Franck-Hertz Experiment

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ABSTRACT: Quantization of energy levels within an atom is a fundamental principle of atomic physics. One of the most revealing experiments to investigate this energy quantization is the Franck-Hertz experiment originally done by James Franck and Gustav Hertz in 1914. Their groundbreaking experiment showed that the amount of energy corresponding to the excitation of a mercury atom was 4.9 electron-volts. In this paper, I will show my findings by following a similar procedure they used on mercury vapor over a century ago, in which I obtained a value of 4.91±0.08 V. I also followed a similar procedure for contained helium gas and found the atomic excitation energies of the first four orbital levels to be 19.59±0.15 eV, 20.43±0.19 eV, 22.59±0.22 eV, and 23.89±0.09 eV respectively. My research also included investigation into the ionization energy of helium which I found to be 24.51±0.08 eV, as well as the effect of temperature of the mercury gas on quantum energy resonance levels.

INTRODUCTION: During the early part of the 20th century the theory of quantum mechanics was still in its infancy. Niels Bohr had developed his theory that an atom consisted of a nucleus with shells around it held stable by electrons orbiting radially around it. This idea predicted a major axiom of quantum mechanics, that atomic energy levels are quantized. [1] A year after Bohr's published atomic model, James Franck and Gustav Hertz would conduct an experiment to investigate the behavior of energetic electrons as they interacted with vaporized mercury. [2] The Franck-Hertz experiment relied on electrons with a fixed kinetic energy colliding with gaseous mercury atoms. Their results showed that these electrons would have inelastic collisions with the mercury atom only when the electron was accelerated to certain kinetic energies. These electrons could excite the mercury atoms, but only at discrete energy levels. [2]

The Franck-Hertz experiment investigates the energy transitions which are produced by collisions between electrons and mercury atoms. Figure 1 shows the apparatus used to cause these collisions. The collisions first take place elastically without a measurable transfer of energy to the mercury atom. As the accelerating voltage is increased, the electron has the kinetic energy of a large enough magnitude to excite the mercury atoms in the space in front of the grid-form anode. These electrons transfer a discrete amount of energy to the impacted mercury atoms and are not able to overcome the -1.5 V braking potential created by the battery connected collector. This causes a decrease in the current measured through the collector pico-amplifier. As the accelerating voltage is further increased, giving the incident electrons more kinetic energy, the zone where the collision takes place moves closer to the cathode.

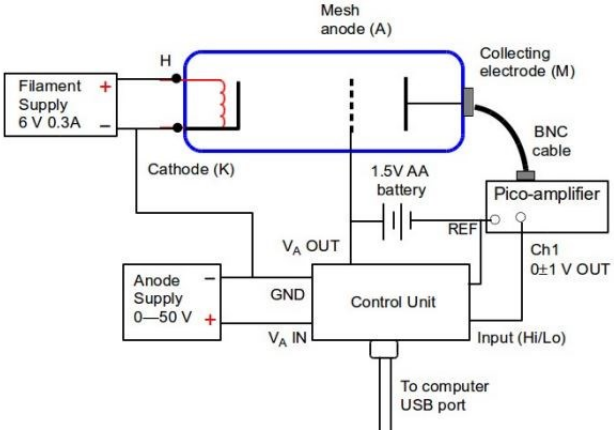

***Figure 1**: Franck-Hertz Mercury Excitation Apparatus*
This figure shows the components of the mercury excitation experimental apparatus. Thermionic emission of electrons occurs at the red filament. The voltage potential of the mesh anode accelerates these electrons through the mercury vapor present between the cathode and anode. The zone where collisions occurs moves closer to the cathode as anode voltage increases. The 1.5 V battery has a negative bias that slowed electrons cannot overcome, thus they are unable to reach the collector/pico-amplifier.

This spacing increase between the collision zone and the anode allows the already slowed collided electron to gain enough kinetic energy to reach the collector. Once the collision zone is far enough away from the anode, or conversely close enough to the cathode, it can accelerate a slowed electron to a level that allows the electron to have another inelastic collision with another mercury atom. These energy transfers reappear periodically as the accelerating voltage is increased as shown in Figure 2.

