Boğaziçi University
Physics Department

Franck-Hertz Experiment

Experiment 2

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Contents

1 Abstract

In this experiment, we try to proof atoms have discrete energy state. We use Frank-Hertz tube which have gaseous mercury atoms. We increased voltage slightly at the same time kinetic energy of the sent electron increased and we measured obtained electrons' kinetic energy by measuring current. We saw absolute decrease in current at some voltage. Difference between this voltage, gave us the first excited state of the mercury atom. We take data in various Temperature and voltages. Then we calculate "weighted average" of "average ΔeV" from each graph.
In conclusion we measured first excited state of mercury atom as 4.94 eV with 0.04 eV of uncertainty and its χ^2 is equal to 1.

2 Introduction

The Frank-Hertz experiment was done by James Franck and Gustav Hertz in 1914, which demonstrated the existence of excited states in mercury atoms. It confirms the prediction of quantum theory that electrons occupy only discrete, quantized energy states. This experiment supports Bohr model of atom. Because of this great invention they have been awarded Nobel Prize in 1925.[1]

3 Theory

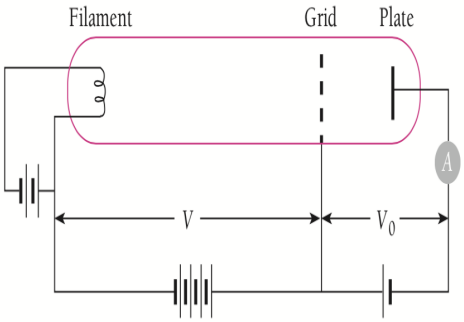

Figure 1: Sketch of Franck-Hertz Apparatus[2]

Franck and Hertz bombarded the vapors of various elements with electrons of known energy, using an apparatus like that shown in Figure 1. A small potential difference V_0 between the grid and collecting plate prevents electrons having energies less than a certain minimum from contributing to the current I through the ammeter. As the accelerating potential V is increased, more and more electrons arrive at the plate and I rises (Figure 2).

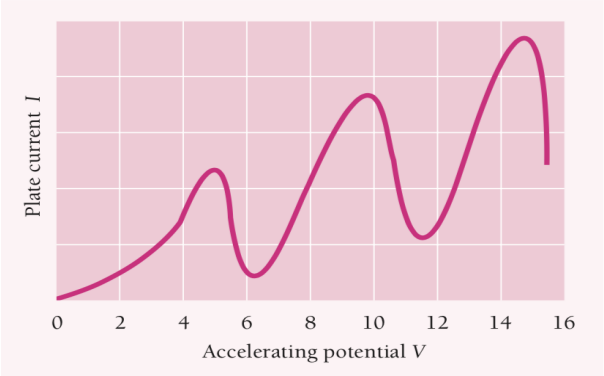

Figure 2: Results of the Franck-Hertz experiment.[2]

If it is an elastic collision when an electron collides with the mercury atoms in the vapor, the electron merely change direction. Because a mercury atom is much heavier than an electron, the electron loses almost no kinetic energy. After a certain critical energy is reached, the plate current drops instantly. This suggests that an electron colliding with the mercury atoms gives up some or all of its kinetic energy to excite the atom to an energy level above its ground state. The critical electron energy equals the energy between the first excited state to ground state.

Then, as the accelerating potential V is increased, the plate current increases same time, since the electrons now have enough energy left to reach the plate after undergoing an inelastic collision on the way. Eventually another sharp drop in plate current occurs, which arises from the excitation of the same energy level in other atoms by the electrons. As Figure 2 shows, a series of critical potentials for a given atomic vapor is obtained. Thus the higher potentials result from two or more inelastic collisions and are multiples of the lowest one.

To check that the critical potentials were due to atomic energy levels, Franck and Hertz observed the emission spectra of vapors during electron bombardment. They found that a minimum electron energy of 4.9 eV was required to excite the 253.6 nm spectral line of mercury and a photon of 253.6 nm light has an energy of just 4.9 eV. The Franck-Hertz experiments were performed shortly after Bohr announced his theory of the hydrogen atom, and they confirmed his basic ideas. [2]

4 Experiment

4.1 Apparatus

- Franck-Hertz Tube with in it Mercury
- Franck-Hertz Supply Unit with Digital Multimeter included
- Thermometer connected to Franck-Hertz Supply Unit
- Electric Oven
- Computer

4.2 Setup

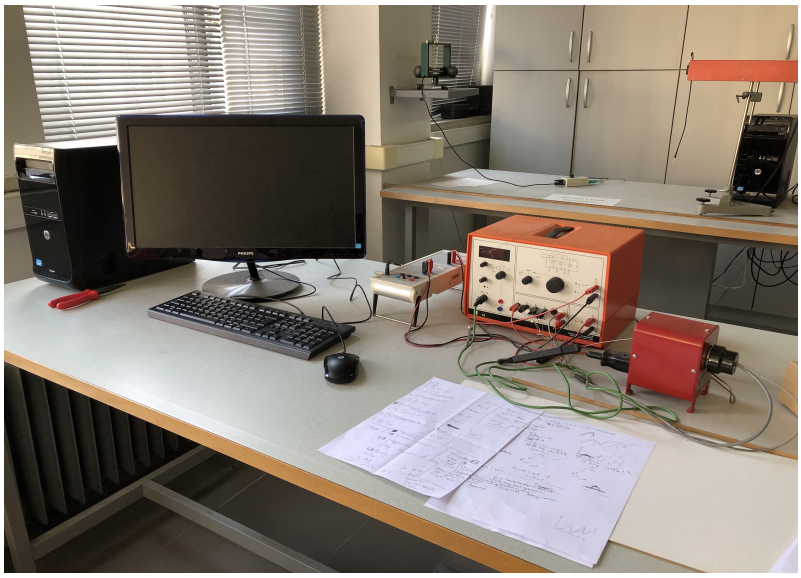

Figure 3: Experiment setup

4.3 Procedure[4]

1. Set U_1 and U_3 voltage
2. Set Temperature between 170 Celsius and 210 Celsius.
3. Wait until the LED's(Hg:...30V) colour turn green from orange. LED indicate tube is ready.
4. Set ready to data taking from computer. Then set U_1 voltage to the automatic mode.
5. Then, computer save all data.
6. Return 1^{st} step and repeat all step at least 10 times with different U_1 , U_3 voltage and, Temperature(°C)

