The Franck-Hertz Experiment

Berat Gönültaş

April 2019

Abstract

In this experiment, we measured the current as a function of increasing voltage applied on the electrons in a tube filled with suitably dense mercury vapor. The aim of the experiment was to observe the behavior of energy transfer between colliding electrons and mercury atoms. We observed that the electrons can only give energies of some certain amount, i.e., the energy transfer for matter is quantized. We found that value as 5.086 ± 0.024 eV, which is around 4σ away from the accepted value, 4.9 eV.

1 Introduction

From the early spectroscopic work, it was clear that atoms emitted radiation at discrete frequencies; from Bohr's model, the frequencies of the radiation ν is related to the change in energy levels through $\Delta E = h\nu$. Further experiments demonstrated that the absorption of radiation by atomic vapors also occurred only for discrete frequencies.

It is then to be expected that the transfer of energy to atomic electrons by any mechanism should always be in discrete amounts and related to the atomic spectrum through the equation given above. One such mechanism of energy transfer is by the inelastic scattering of electrons from the entire atom. If the atom that is bombarded becomes[1] ionized, and since little energy is needed for momentum balance, almost the entire kinetic energy of the bombarding electron can be transferred to the atomic system.

J. Franck and G. Hertz in 1914 set out to verify these considerations, namely that (a) it is possible to excite atoms by low-energy electron bombardment, (b) that the energy transferred from the electrons to the atoms always had discrete values, and (c) that the values so obtained for the energy levels were in agreement with the spectroscopic results.

For detecting the excitation of the atoms in the vapor, it is possible to observe, for example, the radiation emitted when the atoms return to the ground state, the change in absorption of a given spectral line, or some other related phenomenon; however, a much more sensitive technique consists of observing the electron beam itself. Indeed, if the electrons have been accelerated to a potential just equal to the energy of the first excited level, some of them will excite atoms of the vapor and as a consequence will lose almost all their energy; if a small retarding potential exists before the collector region, electrons that have scattered

[1] In the original script this sentence was "If the atom that is bombarded does not become..", but we concluded that it is a mistake and we corrected the script.

inelastically will be unable to overcome it and thus will not reach the anode.[2] The result will be a decrease in the current flowing through the anode circuit. In this way, most of the electrons will not be able to reach energies that could excite the mercury atoms to their second excited levels. They would have lost their energies in exciting the mercury atoms to their first excited states. However, the higher levels can be excited also by letting the electrons gain the full energy quickly before they enter the region filled with mercury vapor. The electrons then will have enough energy to excite the higher levels also.[3]

Another important point is that in principle the experiment must be performed with a monatomic gas; since if a molecular vapor is bombarded, it is possible for the electrons to transfer energy to the molecular energy levels which form almost a continuum. Some of the preferred elements for the Franck-Hertz experiment are mercury, neon and argon.[4]

The Rydberg formula is used in atomic physics to describe the wavelengths of spectral lines of many chemical elements. It was formulated by the Swedish physicist Johannes Rydberg, and presented on 5 November 1888.[5] For any hydrogen-like element, the Rydberg formula is given as

$$\frac{1}{\lambda_{\text{vac}}} = RZ^2 \left(\frac{1}{n_1^2} - \frac{1}{n_2^2} \right) \tag{1}$$

where R is the Ryberg constant for that element, Z is the atomic number, n_1 and n_2 are the integers corresponding to the principal quantum numbers of the orbitals occupied before and after.

Thus we can find the energy of the emitted light as

$$E = h\nu = \frac{hc}{\lambda} = hcRZ^2 \left(\frac{1}{n_1^2} - \frac{1}{n_2^2} \right) \tag{2}$$

Here, one must be careful about that these identities (Equation 1 and 2) holds only for hydrogen-like elements, that is, isotopes having one electrons. Thus, one can not calculate the energy of the mercury atom by them. Atoms having more than one electron necessitates a much more detailed approach which includes Pauli exclusion principle.

2 Setup and Procedure

In the experiment, we used Franck-Hertz tube, electric oven, temperature probe, power supply, and computer.

A close view of the Franck-Hertz tube is given at appendix. The internal structure of the tube is given below.(see Figure 2) In that figure, U_1 represents the small current we use to free electron from the cathode. U_2 is the voltage we use to give energy to the free electrons.