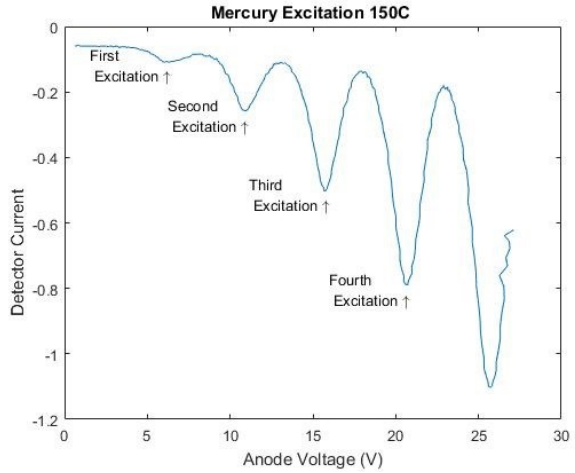

***Figure 2**: Mercury Excitation Voltage Levels at 150 C*
This figure shows detector current measured through the pico-amplifier as a function of anode voltage. The anode voltage is directly proportional to the kinetic energy of the accelerated electrons. Note the spacing of the minima being 4.9 V for each excitation. However, the voltage of the first excitation is not 4.9 V away from the zero voltage, revealing the work function of the oxide coated cathode undergoing thermionic emission.

The clear periodicity of the minima that corresponds to a drop in collector current measured by the pico-amplifier shows that these inelastic collisions occur at discrete energy levels. Our measurement data shows this energy level to be 4.91±0.08 V in agreement with accepted values for mercury first excitation level.

Figure 2 also allows us to deduce the work function of the cathode undergoing thermionic emission of electrons. Since the minima spacing is uniform across each excitation event, one would expect the very first excitation event to occur at that spacing value. However, there is an amount of energy required to release the electron from the cathode. This work function is the measured value of the first excitation event at 5.995± 0.08 V minus the minima spacing of 4.91±0.7 V. This gives a work function for this metal of 1.085±0.08 eV.

Investigation into the effect the temperature of the mercury gas reveals the same characteristic 4.9 V minima spacing as shown in Figure 3 below. This indicates the temperature of the gas, and thus each mercury atom's average kinetic energy, has no effect on the discrete energy level at which it can accept energy from the electron that collides with it.

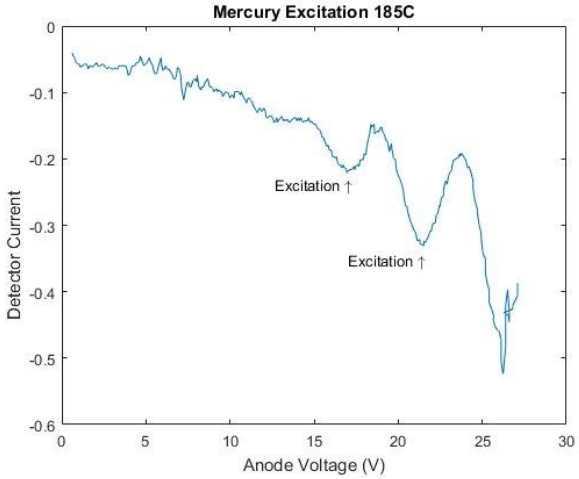

***Figure 3**: Mercury Excitation Voltage Levels at 180 C*
The initial excitation events are difficult to see and hidden in noise however the spacing between the visible excitations is clearly the same as those measured at 150C shown in Figure 2.

Using a similar procedure as that done by Franck and Hertz, and reproduced above, one can determine the excitation energy of helium gas. Figure 4 shows the apparatus used in this experiment.