5 Raw Data

5.1 Raw Data Tables

Temp (°C)	$U_1(V)$	$U_3(V)$
203	1.87±0.01	1.27±0.01
209	1.98±0.01	1.15±0.01
202	2.00±0.01	1.24±0.01
175±1	2.04±0.01	2.11±0.01
183	2.06±0.01	1.85±0.01
188	2.06±0.01	1.85±0.01
194±1	2.07±0.01	1.33±0.01
191±1	2.12±0.01	1.76±0.01
190±1	2.13±0.01	2.86±0.01
194±1	2.17±0.01	2.86±0.01
179±1	2.17±0.01	2.87±0.01
200±1	2.17±0.01	2.87±0.01
190±1	2.22±0.01	1.33±0.01

Table 1: Temperature (°C) U_1 and U_3 values

5.2 Raw Data Plots

In each graph, We don't consider data from the noisy parts and when the current reach saturation region.

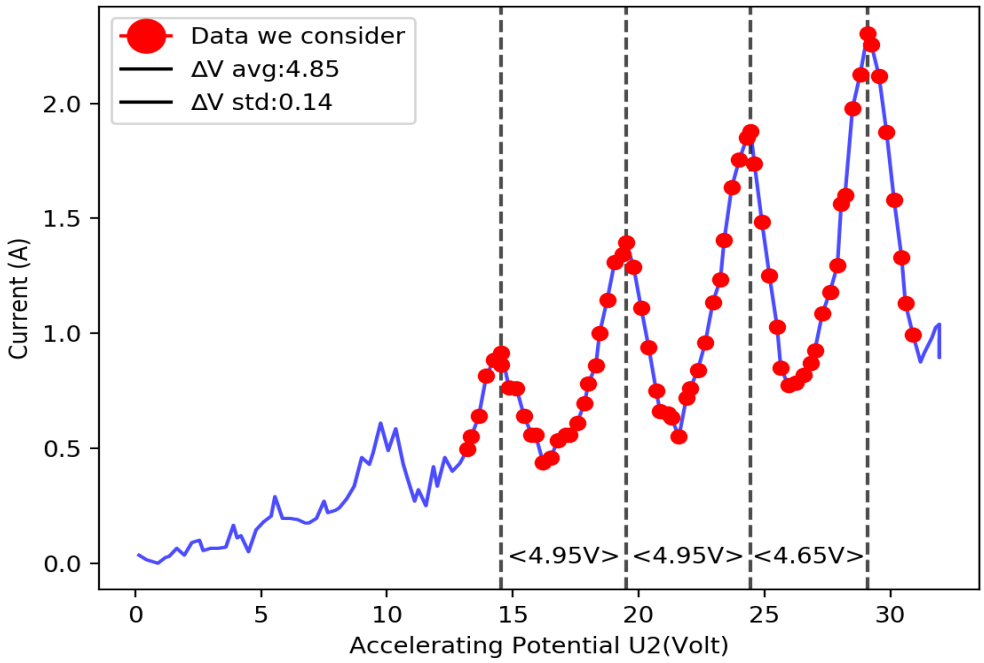

Figure 4: $U_1 = 1.87 \pm 0.01V$, $U_3 = 1.27 \pm 0.01V$, T=203°C

