Laboratory 4: The Franck-Hertz Experiment for Mercury and Neon

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CONTENTS

1 Abstract

In this experiment, using Franck-Hertz graphs, the excitation energies of Mercury and Neon were determined. We found that the excitation energy of mercury to be $E_{Hg} = (5 \pm 0.0063246)\, eV$, and the excitation energy of neon to be $E_{Ne} = 17.85eV \pm 0.008165eV$. This lead to the conclusion that there are discrete energy levels in atoms since the ΔU_2 between the maxima in the Franck-Hertz graphs is relatively constant. For the mercury experiment we also found that the contact potential between the cathode and the grid G2 is $ContactPotential = (1.98 \pm 0.01552)\, V$ and the mean free path of electrons in mercury vapour is $40.698\mu m$. In the neon experiment a correlation can be found between the appearance of the luminance bands and the Franck-Hertz curve, specifically the minima on the curve. Using this fact it can be predicted that the forth luminance band will appear at 82.15 V $\pm$ 0.1003 V. Overall the experiment was a success allowing us to gain a deeper understanding of the structure of the atom.

2 Introduction

The aim of the first part of the experiment involving Mercury is to record a Franck-Hertz curve and use it to estimate the first excitation potential of mercury. In the second part of the experiment involving neon, the aim is to again record a Frank-Hertz diagram except this time for neon. We also aim to calculate the first excitation energy of neon, to identify which energy levels contribute to its Franck-Hertz curve and to investigate the relationship of the luminance bands in the neon tube to the characteristic Franck-Hertz curve of neon.

3 Theory

3.1 The Franck-Hertz Experiment

The Franck-Hertz experiment was first performed in 1914 by James Franck and Gustav Hertz. It was the first experimental verification of the existence of discrete energy states in atoms. Later in the same year Neils Bohr recognised this as evidence confirming the *Bohr Model* of the atom. The two physicists, Franck and Hertz, reported an energy loss in distinct steps for electrons passing through mercury vapour, and a corresponding emission at the ultraviolet line ($\lambda = 254nm$) of mercury.

At this critical energy level, the gas atoms began absorbing energy from the electrons. This absorption only occurred when the electron energy reached a specific threshold, indicating a sudden and abrupt transition of atomic electrons within the gas atoms to discrete higher energy levels. Below this critical energy threshold, no energy transition or absorption occurred, suggesting a distinct threshold for energy transfer within the gas atoms.

The collision dynamics between the electrons and the atomic electrons were crucial to this observation. Electrons with exactly the critical energy level lost all their energy in collisions with atomic electrons. As a result, the atomic electrons were promoted to higher energy states,

effectively storing the absorbed energy within the gas atoms.

This proved to be an all-important experiment in the world of physics to help deduce the structure of the atom.

3.2 Energy levels

The Bohr Model of the atom suggests that there are energy levels with discrete energy values of electrons. These energy levels are broken down into sublevels and orbitals. The sublevels have set number of electrons they can contain; for example the s-sublevel can contain up to 2 electrons, the p-sublevel can contain up to 6 electrons.The sublevels contain orbitals. Orbitals are spaces that have a high probability of containing an electron. In other words, an orbital is an area where the electrons live. There can be two electrons in one orbital maximum. The s sublevel has just one orbital, so can contain up to 2 electrons. The p sublevel has 3 orbitals, so can contain up to 6 electrons.

When an atom is in it's ground state the atom it at it's lowest energy state and it's most stable arrangement. However if the atom is given energy, by heating it perhaps, the electrons can jump up to a higher excited energy level and, as seen in figure 3.1, the electrons release energy when they are falling back down to the ground state.

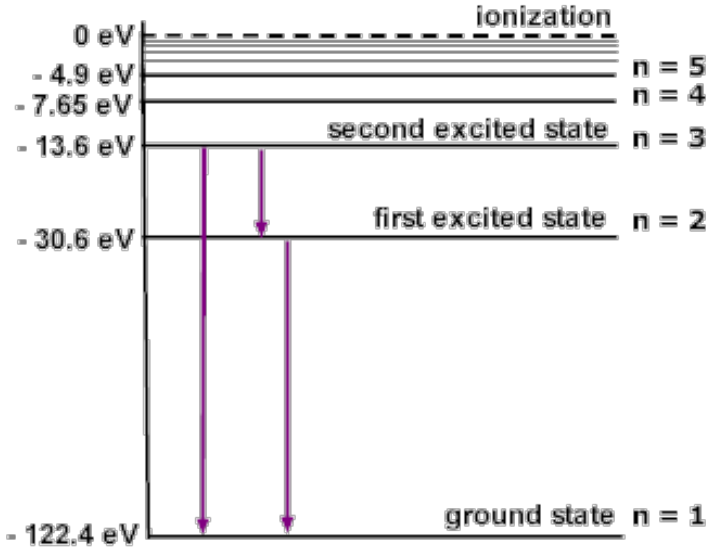

Figure 3.1: Ground state to excited states in the energy levels of atoms [1]

