A PHOTOCELL EXPERIMENT FOR

SECONDARY SCHOOL PHYSICS

by

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ABSTRACT

There was recently introduced into the secondary schools
of British Columbia a course in physics based primarily upon
the work of the Physical Science Study Committee. At the end
of the course a study is made of atomic physics. A fundamental
concept involved in the study of atomic physics is that of the
quantum of light energy. A photocell experiment suitable for
use in secondary schools has been developed which is intended
to help the student to come to major conclusions regarding the
photoelectric effect and the nature of light.

In developing this experiment investigations were made to
determine the suitability of available apparatus and methods.
Among the aspects investigated were photocells, light sources,
filters, methods of measuring small currents, and methods of
investigating the photoelectric effect. The experiment which
evolved was then performed under conditions more suitable than
exist in secondary schools. The results of the experiment
agreed with the major points of the theory and yielded a value
for Planck's constant within ten per cent of accepted value.

It was concluded that a photocell experiment can be per-
formed in secondary schools which will yield results which
agree with the theory.

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CHAPTER 1. INTRODUCTION

1.1 The Problem.

Recently there was introduced into the secondary schools of British Columbia a course in physics based primarily upon the work of the Physical Science Study Committee (PSSC). In two years, work in this course the student is given the opportunity to study the behaviour of matter and energy and to discover some of the fundamental concepts which have been developed concerning this behaviour. At the conclusion of the course the student is introduced to the study of atomic physics, giving him the opportunity to begin to understand the relationship among some of the topics studied earlier. Fundamental to an understanding of atomic phenomena is the concept of a quantum of energy. At present there is no method consistent with the philosophy of the course to develop this concept.

The philosophy upon which the present course is based is primarily an experimental one. Among its most important aims is the development in the student of an appreciation for the methods used in physics, and to this end the student is required to do physics rather than watch it being done. An expression of this philosophy is to be found in the introduction to the curriculum guide published by the British Columbia Department of Education.

> Traditional physics courses generally have been concerned with description and information. This information has been at the expense of learning processes and methods. The tremendous expansion of knowledge in this field has now made it impossible to give all the factual detail. It has

been considered desirable to concentrate the efforts of students on principles and methods.[1]

In keeping with this philosophy, each step in the development of a topic must be arrived at by experiment, preferably by the students themselves. At no point can the teacher fall back upon dogmatism which is to be blindly accepted by the students as truth. However, no experiment is available at the present time which can be used to develop the concepts of a quantum of energy.

The two year course is intended to present to the student the total picture of physics, so that even the student who will never again study physics as a discipline will have done a comprehensive piece of work in physics. For this reason the inclusion of atomic physics cannot be avoided. Many of the most important advances of this century have been in the field of atomic physics and in this respect atomic physics is no longer a modern and specialized study. It is very much a part of everyday living and so has an important place in general education.

In developing the unit on atomic physics it was decided that the concept of the photon is basic. In view of the experimental nature of the course, there is a need for an experiment or series of experiments which can be performed either by the students or by the teacher to develop an understanding of this concept. Since the discovery of the nature of the photoelectric

1 British Columbia, Department of Education, Division of Curriculum, Senior Secondary School Science, Physics 12, 1965, p. 7.

effect was largely responsible for the acceptance of the exist-
ence of quanta of energy, an experiment involving the photo-
electric effect is thought to be a most useful way to develop the
concept of the quantum of energy.

It is the purpose of this thesis to develop an experiment
or series of experiments for secondary school physics based
upon the photoelectric effect. The purpose of the experiments
is to develop the concept of the quantum of energy and to measure
Planck's constant.

1.2 History of the Photoelectric Effect.

In 1887, while in the process of doing research on the reson-
ance of electrical circuits, Hertz[2] discovered the photoelectric
effect. He observed that the length of a spark which could be
induced in a secondary circuit was much reduced if the spark gap
was shielded from the light of the spark in the primary circuit.
He went on to determine that the effect was due entirely to the
illumination of the electrodes, that only the ultra-violet
portion of the light was effective, and that the spark was long-
est when the negative electrode was being illuminated. In further
investigations Hallwachs[3] showed that a polished zinc plate
connected to an electroscope would retain a positive charge while
being illuminated by light from a carbon arc, but would lose a

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2 A. L. Hughes and L. A. DuBridge, Photoelectric Phenomena,
New York, McGraw-Hill, 1932, p. 3.

3 Ibid., p. 3

negative charge when illuminated. This effect could only be due to loss of negative electricity, for any gain in positive electricity would have to result from positive electricity arriving with the light. Such a theory cannot be supported by experiment. It has recently been shown that an electroscope can also be charged by illuminating it under the right conditions.[4]

By 1899 both Lenard[5] and Thomson[6] had shown that the negatively charged particles involved were indentical to those found in cathode rays and thus were electrons. Lenard[7] also showed that the maximum kinetic energies of the released electrons were independent of the intensity of the light used but that the number of electrons released was directly proportional to the light intensity.

The experimental fact that the maximum kinetic energies of the photoelectrons are independent of the intensity of the light contradicts what one would expect from a consideration of the classical wave theory of light. According to this theory, an increase in light intensity is due to an increase in the amplitude of the electromagnetic wave. An electron close to the sur-

4 J. E. Miller, A. R. Reed, and D. P. Miller, "Photoelectric Charging of an Electroscope", American Journal of Physics, vol. 34 (1966), p. 172.

5 P. Lenard, "The Production of Cathode Rays by Ultra-violet Light", Annalen der Physik, vol. 2 (1900), pp. 359-375.

6 J. J. Thomson, "On the Masses of Ions at Low Pressures", Philosophical Magazine, series 5, vol. 48 (1899), pp. 547 - 567.

7 Hughes and DuBridge, Photoelectric Phenomena, p. 4.

face of a metal would experience a much greater force due to the large electric field than it would due to the smaller electric field of lower intensity light. This greater force would be expected to give the electrons it pulls from the metal greater acceleration and greater kinetic energy than the force due to the less intense light.

There is a further contradiction as well. According to the wave model of light an atom would require a time of order of hours to absorb enough energy from an electromagnetic wave train to eject an electron with the kinetic energy observed. It has been shown that the time lapse between illumination and the onset of photoelectric current is not more than 3×10^{-9} seconds.[8]

In 1905 Einstein[9] published a hypothesis which enabled him to predict the maximum kinetic energy that an electron could have when emitted from an illuminated metallic surface. Einstein postulated the existence of a light corpuscle or photon with energy of magnitude hf, where f was the frequency of the light. The constant,h,was Planck's constant, 6.63×10^{-34} joule-second, which had recently been introduced by Planck in his quantum theory. Einstein assumed that this photon gave all of its energy to one electron. If this electron had to do an amount of work,w, to escape from the metal, then its kinetic energy,K,after leaving

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8 G. P. Harnwell and J. J. Livingood, Experimental Atomic Physics, New York, McGraw-Hill, 1933, p. 214.

9 A. Einstein, "Light Generation and Light Absorption," Annalen der Physik, vol. 20 (1906), pp. 199 - 206.

the surface would be given by

$$K = hf - w \qquad\qquad (1.1)$$

An explanation of the phenomena observed by Lenard is readily arrived at using the above model. In this case increased light intensity is due to an increased number of photons. Since each photon has energy of magnitude hf, the result is more electrons emitted and thus larger photocurrent, but no increase in the kinetic energies of these electrons. Since all of the energy of the photon is given to an electron at once, the time lapse required by the wave model is no longer necessary.

The Einstein hypothesis had still to be verified experimentally and during the next ten years much work was done. By 1915 the results were still not clear, however. Slopes for the kinetic energy - frequency graphs varied by as much as sixty per cent and it was not even clear that the relationship between kinetic energy and frequency was linear.[10] In 1907, for example, Ladenburg concluded that the energy was directly proportional to the square of the frequency, but Joffe later worked over Ladenburg's data and showed that they just as well fit a linear relationship between energy and frequency because of the small range of frequencies used and the large uncertainties involved.[11]

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10 R. A. Millikan, "A Direct Photoelectric Determination of Planck's 'h'," The Physical Review, series 2, vol. 7 (1916), p. 357.

11 Ibid., p. 357.

Richardson and Compton[12] did much more reliable work in 1912 and concluded that the maximum electron energy was a linear function of the frequency of the light. About the same time Hughes[13] found that the energy - frequency relationship was linear, but found that the slope of the graph of this relationship was consistently lower than expected, concluding that not all of the energy of the photon was transferred to the electrons. Millikan later critized this work on the grounds that only three points on the graph were located and that three points cannot justify any conclusions about the shape of the graph.

It was left to Millikan[14] to check Einstein's hypothesis to a high degree of accuracy. In 1915 a large glass tube was developed which would remove in a vacuum all of the surface films from the metal being studied. A method was developed to measure simultaneously the magnitude of the photocurrent, the energies of the photoelectrons, and the contact potential differences between the surfaces involved. Measurements were made over as great a range of frequencies of light as possible. After taking many precautions to avoid the errors and uncertainties encountered in the work of most of the other investigations

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12 O. W. Richardson and K. T. Compton, "The Photoelectric Effect," Philosophical Magazine, series 6, vol. 24 (1912), pp. 575 - 594.

13 A. L. Hughes, "On the Emission Velocities of Photo-Electrons," Philosophical Transactions of the Royal Society of London, series A, vol. 212 (1913), pp. 205 - 226.

14 Millikan, "Planck's 'h'," pp. 355 - 388.

to that time ,Millikan concluded that a linear relationship did exist between maximum electron energies and the frequency of the light. The slope of the energy - frequency graph was found to agree with the known and accepted values of h.

1.3   Review of the Literature.

A review of the physics abstracts from 1910 to 1964 reveals that, although much work has been done investigating the photo-electric effect and developing photoelectric cells, few attempts have been made and reported to develop a photocell experiment suitable for use in secondary school physics.

The earliest photocell demonstration for secondary schools reported was due to Suhrmann.[15] He used a photocell irradiated successively by the blue and yellow lines of the mercury spectrum. Using a simple potentiometer circuit the maximum potential diff-erence developed by the cell was measured in each case. Planck's constant was then calculated from

$$h = e \; \frac{V_2 - V_1}{f_2 - f_1} \qquad (1.2)$$

where e is the charge on an electron, V is the potential diff-erence, and f the frequency of the light used.

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15 R. Suhrmann, "Determination of Planck's Constant as a Quantitative Lecture Experiment," Physikalische Zeitschrift, vol. 33 (1932), p. 579.

A somewhat different arrangement was used by Aussenegg[16] to measure the maximum potential difference developed by the photocell. He connected a capacitor between the emitter and collector of a photocell and charged the capacitor by illuminating the photocell with light of known frequency. The maximum charge Q accumulated on the capacitor was measured for each frequency by discharging it through a ballistic galvanometer. The potential difference V across the capacitor was found from

$$V = \frac{Q}{C} \qquad (1.3)$$

where C was the capacitance. Since V was also the potential difference across the photocell, h was calculated from equation 1.2.

Still another variation was reported by Davis.[17] A chopper consisting of a rotating disc with equally spaced holes around its perimeter was placed between the light source and the photocell. Since the light was passed at intervals, the photocurrent produced was an alternating one. This was amplified using an audio amplifier and detected with earphones. A stopping potential difference was applied to the photocell, making the collector

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16 F. Aussenegg, "A Simple Method for the Determination of Planck's Constant," Acta Physica Austriaca, vol. 14 (1961), pp. 440 - 444.

17 S. P. Davis, "Photoelectric Effect Experiment," American Journal of Physics, vol. 29 (1961), pp. 706 - 707.

negative with respect to the emitter. The minimum negative
potential difference for which a signal was audible was used as
a measure of the maximum kinetic energy of the electrons.
Planck's constant was then calculated using equation 1.2.

An evaluation of two commercial systems for the measurement
of Planck's constant which are suitable for use in secondary
schools has been made by Hansen and Clotfelter.[18] The first
of these is the system manufactured by E. Leybold's Nachfolger
of West Germany consisting of a mercury vapour lamp, direct
vision prism, photocell measuring amplifier, and appropriate
lenses, slits and holders. It was found that appreciable collect-
or currents due to photoelectrons being emitted from the collect-
or and going to the emitter made the determination of the applied
potential difference necessary to reduce the photocurrent to
zero very uncertain. Further problems were encountered when
the collector was heated as instructed in the literature supplied
with the equipment. The potential difference across the cell
was found to vary with the length of time elapsed between heat-
ing the collector and making the measurements. These problems
were largely offset by the fact that the apparatus is clearly
visible to the students.

The experimental arrangement has significant instruct-
ional value. Nearly all parts are clearly visible and are

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18 R. J. Hansen and B. E. Clotfelter, "Evaluation of Commer-
cial Apparatus for Measuring h/e," American Journal of Physics,
vol. 34 (1966), pp. 75 - 78.

very accessible. Selecting the desired line by adjustment
of the direct vision prism, varying the retarding potential,
and reading the current are all operations which help the
student to understand the method clearly. Although precise
results cannot be reliably obtained with the equipment,
the experiment definitely has educational value.[19]

The second system is manufactured by Madison Associates

of Madison, New Jersey. In this arrangement the photocell is

housed in a casing with ten filters, a filter magazine, and a

powerful mercury lamp. The photocell is used to charge a

capacitor, its potential difference being measured with an

electrometer-type direct current vacuum-tube voltmeter. The unit

is compact, easy to use, and yields accurate results. Its chief

disadvantage is that the student cannot see inside the casing

and so does not have an opportunity to fully understand what he

is doing. The total cost of the unit is in the neighbourhood of

$750.

It is significant that in neither case was any mention made

of varying the intensity of the light although this is a very

important aspect of the experiment.

1.4   Criteria to be Met by the Experiment.

Two basic criteria must be met by a photocell experiment

for secondary schools. The experiment must clearly demonstrate

the major phenomena involved and do so in a manner readily under-

stood by secondary school students.

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19 Ibid., p. 77.

With regard to the first criterion, two experimental facts should become clear as the results of the experiment are analyzed. The maximum kinetic energy of an electron ejected from the illuminated surface of a metal is a linear function of the frequency of the light. This energy is in no way affected by the intensity of the light, however. Most of the available methods of demonstrating the photoelectric effect do not emphasize the effect of the changing light intensity, but the whole quantum approach to the photoelectric is meaningless unless this independence of electron energies from the intensity of light is established.

The method used to arrive at the above conclusions must be readily understood by the students performing the experiment. Instrumentation must be kept as simple as possible and data should be such that it can be analyzed using methods familiar to the student. The student should then be free to concentrate upon the significance of the results he has obtained.

Although from equation 1.1 the photoelectric effect appears
to be a relatively simple phenomenon to investigate, many
factors enter to make the data gathered in an experiment diffi-
cult to interpret. Chief among these factors are contact poten-
tial differences between emitter and collector, and currents in
a direction opposite to that of the photocurrent. A method must
be found to measure the kinetic energy of photoelectrons and the
frequency of the light must be clearly defined. Only after
careful consideration of these factors can the data be used to
arrive at conclusions consistent with equation 1.1.