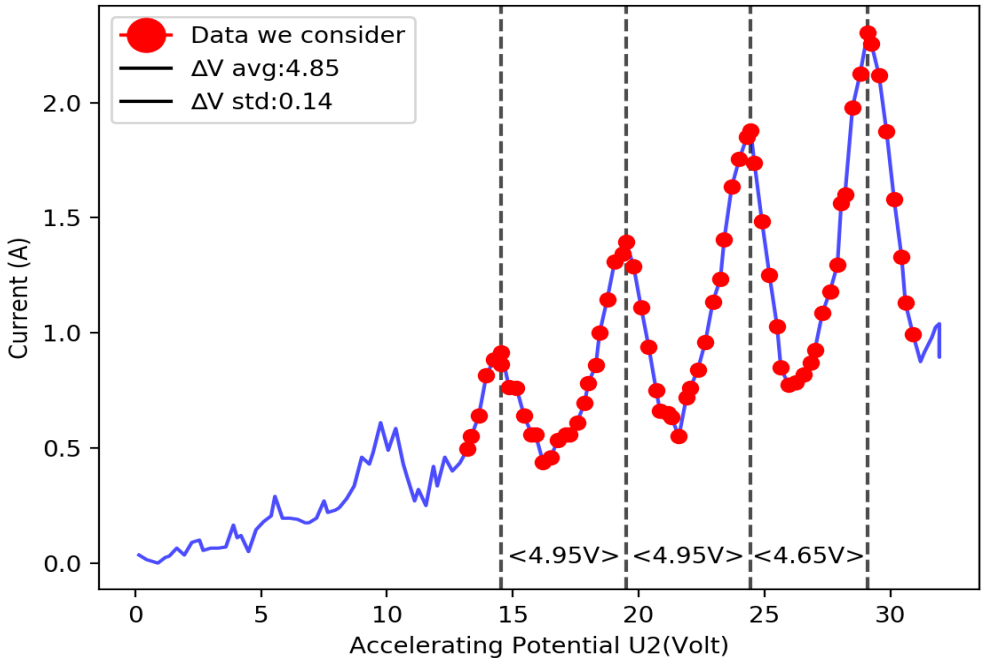

Figure 5: $U_1 = 1.98 \pm 0.01V$, $U_3 = 1.15 \pm 0.01V$, T=209°C

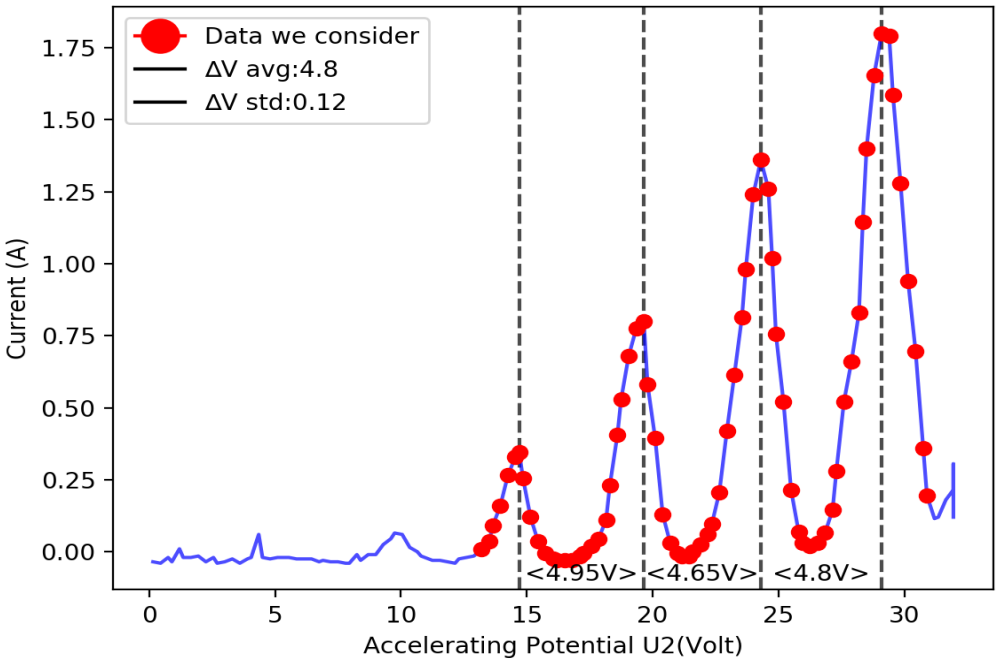

Figure 6: $U_1 = 2.00 \pm 0.01V$, $U_3 = 1.24 \pm 0.01V$, T=202°C

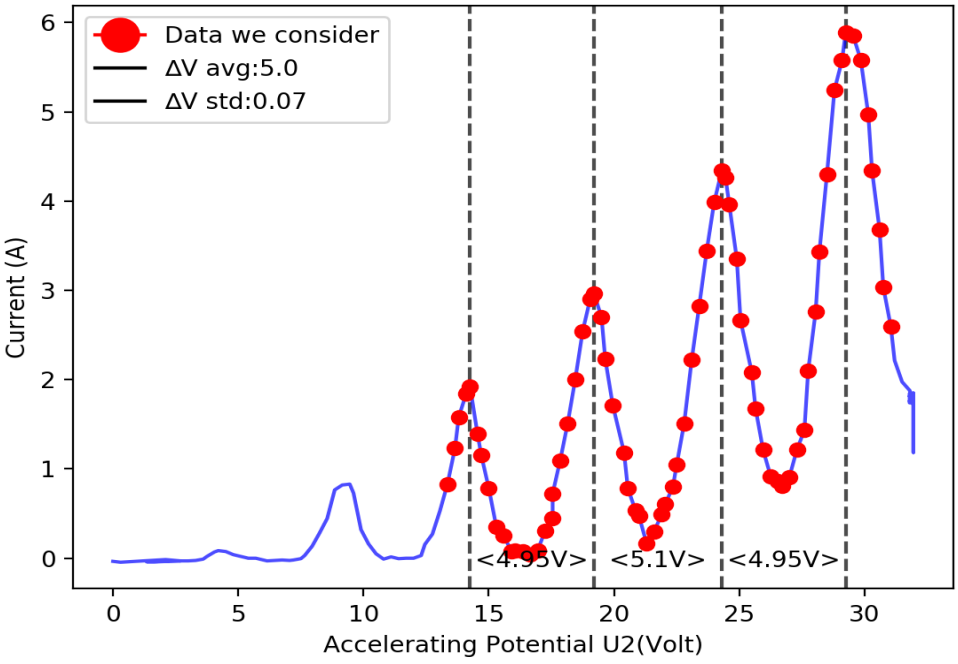

Figure 7: $U_1 = 2.04 \pm 0.01V$, $U_3 = 2.11 \pm 0.01V$, T=175±1°C

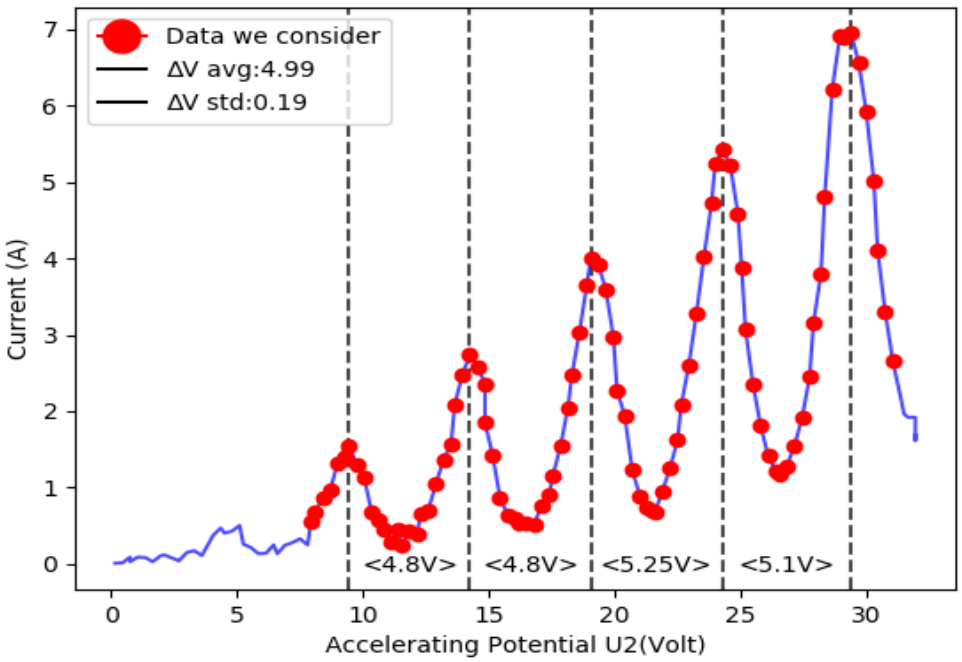

Figure 8: $U_1 = 2.06 \pm 0.01V$, $U_3 = 1.85 \pm 0.01V$, T=183°C

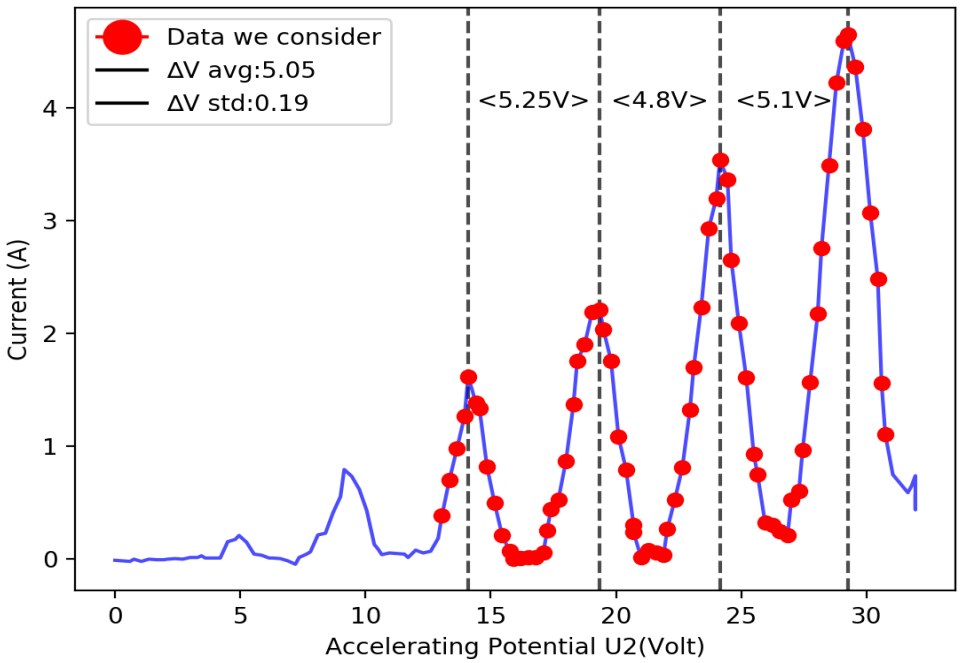

Figure 9: $U_1 = 2.06 \pm 0.01V$, $U_3 = 1.85 \pm 0.01V$, T=188°C

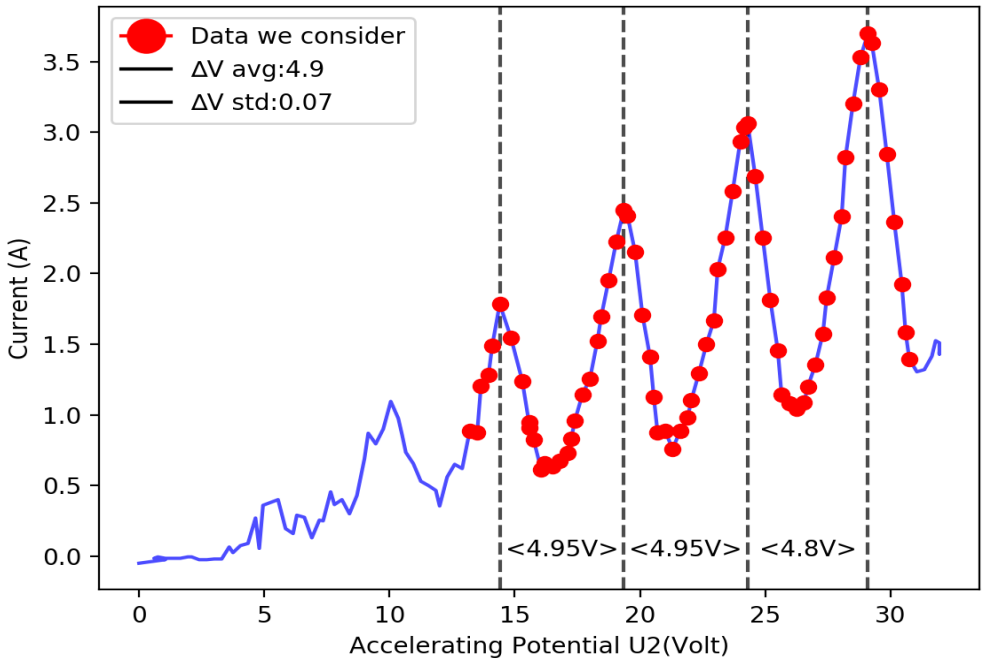

Figure 10: $U_1 = 2.0 \pm 0.01V$,7 $U_3 = 1.33 \pm 0.01V$, T=194±1°C

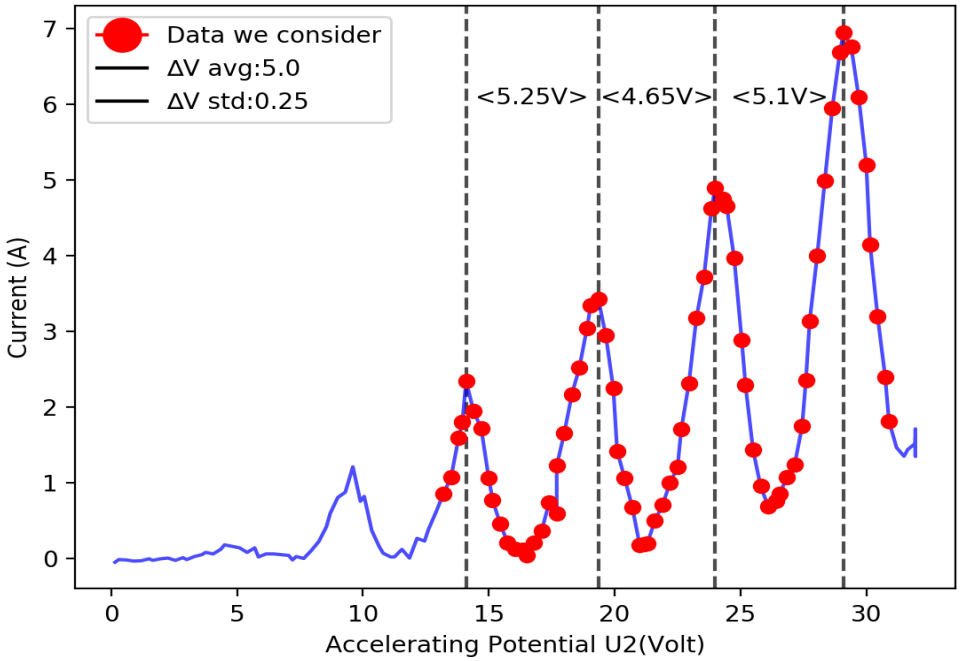