[2] A.C. Melissinos, J.Napolitano; Experiments in Modern Physics, Academic Press, Second Edition, page 10-11

[3] Advanced Physics Experiments by Erhan Gülmez (Boğaziçi University Publications, 1999, ISBN 975-518-129-6)

[4] A.C. Melissinos, J.Napolitano; Experiments in Modern Physics, Academic Press, Second Edition, page 13

[5] `https://en.wikipedia.org/wiki/Rydberg_formula`

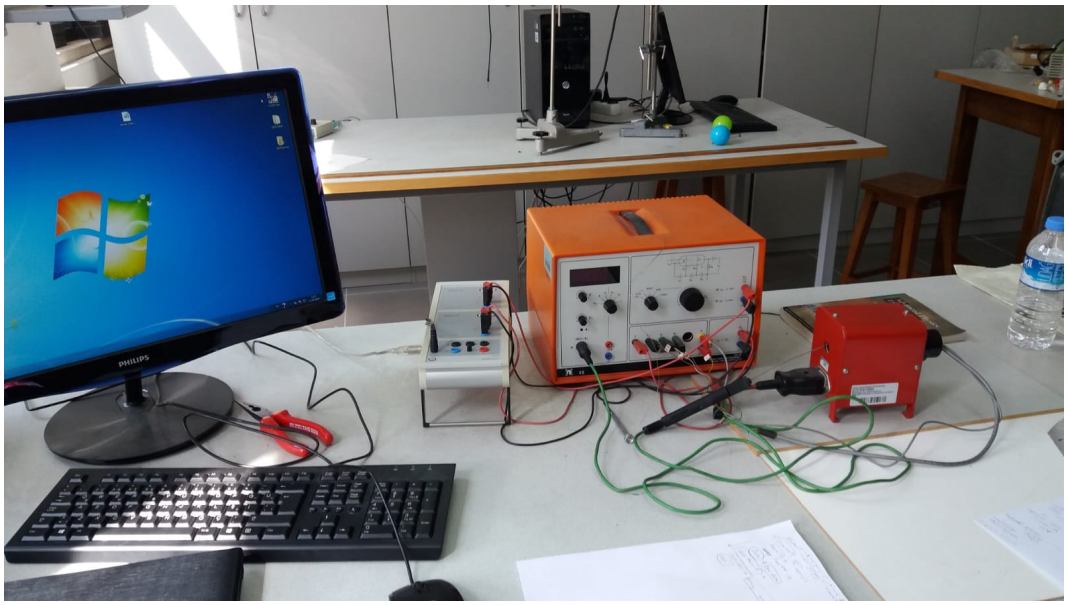

Figure 1: General view of the apparatus

Finally, not to add to the current, U_3 is the small retarding voltage which is applied to block electrons which excite mercury atoms.

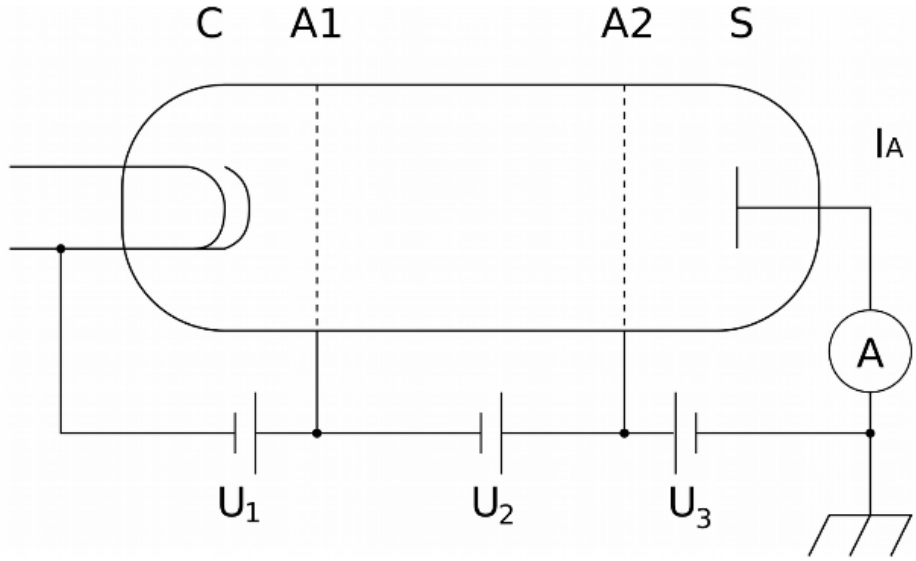

Figure 2: Structure of the Franck-Hertz tube

We first let the tube to become to the temperature of around 170 Celsius degrees, which is the temperature we took data around. There should be a certain amount of mercury concentration in the tube for the proper operation. Mercury vapor concentration increases as the temperature of the tube increases. At low temperatures, the concentration is not sufficient and a breakdown occurs very easily because of the complete ionization. At very

high temperatures, where the mercury vapor concentration is too high, the number of the electrons reaching the anode is minimal.[6]

After heating the tube to around a certain temperature value, we took 10 data from the various configurations[7] to be sure that the behavior we observe is not dependent of temperature T, voltages U_1 or U_3. The data we get from the computer was U_2 versus current graph. The value of the U_2 was changing automatically by our poer supply gradually. After obtaining the graphs, we determined the peak positions. The first peak includes the contact potential of the electrode material used in the tube. But the difference between the successive peak positions would give you the energy of the excited levels in the mercury atom. We are informed that, on average, the value of the energy of the first excitation, which we observed, is around 4.9 eV.