From equation 1.1 it can be seen that a graph of the kinetic
energy of photoelectrons as a function of light frequency is a
straight line with slope h. Equation 1.1 was written after a
consideration of only one photon and one electron, however. If
the light is monochromatic it can be assumed that each photon
has energy hf. These photons affect the free electrons within
a very thin layer on the illuminated surface,[1] and these electrons
have a distribution of kinetic energies after escaping the
surface, depending upon the amounts of energy expended in removing
the electrons from the metal. Since there is no reason to
assume that the energy expended is the same for each electron,
equation 1.1 must be written for the more general case of many
electrons. If the assumption is made that there is a minimum
amount of work necessary to remove an electron from the metal,

1 A. L. Hughes and L. A. DuBridge, Photoelectric Phenomena,
New York, McGraw-Hill, 1932, p. 9.

the work function p, then there is a maximum kinetic energy of
the photoelectrons,K_M,defined by equation 1.1. Thus, equation
1.1 may be written in the form

$$K_M = hf - p \qquad (2.1)$$

Various methods have been tried to measure K_M. Ramsauer[2]
measured the velocities of the photoelectrons by means of magnet-
ic deflections. If a magnetic field B is applied at right angles
to the direction of motion of a photoelectron, the electron
experiences a force at right angles to both of magnitude Bev
where v is the velocity of the electron. The electron will
turn in a circle of radius r defined by

$$r = \frac{mv}{Be} \qquad (2.2)$$

where m is the mass of the electron. The velocity and hence
kinetic energy of the electrons can be determined by measuring
r.

Another method involves the use of a capacitor connected
between the emitter and collector of the photocell. As the
photocurrent charges the capacitor, each successive electron
must do more work in overcoming the force of repulsion between
itself and the electrons already on the capacitor. Eventually
enough electrons have accumulated on the capacitor to make it
impossible for a photoelectron to reach the collector. The

2 C. Ramsauer, Annalen der Physik, vol. 45 (1914), p. 961,
cited in Hughes and DuBridge, Photoelectric Phenomena, p. 24.

potential difference across the capacitor may be measured
directly with an electrometer or by using equation 1.3. Since
an electron loses kinetic energy eV in overcoming a potential
difference V which is due to a force of repulsion, the maximum
potential difference across the capacitor, V_M, is a measure of
K_M and

$$eV_M = hf - p \qquad (2.3)$$

The method commonly used to determine K_M is to apply a
known retarding potential difference V between the emitter and
collector which the photoelectrons must overcome in order to
reach the collector. This potential difference is a measure
of the amount of work an electron must do in order to reach the
collector, for the electron has lost an amount of energy eV
upon reaching the collector. When the emitter is illuminated,
electrons with varying kinetic energies are released, and those
which initially have more energy than eV can reach the collector.
V may be varied until a photocurrent ceases to flow. The
value of V which just stops the most energetic electrons, V_M,
is again a measure of the maximum kinetic energy of the photo-
electrons and equation 2.3 again applies.

V_M is not determined solely by the applied retarding
potential difference, V_A, however. There is also a contact
potential difference V_C between the emitter and collector. To
understand this contact potential difference, the distribution
of energies of the free electrons in a metal must be considered.

A metal is composed of many atoms bound together in a
crystal lattice. Each atom has a number of electrons which are
associated specifically with that atom, but some electrons do
not appear to be associated with any atom in particular. These
electrons are the free or conduction electrons. They are free
to move within the metal under the influence of any electric
field in the metal. If one of these free electrons were to be
removed from the metal itself a net positive charge would be
left in the metal, since initially there are equal amounts of
positive and negative charge. Work must be done on the electron
in removing it to overcome the force of attraction between the
electron and the net positive charge left behind.

The distribution of the kinetic energies of the free
electrons is not the Maxwell distribution which applies to the
kinetic energies of the molecules in a gas. The distribution of
electron energies obeys the Fermi-Dirac statistics.[3] The number
of electrons per unit volume,dn,which can have kinetic energy
between E and E + dE is given by the relation

$$dn = \frac{3nE^{\frac{1}{2}}dE}{2E_F^{3/2}} \quad \text{for } E < E_F \quad (2.4)$$

At absolute zero of temperature the electrons will have the
lowest possible energy allowed and so will fill up the energy

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3 L. A. DuBridge, New Theories of the Photoelectric Effect,
Paris, Hermann and Co., 1935, p. 7.

band to a certain value E_F called the Fermi energy.[4] As the

temperature increases the average electron energy changes little,

but the upper limit of the energy distribution becomes less

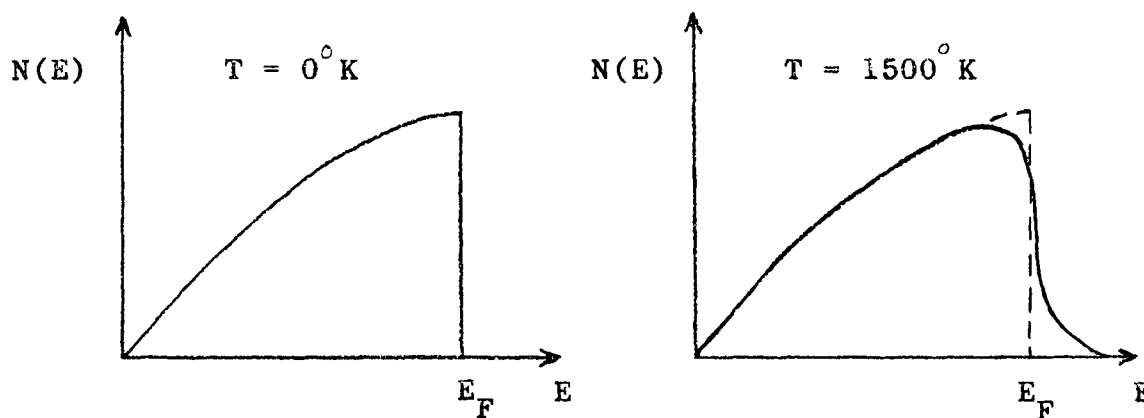sharply defined. These distributions are shown in figure 2.1.

Figure 2.1 - The Fermi-Dirac distribution of kinetic energies
of the free electrons in a metal. N(E)dE is the
total number of electrons with kinetic energy
between E and E + dE.[5]

Let a point at infinity be the reference point for the

potential energy of a free electron. A free electron at in-

finity is attracted toward the metal by the net positive charge

it has left in the metal, and loses potential energy as it

approaches the metal. If the potential energy of the electron is

zero at infinity and it falls into the metal at the Fermi energy

level, it will have a potential energy of magnitude -p, since

an amount of work p must be done on the electron to take it

from the metal back to infinity. This amount of work p is called

4 B. I. Bleaney and B. Bleaney, Electricity and Magnetism,
Oxford University Press, London, 1957, p. 84.

5 G. P. Harnwell and J. J. Livingood, Experimental Atomic
Physics, New York, McGraw-Hill, 1933, p. 214.

the work function of the metal.

Consider two metals, A and B, close together in a vacuum but not in contact. Let the work function of A be p_1, and that of B be p_2, and the Fermi energy of A be E_{FA} and that of B be E_{FB}. If an electron in A with energy E_{FA} is removed from the metal to infinity it gains potential energy p_1. If it then falls into B at the E_{FB} level, it loses potential energy p_2. Thus, its net change in potential energy is $p_1 - p_2$. The quantity called the contact potential difference V_C between metals A and B is defined by the relation

$$eV_C = p_1 - p_2 \tag{2.5}$$

If, on the other hand, the two metals are placed in contact, no energy must be supplied to transfer an electron from A to B. Let p_1 be greater than p_2. Then electrons at the E_{FB} level have greater potential energy than those at the E_{FA} level and electrons will flow from B into A. This flow will continue until the potential energy difference caused by the net positive charge remaining in B and the net negative charge accumulating in A is equal and opposite to the initial potential energy difference. This is illustrated in figure 2.2.
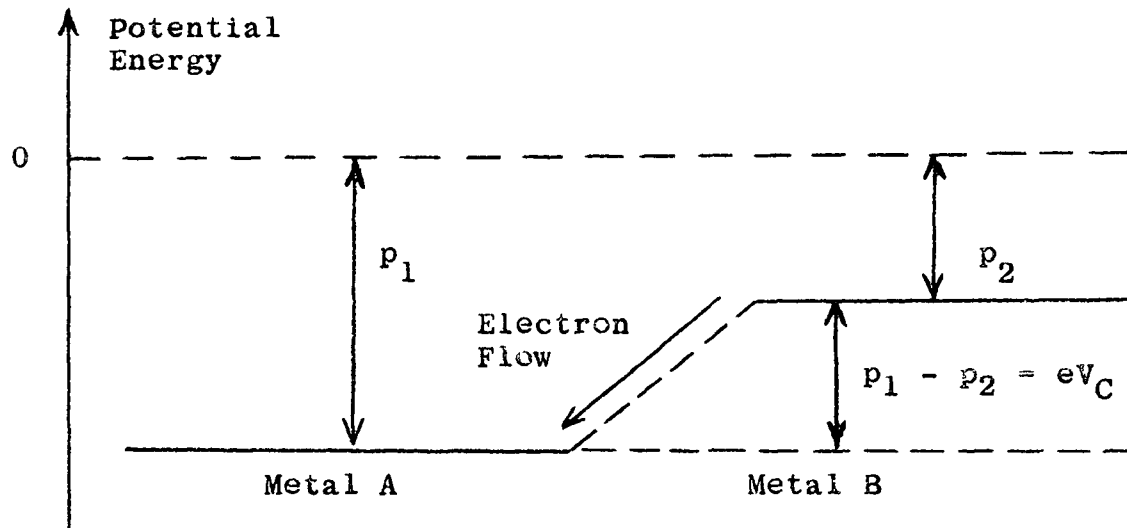
Figure 2.2 - Contact potential difference V_C due to electron flow between two metals in contact.

In practice the work function of the emitter is smaller than that of the collector. An electron loses potential energy in going from the emitter to collector, and thus gains kinetic energy. The contact potential difference is an accelerating one. V_C opposes the action of V_A and

$$V_M = V_A - V_C \qquad (2.6)$$

It must be noted that V_M and V_A are both potential differences between collector and emitter and are negative when measured with respect to the emitter. Equation 2.6 applies to absolute values of V_M, V_A, and V_C only.

Inspection of equation 2.3 shows that at some frequency of light f_o, the energy of the photons is equal to the work function of the emitter

$$hf_o = p. \qquad (2.7)$$

The frequency f_o is called the threshold frequency of the metal. Light with frequency less than f_o cannot release electrons from the metal no matter how intense this light may be.

Equation 2.3 may be written in the form

$$eV_M = hf - hf_o \qquad (2.8)$$

V_M may readily be determined by plotting photocurrent I as a function of V. Since in practice V_C is not known with a degree of certainty, it is usual to obtain V_A from this graph. When V is large and positive all of the photoelectrons reach the collector and I remains constant as V is increased. The photocurrent is said to be saturated. The photoelectrons have kinetic energies ranging from zero to K_M. As V becomes retarding, fewer and fewer photoelectrons reach the collector and the photocurrent decreases uniformly to zero. The expected graph is shown in figure 2.3.
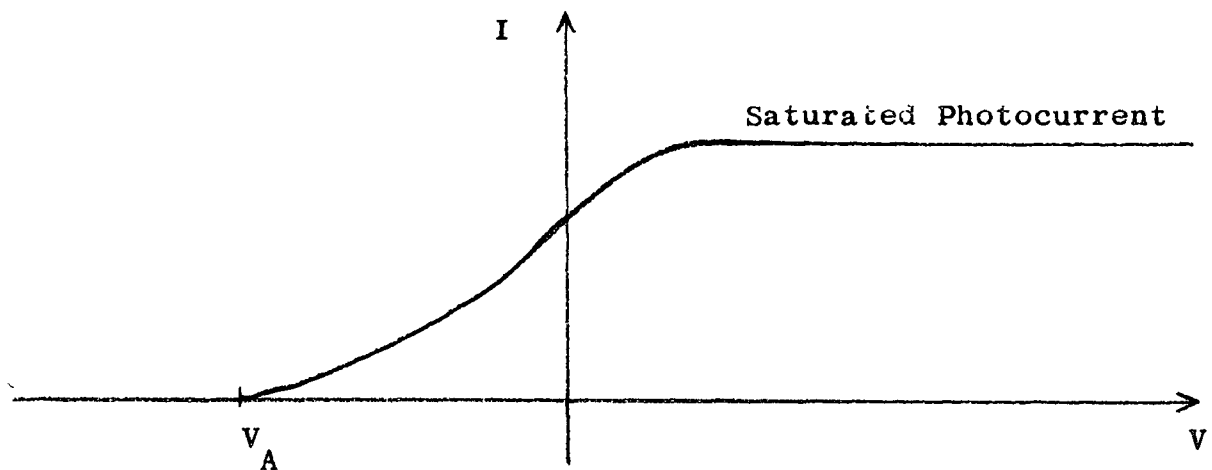
Figure 2.3 - Photocurrent I as a function of applied potential difference V between emitter and collector.

According to the classical theory of electrons in a metal, the kinetic energies of the free electrons are too small to take into consideration and so a definite amount of energy p must be supplied to the electrons to remove them from the metal. The maximum energy of the photoelectrons should be a sharply defined value, and the photocurrent - potential difference curve should approach the horizontal axis at a finite angle. When Millikan found that this was not the case, he attributed the error to small amounts of scattered light of high frequency, and ignored the small error resulting.[6]

According to the Sommerfeld Theory[7], however, some electrons already have enough energy at room temperature to put them above the Fermi energy level. It is possible to remove these electrons from the metal by doing an amount of work less than p. In practice, the maximum energy of the photoelectrons is not a sharply defined value, for some photoelectrons can have energies up to 1/40 electron-volt greater than K_M at room temperature. The resulting uncertainty is small enough to ignore at room temperature, but is temperature dependent and does increase with an increase in temperature.

A number of other factors can also alter the shape of the I-V curve. If the geometry of the collector is such that it captures few electrons easily, saturation will not occur until

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6 R. A. Millikan, "A Direct Determination of Planck's 'h'," The Physical Review, series 2, vol. 7 (1916), pp. 368 - 369.

7 DuBridge, New Theories, p. 6.

values of V are applied which are much larger than that necessary
to saturate the current in the ideal case. It is possible that
reflection of electrons or secondary emission of electrons can
occur at the collector, again making it necessary to apply
larger values of V than expected to achieve saturation. If
the work function of the collector is small enough, emission
of electrons from the collector can occur from reflected light
giving rise to reverse currents.