3.3 Franck-Hertz Curve

In this experiment by fixing the breaking voltage U_3 and the driving potential U_1, and varying the acceleration voltage U_2 and noting the collector current I_A; a graph similar to figure 3.2

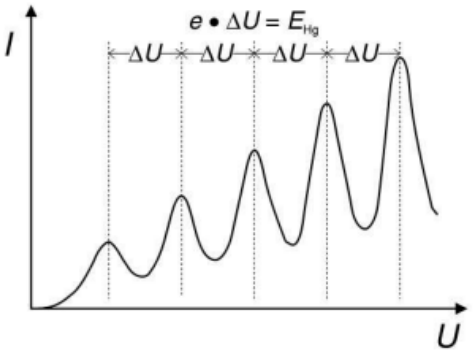

Figure 3.2: Classic example of a Franck-Hertz curve for mercury [2]

can be obtained. Using this I-V plot the value for ΔU_2 can be obtained by taking the values of U_2 from the centre of the peak. ΔU_2 is the excitation potential of mercury in this case and tells us a lot about structure of the atom.

4 Experimental Setup [2]

Ensure the Frank-Hertz supply unit is switched off. Use the 4mm safety sockets on the rear of the supple unit to connect the heating oven. Connect the copper lead of the copper sleeve in the heater to the green-yellow socket on the rear of the supply unit to screen the Franck-Hertz tube from the interference. Insert the DIN plugs of the temperature sensor and of the Franck-Hertz tube in to their sockets on the supply unit.
Before switching on the supply unit ensure the $U_1, U_2 and U_3$ dials are turned to zero. If a voltage is passed across the grids before the valve is heated fully, any remaining liquid mercury could short across the grids, damaging the valve.
Switch the operating mode to "MAN" and switch on the supply unit. The default setting is $\theta_s = 175°C$ and will take approximately 15 minutes to heat up.

Oscilloscope: Connect the sockets $U_1/10$ to channel 1 and output sockets U_A to channel 2 of the oscilloscope. Switch the oscilloscope to XY mode and move the graph around on the oscilloscope until the curve is displayed completely. It may help to switch the operating mode to "Auto" and use the "Persist" option to retain the trace.

4.1 Optimising the Driving and Breaking Potentials

We are using the Trinity Physics lab-book's method in figure 4.1 and 4.2 of optimising the potentials.

1) Optimising U_1: A higher driving potential U_1 results in a larger electron emission current.

- If the Franck-Hertz curve rises too steeply, i.e the current saturates for U_2< 30 V, (see fig. 3b): Reduce U_1 until it looks like fig. 3d.
- If the Franck-Hertz curve is too flat i.e. the collector current I_A remains below 5 nA in all areas (fig. 3c): Increase U_1 (max. 4.8 V) until the curve steepness corresponds to that shown in fig. 3d.

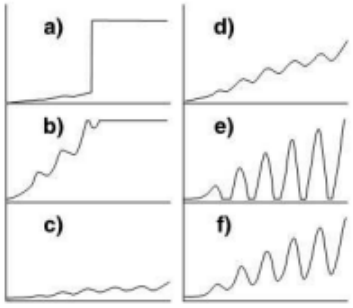

Fig. 3. Overview for optimizing the Franck-Hertz curves by selecting the correct parameters U_1 and U_3

Figure 4.1: Calibrating U_1 and U_2 [2]

- If the Franck-Hertz curve is flat even after increasing U_1: Inform a demonstrator, who can reduce the set value θ_s for the oven temperature using the screwdriver-operated potentiometer.

2) Optimising U_3: A greater braking voltage U_3 causes better defined maxima and minima of the Franck-Hertz curve; at the same time, however, the total collector current is reduced.

