Technobius Physics, 2023, 1(3), 0003, DOI: https://doi.org/10.54355/tbusphys/1.3.2023.0003

Technobius Physics

https://technobius.kz/

e-ISSN
3007-0147

Article

Experimental investigation of electron-mercury atom collisions: insights into atomic interaction dynamics

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Abstract. This experiment aims to validate the Bohr's model, which posits the existence of discrete energy levels within Hg and Ne atoms, through the Frank-Hertz experimental methodology. Utilizing two specialized tubes, one containing Neon gas and the other Mercury gas, electrons are accelerated to collide with the gas atoms. As the applied voltage is gradually increased, a distinct min-max pattern emerges on the current-voltage graph, with the equidistant minima and maxima, indicating the quantization of atomic energy levels, a phenomenon predicted by Bohr's model. The experimentally determined distance between these peaks correlates with the energy required to excite the respective gas atoms to a higher energy state. The measured excitation energies – 16.58±2.36 eV for neon and 4.90±0.12 eV for mercury – align closely with the widely accepted energy levels for these atoms. These findings not only corroborate the quantized nature of atomic properties but also reinforce the validity of Bohr's atomic model.
Keywords: electron-mercury collisions, atomic interactions, mercury atom, electron scattering, collision dynamics.

1. Introduction

The study of electron scattering from atoms is pivotal for grasping the nuances of electron-atom interactions and the dynamics of their collisions, with significant implications across various scientific fields. The process's cross-sectional measurements are crucial for applications spanning from Auger electron spectroscopy and electron microscopy to research in microbiology and materials science. Scattering parameters, including differential, integral, viscosity, and momentum transfer cross-sections, are instrumental in many practical and technological contexts [1].

Subsequent research has intensively focused on spin-polarization in electron-atom scattering, both from experimental and theoretical perspectives. Spin-polarization parameters such as S(θ), U(θ), and T(θ) are not only vital for testing the precision of theoretical models but are also key to deciphering spin-dependent interactions within collision dynamics [1].

Recent studies by the Blum group on electron-hydrogen (e^{-}–H) and Bartschat and Santos on electron-lithium (e^{-}–Li) scattering have revealed that spin-polarization S(θ), also known as the Sherman function, results from quantum spin-entanglement in the projectile-target system [1]. This phenomenon occurs alongside the separable total spin and Bell correlation and is influenced by the collision energy and scattering angle [2].

Electron polarization upon scattering from non-polarized atoms predominantly arises from the spin-orbit interaction between the continuum electron and the atomic nucleus, a phenomenon commonly referred to as Mott scattering [3]. Additionally, electron polarization can be induced by fine-structure effects, which involve the interplay of spin-orbit splitting within atomic fine-structure states [3].

The influence of various spin-dependent interactions on the polarization of scattered electrons has been documented in the world literature [4]. Moreover, effects such as electron-electron interactions, exchange processes, and the influence of the electron configuration of the outer shell have been reported by several research groups [5-6].

From the aforementioned studies [7-8], it is clear that for elastic scattering off closed-shell configurations, for example in mercury (Hg), the polarization of high-energy electrons is predominantly due to spin-orbit coupling. However, fine-structure effects become significant in systems with open-shell configurations. Correlation effects, including polarization of the charge cloud and electron exchange phenomena, retain their importance in scattering events at lower collision energies.

2. Methods

The core objective of the present experiment is to investigate the behavior of gases when subjected to bombardment by accelerated electrons. Utilizing a Control Unit apparatus, we direct a stream of electrons at tubes filled with Neon and Mercury gases to measure the current (I) and voltage (U) values. These readings are then meticulously recorded and analyzed using the 'Phyme' software, which serves as a repository for the experimental data (Figure 1).