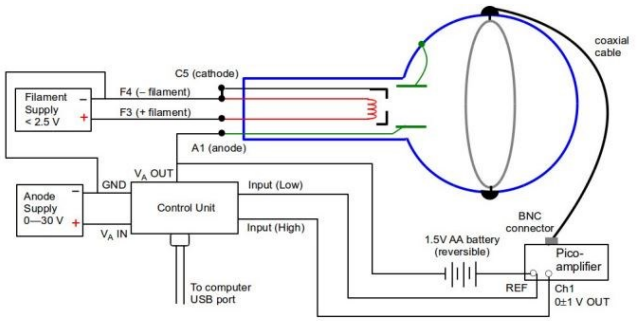

***Figure 4**: Helium Critical Potentials Tube Setup*
This figure shows the components of the helium excitation experimental apparatus. Thermionic emission of electrons occurs at the red filament. The voltage potential of the green anode accelerates these electrons to the right in this diagram. Those electrons that are not slowed by inelastic collisions will strike the bulb face which grounds to the anode.

The helium excitation tube has several key differences from the mercury bulb used earlier. The most important of these is that in this case the collector ring that is similar to the collector anode in the mercury setup is at a potential which allows the collection of slowed electrons

that have been involved in an inelastic collision. Figure 5 shows a plot of the current through the collector ring as a function of accelerating anode voltage. Again, a pico-amplifier is used to boost the signal from the collector ring.

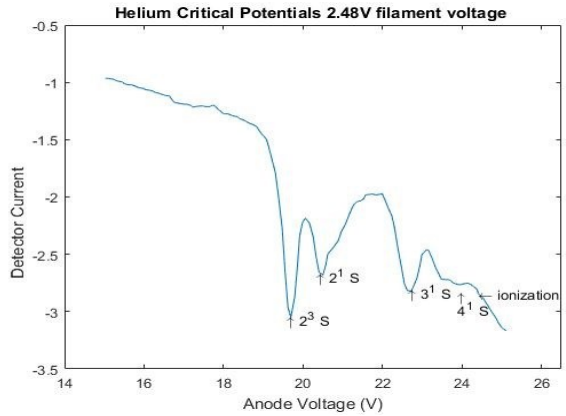

***Figure 5**: Mercury Excitation Voltage Levels*
With a filament voltage of 2.48 V this plot shows the minima that correspond to the excitation levels of Helium. The spacing between each minima is not periodic like the mercury excitation (see Figure 2) because helium's excitation levels fall within our 0 – 30 V range whereas the mercury data shows each atom only being excited to its first excitation level.

This setup also allows us to study the effect of filament voltage on the helium excitation levels. Figure 6 shows the current through the collector electrode for a smaller filament potential than above. This smaller potential causes the filament to heat up to a lower temperature in comparison to the higher filament potential.

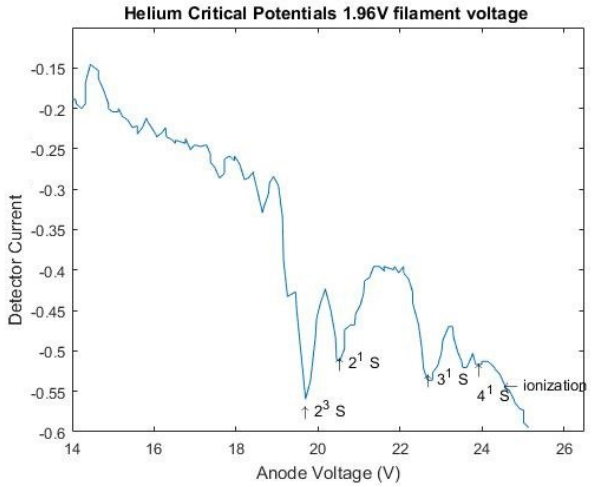

***Figure 6**: Mercury Excitation Voltage Levels*
Lowering of the filament potential to 1.96 V produces the data shown in Figure 6. Notice how the excitation levels that correspond to the miniuma in the collector current are at the same anode voltage. This shows that as the filament voltage is decreased the kinetic energy of the thermionic emitted electrons is unchanged. However, the number of these emitted electrons has decreased as shown by the change in the relative magnitude of current shown along the plot's ordinate.