- If the maxima and minima of the Franck-Hertz curve are insufficiently defined (fig 3d): Alternately increase first the braking voltage U_3 (maximum 4.5 V) and then the driving potential U_1 until you obtain the curve form shown in fig. 3f.
- If the minima of the Franck-Hertz curve are cut off at the bottom (fig. 3e): Alternately reduce first the braking voltage U_3 (maximum 4.5 V) and then the driving potential U_1 until you obtain the curve form shown in fig. 3f.

Figure 4.2: Calibrating U_1 and U_2 [2]

4.2 MERCURY [2]

Switch the mode to MAN, and use the Franck-Hertz supply to measure U_2 and I_A. Or a multimeter in voltage mode can measure U_2 and I_A from the voltage outputs.

4.3 NEON [2]

Ensure the Franck-Hertz supply unit is switched off and the $U_1, U_2, and U_3$ dials are turned to zero. Using the grey DIN plug connect the neon Franck-Hertz experiment box to the supply unit. Turn the operating mode to MAN and switch to supply unit.
Since the light emitted from the neon filled tubes is within the visible range between red and green, the luminance bands can be seen by the naked eye. The luminance bands that appear between grids are as such in figure 4.3.

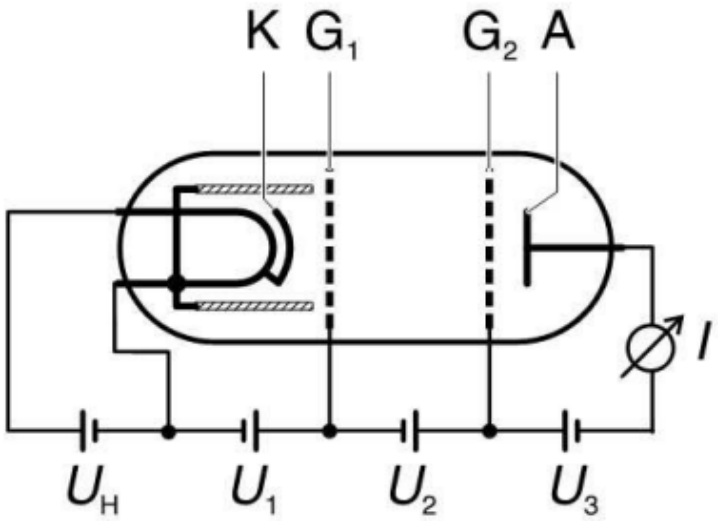

Figure 4.3: Luminance bands that appear between grids G_1 and G_2 [2]

5 METHODOLOGY

5.1 MERCURY

Follow the experimental setup in section 4.2. Slowly increase the acceleration voltage U_2 from 0-30V. Increase in fixed intervals however around the peaks take more points for accuracy. At each interval note the current produced I_A.
Use the data to then plot an I-V curve, and then estimate the first excitation potential of mercury. Where the kinetic energy of the electrons at grid G_2 is $U_1 + U_2$. An estimate of the contact potential can be obtained by subtracting the value from ΔU_2 from the value for the kinetic energy for the first maximum. An estimate for the mean free path of an electron in mercury vapour can be obtained for a temperature of $160°C$ and a vapour pressure of 11.28 mmHg. Mean free path of an electron:

$$\lambda = \frac{k_B T}{\sqrt{2}\pi d^2 P} \tag{5.1}$$

Where k_B is Boltzmann's constant, T is the temperature in Kelvin, d is the diameter of the mercury molecules and P is the pressure.

1. U_2 V	2. U_2 V	ΔU_2 V	$\delta\Delta U_2$ V	Average	
4.6	9	4.4	0.01414	ΔU_2 V	$\delta\Delta U_2$ V
9	14.1	5.1	0.01414	5	0.0063246
14.1	19.2	5.1	0.01414		
19.2	24.1	4.9	0.01414		
24.1	29.6	5.5	0.01414		

5.2 Neon

Follow the experimental setup in section 4.3. Set U_1 to 1.53V and U_3 to 10.25V. Slowly increase the accelerating voltage U_2 from 0-80V noting the collector current in each case, and ensure to take more data points around each peak for accuracy. The first maximum should appear around 15V.
For increasing acceleration voltages luminance bands will appear. Record the voltage required to see 1,2 and 3 bands. For accuracy ensure to minimise external light so that the bands can be seen more accurately.
Plot an I-V curve for neon. When obtaining a value for ΔU_2 take the values of U_2 from the centre of the peak instead of the maximum. To extract essential information about the structure of the atom we must analyse which energy levels the neon atoms are excited to; the 3p-sublevels $(18.4 - 19.0eV)$ or the 3s-sublevels $(16.6 - 16.9eV)$. The number of luminance bands are then tabulated along with the required acceleration voltage U_2. And this is then related to the Franck-Hertz curve for neon.