Such reverse currents can cause large errors in the
determination of V_A. If V is retarding for photoelectrons
emitted by the emitter, it is accelerating for photoelectrons
emitted from the collector. Such photoelectrons will be collect-
ed by the emitter causing a photocurrent in the opposite direct-
ion. The value of V_A obtained from the I-V curve indicates
when these two photocurrents are equal but opposite. The actual
value of V_A occurs when photocurrent from the emitter becomes
zero, and is larger than the apparent V_A. The problem is further
compounded by the fact that in the region of V_A, photocurrent
from the collector is much more dependent upon intensity of
light than is photocurrent from the emitter. Thus V_A becomes
dependent upon light intensity. The only way to reduce the
resulting uncertainty in V_A is to reduce this reverse current.
The I-V curve for the case of reverse current is shown in figure
2.4.
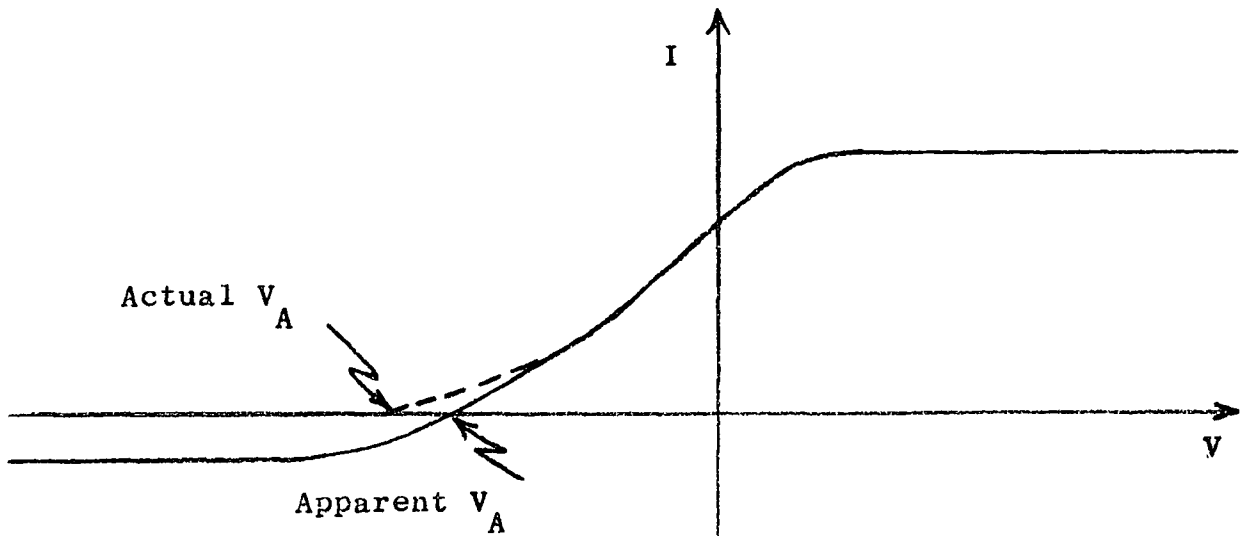
Figure 2.4 - Characteristics of a photocell with reverse current.

In determining the frequency of the light used, it is necessary to ensure that no light of greater frequency than that being studied is incident upon the emitter, since such light would give rise to photoelectrons of greater energy than those being studied. If light of frequency less than that being studied is incident upon the emitter, photoelectrons with less energy than those being studied will be emitted, but will not reach the collector in the region of V_A. These lower energy photoelectrons alter the shape of the I-V curve, but in no way affect the value of V_A.

The values of V_A for several frequencies of light having been measured, a plot of V_A as a function of f may be made. If equations 2.3 and 2.6 are combined, equation 2.9 may be obtained.

$$eV_M = hf - p \qquad (2.3)$$

$$V_M = V_A - V_C \qquad (2.6)$$

$$e \ (V_A - V_C) = hf - p$$

$$eV_A = hf - p + eV_C \qquad (2.9)$$

A plot of V_A as a function of f is a straight line whose slope is h/e. The accpeted value of h/e is 4.14×10^{-15} volt-seconds. Using the accepted value of e, 1.6×10^{-19} coulombs, h may be calculated from this slope.

The intercept with the V_M axis in equation 2.3 is -p/e. In equation 2.9 the intercept with the V_A axis is $-p/e + V_C$. If the accepted value of p for the emitter is known, V_C for the photocell may be calculated from the latter intercept.

CHAPTER 3.   EXPERIMENTAL INVESTIGATIONS AND RESULTS.

The experimental investigations focussed on two major questions. The first of these concerned the apparatus to be used. A photocell, a means of isolating several spectral lines, a means of changing light intensity, and instruments to measure small currents had to be found which could be put together into an experiment readily performed by secondary school students. The second major question concerned the method to be used. Two methods were apparent. The potential difference between emitter and collector could be varied and the photocurrent measured, or the photocell could be used to charge a capacitor and the maximum potential difference across it measured. The method chosen had to yield a reasonable result and be easily repeated by students. The procedures followed and results obtained are outlined below.

3.1 Photocells.

The first photocell investigated was that manufactured by the Leybold Company. This photocell has an emitter consisting of a layer of potassium on the inside of the glass wall. The collector is a platinum wire in the shape of a circular loop. The collector has electrical connections enabling the user to pass an electric current through it to evaporate any impurities. This process is called "flashing" the photocell in the literature provided with the photocell. The electrical connection between the emitter and the external circuit is well insulated from the

housing of the photocell to prevent leakage currents. The
photocell is illuminated through a small hole in the housing.
The housing itself is grounded to shield the photocell from any
external electrostatic effects.

Three such photocells were tested. The first was an old
cell having been in use for some time. The other two photo-
cells were new. The collector on one of these had been bent out
of its circular shape either in being manufactured or shipped,
however. The characteristics of the old and new photocells
shown in figures 3.1 and 3.2 were taken under similar conditions.
The characteristics of the photocell with the distorted collector
did not vary significantly from those of the other new photocell.

Figure 3.1 shows the large reverse currents which were
experienced with the older photocell. These reverse currents
were especially evident with an ultra-violet light source. The
apparent cut-off voltage V_A for ultra-violet light was consist-
ently found to be between V_A for blue light and V_A for green
light, a result attributed to the reverse current. Figure 3.2
shows that the reverse currents were much smaller when the new
photocells were used.

The old photocell was flashed several times in an attempt
to reduce the reverse current. At no time did the reverse
current decrease after flashing, and at one time the reverse
current increased. The new photocells were not flashed.

An optical system was devised which reduced the large

I Scale:
    Blue - 1 unit = 0.25 x 10^{-8} amp.
    Green - 1 unit = 0.25 x 10^{-10} amp.
Mercury light source
Corning filters

Figure 3.1 - Characteristics of old Leybold cell. Current
            measured with Keithley electrometer.
            V = potential difference between collector and
            ground.

I Scale:
    Blue - 1 unit = 0.25 x 10^{-8} amp.
    Green - 1 unit = 0.25 x 10^{-10} amp.
Mercury light source
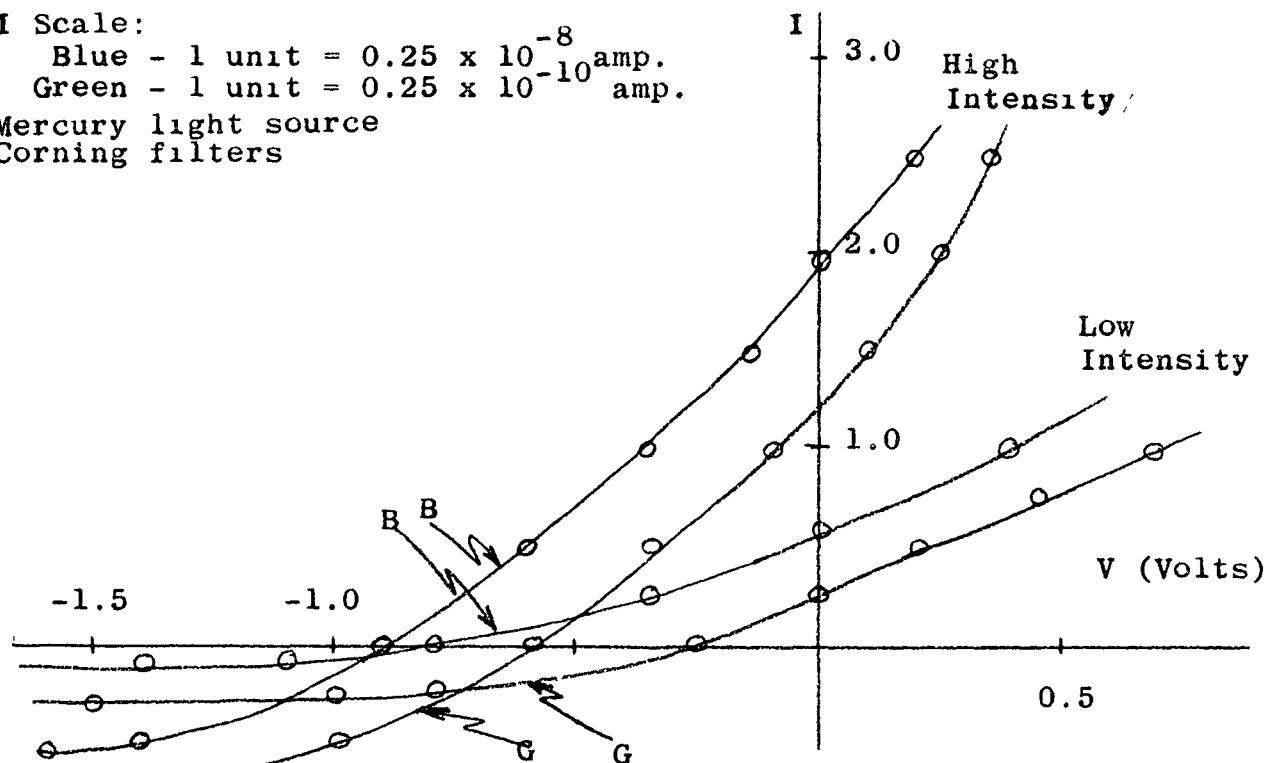Stark filters
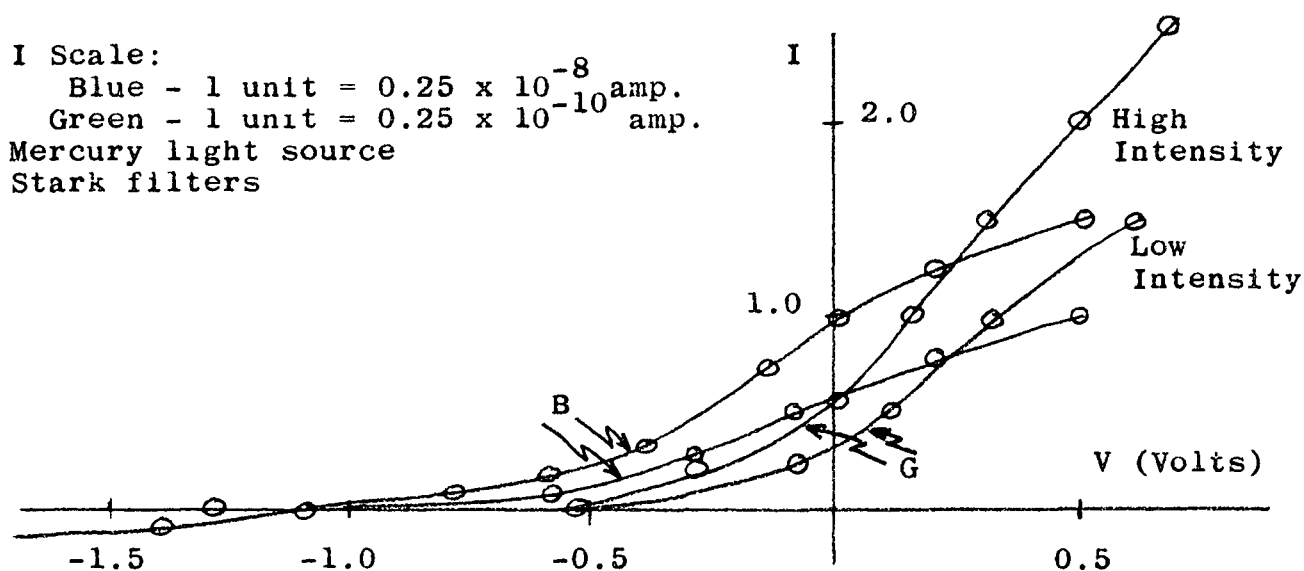
Figure 3.2 - Characteristics of new Leybold cells. Current
            measured on Keithley electrometer.
            V = potential difference between collector and
            ground.

reverse current experienced with the older photocell. A spot of light approximately one centimeter in diameter was focussed onto the plane of the collector reducing the amount of light reaching the collector. Currents of the order of 10^{-10} ampere were produced by this spot source, but the disadvantage of having to measure such a small current was largely offset by two major advantages. The reverse current was small and the same area of the emitter could be used for all measurements keeping the work function of the emitter constant.

It was thought at one point that the reverse current may be of thermionic origin. The photocell housing was packed in dry ice, but no significant change in reverse current was noted. Since the magnitude of a current of thermionic origin decreases as the temperature decreases, it was concluded that the reverse current was not thermionic in origin.

Four commercial photocells were investigated. Their main advantage was that they were much less expensive than the Leybold photocell. Three of these photocells, numbers 929, 1P39, and 5581, were similar in construction, having an emitter shaped like part of a cylinder coated with a composite of materials and separated from the glass wall of the photocell. The collector in each case was a single post in front of the emitter. With such a design it was very difficult to illuminate the emitter without illuminating the collector as well. The characteristics of the 929 and 1P39 photocells were very similar and are shown in figure 3.3. The characteristics of the 5581, a gas

I Scale: Blue - 1 unit = 0.5 x 10^{-6} amp.
        Green - 1 unit = 0.5 x 10^{-7} amp.
Mercury light source
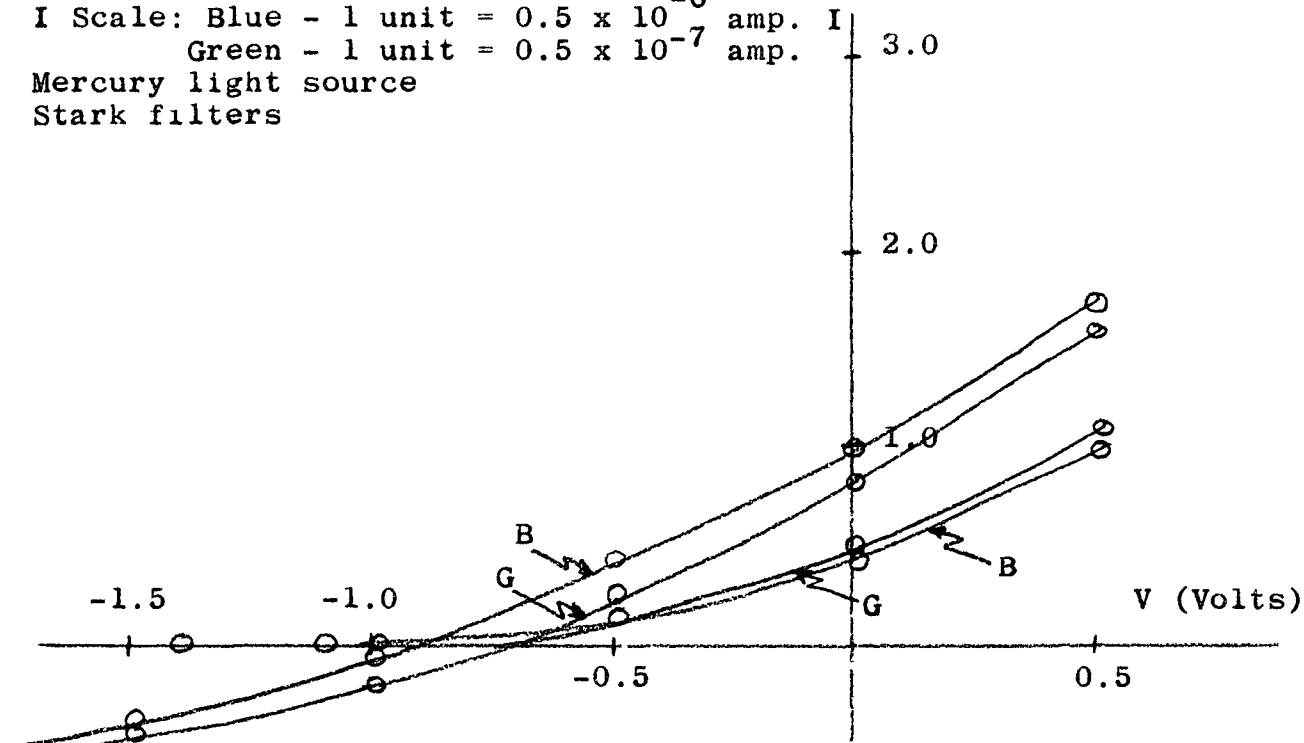Stark filters

Figure 3.3 - Characteristics of 929 and 1P39 commercial photo-
            cells. Current measured with Keithley electrometer.

