Physics

# Students' laboratory book

Nuffield Advanced Science

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Physics **Students' laboratory book**



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Nuffield Advanced Science

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Physics

# Students' laboratory book

**Nuffield Advanced Science**

Published for the Nuffield Foundation by Penguin Books

Penguin Books Ltd, Harmondsworth, Middlesex, England
Penguin Books Inc., 7110 Ambassador Road,
Baltimore, Md 21207, U.S.A.
Penguin Books Ltd, Ringwood, Victoria, Australia



Design and art direction by Ivan and Robin Dodd
Illustrations designed and produced by Penguin Education

Filmset in 9 on 11 pt 'Monophoto' Univers
by Keyspools Ltd, Golborne, Lancashire
and made and printed in Great Britain
by C. Tinling & Co. Ltd, London and Prescot

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# Foreword

It is almost a decade since the Trustees of the Nuffield Foundation decided to sponsor curriculum development programmes in science. Over the past few years a succession of materials and aids appropriate to teaching and learning over a wide variety of age and ability ranges has been published. We hope that they may have made a small contribution to the renewal of the science curriculum which is currently so evident in the schools.

The strength of the development has unquestionably lain in the most valuable part that has been played in the work by practising teachers and the guidance and help that have been received from the consultative committees to each Project.

The stage has now been reached for the publication of materials suitable for Advanced courses in the sciences. In many ways the task has been a more difficult one to accomplish. The sixth form has received more than its fair share of study in recent years and there is now an increasing acceptance that an attempt should be made to preserve breadth in studies in the 16–19 year age range. This is no easy task in a system which by virtue of its pattern of tertiary education requires standards for the sixth form which in many other countries might well be found in first year university courses.

Advanced courses are therefore at once both a difficult and an interesting venture. They have been designed to be of value to teacher and student, be they in sixth forms or other forms of education in a similar age range. Furthermore, it is expected that teachers in universities, polytechnics, and colleges of education may find some of the ideas of value in their own work.

If this Advanced Physics course meets with the success and appreciation I believe it deserves, it will be in no small measure due to a very large number of people, in the team so ably led by Jon Ogborn and Dr Paul Black, in the consultative committee, and in the schools in which trials have been held. The programme could not have been brought to a successful conclusion without their help and that of the examination boards, local authorities, the universities, and the professional associations of science teachers.

Finally, the Project materials could not have reached successful publication without the expert assistance that has been received from William Anderson and his editorial staff in the Nuffield Science Publications Unit and from the editorial and production teams of Penguin Education.

K. W. Keohane
*Co-ordinator of the Nuffield Foundation Science Teaching Project*

# Introduction

This book is a collection of notes and information to use in the laboratory. The book is arranged as follows: Part One 'Tools'; Part Two 'Long experiments'; Part Three 'Notes on some other experiments'.

Part One contains short notes on the use of some of the important equipment and apparatus which you will be using quite often in physics. From these notes you can learn to use the instruments effectively and safely by yourself. From time to time you may need to refresh your memory, and the short summary which precedes most of these notes may help you to do this.

Part Two contains detailed notes on some difficult and lengthy experiments. These notes give details of the techniques which you will need in order to make careful measurements. One of the skills a physicist needs is to be able to manipulate apparatus and make it yield reliable results. These experiments are intended to give you practice in this. The detail in this book should be enough for you to be able, by yourself, to tackle any one of these experiments at any time during the course.

The notes in Part Three will help you at least to make a start on some of the experiments you will meet during the course. Enough details are given of techniques and apparatus for you to be able to concentrate on deciding what to do, and thinking about what the results mean, without being held up by wondering how the apparatus is supposed to work.

In Parts Two and Three, numbers, such as 2.24, appearing against experiments, are reference numbers taken from the *Teachers' guides*. Thus, experiment 2.24 is from Unit 2, experiment 24. Item numbers shown against apparatus are taken from the *Teachers' handbook.*

In the list on page 135, you will find details of books referred to in the text.

Part One

# Tools

## Multimeter

*Summary of operating procedures*

A detailed summary covering all the available instruments cannot be given, because, although they all are similar in principle, the many makes and models differ widely in detail. Always read the instructions provided with the instrument, which are often printed on its back. The following notes indicate some of the main points.

1 *Range selection* Two-dial instruments (figure 1) have d.c. ranges of current and voltage selected by one dial, and a.c. ranges selected by the other. Each dial is brought into use by first selecting d.c. or a.c. as appropriate, on the *other* dial.

One-dial instruments have a single dial for selecting the range of current or voltage required, together with different input sockets for use with d.c. or a.c.

On some two-dial instruments, high voltage ranges (over 1 kV) are also selected by the use of special, marked, input sockets rather than by using the dials, though the dials may still need to be set for d.c. or a.c.

2 *Use as an ammeter or voltmeter* With d.c. ranges, remember to connect the meter in the correct polarity. Always start by selecting a range of current or voltage *higher* than the expected value in the circuit, and *then* select more and more sensitive ranges until a substantial deflection is obtained.

3 *Measuring resistance* On two-dial instruments, one dial is used to select the resistance measurement facility, the other to select the range required. One-dial instruments have separate input sockets for the measurement of resistance.

The resistor which is being tested is connected across the appropriate terminals of the meter. Because the instrument is actually indicating the current passed by the resistor under test when connected to the meter and its internal batteries, the resistance scale zero is at the high-current end of the scale. For the same reason the instrument must be brought to zero each time it is used, and this must be done separately for each resistance range. The way to do this is to short-circuit the input terminals and adjust the appropriate resistance range zeroing control. If a zero cannot be obtained, the batteries probably need replacing. The appropriate resistance range has to be found by trial and error.

It is usual for the scale to carry only one set of resistance markings, which you are intended to multiply or divide by a factor, say, of 100, when a high or low resistance range is in use.

*Never attempt to measure the resistance of a resistor already carrying a current.*

## The instrument

The multimeter is a moving coil meter with built-in switched circuits to enable it to indicate a wide range of currents or voltages. It also includes batteries, so that it can record resistances by indicating the current they pass.

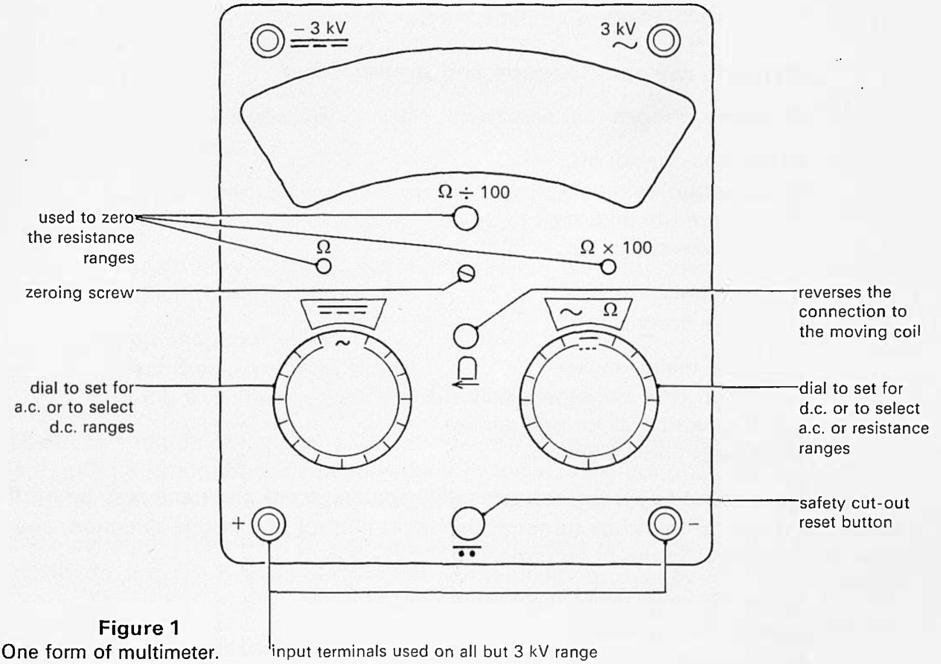



**Figure 1**
One form of multimeter.

There are many forms of multimeter. All are the same in principle, but they differ in detail. One type of instrument is illustrated in figure 1. Others will have controls, similarly coded by word or symbol, but possibly in different places.

The scale over which the pointer moves has many different ranges. It is important to find and use the one appropriate to the measurement you are making.

The basis of the instrument is a sensitive, moving coil system which can easily be damaged if it is overloaded. That is why we suggest in the summary that you should always start with the highest range and work downwards. The meter should *never* be connected into a circuit before the dials have been set appropriately. If the meter is accidentally overloaded an automatic cut-out will operate, springing out and breaking the meter connection. Only after the fault has been traced and remedied is it permissible to reset the overload button by pressing it back into position. The cut-out does not act quickly enough to protect the meter against being grossly overloaded, so care is necessary despite this safety device.

If the meter does not indicate zero when disconnected, the pointer can be brought to zero by adjusting the small screw below the scale. A screwdriver is required. The button which reverses the connection to the moving coil may be used if the current or voltage changes polarity during a series of measurements. It is poor practice to use it to correct an initially incorrect connection of the meter into a circuit.

### Cathode ray oscilloscope and preamplifier

*Summary of operating procedure: class oscilloscope*

brightness control off
focus control midway
Y-shift control midway
a.c.–d.c. switch to d.c.

Y-gain control to 1
time base control to 1

plug into mains socket
switch on (use brightness control)
allow to warm up for one minute
brightness control full on

A bright trace should now appear across the screen. If not, the trace may be off the screen, and can be found by turning the Y-shift control first in one direction, and then (if necessary) in the other direction.

centre the trace using the Y-shift control
reduce the brightness
focus sharply

switch the time base control to the required range
apply the input voltage
select the appropriate Y-gain

*Summary of operating procedure: demonstration oscilloscope*

brightness control off
focus control midway
Y-shift control midway
a.c.–d.c. switch to d.c.

X-gain low (control fully anti-clockwise)
X-shift control midway
trigger switch to +
trigger level control fully clockwise
stability fully clockwise
Y-gain control to 0.5 V $cm^{-1}$
time base control to 1 ms $cm^{-1}$
variable time base control fully clockwise

plug into mains socket
switch on (use brightness control)
allow to warm up for one minute
brightness control full on

A bright trace should now appear across the screen. If not, the trace may be off the screen. To find it, rotate the X-shift control each way, while rotating the Y-shift control gradually.

centre the trace using Y-shift and X-shift controls
reduce the brightness
focus sharply

turn back the stability control until the trace *just* vanishes
switch the trigger level control to automatic

The trace should now reappear, but may be rather dim. If it does not, the stability control has been turned too far back.

apply the input voltage
select the appropriate Y-gain.
set the time base control to the required range

The trace should now appear and be bright, showing the input voltage variation. It should be stable. If no trace appears, turn the stability control clockwise a little. If the pattern is not stable, turn the stability control anti-clockwise a little.

If the calibrated time base is required, set the variable time base control at maximum, and the X-gain at minimum. These positions may be marked 'cal'.

### The oscilloscope

The simple class oscilloscope and the larger, more complicated demonstration oscilloscope are both described here and shown in figures 4 and 5.

A cathode ray oscilloscope is a voltmeter. Its electron beam can be deflected in the vertical, Y, direction, by a potential difference applied across the Y-input terminals. The deflection is proportional to the p.d., and the sensitivity can be varied (from about 0.1 V $cm^{-1}$ to 50 V $cm^{-1}$ in the case of the school demonstration oscilloscope) by the Y-gain control.

The beam can also be deflected in the horizontal, X, direction. For most purposes, this is used to sweep the spot on the screen sideways at a steady speed, using the built-in time base. The time base of the demonstration oscilloscope is calibrated, and can be varied from about 0.1 s $cm^{-1}$ to about 1 $\mu s$ $cm^{-1}$

The beam, and thus the spot, can be moved to different places on the screen using the shift controls. The class oscilloscope usually has no X-shift facility when the time base is in use.

It is often useful to be able to start the spot on its sweep across the screen only when a signal arrives at the Y-input. The trigger and stability controls are for this purpose.

The brightness of the spot on the screen is controlled by the brightness control, which is also the on/off switch. It is usually necessary to increase the brightness at high time base sweep speeds. The sharpness of focus is varied by a focus control, which may need adjustment after the brightness has been altered.

A good oscilloscope for you to use in the laboratory will be able to register deflections from steady as well as from varying voltages applied to the Y-input. A switch, marked a.c.–d.c., is used to select these possibilities: in the d.c. position the oscilloscope will respond to both a.c. and d.c., and this is the position normally selected. Use the a.c. position when you want to examine a small varying voltage which is accompanied by a large 'unwanted' d.c. voltage. See figure 3.

Normally, one of the two Y-input sockets is joined to earth, so that if the circuit being examined also has an earth connection, it is essential to connect these earthed terminals together. Otherwise, the earthed oscilloscope connection may short-circuit part of your circuit.

Other facilities provided are less often used. With the time base off, it is possible to deflect the spot in the X-direction using X-input sockets if these are provided. If there is an X-gain control, it also affects the time base, and must be in one definite position for the time base to have its calibrated speed. There may be Z-input sockets also: an input voltage here modulates the brightness of the spot.

It is possible to calibrate the Y-input of the class oscilloscope (figure 4), using the circuit shown in figure 2. It is often convenient to apply 5 V to the oscilloscope, as indicated on the voltmeter, and to adjust the gain so that the spot is deflected by five graticule divisions. One division then corresponds to 1 V.

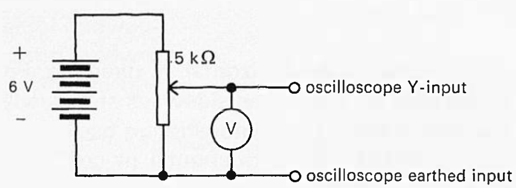



**Figure 2**
Calibration circuit.

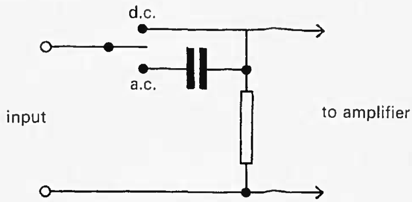
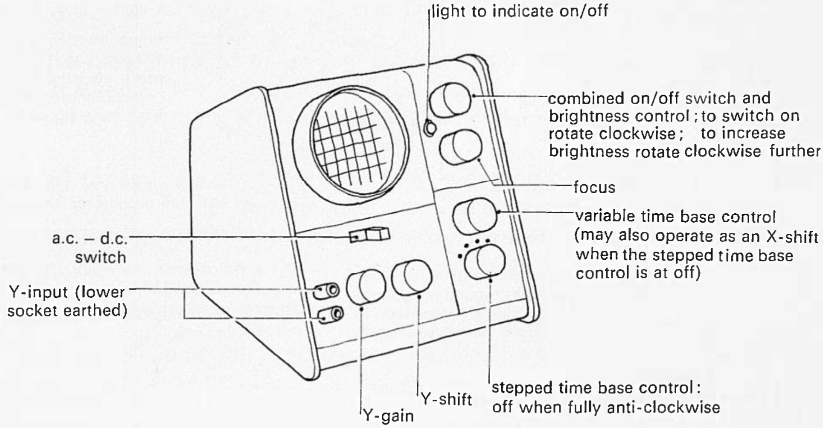



**Figure 3**
An a.c.–d.c. switch circuit.




**Notes**
Automatic triggering is supplied by an internal circuit operated by the input signal.
In some class oscilloscopes X-input terminals are provided.

**Figure 4**
One form of class oscilloscope.

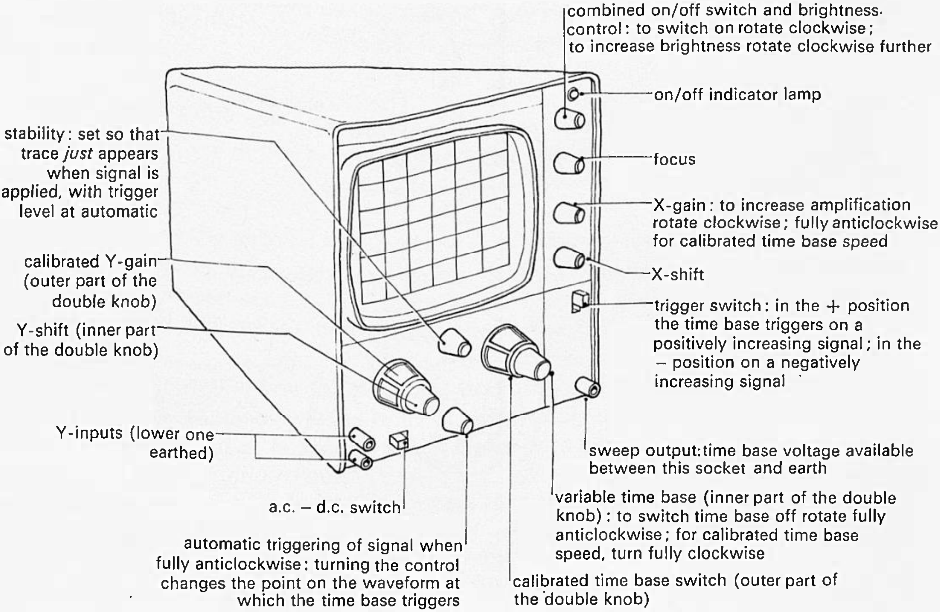



**Figure 5**
One form of demonstration oscilloscope.

### The preamplifier

The maximum Y-sensitivity of the oscilloscopes described here is not better than $0.1\,V\,cm^{-1}$, and this is not enough for all purposes. Signals smaller than about 0.1 V can be amplified before being applied to the oscilloscope input, using a preamplifier.

Figure 6 illustrates a small, battery-powered preamplifier. It may require connection to an external 9 V battery, in which case the positive and negative connections must be made correctly. For the amplifier shown in figure 6, the negative battery lead goes to one of the terminals marked E.

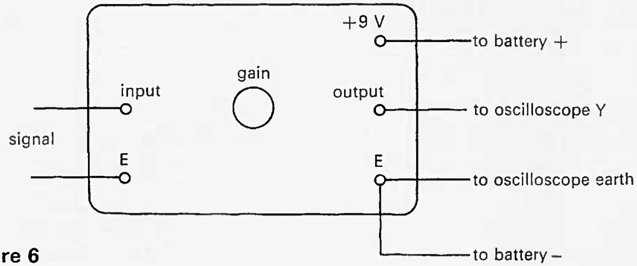



**Figure 6**
A preamplifier.

An input to the preamplifier is connected across the preamplifier's input terminal and the one marked E. The output goes to the oscilloscope, whose earth terminal must be joined to the output terminal of the preamplifier which is marked E.

The preamplifier may have a variable gain. In general, the oscilloscope should be used at its most sensitive, so that the least possible preamplifier gain is required. Note that the preamplifier will introduce distortions into large signals fed into it.

## Light-beam galvanometer

*Summary of operating procedures*

When the galvanometer is not in use or is being moved, or when making connections to it, always turn the range switch to the 'shorted' position.

Handle the instrument gently. Never move it while leads are connected to it. Always lift rather than slide it. When setting the zero, turn the range switch to the $\times 0.001$ position.

Always start with the range switch at the least sensitive, $\times 0.001$ position, and then increase the sensitivity as required. In general, use a resistor in series with the meter as an additional safety measure.

Always check the circuit connected to the meter *twice*, before switching on. Never connect the meter to a 'live' circuit.

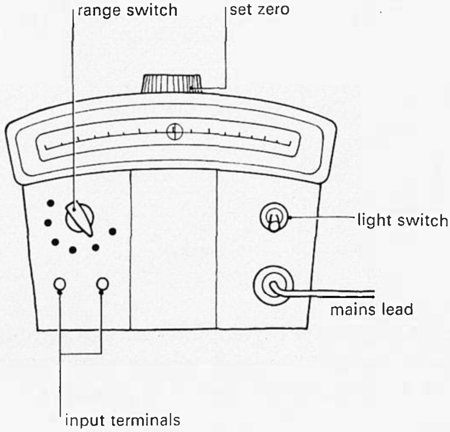



**Figure 7**
One type of light-beam galvanometer.

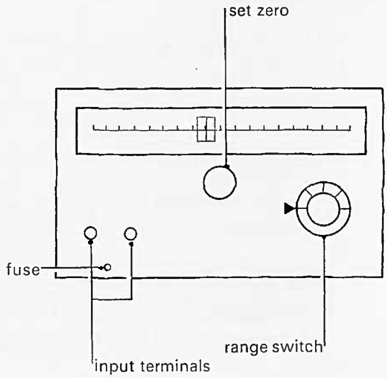



**Figure 8**
Another type of light-beam galvanometer.

## The instrument

A light-beam galvanometer is a very sensitive, moving coil instrument, with a full-scale deflection corresponding to a current of less than $10\,\mu A$. Instead of having a needle to indicate rotation of the moving coil, a mirror is attached to the coil, from which a beam of light is reflected onto a scale. Readings are taken from the dark hair-line which crosses the spot of light.

The delicate moving coil system is more easily damaged by mechanical shock than is the movement of an ordinary meter, so the instrument must be handled with care. Short-circuiting the coil protects the movement, since any motion of the coil in the field of the magnet around it will induce a current in the coil which will tend to reduce the motion and to 'cushion' the coil against shocks. The effect can be seen by switching from, say, the $\times 0.001$ range to 'shorted' while the coil is swinging. The spot of light then crawls slowly towards zero. The range switch should be set to 'shorted' whenever the meter is to be moved, or when connections are made to it. Some types include a shorting switch in one foot of the instrument, which shorts the coil whenever the instrument is lifted. This is why you must always lift and never slide the instrument, when you move it.

The zero current position of the spot can be chosen at will. It is usual to place it either at one end of the scale, or in the middle. To alter the zero, turn the range switch to $\times 0.001$, and rotate the set-zero knob.

When the range switch is at 'direct', the instrument has its greatest sensitivity (see table 1) and the coil swings freely. On $\times 1$, the sensitivity is almost the same, but internal resistors are connected across the coil so that it does not oscillate before coming to rest at a steady indication. (In this condition, the meter is said to be critically damped.) The range $\times 0.001$ is 1000 times less sensitive. Other intermediate ranges are provided. The resistance between the input terminals is the same, and the movement is critically damped, on all ranges except 'direct'.

Sometimes there is a range switch position marked 'series' which introduces a resistance in series with the coil. This is used when the external circuit has a low resistance, and will avoid heavy damping.