6 Results and Discussions

6.1 Mercury

U_1 and U_3 were kept constant at 2.38 V and 1.51 V respectively. U_2 is then varied to obtain values of I for the following plot.

The expected first excitation potential of mercury was 4.7V however due to contact potential difference between the cathode K and the grid G2 the first maximum was expected to be at a slightly higher voltage. However this is not the case here. From the plot the first maximum is at approximately 4.6V $\pm$ 0.1V. This error may be due to inaccuracy when taking measurements. If the experiment were to be repeated we would take more points around the maximum for accuracy.
From figure 6.1 we can calculate ΔU_2 by subtracting each maximum by the maximum before it and take an average. Equation 8.1 is used for the error in ΔU_2. Our final value is $\Delta U_2 = 5 \pm 0.0063246$. ie. $E_{Hg} = (5 \pm 0.0063246)\, eV$.
To estimate the contact potential we can subtract ΔU_2 from $U_1 + U_2$.

$$(2.38 + 4.6 - 5)\, V \pm \left(\sqrt{(0.01)^2 + (0.01)^2 + (0.0063246)^2} \right) V$$

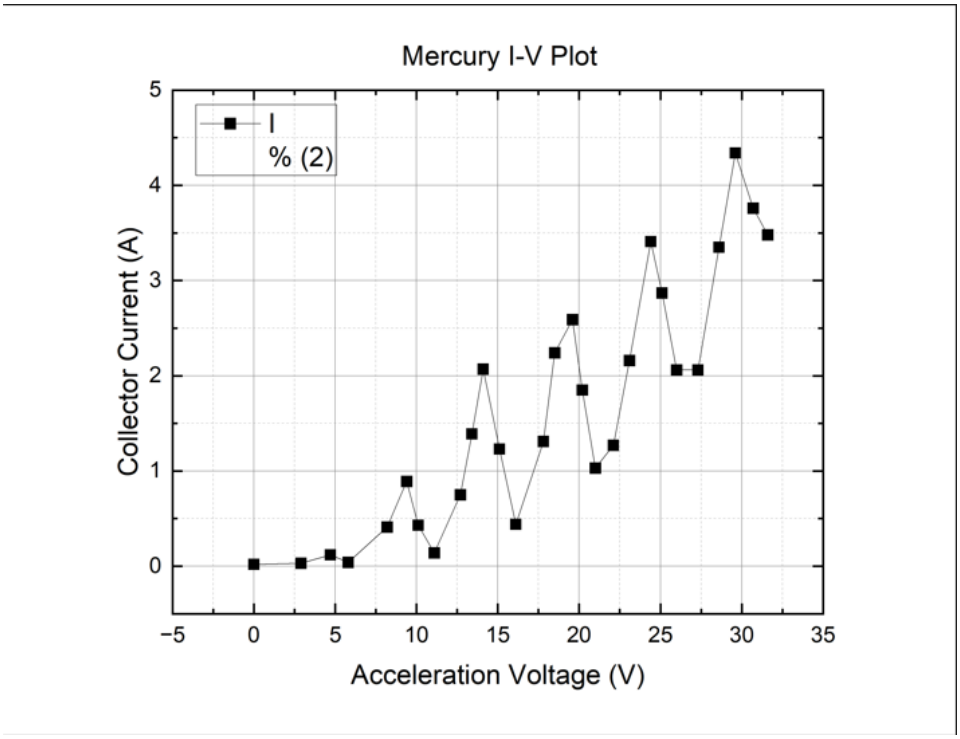

Figure 6.1: Franck-Hertz Curve for Mercury

$$Contact Potential = (1.98 \pm 0.01552)\, V$$

Using the equation 5.1 we can estimate the mean free path of an electron in mercury vapour, when T = 160°C (443.15K), P = 11.28 mmHg (1503.8765Pa) and d = 150 pm.

$$\lambda_{Hg} = 40.698 \mu m$$

An excited mercury atom may lose it's energy due to photon emission but also due to collisions with other atoms or molecules, if the mean free path of electrons in mercury vapor is relatively short compared to the characteristic decay times associated with radiative processes (such as fluorescence or phosphorescence), collisional processes are likely to dominate the de-excitation of excited mercury atoms.