3 Data and Analysis

We plotted our data as below (see Figure 3).[8]

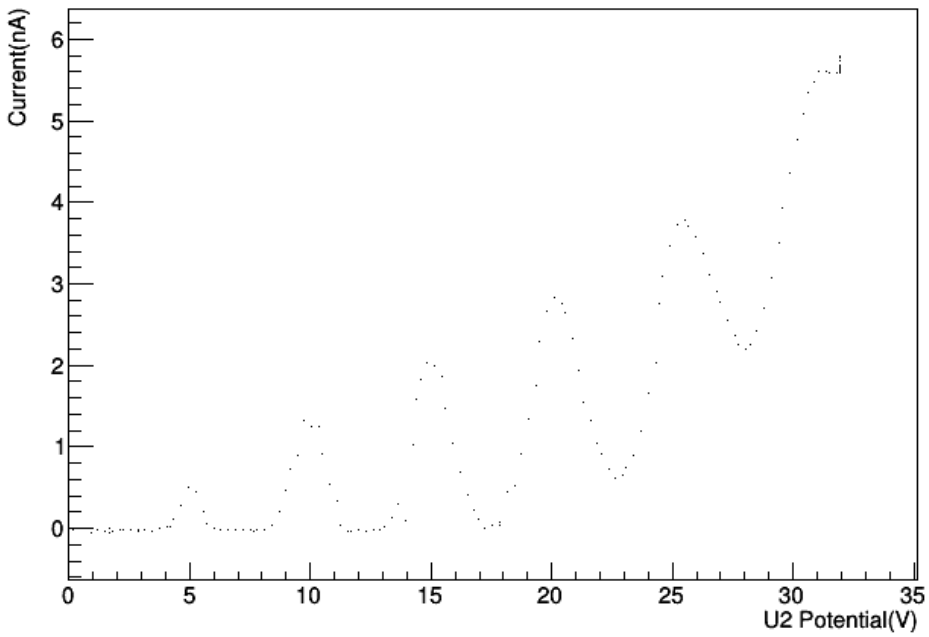

Figure 3: Graph for 172 Celsius degree, 1.40 U1 and 2.29 U3

[6]Advanced Physics Experiments by Erhan Gülmez (Boğaziçi University Publications, 1999, ISBN 975-518-129-6)

[7]Configurations are (0) 172 Celsius degree, 1.40 U_1, 2.29 U_3; (1) 172 Celsius, 1.61 U_1, 2.29 U_3; (2) 172 Celsius, 1.76 U_1, 2.29 U_3; (3) 172 Celsius, 1.76 U_1, 2.52 U_3; (4) 172 Celsius, 1.76 U_1, 2.71 U_3; (5) 172 Celsius, 1.76 U_1, 2.88 U_3; (6) 180 Celsius, 1.76 U_1, 2.88 U_3; (7) 188 Celsius, 1.76 U_1, 2.88 U_3; (8) 194 Celsius, 1.76 U_1, 2.88 U_3; (9) 208 Celsius, 1.76 U_1, 2.88 U_3

[8]Graphs for other data can be found in appendix.

Then we found the peak points by fitting Gaussian to the peaks and taking their mean value. We have given two examples of these procedure below. (see Figure 4 and 5)