The makers supply an individual calibration for each galvanometer. This may be used if it is necessary to know the sensitivity in order to convert a scale reading into amperes or volts. Table 1 may give you some idea of the orders of magnitude to expect.

| | **Pye Scalamp 7891/S** | **WPA KN90** |
|---|---|---|
| galvanometer resistance, 'direct' | 25 Ω | 14 Ω |
| galvanometer resistance, '×1, etc.' | 20 Ω | 13 Ω |
| sensitivity, 'direct' | 25 mm $\mu A^{-1}$ | 25 mm $\mu A^{-1}$ |
| | 1 mm $\mu V^{-1}$ | 1.8 mm $\mu V^{-1}$ |
| sensitivity, '×1' | 20 mm $\mu A^{-1}$ | 23 mm $\mu A^{-1}$ |
| | 1 mm $\mu V^{-1}$ | 1.8 mm $\mu V^{-1}$ |
| critical damping resistance | 100 Ω | 120 Ω |
| period of swing | 2 s | 2 s |
| charge sensitivity (ballistic swing) | 78.5 mm $\mu C^{-1}$ | 78 mm $\mu C^{-1}$ |

**Table 1**
Typical data for two representative galvanometers.

## Electrometer

*Summary of operating procedures*

Locate the following parts of the instrument:

input terminal
earthed input terminal
output terminals for display meter (unless a meter is incorporated)
the means of shorting the input ('rest' position of a switch, or a push button)
the means of connecting resistors or capacitors across the input (dial switch, dial switch and plug-in components, or screw-in connectors)
the set-zero control
the gain or sensitivity control (you may need a screwdriver)
on/off switch

If an output display meter is not provided, connect a 1 mA or 100 μA meter, as indicated on the instrument.

Short-circuit the input.

Switch from off to on, pausing at any intermediate switch position. Wait until the meter is steady, then set it to zero. Remove input short circuit. If necessary, calibrate by applying 1 V d.c. across the input or by using the internal 1 V calibrating voltage provided on some instruments, adjusting the gain until the meter gives, say, full-scale deflection.

*To use as a voltmeter:* no resistor or capacitor need be connected across the input.

*To use to measure current* up to a value $I$: connect a resistor across the input, such that $IR = 1$ V.

*To use to measure charge* up to a value $Q$: connect a capacitor across the input, such that $Q/C = 1$ V. Short the input momentarily between readings to discharge the capacitor.

Check the zero frequently, and the calibration occasionally. Remember to switch off when finished, noting that if the on/off switch has more than two positions then the batteries will run down if the switch is left in any but the off position.

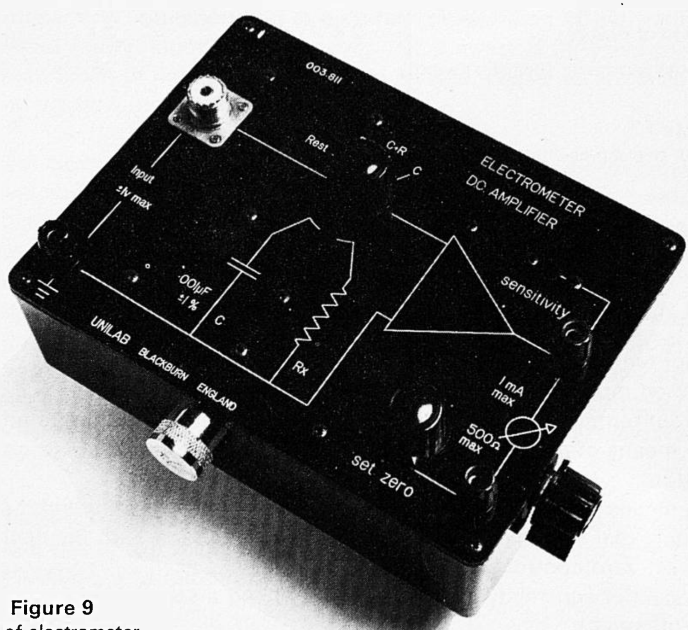



**Figure 9**
One type of electrometer.
*Photograph, Michael Plomer.*

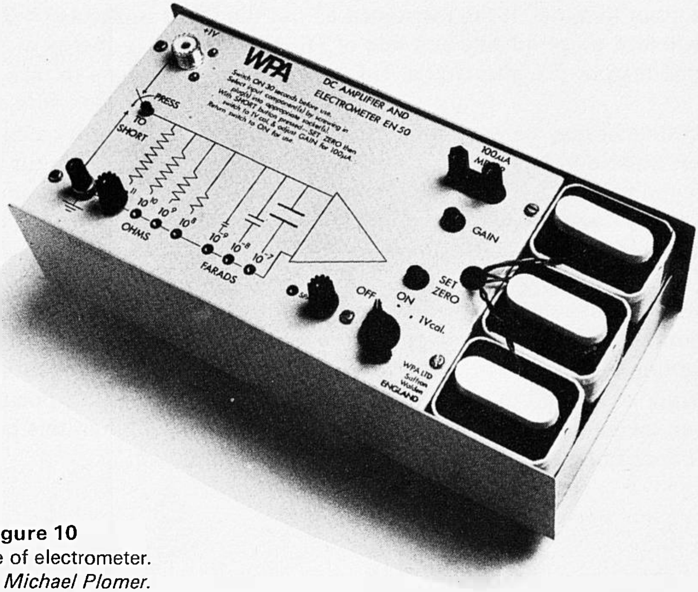



**Figure 10**
Another type of electrometer.
*Photograph, Michael Plomer.*

### The instrument

An electrometer behaves like a voltmeter with a resistance as high as $10^{12}\,\Omega$ to $10^{13}\,\Omega$. A steady voltage between 0 and 1 V across its input goes to an amplifier, which although it draws only $10^{-12}$ or $10^{-13}$ A, produces at the output a current in the range 0–1 mA or 0–100 µA, which is proportional to the voltage across the input.

In all its applications, *the electrometer indicates the voltage across its input.* Small currents can be measured by connecting a resistor across the input (as in figure 11) through which the current flows. If the resistor has a resistance of, say, $10^{10}\,\Omega$, an output indication corresponding to 1 V across the input shows that the current in the resistor is $10^{-10}$ A (neglecting the higher input resistance of the amplifier in parallel with the $10^{10}\,\Omega$ resistance).

Small charges may be measured by connecting a capacitor across the input terminals as in figure 12. If its capacitance is, say, $10^{-8}$ F (0.01 µF), an output indication corresponding to 1 V across the input shows that the charge on the capacitor is $10^{-8}$ C (neglecting the input capacitance of the electrometer). If the capacitance of the object from which the charge came (a charged ball, for example) is small compared with that across the electrometer input, nearly all this charge will have passed to the electrometer capacitor, if the object was touched onto the input terminal. If the resistance across the input is, say $10^{12}\ \Omega$, at 1 V the charge will leak away initially at a rate of $10^{-12}$ A, so that a charge of $10^{-8}$ C will only be reduced by 1% after 100 s. This will give plenty of time to take a reading.

The electrometer may be provided with an internal 1 V source for calibration (such as the one shown in figure 10). If not, 1 V can be applied to the input for calibration using a circuit like that in figure 13, with a battery, a potentiometer, and a voltmeter. The electrometer is then adjusted, by using the gain or sensitivity control, so that the output meter gives a convenient indication (1 mA or 100 μA).

Electrometers usually need time to warm up after they have been switched on, and the output meter may swing violently for a while. The type shown in figure 9 has a three-position on/off switch. In the intermediate position, the filament of a valve in the amplifier is allowed to warm up, and it is best to pause at this position for about 15 s when switching on. It is essential *not* to leave the switch in this position when putting the electrometer away, or the battery will run down.

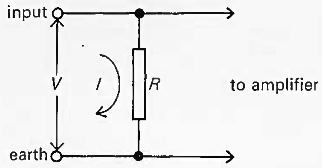



**Figure 11**
Current measurement.

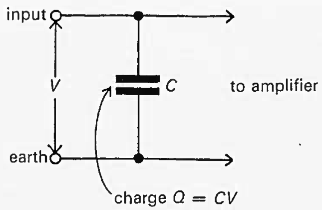



**Figure 12**
Charge measurement.

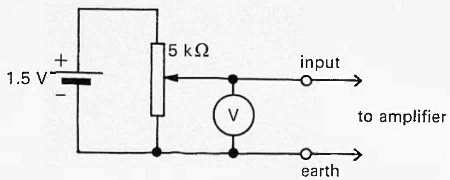



**Figure 13**
A calibration circuit.

### Reed switch

*Summary of operating procedures*

Identify the following (see figure 14):

reed switch coil terminals
d.c. voltage supply terminals
capacitor terminals
meter terminals

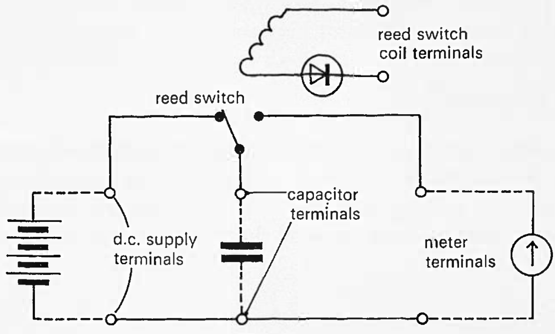



**Figure 14**
A reed switch circuit.

For use with capacitances of the order of 1 μF, the reed may be switched at 50 Hz, and the meter may be a 100 μA meter, with shunts as necessary.

For use with a capacitor made of parallel metal plates about 0.3 m square, the reed should be switched at about 400 Hz. A light-beam galvanometer is required in this case.

For 50 Hz operation, connect 2 V a.c. across the reed switch coil terminals, increasing this to 4 V if the switch cannot be heard operating.

For higher frequencies, connect the reed switch coil terminals to the low impedance output of a signal generator, setting it to provide a sinusoidal output in the range 100 to 400 Hz. Raise the gain of the oscillator until the switch is heard operating.

Connect the capacitor to the capacitor terminals.

Connect the meter to the meter terminals.

Connect a smooth d.c. supply of no more than the limit indicated on the reed switch (usually 25 V) across the d.c. voltage supply terminals.

When the reed switch operates correctly, the meter should give a steady deflection. If the meter reading is erratic, the reed switch is probably not being driven hard enough, and a larger voltage across the coil terminals of the reed switch should be tried. If the current in the meter is $I$, and this is the result of the discharge of charge $Q$ from the capacitor, $f$ times a second,

$$I = Qf.$$

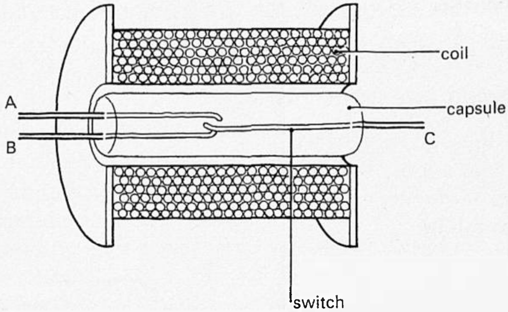



**Figure 15**
A reed switch.

### The instrument

The reed switch consists of a small glass capsule containing the switch, inside a coil. The switch is two-way and is controlled by a current. When the current through the coil reaches a certain value, the switch closes one pair of contacts. When the current through the coil drops below this value, the other pair of contacts is closed.

The glass capsule contains three metal strips, A, B, and C (figure 15). When no current flows in the coil, C is in contact with B but not with A. When a big enough current is passed through the coil, A and C become magnetized and attract one another into contact. B is made of a material which is not magnetized in this way. Thus, if C and B are one pair of switch contacts, and C and A another pair, the first pair will be closed for currents below a certain value, and the second pair for currents above this value.

If a large enough fluctuating current is fed to the coil the switch contacts will be continually opening and closing as the current rises and falls. If the coil is fed from an alternating supply with a diode rectifier in the circuit, so that current only flows during one-half of each cycle, then the switch operates once in each cycle. Thus, if the frequency of the alternating current is 50 Hz, the switch will operate 50 times a second.

The reed switch finds its main use in this course in the rapid charging and discharging of capacitors. The rapid succession of discharge pulses, each carrying a charge $Q$, at the rate $f$, passes through a meter which deflects as if a steady current $I = Qf$ were flowing. If $I$ and $f$ are known, $Q$ can be found. If the capacitor used has capacitance $C$, then $C = Q/V$ ($V$ being the voltage to which it was charged).

Here are two sets of more or less typical values illustrating the use of the reed switch at low and high frequencies.

| | | |
|---|---|---|
| $C$ | 2 μF | 250 pF $(2.5 \times 10^{-10}$ F) |
| $V$ | 10 V | 10 V |
| $Q$ | 20 μC | 2.5 nC $(2.5 \times 10^{-9}$ C) |
| $f$ | 50 Hz | 400 Hz |
| $I$ | 1 mA | 1 μA $(10^{-6}$ A) |

It is desirable to connect a protective resistance in series with the meter, so that it will not be damaged should the d.c. supply be connected accidentally to the meter terminals. If this resistance is not too large, it will not change the current $I$ at all. If it is too large, the discharge may not be complete in the time available, a fraction of one switching cycle. The point can be checked experimentally by connecting an oscilloscope across the protective resistor, to see if the pulses of discharge current fall to zero between pulses. As a guide, the product of $CR$ should be less than the time $1/10\,f$. Alternatively, increase the resistance until the current starts to fall, and then set the resistance at a somewhat lower value.

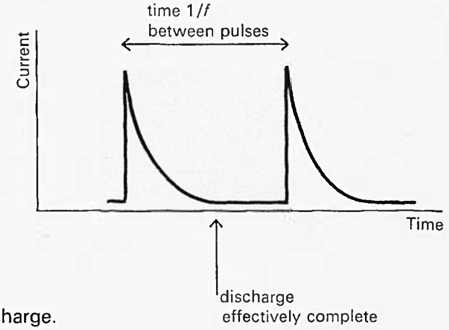



**Figure 16**
The completion of the discharge.

The switch cannot handle large potential differences, and may be limited to as little as 25 V. The current it can handle is usually less than 250 mA.

### Vacuum pump

*Summary of operating procedures*

Identify the gas ballast valve, the air admittance valve, and the isolation valve. (See figures 17 and 18.) Connect the system to be evacuated to the pump inlet, using pressure tubing.

It is best to place a safety screen between yourself and the glass parts of the evacuated system.

Open the gas ballast valve.
Close the air admittance valve, unless it is the automatic type.
Open the isolation valve.
Switch on.

If the lowest possible pressure is required, close the gas ballast valve after a few minutes of pumping, and continue to pump. (When the valve is closed, the sound of air being drawn into the pump through this valve will cease.)

Close the isolation valve if it is desired to isolate the system, or to switch off the pump with the system evacuated.

To switch off, having closed the isolation valve, open the air admittance valve if it is not automatic, and cut off the electrical supply to the motor. If the air admittance valve is left closed, oil might be drawn into any evacuated part of the apparatus open to the pump.

To admit air to the evacuated system, open the air admittance valve (if this is automatic, by switching the pump off) and the isolation valve.

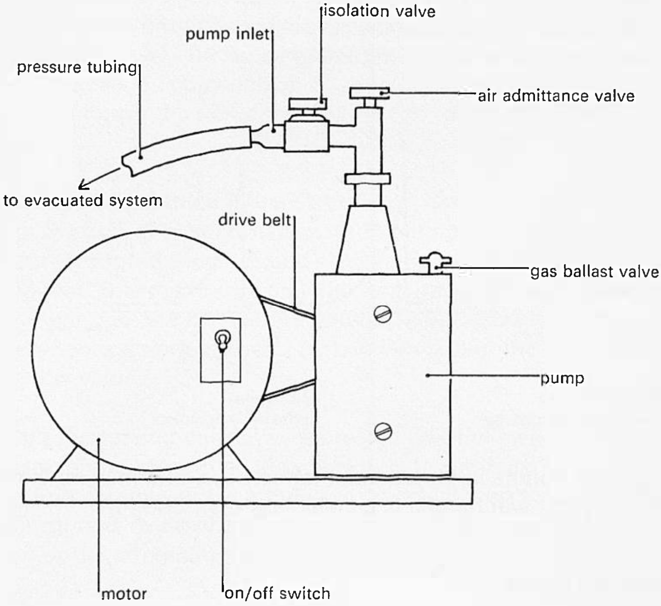



**Figure 17**
One type of rotary vacuum pump.

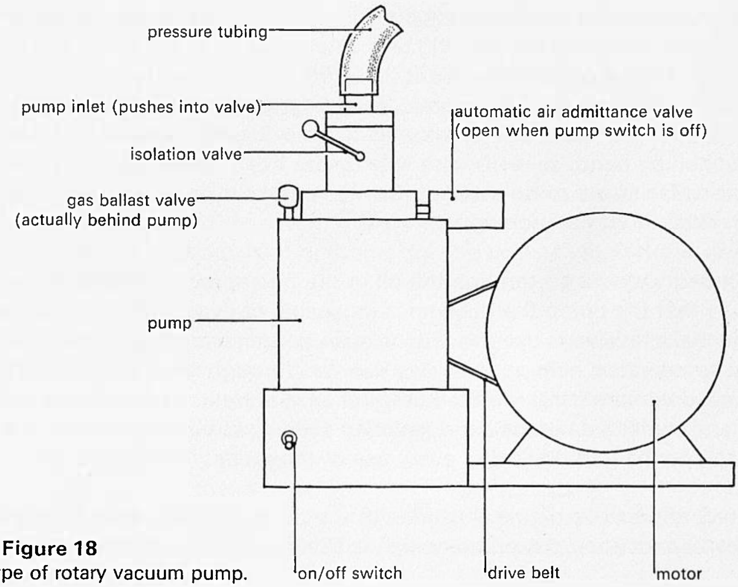



**Figure 18**
Another type of rotary vacuum pump.

## The pump

A rotary pump consists of vanes on a rotor which turns in an oil bath, sweeping air out of a system connected to it. Apart from leaks in the system, any problems which arise will usually concern the oil, involving contamination, or seepage into the system.

*Seepage*. If the pump is stopped while it is connected to an evacuated space, the pressure of air at the pump outlet may force oil out of the pump into the evacuated system. The isolation and air admittance valves can be used to prevent such seepage of oil. The isolation valve seals off the evacuated system from the pump, so that the air admittance valve can admit air to the pump without admitting it to the system. In the type of pump shown in figure 18, the air admittance valve opens automatically when the pump is switched off; therefore, it is essential to close the isolation valve *before* switching the pump off.

In the type of pump shown in figure 17, if the evacuated system is to be sealed off under vacuum, it is essential both to close the isolation valve, and to open the air admittance valve, in that order.

*Contamination*. Water vapour is the most common contaminant. 1 g of water vapour occupies about 1000 $dm^3$ at a pressure of 1 mm of mercury. Since the pump will remove gas at only about 20 or 30 $dm^3$ per minute, it takes a long time to remove contaminating water vapour. Volatile greases are another source of contamination, so the inside of systems to be evacuated should be clean and dry (untouched by hand, as well), and substances like Vaseline, wood, paper, and all painted surfaces, are to be avoided. Clean, sound tubing should be used. (Remove French chalk from new tubing.)

All pumped vapours go through the oil in the pump, and are liable to condense there, so that the pump then becomes incapable of evacuating even a clean system. The gas ballast valve is used to reduce such contamination. It admits air to the oil as the pump operates, helping to sweep vapours through the oil. To clean the oil of condensed contaminant, run the pump for several hours with the gas ballast valve *open*, and the air admittance and isolation valves *closed*. As a rule, it is a good idea to do this for half an hour after every use of the pump.

If a mercury pressure gauge is used with the pump, it is *essential* to arrange that mercury cannot enter the pump, which is likely to be ruined if it does.

*Leaks*. Avoid greases as a means of sealing a system. O-rings should not need grease. Tight, well-fitting joints are better than loose, greased ones. Taps and ground glass cone joints may need a *little* high vacuum grease. Use a grease with a low vapour pressure, such as Apiezon grease.

## Stroboscopic photographs

### Using multiflash photography

In multiflash photography it is necessary to highlight the body being photographed against a dark background, in order to ensure good contrast in the picture. The successive photographs of the event, at regular time intervals on the same negative frame, are achieved either by using constant illumination and a motor-driven stroboscope, or by using intermittent illumination with a xenon stroboscope. Notes on these two methods follow.

### Using a 35 mm camera and a slotted disc

A camera focusing down to about 1.5 or 2 metres is required. It must have a lens aperture of at least f/8, though f/6, f/4.5, or f/3.5 are to be preferred. A 35 mm camera is best, because the technique of developing the film in the cassette described here has been worked out for 35 mm film. The shutter should be fitted with time (T) or brief (B) settings: in practice the brief setting is the more convenient.

Unless the camera has a reflex viewfinder, it is as well to check the field of view by putting a strip of translucent material in the position normally occupied by the film, opening the shutter, and seeing directly that all the motion you wish to photograph is in view.

The camera is set up firmly, on a level with, and about 1.5 m away from, the experiment to be recorded. The lens is then focused for this distance.

The synchronous motor is then fitted with the appropriate black slotted disc. A 5-slit disc gives intervals of 1/25 s, and a 6-slit disc, intervals of 1/30 s between shots. The disc is placed about 10 mm in front of the camera, so that the rotating slits will sweep across the lens.

The interval between exposures can be varied by covering unwanted intermediate slits with black adhesive tape. This will enable you to choose a suitable number of exposures to appear in the final picture. The width of the slit controls the sharpness of the images obtained, and you should choose the narrowest slit which is consistent with adequate illumination.

The scene can be illuminated with a slide projector, placed so that its beam lights the whole of the action without either illuminating the background or spilling light onto the camera.

A dark background is required. A matt black, cloth surface gives good contrast, but this is not essential. The method can be used in very subdued room lighting.

### Using a 35 mm camera and a xenon stroboscope

Sharper pictures than those taken with the motor stroboscope are possible if a xenon stroboscope is used. The slide projector and slotted disc are replaced by a flashing xenon lamp. Otherwise, the procedure is the same as for motor-driven stroboscopic photography. It is now *essential* to have a first class blackout. The beam from the xenon stroboscope must be directed along the path of the motion to be photographed, and kept off the background. It should not be used as a general floodlight, since this will produce pictures which lack essential contrast.

### Using a Polaroid camera

The types of Polaroid camera which have only an automatic exposure time, and no facility for holding the shutter open for several seconds, cannot usually be used.

