2. Theory

According to Bohr's theory, atoms can only remain stable in some specific states (i.e. steady-states). Each of which corresponds to a certain amount of energy, and the steady-state energy is discrete. Atoms can only absorb or release energy equivalent to the energy difference between two discrete states. To excite an atom from the ground state to the first excitation state, the impact energy must be greater than the energy difference between the two states. Franck-Hertz experiment implements the energy exchange for state transitions through the collisions of atoms with electrons of certain energy, which is obtained by applying an accelerating electric field. The process can be represented by using the equation below:

$$\frac{1}{2}m_e v^2 \geq eV_1 = E_1 - E_0$$

where e, m_e, and ν are the charge, mass and speed (before collision) of an electron, respectively; E_1 and E_0 are the energy of the atom at the first excitation and the ground states, respectively; V_1 is the minimum voltage of an accelerating field required to excite the atom from the ground state to the first excitation state, called the first excitation potential of the atom. eV_1 is therefore called as the first excitation potential energy.

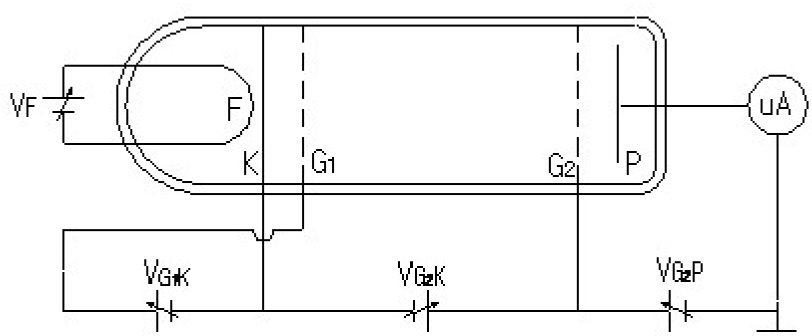


Figure 1 Schematic of Franck-Hertz experiment

The principle of Franck-Hertz experiment is shown in Figure 1. In an argon-filled Franck-Hertz tube (F-H tube), electrons are emitted from hot cathode K. A relatively low voltage V_{G1K} is applied between cathode K and grid G_1 to control the electron flow entering the collision region. An adjustable accelerating voltage V_{G2K} is applied between grid G_2 and cathode K to accelerate electrons to desired energy. A braking voltage V_{G2P} is applied between anode P and grid G_2. The electric potential distribution in the F-H tube is shown in Figure 2. When electrons pass through grid G_2, if their energy is higher than eV_{G2P}, they can arrive at anode P to form current I_P.

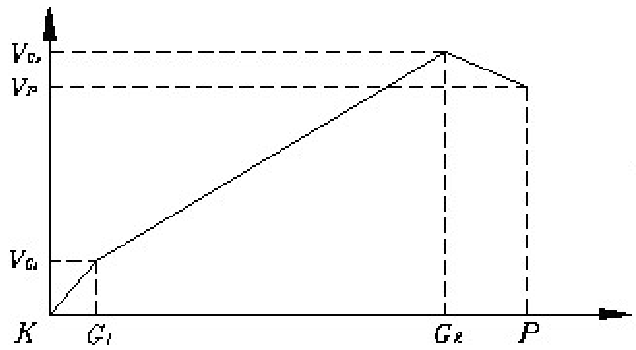


Figure 2 Schematic of potential distribution in the F-H tube

At the beginning, accelerating voltage V_{G2K} is relatively low and the energy of electrons arriving at grid G_2 is less than eV_{G2P}, so the electrons cannot reach anode P to form a current. By increasing V_{G2K}, the electron energy increases accordingly (the number of electrons with energy higher than eV_{G2P} increases too), so current I_p rises to the point that electron energy is higher than the first excitation potential energy eV_1 and electrons pass energy eV_1 to atoms by inelastic collisions. As a result, electron energy is less than eV_{G2P}, leading to a reduced anode current I_p.

By continuously increasing V_{G2K}, anode current I_p rises again until the electrons regain energy eV_1. Due to the inelastic collisions of electrons and atoms for the second time, anode current reduces again.

By increasing V_{G2K} from low to high, multiple inelastic collisions occur between electrons and Argon atoms leading to multiple rise/fall cycles on I_p ~ V_{G2K} curve, as shown in Figure 3.