I Scale: 1 unit = 10^{-10} amp.
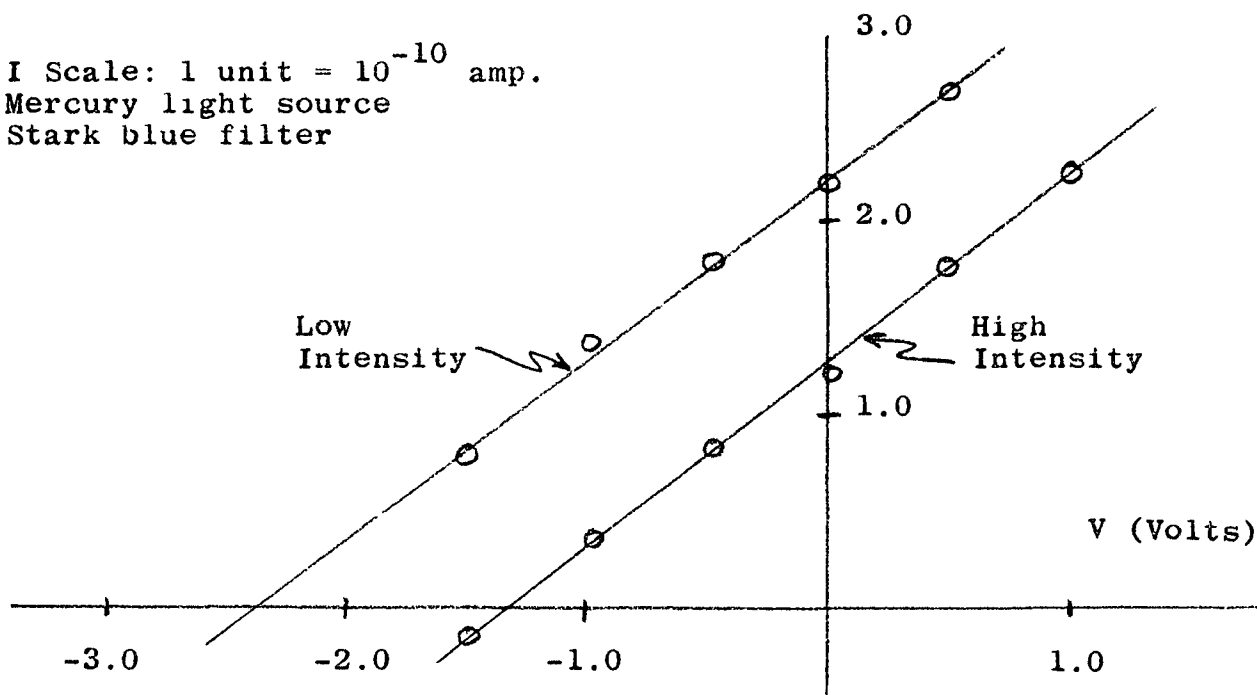Mercury light source
Stark blue filter

Figure 3.4 - Characteristics of 5581 commercial photocell.
            Current measured with Keithley electrometer.

filled photocell, are shown in figure 3.4.

None of these photocells was considered suitable for this experiment. Figure 3.4 shows that the 5581 photocell apparently had large reverse currents. In any case, V_A was found to depend upon intensity. The other two photocells had large reverse currents for high intensity light. These reverse currents were probably due to the fact that the whole photocell was flooded with light. No way could be found, however, to illuminate these cells without obtaining reverse currents. Furthermore, the values of h/e obtained using the 929 and 1P39 cells were consistently too low. It was concluded that these photocells were unsuitable for these reasons.

A commercial photocell, number 926, was found whose collector was a disc mounted to one side of the emitter and at right angles to the emitter. This arrangement allowed the photocell to be illuminated without illuminating the collector. Large reverse currents were still obtained, however, even with the end of the photocell containing the collector masked with tape. The characteristics of this cell are shown in figure 3.5.

It was concluded from these investigations that the Leybold photocell was better suited for this experiment than any of the commercial photocells investigated.

3.2 Filters and Light Sources.

The problem was to isolate intense spectral lines so that

I Scale: 1 unit = 0.25 x 10^{-9} amp.
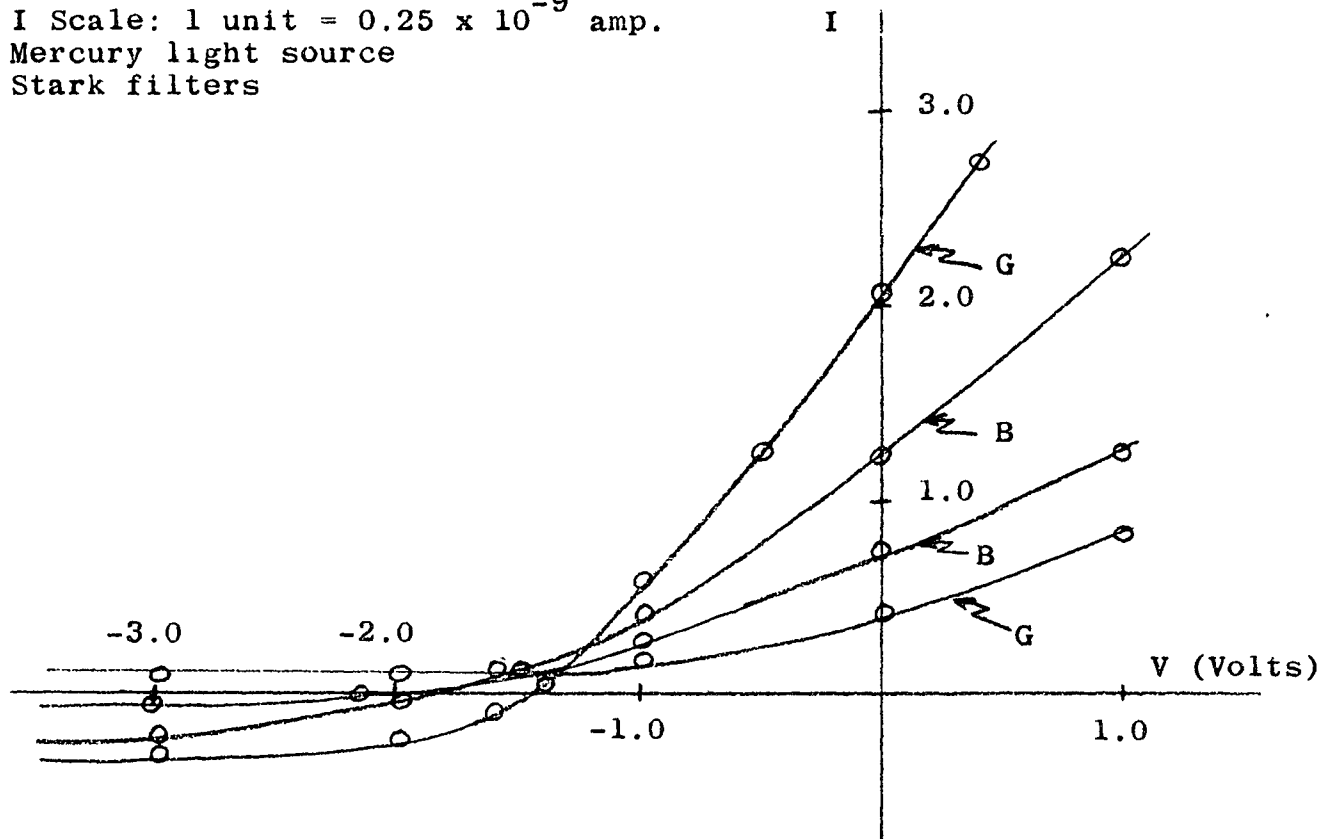Mercury light source
Stark filters

Figure 3.5 - Characteristics of 926 photocell for two intensities of blue and green light. Current measured with Keithley electrometer.

no light of frequency higher than that being studied would reach the emitter. The mercury spectrum was chosen because of the presence of three strong lines, the wavelengths of which are 3650Å (ultra-violet), 4360 Å (blue), and 5460 Å (green). The 5890 Å line of the sodium spectrum was also used. The mercury spectrum had less intense lines as well, but no attempt was made to isolate or use these.

Since a small spot of light was needed to reduce the reverse current, an intense light source was needed. For this reason the low power mercury light source presently available in the secondary schools was not found to be satisfactory. To obtain reasonably large photocurrents, the Leybold photocell had to be completely flooded with light from this source and large reverse currents resulted. A mercury arc lamp was used for the measurements made in this investigation.

Two sets of filters were investigated. The first set consisted of three Corning glass filters, an ultra-violet filter, a blue-pass filter and a green-pass filter. The light passed by each of these filters was inspected with a direct vision spectrometer. The green-pass filter passed no light of shorter wavelength than the 5460 Å mercury line. The blue-pass filter was found to pass the 4046 Å and 4077 Å lines as well as the 4360 Å line. For this reason it was not suitable. The ultra-violet filter passed no visible light other than the 4046 Å and the 4077 Å lines which were extremely weak. These

filters were found to have a further disadvantage in that it was possible for light to enter the photocell without being first filtered.

The other set of filters investigated was that provided with the low power mercury light source referred to above. This set consists of four filters made of a flexible plastic-like material. Light passing through these filters (to be referred to as the Stark filters) was also inspected with a direct vision spectrometer. The blue-pass filter isolated the 4360 $\overset{\circ}{A}$ line, the green-pass filter allowed no light of shorter wavelength than 5460 $\overset{\circ}{A}$ through, but the two yellow filters failed to eliminate the 5460 $\overset{\circ}{A}$ line in order to isolate the 5770 $\overset{\circ}{A}$ line. These filters could be taped right over the opening in the housing and so filtered all light entering the photocell. They are readily available in most secondary schools. It was therefore concluded that the Stark filters were suitable for isolating the blue and green lines of the mercury spectrum.

A check was made to determine if the Stark blue-pass filter passed any ultra-violet light. This blue filter and the Corning ultra-violet filter were used together as a compound filter. Since it had already been determined that the ultra-violet filter passed no blue light, and light passing both filters had to be ultra-violet. No measureable photocurrent was observed. It was concluded that the Stark blue-pass filter does not pass ultra-violet light.

An attempt was also made to obtain a photocurrent using

the mercury light source and red filter material. A photocurrent
of the order of 10^{-11} ampere was observed. It was concluded
that the Leybold photocell is insensitive to red light, since
such a small photocurrent could well be due to scattered light
of shorter wavelength than 6000 Å.

An attempt was made to eliminate the need for filters by
isolating the spectral lines with a crude monochromator. Light
from the mercury arc was passed through the direct vision
spectrometer and focussed onto the photocell. Although reason-
able results were obtained once, these results were not reprod-
ucible, and the currents produced by the photocell were smaller
by a factor of at least ten than those produced using the filters.

A simple method was found to reduce scattered light reaching
the photocell. At all times when measurements were being made
the room was completely darkened. A piece of black paper was
placed between the small circular light source and the photocell.
The paper had a hole in it just large enough to pass the spot
of light. With the filter taped over the hole in the photocell
housing, it was reasonably certain that little light other than
that being investigated reached the emitter.

A problem was encountered in changing light intensity
without altering the shape of the spot or the spectral quality
of the light. A neutral filter was tried but abandoned when no
result could be obtained for the ultra-violet light. The method

finally used was to reduce the area of the focussing quartz lens using stops of black paper. Each stop consisted of a black paper disc the size of the lens. The disc had a hole cut in it, the intensity of the light passed being directly proportional to the area of the hole. The stops were taped over the focussing lens. This method not only, reduced the intensity without altering the quality of the light, but also ensured that the same area of the emitter was used throughout keeping the work function constant within reasonable limits.

It was concluded from these investigations that a strong mercury arc source used with the Stark blue and green filters isolated the 4360 Å and 5460 Å lines of the mercury spectrum. The 3650 Å line could be isolated using an ultra-violet filter. The intensity of the light could best be changed by changing the aperture of the focussing lens by means of paper stops taped over the lens.

3.3 Method.
3.3a Current Measuring Method.

The initial attempts to perform the experiment were made by measuring photocurrent as a function of the applied potential difference V between emitter and collector. Characteristics such as those shown in figures 3.1 and 3.2 were obtained. The cutoff voltage V_A was interpreted as being the applied potential difference for which the photocurrent became zero.

A major problem soon became evident whenever large reverse

currents were encountered for the true value of V_A is not easily found on the graph. The potential difference at which the current became zero was in fact the potential difference at which the photocurrent and the reverse current were equal. This effect was especially evident in the case of ultra-violet light for which V_A was found to lie between V_A for blue and V_A for green. Because the reverse current was so large for the ultra-violet light the true value of V_A was larger than the value indicated on the graph. Because of the large reverse currents this method yielded values of h/e ranging from 7.5×10^{-16} volt-seconds $\pm 20\%$ to 5.0×10^{-15} volt-seconds $\pm 20\%$ with no apparent consistency. This method was therefore abandoned.

It was then noted that part of the potential difference - current curve always appeared to be linear and that the photocell apparently obeyed Ohm's law in a certain region. It was further noted that straight lines drawn through the linear portions of the curves for various intensities of the same frequency of light intersected the potential difference axis at the same point. This is illustrated in figure 3.6.

The photocell was treated as a device obeying Ohm's law. The point of intersection of the straight lines was interpreted as V_A. With the Leybold cell and the green and blue lines of mercury, h/e was found to be 4.3×10^{-15} volt-seconds $\pm 20\%$ with this interpretation of the data. No result that was meaningful could be obtained with the ultra-violet light, however.