The Polaroid camera combines the making of an exposure and the production of a print, which makes the whole process simpler and quicker, though expensive. The film used is much faster (3000 ASA) but this is counteracted to some extent by the comparatively small aperture (f/9 approximately) which is available.

The techniques of using the Polaroid camera for multiflash photography are similar to those for the 35 mm camera. A typical exposure value to use is EV13 (f/9).

## 35 mm film: developing and printing in the laboratory

### Developing in the cassette

This technique employs a special Kodak monobath, and it is best to use the recommended Kodak film.

The film used must not be longer than a 20-exposure length, otherwise the pumping action which takes place in the cassette will be ineffective. The solution is alkaline, so if your skin is sensitive wear rubber gloves.

Make four blank exposures at the beginning of the film. After making up to 16 exposures, wind the 20-exposure length of film back into its cassette leaving the last few centimetres of film, and the tongue, protruding. Cut the tongue off and bend the last piece of film back: secure it with an elastic band.

Take a short, slotted rod and fit the slot over the key in the cassette. Then wind the film, without forcing it, onto its spool. A length of PVC tubing can be used in place of the slotted rod.

Lower the cassette gently into 40 $cm^3$ of the monobath solution in a small container, until all but the top of the cassette is immersed. The container is a glass vessel of about 70 $cm^3$ capacity. (See figure 19.)

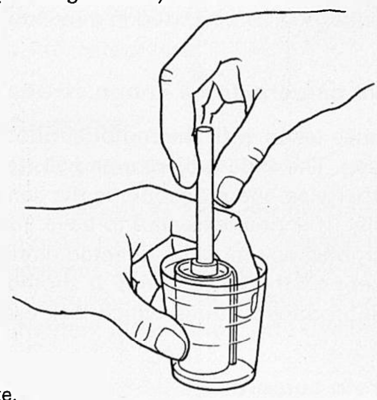


**Figure 19**
Developing film in the cassette.

As you lower the cassette into the container, gently unwind the film with the rod. Air will bubble out. Gently, but not slowly, rewind the film so that the monobath is pumped through the cassette, and repeat the process until the liquid is forced out of the top of the cassette. All air bubbles have now been removed and the cassette may be lowered completely into the small container. With the cassette thoroughly immersed, wind and unwind the film gently through $1\frac{1}{2}$ turns every two seconds, so continuing the pumping action.

After the correct time has elapsed ($3\frac{1}{2}$ to 4 minutes at 20°C), take the cassette from the container and plunge it into water. Pull out the film under water. (Should the film appear cloudy, transfer it at once to a bath of an acid fixer containing a hardener.) Wash the film in water for 10 seconds and inspect it. Should dark bands occur across the width of the film at its ends, then the rotating backwards and forwards was performed using too many revolutions in each direction. Should scratches occur along lengths of the film, then the processing has been performed too vigorously.

Select a suitable negative, cut it out with scissors, mount it (wet if necessary) in a cardboard mount, and project it. Throw the monobath away after use. Refixing and further washing improve the permanence of the negative, but the method is not intended to produce high quality results.

### Developing in a tank

The easiest method is to use a daylight loading tank. Otherwise, either a darkroom is needed, or a changing bag. Good photographers will use the method they prefer; here we are concerned only with simple methods which will produce results, not with work of any quality.

In a daylight loading tank, the cassette is put into the tank with the film attached to another spool, and is then wound out of the cassette into the tank, with the lid on, and with the liquid in the tank. With this type of tank the film needs to be agitated constantly while it is being developed.

It is easiest to use a proprietary, single-bath developer and fixer. Developing and fixing take about six to eight minutes, followed by a wash in water.

### Making positive prints

The mounted negative may be used to produce prints within a matter of minutes if document copying paper such as Kodak P153 is used. The paper must be such that it will not fog if exposed to normal tungsten room lighting for about half a minute.

The technique requires a simple printing frame (figure 20) and a slide projector. It can all be done in a room lit with tungsten lighting. Project an image of the chosen negative onto the printing frame. Switch the projector off and slip a piece of cut printing paper into the frame. Expose for about 5 seconds to the light from the projector, which should be about 1 metre away.

Develop the paper immediately, face down, in a dish of developer (normal dilution) for half a minute, and then transfer the paper print to a bath of fixing solution for one minute. Rinse it briefly in clean tap water. If it is intended to preserve the print, it should be washed more thoroughly for about 20 minutes in running water.

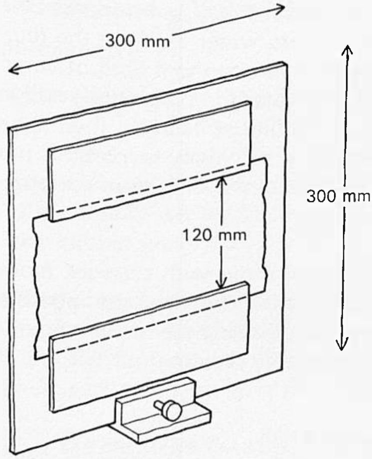



**Figure 20**
A simple printing frame.

## Scaler

*Summary of operating procedures*

Locate the following parts and controls (see figures 21 and 22):

mechanical register and its reset button
two dekatron counters
counting switch, to start counting
reset switch, to reset dekatrons (unless this is done by counting switch)
selector switch, to select pulses from GM tube or from internal oscillator
on/off switch
socket for lead from GM tube
pair of sockets 'make to count' ('start')
pair of sockets 'make to stop' ('stop')
e.h.t. control, to vary the voltage fed to a GM tube

Switch on, and wait for the dekatron counters to light.

*To test.* Short-circuit 'make to count' sockets.
Set selector switch to select pulses from internal oscillator.
Set counting switch to 'count'.
Check whether the counter operates at the oscillator frequency.
Set counting switch to 'stop'.

*Resetting.* Move the reset switch (it may also be the counting switch) to 'reset'.
Press the reset button beside the mechanical register. (Sometimes this also resets the dekatrons.)

*GM counter.* Switch off.
Plug in GM tube lead, using the knurled ring to screw it home.
Set e.h.t. control to voltage required for the GM tube.
Switch on.
Set selector switch to GM position.
Start and stop counting, using the counting switch.
Reset as above.

*Clock.* Set selector switch to select pulses from internal oscillator.
Set counting switch to 'count' if necessary.
Arrange connections to 'make to count' and 'make to stop' sockets as required to time the duration of an event.
Reset as above.

*Solid-state detector or counting other pulses.* Obtain assistance unless you know how to use the type of scaler you have for these purposes.

### The instrument

Figures 21 and 22 illustrate the controls of two scalers intended for use in schools. There are other models, and the placing of the controls, and the way they are

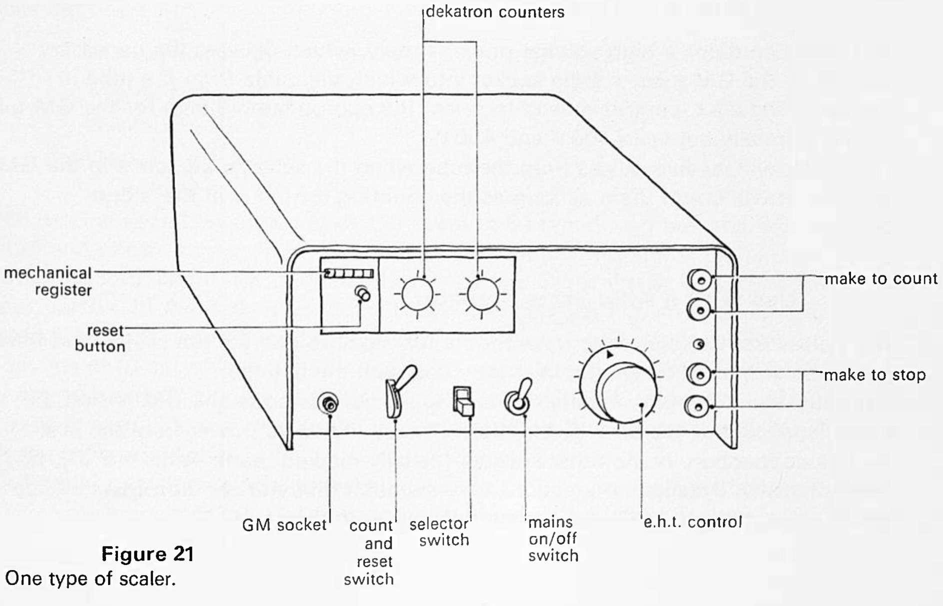



**Figure 21**
One type of scaler.

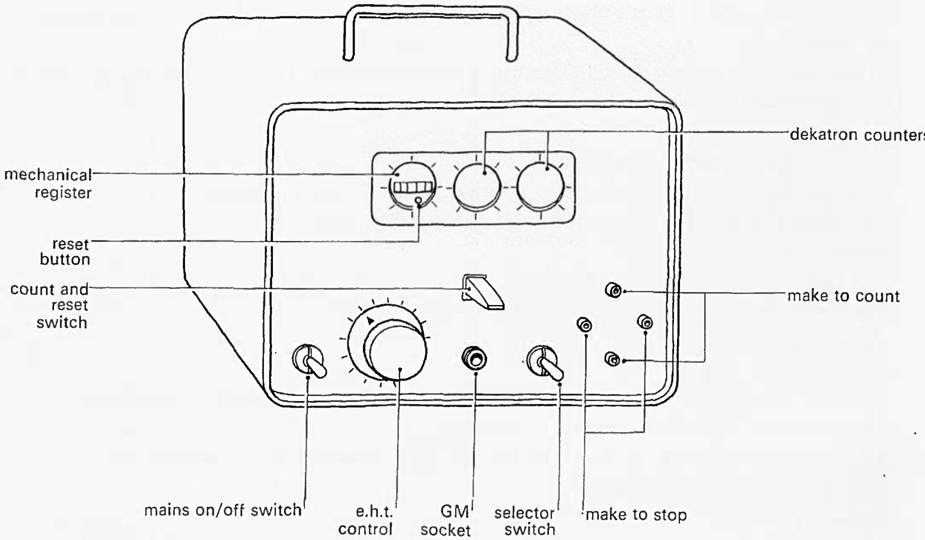



**Figure 22**
Another type of scaler.

combined in multi-position switches, vary from make to make.
A scaler counts pulses, at any count-rate up to something of the order of 1000 pulses a second. Two dekatrons count 'units' and 'tens', while a mechanical register records hundreds and above.

### Use with a GM tube

The scaler contains a high voltage power supply, which delivers the necessary voltage to the GM tube, via the socket into which the cable from the tube is plugged. The e.h.t. control is used to select the appropriate voltage for the GM tube in use; normally between 400 V and 450 V.
The scaler will receive pulses from the tube when the selector switch is in the GM position. It will count them as long as the counting switch is in the 'count' position.

### Use with a solid-state detector

The pulses from a solid-state detector are too small to operate the scaler, and have *first to be amplified by an amplifier provided with the detector.*
The solid-state detector amplifier is *not* usually connected to the GM socket, but to a special socket at the back of the scaler. It may derive its power from the scaler, via this connection, or via other sockets (usually marked 'earth' and '−9 V'), or from a battery. Detailed connections vary so much that you should obtain advice before attempting to use a solid-state detector with the scaler.

### Use as a clock

The scaler has an internal oscillator which produces pulses at 1 kHz, or in some models, at 100 Hz or at 50 Hz. If the beginning and end of an event, such as the falling of a ball, can be made to start and stop the scaler, the event can be timed (in milliseconds if the scaler's oscillator provides 1 kHz).
Figure 23 indicates how the two 'make to start' sockets pass pulses from the oscillator to the scaler when these sockets are linked. Figure 24 indicates how the 'make to stop' sockets, when they are linked, effectively short-circuit the oscillator, stopping the counting process. It will be seen that the 'stop' connection over-rides the 'start' connection, if both are linked.

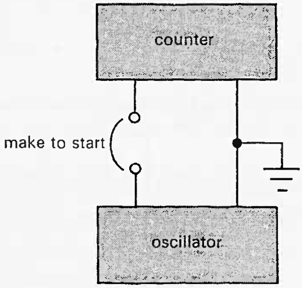



**Figure 23**
'Make to start' connection.

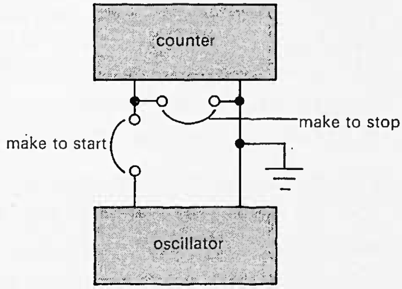



**Figure 24**
'Make to stop' connection.

The possibilities are shown in table 2, in which '1' indicates that the terminals are linked, and '0' that they are not. For the counter, '1' indicates that it runs, '0' that it does not.

| | | | | |
|---|---|---|---|---|
| 'Make to start' | 0 | 1 | 0 | 1 |
| 'Make to stop' | 0 | 0 | 1 | 1 |
| Counter runs | 0 | 1 | 0 | 0 |

**Table 2**

Mechanical switches, operated by the event to be timed, can be used. More often, a lamp and photo-transistor are used. When the photo-transistor is illuminated, it conducts well, and if it is connected across a pair of terminals, it behaves like a short circuit. In the dark, it conducts badly, and behaves like an open circuit. In table 2, then, '1' can be read as 'light on' and '0' as 'light off'. It is often convenient to cut off the light by letting an opaque card pass between lamp and photo-transistor. Thus, for example, if 'make to start' is shorted with a wire, and 'make to stop' is connected to the transistor, the counter operates only for as long as the light is cut off.
The scaler may have a pair of sockets (2.2 V a.c.) for supplying the lamp or lamps. The photo-transistor must be connected to the 'start' or 'stop' sockets with the

correct polarity. If the scaler fails to start and stop, try reversing these connections. The selector switch needs to be in the position which connects the scaler to the oscillator, and the counting switch needs to be in the 'count' position.

### Using the scaler to count other pulses

If the scaler is provided with an input socket *other than the GM tube socket*, at which a high voltage does *not* appear, it can be used to count pulses from, for example, switches operated by apparatus or from electronic systems you may have built. To operate the scaler, the pulses are likely to have to rise sharply, and to be a volt or more in magnitude.

### Diffusion cloud chamber

*Summary of setting up procedure*

Using a dropper, put methylated spirit on the felt strip inside the top of the chamber, and one drop on the base plate.

Put dry ice (solid carbon dioxide) in the base and screw the base cap back on so that the sponge plug presses the dry ice against the chamber base.

Insert the source, set the chamber on three levelling wedges, and rub the chamber top with a wool cloth, or duster, to charge it.

Illuminate a layer a few millimetres above the base plate.

Observe the tracks and then level the chamber, so that there is no general drift.

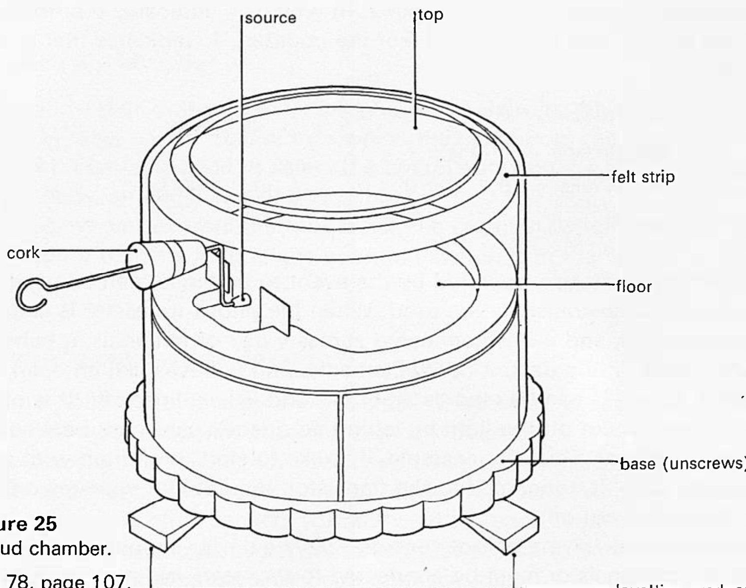



**Figure 25**
A diffusion cloud chamber.
See also figure 78, page 107.

### Use of the chamber

To set up a diffusion cloud chamber, about 2 $cm^3$ of ethanol or methylated spirit should be put on the felt strip inside the top of the chamber with an eye-dropper. The alcohol should not be mixed with water, as this will cause a white frost to form on the chamber floor and make observations more difficult.

The base of the chamber should then be unscrewed, the foam-plastic plug removed, and some small pieces of dry ice (solid carbon dioxide) placed in contact with the underside of the chamber floor. There should be enough dry ice to cover the floor. Replacing the plug and the base cap of the chamber ensures that the dry ice is kept in contact with the floor.

The mounted source is then inserted in the split cork which should be placed in the hole in the side of the chamber, with the source near the chamber floor. The inside of the chamber lid should be cleaned with a soft cloth, and then put back on the top of the chamber; rest the latter on three levelling wedges.

It is not vital to illuminate the chamber brightly for observing alpha particle tracks. For less dense tracks, however, some care is required to see that light from the source illuminates the sensitive layer a few millimetres above the floor. This can be achieved with a flat parallel beam of light obtained as shown in figure 26.

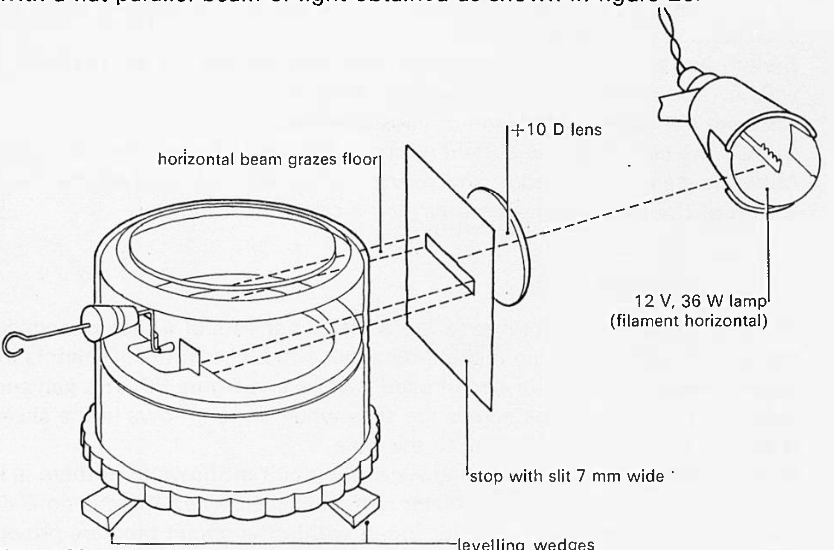



**Figure 26**
Illumination of the chamber floor.

The lid of the chamber should be charged by rubbing it with a woollen cloth. This cloth must be free of dust and grit to avoid scratching the lid. Tracks should be observed when the internal turbulence has died away. Recharging will be necessary at intervals in order to sharpen up the tracks. If the chamber is not level, the tracks will drift downhill, and the levelling wedges should be adjusted to eliminate this.

## Hall probe and search coils

*Summary of operating procedures*

*The Hall probe*, with its circuit box (figures 27 to 29), is used with a light beam galvanometer to measure steady magnetic fields.
Zero the galvanometer (see 'Light beam galvanometer', page 11).
Connect the probe, circuit box, and galvanometer together. (Leads from the probe to the circuit box and the terminals they go to may be colour-coded.)
Switch on the circuit box. Check that the lamp lights. If not, replace the cell in the circuit box.
Reset the galvanometer to zero, using the balance control on the circuit box, with the galvanometer on its *least* sensitive range.
Reset to zero as above, with the galvanometer switched to successively more sensitive ranges. On the $\times 1$ range, zeroing is not easy, and need not be perfect.
Record the zero reading of the galvanometer.
Place the probe in the $B$-field to be measured, and note the change in the galvanometer reading, which is (to a good approximation) proportional to the component of $B$ perpendicular to the slice of semiconductor on the end of the probe.
When using the apparatus, check the zero reading frequently.

*Search coils* are used, with an oscilloscope, to measure alternating $B$-fields.
Switch on the oscilloscope, with the time base off and the spot centred on the screen (see 'Cathode ray oscilloscope', page 6).
Connect the search coil to the oscilloscope input.
Supply the circuit whose $B$-field is to be investigated with alternating current.
Move the search coil about, and adjust the oscilloscope gain so that the vertical length of the trace obtained varies over a convenient range.

### The Hall probe

The Hall probe device for measuring $B$-fields consists of a slice of semiconductor on the end of a probe rod, connected by a cable to a circuit box, which is joined to a galvanometer. The type of circuit used is shown in figure 29. The galvanometer indicates the Hall voltage across the slice when current flows in the slice and when there is a $B$-field perpendicular to the slice.
Because there is a p.d. across the slice when current flows in it, there is likely to be a small p.d. across the galvanometer terminals even when there is no $B$-field at the slice. The balance control, and its circuit within the circuit box, are provided so that this p.d. can be reduced to zero, resulting in a galvanometer deflection proportional to the Hall voltage across the slice.

