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Using the Franck–Hertz Experiment To Illustrate Quantization

Energy States of the Neon Atom by Electron Impact

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Laboratory exercises that illustrate quantum phenomena provide students with motivation for the study of quantum mechanics. That microscopic matter exists in quantized states can be demonstrated with modern versions of historic experiments: atomic line spectra (*1*), resonance potentials, and blackbody radiation. The resonance potentials of mercury were discovered by Franck and Hertz in 1914 (*2*). Their experiment consisted of bombarding atoms by electrons, and detecting the kinetic energy loss of the scattered electrons (*3*).

Prior to the Franck–Hertz experiment, spectroscopic work by Balmer and Rydberg revealed that atoms emitted radiation at discrete energies. The Franck–Hertz experiment showed directly that quantized energy levels in an atom are real, not just optical artifacts. An atom can be raised to excited states by inelastic collisions with electrons as well as lowered from excited states by emission of photons. The classic Franck–Hertz experiment is carried out with mercury (*4–7*). Here we present an experiment for the study of resonance potentials using neon.

Historical Background

James Franck was a physicist whose work significantly affected chemistry and biology (*8*). His first serious research in physics began in 1902 when he moved to Berlin, at that time the center of physics in Germany. He joined Emil Warburg's laboratory group and started a study of ion mobilities. Franck found that collisions of electrons with noble gas atoms were mainly elastic, without loss of electron kinetic energy.

Gustav Hertz later joined Franck for a thorough study of elastic collisions, and this work led to the discovery of quantized transfer of energy during inelastic collisions between electrons and atoms. In their famous experiments in the year 1914 (*2*), they showed that electrons could impart energy to a mercury atom only if the electrons had a kinetic energy exceeding 4.9 eV. It was this quantum of energy that was absorbed by the mercury atom, causing it to emit a radiation line at 2537 Å. This was the first direct proof of the quantized nature of energy transfer and of the connection of the quantum of energy (E) with the frequency ($\upsilon=\Delta E/h$) of light emitted as a result of energy transfer. Franck and Hertz were awarded the Nobel Prize in physics in 1925 for their experiments that were decisive proof of the quantized energy levels that had been postulated by Niels Bohr in 1913.

Experimental Method

Franck and Hertz performed their famous experiment with mercury atoms. Today, common experimental replications use neon,[1] mercury,[2] or helium[3] atoms. We recommend the use of neon for several reasons. First, mercury must be heated to obtain sufficient vapor pressure to run the experiment. This presents problems for students because the observed signal depends critically on temperature. Maintaining a constant temperature is a demanding and frustrating part of a traditional Franck–Hertz experiment. Second, the helium system displays three signals, each corresponding to a different group of excitations. This makes determination of the resonance energies complicated since the contact potential of the electrodes in the apparatus must be included in the calculation. In contrast to helium, the neon apparatus shows three signals corresponding to the same excitation, allowing for two determinations of the resonance potential. Third, the progress of neon excitation can be tracked visually because many of the excited levels emit visible radiation. A red glow in the gas can be observed to move toward the cathode in the apparatus as the electron bombardment energy is increased.

The apparatus for this experiment consists of a neon-filled Franck–Hertz tube, a control unit with power supplies, and a DC current amplifier with a shielded cable. The control unit also can be used with a mercury tube. Advantages of the CENCO control unit are that it eliminates the problems associated with connecting four floating power supplies, and that it is simple for students to operate. The power supply section of the control unit delivers the control voltage (fixed at 10 V), accelerating voltage (continuously variable from 0 to 70 V), filament heating voltage for the tube (up to 8 V), and retarding voltage (up to 10 V). The accelerating potential can be adjusted manually or swept automatically. The apparatus is outlined in Figure 1.[4]

Electrons are emitted thermally from the barium oxide cathode and are accelerated toward the collector electrode by an attractive potential. The control grid helps to keep the emission current constant as the accelerating potential is varied. Electrons that pass through the control grid are accelerated by the potential applied between the cathode and the anode. Electrons passing through the anode with an energy greater than the retarding voltage applied to the collector electrode are collected at the plate and give rise to a plate current that is measured with a sensitive current-to-voltage amplifier connected to a voltmeter.