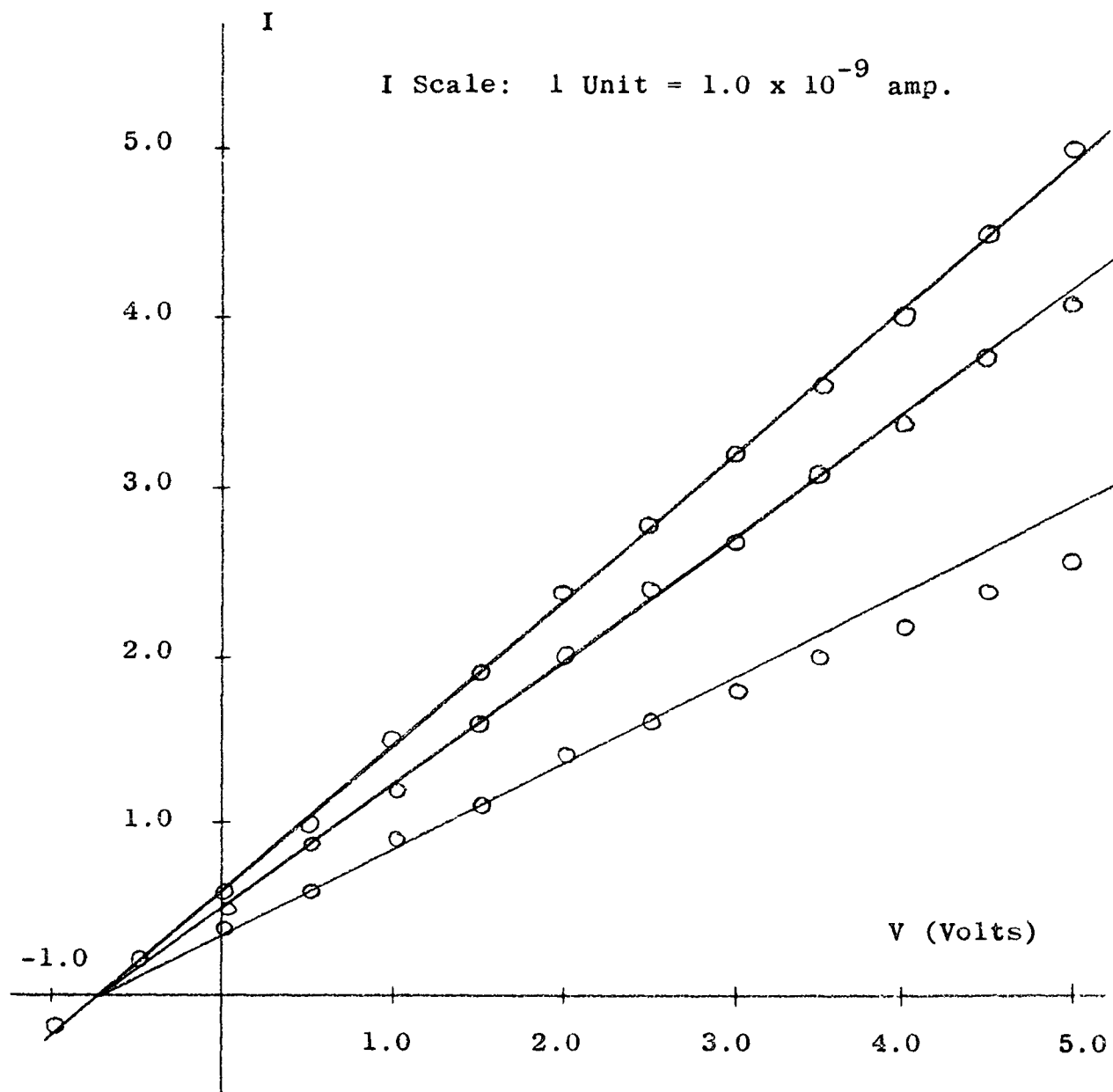The major problem encountered using this interpretation of

Figure 3.6 - Characteristics for various intensities of blue light using Leybold cell. I measured with Keithley electrometer. V is potential of collector with respect to ground.

the data was lack of consistency in the results. A measurement using the Leybold cell and the spectrometer used as a monochromator yielded h/e = 4.0 x 10^{-15} volt-seconds $\pm 20\%$. Several weeks later using the same apparatus and procedure the value of V_A had increased by approximately one volt and h/e was found to be 3.3 x 10^{-15} volt-seconds $\pm 20\%$. The change in the value obtained for h/e may not have been significant since the uncertainties in the two values overlapped, but the change in the value of V_A certainly was significant. Since no theoretical reason could be found to explain why any part of the curve should be straight, it was concluded that this interpretation of the data cannot be justified. To support this conclusion, it was found in many cases that the point of intersection of the straight line with the potential difference axis did depend upon light intensity.

3.3b Capacitor Method.

The theory of this method has been discussed in chapter 2. A capacitor was connected between the emitter and the collector and the Keithley electrometer on open circuit was used to measure V_M. At first it was hoped that the commercial photocells could be used with this method. It was found that, using the 929, IP39, and 926 photocells, V_M was a function of the light intensity. It was concluded that the Leybold photocell was again superior.

An optimum sized capacitor had to be found to be used

with the Leybold photocell.   Since this photocell produces

currents as small as 10^{-10} ampere, a one microfarad capacitor

needs a time of the order of 10^{4} seconds or a few hours to charge.

Thus the capacitance must be small to be practical.   Measurements

of V_M were made for the blue and green lines of the mercury

spectrum under optical conditions similar to those described in

section 3.2.   These measurements are given in table 3.1.

	BLUE LIGHT			GREEN LIGHT		
Capacitance	full int.	lower int.	low int.	full int.	lower ₋int.	low int.
Nil	1.08	1.30	1.30	0.84	0.73	0.81
Nil	0.97	0.97	1.11	0.65	0.63	0.55
5×10^{-10} farad	1.07	1.05	1.05	0.72	0.90	1.00
2×10^{-9} farad	0.65	0.68	0.68	0.30	0.28	0.24
1×10^{-8} farad	0.75	0.74	0.74	0.26	0.25	0.20

Table 3.1 - Maximum potential difference V_M in volts across
capacitors charged with a Leybold photocell.

From table 3.1 it can be seen that V_M was determined

both by the capacitance and the intensity of the light.   It

was decided that the 5×10^{-10} farad (500 micro microfarad)

capacitor gave the most consistent results within reasonable

lengths of time.   For example, with very low intensity light

this capacitor took no more than five minutes to charge.

Using this capacitor and a new Leybold photocell a measure-

ment of h/e was made.   The best slope of the V_M - frequency

line was 2.6×10^{-15} volt-seconds $\pm 20\%$.   This value is very low.

Since V_M was definitely a function of light intensity, and the value of h/e obtained was too small, this method was also abandoned.

3.3c Final Result.

A return to the original method with the new Leybold photocells revealed very much smaller reverse currents. Using a quartz lens results were obtained for ultra-violet, blue, green, and yellow light which were much more reasonable than those obtained with the older photocell. This method was finally used and the results obtained are outlined in Chapter 4.

3.4 Methods of Measuring Small Currents.

Since the Leybold photocell produced currents as small as 10^{-10} ampere a method of measuring these small currents had to be established. Two electronic circuits and a Keithley electrometer with a decade shunt were used.

The first circuit tried was the twin triode bridge circuit shown in figure 3.7.
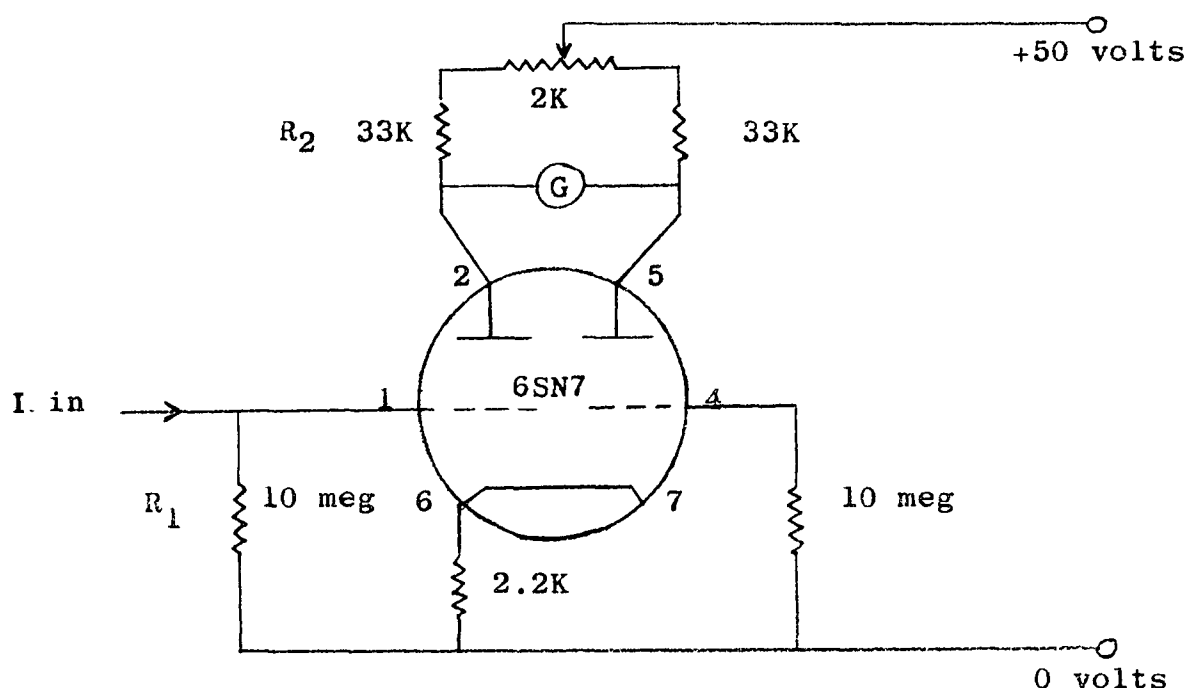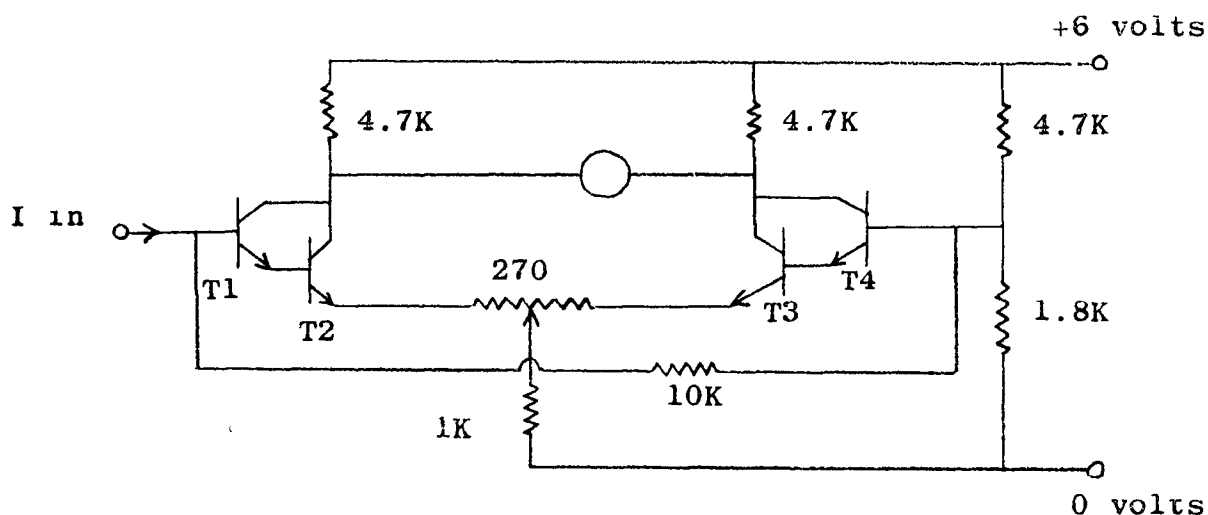
Figure 3.7 - Twin triode bridge circuit.

With no current flowing into the input of this circuit
the 2000 ohm potential divider can be adjusted so that there is
zero potential difference across galvanometer G. When current
flows into the circuit and through the 10 megohm resistor R_1
the potential of the grid on one triode is altered changing
the current passing through this triode. The other triode
remains unchanged. This current flows through the 33,000 ohm
resistor R_2 changing the potential of one side of the galvano-
meter. A potential difference thus appears across the galvano-
meter and a current flows through it. Thus, the introduction
of a current in the grid circuit causes the galvanometer to
register a current.

This circuit worked reasonably well for currents as small

as 10^{-9} ampere if a sensitive galvanometer was used. The galvanometer's sensitivity was 5.5 x 10^{-7} amp/cm on its most sensitive range. The circuit was found to have two main disadvantages. The major problem was encountered with the zero point which had a tendency to wander slowly. In this situation it was not possible to determine if an apparent change in current was due to a real change in current or due to this instability of the circuit. The other disadvantage was that the sensitivity of the circuit was determined directly by the sensitivity of the galvanometer used. In general, galvanometers suitable for use in this experiment are not to be found in secondary schools. Other than these problems, the circuit was found to be suitable for use in this experiment.

The second circuit tried replaced the twin triode tube with transistors in an attempt to correct the tendency of the zero point to wander. This circuit is shown in figure 3.8.

T1, T2, T3, T4 all
   T1417 transistors.

Figure 3.8 Transistor circuit to measure small currents.

This circuit works basically on the same principle as the twin triode bridge. The 270 ohm potential divider can be adjusted so there is zero potential difference across the galvanometer. When a current is introduced it turns the current on through T_1 which turns the current on through T_2. This current upsets the balance and the galvanometer registers this unbalanced condition. The transistors are arranged in tandem to increase the sensitivity of the circuit.

This circuit was not as sensitive as the twin triode bridge, and was not useful in measuring currents smaller than 10^{-8} ampere. Moreover, the zero point of the galvanometer still fluctuated. The circuit was therefore abandoned as being no improvement over the twin triode bridge circuit.

The Keithley electrometer proved to be the most useful instrument for measuring the small currents produced by the Leybold photocell. The zero point of the instrument did not wander and could easily be checked again after each measurement. Currents of the order of 10^{-10} ampere could be measured with relative ease and reliability. This instrument was used for the determination of h/e in Chapter 4.

3.5 Summary.

1. The Leybold photocell was found to yield a reasonable and consistent value of h/e when used with the Keithley electrometer and a spot source of light. The commercial photocells investi-

gated gave reverse currents which made them unreliable.

2. A strong mercury light source used with the filters supplied with the Stark low power mercury light source isolated the green and blue lines of the mercury spectrum. Intensity could best be changed by changing the aperture of the focussing lens. The light had to be concentrated in a small spot and the cell had to be shielded from stray light.

3. The current - measuring method proved to be much more reliable than the capacitor method.

4. The Keithley electrometer was the most reliable instrument for measuring the small currents produced by the Leybold cell. The twin-triode bridge circuit was suitable, but had some disadvantages.