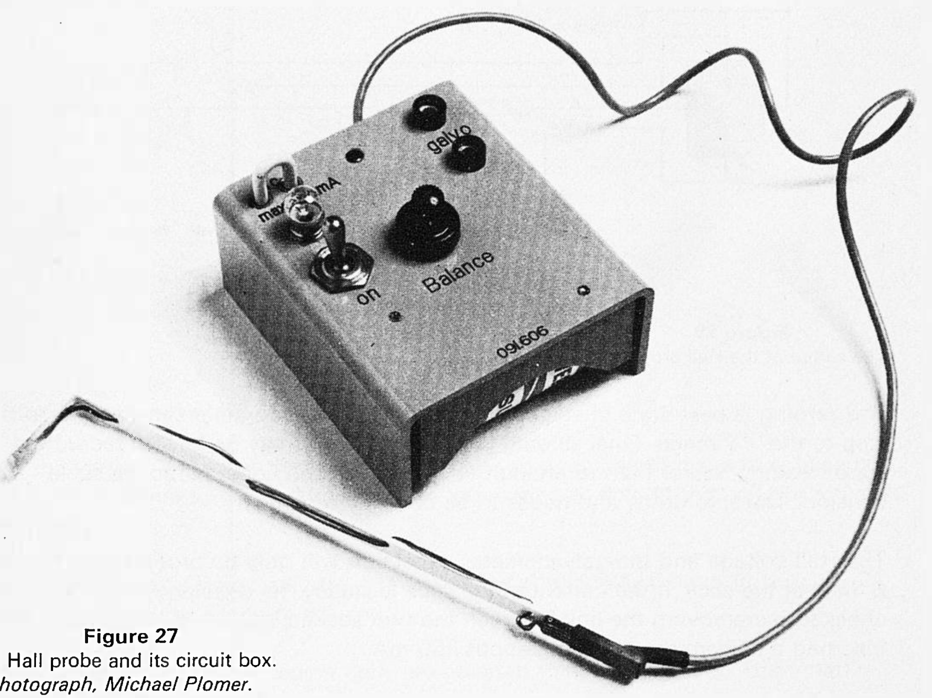



**Figure 27**
A Hall probe and its circuit box.
*Photograph, Michael Plomer.*

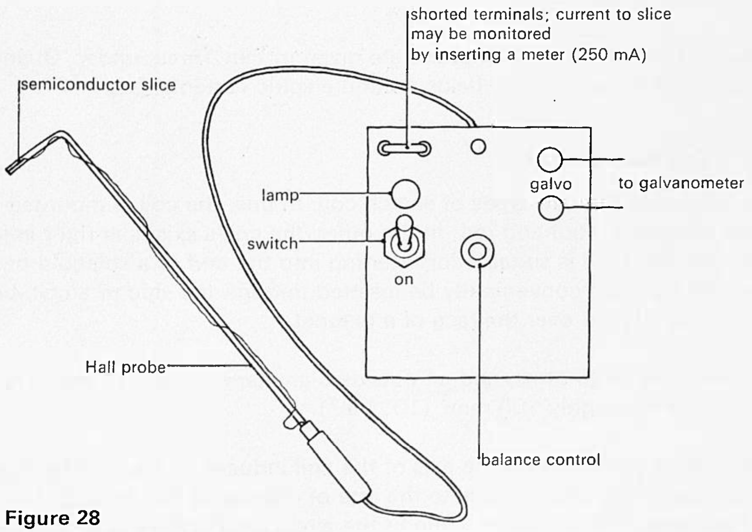



**Figure 28**
Parts and connections of the Hall probe system.

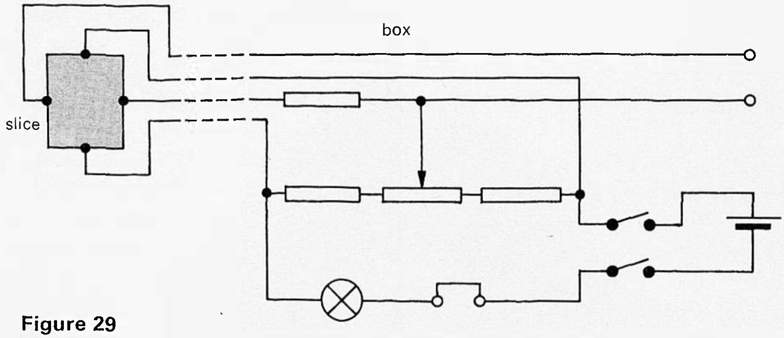



**Figure 29**
The circuit of the Hall probe and the circuit box.

The zeroing is best done in stages, increasing the galvanometer sensitivity step by step to the $\times 1$ range. Final zeroing is not easy, and it may be best to record the 'zero' reading, rather than to attempt to set the zero on some particular scale division. The zero drifts, and needs to be checked repeatedly.

The Hall voltage and the galvanometer deflection will only be proportional to the $B$-field at the slice, if the current in the slice is steady. Its constancy can be checked by removing the link between the two sockets indicated in figure 28, and inserting a milliammeter reading about 250 mA.

Note that the device indicates the strength of the component of $B$-field *perpendicular* to the slice.

Suggestions for using the Hall probe are given in Part Three, under 'Quantitative magnetic field investigations: fields around electric currents' page 127.

### The search coils

Figure 30 shows the two types of search coil. In one, the coil is mounted so that its axis lies along the mounting rod; in the other, the coil's axis is at right angles to the mount. The first type is suitable for inserting into the end of a solenoid or coil, while the second type can conveniently be inserted through the side of a coil, between gaps in coils, or held over the face of a magnet.

Both coils have 5000 turns, and an outside diameter of about 15 mm. The mean area of a turn is roughly 100 mm$^2$ ($10^{-4}$ m$^2$).

An alternating $B$-field along the axis of the coil induces an alternating voltage across the coil's terminals, proportional to the rate of change of flux through the coil. At a fixed frequency, the maximum value of the alternating voltage is proportional to the maximum value of the alternating $B$-field. Because the voltage depends on the *rate of change* of flux, the coil is a very sensitive detector of $B$-fields at high frequencies, such as 10 kHz. The oscilloscope trace displays the alternating voltage from the

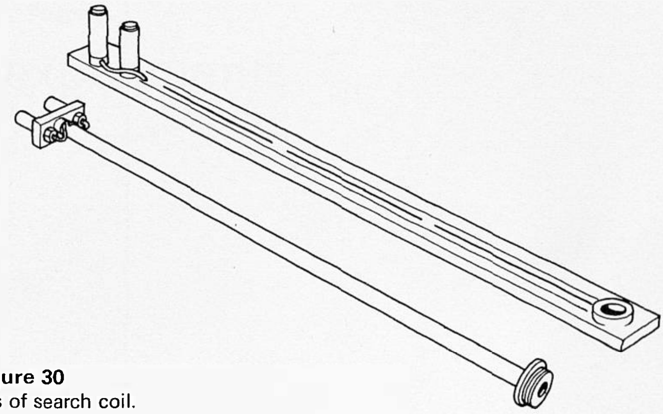


**Figure 30**
The two types of search coil.

coil; the vertical length of the trace (or the peak to peak height if the time base is on) is proportional to the maximum of the alternating $B$-field at the coil, for a fixed frequency.

Note that the coil detects only the component of $B$ which lies along its axis, perpendicular to the plane of the coil.

Suggestions for using the search coils are given in Part Three, under 'Quantitative magnetic field investigations', page 127.

Part Two

# Long experiments

## 2.24 The Millikan experiment (charge on an electron)

This experiment belongs to the long tradition of those that are simple in principle and need little complicated apparatus. Indeed, it can be done just as well with home-made equipment as with that supplied by a manufacturer. Everything looks as if anyone should be able to repeat it, and see for himself the direct evidence that electric charge is supplied to us by nature in lumps of a definite size, never less than $1.6 \times 10^{-19}$ coulomb. However, the experiment turns out in practice to need quite a lot of patience and skill, especially skill at doing the right thing at the right moment, so that time spent obtaining a tiny oil drop carrying only a few electrons is not wasted by letting the drop go out of sight. The purpose of these notes is to help you to become skilful enough to do the experiment for yourself, if you want to. If you take this trouble, you should be able to make a personal check on one of the most fundamental (and still unexplained) facts about the world of atoms and particles.

*How to use these notes*

It is assumed that you understand the point of the Millikan experiment: that the tiny charge on an oil drop will be measured by using the pull on that charge of the electric field between two plates. The pull, which is equal to *charge* × *field*, is adjusted by changing the field, until the drop is poised with the pull equal and opposite to its weight.

Then $$\textit{charge} \times \textit{field} = \textit{weight}$$
$$\textit{charge} = \textit{weight}/\textit{field}.$$

The notes below are in the form of a series of short sections, planned to help you to learn how to do the experiment as you are doing it. Some sections tell you how to avoid or solve difficulties. If the difficulty occurs later in the experiment, you will be directed back to a section which should help you to cope with it; then you can return to the point you had reached before.

Since the idea is that you use the notes *as you do the experiment*, you have only to remember the suggestions in one section at a time. But treat them intelligently, not slavishly, and if you can do the experiment in a better way – do so.

*Preliminary measurements*

Before you put the apparatus together, it will be useful to make two preliminary measurements.

a *The plate spacing*. This may be stamped on the cell and you may decide to trust it. If not, as the spacing is small, you will need to measure it rather carefully, perhaps with callipers but more probably with a travelling microscope.

b *The graticule*. As you look down the eyepiece of the microscope, you should see a set of lines in focus. There may be a grid, or a pair of lines with a third crossing them, or a scale on a single line. See figure 31. You will need to time the fall of a drop between two points, a known distance apart, which are in focus in front of the microscope. The microscope, with graticule, can now be focused on a scale or on a wire of known diameter, so that you can find the distance in millimetres at a place in front of the microscope, which corresponds to the distance (arrows in figure 31) between a pair of lines or on a scale on the graticule.

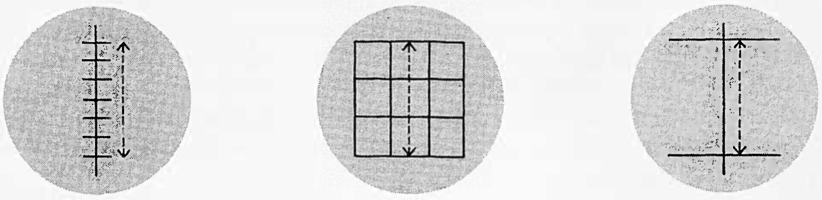


**Figure 31**
Graticules for the Millikan experiment.

### 1 Assembly

It is best to follow the manufacturer's instructions for putting the apparatus together. In all forms of the apparatus, a microscope looks into the space between two horizontal metal plates, about 5 mm apart (figure 32), and a beam of light shines in from the side or from the back at an angle. There is a hole in the top plate, through which oil drops will fall into the space between the plates. The levelling screws can be used to set the plates roughly horizontal by eye or with a spirit level. Accurate levelling comes later.

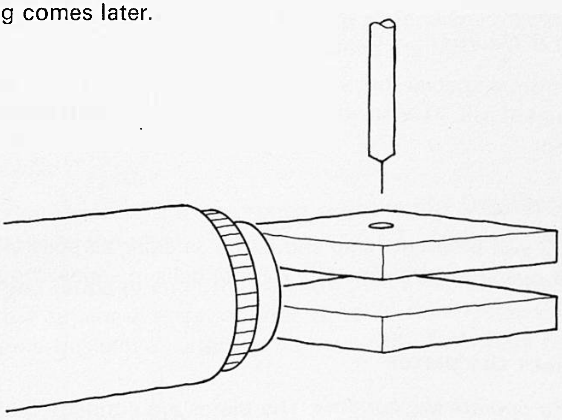


**Figure 32**
Focusing the microscope.

### 2 Focus on the space below the hole

A fibre or needle is usually provided, which will pass through the hole in the top plate. With the light on, the microscope can be focused on the needle. You are less likely to break the window in front of the microscope, or to damage the objective, if you focus by moving the microscope *back* from as close to the cell as it will go. *Notice whether the image is inverted and whether it is reversed left for right.*

### 3 Adjust the light

The needle should be brightly lit down one side, almost dazzling at its brightest. Try moving the light source a little so as to have the needle lit as brightly as possible. A fairly dimly lit part of the laboratory is best, although it should not be necessary to work in a blacked out room.

Here and later on, we have included comments about the use of individual makers' versions of the apparatus. Look for the comments on the type you are using, and ignore the others.

*Philip Harris*

A high power lamp (24 watt) is supplied and a heat filter is needed to stop the air between the plates being heated. The filter swings over the front of the lamp house. Work away from windows or direct sunlight.

*Nicholson*

A rather low power lamp is provided. It can be swung round, and it can be focused onto the needle to give the brightest illumination. Shield the back of the apparatus with a dark cloth or card, and work in a very dim light.

*Griffin & George*

Light from a special low voltage lamp passes into the cell along a transparent rod. The position of the lamp can be adjusted for the brightest lighting.

*MLI (Nuffield)*

The 2.2 volt prefocus lamp should be as close as possible to its window. It is best over-run from two 1.5 volt dry cells in series, though this reduces its life.

### 4 Connect the plates

*Find out how to operate the controls.* The plates are connected to a variable potential difference, which is measured on a suitable voltmeter connected across the supply. The range of voltage is indicated below.

*Nicholson* (0–1000 V)
*Griffin & George* (0–300 V)

A power supply and a switch box are provided. One switch can be used to short-circuit the plates, and also to reverse their connections. The other controls raise or lower the voltage applied.

*Philip Harris*
*MLI (Nuffield)*
(0–2500 V)

A separate power pack with its own variable voltage control is needed. A 5 kV e.h.t. power supply is suitable, and one with a *stepped* coarse control is best. A switch short-circuits the plates, or connects them to the supply.

You will find it helps in the long run to place the controls so that you can reach them all with one hand, when you are looking down the microscope. *Practise finding each control without looking away from the microscope.*

### 5 Check the spray

See that the spray is working. As it is squeezed, a fine mist of oil drops should be visible in a beam of light. Apiezon A silicon oil, density 864 kg $m^{-3}$, is very convenient and the calculations will be easier if this oil is used. If the spray contains large droplets, try adjusting the nozzle. Large drops will be a nuisance and may lead to the hole in the top plate of the apparatus becoming clogged.

### 6 Spray oil drops into the cell

*Nicholson*

A funnel is provided, and an oil mist is sprayed into it so that some drops pass down a tube to the hole in the top plate. *Wipe the funnel out regularly*, or oil will run down it and block the hole.

*Griffin & George*
*MLI (Nuffield)*
*Philip Harris*

The spray is directed into the space over the top plate. Avoid letting large drops fall onto the plate.

*Note.* For charged drops to enter the cell, the plates must be short-circuited. Drops should either appear at once, or after 10 to 20 seconds as they fall through the hole, and should be seen as bright 'stars' against a fairly dark background.

### 7 No drops can be seen

Very probably the hole in the top plate is blocked with oil. But remember, the plates must not be connected to a p.d., if charged drops are to go through the hole.

*Nicholson*
*Griffin & George*
*MLI (Nuffield)*

The plate can be removed and cleaned.

*Philip Harris*

The tube over the top plate lifts off, and the hole can be cleared with a clean rag.

### 8 The drops are very few or faint

The lighting needs adjustment. It should be possible to see at least 10 drops quite clearly, preferably more, and the experiment will not succeed unless you can obtain a cloud of 10 to 50 drops visible in the microscope. You may have to darken the region around the apparatus at this stage.

### 9 Can you see the graticule?

If the lines on the eyepiece graticule are not visible, adjust the light until you can see them, while still being able at the same time to see plenty of drops.

### 10 Practise controlling the movement of drops

Switch a p.d. of about 100 volts across the plates, when you have a cloud of drops. Go back to 4 if you can't remember how to do this while looking down the microscope.

Before the p.d. is applied the drops are falling. Observe their motion in the microscope. If they 'rise', the microscope has inverted the image. Check back to 2 if you are not sure about this.

*Note.* In the rest of these notes, we say 'fall' when the drops are really falling, which may mean 'rise' as you see them through the microscope. Similarly, 'rise' means really rising, though the drops may seem to be going 'down'.

When the p.d. is applied to the plates, some drops with enough charge should reverse their motion, stop falling, and be pulled upwards. Try a larger p.d. if necessary.

*Griffin & George*

If the spray is all glass, few drops may be charged, and nearly all may continue to fall. If a 5–10 $\mu$Ci radium source is held near the spray over the hole in the cell cover as the spray is operated, more drops will be charged.

Switch the p.d. on and off, looking at the drops. Pick on one that reverses its motion when the p.d. goes on, and watch it. Practise letting it fall to near the edge of the field of view, then pulling it up to the opposite edge, letting it fall again, and so on. It is worth saying to yourself 'Off: drop falling. On: drop rising' as you do it, to become used to the way the drop *seems* to move, when you know how it is *really* moving.

### 11 Practise balancing a drop

Obtain another cloud of drops in the cell. (No drops? Go back to 7.)

Switch on a p.d. of about 100 volts, and look for as *bright a drop as you can see* that is affected. If it reverses its motion, reduce the p.d. *until it is held almost still.* If you see one slow down, raise the p.d. *until it stops falling.*

The reason for picking a bright drop now is that bright drops are big. *Big drops fall at a higher steady terminal velocity than small, light ones, so that you can soon see whether the drop is balanced or not. Later, big heavy drops will be quite unsuitable,* as they will be carrying far too many electrons. Go straight on to 12 *with this drop balanced, if you can.*

### 12 Levelling with a big oil drop

You can now level the plates accurately, and see why levelling is worth the bother. Use the big balanced drop from 11 if you still have it, or obtain another. See below for a test of whether the drop is big enough.

Watch your bright balanced drop for a minute or two, raising or lowering the p.d. from time to time, to keep it from rising or falling too far from the middle. It will almost surely go out of focus as you watch. Turn the microscope screw when the drop has become a blur, and find out whether the microscope needs to go towards the cell or away from it to bring the drop into focus again. This, of course, is the same as the direction in which the drop moved when it went out of focus.

*Correcting the tilt of the plates.* Suppose the drop moves away from you. Then the plates are tilted as shown in figure 33 (much exaggerated).

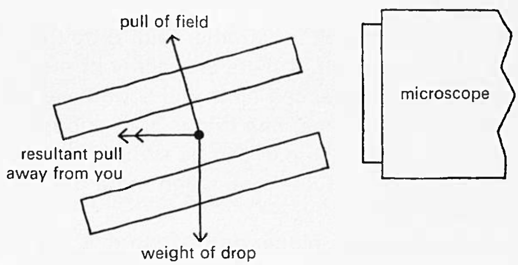



**Figure 33**
The effect of tilted plates (exaggerated).

If the levelling screws are turned so as to raise the side of the plates furthest from you, this drift can be corrected. Of course, if the drop moves *towards* you, the *near* side of the plates must be raised. Then repeat until the drop stays in focus for at least a minute, preferably two or three minutes.

*Size of drop to use.* If the drop is heavy, the forces on it are large and it moves quickly, so that you do not have to wait too long before it goes out of focus if it is going to. As an approximate guide to a suitable size of drop, switch off the p.d. and start counting seconds roughly. A suitably heavy drop will have fallen about halfway across the field of view in a count of five. If it goes halfway in much more than a count of ten, it is going to take a very long time to respond to the tilt of the plates, and you will save time in the end by starting again and looking for a bigger (brighter, faster falling) drop to balance.

*Correcting sideways tilt.* You will probably also find the balanced drop drifts sideways. The motion may not be visible, but the drop will surprise you by being to the left or right of where you last saw it. Having decided which way it is *really* moving (does the microscope swop left for right?) you can tell (figure 33) which side of the plates is low, and raise that side.

### 13 Emergency : tilting to bring a drop back to the middle

The movement produced by tilting the plates can be useful. If a drop has drifted a long way off centre, say to the right, then if the whole apparatus is bodily lifted on the righthand side and tilted through 20 to 30 degrees, the drop will drift to the left, back to the middle. If the tilt is big, this will happen quite quickly, and can be used to save a drop from going out of sight when you still want to go on observing it. But be careful not to tip the apparatus over or disturb the position of cell, microscope, and lamp.

### 14 Pick a small charged drop for a measurement of its charge

Having obtained a cloud of charged drops, switch on a p.d. of about 500 volts (*Griffin & George*, 300 volts).
(No drops? Go back to 7.)
Switch the p.d. on and off, and look for a rather faint drop that more or less stops falling when the p.d. is switched on. If there are plenty of drops, the p.d. can be left on, when all but the nearly balanced ones will soon have gone away.
You want a fairly small drop this time; one that is light enough to balance, carrying only a few electrons. As a check, the p.d. can be switched off, and a rough count of seconds made. A suitable drop will *not* have fallen more than halfway across the field of view by a count of ten.
If you find you can only see faster, bigger drops than this, go back to 8, as the lighting may not be good enough to see small drops.
Now that you have a drop which you know *can* be balanced, it is best to 'weigh' it by timing it *before* you try to measure the balance voltage accurately. So pull it up, and then let it fall, with no p.d. on the plates, past a pair of lines on the graticule, and time its fall between these lines with a stop watch.
If you cannot manage the business of raising the drop, letting it fall when you want, 'catching' it again, bringing it back to the middle, and then balancing it roughly, go back to 10 and 11 for more practice.

### 15 Measure the balance voltage accurately

Having timed the drop (14) and brought it to the middle of the field of view, you can balance it more carefully. The usual mistake is to make too large a change to the p.d., when the drop is seen to be moving up or down. It is better to be patient, change the p.d. a little, and look away from the apparatus for a little time – perhaps 10 seconds at first and 30 seconds later on. Then when you look back, the drop can be seen to have shifted definitely, and you can make another change.
Once the balance is roughly right, it is worth writing down the potential differences you are trying, as their average will give some idea of the right value even if you never satisfy yourself that the drop is exactly balanced. Remember that there will be some random 'Brownian' motion of the drop as well, because it is being struck by air molecules. For worthwhile results, you need to know the balancing voltage to at least 5 parts in 100 and preferably better.
It is now that your levelling will be tested. If the drop persistently goes out of focus, or drifts sideways, go back to 12.

### 16 Find the weight of the drop

The graph in figure 34 gives the weight in newtons of drops that fall 1 mm in air in times from 5 to 20 seconds. It is plotted for an oil density of 864 kg $m^{-3}$.
If your oil has a different density, the weights need to be corrected. Drops of *more* dense oil have a *smaller* weight for a given time of fall. To find the weight, *multiply* the weight read from the graph by $\sqrt{864/\textit{your oil density}}$. Thus, for an oil density of 900 kg $m^{-3}$, a drop that falls 1 mm in 10 seconds has a weight $W$ given by

$$W = \text{weight from graph at 10 seconds} \times \sqrt{864/900}$$
$$W = 3.0 \times 10^{-14} \times 0.98$$
$$W = 2.94 \times 10^{-14} \text{ newton}$$

To find the time of fall *for 1 mm*, you will need the measurement of the distance in front of the microscope corresponding to the space between the graticule lines used for timing. See under 'Preliminary measurements'.
The graph has been drawn for an air temperature of 23 °C in the cell. Very accurate experimenters may possibly want to correct for different temperatures, by increasing the weight read from the graph by 1 per cent for each 3 degrees by which the temperature in the cell rises above 23 °C. For lower temperatures, $W$ is decreased in the same proportion. Normally, the accuracy does not justify this refinement.