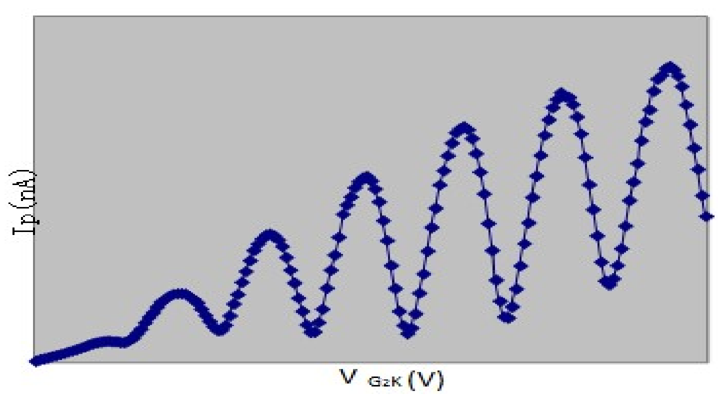


Figure 3 Relationship curve of anode current I_p and accelerating voltage V_{G2K}

For argon atoms, the voltage difference between adjacent valleys or peaks as shown in Figure 3 is the 1st excitation potential of an argon atom, which proves the discontinuity of argon atomic energy states.

The absorbed energy of the argon atom will be released through electron transition to lower state, and therefore a strong emission spectral line can be found that is corresponding to an energy of eV_1. According to published literatures, the measured argon atom resonance line is 106.7 nm (or 11.62 eV). Using the acquired 1st excitation potential, Planck's constant h can be calculated based on the formula: $h = eV_1\lambda / c$, where e=1.602×10^{-19} C, λ=106.7 nm, and c=3× 10^8 m/s.

5. Experimental contents

1) Observe the anode current versus accelerating voltage curve on an oscilloscope
2) Understand the process of electron-atom collision and energy exchange
3) Record data, plot curve, and calculate the 1^{st} excitation potential of Argon atom
4) Automatic measurement of excitation potential by using software (optional).

6. Experimental procedure

Note: the voltage values provided on the label attached to apparatus are only for reference purpose. You may finely adjust these values to achieve optimal results during experiment. Especially, the filament voltage can significantly influence the output current Ip. If the reading of the current (manual mode) is too high or the waveform acquired on the oscilloscope or on PC (auto mode) is saturated or distorted, it means the anode output current is too high. Under this case, the filament voltage should be decreased and/or the current multiple selector should be adjusted. The optimal filament voltages for manual mode and auto mode could be different. After changing filament voltage, allow one or two minutes to let the instrument stabilize. For auto mode, turn V_{G2P} to maximum to achieve the most peaks.

A. Measurement using oscilloscope

a. Connect "V_{G2} Output" and "I_p Output" on the main machine to the "X-Axis" and "Y-Axis" of an oscilloscope using BNC cables.
b. Set scanning switch to "Auto", scanning speed to "Fast", and micro-current amplifier to "10 nA".
c. On the oscilloscope, set scanning mode to "Auto", set "X" and "Y" voltage divisions to "1 V", "POSITION" to "$x-y$", and all "DC/AC" selectors to "DC".
d. Turn on the main machine and the oscilloscope, wait to preheat the apparatus.
e. Adjust V_{G1}, V_p, and V_F to proper values (refer to the label attached on the apparatus), while gradually increasing V_{G2} (**caution**: not too high to avoid breakdown of the F-H tube) until a stable $I_p \sim V_{G2}$ curve of the F-H tube is displayed on the oscilloscope. Observe the phenomenon of atom energy quantization.

   Note: the output voltage at the "V_{G2K} Output" terminal is attenuated by a factor of 10 from the actual V_{G2K} voltage which is applied on the F-H tube. Also, at "Auto" mode, the voltage reading on the voltmeter of the instrument front panel is an average value of the scanning V_{G2K} voltage rather than the peak-to-peak value.
f. If the oscilloscope is a digital storage oscilloscope with a USB port, the experimental results (observed on the oscilloscope) can be displayed and processed with a PC using the software of the oscilloscope. An example graph is shown in Figure 5.