[1] Our experimental apparatus was purchased from Central Scientific Company (CENCO), 11222 Melrose Avenue, Franklin Park, IL 60131-1364. Current CENCO catalog number and price: Franck–Hertz tube in a housing; a control unit with power supplies, reverse voltage source and DC preamplifier; and a shielded cable with BNC #32048, $2250. The handheld prism spectroscope was obtained from Edmund Scientific #A42586, $195. An oscilloscope with x-y capability is optional. It is helpful for the instructor to examine the entire spectrum prior to the student laboratory to ensure proper setting of controls. Optional computer control was obtained by Vernier Software's Multipurpose Laboratory Interface, using the x-y oscilloscope mode.

[2] CENCO model #30221, $839. Also requires an electric oven, model #55532, $239. Alternatively, CENCO model 32047, $2580.

[3] CENCO model #32057, $729.

[4] In some implementations of electron spectroscopy, X-ray emission is a safety concern. Here, the maximum accelerating potential is only 75 V, and we do not detect any ionizing radiation from the apparatus. Evidently, air and the glass envelope of the Franck–Hertz tube furnish an adequate shield against the ultraviolet light that is emitted when a neon atom makes a transition to the ground state.

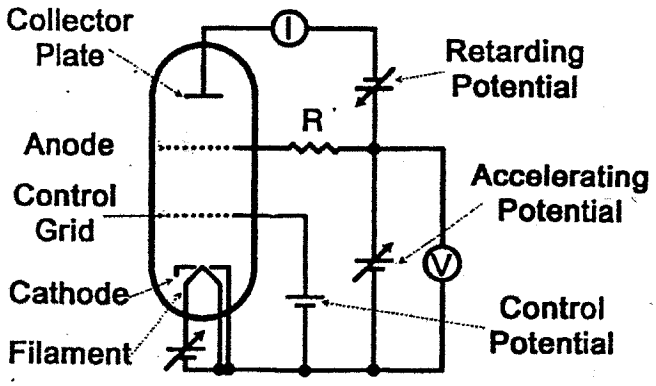

Figure 1. Schematic Diagram of the Apparatus. The neon gas and the electrodes are encapsulated in a glass tube. The ammeter symbolized by "I" represents a sensitive current-to-voltage amplifier; the voltmeter represented by "V" can be either a digital multimeter (for manual operation) or an oscilloscope (for real-time graphical output). The resistor "R" protects the ammeter circuit in case of a discharge in the tube. The control potential helps to keep electron emission current independent of the accelerating potential.

The neon tube should be turned on for approximately 30 min to allow the unit to stabilize. The experimenter proceeds by slowly increasing the accelerating voltage from an initial value of zero. The current should increase uniformly, reach a maximum, and then decrease as accelerating voltage is increased. A reduction in collector current occurs starting at about 20 V. This is accompanied by the appearance of a glowing red layer at the anode. As the anode voltage is increased, the collector current decreases and the glow moves toward the cathode. The emission current must be at a low enough level so that gas discharge does not occur at an accelerating potential of approximately 70 V. The retarding voltage between anode and collector electrodes should be set between 6 and 10 V so that the minima in the current/voltage curve are clearly recognizable.

Data may be collected manually as Franck and Hertz did, with an oscilloscope, or with a computer. We have had our students collect data by each of the three methods. As with many student experiments, manual data collection most clearly demonstrates the desired effect, while computer-aided acquisition eliminates drudgery. For manual data collection, students should carefully record data around the three maxima and three minima in collector current, and plot current intensity versus voltage to locate the extrema.