### 17 Find the charge on the drop

When a drop is balanced, there is an electrical force on it equal to its weight $W$. The electrical force is $qV/d$, where $d$ is the plate spacing in metres, $V$ the p.d. in volts, and $q$ the charge on the drop in coulombs. You will need the value of the plate spacing made earlier under 'Preliminary measurements', page 38.

$$\text{Thus } q = \frac{W}{V/d}.$$

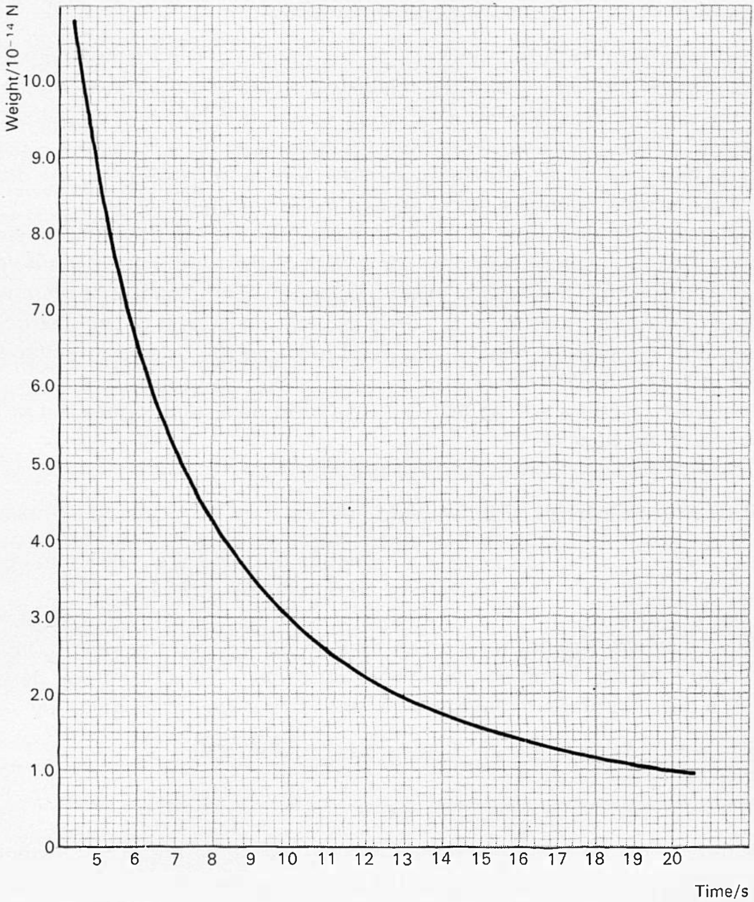



**Figure 34**
A graph of weight against time for oil drops (density 864 kg $m^{-3}$) falling 1 mm in air at 23 °C.

Record the charge, which should be in the range $10^{-19}$ to $10^{-18}$ coulomb, and go back to 14 to repeat the measurements for another drop.

## 18 Integral numbers of charges

After some time, you should have built up a number of results: a series of charges on drops.
If the charges are in the range of 1 to 10 electron charges, it should be quite easy to see that each is close to a simple multiple of one basic charge. If so, you can find the value of that basic charge, which may be in the vicinity of $1.6 \times 10^{-19}$ coulomb, although there may be a fairly large error, perhaps 10 per cent or more.
In this way, you can see for yourself the experimental evidence that electric charge comes in lumps, and obtain your own value for the size of the lumps.

### **Additional information** Mainly for teachers

The graph in figure 34 was plotted from the data in table 3, which may be useful for those who want to make a plot on a larger scale. The weights are corrected for the small deviations from Stokes's Law that arise for very small drops.

For a drop with a weight of $1.0 \times 10^{-14}$ N, and a time of fall of about 20 s over 1 mm, the p.d. required between plates 5 mm apart, to balance it when it is carrying 1 electron, is about 300 volts. For a drop with a weight of $10 \times 10^{-14}$ N, the corresponding p.d. is 3000 V. This information is useful for deciding roughly how many electron charges a particular drop carries, when its balance voltage and time of fall are roughly known, or for the purpose of selecting a drop with a given number of electron charges.

| **Weight** $/10^{-14}$ **N** | **Time** /s | **Weight** $/10^{-14}$ **N** | **Time** /s |
|---|---|---|---|
| 10.81 | 4.39 | 4.11 | 8.21 |
| 9.73 | 4.70 | 3.55 | 9.01 |
| 8.73 | 5.04 | 3.04 | 9.95 |
| 7.79 | 5.43 | 2.59 | 11.04 |
| 6.93 | 5.86 | 2.18 | 12.31 |
| 6.13 | 6.34 | 1.82 | 13.83 |
| 5.39 | 6.88 | 1.50 | 15.63 |
| 4.72 | 7.50 | 0.97 | 20.51 |

**Table 3**

$\rho = 864$ kg m$^{-3}$ temperature 23 °C. At a temperature $(23 + \Delta T)$ °C, increase $W$ by $\Delta W$, given by $\Delta W/W = 3\Delta T/800$.

### Reading

Arons, *Development of concepts of physics*, pages 759–767.
Bennet, *Electricity and modern physics*, pages 158–160.
Born, *The restless Universe*, pages 88–91.
Caro, McDonell, and Spicer, *Modern physics*, pages 15–18.
Millikan, *The electron*, Chapters 3, 4, and 5 in particular.
P.S.S.C. *Physics*, 2nd edition, pages 490–497.
Rogers, *Physics for the inquiring mind*, pages 611–613.

**Apparatus** for experiment 2.24

You may need:

1043 Millikan apparatus

14 e.h.t. power supply

1005 multi-range meter

507 stop watch or stop clock

1033 cell holder with two U2 cells or appropriate supply for lamp

16 radium source, 5–10 μCi

1055 vernier callipers (or travelling microscope)

1000 leads

## 3.9 Measurement of the gravitational force constant *G*

Newton supposed, from the ways in which the Moon and the planets move, and from the force called 'gravity' on the Earth, that all objects attract one another. In the simple case of two small but massive objects, he suggested that the force $F$ of attraction between them would be proportional to the masses of each, $M$ and $m$, and inversely proportional to the square of their distance $r$ apart,

$$F = GMm/r^2.$$

$G$ is a constant, numerically equal to the force which two small one-kilogramme masses would exert on one another if they were one metre apart. The force $F$ between any two objects which can be handled is so small that it is only just possible to measure it. This experiment, which is designed to do this, is consequently very difficult. The difficulty is not only in detecting such a small force, but in preventing draughts or electrical attractions or repulsions from exerting bigger ones.

The apparatus uses the same principle as Henry Cavendish's in 1797–8, but is much smaller. See figure 35. Each big sphere K, a flask of mercury, attracts a little sphere L, of lead, which is at the end of a short horizontal brass wire. The little sphere can move towards the big one by twisting a fine tungsten wire which supports the brass wire at its centre. Another little sphere attracted by another big one is put at the opposite end of the brass wire, to balance it and to increase the twist on the tungsten wire. The movement of the little spheres towards the big ones is used to calculate the attraction between them. It is measured by a spot of light reflected off a concave mirror hung on the brass wire. See figure 36.

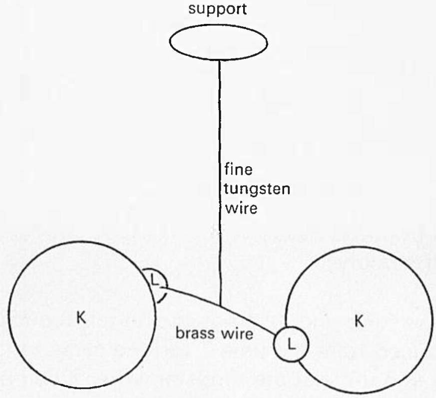



**Figure 35**
The principle of the measurement of *G*.

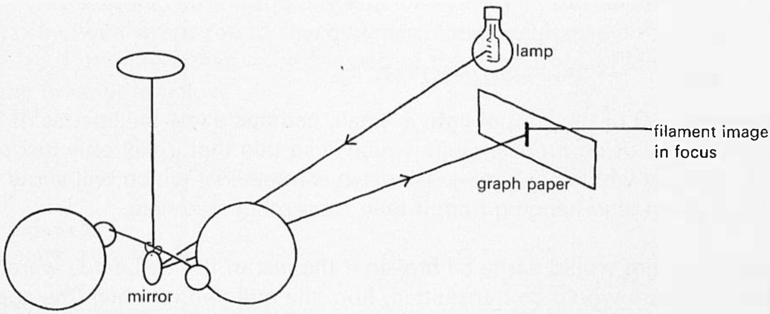



**Figure 36**
The arrangement of the optical system.

The simplest optical system is the best. A piece of millimetre graph paper is put facing the mirror, one metre away from it. A lamp with a narrow vertical filament is placed about one metre from the mirror, and adjusted so that an image of its filament falls on the graph paper. The light should be shielded so that it does not shine directly on the graph paper.

If the image moves sideways a distance $D$, measured in metres, the beam of light has turned through an *angle* equal to $D$, the angle being measured in radians. The mirror has turned through an angle $D/2$, also measured in radians.

The beam and mirror are turned by forces $F$ on the small lead spheres, at right angles to the brass wire joining the spheres. If the little spheres are a distance $d$ apart, the pair of forces $F$ on the spheres will exert a turning effect, or couple, about the suspension equal to $Fd$. This couple twists the tungsten wire until the wire exerts an equal and opposite couple. Writing $c$ for the couple exerted by the wire for each radian of twist, the couple it exerts when it is twisted through the angle $D/2$ is $Dc/2$.

Thus

$$Fd = Dc/2$$

so that $$F = GMm/r^2$$

becomes $$Dc/2d = GMm/r^2$$

or $$G = Dcr^2/2dMm.$$

$r$ here is the distance from the centre of a small lead sphere to the centre of the nearest large sphere (mercury).

You may be told values for $c$ and $m$, so as to shorten the experiment. Otherwise their ratio can be deduced from the time $T$ for one cycle in the swinging of the little spheres as they twist and untwist the tungsten wire. $T$ can be shown to be almost exactly given by

$$T = \pi d \sqrt{2\, m/c}$$

so that $$c/m = 2\pi^2 d^2/T^2$$

and $$G = \pi^2 d D r^2/(T^2 M).$$

The movement $D$ of the spot of light is small, perhaps a few millimetres. It is made as big as this by using tungsten wire which is so thin that it will only just support the lead spheres which hang on it. Tungsten is a material which will allow more twist for a given load hanging from it than most other materials.

The tungsten wire would easily be broken if the rest of the apparatus were rigid, and also vibration would be transmitted, from the building in which the apparatus was used, to the lead spheres and the mirror. The brass wire between the lead spheres is springy so as to absorb shock, and the tungsten wire hangs from a foam-plastic support which damps any vibrations except the one in which the wire is twisted. A rigid suspension would be easier to set up, but much more difficult to use.

### Hanging the lead spheres

Unless the lead spheres are already hanging on a tungsten wire, the glass sides and the rubber band around the three wheels at the top of the apparatus should be removed. The tungsten wire is fine and can be seen best against a well lit, white paper background. This paper should have marked on it the distance apart (about 75 mm) of the brass hook H and the brass wire as they will be when the spheres are suspended. Lengths of tungsten wire may already have been stuck to the paper by their ends. Put a little adhesive (such as Durafix) on the brass pin at P and stick it to one end of a wire. See figure 37.

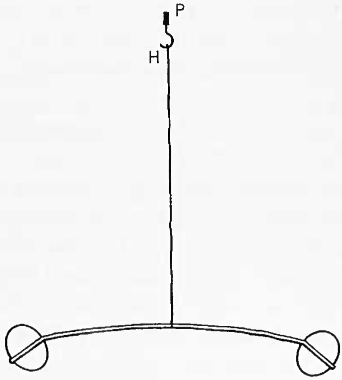



**Figure 37**
The suspension for the lead spheres.

When the wire is stuck, cut off the unwanted end with a razor blade and twist the pin so that the wire wraps round several times, approaching the bottom of the hook as it does so. Put more adhesive on the part of the hook from which the wire will drop to the brass wire below.

**Figure 38**
The shape of the brass wire.

Take the lead spheres off the brass wire, which would be as shown in figure 38, with the loops at the ends shaped so as to grip the lead spheres at the points marked by arrows. The lead spheres should be firmly gripped, but not so as to make it difficult to move them, for sliding the spheres is a way of making the brass wire hang horizontally. Put adhesive on the centre of the brass wire and stick it to a point on the tungsten wire further from the hook than it will finally be. Roll the tungsten wire onto the brass, keeping it in the centre of the brass wire, until the correct length of tungsten wire is left. Then put on more adhesive, and when it is dry, put on the lead spheres and *gently* lift the hook by the brass wheel it is mounted on. Adjust the lead spheres until they hang at the same level. The brass wheel has a flange to rest on three knurled smaller wheels. Gently put the large wheel in position, hang the mirror from the brass wire, adjust the brass pin for height, put the glass plates in position and hold them with a rubber band, and put a rubber band around the three knurled wheels. The purpose of the second rubber band is to make all three knurled wheels and the large central wheel turn if any of the three knurled wheels is turned by hand. Zero the apparatus, that is, make the image swing roughly symmetrically about a point near the middle of the graph paper by turning a knurled wheel. It will be seen that the wheels turn in the opposite direction to the brass pin, and that a movement of one millimetre at the circumference of a knurled wheel should alter the zero on the graph paper scale by a distance of about 25 mm.

Bringing the apparatus to zero is much easier if the rubber band around the three wheels is only slightly stretched when in position. A highly stretched band increases friction and makes the movements of the wheels jerky.

Levelling the apparatus is not vital. If the two symmetrically placed screws at the top are loosened, the whole suspension may be moved horizontally to let the lead spheres swing through the greatest amplitude, and the experiment is easier if this is done. Lead is diamagnetic, and a bar magnet brought close to one of the spheres will repel it enough to help to bring the balls to rest when the apparatus is to be zeroed. Once this has been done the apparatus can be gently moved from one horizontal surface to another without needing readjustment. For rougher movement the pin should be lowered so that the lead spheres rest on the wood below.

### Dealing with complications

*Electrical forces* can be much bigger than the gravitational force to be measured. The foam plastic can enable the lead spheres to be insulated and so to act like the gold leaf in an electroscope. Therefore, a metal cap must be put over the brass pin at the top to shield it from electrostatic fields. Electric charge on the mercury flasks can pull the lead spheres, so a conducting shield must be put round the outside of the glass plates, leaving only a small opening for the beam of light. A strip of aluminium foil held by a rubber band is suitable. See figure 39. A thin wire or another strip of foil should connect the cap at the top to the aluminium lower down. Even with these precautions, it is possible to deflect the lead spheres by bringing a charged insulator near to the apparatus, and the Perspex case cannot be used on it because it cannot be sufficiently discharged. You may find that you need to touch an earth connection while making adjustments. Cleaning the glass plates may put charge on them which will affect measurements for some days.

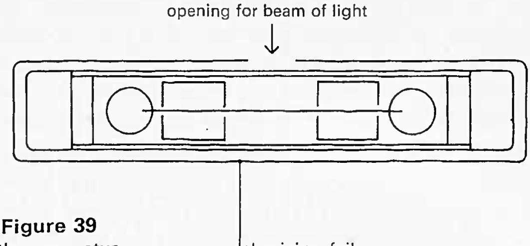



**Figure 39**
Shielding the apparatus.

*Draughts* can be excluded by sealing all the way round the edges of the glass plates. The disadvantages of doing this are that it is then less easy to replace the tungsten wire if it gets broken, and simple ways of sealing, using Sellotape for instance, may put electric charge onto the apparatus. A method which is satisfactory, where draughts are slight anyway, is to put a polythene bag over the apparatus down to below the bottom of the glass plates. The bag can be held by another rubber band. The flasks of mercury should be outside the bag so that they can easily be moved while readings are being taken. A small hole or slit must be cut in front of the mirror.

*Vibrations* from the floor of the building may prevent the mirror from settling down to give a steady reading on the graph paper scale. A windowsill, a shelf on the wall, or a heavy bench on a concrete floor should be steady enough. Light, movable benches, or benches on a floor supported by wooden joists, are the least satisfactory supports for the apparatus.

*Air resistance*. When they are deflected by the attraction of the big spheres, the little spheres move in a narrow channel and the air resists their movements so that the amplitude of swing decreases rapidly. This makes it easier to measure the steady deflection $D$ but hinders measurement of the time of swing $T$.

*Apparatus*. When you set up the apparatus the following may be wanted, apart from what is supplied by the makers: 100 $cm^3$ of mercury, a 12 volt straight filament lamp, millimetre graph paper, Durafix, aluminium foil, Sellotape, a razor blade or scissors, and a polythene bag. Possible replacements are tungsten wire, glass slides, 26 s.w.g. brass wire (copper can be used but is less springy), and rubber bands.

*Supports*, on which the two mercury flasks can rest when they are not in use, should be provided near the apparatus before measurements are started. Two polythene beakers in a mercury tray are suitable. *Keep the mercury filled flasks sealed and avoid spills, since mercury vapour is poisonous.*

## Measurements

It is convenient to plot readings from the graph paper scale taken every half minute, directly onto a graph of deflection against time. If the spot of light is stationary, it can be given a deflection of a few centimetres by using a magnet to repel one of the lead spheres, and the graph can be started. After twenty or thirty minutes the movement will have died away, and a graph of smoothly decaying harmonic motion shows that the spheres are free to move. See figure 40.

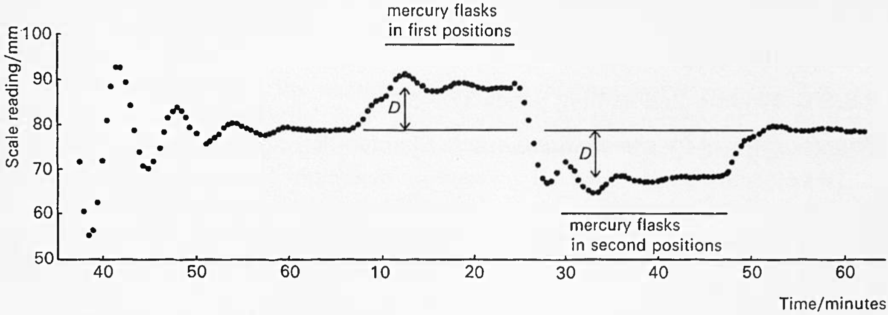



**Figure 40**
A typical graph of deflections with $G$-apparatus.

A mercury flask can now be put gently in position. The lead spheres will overshoot their equilibrium position. When they have nearly stopped moving, the second flask should be put gently in its position, which is diagonally opposite the first. After a few swings the spot of light should again become stationary at a distance $D$ from where it became stationary before.

Next, one mercury flask can be moved to one of the remaining positions. When the lead spheres have overshot their equilibrium position and are again nearly stationary, the second flask can be moved until it is diagonally opposite the first. After settling down, the spot of light should be at a distance $D$ on the opposite side of the first stationary position.

Finally, one flask, and then, as the spot of light nearly stops, the second flask, can be removed, to check that the zero has remained constant.

The quantities $d$, $r$, and $M$ can easily be measured more accurately than the estimate of $D$ from the graph.

### Results

Setting up this experiment, taking readings, and calculating a result are, altogether, an arduous undertaking. Cavendish spent a time comparable with the length of this entire course in doing it. An Advanced level student who starts but cannot finish should not feel any sense of failure. He will have gained experience of the difficulties of measuring an exceedingly small force, and it will be good experience because the same difficulties exist in many other situations.

Some of you may see faults in the design of the experiment. One of these is the attraction of each big sphere for the little sphere which is furthest from it. Another is the use of $T = \pi d\sqrt{2m/c}$ for heavily damped harmonic motion. There are ways of making allowance for these faults, but they take too much time to be profitable at this stage.

### Reading

P.S.S.C *Physics* 2nd edition, pages 373–375.

Rogers, *Physics for the inquiring mind*, Chapter 23.

### Apparatus

| | |
|---|---|
| 1026 | kit to make gravitational constant apparatus |
| 535 | bottle of mercury (100 $cm^3$ needed) |
| 94A | lamp, holder, and stand with shield |
| 94B | |
| 524 | mercury tray |
| 1055 | soft container (e.g. polythene beaker) |
| 501 | metre rule |
| 50/1 | cylindrical magnet |
| 507 | stop watch or stop clock |
| 1054 | graph paper (mm squares) |
| 1053 | aluminium foil |
| 1053 | polythene bag (about 0.25 m square) |
| 1053 | rubber band |
| 1053 | Durafix glue |
| 1053 | adhesive tape |
| 1053 | razor blade |

## 2.11 Measuring a voltage without a voltmeter

In the apparatus for this experiment, a heating coil has been placed in (or around) a metal block so that energy can be supplied to the block electrically. When this is done, the block is warmed and its temperature rises by, say, $\theta_1$. One way of finding how much energy was supplied to the block is to give it some mechanical energy by rubbing it. The amount of work involved can be calculated and the rise in temperature caused by it, say $\theta_2$, can be measured. In an ideal case, where all the energy goes to warming the block, the energy transformed is proportional to the rise in temperature produced, so that we can write:

$$\frac{\textit{energy transformed electrically}}{\textit{energy transformed mechanically}} = \frac{\theta_1}{\theta_2}.$$

Thus, if $\theta_1$ and $\theta_2$ are measured, and the energy transformed mechanically is known, the energy supplied electrically can be ascertained.

To find the voltage across the heating coil (that is, the number of joules transformed by each coulomb), it is necessary to know the number of coulombs which were passed through the coil. This is simply the number passing per second (or the current in amperes) multiplied by the time for which the current flowed. Therefore, it is possible to find how many joules per coulomb are transformed in the coil without using a voltmeter. The voltmeter is a convenient and practical means of measuring a voltage, but it is not essential.

However, this method of measuring a p.d. is not normally used because it is difficult to use it accurately. Not all the energy supplied, either electrically or mechanically, is stored in the block, because some escapes to warm the air surrounding the block and whatever is supporting the block. It is important to keep this 'loss' small compared with the energy stored, and to perform each part of the experiment under circumstances as nearly identical as possible. If the initial and final temperatures are the same in each part and if the time over which energy is supplied is the same; then error is minimized. (Can you see why?) When you do this experiment, you should try to achieve these conditions, but there is no need to spend a lot of time in getting them exactly the same.

A band brake is used to transfer energy mechanically to the metal block. In apparatus like type A (illustrated in figure 41) the band brake is a cord wrapped round the cylindrical part of the block and energy can be transferred continuously by turning the block with the handle. With apparatus like type B (illustrated in figure 42), the band brake is a split metal tube clamped round the block, and energy is transferred by pulling a cord of limited length off a pulley wheel fixed to the block which turns inside the tube.