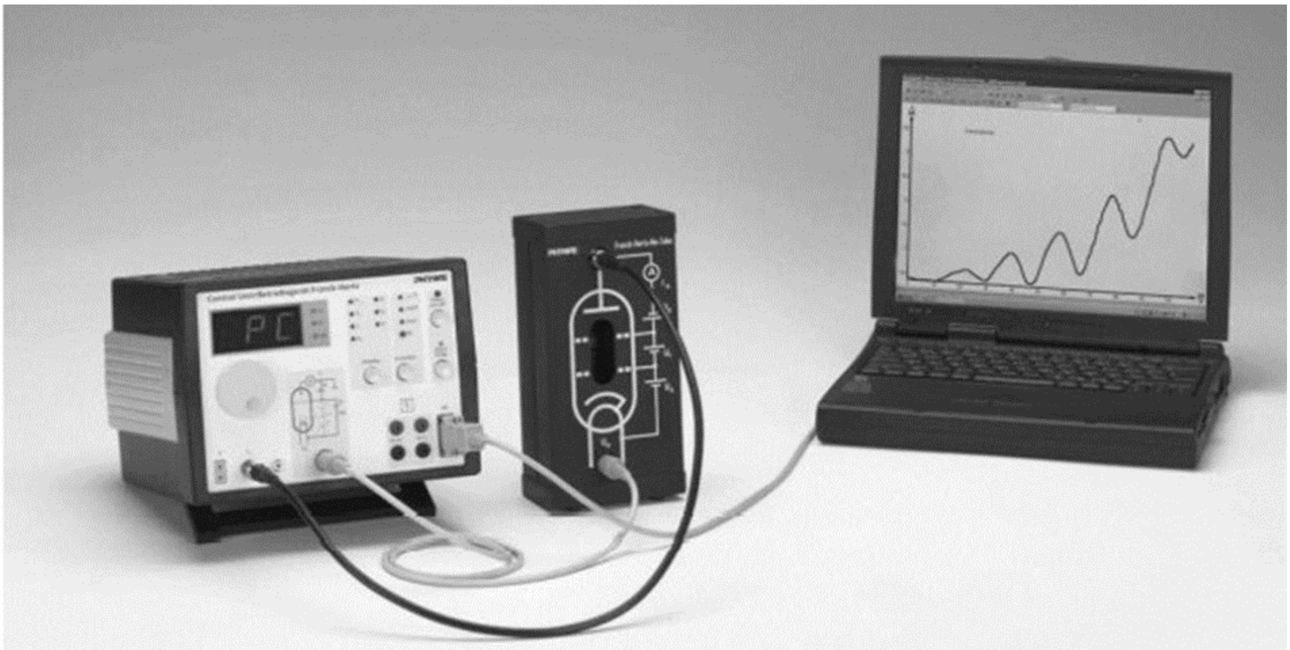

Figure 1 – A fully assembled Franck-Hertz experimental apparatus with a neon-filled tube, connected to a personal computer for data acquisition and analysis

The culmination of this experiment is the determination of the average difference between the maxima of potential values, alongside their respective standard deviations, for both Neon and Mercury gases. By accurately measuring these values, we aim to provide further empirical substantiation for the quantized energy levels of atoms, as initially proposed by Bohr, and to understand more deeply the interactions between electrons and gas atoms under experimental conditions.

The Franck-Hertz experimental setup with a neon tube is an intricate apparatus designed to investigate the quantized energy levels of electrons within an atom. This setup includes a sealed glass tube containing neon gas, electrodes to facilitate the acceleration and collision of electrons with the neon atoms, and a means to measure the current flowing through the tube. As electrons are accelerated and collide with the neon atoms, they can excite the neon electrons to higher energy levels, which upon de-excitation, release energy and cause observable changes in the current. These changes correspond to the discrete energy levels that the electrons occupy within the neon atoms. The entire system is interfaced with a personal computer, which is equipped with specialized software to control the experiment and record the voltage-current data. This allows for precise measurements and analysis, providing a visual representation of the quantized energy levels, as originally postulated by Bohr and further confirmed by Franck and Hertz.

Within the software environment, the specific module for the Franck-Hertz experiment is accessed. Parameters as depicted in Figures 2 and 3 are input for the neon (Ne) and mercury (Hg) tubes, correspondingly. Following these adjustments, the software commences the recording of voltage (U_1) and current (I_A) data, presenting the relationship between these variables in graphical format on the Phywe program interface, thus enabling the analysis of quantized energy transitions within the experimental framework.

