2.3 Analysis of the Data

Table 1.1 is a sample of data obtained by a student.† Two drops were used and several charges were measured; for each charge six measurements were performed and averaged as shown in Table 1.1.

The pertinent parameters for these data were

Distance of fall	$d = 7.63 \times 10^{-2}$ cm
Temperature	$T = 25°$ C
Pressure	$P = 76.01$ cm Hg
Density	$\rho' - (\rho \quad \sigma) = 8.82 \times 10^{-1}$ gm/cm^3
Potential	$V = 500$ V $= 1.666\ldots$ statvolts
Plate separation	$s = 4.71 \times 10^{-1}$ cm

A plot of the data and the linear least squares fit are shown in Fig 1.4. From the least squares fit we obtain (see Eq. 2.5)

$$A_1 = 0.153 \pm 0.003 \qquad B_1 = -0.038 \pm 0.016$$
$$e = (4.90 \pm 0.1) \times 10^{-10} \text{ esu}$$
$$A_2 = 0.144 \pm 0.006 \qquad B_2 = -0.321 \pm 0.014$$
$$e = (4.69 \pm 0.1) \times 10^{-10} \text{ esu}$$

where the values of e are calculated‡ from A using the drop radius shown in Table 1.1 obtained from $\langle 1/t_0 \rangle$. The values of e are in good agreement with the accepted value

$$e = 4.803 \times 10^{-10} \text{ esu}$$

3. The Frank-Hertz Experiment

3.1 General

From the early spectroscopic work it was clear that atoms emitted radiation at discrete frequencies; from Bohr's model the frequency 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 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 through the inelastic scattering of electrons from the

† D. Peters, class of 1962.

‡ It is seen that in this special case (partly because of the low voltage) the diameter of the drops is so small that the correction to the Stokes equation is considerable (15 percent).

§ They are still bound after the process.

entire atom. If the atom that is bombarded does not become 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.

Frank and 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.

The necessary apparatus consists of an electron-emitting filament and an adequate structure for accelerating these electrons to a desired (variable) potential. The accelerated electrons are allowed to bombard the atomic vapor under investigation and the excitation of the atoms is studied as a function of accelerating potential.

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, or the change in absorption of a given spectral line, or some other related phenomenon; however, a much more sensitive technique consists in 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; clearly, if a small retarding potential exists before the collector region, electrons that have scattered inelastically will be unable to overcome it and thus will not reach the anode.

These conditions are created in the experimental arrangement by using two grids between the cathode and collector. When the potentials are distributed as in Fig. 1.5a, the beam is accelerated between the cathode and grid 1; then it is allowed to drift in the interaction region between the two grids and has to overcome the retarding potential between grid 2 and the anode. When the threshold for exciting the first level is reached, a sharp decrease in electron current is observed, proportional to the number of collisions that have occurred (product of atomic-density and cross section). It is clear that when the threshold of the next level is reached, a further dip in the collector current will be observed. These current decreases (dips) are superimposed on a monotonically rising curve; indeed the number of electrons reaching the anode depends on V_{acc}, inasmuch as it reduces space charge effects and elastic scattering in the dense vapor. In addition, the dips are not perfectly sharp because of the distribution of velocities of the thermionically emitted electrons, and the rise of the excitation cross section.

An alternate distribution of potentials is shown in Fig. 1.5b, where V_{acc} is applied at grid 2 so that an electron can gain further energy after a col-

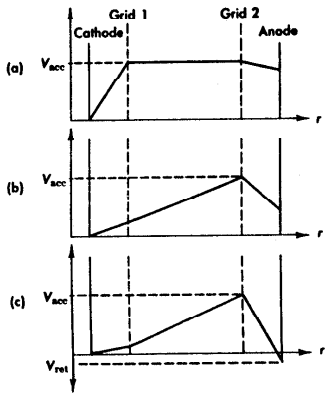


FIG. 1.5 Different configurations of the potential in a Frank-Hertz arrangement. (a) For observation of single excitation. (b) For observation of multiple excitation. (c) For measuring the ionization potential.

lision in the space between the two grids. In this case when V_{acc} reaches the first excitation potential, inelastic collisions are again possible and the decrease in electron current is observed at the anode; when, however, V_{acc} reaches a value twice that of the first excitation potential, it is possible for an electron to excite an atom halfway between the grids, lose all its energy, and then gain anew enough energy to excite a second atom and end with practically zero energy at grid 2; thus it is not able to overcome the retarding potential and reach the anode, giving rise to a second dip in the current.