Figure 11: $U_1 = 2.12 \pm 0.01V$, $U_3 = 1.76 \pm 0.01V$, T=191±1°C

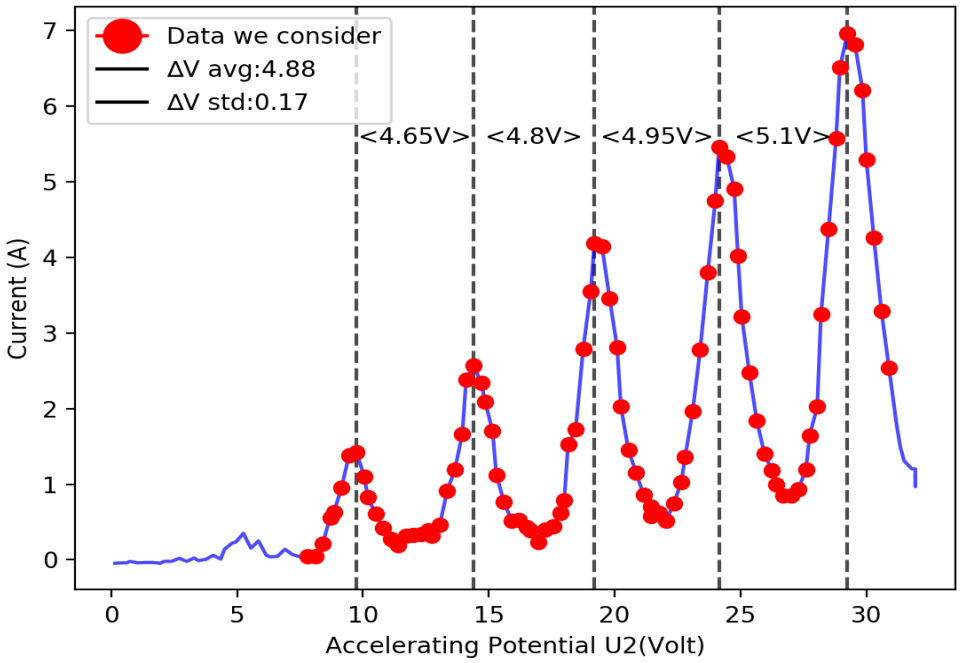

Figure 12: $U_1 = 2.13 \pm 0.01V$, $U_3 = 2.86 \pm 0.01V$, T=190±1°C

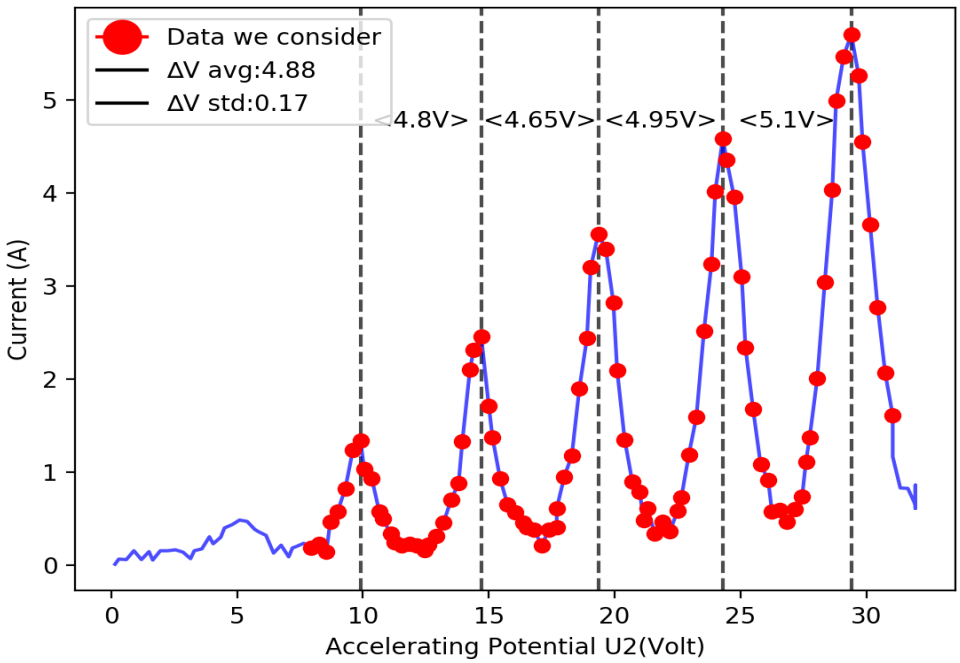

Figure 13: $U_1 = 2.17 \pm 0.01V$, $U_3 = 2.86 \pm 0.01V$, T=194±1°C

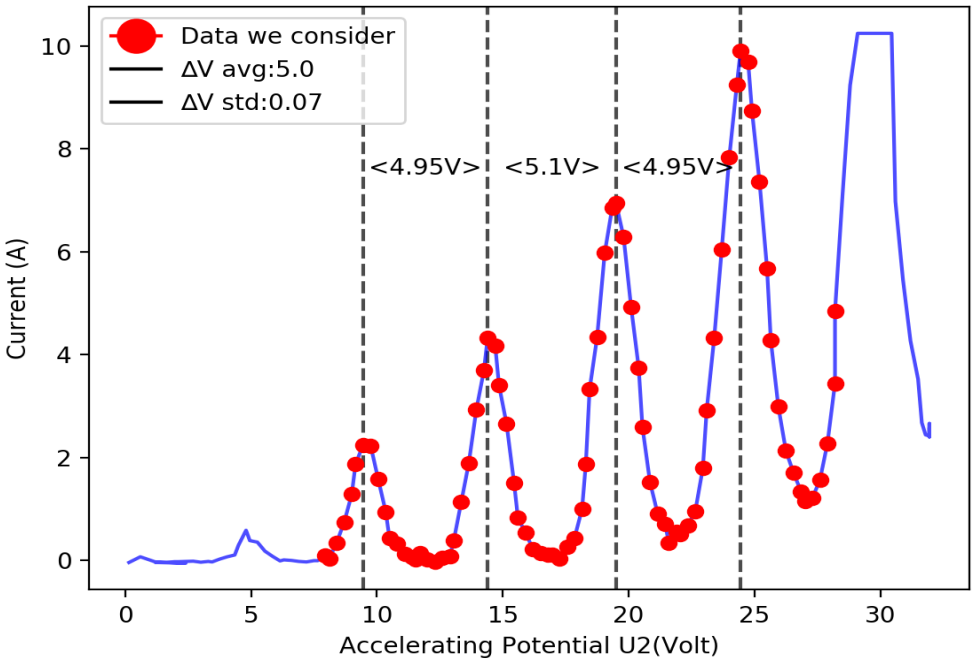

Figure 14: $U_1 = 2.17 \pm 0.01V$, $U_3 = 2.87 \pm 0.01V$, T=179±1°C

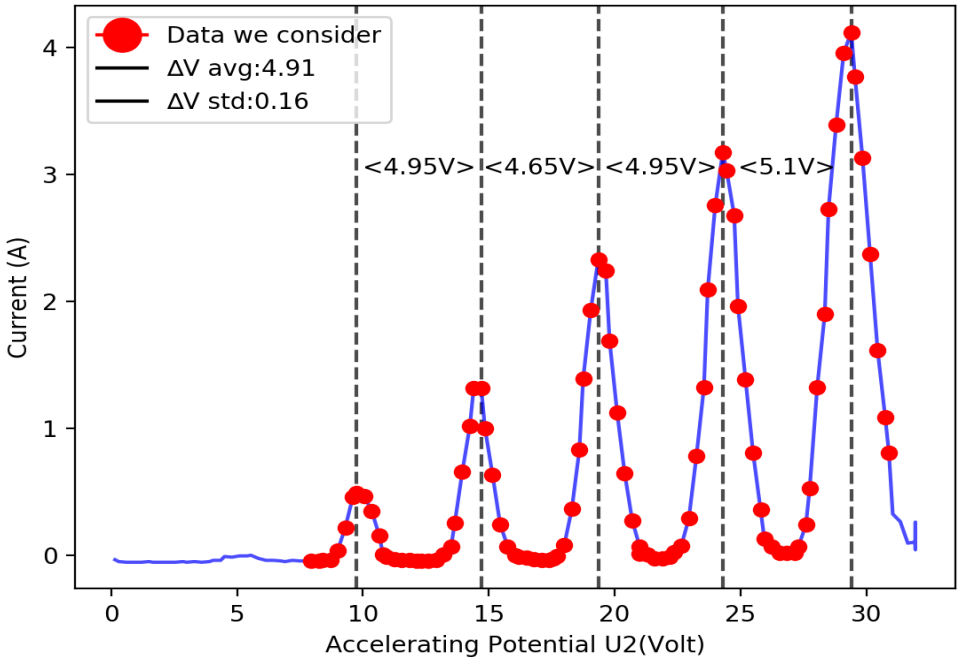

Figure 15: $U_1 = 2.17 \pm 0.01V$, $U_3 = 2.87 \pm 0.01V$, T=200±1°C

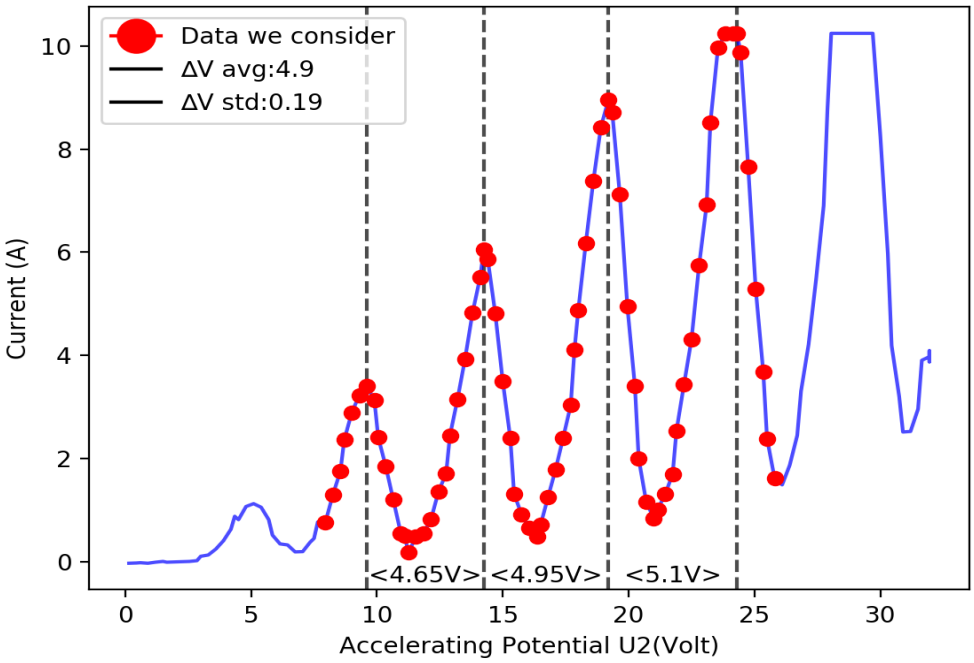

Figure 16: $U_1 = 2.22 \pm 0.01V$, $U_3 = 1.33 \pm 0.01V$, T=190±1 °C

6 Data Analysis