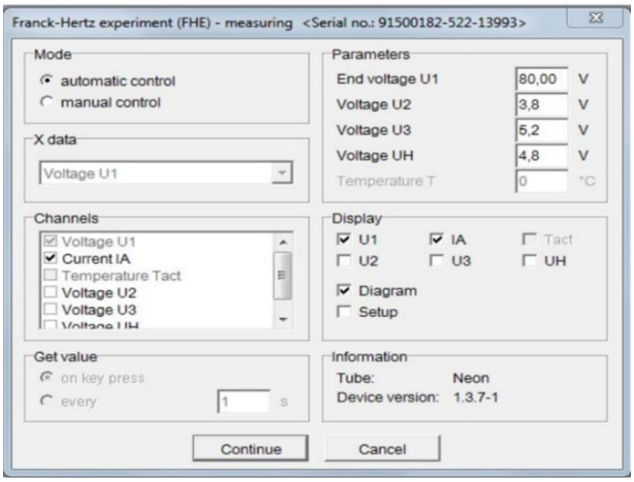

Figure 2 – Optimal parameter configurations for Ne

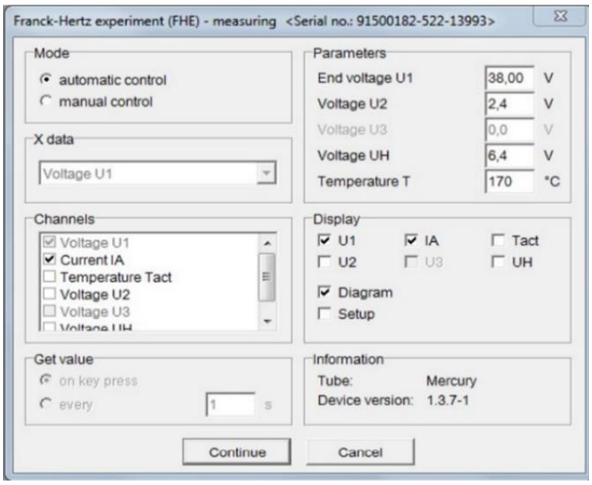

Figure 3 – Optimal parameter configurations for Hg

Upon calibration of the experimental configuration and establishing the requisite electrical connections, the control unit is activated. Subsequently, within the "Function" settings, the "PC" mode is selected to facilitate data acquisition via computer interface. Progressing to the computational aspect, the "Measure" software provided by Phywe is launched.

3. Results and Discussion

This study investigates the electron emission properties of a Ne-tube under controlled conditions of heating voltage (UH), accelerating voltage between grid anodes A_1 and A_2 (U_1), and counter voltage (U_2). The experiments involve measuring the accelerating voltage between the cathode and grid anode A_1 (control voltage, U_3) to understand its impact on the electron emission characteristics. The data obtained is presented in Table 1 and Table 2 and graphically represented in Figure 4.

Table 1 – Electron Emission Characteristics of the Neon Gas (No. 1)

Start [V]	Max. value [V]	Deviation [V]	Altitude [nA]	Zone [nAV]
0.41±0.01	13.82 ±0.01	15.55±0.01	0.74±0.01	9.9963± 0. 0001
19.26±0.01	26.98 ±0.01	31.03±0.01	1.16±0.01	11.6517± 0. 0001
35.75±0.01	44.46±0.01	46.1±0.01	2.08±0.01	15.1165± 0. 0001
53.45±0.01	63.34±0.01	64.24±0.01	3.68±0.01	23.6911± 0. 0001

Table 2 – Electron Emission Characteristics of the Neon Gas (No. 2)

Start [V]	Max. value [V]	Deviation [V]	Altitude [nA]	Zone [nAV]
5.19 ±0.01	14.11 ±0.01	14.87 ±0.01	0.76 ±0.01	7.6128 ±0.0001
18.98±0.01	28.03±0.01	28.93±0.01	1.24±0.01	10.2897±0.0001
34.67±0.01	45.1±0.01	43.12±0.01	2.25±0.01	17.1247±0.0001
52.58±0.01	62.84±0.01	63.16±0.01	4.21±0.01	26.6981±0.0001

The Ne-tube was subjected to a heating voltage (UH) of 8.0V ± 0.1V. Accelerating voltage between grid anodes A_1 and A_2 (U_1) varied from 0V to 99.9V ± 0.1V, while the counter voltage (U_2) was maintained at 7V ± 0.1V. The control voltage (U_3) between the cathode and grid anode A_1 was set at 3V ± 0.1V.