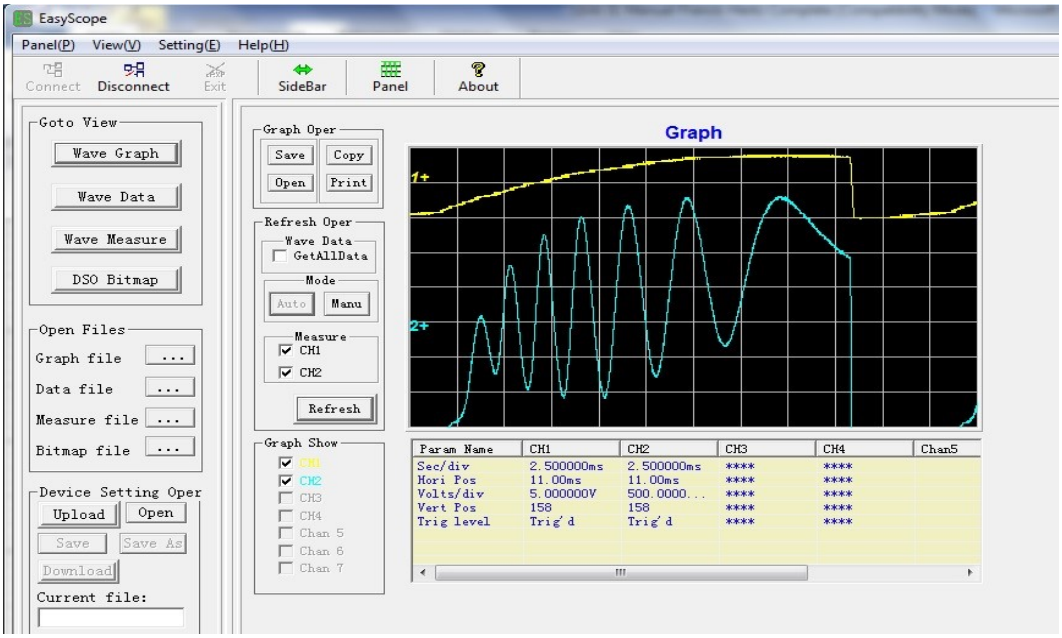


Figure 5 Experimental results acquired by PC from digital oscilloscope

B. Measurement using manual mode

a. Set V_{G2} to minimum and scanning switch to “Manual”, turn on the main machine.

b. Set V_{G1}, V_p, and V_F to proper values such as 1 V, 8 V, and 2 V, respectively, and increase V_{G2} gradually while observing I_p.

c. Record I_p versus V_{G2} from the digital meters, and plot $I_p \sim V_{G2}$ curve. Remember to multiply displaying values with scale factors. For example, if the current meter displays “3.23” while the current scale is set at “10 nA”, the actual value of I_p should be“32.3 nA”; if the voltage meter displays “6.35”, the actual value of V_{G2} should be “63.5 V”.