The advantage of this setup is that the current dips are much more pronounced, and it is easy to obtain fivefold or even larger multiplicity in the excitation of the first level. However, it is practically impossible to observe the excitation of higher levels. As before, a slight retarding potential is applied between grid 2 and the anode, and an accelerating potential between the cathode and grid 1, sufficient to overcome space charge effects and to provide adequate electron current. It is evident that the density of the atomic vapor through which the electron beam passes greatly affects the observed results. Low densities result in large electron currents but very small dips; on the contrary, high density has as a consequence weaker currents but proportionally larger dips. When mercury vapor is used, obviously the adjustment of the tube temperature provides control of the density.

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 Frank-Hertz experiment are mercury, neon, and argon.

The same apparatus can be used for the measurement of the ionization potential—that is, the energy required to remove an electron completely from the atom. In this case, instead of observing the bombarding electron beam, it is easier to detect the ions that are formed. The distribution of potentials is as shown in Fig. 1.5c, where the anode is made slightly negative with respect to the cathode; no electrons can then reach the anode, which becomes an ion collector. The accelerating potential is increased until a sharp rise in the ion current measured at the anode is observed.

In both types of measurements the values obtained for the accelerating potential have to be corrected for the contact potential difference (cpd) between cathode and anode.† If in the excitation experiment the same level has been observed two or more times, however, the potential difference between adjacent peaks is an exact measure of the excitation energy, since the contact potential difference shifts the whole voltage scale. Once the excitation energy has been found the contact potential difference is given by the difference between this true value and the first peak; in turn the contact potential difference so found can be used to correct the ionization potential measurement.

3.2 THE EXPERIMENT

In this laboratory a mercury-filled tube made by the Leybold Company (55580) is used; the electrode configuration is shown in Fig. 1.6; the circuit diagrams for the measurement of excitation and of ionization potential are given in Figs. 1.7a and 1.7b respectively.

As can be seen from the circuit diagram, grid 1 is operated in the neighborhood of 1.5 V, and the retarding potential is of the same order. The anode currents are of the order of 10^{-9} amp and are measured either with a sensitive galvanometer (for example Leeds and Northrup No. 2500) or with a Keithley 600A electrometer (see Chapter 4); adequate shielding of the leads is required to eliminate a-c pickup and induced voltages. The diagram of Fig. 1.7a uses the distribution of potentials as shown in Fig. 1.5b and the accelerating voltage can be measured with an ordinary voltmeter (for example, Triplet 625) in steps of 0.1 V, or with a vacuum tube voltmeter.

† See Chapter 3. Briefly this is because the "work function" for the metal of which the anode is made is usually higher than that of the cathode. The work function is a measure of the "ionization potential" of the metal; that is, of the energy needed to extract an electron from it.

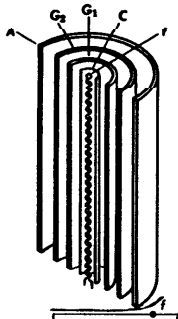
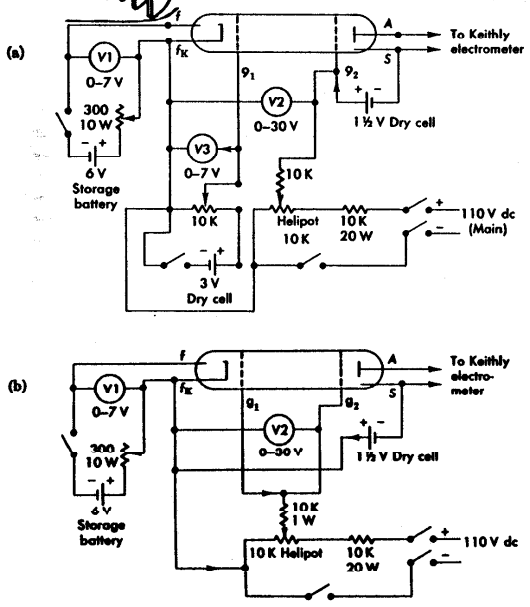


FIG. 1.6 (*Left*) Sketch of a cylindrical Frank-Herts tube.

FIG. 1.7 (*Below*) Wiring diagram for the Frank-Herts experiment. (a) For observation of excitation. (b) For observation of ionisation.



The Frank-Hertz tube is placed in a small oven which is heated by line voltage through a variac; it should be operated in the vicinity of 200° C for the excitation curve and between 100° to 150° C for the ionization curve. To measure the temperature a copper-constantan thermocouple should be inserted through the small hole of the furnace. The junction should be positioned on the side of the tube near the electrodes. The other junction is immersed in a thermos of ice and water bath. The potential developed across the thermocouple is measured with a potentiometer (usually set on its lowest scale); Fig. 1.8 gives a calibration curve for a copper-constantan thermocouple.