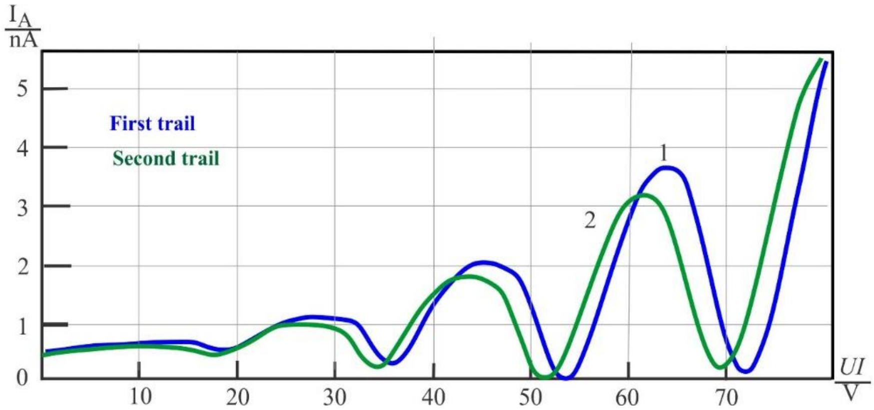

Figure 4 – *I-V* Characterization of Neon Gas

In the initial part of the experiment, a tube containing neon gas is utilized. As the voltage is incrementally increased, the thermionically emitted electrons accumulate energy. When these electrons acquire sufficient energy to excite neon atoms from their ground state to the first excited state, a minimum in the observed current is recorded. However, just prior to reaching the excitation energy, there is a peak in the current because the electrons attain the collector with greater energy, not having enough energy to excite the neon atoms. By determining the difference between the minima or the maxima, we can calculate the required energy (in electron volts) to excite a neon atom from the ground state to the first excited state. In our case, only the data for the maxima are available, hence the differences between the maxima were exclusively calculated.

Further experiments were carried out on a Hg-tube. A heating voltage (UH) of 6.3V ± 0.1V is applied to the tube. The accelerating voltage from the cathode to the anode (U1) is systematically varied, spanning from 0V to 60V ± 0.1V.

Concurrently, a fixed counter voltage (U2) is maintained at 2V ± 0.1V. It is noteworthy that the absence of direct control over U3 necessitates the introduction of an oven into the experimental arrangement. The oven is employed to regulate and exert influence over the acceleration of electrons within the tube, compensating for the uncontrolled variable. This innovative approach allows for the exploration of electron emission characteristics under specific heating and accelerating conditions, providing valuable insights into the behavior of the Hg-tube within the prescribed voltage parameters.

Table 3 – Electron Emission Characteristics of the Mercury Gas (No. 1)

Start [V]	Max. value [V]	Deviation [V]	Altitude [nA]	Zone [nAV]
14.97± 0. 01	17.02± 0. 01	16.88± 0. 01	1.76± 0. 01	3.6719± 0. 0001
19.71± 0. 01	20.89± 0. 01	23.06± 0. 01	3.04± 0. 01	6.0012± 0. 0001
23.95± 0. 01	25.95± 0. 01	27.61± 0. 01	4.61± 0. 01	10.697± 0. 0001
29.01± 0. 01	30.85± 0. 01	33.04± 0. 01	6.57± 0. 01	15.3781± 0. 0001
34.02± 0. 01	36.24± 0. 01	38.12± 0. 01	8.98± 0. 01	22.633± 0. 0001

Table 4 – Electron Emission Characteristics of the Mercury Gas (No. 2)

Start [V]	Max. value [V]	Deviation [V]	Altitude [nA]	Zone [nAV]
15.04± 0.01	16.25± 0.01	17.01± 0.01	3.21± 0.01	3.8157± 0.0001
19.33± 0.01	21.25± 0.01	23.03± 0.01	5.37± 0.01	11.6671± 0.0001
24.12± 0.01	26.15± 0.01	28.12± 0.01	8.68± 0.01	19.2143± 0.0001
29.02± 0.01	31.02± 0.01	32.11± 0.01	12.55± 0.01	29.3416± 0.0001
34.04± 0.01	36.11± 0.01	38.13± 0.01	17.97± 0.01	44.1534± 0.0001