6.2 NEON

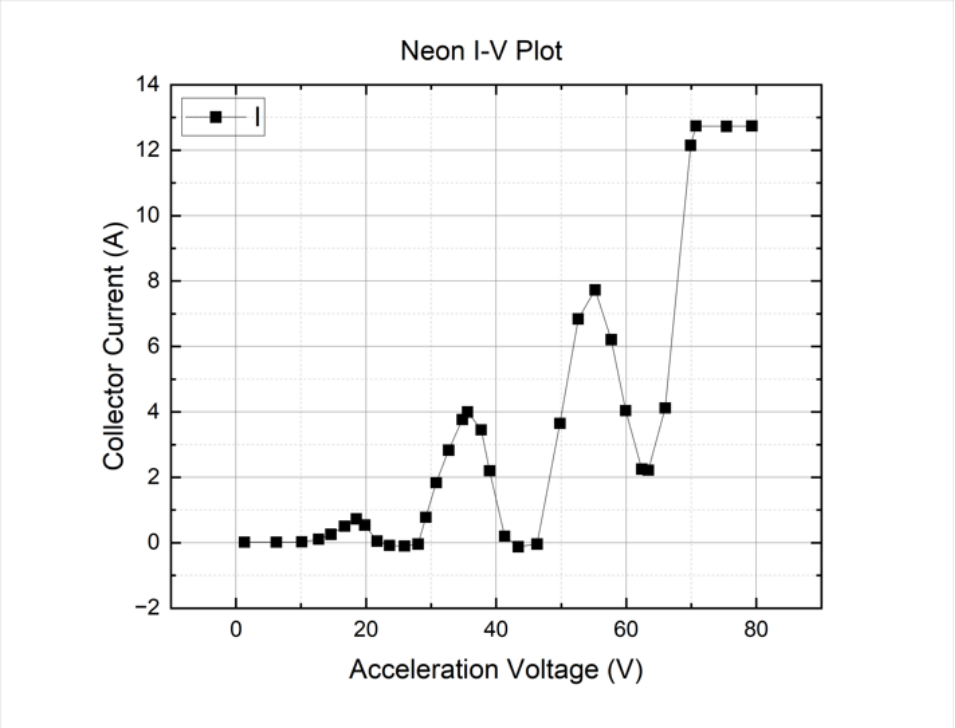

Figure 6.2: Franck-Hertz Curve for Neon

When determining ΔU_2 it was ensured to take the difference in U2 from the centres of the maximums rather than the peaks.

With $\Delta U_2 = 17.85 \pm 0.008165V$ we can conclude that $E_{Ne} = 17.85eV \pm 0.008165eV$. In

1. U_2 V	2. U_2 V	ΔU_2 V	$\delta\Delta U_2$ V	Average	
				ΔU_2 V	$\delta\Delta U_2$ V
16.85	34.9	18.05	0.01414		
34.9	54.85	19.95	0.01414	17.85	0.0081650
54.85	70.4	15.55	0.01414		

regards to which energy levels the neon atoms are being excited to it is hard to draw a precise conclusion. However it can be seen for the final ΔU_2 is a slight outlier. Could this be due to electron transitions between both the 3s and 3p levels? It may possibly be due to the subjectivity of determining when the bands are at their brightest. However the average ΔU_2 is closest to the energy of the 3p-levels $(18.4 - 19.0)\, eV$ so this excitation is more probable.
Below in figure is the tabulated data for the number of luminance bands and the required acceleration voltage.

In an attempt to correlate this data with our Franck-Hertz curve we can compare the data with figure 6.2. The first band appears at 36.5 V, which correlates to our second maximum on our Franck-Hertz curve. The second band appears at 46 V which oddly enough correlates with

Bands (sharpest)	U_2
1	36.5
2	46
3	64.3

the minumum straight after our second maximum where the first band appears. Our final band appears at 64.3 V which also correlates with a minumum on our plot, the next minimum following where the second band appeared.
From this I believe there is some experimental error with the first band. I believe that the bands correlate to minimums on the plot, where the electrons are coming down from the excited state, emitting energy in the form of light. If this deduction is correct, another luminance band should appear at 82.15 V $\pm$ 0.1003 V. This value is obtained by adding ΔU_2 to 64.3 V.