CHAPTER 4.   A PHOTOCELL DETERMINATION OF PLANCK'S CONSTANT.

The apparatus and method having been decided upon a measurement of h/e was made. The purpose in making this measurement was twofold. It was necessary to ensure that the physics involved in the experiment was correct and that the quantity being measured was really h/e. At the same time the results to be expected from the experiment under optimum conditions could be obtained.

4.1 Method.

The apparatus was assembled as shown in figure 4.1. The photocell casing was clamped down to the table so that the chance of an accidental change in the photocell's position was minimal. The electrical lead from the emitter to the Keithley electrometer was kept as short as possible to reduce possible leakage currents. The entire apparatus including the photocell housing was grounded to a water pipe. In the optical system, a quartz lens was used to ensure passage of the ultra-violet light. Light intensity was changed by the use of the black paper stops described in section 3.2. The lens was placed at a distance of twice its focal length from both the photocell and the light source so that a spot of light the same size as the source could be focussed onto the plane of the collector keeping the amount of light incident on the collector as small as possible. A black paper screen was placed a few centimeters in front of the light source. This screen had a hole in it large enough to pass the light beam to the photocell, but served to
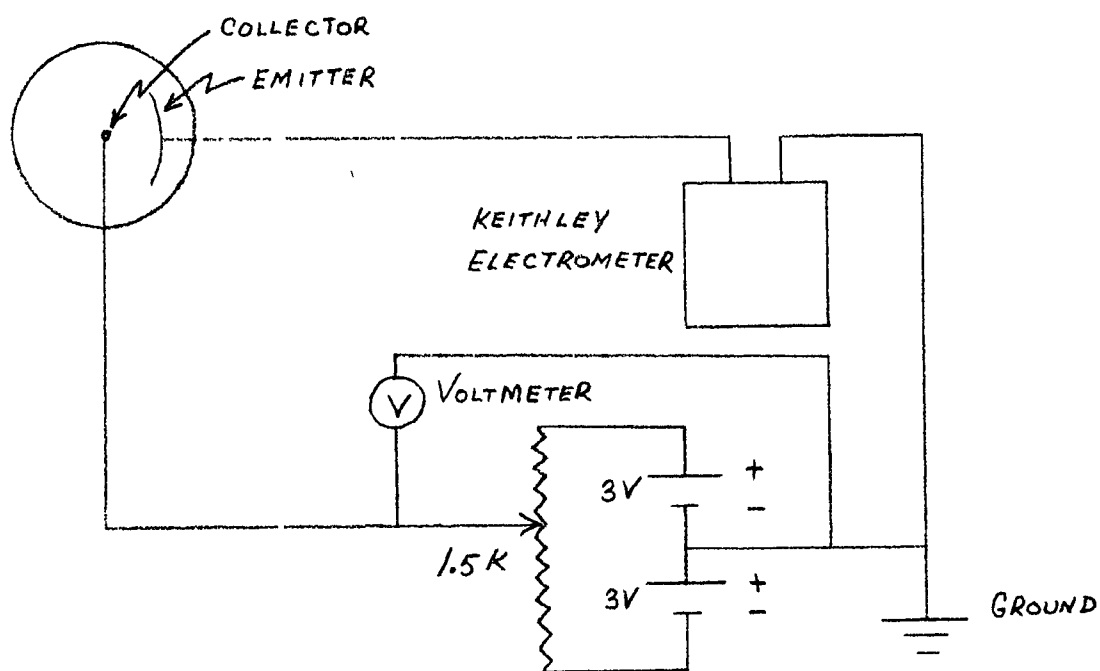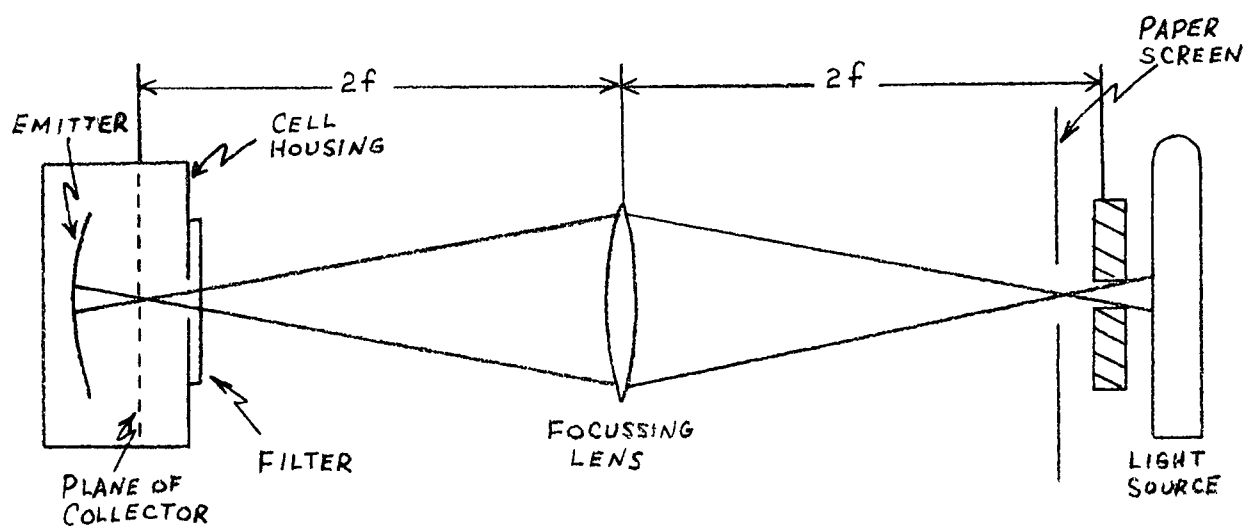
Figure 4.1 (a) - Electrical circuit.

Figure 4.1 (b) - Optical system.

reduce the scattered light reaching the photocell. The room had no windows and was completely dark other than the light from the light source. The Leybold photocell and its mount were used throughout. The mercury arc lamp was used for the ultra-violet, blue, and green light, and a sodium lamp for the yellow light. A Corning ultra-violet pass filter was used for the ultra-violet and Stark filters used for the blue, green, and yellow.

It was necessary to apply a correction to the potential difference measured to obtain the potential difference between emitter and collector. The Keithley electrometer measures current by passing the current through a standard resistance and measuring the potential difference across the resistor. This potential difference was subtracted from the potential difference measured, that between the collector and the ground, to obtain the potential difference between the collector and the emitter. No correction was made for contact potential difference as this quantity was unknown.

Data for two intensities of each frequency of light were plotted directly on graphs and are shown in figures 4.2, 4.3, 4.4, and 4.5. Further data for a greater variety of intensities of light are to be found in appendix A. These are not included here because the quartz lens was not used and the light intensity was varied using a neutral filter.

4.2 Results.

A graph of stopping potential difference V_A as a function

Figure 4.1 (c) - Apparatus for photocell experiment.

3650 Å Line (Hg)

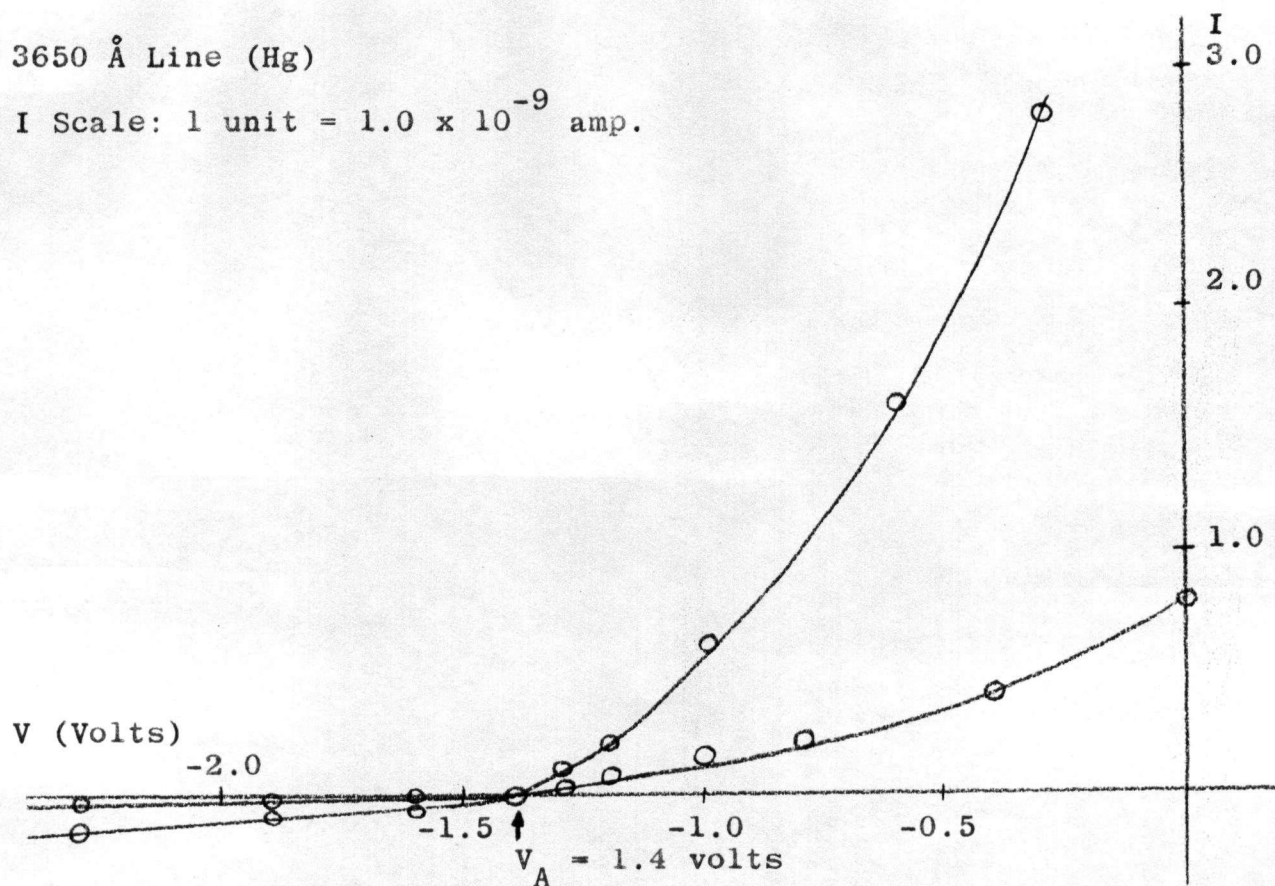I Scale: 1 unit = 1.0×10^{-9} amp.

V_A = 1.4 volts

Figure 4.2 - Ultra-violet (f = 8.2×10^{14} seconds^{-1})
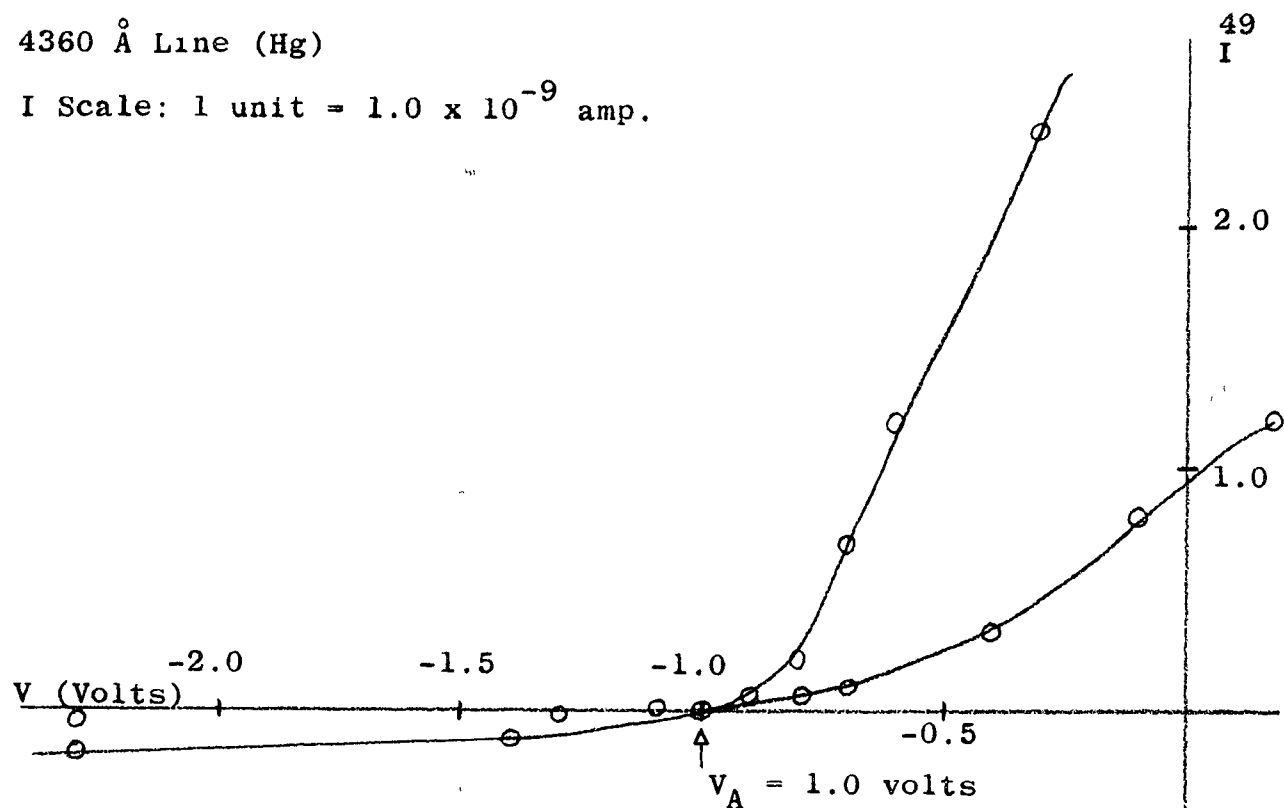
4360 Å Line (Hg)

I Scale: 1 unit = 1.0 x 10^{-9} amp.

Figure 4.3 - Blue (f = 6.9 x 10^{14} seconds^{-1})

5460 Å Line (Hg)

I Scale: 4 units = 1.0 x 10^{-9} amp.