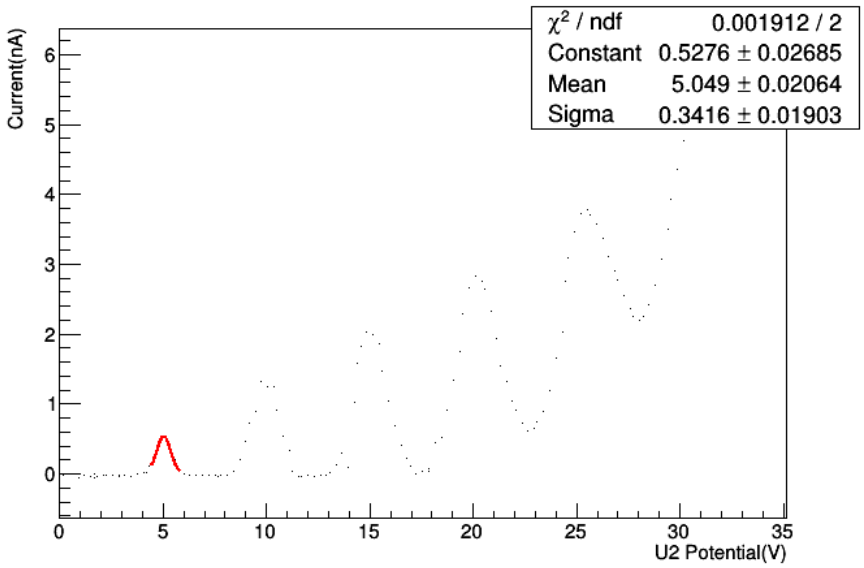

Figure 4: Fit for first peak

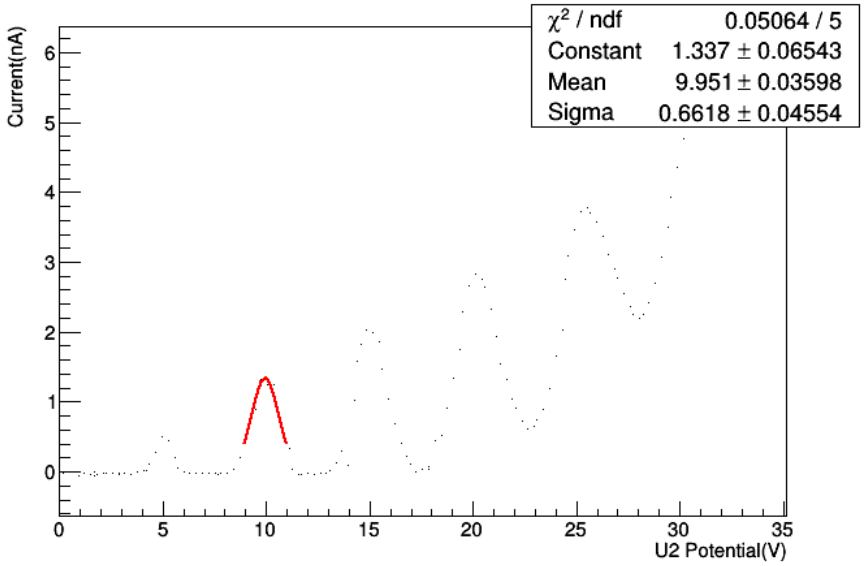

Figure 5: Fit for second peak

Then we found the difference between each successive peaks. This value is equal to the E_1, i.e, first excitation energy of the mercury atom. To propagate error of mean values to the E_1 values, we used following method throughout the analysis:

$$\sigma = \sqrt{\sum_i \left(\frac{\partial f}{\partial n_i}\right)^2 \sigma_i^2} \tag{3}$$

which, in this case, simply gives

$$\sigma_E = \sqrt{\sigma_1^2 + \sigma_2^2} \tag{4}$$

After finding E_1 values, we calculated their weighted average for each graph. Thus we left with 10 average values, one from each graph. Then we put them into an histogram and made a Gaussian fit.[9] (Figure 6)

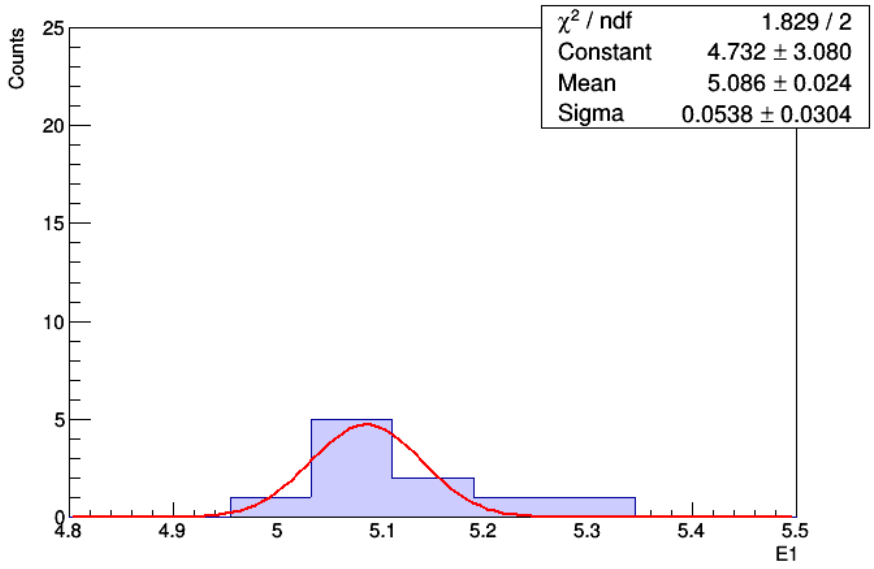

Figure 6: Histogram of E1 values

From the histogram, we can read mean value, which is equal to the E_1 as

$$E_1 = 5.086 \pm 0.024eV \tag{5}$$

4 Conclusion

Our result is 4σ away from the accepted result. Still, regardless of different configurations, we found a constant value for each configuration, which implies the quantum nature of atoms. Looking at our peak values, we observe that, for example, we have both 5.212 ± 0.030 and 4.790 ± 0.077 for first peak values. Although, these values involves the contact potential value, still we would expect them to be same. (contact potential + E_1) However, there is a huge gap considering their uncertainty values.