7 Conclusions

In this experiment we set out to gain a deeper understanding of the structure of the atom, in particular energy levels. In the first part we found that the first excitation energy of mercury to be $E_{Hg} = (5 \pm 0.0063246)\, eV$ which is agrees with the accepted value 4.9eV within experimental error. The contact potential between the cathode and the grid G2 was found to be $Contact Potential = (1.98 \pm 0.01552)\, V$. The mean free path of electrons in mercury vapour was determined to be $40.698 \mu m$ and also concluded that an excited mercury atom may lose it's energy due to photon emission but also due to collisions with other atoms or molecules.
In the second part of the experiment we used the same method to investigate the neon atom. It was found that the first excitation potential of neon is $E_{Ne} = 17.85eV \pm 0.008165eV$. Conclusions could also be made about the sublevel transitions in the excitation of a neon atom. The exitation that is more probable is excitation to the 3p-levels. The luminance bands were also analysed and it was found that the energys where they appear is linked to the Franck-Hertz curve, specifically the minima. This is because when an excited atom is losing its energy and the electrons are falling towards their ground energy levels they release energy as photons which create the bands. We could use this to predict that the next luminance band would appear at 82.15 V $\pm$ 0.1003 V
What we can take from this experiment is that atoms have discrete energy levels, this can be seen by the constant ΔU_2 between the maxima on the Franck-Hertz curve, and even by the discrete appearance of the luminance bands.

References

[1] PhysicsLab.org. *Energy-Level Diagrams*. URL: `https://www.physicslab.org/DocumentPrint.aspx?doctype=3&filename=AtomicNuclear_EnergyLevelDiagrams.xml`.

[2] *Trinity Lab Manual*. 2024.

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8 Appendix

8.1 Error Propagation

The voltages have constant error: $\pm 0.01V$

Current - constant error: $0.01A$

$$\begin{aligned} Q &= a + b + \ldots + c - (\delta x + \delta y + \ldots + \delta z) \\ \delta Q &= \sqrt{(\delta a)^2 + (\delta b)^2 + \ldots + (\delta c)^2 + (\delta x)^2 + (\delta y)^2 + \ldots + (\delta z)^2} \end{aligned} \tag{8.1}$$

$$\frac{\partial z}{z} = \sqrt{\left(\frac{\partial x}{x}\right)^2 + \left(\frac{\partial y}{y}\right)^2}$$

When x and y are the same (ie. x^2) we get:

$$\delta x^2 = x^2 \sqrt{2} \delta x$$

$$\frac{\Delta z}{z} = \sqrt{\left(\frac{\Delta x}{x}\right)^2 + \left(\frac{\Delta y}{y}\right)^2}$$

8.2 Data

Mercury			Neon		
$(U_2 \pm 0.01)\ V$	$(I \pm 0.01)\ A$	U1 = 2.38 V	$(U_2 \pm 0.01)\ V$	$(I \pm 0.01)\ A$	U1 = 1.53
0	0.02	U3 = 1.51 V	1.3	0.02	U3 = 10.25
2.9	0.03		6.2	0.02	
4.7	0.12		10.1	0.03	
5.8	0.04		12.7	0.11	
8.2	0.41		14.6	0.26	
9.4	0.89		16.7	0.51	
10.1	0.43		18.5	0.73	
11.1	0.14		19.8	0.54	
12.7	0.75		21.7	0.05	
13.4	1.39		23.6	-0.08	
14.1	2.07		25.9	-0.1	
15.1	1.23		28	-0.04	
16.1	0.44		29.2	0.78	
17.8	1.31		30.8	1.84	
18.5	2.24		32.7	2.83	
19.6	2.59		34.8	3.77	
20.2	1.85		35.6	4	
21	1.03		37.7	3.45	
22.1	1.27		39	2.202	
23.1	2.16		41.3	0.2	
24.4	3.41		43.4	-0.12	
25.1	2.87		46.3	-0.04	
26	2.06		49.8	3.65	
27.3	2.06		52.6	6.84	
28.6	3.35		55.2	7.73	
29.6	4.34		57.7	6.21	
30.7	3.76		59.9	4.04	
31.6	3.48		62.4	2.25	
			63.4	2.22	
			66	4.12	
			69.9	12.15	
			70.7	12.74	
			75.4	12.73	
			79.3	12.74	