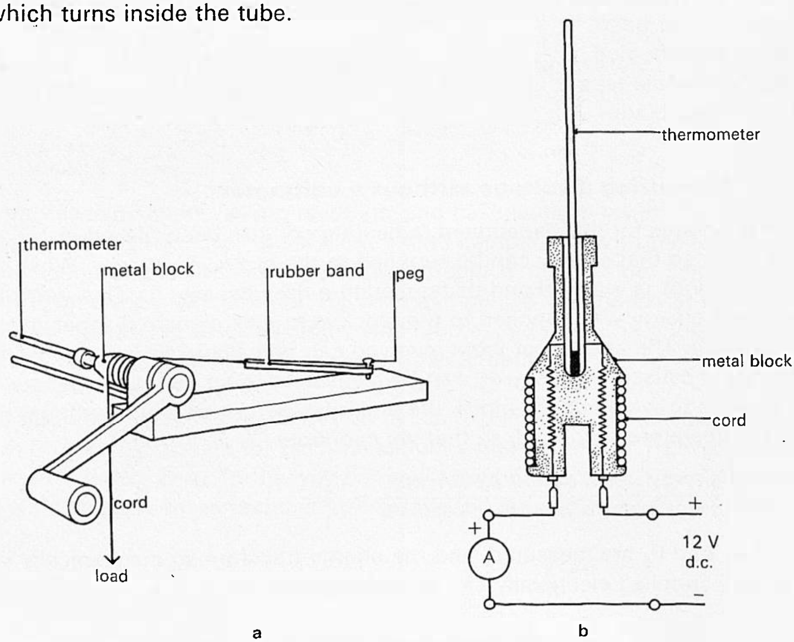



**Figure 41**
Apparatus for measuring a voltage without a voltmeter (type A).

### **Apparatus** Type A

In the electrical part of the experiment, current is supplied to the heater by standing the block on the special holder (figure 41 *b*). Later the drum will have 5 or 6 turns of nylon cord wrapped round the cylindrical portion, and it should have that cord round it now so that conditions will be more nearly the same in both parts. It is important to make sure that the two small studs, to which the heating coil is connected, make good contact with the two points on the stand, which are connected to the sockets. A 12 V d.c. supply is needed, together with a 1 A meter to measure the current. The current should be switched on for a few seconds to ensure that there is good electrical contact with the coil (current about 0.7 A). It is a good idea to put a drop or two of glycerol in the thermometer hole before inserting the thermometer, so that good thermal contact is made, and the temperature indicated by the thermometer will not lag far behind that of the drum.

The initial temperature of the drum needs to be recorded before passing the current for a measured time. Two minutes is about the time required. At the end of that time, turn the current off and watch the temperature carefully to find the highest value reached.

The block must now be cooled back to room temperature. (You can speed this up by using an aerosol freezer spray or by standing the block in a container surrounded by cold water.) Then screw it to the handle. The whole assembly needs to be firmly clamped near the edge of the bench so that the cord can hang freely below bench level. The free end of the cord is securely fixed to a load with a mass of 8 kg and, after 5 or 6 turns have been wound around the drum without any overlap, the other end is fastened by a rubber band to the peg on the baseboard. The cord must now be shortened where it is attached to the load so that the rubber band is stretched when the handle is not being turned and so that the load 'floats' just above floor level with the rubber band slack and free of tension, when the handle is turned. It is advisable to give the handle a few turns to ensure that the cord does not travel to one end of the drum while it rotates. It will do this if the axis of rotation is not horizontal and you will have to place cardboard packing under the base to prevent it happening.

After measuring the initial temperature, turn the handle steadily at about one revolution per second for 2 minutes, so as to keep the load 'floating'. It will be necessary to know how many turns were made, and also the highest temperature reached by the drum at the end. The temperature rise will not be exactly the same as in the first part, but the effect of losses will very nearly cancel out.

For every revolution of the drum the work, which measures the energy which is transferred, is equal to the weight supported multiplied by the circumference of the drum. Now you can find the energy, which is supplied mechanically, and so calculate the energy transformed electrically in the first part. The p.d. across the heater was the number of joules of energy supplied electrically by each coulomb passed.

### **Apparatus** Type B

With this apparatus, it is more convenient to do the mechanical part of the experiment first. The apparatus needs to be securely clamped to the bench. Fix just over 5 m of strong cord at one end through the small hole in the rim of the pulley wheel, wind the cord around the wheel, and tie a loop in the free end. The friction brake should be tightened until it takes a pull of about 40 N to turn the wheel. This pull can be measured with a spring balance – and it is a good idea to practise turning the wheel with a steady pull. A drop or two of glycerol placed in the thermometer hole will ensure good thermal contact between the thermometer bulb and the drum and reduce time lag.

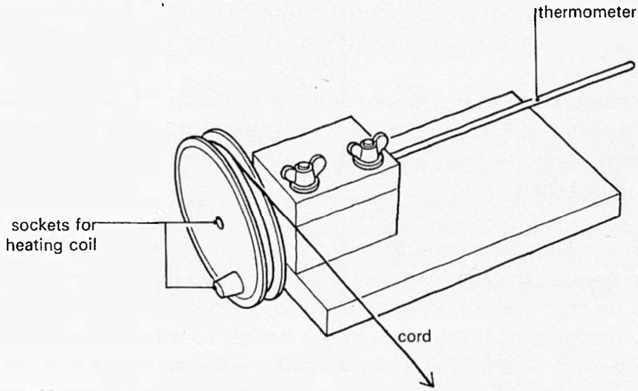



**Figure 42**
Apparatus for measuring a voltage without a voltmeter (type B).

When the drum has returned to room temperature (this can be speeded up with an aerosol freezer), note the temperature and then pull 5 m of string off the wheel as steadily as possible with the spring balance. The string can then be quickly rewound on the wheel and 5 m pulled off again. In each case you will need to know the average force used in order to calculate the total work involved. You will also need to measure the highest temperature reached by the drum.

For the electrical part of the experiment, a supply of smooth d.c. at 10 V is suitable. This is connected to the heating coil through an ammeter (1 A) and the two sockets on the outside of the pulley wheel. Before the current is started, the drum must be cooled so that its initial temperature is about the same as in the first part. Current should then be passed through the heating coil until the temperature has risen to a value about 1 °C below the maximum reached previously and then switched off. The highest temperature reached in this case, the size of the current, and the time during which it was on should be recorded.

Now you can calculate how many joules of energy were transferred electrically from the work and the temperature changes. The p.d. across the heating coil was the number of joules of energy transformed by each coulomb passed.

When you have done this experiment once, you will know better how to vary certain factors so that the temperatures and the times taken for the rise are more nearly the same. If you have the time to spare, you could do the experiment again, making any changes you consider necessary in order to achieve a greater accuracy.

**Apparatus** for experiment 2.11

| | |
|---|---|
| 1011 | apparatus for measuring joules per coulomb |
| 1003/4 | ammeter (1 A) |
| 507 | stop watch or stop clock |
| 542 | thermometer (0–50 °C in 0.2 °C) |
| 501 | metre rule |
| 176 | 12 V battery (or other suitable supply of smooth d.c. 12 V, 1 A) |
| 1021 | freezer |
| 32 | 1 kg weight *8* |
| | *or* |
| 85 | spring balance (5 kg force) |
| 1000 | leads |

## 3.7 Measurement of $\varepsilon_0$

The capacitance $C$ of a pair of parallel plates, each of area $A$ and separated by a distance $d$, is given by

$$C = \varepsilon_0 A/d$$

where $\varepsilon_0$ is a constant. This experiment is concerned with a reasonably accurate measurement of $\varepsilon_0$ by the use of a large pair of capacitor plates.
There are many ways of measuring the capacitance $C$. The method recommended here is based on the use of the reed switch (see page 17 in Part One). The reed switch repeatedly charges a capacitor and discharges it through a meter many times each second. The current $I$ registered by the meter is, if the capacitor is fully charged and discharged during each contact of the switch, the product of the frequency $f$ of the switching and the charge $q$ on the capacitor plates:

$$I = fq.$$

See figure 43. The supply connected to M and N should be between 12 and 24 volts and it must not fluctuate (as unsmoothed rectified a.c. does). Little current is used, so dry cells are adequate. P and Q should be connected to the capacitor plates. Because very small quantities of electricity are to be measured, leakage may be important. It may be necessary to connect P to the top plate by a wire which does not touch anything except at its ends. K and L should be connected to the low impedance output terminals of an audio-frequency oscillator. A suitable frequency is 300 to 500 Hz. It must remain constant during the experiment. R and S should be connected to a light-beam galvanometer. It should be zeroed at the lefthand end of its scale. It will need to be used in the '× 1' position to give big enough deflections. You may be given a high resistor, perhaps 100 kΩ, to put in series with the meter, to protect it against faults in the circuit. See under 'Light-beam galvanometer' in Part One, page 11.

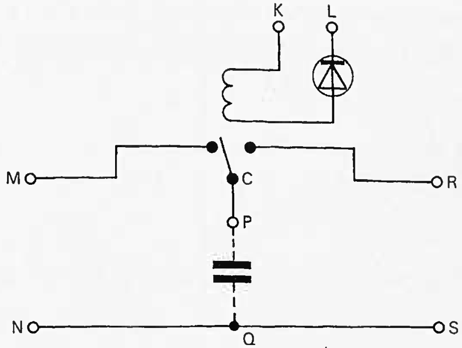



**Figure 43**
Connections to the reed switch.

Try to arrange that the greatest deflection you get on the galvanometer is nearly all the way across the scale. This may not be possible without too big a voltage for the reed switch, or too high a frequency, but in any case you should try to use as big a deflection as possible.

The steady reading of the galvanometer, when the apparatus is connected up and working, is proportional to the quantity of electricity on the capacitor plate connected to P and on the reed and wire CP, each time the capacitor is discharged through the meter. The top capacitor plate can rest on three chips of polythene on the bottom plate. The chips of polythene should be small, only a few millimetres square, so that the properties of polythene do not affect the behaviour of the capacitor as they would do if all, or a fair proportion, of the space between the plates were filled with polythene.

The capacitor plates may be of thick metal, but they must be carefully treated, as slight bends in them would affect the results. (How?) The galvanometer reading should be taken when the top plate is exactly over the bottom plate. The galvanometer manufacturer's data sheet should be used to convert this reading into amperes.

Before the charge on the capacitor plate can be calculated, the frequency of the supply used to operate the reed switch has to be determined. The frequency reading given by the dial on the oscillator can be checked on a cathode ray oscilloscope by comparing it with a 50 Hz waveform obtained from a low voltage mains alternating current supply, or by counting the pulses using a scaler.

The capacitance of the parallel plate arrangement can be calculated from the potential difference $V$ across the plates, and the charge obtained from the reed switch experiment:

$$C = q/V.$$

This, when used in conjunction with measurements of the area of one plate and the separation, enables a value of $\varepsilon_0$ to be obtained.

**Apparatus** for experiment 3.7

| | | |
|---|---|---|
| 1010 | reed switch | |
| 1009 | signal generator | |
| 1025 | capacitor plates, with spacers | *1 pair* |
| 15 | h.t. power supply (25 V) | |
| | *or* | |
| 59 | l.t. variable voltage supply | |
| | *and* | |
| 1064 | low voltage smoothing unit | |
| 1004/3 | voltmeter (100 V) | |
| 1001 | galvanometer (internal light-beam) | |
| 1017 | resistance substitution box | |
| 501 | metre rule | |
| 1055 | micrometer screw gauge | |
| | *or* | |
| 1055 | vernier callipers | |
| 1000 | leads | |

*You may also need:*

| | | |
|---|---|---|
| 158 or 64 | cathode ray oscilloscope | |
| | *or* | |
| 130/1 | scaler | |

## 4.3 Measurement of the speed of light

The basic difficulty in measuring the speed of light is that the speed is so high. In the apparatus designed for Nuffield Advanced Physics, and in most of the other commercially available forms, a pulse of light is 'timed' over a distance of 4 metres or so. Light takes about one hundred millionth of a second to cover such a distance.

The Nuffield apparatus is based on a method first suggested by Sir Charles Wheatstone in 1834 and developed by Arago (1850) and Foucault (1850 and 1862). A beam of light is reflected from a small rotating mirror to a large fixed mirror. The fixed mirror reflects the light back to the rotating mirror and so to a focus on a scale. If the rotatable mirror is stationary, the image appears at a certain place on the scale. The image is displaced from this position if the mirror rotates. See figure 44.

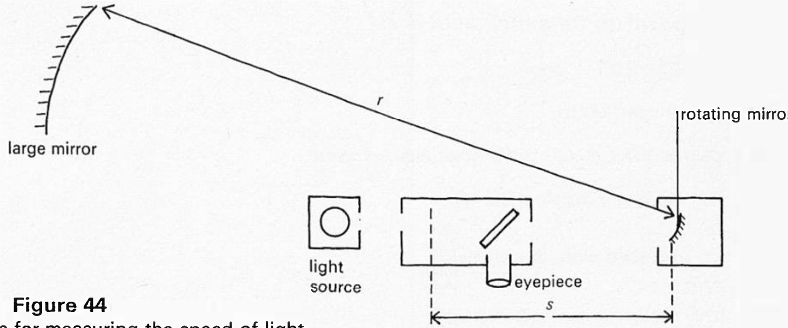



**Figure 44**
Apparatus for measuring the speed of light.

You should be able to show (*Students' book*, Unit 4, question 8) that the speed of light $c$ is given by

$$c = \frac{8\pi nsr}{d}$$

where $d$ is half the movement of the eyepiece image as the rotation of the mirror is changed from $+n$ to $-n$ revolutions per second. $r$ is the distance of the rotating mirror to the fixed mirror, and $s$ is the distance from the illuminated slit to the rotating mirror.

The rotating mirror box is mounted on a large retort stand base, and the large mirror (on a retort stand) is placed so that it is as accurately as possible its own radius of curvature (about 2 metres) away from the axle of the rotating mirror. The eyepiece box, also mounted on a retort stand base, should be about 0.65 m from the rotating mirror, with a compact light source on the same support so that light passes through the eyepiece box. The lamp may be connected to 8 or 10 volts from the transformer while the apparatus is being set up, so as to prolong its life. The eyepiece box and the rotating mirror box are adjusted so that light falls on the rotating mirror. The small mirror is then rotated, *without touching its surface*, so that the beam of light is reflected towards the large mirror. The large mirror should be placed so that angles of incidence and reflection at the rotating mirror are as small as possible. A sheet of paper can be used to locate the reflected beam of light in order to adjust the two mirrors so that the beam of light falls on the middle of the large mirror. The distance of the eyepiece box from the small mirror is altered until the image of the cross wire is sharply in focus on the surface of the large mirror; use a sheet of paper against the mirror. The beam of light is similarly located as it returns from the large mirror, which should be adjusted so that the light returns exactly to the small one. For this it may be convenient to open the rotating mirror box. A bright image should now be visible in the eyepiece. A second image is formed to the left of it by the second surface of the glass plate in front of the eyepiece: this should be ignored. Further adjustments to the distance of the eyepiece box from the small mirror should be made until the image of the cross wire in the eyepiece is sharp. The motor is then replaced and connected via the reversing switch to 3 or 4 V d.c.

When the small mirror is rotating, the image is much dimmer because light returns to it for only a small fraction of each rotation. Slight adjustment of the position of the rotating mirror box in a direction perpendicular to the light paths, and further slight adjustment of the eyepiece box may improve definition. Reversing the motor should result in a small shift (0.1 or 0.2 mm) of the image in the eyepiece. This shift should be estimated by whatever means has been provided for this purpose.

If the speed of rotation of the mirror for a particular voltage applied to the motor is not already known, one of the following methods can be used. The speed can be estimated by tuning a signal generator feeding a loudspeaker, until the note from the loudspeaker is the same pitch as that from the motor and rotating mirror. The required frequency may be around 500 Hz. Another method is to place a photo-transistor so that the beam of light enters it at each rotation. The pulse across a load resistor (1 kΩ) in series with the supply to the transistor may go either to an oscilloscope with a calibrated time base, or to a scaler with an unpolarized input.

Definition and brightness of the image are very susceptible to the cleanness of the surfaces of the rotating mirror and the window in front of it.

The possibility of the small mirror breaking under internal stress when rotating at high speed should always be remembered. The mirror should never be rotated without the Perspex window in front of it and the apparatus should be set up so that the open back of the rotating mirror box faces a wall or a wooden screen. The motor should never be connected to more voltage than the maker recommends, and a tighter rubber band should not be used.

The mirror bearings need occasional oiling unless they are ball-bearings; oil should be applied in as small a quantity as possible.

**Apparatus** for experiment 4.3

| | |
|---|---|
| 1032 | speed of light apparatus |
| 503 | retort stand base *3* |
| 504–5 | retort stand rod and boss *2* |
| 21 | compact light source |
| 27 | transformer |
| 176 | 12 volt battery |
| 1055 | reversing switch |
| 507 | stop watch or stop clock |
| 501 | metre rule |
| 1000 | leads |

## 4.4 Measurement of the speed of microwaves

The speed of microwaves can be determined from measurements of the frequency and wavelength and the use of the relation $c = f\lambda$, or from a direct measurement of the time taken for a pulse of microwaves to cover a measured distance. In this experiment the latter method is adopted.

The 3 cm microwave transmitter is made to transmit in sharp pulses by a rapid switching circuit, and those sharp pulses are displayed on an oscilloscope. Then the beam of microwave pulses is sent down the room to a reflector and back to the receiver, and after amplification the returning microwave bursts are also shown on the oscilloscope. The microwave pulses arrive just a little later than they were sent out, and the delay can be estimated.

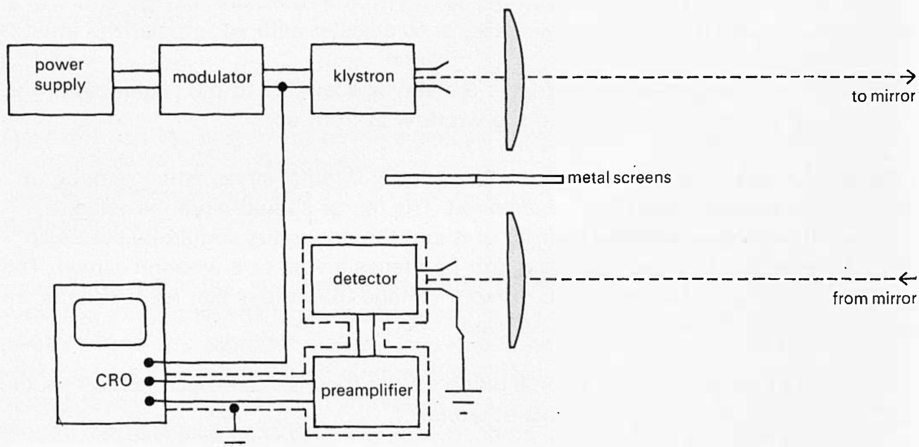



**Figure 45**
Apparatus for measuring the speed of microwaves.

### The path of the microwaves

In figure 45 the klystron and detector are placed roughly at the focal points of wax lenses with diameters of about 0.3 m and focal lengths of 0.6 m, the axes of the lenses being 0.5 m to 1 m apart. Such a lens (being only about ten wavelengths wide) cannot produce a beam which is parallel to less than several degrees. A large reflecting surface is required: a mirror or metal sheet. Melinex sheet (1 m × 0.75 m) on stiffened plywood stretchers can be used, but it should be backed with plywood to prevent disturbance by draughts. There is some advantage if the reflector shows visible reflections too.

When part of a beam of radiation takes a path differing by more than $\lambda/4$ from the path of the rest of the beam, the contribution of that part differs in phase by more than $\pi/2$ from the rest and the total intensity is significantly reduced from what it could be. For reflections of a beam incident normally on a mirror, such a path difference occurs if part of the mirror is more than $\lambda/8$ behind or in front of the rest. The mirrors should, therefore, be flat to within 2 or 3 mm.

With a short microwave path, say 50 m, there is no serious problem in getting enough intensity of radiation at the detector. If a long path (100 m or more) with a single mirror is used, the energy reflected into the detector varies almost as the fourth power of the mirror's linear dimensions. In the same conditions, the energy reflected into the detector varies inversely almost as the fourth power of the distance from the mirror to the klystron and detector, so a big mirror is essential for a long path.

The mirror should be mounted to allow easy alignment and it helps enormously if the person adjusting the mirror is immediately made aware (for example, by using a loudspeaker and the 1000 Hz modulation) of the effect of any adjustments made. Any conducting objects near the path of the beam should be removed, and metal screens are needed between the lenses so that radiation reaching the detector by stray paths is reduced. These stray contributions to the detector's response may be checked by tilting the mirror from its correct angle to see what radiation is still detected.

### Detector, preamplifier, and oscilloscope

The detecting diode is connected directly to the input of the preamplifier; the microammeter and capacitor mounted with the detector are disconnected. The detector and preamplifier are put in an earthed metal enclosure (a biscuit tin for example), with the horn of the detector (earthed independently of the tin) protruding through a hole. It is also necessary to use screened two-core cable for connections, and to connect all screening to the earth socket of the oscilloscope by paths independent of the signal. Unless this is done there may be excessive direct pick-up from the modulator circuit, and from radio transmissions.

A double-beam oscilloscope is used, so that the modulator output can be fed into one input, from which the time base is triggered, while the output from the preamplifier is fed into the other input. A sensitivity of 100 mV $cm^{-1}$ is needed to show the preamplifier's output and about 2 V $cm^{-1}$ for the modulator output. The modulator's pulse is sharp and constant, so that the trace is easily held stationary on the oscilloscope. With the metal screens in the position shown in figure 45 the klystron reflector voltage is then adjusted to give a pulse on the detector's trace (figure 46). The time base controls should be set in the calibrated position with a sweep speed of 1 μs $cm^{-1}$.

### Measuring the delay

The two metal screens shown in figure 45 between the klystron and the detector are moved to the positions shown in figure 47 so that radiation is reflected by them to enter the detector by a short path. They are adjusted until only the same intensity of radiation enters the detector as when the radiation has travelled the path shown in figure 45, but the trace is no longer as far to the right of the modulator's pulse (figure 48). The delay is measured by noting the position of the trace and then quickly moving the screens back to their position in figure 45 to estimate the movement of the trace. With a path of 60 m the movement will only be about 2 mm, so that it cannot be measured accurately. The screens should be adjusted so that the detector pulse shapes in figures 46 and 48 are as nearly the same as possible.