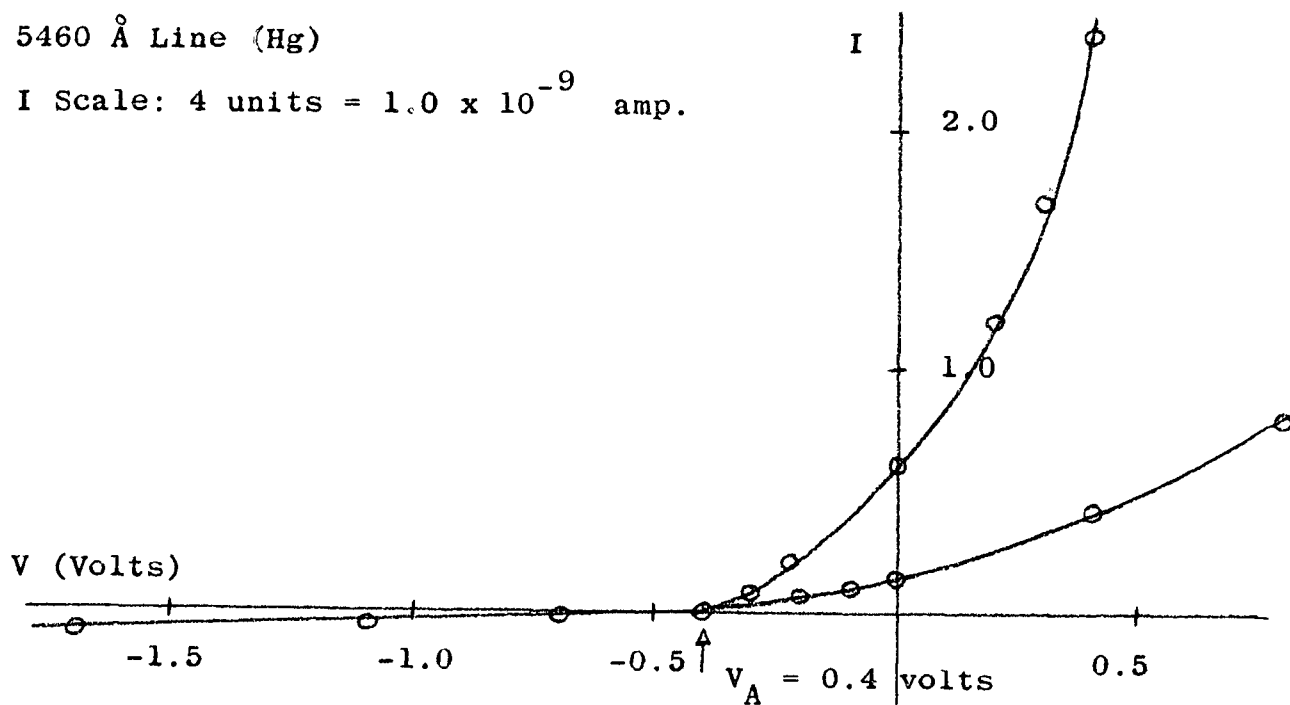Figure 4.4 - Green (f = 5.5 x 10^{14} seconds^{-1})

5890 Å Line (Na)

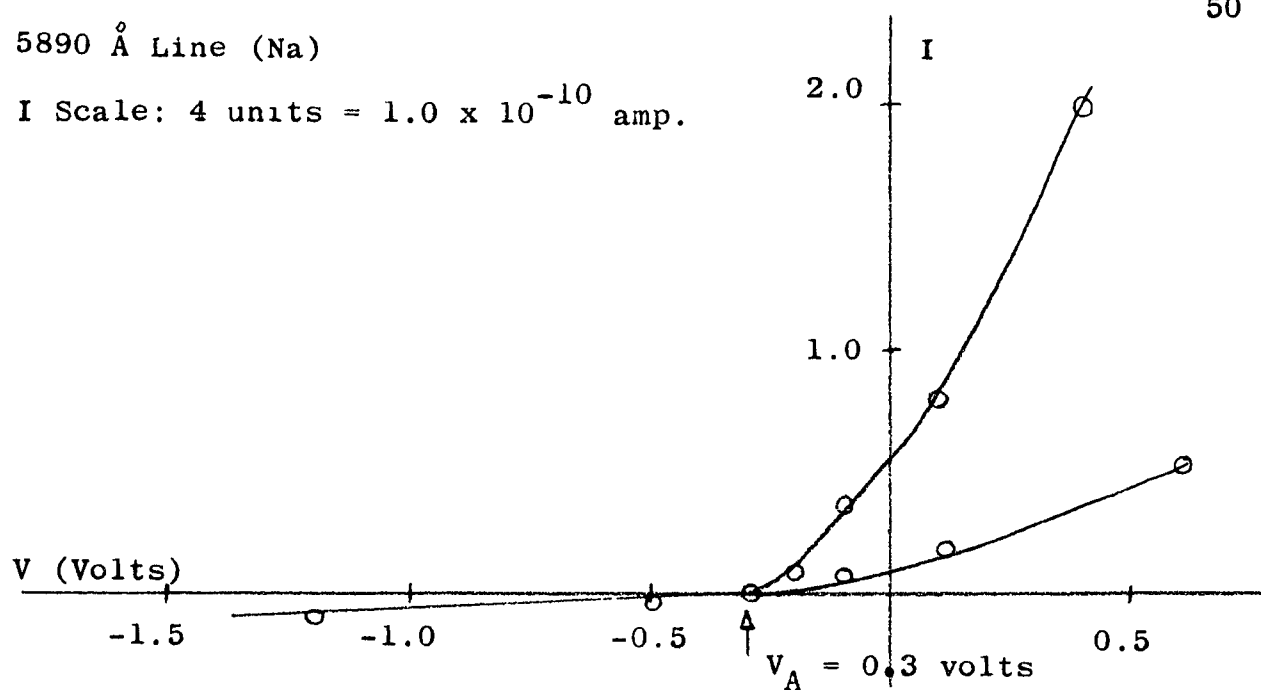I Scale: 4 units = 1.0×10^{-10} amp.

V_A = 0.3 volts

V (Volts)

Figure 4.5 - Yellow (f= 5.1×10^{14} seconds^{-1})
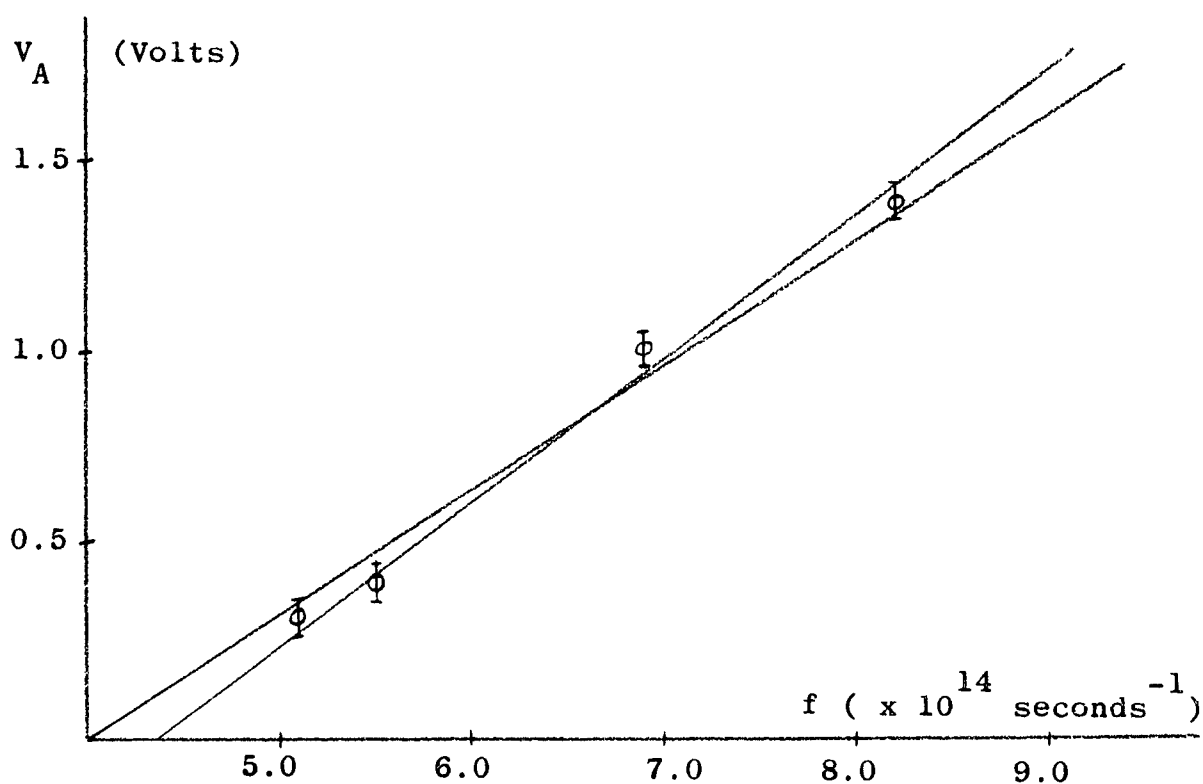
V_A (Volts)

f (x 10^{14} seconds^{-1})

Figure 4.6 - Relationship between stopping potential and frequency.

of light frequency f is shown in figure 4.6. The points lie along a straight line within experimental uncertainty. The relationship between V_A and f thus has the form

$$V_A = k_1 f + k_2 \qquad (4.1)$$

where k_1 is the slope of the graph and k_2 is the value of V_A when f is zero.

Lines of maximum and minimum slope were drawn through the points. The maximum slope $\Delta V_A / \Delta f$ was found to be 3.8×10^{-15} volt-seconds, and the minimum slope to be 3.7×10^{-15} volt-seconds. From equation 2.3 this slope is h/e. Therefore

$$h = e \frac{\Delta V_A}{\Delta f} \qquad (4.2)$$

and h_{max} = 1.6×10^{-19} coul x 3.8×10^{-15} volt-seconds.
= 6.1×10^{-34} joule-seconds.

h_{min} = 1.6×10^{-19} coul x 3.7×10^{-15} volt-seconds.
= 5.9×10^{-34} joule-seconds.

Thus $h = (6.0 \pm 0.1) \times 10^{-34}$ joule-seconds.

This measured value of h differs from the accepted value 6.6×10^{-34} joule-seconds by 9%. The uncertainty quoted in the measured value of h reflects only the uncertainty in the slope and not any systematic error.

From equation 2.9, k_2 is -p/e + V_C. The value of k_2 is given by

$$0.4 \text{ volts} = 3.8 \times 10^{-15} \text{ volt-seconds} \times 5.5 \times 10^{14} \text{ seconds}^{-1} + k_2$$

$$(4.3)$$

where the point for green light in figure 4.6 has been used. Therefore

$$k_2 = -1.7 \text{ volts}$$

The value of p/e is 1.8 volts for potassium.[1] Therefore

$$V_C = k_2 + p/e = -1.7 \text{ volts} + 1.8 \text{ volts}$$
$$= 0.1 \text{ volts}.$$

Since the work function of platinum is greater than 6.2 electron volts,[2] the contact potential difference between platinum and potassium should be of the order of 4 to 5 volts.

4.3 Discussion of Results.

The first important fact evident from the results was that V_A was independent of the intensity of the light used. This fact was further emphasized in the data presented in appendix A where, for four intensities each of green and blue light, the magnitude of the photocurrent varied, but V_A varied by no more than 0.05 volt.

It was also evident that V_A was a linear function of f. Since only four points on the graph were found, however, the evidence supporting this conclusion was not at all strong.

The main source of error in this determination of h was the reverse current. This reverse current was larger for the ultra-violet and blue light than it was for the green and yellow light. For the ultra-violet and blue light, the value of V_A

1 B. I. Bleaney and B. Bleaney, Electricity and Magnetism, Oxford University Press, London, 1957, p. 86.

2 Ibid., p. 86.

chosen was in fact the value of V for which photocurrent and reverse current were equal, and the true value of V_A was probably a little larger than the value chosen. If this were the case, the measured value of the slope should be lower than expected as was found. Thus the reverse current supplies the major systematic error.

The small value of the contact potential difference between the emitter and collector may account for the reverse currents. This small contact potential difference indicates that the work function of the platinum collector was not as large as expected and so the threshold frequency of the platinum wire was in the region of the frequencies being used in this experiment. The platinum wire was thus capable of giving rise to its own photo-current, the reverse current.

The other major source of error was due to the uncertainty in identifying the frequencies of light responsible for the results. The Stark filters appeared to isolate the blue and green lines of mercury reasonably well as far as could be determined by examining the light they passed with a direct vision spectroscope. It is doubtful, however, if the blue filter completely eliminates the two violet lines in the neighbourhood of 4050 Å. This light has a higher frequency than that of the blue light being studied and may be the cause of V_A being a little higher than expected, the point for blue being a little above the straight line through the other points on the V_A - f graph shown in figure 4.6.

It is of interest to compare these results with those

obtained by Hansen and Clotfelter[1] using the complete Leybold

apparatus. They found that the data obtained were a sharp

function of the time interval between heating the collector

and taking the data. In all cases the values of h/e obtained

were lower than the accepted value. The results obtained in the

present study differ from those obtained by Hansen and Clotfelter

in that the data are more consistent and the relationship between

V_A and f is more definitely linear.

4.4 Conclusions.

1. The relationship between the stopping potential difference

V_A and the frequency of light f is linear.

2. V_A is independent of the intensity of the light.

3. The relationship between V_A and f has the form

$$V_A = k_1 f + k_2$$

where k_1 and k_2 are constants. This relationship is similar

to that in equation 3.2.

4. The value of k_1 was found to be 3.8×10^{-15} volt-seconds

which is 9% lower than the accepted value of h/e.

5. Assuming k_1 to be h/e, h was found to be $(6.0 \pm 0.1) \times 10^{-34}$

joule-seconds. This value is 9% below the accepted value.

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1 R. J. Hansen and B. E. Clotfelter, "Evaluation of Commercial Apparatus for Measuring h/e," American Journal of Physics, vol. 34 (1966), p. 77.

6.   The contact potential difference between emitter and collector of the Leybold photocell was found to be 0.1 volt.

7.   The chief sources of systematic error are due to the reverse current and the uncertainty in the determination of the frequency of the light.

8.   The major conclusion reached is that a photocell experiment developing the concepts involved in the quantum model of light is feasible for use in secondary schools. The experiment described in this chapter is capable of yielding results which are in agreement with the major points in the theory of the photoelectric effect. Such an experiment involves techniques and instrumentation very similar to that encountered by the student in his previous experimental work. The data collected by the student can be analyzed using graphical analysis with which the student is very familiar. The only major problems involve the cost of apparatus, several hundreds of dollars, and the amount of time necessary to assemble the apparatus and collect data. It is likely that four to five hours of experimental work will be required to do the entire experiment.

CHAPTER 5.   A PHOTOCELL EXPERIMENT FOR SECONDARY SCHOOL PHYSICS.

5.1 Introduction.

Section 29 of A Laboratory Course in Physics, Book Two[1]
deals with the topics to which this experiment is related. The
photoelectric effect is introduced by shining ultra-violet light
on a zinc plate attached to an electroscope. It is noted that
the electroscope loses negative charge but does not lose positive
charge.[2] In the ensuing discussion reference is made to the
two PSSC films, Photons[3] and Interference of Photons[4] in which
evidence of the existence of quanta of light or photons is
presented. At this point the relationship between the maximum
kinetic energies of photoelectrons and the frequency of light
used is discussed. The following experiment is meant to replace
this discussion.

The experiment itself is meant to be more qualitative than
quantitative. Its purpose is to lead the student to the con-
clusion that the maximum photoelectron energy is independent of
the intensity of incident light, but that a linear relationship
exists between this maximum energy and the frequency of the
incident light. The twin triode bridge circuit is used because

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1 D. L. Livesey, G. H. Cannon, and T. Ryniak, A Laboratory
Course in Physics, Part Two, Vancouver, Copp Clark, 1965,
pp. 158 - 178.