Data Reduction

Three maxima are observed, allowing for two determinations of the resonance potential: by subtraction of the first peak from the second peak and by subtraction of the second peak from the third peak. This method is superior to determination of the resonance potential three times, where the resonance potential is taken as the average of peak one, peak two divided by two, and peak three divided by three. This is because the "zero" point introduces error as a consequence of the contact potential of the electrodes. Of course the contact potential could be given (about 2.5 V for the iron/barium contact), but determination of the resonance potential without outside help is more satisfying to students. If data are collected by hand, it should be plotted and fit to a curve to allow an accurate determination of the accelerating voltage corresponding to maximum collector current. Once the three maxima are determined, along with an estimate of the uncertainty in each peak position, the resonance potential can be calculated by subtraction.

Results and Discussion

A computer-generated graph is presented as Figure 2. The nature of the three-peak maxima is described as follows. The emitted electrons collide with many neon atoms while traversing from the cathode to the plate. Two kinds of collisions may occur, inelastic collisions where the bombarding electrons lose energy to the electrons of the neon atoms, and elastic collisions where translational energy may be exchanged between bombarding electrons and neon atoms. Elastic collisions do not change the energy of accelerated electrons because momentum must be conserved during the brief collision.

Inelastic collisions are effective at lowering the energy of the electrons because of the relatively large amount of energy involved. Because atomic energy levels are quantized, inelastic collisions are not possible unless the accelerated electrons possess sufficient energy to excite atoms from one state to another. If the accelerating voltage is raised from an initial value of zero, a reduction in collector current occurs starting at an approximate value of 20 V. This is accompanied by the appearance of a glowing red layer at the anode. This layer is created because the electrons emitted from the cathode are accelerated by a uniform electric field, and, therefore, reach the energy necessary for excitation at essentially the same distance from the cathode.

As the anode voltage is increased the collector current decreases and the glow moves toward the cathode. The collector current reaches a minimum when the glowing layer detaches from the anode. The current then begins to increase because the inelastically scattered electrons are accelerated sufficiently to overcome the retarding potential and reach the collector. As the anode voltage is raised, a dark zone appears.

When the accelerating potential is raised to about 40 V, a second current maximum is attained. The second peak results from the scattered electrons reaching the correct energy to excite neon atoms a second time. A third layer around 59 V signifies that three regions of neon atoms have been excited by the same electrons. The third layer is the most poorly defined because multiple inelastic collisions cause the electrons to spread perpendicular to the electric field.

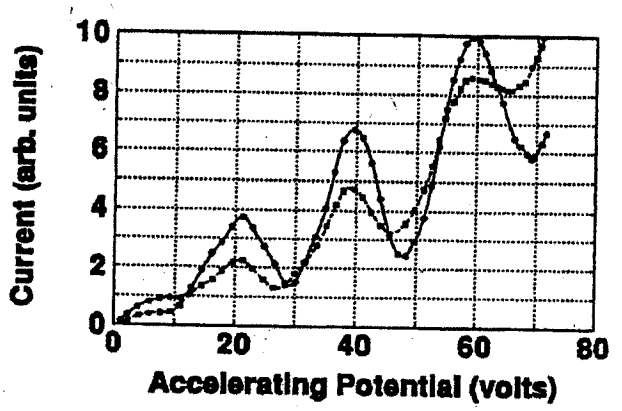

Figure 2. Electron current versus Accelerating Potential. Data taken with a retarding potential of 8 V are shown with the solid curve; the actual points are marked by circles. Data taken with a retarding potential of 6 V are shown with the dashed line; the actual points are marked by squares. As the retarding potential was reduced, the gain of the current-to-voltage amplifier was also reduced in order to keep the same maximum output. Note that the positions of the maxima are the same in both curves, while the positions of the minima are shifted.

As can be seen from Figure 2, the voltage difference between the first and second peaks and between the second and third peaks average around 19 ±1 V. As the retarding voltage is decreased, more electrons can reach the detector at a given acceleration potential. Note in Figure 2 that the maxima remain the same, yet the minima occur at lower acceleration voltages with a reduction in retarding voltage, because the electrons require less energy to reach the collector plate as the retarding voltage is decreased. In fact, the retarding potential is the difference in potential of corresponding minima and maxima.