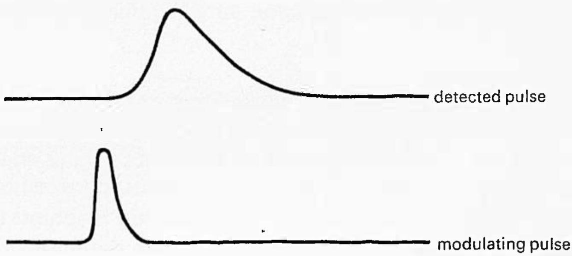



**Figure 46**
Pulses obtained with the arrangement shown in figure 45.

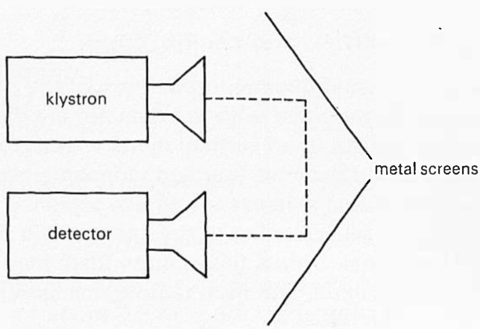



**Figure 47**
A short-path arrangement.

### Modulating the microwaves (producing the pulses)

If the klystron unit has an 'external modulation' socket, the 200 kHz pulse generator should be connected to it and the 'modulation selector switch' set to the external modulation position. With some equipment, the pulse generator has 3 sockets labelled 'a', 'b', and 'c', and the klystron power supply has 3 sockets, one marked 'earth', one not marked, and the other labelled 'r' (for reflector). To modulate the klystron the selector switch is set to 'off'; socket 'c' is connected to the earthed socket, 'a' to the unmarked socket, and 'b' to 'r'.

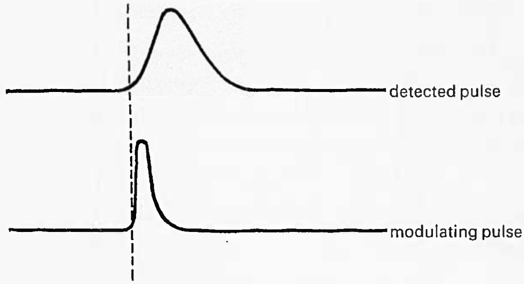



**Figure 48**
Pulses obtained with the short-path arrangement shown in figure 47.

If such facilities are not provided, then socket 'b' is connected to the reflector socket on the klystron unit, the lead from the power supply which normally goes to the reflector (and which supplies the negative voltage) is connected to socket 'a', and socket 'c' is connected to the power supply socket labelled '0 volts'. With the exception of the reflector, all the leads to the klystron unit should be connected as usual. The 1000 Hz or 100 Hz modulation should not, of course, be used.

### **Additional information** mainly for teachers

Figure 49 shows how the klystron output is related to the reflector voltage which is negative in relation to the cathode. Big changes of output result from small changes of reflector voltage in certain critical ranges, about −180 V for example. The klystron power supply will provide any steady reflector voltage between 0 V and about −250 V, and also allows a.c. of 1000 Hz or 100 Hz to be superimposed if required. The 200 kHz pulse generator was designed to superimpose the positive voltage shown in figure 50 onto a steady reflector voltage, resulting in a very short, sharp pulse of radiation from the klystron whenever the modulating voltage exceeds 2 or 3 V. Not all klystrons will have a response curve like the one shown in figure 49 and some may modulate better with negative pulses. Occasional readjustment of the reflector voltage may also be needed to keep good modulation, because of small drifts in the klystron power supply.

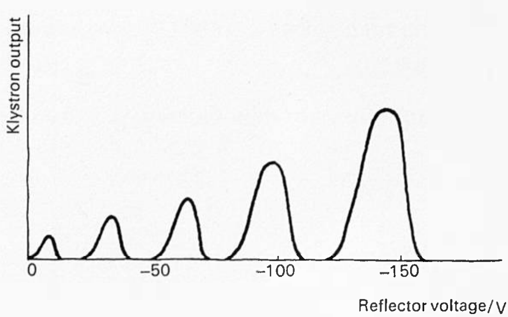



**Figure 49**

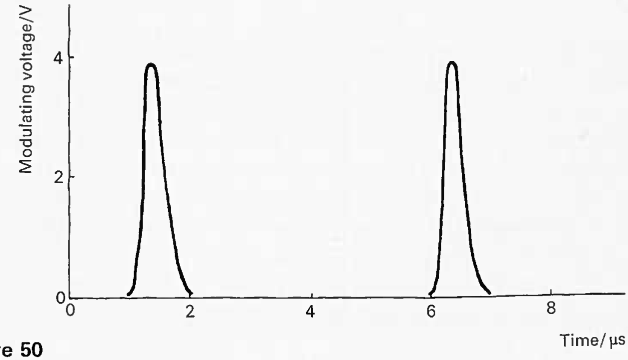



**Figure 50**

The shape of the detector's trace depends on the klystron reflector voltage. The best voltage gives small but sharp modulation, with the peaks of the pulses in figure 50 only just reaching the steep slope at about −180 V in figure 49. It is not possible to make the shape of the detector's trace the same as the shape of the modulator's trace, because the difference in shape results from non-linear behaviour in the klystron, detector diode, and preamplifier.

**Apparatus** for experiment 4.4

| | |
|---|---|
| 184/1 | 3 cm wave transmitter |
| 184/2 | 3 cm wave receiver |
| 181 | general purpose amplifier |
| | *and* |
| 183 | loudspeaker (if not included with the above) |
| 1031 | 200 kHz pulse generator |
| 1014 | wax lens *2* |
| 1035 | preamplifier |
| 1007 | double-beam oscilloscope |
| 1033 | cell holder with four U2 cells |
| 1053 | metal screen *2* |
| 1065 | big mirror |
| 501 | metre rule |
| 1000 | leads |
| | biscuit tin |

## Estimation of the Planck constant *h*

The quantity *h* is named the Planck constant after Max Planck, who first introduced it into physics. It is a constant which says just how grainy light is: how big the quanta of energy will be at a particular frequency. Einstein, in a paper of 1905, applied this quantum idea to explain the photo-electric effect. Here is a translated quotation from the paper.

> 'According to the concept that the incident light consists of energy quanta of magnitude $hf$, however, one can conceive of the ejection of electrons by light in the following way. Energy quanta (photons) penetrate into the surface layer of the body, and their energy is transformed, at least in part, into kinetic energy of electrons. The simplest way to imagine this is that a light quantum delivers its entire energy to a single electron; we shall assume that this is what happens. . . . An electron to which kinetic energy has been imparted within the body will have lost some of this energy by the time it reaches the surface. Furthermore, we shall assume that in leaving the surface of the body each electron must perform an amount of work $W_0$, characteristic of the substance of which the body is composed. The ejected electrons leaving the body with the largest normal velocity will be those that were directly at the surface. The kinetic energy of such electrons is given by
>
> $$KE_{max} = hf - W_0$$
>
> If the emitting body is charged to a positive potential difference relative to a neighbouring conductor, and if $V$ represents the potential difference which just stops the photo-electric current, then
>
> $$eV = hf - W_0$$
>
> where $e$ denotes the electronic charge.
>
> 'If the deduced formula is correct, a graph of $V$ versus the frequency of the incident light must be a straight line with a slope that is independent of the nature of the emitting substance . . .'
>
> *From Einstein, A. (1905)* Annalen der Physik, ***17****, 132, as reproduced in translation in Arons, A. B. (1965)* Development of concepts of physics, *Addison-Wesley.*

The experiment that follows is concerned with the use of this idea of Einstein's to arrive at a value for *h*.

## 5.17 and 10.2 Colour of light and energy of photo-electrons

*Spectrum*. See figure 51. Cut a slit about 2 mm wide in the card shown in figure 51, and place the slit over the aperture of the tube containing the photo-cell. The parallel-beam projector, with the prism on its front platform, is then placed so as to cast a spectrum on the card. The lamp may be overrun by up to 30 per cent to obtain a brighter spectrum. It is best to work in dim light, and to shield the photo-cell from stray light as well as possible. Make sure that light going through the slit shines on the surface of the photo-cell.

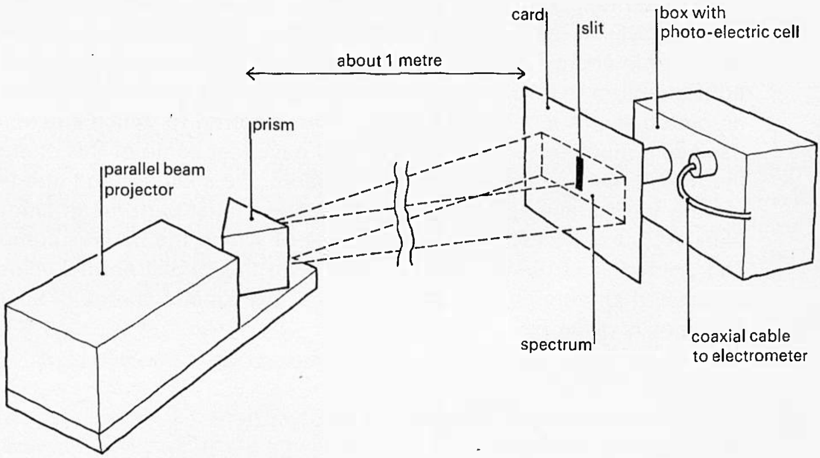



**Figure 51**
A photo-electric cell with a spectrum shone on it.

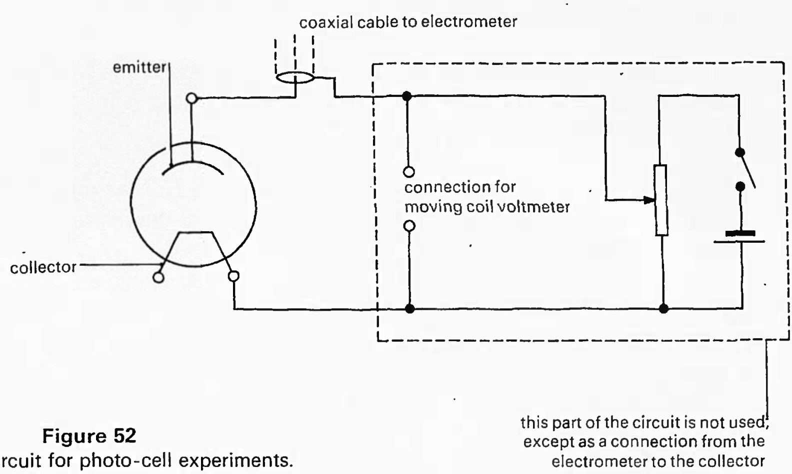



**Figure 52**
The circuit for photo-cell experiments.

*Photo-cell.* So that visible light may be used in this experiment, potassium is used for the electron emitting surface. The metal is kept permanently clean by having it in a vacuum inside a ready made sealed photo-electric cell. The emitted electrons can be collected by another electrode also sealed in the cell.

*Circuit.* See figure 52. The circuit does not use all the facilities that may be provided with the photo-cell; some of these are intended for experiments in which a p.d. is applied to the cell from a battery, using a potentiometer and a moving coil voltmeter.

In this circuit, if there is a battery, it should be removed or switched out of circuit. The circuit and the technique suggested below are suited to an electrometer whose input resistance can be made as high as $10^{13}\ \Omega$, usually by removing the input resistor altogether. An electrometer with switched current ranges may have resistors of the order $10^{11}\ \Omega$ permanently across the input; and may be better suited to the balance voltage technique for which a battery and potentiometer are provided.

Before connecting the electrometer to the photo-cell, place a 1.5 V dry cell across its input, and alter the sensitivity until the display meter is at full scale. Then connect the electrometer to the photo-cell, with the positive-going input to the potassium emitter, and physically remove any input resistor (or switch the electrometer) so that it will act as a voltmeter of the highest possible resistance. (For details see under 'Electrometer' in Part One, page 13.)

One way of doing the experiment is to connect the electrometer directly across the photo-cell to act as a voltmeter. When light is shone on the cell, electrons travel from the emitting surface to a collecting wire, which is made of a metal that does not emit electrons in visible light and (it is to be hoped) has no trace of potassium on it. From the moment the light starts to shine, the voltmeter indication rises, but ultimately becomes steady.

The collector now has a negative charge, as it would if electrons had accumulated on it, charging up the effective capacitance across the electrometer. The steady potential difference indicates that very few more electrons are now arriving at the collector (only those required to pass through the very high input resistance of the electrometer). If the potential difference is, say, 0.5 volt, then the electrons from the emitter must be ejected with energies of no more than 0.5 electronvolt each, or they would continue to arrive. So the electrometer indicates very nearly the maximum energy of ejected electrons, as long as it draws a current which is small compared with the number of electrons ejected in a second.

With the electrometer short-circuited, position the spectrum so that the dark region beyond the *red* falls on the slit. Then, with the electrometer switched to read the p.d. across the photo-cell, sweep the spectrum from red to violet *slowly* across the slit. Allow time for the p.d. to rise to a steady value at each stage.

The reading rises beyond the violet, in the ultra-violet. Beyond that, it may stay steady, even if the light is cut off altogether. When no light falls on the cell, the electrometer cannot discharge. If it is momentarily short-circuited, the reading should stay at zero beyond the ultra-violet or in the dark, but should rise again in the visible or ultra-violet, returning to the values seen before.

If the spectrum is swept back from violet to red the reading falls, though one would expect it not to do so, since low energy electrons ought not to be able to reach a collector across a high potential difference. The reason is that some potassium gets onto the collector, and some electrons flow the 'wrong' way. If the collector can be heated to drive off any potassium which is on it, this reverse current can be reduced.

If sufficient results can be obtained, a graph of the potential difference $V$ plotted against the frequency $f$ of the light falling on the cell should give a straight line. Results must be taken at more than one frequency in order to eliminate $W_0$, the energy needed for an electron to escape from the potassium. See table 4.

Two values are sufficient. If the frequencies are $f_1$ and $f_2$, and the voltages are $V_1$ and $V_2$, then

$$eV_1 = hf_1 - W_0$$
$$eV_2 = hf_2 - W_0$$

so that $h = e(V_1 - V_2)/(f_1 - f_2)$.

Alternatively, the slope of a graph of $V$ against $f$ is equal to $h/e$.

Rough estimates of the frequencies falling on the photo-electric cell can be obtained by noting the colour of the light used. A continuous spectrum, in colour, with wavelengths and frequencies marked, appears in the front of Nuffield Advanced Chemistry *Students' book 1*.

| **Middle of colour** | **Frequency/$10^{14}$ Hz** |
|---|---|
| red | 4.6 |
| yellow | 5.0 |
| green | 5.4 |
| blue | 6.5 |
| violet | 7.3 |
| ultra-violet | from 7.7 |

**Table 4**

**Apparatus** for experiments 5.17 and 10.2

| | |
|---|---|
| 1068 | parallel-beam projector |
| 59 | l.t. variable voltage supply |
| 69 | high dispersion prism |
| 1074 | photo-electric cell |
| 1006 | electrometer |
| 1003/1 | milliammeter (1 mA) |
| 1033 | cell holder with one U2 cell |
| 1053 | card with slits |
| 1067E | set of stops |
| 1000 | leads |

**Reading**

Millikan, *The electron*, Chapter 10.
This gives details of Millikan's original measurement of $h$, using the photo-electric effect, in a test of Einstein's prediction.

## 7.6 Measurement of the charge to mass ratio for electrons

There are several different forms of apparatus which can be used to measure the charge to mass ratio of electrons. Those recommended for this work consist of an evacuated bulb in which there is an electron gun. When suitable voltages are applied to the gun, electrons are projected from it at high speed.

The bulb is held symmetrically between two coils with their planes vertical. An electric current is passed through these coils in series in order to produce a $B$-field in the space inside the bulb. The purpose of having two coils is to make the $B$-field fairly uniform over the plane midway between the coils.

The electron gun is positioned to shoot electrons into this mid-plane at right angles to the $B$-field. The electrons, moving at right angles to $B$, experience a force perpendicular both to $B$ and to the direction of motion, and so travel in a circular path. If the radius of the track is $r$, then the inward acceleration of the electrons is $v^2/r$, where $v$ is the electron speed. This requires an inward force of $mv^2/r$ (*mass* $\times$ *acceleration*), the force being provided by the $B$-field and equal to $Bev$ ($e =$ charge on the electron).

So $\quad Bev = mv^2/r. \qquad$ **1**

To obtain the ratio $e/m$, a value for the electron speed is needed. The electrons produced by the electron gun are released – at relatively low speeds – from the surface of a metal when it is raised to a high temperature. In some cases the emitting surface is a tungsten wire, heated until it is white-hot by passing an electric current through it. In other cases, the emitting surface is heated by an electrical heater placed near it but insulated from it. The electrons are caused to move towards a metal conductor (the anode) near the emitting surface (the cathode) by having an electric field between these conductors, the anode being made positive relative to the cathode. If the anode to cathode p.d. is $V$, then the electrons gain kinetic energy equal to $eV$ as they accelerate from cathode to anode.

Thus, $eV = \frac{1}{2}mv^2$ or $2eV = mv^2$. **2**

There is a small hole or slit in the anode so that some of the electrons emerge from the gun with the speed given by equation 2.

If the value for $mv^2$ given by equation 2 is substituted in equation 1, $e$ cancels, giving

$$Bv = 2V/r$$

so that $v = 2V/Br$. **3**

By measuring the anode-cathode p.d., $V$, the strength of the $B$-field and the radius of the electron's orbit, the electron speed can be calculated. The speed can then be used in equation 1 to calculate $e/m$. Since $Bev = mv^2/r$, dividing each side by $v$ and rearranging gives

$$e/m = v/Br.$$

You will now have to follow the instructions for the type of tube you have been provided with.

### Details of types of tube

*The fine-beam tube*

This tube has a gun which is arranged to project electrons vertically. The bulb is not completely evacuated but contains a little hydrogen, some molecules of which are ionized by the electrons from the gun. The light subsequently emitted by these ions shows up the path taken by the electrons. The light is faint and it will be necessary to work in a darkened room.

Voltages are applied to the electron gun, and to the coils, via a connecting box as in figure 54, the anode–cathode voltage (applied between A and C), and the 6.3 V a.c. for the heater (HH) being obtained from an h.t. power supply. Note that because electric deflection is not needed, the deflector plates (D, D) are connected to the anode. The cathode, the electrode marked w, and one side of the heater should be connected together.

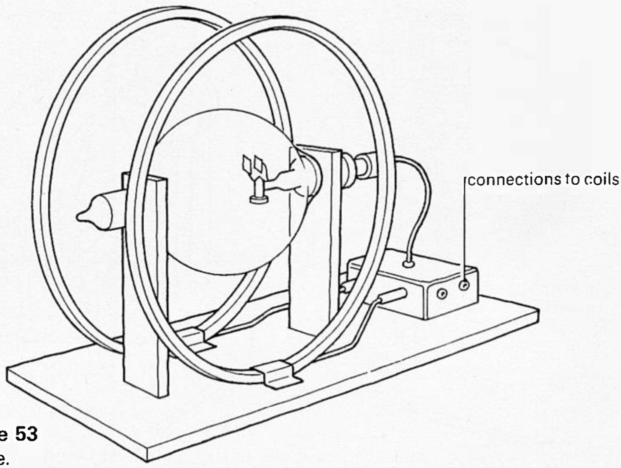



**Figure 53**
A fine-beam tube.

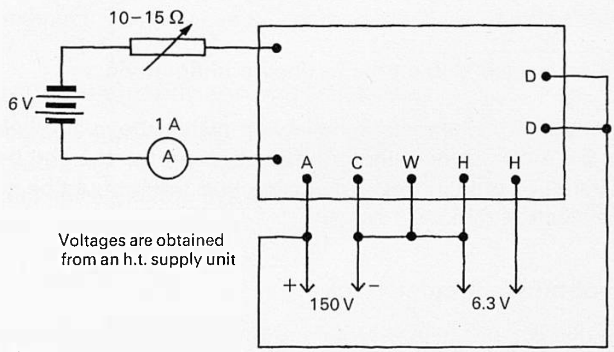



**Figure 54**
The connecting box for the fine-beam tube.

*The deflection e/m tube*

This tube has a gun situated in the neck of the bulb and projects electrons horizontally towards a translucent screen placed across the centre of the bulb. This screen has a graticule marked on it and has been treated with material which fluoresces when electrons fall on it at a sufficiently high speed. The aperture in the anode of the gun is a small slit so that a narrow fan of electrons falls across the screen, producing a fluorescing line to indicate their track.

To mount the tube, the coils should be removed from the stand and the bulb inserted between the jaws with the neck of the bulb passing through the hole in the upright of the stand. The jaws can be rotated so that the plane of the screen is vertical. The coils should now be replaced with the connection sockets outwards and so that their planes are parallel. The coils are connected in series.

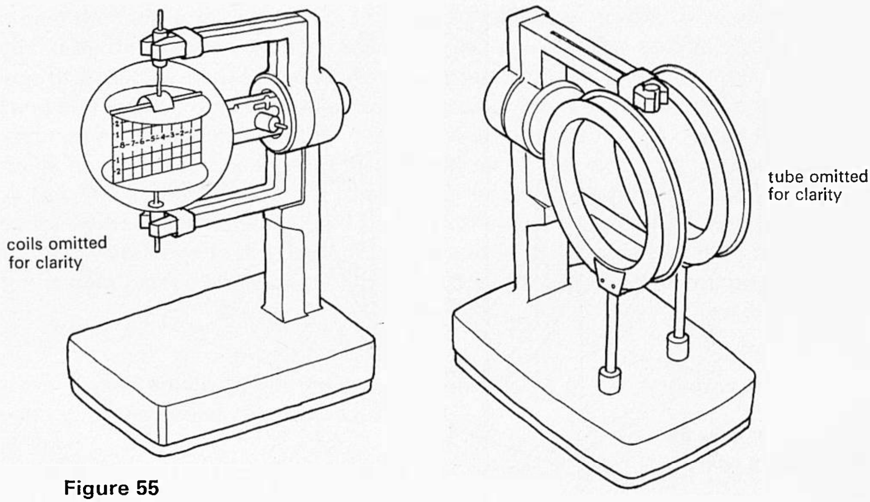



**Figure 55**
The deflection *e/m* tube.

Supplies are connected to the tube as shown in figure 56.

The tube is fitted with electrostatic deflection plates above and below the screen; connections are made to them through the plugs on the top and bottom of the bulb. These plates are not used in this experiment, and they should be connected to the anode of the electron gun.