[9] I didn't know how to determine what value of the error bars to put on histogram bins and there were no time to ask. Thus, I left it without error bars.

Since the setup was very compact and close (didn't exactly see what was going on inside), we relied on the values we read on computer without doubt. Besides, being such a close system keeping the experimenter out of the action, it is hard to tell what to do in order to improve result.

Finally, we see that the contact potential value is around 0.1 V. It can be calculated by first peak values - E_1

5 Appendix

The codes used in analysis as well as the data file involving peak positions and E_1 values can be found in the following github link: `https://github.com/beratgonultas/phys442/tree/master/franck_hertz`

The close view of the Franck-Hertz tube is given below.

Figure 7: Franck-Hertz tube

The graphs for other configurations are given below.[10]

[10]Number of the configurations are given at footnote 7

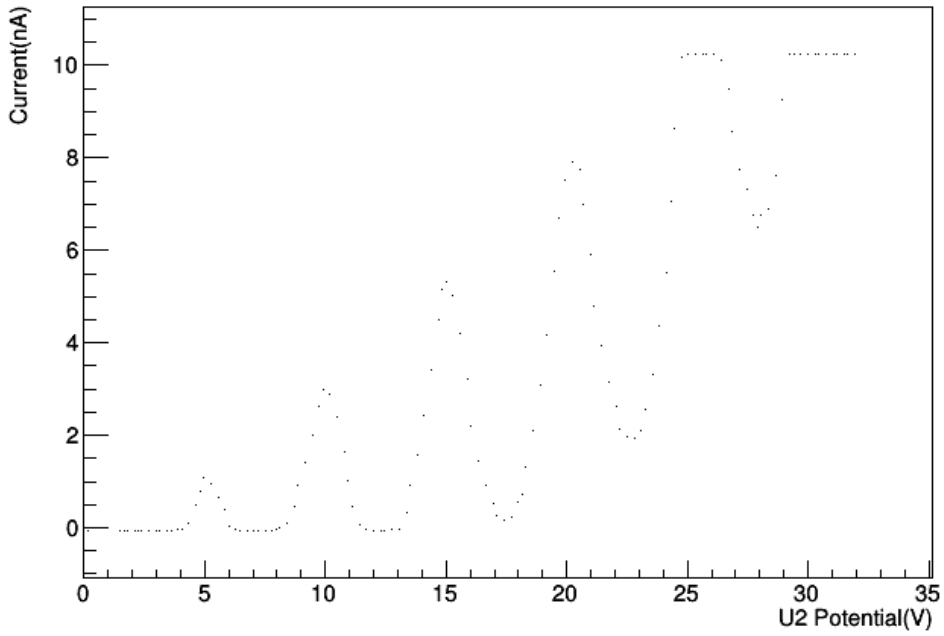

Figure 8: Confg. 1

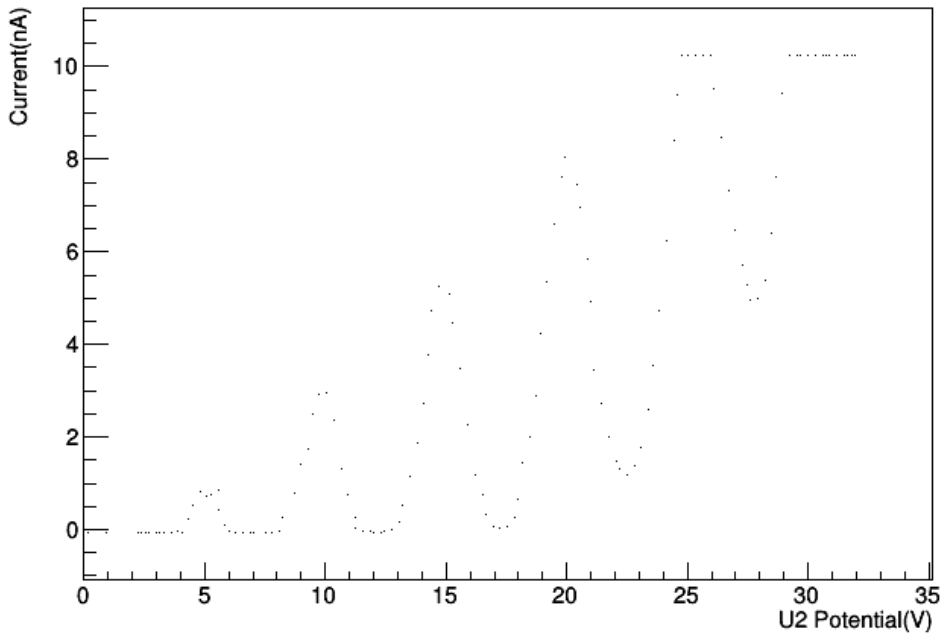

Figure 9: Confg. 2

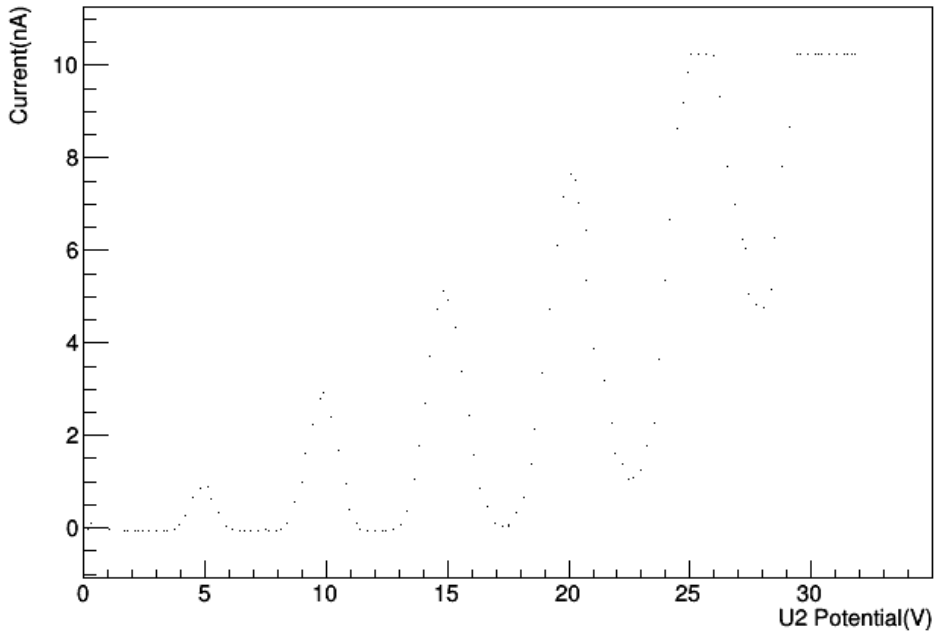

Figure 10: Confg. 3