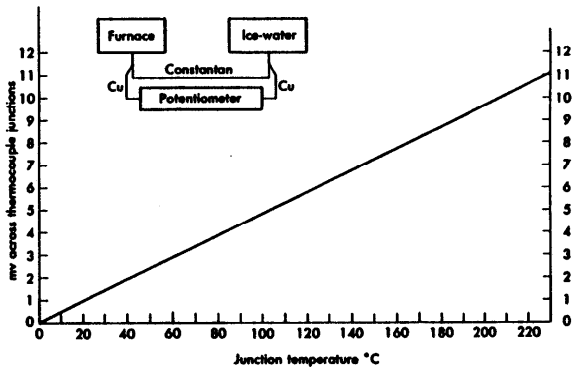


FIG. 1.8 Calibration of copper constant thermocouple using ice standard.

The resolution and definition of both the excitation and ionization curves is a function of atom density (temperature) and electron beam density (filament and grid 1 voltage) and the experimenter has to find the optimum conditions. However, for large beam densities a discharge occurs, which obviously is to be avoided.

A suggested adjustment procedure is to set grid 2 at 30 V and then advance grid 1 until the discharge sets in, as evidenced by the immediate build up of the anode current. Grid 2 should then be quickly returned to 0 V and grid 1 set slightly below the breakdown voltage; a reasonable filament voltage is between 4 and 6 V. To determine whether the tube is overheated it can be taken out of the oven for about 30 sec; the collector current will then increase and maxima may appear if such is the case. If

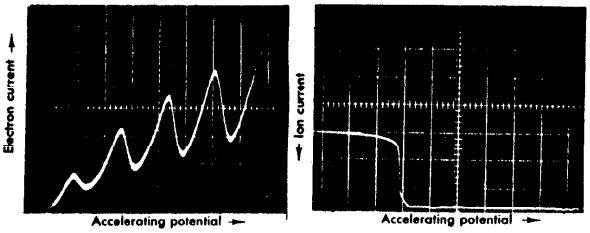


FIG. 1.9 Oscilloscope display of Frank-Hertz experiment. (a) Beam current vs. accelerating potential. (b) Ion current vs. accelerating potential.

the tube is too cool, the emission current will be large, and the maxima, particularly those of higher order, will be washed out.

With present-day techniques it is possible to use an oscilloscope for a simultaneous display of the electron or ion current against accelerating potential. In this laboratory a Tektronix 545 oscilloscope was used; its sweep generator (sawtooth) output is fed to the accelerating grid, while it synchronously drives the horizontal sweep; the output of the Keithley is fed to the vertical input. An excitation curve as well as an ionization curve obtained by a student† in this fashion are shown in Fig. 1.9. The oscilloscope method can be very useful in finding optimum operating conditions for mercury vapor pressure and electron beam density.

3.3 ANALYSIS OF THE DATA

Two sets of data obtained by a student‡ for the excitation potential point by point are shown in Fig. 1.10; both curves are obtained at a temperature of 195° C and with +1 V on grid 1. The filament voltage is 2.5 V for curve *C* and 1.85 V for curve *D* with the consequent decrease of the electron current by a whole decade.

Readings are taken for 1-V changes on grid 2 with smaller steps in the vicinity of the peak. A significant decrease in electron (collector) current is noticed every time the potential on grid 2 is increased by approximately 5 V, thereby indicating that energy is transferred from the beam in (bundles) "quanta" of 5 eV only. Indeed, a prominent line in the spectrum of mercury exists at 2537 Å, corresponding to 12378/2537 = 4.86 eV, arising from the

† D. Statt, class of 1963.

‡ D. Owen, class of 1963.

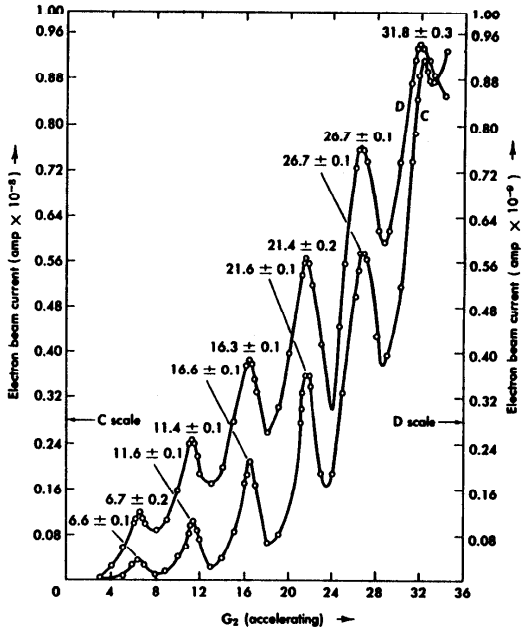


FIG. 1.10 Plot of beam current versus accelerating voltage in Frank-Hertz experiment. Curve C (left-hand scale) is obtained with the filament set at 2.5 volts while Curve D (right-hand scale) with filament at 1.85 volts.

transition of the $6s6p\ ^3P_1$ excited state to the $6s6s\ ^1S_0$ ground state.† Thus our interpretation is that the electrons in the beam excite the mercury atom from the ground state to the $^3P_1$ state, thereby losing 4.86 eV in the process.