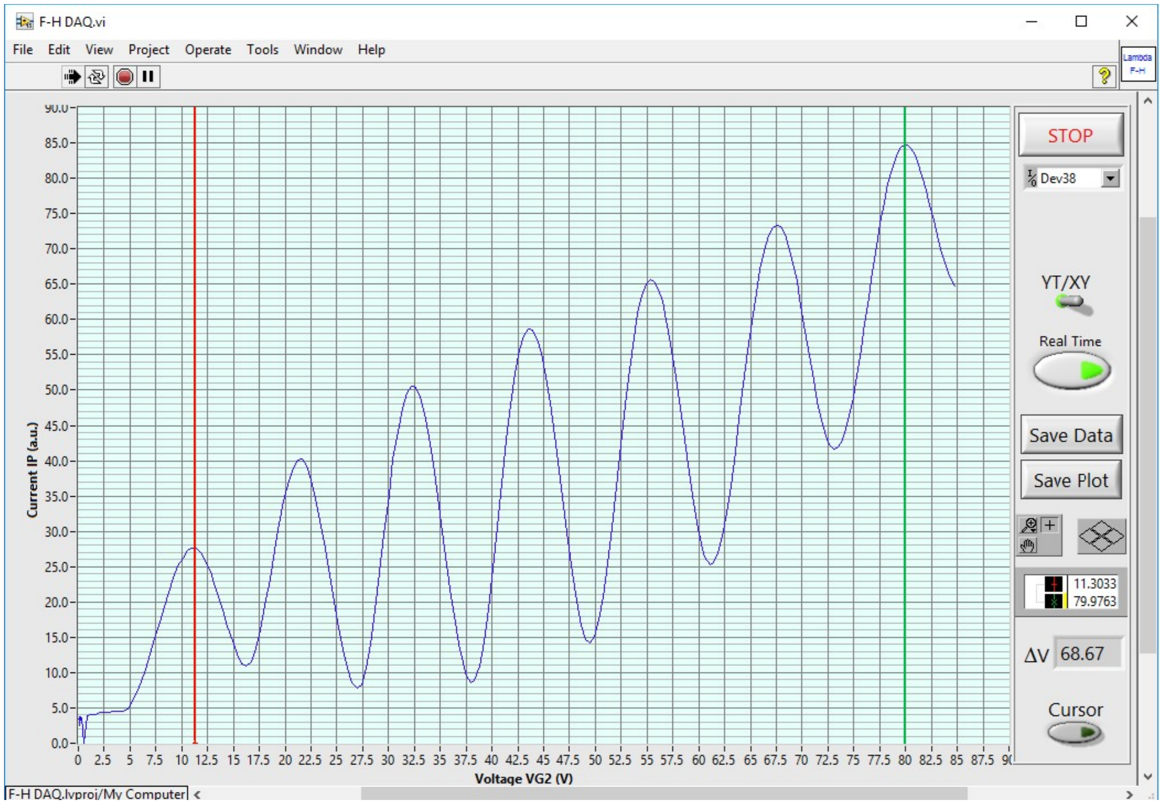
d. Calculate the first excitation potential of the Argon atom from the $I_p \sim V_{G2}$ curve.

e. Calculate Planck’s constant using formula: $h = eV_1\lambda / c$, where $e=1.602\times10^{-19}$ *C*, $\lambda=106.7$ *nm*, and $c=3\times10^{8}$ *m/s*, and compare it with the accepted value ($h_0 = 6.626 \times 10^{-34}$ J•s) .

C. Measurement using software

Data acquisition software named “F-H DAQ” is provided with this apparatus for PC use via a USB port. By running this software, the relationship curve between plate current (I_P) and accelerating voltage (U_{G2K}) can be acquired by PC as shown in Figure 6, in XY mode or YT mode, respectively. An instruction for installing and using this program is given in Appendix.

The waveform data shown in Figure 6 can be saved into a text file with a file extension of “txt”, which can be further imported to Excel for subsequent data processing and analysis.



