potentials in the apparatus. There is likely to be a difference in work function between the filament and collector plate. As you recall from the photoelectric effect, the work function is the minimum energy required to move an electron from a metal to the vacuum. This potential energy must be supplied when the electron leaves the filament and a similar energy is gained when the electron enters the collector. If the two potentials are not the same, the voltage scale will be shifted by a constant amount, of the order of 1-2 volts. Since there are temperature gradients in the apparatus, there can also be thermoelectric voltage differences, amounting to a few tenths of a volt. Finally, the deliberately imposed retarding potential may vary somewhat from the nominal 1.2 V. Fortunately, constant offsets do not affect the voltage differences we want to measure.

III. Measurement and analysis

The laboratory is equipped with a mercury-filled tube in a small oven, power supplies and appropriate meters. Using this apparatus it is possible to plot the collector current as a function of filament to grid voltage, and to observe the effect of varying both the electron current and the gas density.

Most of the equipment is contained in two boxes. An electric oven is used to raise the temperature of the tube to 150-250 °C to produce the desired vapor pressure of mercury. The other box contains the voltage sources and a current-to-voltage amplifier for the collector signal. (Contrary to the diagram on the oven, it does not contain any electronics.) The manufacturer's operating instructions are available (in translation) for reference in the lab.

The apparatus should be wired as in Fig. 2. An X-Y recorder is used to directly plot the collector signal vs accelerating voltage. The DMM provides for precise calibration of the accelerating voltage scale. An alternative procedure to display the data on an oscilloscope is

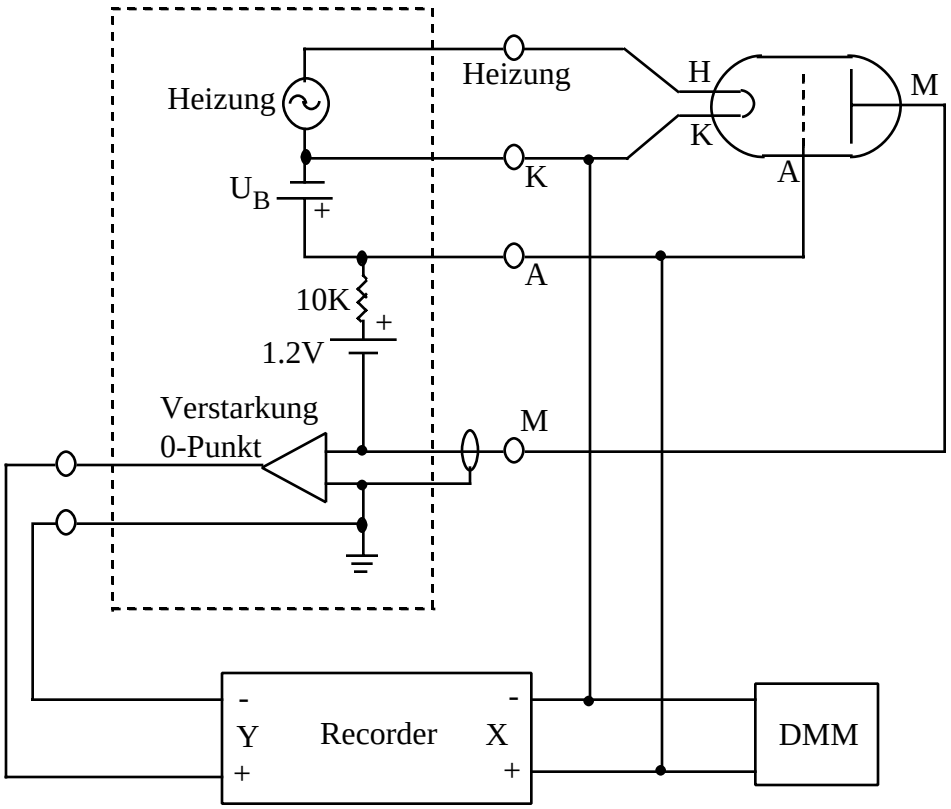

Fig. 2 Connection diagram for the NEVA Franck-Hertz apparatus. The circuitry inside the dashed lines is contained in the electronics box. The tube is housed in an oven, which is not shown.

given by the manufacturer but turns out to be less useful in practice.

Once the apparatus is wired you can proceed to make measurements as follows:

1. Stabilize the oven temperature at about 200 °C. The thermostat provided allows large temperature swings so it is better to turn the control all the way up and use the variable transformer to set the input power level. Transformer settings in the range 80-90 will usually give the desired temperature.

2. Set the amplifier gain (Verstarkung) and zero-offset controls (0-Punkt) to mid-range. The filament current (Heizung) should also be at mid-range initially. The accelerating voltage control is labeled U_B. It's switch should be set for DC (straight line) operation, not sweep (ramp line). Be sure the unit is switched on.

3. Adjust the gain on the X-Y recorder x-axis so that an accelerating voltage range of 0-40 V can be displayed. Mark a couple of reference points on the chart at known voltages read on the DMM. Set the y-axis gain so that you can display the full range of the signal.

4. If you now sweep U_B slowly through its range you should get a curve with several relatively abrupt dips, terminated by an abrupt jump in the current when ionization occurs. At this point U_B will also decrease sharply due to a resistor that limits the arcing current.

5. Darken the room and closely observe the tube as you vary the voltage U_B. Can you explain the pattern of light emission you see in terms of the collector current you have just plotted?

Once you have verified that the apparatus is working, you can explore the effect of varying the filament current and the temperature. Obtain curves for low, medium and high values of the filament current at one temperature. Notice that the amplitude of the dips and the breakdown voltage both depend on these parameters, allowing you to observe different numbers of successive excitations. By varying the temperature over the range of about 150-250 °C you can control the mercury vapor density over a wide range. This is of interest, since it should change the apparent excitation energy.

Ideally, your curves would show a sharp sawtooth pattern, dropping abruptly at each excitation point. Because of the spread in electron energies and the variation in collision probability with energy there will be some spread in the curves. It is probably reasonable to take the half-way point on the drop as an average for the excitation voltage. Find these points on each of your curves, and determine the corresponding U_B from the plot. Plot the values against sequential dip number, assigning serial number one to the lowest-voltage dip. A straight-line fit to this plot yields the apparent mercury excitation voltage.

Since the choice of the half-way point on the dip is essentially arbitrary, it could lead to a systematic error in the estimate of the excitation voltage. Explore this possibility by re-analyzing a few of the curves with some other choices for the excitation energy.

In your report you should present your data for the excitation voltage and any other observations you consider pertinent. Discuss the extent to which your data are consistent with the claims made in the reprint. Also, be sure to explain the tests you have made for systematic errors in the apparent excitation voltage.