2 Ibid., p. 159.

3 Physical Science Study Committee, Teacher's Guide to the
PSSC Films, New York, Modern Learning Aids, 1963.

4 Ibid.

it is relatively easy to construct and the Keithley electrometer is not an instrument found in most secondary schools.

5.2 The Experiment.

The photoelectric effect can best be studied under more controlled conditions than were present with the electroscope experiment by using a photocell. The back of the photocell is coated with potassium and emits electrons when light shines on it. These electrons can be collected by the platinum loop in the photocell if the platinum loop is made positive with respect to the potassium surface. Study the circuit shown in figure 5.1. The platinum loop can be made either positive or negative by adjusting the potential divider R_1. (Review Section 26.B.2.)

The very small current produced by the photocell must be measured using the twin triode bridge circuit or an electrometer. In the twin triode bridge a current through R_2 sets up a potential difference between the grid and cathode of one side of the tube altering the current passed by that side of the tube. This change in current causes a potential difference to appear across the galvanometer and the galvanometer indicates the presence of the current. R_3 can be adjusted so that the galvanometer reads zero when no current is passing through R_2.
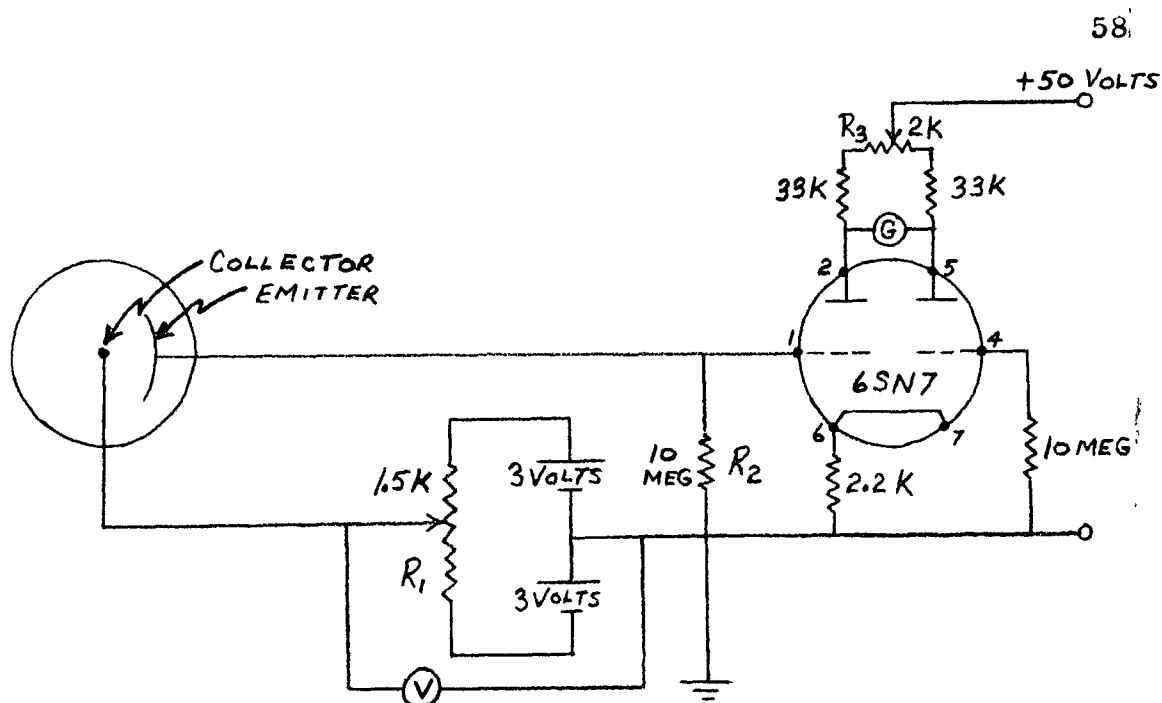
Figure 5.1 - Circuit for photocell experiment.

Wire the circuit shown in figure 5.1. Adjust R_3 in the twin triode bridge so that the galvanometer reads zero. Arrange a quartz lens between the photocell and a mercury arc lamp so that both the lamp and the photocell are at a distance equal to twice the focal length of the lens. DO NOT LOOK DIRECTLY AT THE MERCURY LAMP AND DO NOT EXPOSE THE PHOTOCELL TO THE FULL INTENSITY OF THE LIGHT. Place a large piece of cardboard with a hole in it about 1 cm. in diameter directly in front of the mercury lamp so that light shines through the hole. Carefully focus the image of the hole onto the potassium surface so that no light shines on the platinum loop. How large is this image compared to the object?

Tape the blue filter (frequency = 6.9 x 10^{14}/second) across

the opening in the photocell housing. Darken the room and measure
the photocurrent as the potential difference between the emitter
and collector of the photocell is varied. Plot a graph of current
as a function of potential difference. For what potential
difference did the current first become zero?

To explain why this potential difference is negative
assume that each photon striking the photocell gives all of its
energy to an electron. Each electron then emerges with kinetic
energy K. In travelling toward the collector which is at a
potential of -V with respect to the emitter, each electron loses
kinetic energy eV where e is the charge on the electron. The
potential difference for which the current becomes zero, V ,
is the potential difference for which the initial kinetic energy
K equals eV .

To determine the effect of light intensity upon K, cut
several discs of black paper the same size as the lens. Cut
holes of various sizes in these. Place one over the lens. What
effect does it have on the image? Plot several more graphs of
photocurrent versus potential difference for various intensities
of light. What effect does changing light intensity have on the
size of the photocurrent at any given voltage? How can this
effect be explained in terms of photons? What effect does
changing intensity have on V ? How does intensity affect the
kinetic energies of the photoelectrons?

Repeat the experiment with several intensities of ultra-

violet light (f = 8.2 x 10^{14}/seconds) and green light (f = 5.5 x 10^{14}/seconds). Plot a graph of V as a function of frequency. What is the relationship between V and f?

This relationship can be written in the form eV = hf - p where eV is the kinetic energy of the electrons, hf is the energy of the photons, and p represents the work done by the electrons in escaping from the potassium. This equation was first suggested by Einstein in 1905 and directly contradicts the wave theory of light which says that the energy of the light depends upon intensity. According to this relationship the kinetic energy received by the electrons depends only upon frequency, not upon the intensity. The constant h is called Planck's constant. Measure the slope of your graph, obtain an estimate of h/e and hence of h.

Note that for some value of f, V becomes zero. This value of f is called the threshold frequency because no matter what the intensity, light with frequency lower than the threshold frequency cannot produce photoelectrons. Why is this so? Estimate the threshold frequency of potassium. What color is this light? Try light of this color on the cell and see if you can produce a photocurrent.

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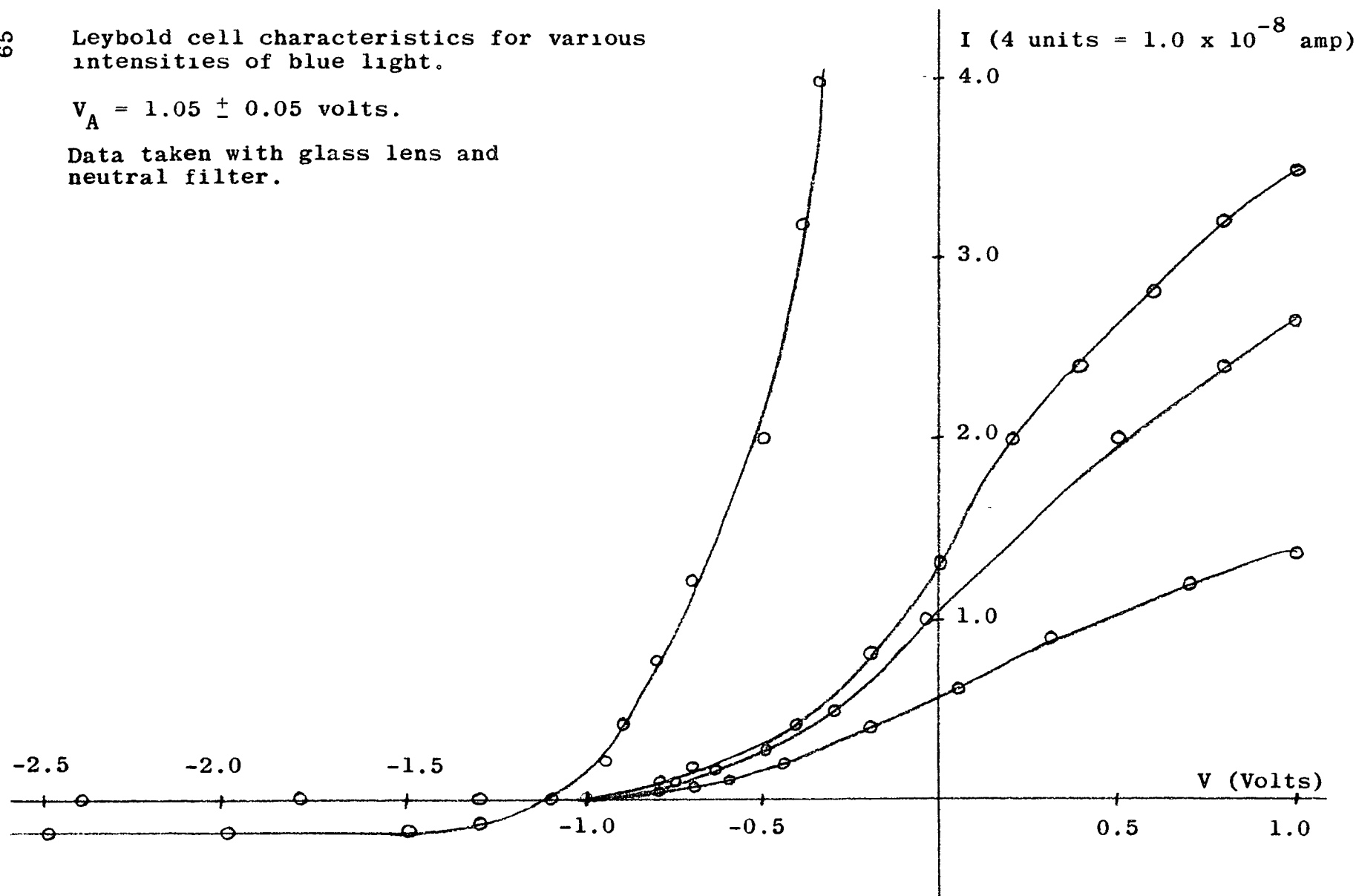   Philosophical Magazine, series 5, vol. 48 (1899), pp. 547 -
    567.

APPENDIX

A

Leybold cell characteristics for various
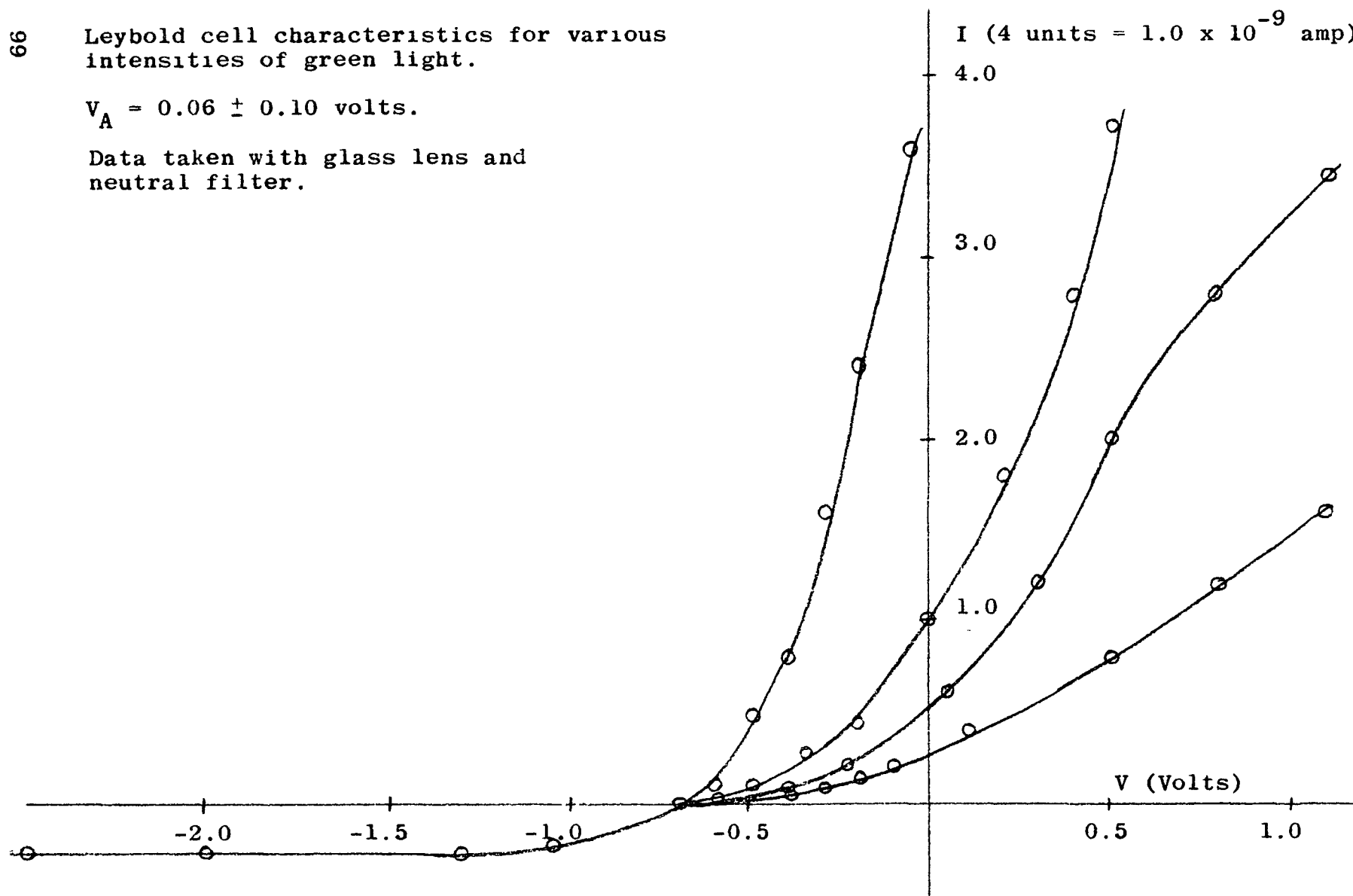intensities of blue light.

$V_A = 1.05 \pm 0.05$ volts.

Data taken with glass lens and
neutral filter.

I (4 units = 1.0×10^{-8} amp)

Leybold cell characteristics for various intensities of green light.

$V_A = 0.06 \pm 0.10$ volts.

Data taken with glass lens and neutral filter.

I (4 units = 1.0×10^{-9} amp)

V (Volts)

APPENDIX

B

SPECIAL APPARATUS AND CATALOGUE NUMBERS

Leybold photocell   Leybold 558 77

Housing for Leybold photocell   Leybold 558 78

Low power mercury light source
and filters   Canlab 3400

Mercury arc lamp   Welch   3720G