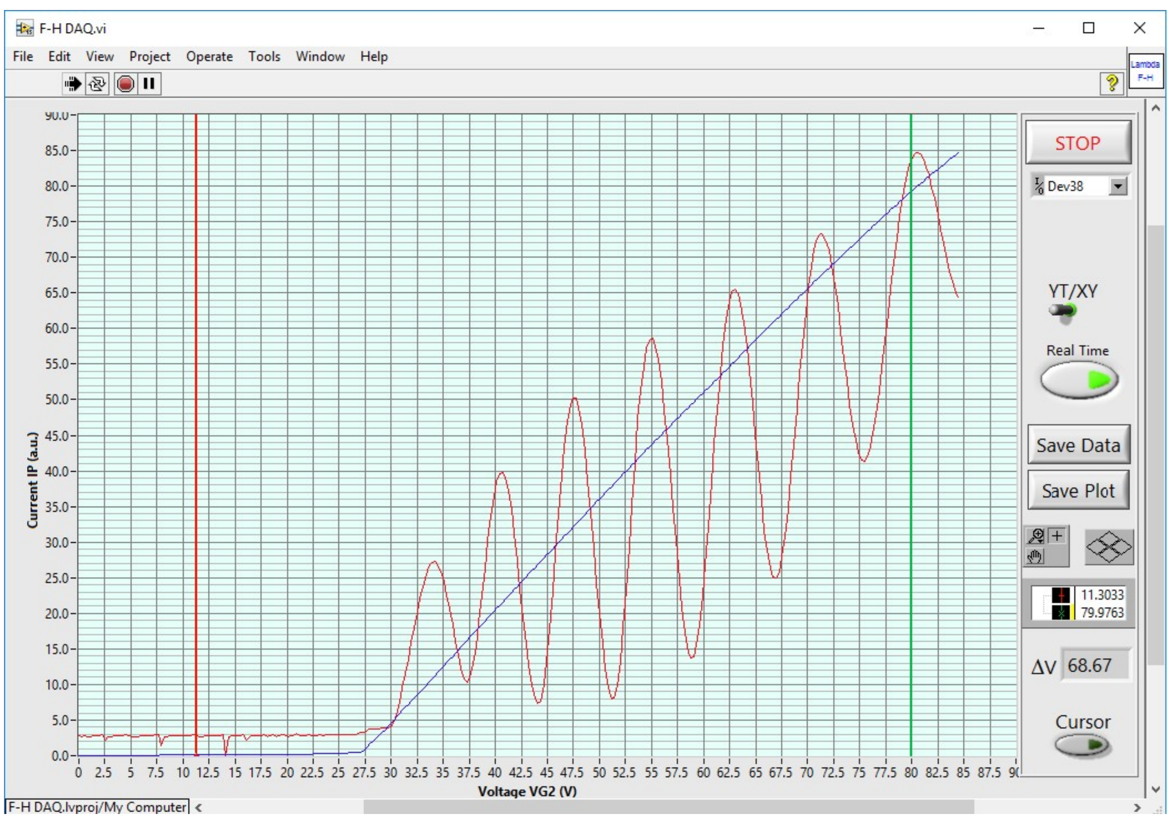


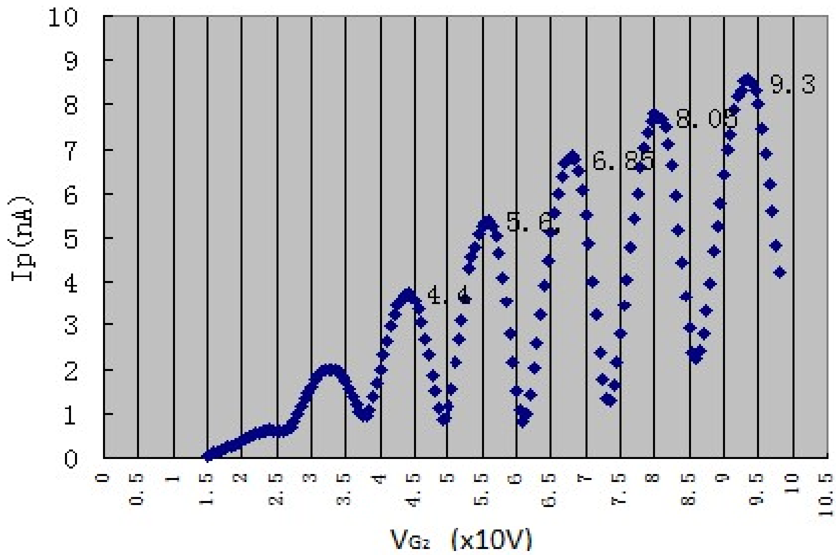
Figure 6 Experimental waveform acquired by software to PC

7. An example for data recording and processing

An example of data is shown for reference purpose, not the criteria for apparatus performance:

V_{G2} (V)	15.0	16.0	17.0	18.0	19.0	20.0	…
I_p (nA)	0.4	1.1	1.8	2.1	2.4	3.1	…

The corresponding $I_p \sim V_{G2}$ curve is plotted below:



Based on the curve, the 1st excitation potential of argon atom is calculated as 12.25 V, leading to a measurement error of 5.5% by comparing with the theoretical value (11.62 V).

To determine the location of each local minimum (valley) or maximum (peak) with a better accuracy, the data segment around each local minimum or maximum should be curve-fitted to a quadratic polynomial function using Excel, as shown below

$$I_p = aV_{G2K}^2 + bV_{G2K} + c$$

Thus, the location of each local minimum or maximum can be determined as

$$(V_{G2K})_{\min/\max} = -\frac{b}{2a}$$

Using the derived minimum/maximum locations, the mean with standard deviation of the 1st excitation potential of argon atoms can be calculated.

Using the acquired 1st excitation potential, calculate Planck's constant *h* based on the formula: $h = eV_1\lambda / c$, where $e=1.602\times10^{-19}$ *C*, $\lambda=106.7$ *nm*, and $c=3\times10^{8}$ *m/s*, and compare it with the accepted value ($h_0 = 6.626 \times 10^{-34}$ J•s) .