We can make a simple adjustment to the apparatus to allow the collector ring to attract positive charge. This adjustment allows us to investigate the ionization potential of helium. Ionization occurs when an accelerated electron collides with a helium atom inelastically and transfers enough energy to allow an electron bound to the helium atom to be completely freed from this atomic attraction. Since helium atoms are net neutral charge, this loss of an electron will give the helium atom a positive charge, which can be collected by an electrode with a negative bias. By switching the bias of the 1.5 V battery connected to the collector ring we achieve the desired condition to collect ionized positively charged helium atoms. Figure 7 shows a plot of current, in this case a positive charge, through the collector electrode.

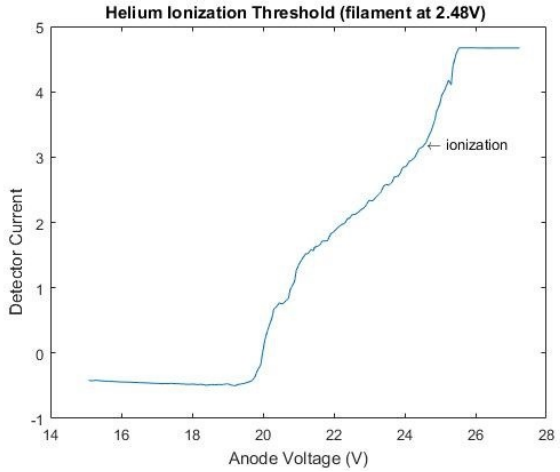

***Figure 7**: Helium Ionization Voltage Threshold*
Of note is the detector current along the ordinate is now positive. As voltage is increased a threshold is reached at 24.6 ± 0.16 V that corresponds with a large increase in detector current with little change in anode voltage. This indicates that every collision between accelerated electrons and helium atoms is causing an ionization of the impacted helium atom. The detector current begins it climb to this threshold before the true ionization potential is reached because the helium gas contained within the excitation tube has some already excited helium atoms. These atoms do not require the full 24.6 eV to release an electron, however after 24.6 eV even a helium atom in its ground state will become ionized.

This experiment does suffer from statistical as well as systemic errors. Chief among these are the resolution of our anode voltage. The LabVIEW program that was used to sweep from 0 to 30 V potential for the anode that accelerated the electrons through the impact area stepped up in increments of 80 mV. Also, the signal from the detector current has an error that can be approximated using a measurement of each minima's full width at half maximum value (FWHM). These values are summarized in Table 1 for helium and Table 2 for mercury.

Helium	FWHM (volts)	σ (volts)
1st excitation	0.3	0.13
2nd excitation	0.4	0.17
3rd excitation	0.5	0.21
4th excitation	0.1	0.04

Table 1:Helium FWHM with error calculations

Mercury	FWHM (volts)	σ (volts)
Excitation (1)	1.6	0.68
Excitation (2)	1.7	0.72
Excitation (3)	1.8	0.76
Excitation (4)	1.8	0.76

Table 2:Mercury FWHM with error calculations

There is also some statistical error due to the data used to generate the plots in the figures above being an average of four separate experimental runs. However, these will be ignored due to the gathered data's standard deviation being an order of magnitude lower than both the 80 mV voltage step and the error in resolution calculated in Table 1 and 2. The oven temperature reported for the vaporization of mercury as well as the filament voltage causing thermionic emission of electrons also has error, but this doesn't affect any direct calculations of ionization or excitation energies. By adding these errors in quadrature, we are able to present our experimental findings in Table 3 along with the propagated errors.

Mercury	
Excitation energy	4.9 ± 0.7 eV
Work Function	1.085 ± 0.08 eV
Helium	
1st Excitation	19.59 ± 0.15 eV
2nd Excitation	20.43 ± 0.19 eV
3rd Excitation	22.59 ± 0.22 eV
4th Excitation	23.89 ± 0.09 eV

Table 3: Experimental Results

In conclusion, our results were very close to accepted values. [3][4] This experiment, and in particular Figure 2, truly are the smoking for quantum energy resonance theory. There is no way to explain classically the behavior of the detected anode current. As my world begins to open to the quantum reality we live in I will look back at this experiment as a milestone in my growth as a student and researcher.

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