The Franck–Hertz Experiment

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1 Background of the Experiment

Reading: Ref. 1, pp. 329-348

In 1912 Niels Bohr developed his model of the atom, in which electrons are allowed only certain discrete orbits. Transitions between these orbits may take place only when the atom absorbs or emits quantized packets of energy \( E = \frac{hc}{\lambda} \). This explains the spectral lines given off by an excited element, such as described by Rydberg’s formula for the series of spectral lines for hydrogen.

Less than a year after Bohr published his theory, J. Franck\(^1\) and G. Hertz\(^2\) proved it experimentally, earning themselves the 1925 Nobel Prize in Physics. They boiled electrons off a hot filament K, used a potential \( U_b \) to accelerate them through a vapor of an element toward a grid A (v. Fig. 1), and looked for them on a plate M, with a small retarding potential \( V_0 = 1.5 \text{ V} \), to stop electrons whose kinetic energy was below a certain value.

If the kinetic energy of the electrons is too small to excite the atoms in the vapor, the electrons collide elastically and lose almost no energy, as required by the conservation of energy and momentum, and a large current is detected at plate M. If, on the other hand, the electrons gain just enough kinetic energy

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\(^1\)James Franck, American (German-born) physicist, 1882-1964

\(^2\)Gustav Hertz, German physicist, 1887-1975, nephew of Heinrich Hertz, who discovered radio waves
to equal the energy level transition of the atoms, some will collide inelastically and transfer energy to the atoms. These electrons will not have enough energy to overcome the retarding potential at plate M, and a smaller current will be detected.

As the voltage is increased further, some electrons will transfer their energy to the vapor early enough to be accelerated again to an energy $eV_0$, and the current detected at M will again increase until the next excitation energy threshold is reacted. This occurs at either the energy of a different transition or twice the energy of the ground state transition. Measurement of the differences in the accelerating voltage between the minima in the detected electron current can be used to determine the first excitation level of mercury atoms.

2 Apparatus

Franck–Hertz tube with connector panel (NEVA No. 6751 and 6753)
Oven, capable of heating to 400° F (200° C)
Franck–Hertz power supply, (labeled Betriebsgerät) (NEVA 6756)
(swept 0–70 V $U_b$ and 1 volt $V_g$, with amplifier to boost the current detected at the plate)
Banana plug cables to run from the power supply to Franck–Hertz tube
Dual banana plug to BNC adapter
Oscilloscope
Voltmeter
Thermometer (to 400° F, 200° C)

3 Procedure

Refer to Fig. 2.

Figure 2: Apparatus arrangement for the Franck–Hertz experiment.

1. With the power supply off, connect cables from the power supply to the oven. The shielded cable connects to the output amplifier, so AC noise from the lights and the oven will not ruin the signal. Make sure all power cords are plugged in securely.

2. The output current detected at M is amplified and sent through a resistor. The voltage $V_g$ measured across this resistor is linearly proportional to the output current and is used to find the accelerating
voltages. The exact value for the current, \( I_g \), remains unknown; only the maxima and minima positions are important. Connect the \( V_g \) output (Y) to the Y channel of the oscilloscope. You will need a dual banana plug to BNC adapter on the power supply to allow you to connect a BNC cable between the power supply and the oscilloscope. Set the Y channel to 1 V per division, on DC coupling.

3. Connect the X-deflection (X-Ablenkung) cable plug of the power supply into the X channel of the oscilloscope. You will again need a converter to hook the power supply to the oscilloscope; you can use a single banana to BNC adapter. Flip the switch for the accelerating potential power supply (\( U_b \)) to the left to the uniform current setting (—). When the oscilloscope runs in X-Y mode, it will graph the instantaneous voltage \( U_b \) on the axis against the current \( I_g \) on the Y axis. Set the X channel of the oscilloscope to .2 V per division, on DC coupling and set the time per division dial to X-Y mode.

4. Connect a voltmeter across \( U_b \). If you use a digital multimeter, leave the power off for now, with the DC setting to read up to 200 V.

5. Put the thermometer in the top of the oven and set the oven thermostat to heat to 338° F (170° C) to vaporize the mercury in the tube inside the oven. The oven will heat in about 15 minutes. Be careful not to touch the hot oven.

6. Before continuing with the experiment have the instructor check the connections.

   The filament heater (Heizung) controls the rate at which electrons are emitted. Adjust it to about half of full scale. Turn the \( U_b \) all the way counterclockwise and turn the amplification (Verstärkung) to about one quarter of its full capacity. After the oven heats, turn on the power to the voltage source and the oscilloscope. Adjust \( U_b \) to 20 V – 26 V, turn the voltmeter off, and switch \( U_b \) to the sawtooth setting. After about thirty seconds the filament will heat up and begin to emit electrons, and a pattern will appear on the oscilloscope. Adjust the offset (0-Punkt) and the X-deflection scale (X-Ablenkung) as necessary. Turn the filament heater knob to vary the filament current, and set the temperature to 329° F (165° C).

![Figure 3: Sample oscilloscope trace demostraing absorption of energy by differing numbers of collisions of electrons with Hg atoms](image)

7. The voltage \( U_b \) is not actually applied as a sawtooth. It is a half-wave rectified, 60 Hz sinusoid. You may see the same signal twice on very different scales, once compacted and once stretched out, as shown in Fig. 3; to avoid the double display, be sure that the X and Y oscilloscope channels are DC-coupled.
8. Adjust \( U_b \) and the gain (Verstärkung) so the maximum number of peaks appear. Part of the signal may be flat at the maximum Y-value, because the amplifier saturates at too high a current. Lowering the gain and the filament current will make sure no minima are off scale. Record the distance between the minima for several filament current settings.

If the oven temperature is raised, more Hg atoms will ionize to react with the electron beam. The current detected will be weaker, but the dips in current at the absorption bands will be larger. If some peaks were hidden, they may now appear. It should not be necessary to raise the oven temperature above 393° F (200° C).

If \( U_b \) is too high, the mercury may ionize and conduct all the current, destroying the Franck–Hertz peaks.

9. Switch the accelerating voltage from sawtooth to continuous and measure \( U_b \) with a voltmeter. This is the maximum voltage that the swept voltage attains. If the oscilloscope signal was aligned so that the left of the screen was at 0 V and the picture exactly fills the screen, then the right side of the screen was at \( U_b \) max. Use this information to calibrate the horizontal scale.

4 Results

1. To find the first excitation energy of mercury, measure the distances between the adjacent minima and convert this to voltage. The value of voltage of the first current minimum will not give an accurate answer for the excitation energy, because a contact potential difference exists between the cathode and the anode. A contact potential difference arises from the fact that the cathode and the anode have different work functions, so it takes a different voltage to extract an electron from them. The difference shifts the whole voltage scale of the Franck–Hertz peaks, so the differences in voltage between peaks for a single atomic transition have the same spacing.

2. Is there an atomic energy level transition other that the ground state excitation occurring. Justify your answer.

3. What are the sources of error?

5 References