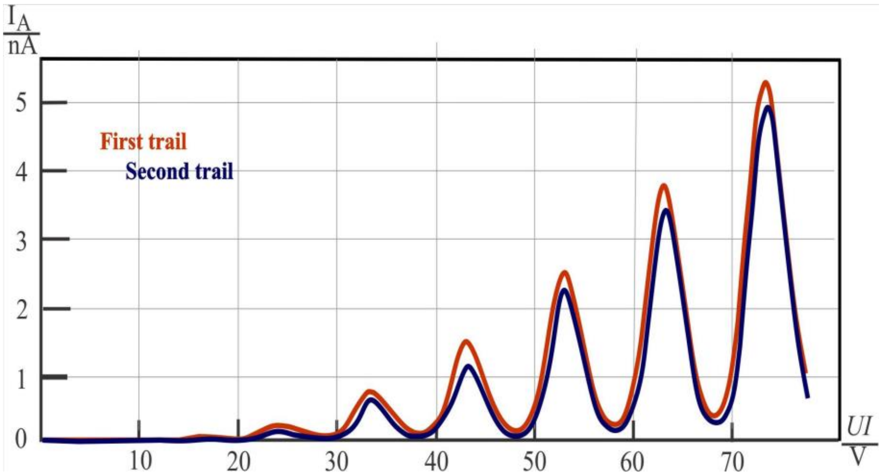

Figure 5 – *I-V* Characterization of Mercury Gas

Table 5 – Results for the excitation energy of Ne and Hg, along with their respective standard deviations

Gas type	Trail	Mean separation among peaks (eV)	Average value (eV)	Standard deviation of the average (eV)
Ne	1	16.53	16.63	2.31
	2	16.74		
Hg	1	4.93	4.91	0.14
	2	4.89		

The distinctive min-max pattern observed in the current-vs-voltage graphs can be elucidated by embracing Bohr's atomic model. According to Bohr, electrons revolve around the nucleus in discrete "stationary states" characterized by a lack of electromagnetic radiation emission during their motion. These stationary states possess definite total energy, with quantized values for radii and energies. Electron transitions between these states result in the emission of photons, where the photon's frequency is proportional to the energy difference between the involved states.

In this investigation, thermionically emitted electrons are accelerated through a voltage, gaining kinetic energy. As the voltage increases, the electron kinetic energy rises, leading to an increase in current. However, at a critical point, electrons gain enough energy to excite gas atoms from the ground state to the first excited state through collisions, causing a dip in the current due to energy loss. Subsequent increases in voltage result in higher current until the energy is once again sufficient for further excitations, leading to a repeating pattern of minima and maxima.

The recurring increase in current maxima after each minimum is attributed to electrons possessing high kinetic energy. Electrons have a significant probability of exciting multiple atoms to the first excited state and losing energy in the process. Although most electrons undergo this process, a small fraction excites fewer atoms or avoids collisions, reaching the collector plate with higher kinetic energy, causing a slight increase in current.

In terms of experimental results, for neon, the determined excitation energy (16.63±2.31 eV) closely aligns with the theoretical value (16.8 eV), despite a substantial standard deviation indicative of potential random errors. Regarding mercury, the obtained excitation energy (4.91±0.14 eV) demonstrates excellent agreement with the accepted value (4.91±0.072473 eV).

4. Conclusions

In conclusion, our experimental investigation into the electron excitation energies of neon and mercury gas tubes yielded insightful results that align with Bohr's atomic model. The observed min-max pattern in the current-vs-voltage graphs is consistent with the quantized nature of electron orbits in "stationary states," as proposed by Bohr. This pattern arises from electrons gaining and losing energy during collisions with gas atoms as they traverse the voltage gradient.

The recurrent minima in the current are indicative of electrons losing kinetic energy to excite gas atoms, causing a temporary dip in current. Conversely, the subsequent maxima correspond to electrons maintaining higher kinetic energy, contributing to an increase in current. The nuanced variations in maxima suggest that, beyond the predominant excitation process, a subset of electrons retains higher energy due to limited collisions or avoidance of collisions.

Notably, our experimental results for neon's excitation energy closely align with the theoretical value, despite a significant standard deviation pointing towards potential sources of random errors. Conversely, the determined excitation energy for mercury demonstrates excellent agreement with the accepted value, showcasing the reliability of our experimental setup.

This investigation enhances our understanding of electron behavior in gas-filled tubes, providing valuable insights into the quantized nature of energy levels and the complex dynamics of electron excitation and emission processes. Further refinement of experimental techniques may help reduce uncertainties and enhance the precision of excitation energy measurements. Overall, our findings contribute to the broader comprehension of atomic models and their application in experimental studies of electron behavior in gaseous environments.

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Received: 21.08.2023
Revised: 22.08.2023
Accepted: 31.08.2023
Published: 31.08.2023