$$\Delta V_{Mean} = \frac{1}{N}\sum_{i=1}^{n} \Delta V_i \tag{1}$$

$$\sigma = \sqrt{\frac{1}{N-1}\sum_{i=1}^{n} (\Delta V_i - \Delta V_{Mean})^2} \tag{2}$$

- The reason of why we divide N-1 instead of N in equation 2; these are not our concluded mean value and we have a small sample. This is called Bessel's Correction[3].

Temp (°C)	$U_1(V)$	$U_3(V)$	ΔV_{mean}	$\sigma_{\Delta V_{mean}}$
203	1.87±0.01	1.27±0.1	4.85	0.14
209	1.98±0.01	1.15±0.01	4.85	0.14
202	2.00±0.01	1.24±0.01	4.8	0.12
175±1	2.04±0.01	2.11±0.01	5.0	0.07
183	2.06±0.01	1.85±0.01	4.99	0.19
188	2.06±0.01	1.85±0.01	5.05	0.19
194±1	2.07±0.01	1.33±0.01	4.9	0.07
191±1	2.12±0.01	1.76±0.01	5.0	0.25
190±1	2.13±0.01	2.86±0.01	4.88	0.17
194±1	2.17±0.01	2.86±0.01	4.88	0.17
179±1	2.17±0.01	2.87±0.01	5.0	0.07
200±1	2.17±0.01	2.87±0.01	4.91	0.16
190±1	2.22±0.01	1.33±0.01	4.9	0.19

Table 2: ΔV_{mean} and $\sigma_{\Delta V_{mean}}$ calculated with respect to equation 1 and 2

Note :Computer took 150 data between $\Delta 30$ Volt. Roughly, It take data per 0.2 voltage. If it takes data exactly per 0.2 voltage, we will have 0.1 voltage uncertainty in every maxima point of U_2 versus current graph. However, it is not take data exactly per 0,2 voltage, take it randomly. Before calculate uncertainty of maxima point, first we will have to calculate uncertainty of U_2 gap. Since all of the calculation is very hard, we didn't consider this situation.

- Weighted average calculation is more proper for this case. By this way, we consider value with small σ_i's more then high σ_i's.

$$Weighted\ Average = \frac{\sum_{i=1}^{N} \left(\frac{\Delta Vi}{\sigma_i}\right)^2}{\sum_{i=1}^{N} \left(\frac{1}{\sigma_i}\right)^2} \tag{3}$$

$$\sigma_{WA} = \sqrt{\frac{1}{N^2} \cdot \sum_{i=1}^{N} (\sigma_i)^2} \tag{4}$$

- Weighted average and its uncertainty calculations are made with Python code. And here is the results;

$$\begin{gathered} \text{Weighted Average} = 4.94\text{V} \\ \text{Uncertainty} = 0.04\text{V} \\ \Delta V_{Measured} = 4.94V \pm 0.04V \\ \Delta eV_{Measured} = 4.94eV \pm 0.04eV \end{gathered} \tag{5}$$