The location of the peaks is indicated in Fig. 1.10 and was measured in this case with a vacuum tube voltmeter (VTVM). The average value ob-

† See Chapter 2.

tained for the spacing between peaks is

$$5.02 \pm 0.1 \text{ V}$$

to be compared with the accepted value of

$$4.90 \text{ V}$$

while the spectroscopic value for the energy level difference (as mentioned before) is 4.86 eV.

Using the value found for the spacing between peaks and the location of the first peak, we obtain the contact potential:

$$(6.65 \pm 0.15) - (5.02 \pm 0.1) = 1.63 \pm 0.18 \text{ V}$$

As mentioned in Section 3.1, with the configuration of potentials used (Fig. 1.5b) it is more probable that the same energy level will be excited twice rather than that several different levels will be excited; indeed this is the way in which the data of Fig. 1.10 have been interpreted. This is not surprising if one considers the excitation probabilities for the energy levels lying closest to the ground state of mercury. It is possible, however, by using different grid and voltage configurations (for example, Fig. 1.5a) and improved resolution, to observe the excitations to other levels, namely, the $6\,^3P_2$, $6\,^3P_0$ and $6\,^1P_1$.

For the ionization potential, data obtained by a student† are shown in Fig. 1.11. A word of caution is to be added to the interpretation of such ionization curves, which seem strongly dependent on filament voltage and vapor pressure: indeed the very sharp increase observed in ion current is due to an avalanche (regenerative effect) of the ejected electrons ionizing more atoms, the thus-ejected electrons ionizing still more atoms and so on; this avalanche does not necessarily occur as soon as the ionization threshold is crossed. If the vapor is too dense, the ions recombine before reaching the anode, thus masking the effect until complete breakdown sets in.

The curve shown was taken at a temperature of 155° C with a filament voltage of 2.6 V. If, then, the onset of ion current is taken to be at 11.4 ± 0.2 V, and using the value for the contact potential previously determined (from the excitation curve), $1.63 \pm .18$ V, the ionization potential is obtained as

$$(11.4 \pm 0.2) - (1.63 \pm 0.18) = 9.77 \pm 0.25 \text{ eV}$$

only in fair agreement with the accepted value of 10.39 eV.

An additional feature of the curve of Fig. 1.11 is a "knee" in the ion current, setting in at approximately 8 V; the observation of this "knee" as well is strongly dependent on the temperature and current density, but

† J. Reed, class of 1961.

can be consistently reproduced over a considerable range of these parameters. In order to understand this behavior we remember that the arrival of ions at the anode is equivalent to the departure of electrons; indeed the observed behavior is due to a photoelectric effect produced at the anode, by short-wavelength light quanta (the electrons are further accelerated by grid 2). When the electron beam reaches 8 V, it can excite the $6\,^1P_1$ level (lying at 6.7 eV above the ground state, plus 1.63 V for contact potential difference), so the mercury atoms radiate the 1849 Å ultraviolet line when returning to the ground state. These quanta are very efficient in ejecting photoelectrons, and the cylindrical geometry of the anode is most favorable for this process.

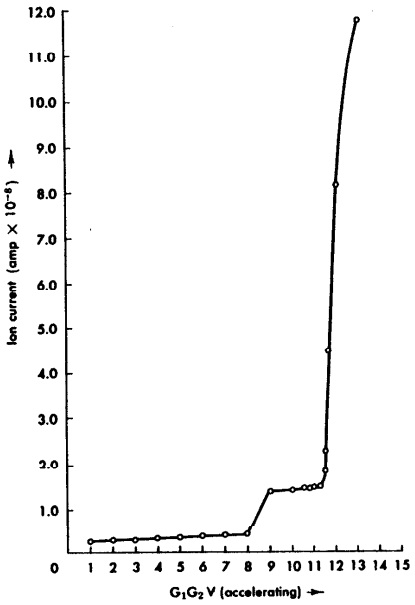


FIG. 1.11 Ion current versus accelerating voltage in Frank-Hertz experiment. Knee at 8 V is due to photoeffect.