Figure 3 displays a partial energy-level diagram for neon (*9*). At first glance, it seems that inelastic scattering should occur when the electrons have sufficient energy to excite the levels between 16.62 and 16.85 eV. Indeed, this is possible,[5] and may be partially responsible for the broad maxima and minima evident in Figure 2. However, this apparatus[1] is designed to emit visible radiation when substantial inelastic scattering occurs. To accomplish this, the manufacturer has selected a pressure of neon that favors inelastic scattering during the excitation of the ten $2p_i$ levels over that of the four $1s_i$ levels. The ratio of the total number of states in these levels is 36:12 = 3:1; that may enhance the effectiveness of the higher energy group. When the electrons have been accelerated to energies near 19 eV, the neon atoms that are excited to the $2p_i$ levels may emit visible photons in transitions to the $1s_i$ levels. Of course, some of the atoms will emit ultraviolet photons in transitions to the ground state.

Conclusion

Student interest in quantum mechanics can be increased through laboratory experiments that illustrate the inadequacy of classical physics for understanding microscopic phenomena. Resonance potentials reveal that quantized electronic energy levels really exist. Quantization is the fundamental concept necessary for appreciating the development of quantum mechanics. An excellent discussion of the use of electron spectroscopic methods in teaching has been presented by Allan in *this Journal* (*10*).

A firm experimental understanding of quantization makes the study of quantum mechanics more meaningful. The experiment described gives students an appreciation for the concept of quantization and the field of electron spectroscopy. In addition, it allows them to imitate a historic experiment in the development of the quantum theory.

Acknowledgment

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[5]Another instrument (Klinger Model K4301) contains a mixture of mercury and neon and is operated at room temperature. There, the collector current reaches a maximum when the accelerating potential is about 17 V. The UV emitted by the neon can be detected. At about 19 V, visible light from the neon appears.

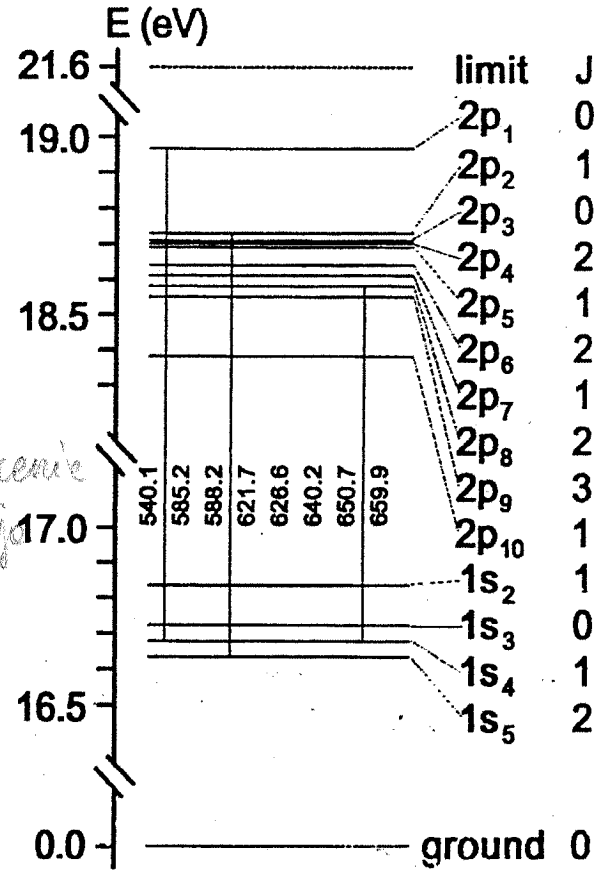

Figure 3. Partial Energy-Level Diagram for Neon. The excited states are labelled with the Paschen notation and the total electronic angular momentum quantum number, J. The 1s levels comprise the four possible states associated with electronic configuration $1s^2\ 2s^2\ 2p^5\ 3s$; the 2p levels comprise the ten possible states associated with the electronic configuration $1s^2\ 2s^2\ 2p^5\ 3p$. The nine strongest visible transitions from the 2p to 1s levels are shown with their corresponding air-wavelengths in nanometers. These consititute the major lines that can be resolved in the glowing regions of neon.

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