7 Conclusion

- In this experiment we saw that collisions between electrons and mercury is elastic up to a certain point, they make a inelastic collision where mercury atom excites from ground state to first excited state. So, atoms have discrete energy state. We measured first excited state of mercury atom as 4.94 eV with 0.04 eV of uncertainty.
- We observe that changing the U_1 , U_t and Temperature doesn't effect the ΔV of local maxima points. They effect position of maxima, shape of the graph.
- Since The Theoretical Value of first excited state of mercury; $\Delta eV_{Theoretical} = 4.9$ eV[2]. This is the χ^2 of our measurement of ΔeV

$$\chi^2 = \left(\frac{4,94eV - 4,9eV}{0.04eV}\right)^2 = 1 \tag{6}$$

- $\chi^2 = 1$; say us, this is acceptable measurement. we are exactly one σ away from the accepted theoretical value. However, it is not mean that we done this experiment perfectly. We would have decreased uncertainty and tried to make stable χ^2 or decreased it. To make χ^2 stable, we should have also increased our accuracy.

- If the mercury does not vaporize perfectly, electrons could not coincide with mercury atoms. Then, many electron reach to the opposite side without losing its kinetic energy. Then we don't see obvious local maxima and this maxima can be shift to the right in some point in U_2 versus current graph. So, difference between maxima points will be less or more than the theoretical value. Since our tube is in the oven and we could not check mercury is vaporize or not, we might take wrong data because of this reason.
- U_2 is increased automatically by Franck-Hertz Supply Unit. And it has some fluctuation. Also computer took 150 data between Δ30 Volt. Roughly, it take data per 0,2 voltage. Since we don't fit the graph. We could not take take exactly true maxima point. This situation have a small effect on accuracy. Because, serial ΔeV values have negative correlation in their sigma. Then, their average doesn't change so much(just first and the last maxima point has effect). But the standard deviation of Δ eV for each graph increase. In conclusion, If we fit the graphs, then our uncertainty decrease considerable.

References

[1] The Franck-Hertz Experiment
http : //hyperphysics.phy − astr.gsu.edu/hbase/FrHz.html

[2] Arthur Beiser - Concepts of Modern Physics (2003, McGraw Hill)

[3] Bessel's Correction: Why Use N-1 For Variance/Standard Deviation?
https : //www.statisticshowto.datasciencecentral.com/bessels − correction/

[4] Advanced Physics Experiments, Erhan Gulmez, Bogazici University Publications, 1999,ISBN 975-518-129-6

[5] Constants
https : //physics.nist.gov/cuu/Constants/

Appendices

```
import numpy as np
import matplotlib.pyplot as plt
import matplotlib.lines as mlines
from scipy.signal import argrelextrema
from numpy import *
import pylab
import pandas

colnames = ['A1', 'B1','C1','D1']
data = pandas.read_excel("u1-1.87 u3-1.27 T203.xlsx", names=colnames)
icc = data.A1.tolist()
vcc = data.B1.tolist()
i=np.array(icc)
v=np.array(vcc)
ir=i[50:120] # arrange where we get th data
vr=v[50:120]
```

```
a=argrelextrema(ir, np.greater)[0]

t=0
delta=[]
pp=[]
for k in range(len(a)-1):
    t=vr[a[k+1]]-vr[a[k]]
    if t>4:      #to not consider, dummy local maxima because of noise
        delta.append((vr[a[k+1]]-vr[a[k]]))
        pp.append(vr[a[k]])
        pp.append(vr[a[k+1]])

pp=list(dict.fromkeys(pp))
for h in range(len(pp)):
    plt.axvline(x=pp[h],ls = "--", color='black', alpha=0.7)
for p in range(len(delta)):
    xx=(pp[p+1]+pp[p])/2
    plt.text(xx,-0.1, '<'+str(round(delta[p],2))+'V>',h
        orizontalalignment='center')



data = mlines.Line2D([], [], color='red', marker='o',markersize=15,
    label='Data we consider')
data2 = mlines.Line2D([], [], color='black', marker=',',markersize=15,
    label= ' V   avg:'+str(round(np.mean(delta),2)))
data3 = mlines.Line2D([], [], color='black', marker=',',markersize=15,
    label= ' V   std:'+str(round(np.std(delta),2)))
plt.legend(handles=[data,data2,data3])
plt.xlabel('Accelerating Potential U2(Volt)')
plt.ylabel('Current (A)')
plt.plot(v,i,'b-', alpha=0.7)
plt.plot(vr,ir,'ro')
plt.show()
print('avg',round(np.mean(delta),2))
print('std',round(np.std(delta),2))

########OUTPUT#########

########GRAPH#########
avg 4.85
std 0.14

####### Weighted average and its uncertainty calculation ########

avg=[4.85,4.85,4.8,5.0,4.99,5.05,4.9,5.0,4.88,4.88,5.0,4.91,4.9]
std=[0.14,0.14,0.12,0.07,0.19,0.19,0.07,0.25,0.17,0.17,0.07,0.16,0.19]

def WA(m,s): #algorithm of Weighted average
    wau=0
    wad=0
    for i in range(len(m)):
```

```
        wau+= m[i]/(s[i]**2)
    for h in range(len(m)):
        wad+= 1/(s[h]**2)
    return wau/wad


def WAS(s): #algorithm of uncertainty of wighted average
    was=0
    for i in range(len(s)):
        was+= (s[i]**2)
    return np.sqrt(was/(len(s)**2))

print('weighted average:',round(WA(avg,std),2))
print('uncertainty:',round(WAS(std),2))
```

OUTPUT

```
weighted average: 4.94
uncertainty: 0.04
```