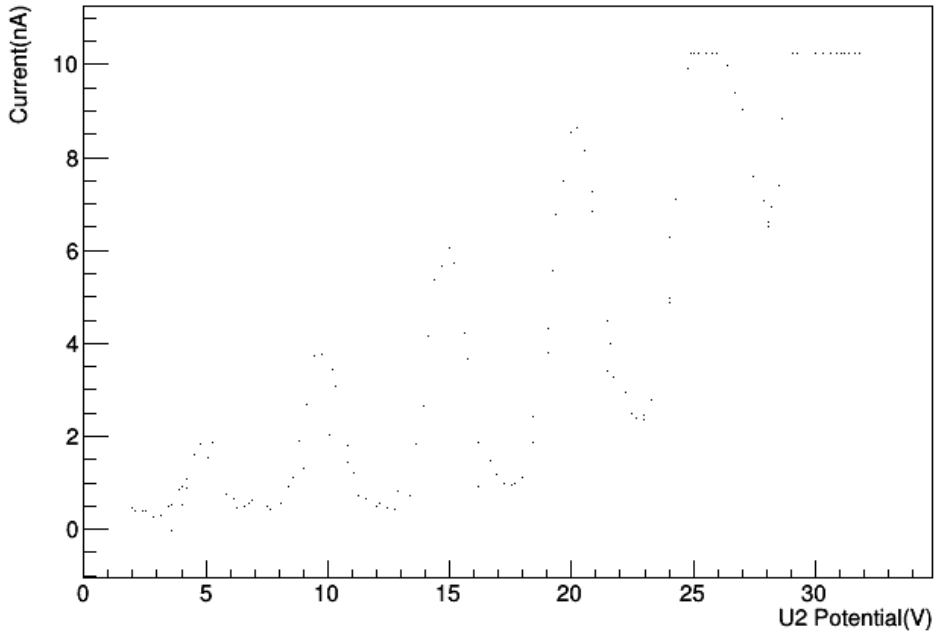

Figure 11: Confg. 4

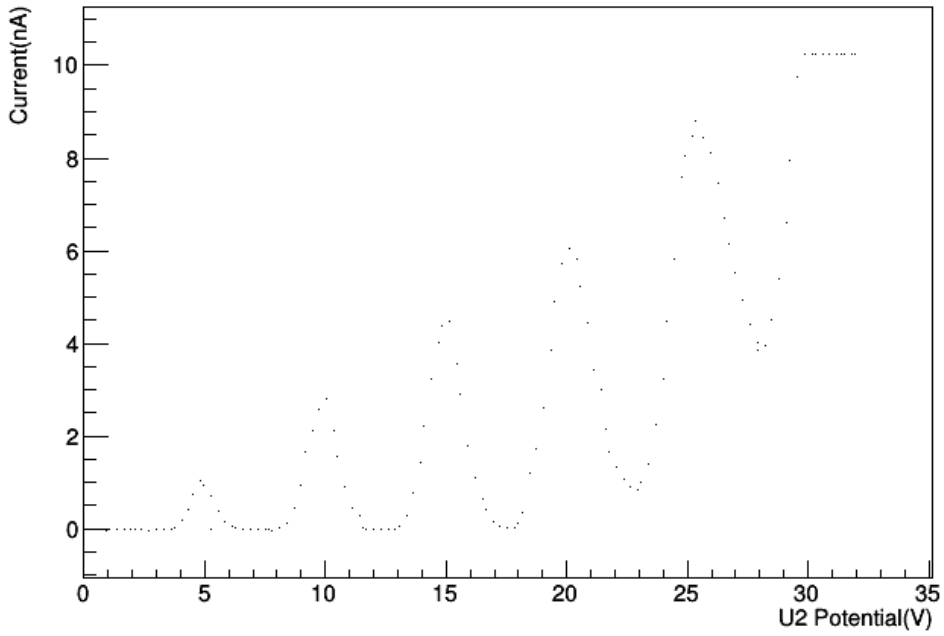

Figure 12: Confg. 5

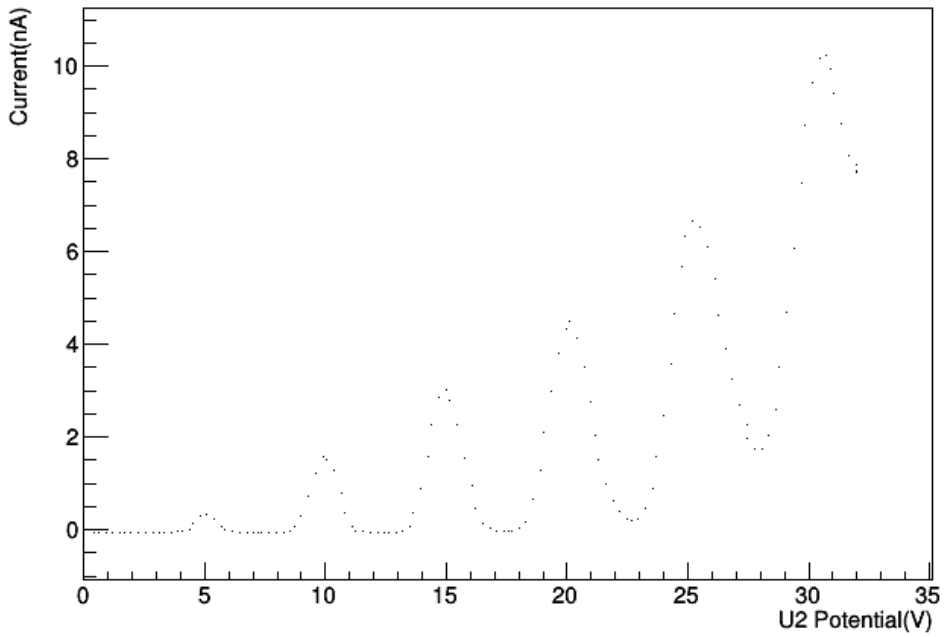

Figure 13: Confg. 6

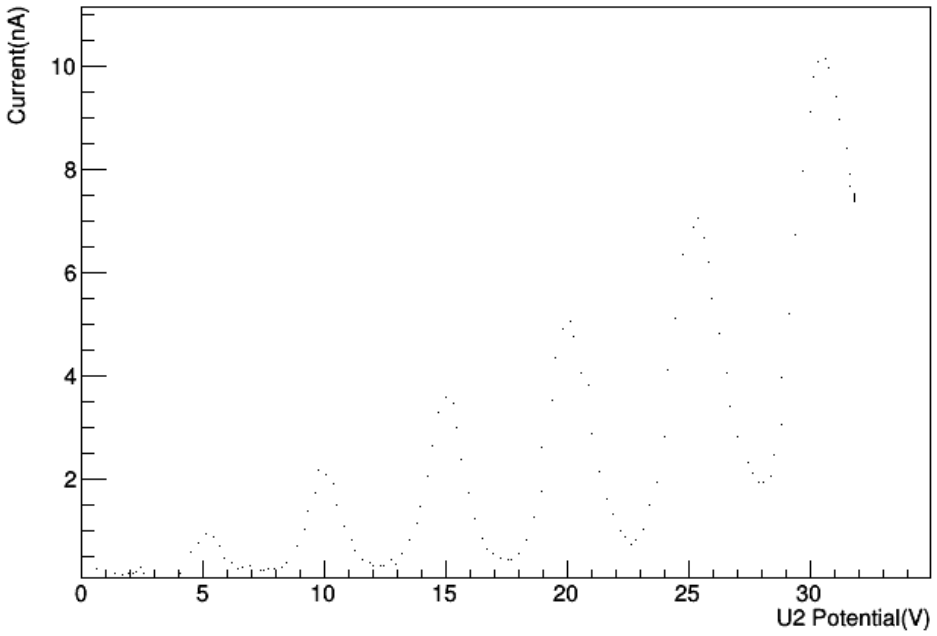

Figure 14: Confg. 7

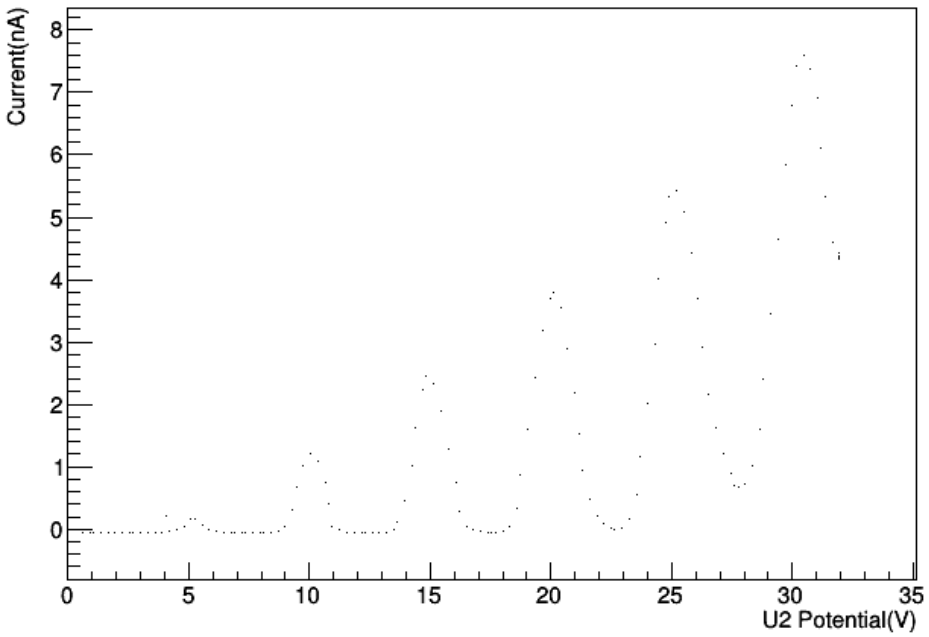

Figure 15: Confg. 8

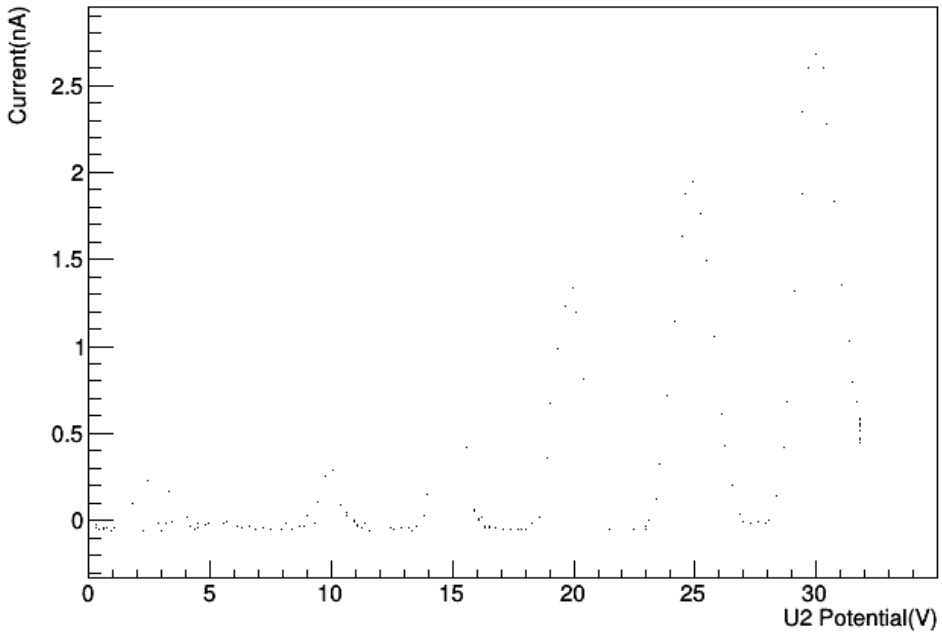

Figure 16: Confg. 9