### To obtain a circular track

Connect the circuits, but before switching on any supplies, turn the variable controls on the h.t. or e.h.t. unit so that the output p.d. will be zero. Switch on the 6.3 V supply to heat the emitter, allow about half a minute for it to reach its working temperature, and then slowly increase the anode potential until a thin streak is seen emerging from the gun. The 6.3 V a.c. supply must be insulated to 6 kV for the deflection tube.

*Fine-beam tube*

The beam appears when the anode potential is in the neighbourhood of 50 V. Further increase of the h.t. supply causes the streak to lengthen until it strikes the glass bulb. It may take a minute or two for this to be clearly visible. The h.t. supply should be set at 150 V (using the voltmeter on the h.t. unit or a suitable one connected between anode and cathode). Note that potential differences in excess of 200 V should not be used, as they will shorten the life of the tube. Bring the voltage down to zero whenever the electron beam is not required.

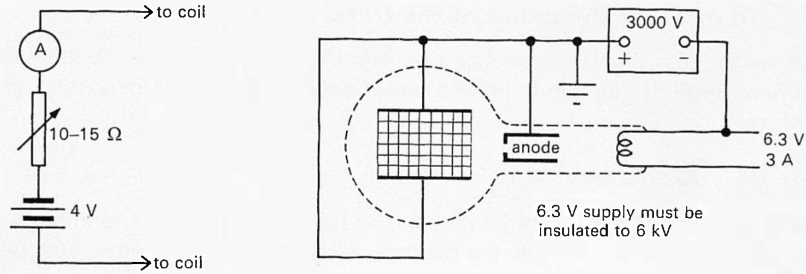



**Figure 56**
Connections for the deflection tube.

*Deflection tube*

A blue line across the screen becomes visible at a p.d. of about 2000 V. Increasing the voltage brightens the line. An anode–cathode voltage of about 2500 V is suitable for the moment. The p.d. can be measured with the meter on the e.h.t. unit.

### Choice of coil current and anode voltage

Connect up the current supply to the coils and adjust the size of the current. The radius of the orbit can be altered by changing the p.d. applied to the gun or the current through the coils. Explore the effect of varying these quantities and note that current changes are more effective.

*Fine-beam tube*

A coil current of about 1 A is suitable. If the beam bends the 'wrong' way, the connections to the coil sockets on the connecting box should be reversed. If the beam spirals towards one of the coils, then the gun is not projecting the electrons at right angles to the *B*-field, and the tube should be rotated in its holder until the electron track lies in one plane. The coil current ($\approx$1 A) and the anode potential ($\approx$150 V) should be adjusted to give a circular orbit approximately central within the bulb.

*Deflection tube*

A coil current of about 0.3 A is suitable. If the bending is small, not circular, and shows little change as the coil current is altered, then it is probable that the coils are incorrectly connected and the connections to one of them should be reversed.

Make a careful note of the coil current and the anode–cathode p.d. *V*.

### To measure the radius of the track

This is not an easy measurement to make, and care taken in doing it will be repaid in the final result. If you can think of a better method than those described, you should try it.

#### *Fine-beam tube*

The simplest way of obtaining the radius is to hold a ruler at arm's length, and close to the bulb, in order to estimate the diameter directly. Since the room must be dark, it is easier to use an illuminated transparent ruler such as a Perspex ruler with a small electric lamp taped on at one end, the lamp itself being covered with black tape to cut off direct light. Another modification is to form a mirror image of an illuminated scale, with the image inside the tube and in the plane of the electron stream. See figure 57. A vertical sheet of clean plate glass is held (firmly) just in front of the tube and an illuminated scale is placed in front of the sheet so that the image is in the middle of the tube. Note that the glass is half-way between the scale and the centre of the tube.

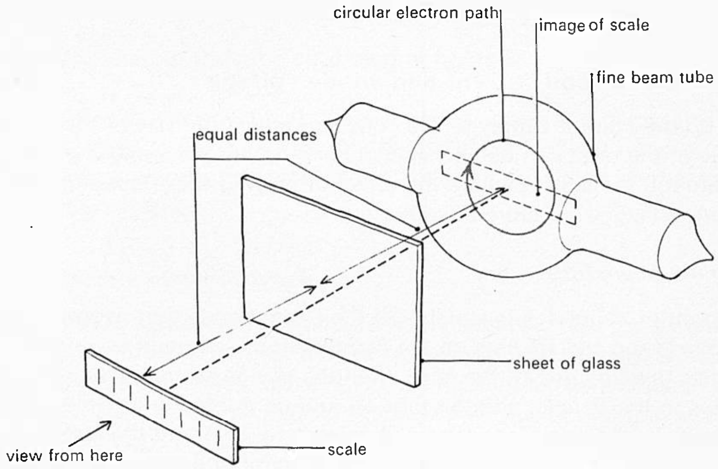



**Figure 57**
One way of measuring the track radius.

#### *Deflection tube*

The co-ordinates of three points on the electron track should be noted, one near the start, one near the end, and one in between. These points can be transferred to graph paper and the centre of the circular path through them found by constructing the perpendicular bisectors of the two chords formed by joining the points, as in figure 58. If you are interested in geometry, perhaps you could prove that the radius of the circle is given by $r = x/(2 \sin\alpha) = xy/2h$ and calculate it that way, but if you cannot, use the graphical method.

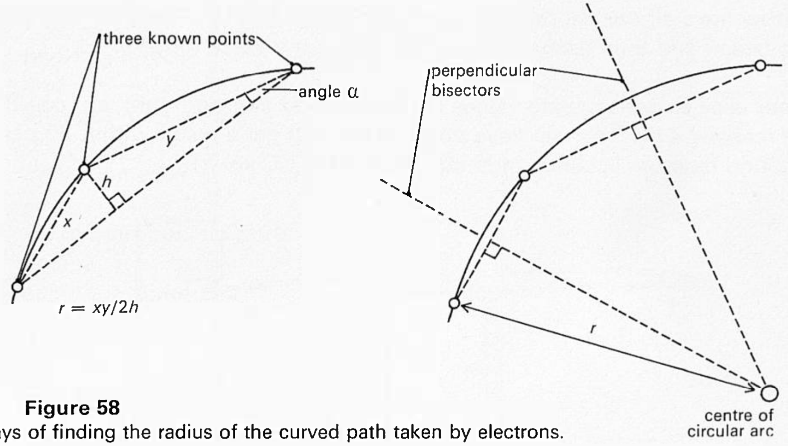



**Figure 58**
Two ways of finding the radius of the curved path taken by electrons.

## To measure *B*

*B* is measured by a current balance designed to fit through one of the coils and it is therefore necessary to remove the tube. The tube is expensive and easily broken, and you should ask for assistance before attempting to remove it.

Figure 59 shows how the balance is set up and arranged between the coils, and the circuits supplying current to the coils and to the balance. No details will be given as the method of use is just the same as with the current balances used elsewhere in Unit 7. Paper tape forms a suitable weight. The washer dipping into the beaker of water (containing a little Teepol) is to damp out any tendency for the beam to oscillate, but you may think that this is not necessary.

There is no need to use the same coil current as you used earlier – indeed it is easier to use a bigger current. If you do use a larger coil current, then the *B*-field you measure with the current balance will be larger in the same proportion, and you will have to calculate what the field was in the first part of the experiment.

### *Fine-beam tube*

The coil current can be about 2 A and the length of paper tape some 50 mm. Meters reading to 5 A should be used for both coil current and the balance current.

### *Deflection tube*

The coil current can be about 2 A and the length of paper tape some 50 mm. do for the coil current, and a 5 A meter will be needed for the balance current.

The value of *B* corresponding to these coil currents is calculated from $F = BIL$. *B* is proportional to the current in the coils, and the value of *B* used in deflecting the electron beam can be calculated.

You now have all the information you need to calculate the speed of the electrons in the beam, and then using that you can find out a value for $e/m$.

It is not easy to get accurate values by this method and no doubt you can think of some reasons why. You will have done well if you get a result within 20 per cent of that found by more accurate methods ($1.76 \times 10^{11}$ C kg$^{-1}$).

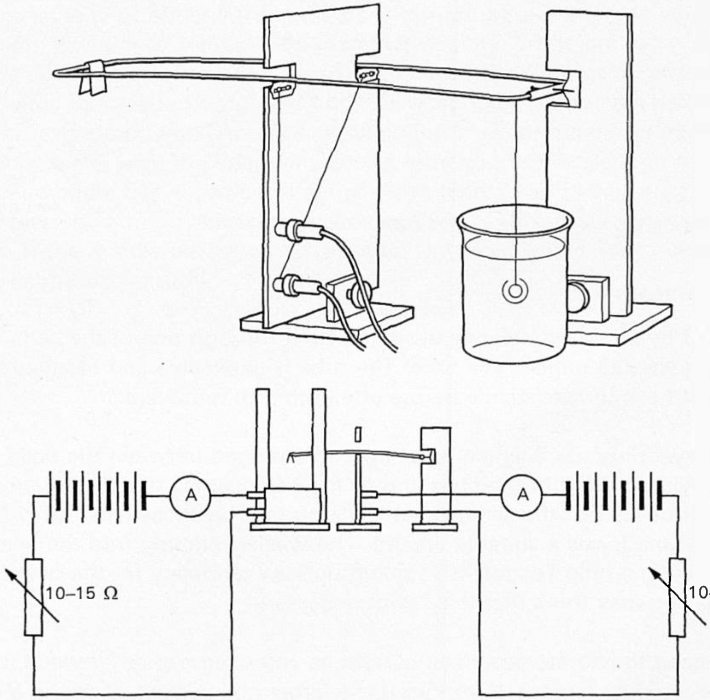



**Figure 59**
Measurement of the magnetic field.

## Reading

Bennet, *Electricity and modern physics,* Chapter 13.

Rogers, *Physics for the inquiring mind,* pages 667–8.

**Apparatus** for experiment 7.6

61 fine-beam tube
*and*
62 fine-beam tube base
*or*
138 deflection tube
*and*
139 set of coils and supports
*and*
140 stand for tubes

15 h.t. power supply (for item 61)
*or*
14 e.h.t power supply (for item 138)

1003/4 ammeter (1 A)

1003/5 ammeter (10 A)

176 12 volt battery

541/1 rheostat (10–15 Ω)

173 Malvern current balance kit

30 slotted base

501 metre rule

108/3 roll of tickertape (plain)

529 scissors

1000 leads

### 7.5 The Hall effect in aluminium (number of charge carriers per atom)

The specimen is cut from cooking foil in a long strip about 10 mm wide, with three narrow strips left attached to the edges for measurement of the Hall voltage. See figure 60. The strip is Sellotaped onto a *thin* polythene sheet and a second thin polythene sheet is Sellotaped on top. Spaces are best left free of Sellotape so that the two C-cores which provide the field need be separated by no more than the thickness of the aluminium foil and two thin sheets of polythene.

The C-cores are magnetized by passing a current of 1 A through the magnetizing coil (400 turns). The flux changes little with current as the core is nearly saturated, but it is very dependent on the thickness of the gap which is therefore left untouched throughout the experiment. A balancing potentiometer (1.5 Ω) is connected as shown, the galvanometer being connected between the sliding contact and the single voltage strip on the other side of the long strip of foil. The potentiometer is used to zero the galvanometer which is used in these circumstances

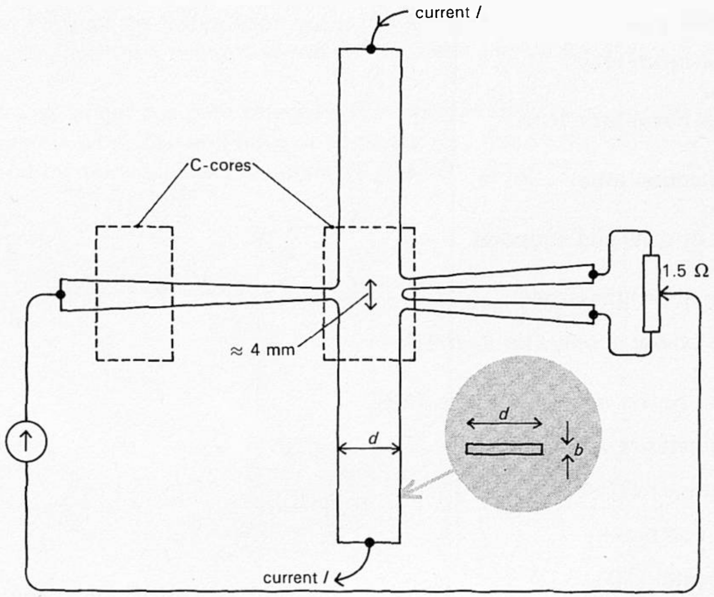



**Figure 60**
*The aluminium specimen and circuit.*

as a microvoltmeter (used on 'direct'). If a suitable potentiometer is not available, a length of bare resistance wire, with a crocodile clip moving contact, can be used.

The galvanometer is first zeroed at the centre of the scale. Then a current of 5 A is passed along the strip from the 2 V supply via a low resistance rheostat and the 0–5 A ammeter. After adjusting this current to 5 A, the galvanometer is re-zeroed with the balancing potentiometer. The field is then applied and the deflection noted, this then being repeated with the field in the opposite sense. The Hall voltage may now be deduced from the galvanometer voltage sensitivity as stated by the manufacturer, allowing if necessary for the resistance of the potentiometer.

It is necessary to know the magnetic field $B$ in the gap, but hard to measure it, as *one cannot disturb the gap to insert a probe, for that would change the field a great* deal. The best method seems to be to measure the flux $\phi$ in the core, and divide that by the area $A$ of one end of a C-core to obtain $B$. The flux $\phi$ is measured by electromagnetic induction.

Wind $n$ turns (five will do) of wire round the *undisturbed* C-cores and connect them in series to the galvanometer used previously, but with enough resistance in series to make a total of $R$ (say 5000 Ω) in circuit. You may obtain the galvanometer resistance from the manufacturer's data sheet for the instrument.

When the current in the C-cores is switched on or off, the flux rises or falls between zero and the wanted value $\phi$.

The e.m.f. induced in the $n$-turn coil as the flux changes by $\phi$ is given by

$$\text{e.m.f.} = \frac{n\phi}{\textit{time taken for flux to change}}.$$

The current in the galvanometer is given by

$$\textit{current} = \frac{n\phi}{R\ (\textit{time taken for flux to change})}.$$

The charge flowing in the galvanometer is given by

$$\textit{charge} = \textit{current} \times \textit{time taken}.$$

Thus $\quad \textit{charge} = n\phi/R,$

the charge being in coulombs if $R$ is in ohms. $B$ can then be found, from $B = \phi/A$ where $A$ is the area of the C-core cross-section.

When the flux is switched on or off, with the galvanometer switched to 'direct', the galvanometer indication will suddenly swing across (and then back) as this pulse of charge passes through it. Record the largest distance it goes from zero; that is, the size of the swing.

For a better result, note the size of the next swing across in the same direction as at first (it will be smaller – why?), and add a quarter of the difference between these swings to the original one, to estimate what it would have been, had the swings not continually diminished.

This is called 'using the galvanometer ballistically'. Find from the manufacturer's data sheet the number of coulombs needed to produce a swing of the size observed. This may be called the 'ballistic sensitivity' and may be tabulated in millimetres per coulomb or coulombs per millimetre. Obtain the charge flowing from the observed swing.

Calculate the flux $\phi$ from the charge, the number of turns $n$, and the value of the resistance $R$.

The remaining measurements to be made are the area of cross-section of the C-core, and the breadth and the thickness of the long strip of aluminium foil. The latter can be measured by folding a piece of the foil three or four times and measuring the total thickness with a micrometer screw gauge.

### Hall voltage and number of charge carriers per atom

The experiment yields the Hall voltage $V$, and the flux density $B$. The first may be about 10 to 20 μV; the second about 1 T. Together with values of the current $I$ in the specimen, and the specimen's width $d$ and thickness $b$, the results can be used to estimate the velocity and density of the charged carriers (electrons) which convey electric currents in aluminium.

Question 19, *Students' book*, Unit 7, shows that if the carriers move with speed $v$,

$$V = Bdv$$

and you can use this to calculate the speed $v$, obtaining a result of the order $10^{-3}$ m s$^{-1}$.

Earlier work, in Unit 2, showed that if the current is $I$, flowing through material with a cross-section of $A = bd$, the number of charge carriers per unit volume, $n$, is given by,

$$n = I/Aqv = I/bdqv$$

where $q$ is the charge on one carrier. Putting $q = 1.6 \times 10^{-19}$ C, the charge on an electron, you can estimate $n$, obtaining a value of the order of $10^{29}$ carriers per cubic metre.

Finally, you can use the result, obtained from the Avogadro constant $6 \times 10^{23}$ mol$^{-1}$, the atomic mass, and the density of aluminium, that there are close to $6.0 \times 10^{28}$ aluminium atoms per cubic metre, to estimate how many electrons per atom take part in conduction.

### Reading

Bennet, *Electricity and modern physics,* pages 325–7.

**Apparatus** for experiment 7.5

1029 Hall voltage apparatus for metals

1041 potentiometer holder with
*with*
1051 potentiometer 1.5 Ω

176 12 volt battery

1001 galvanometer (internal light-beam)

1003/4 ammeter (1 A)

1003/5 ammeter (10 A)

541/1 rheostat (10–15 Ω)

1017 resistance substitution box

1055 micrometer screw gauge

1000 leads

## 7.15 Absolute measurement of current (and other electrical quantities)

Electrical measurements are usually made with ammeters, voltmeters, oscilloscopes, resistance networks, and so on. Such a measurement is only a comparison with what the instrument maker thought was correct. Absolute electrical measurements are needed to tell the maker what the sizes of one ampere, one volt, etc., are. These absolute measurements are made in ways that relate the electrical quantities to basic non-electrical quantities; metres, kilogrammes, and seconds.

If one or two electrical quantities are measured absolutely, the others can be derived from them. For example, if a current of one ampere and a resistance of one ohm have been measured absolutely, passing the current through the resistor will give one volt between the ends of the resistor. The following experiments illustrate the ideas involved in absolute measurements, although a standards laboratory would do the job very differently because of its need for great accuracy. If you do one of the experiments, it is worth trying to make it as accurate as you can, but it is more important to see that the result does not really depend on any information about the equipment that you cannot check for yourself or measure non-electrically.

### 1 Measurement of current

Current can be measured by making it produce a magnetic field, and then measuring the force which the field will exert on the same current flowing along a movable conductor placed in the field. If the magnetic field is uniform within a considerable space, it is unnecessary to know the exact position of the movable conductor (as it would be necessary if a slight movement of the conductor would take it to a place where the field was stronger or weaker), and also the movable conductor can consist of several parallel wires which the current flows through successively, giving a bigger total force.

A flat solenoid (figure 61) will produce a nearly uniform field wide enough for a fairly long conductor to be inside it. The conductor can be the part PQ of a rectangular coil PQRSTU pivoted at R and U and bent at R and U so that the centre of gravity is slightly below the line RU.

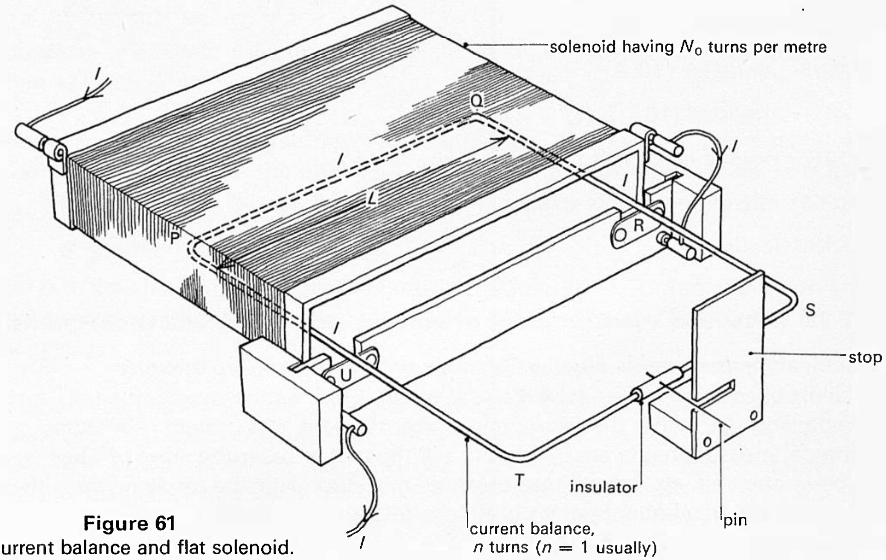



**Figure 61**
Current balance and flat solenoid.

If the solenoid has $N_0$ turns per unit of length and carries the current $I$ which is to be measured, the magnetic field inside is (very nearly)

$$B = \mu_0 N_0 I.$$

Note that this equation is the same as the more usual one, $B = \mu_0 NI/L$, where $L$ is the length of the solenoid and $N$ is the total number of turns, but we have written $N_0$ for the number of turns per unit of length, $N/L$.

If the coil PQRSTU has $n$ turns at PQ ($n$ may be only one) and $L$ is the length of PQ, the field is at right angles to the current, and both are horizontal, so a vertical force $F$ will act on the wire.

Then, $$F = BILn$$
$$= \mu_0 N_0 I^2 Ln$$
and $$I^2 = \frac{F}{\mu_0 N_0 Ln}$$

The connections to the solenoid can be reversed, if necessary, to make $F$ act downwards, so that it can be measured (in newtons) by balancing it against the weight $mg$ of a mass $m$ put on ST. $\mu_0$ is $4\pi \times 10^{-7}$ N A $^{-2}$. $N_0$, in turns per metre, is found by measuring and counting. $L$ is measured with a ruler. Then, if $m$ is $10^{-4}$ kg, $g$ is 9.81 m s$^{-2}$, $N_0$ is 1200 turns per metre, $L$ is 0.25 m, and $n$ is 1,

$$I = 1.67 \text{ A}.$$

In practice it is not easy to adjust a weight on ST by small amounts, but a mass $m$ which is slightly too big may be moved along RS to get an exact balance. A simple calculation of the moments of $F$ and $mg$ about RU then gives $F$. Alternatively, with the mass $m$ on ST, the current can be varied, by use of a rheostat, to get an exact balance.

It is suggested that the experiment should be used to check the reading of an ammeter at some point between one and two amperes. As the force $F$ is not reversed when the current is reversed, the method is as effective with a.c. as with smooth d.c.

Two approximations in the theory will make the result smaller than it should be. You may be able to calculate and allow for both.

The first is that the field at the centre of the solenoid is smaller than is supposed above, because the length of the solenoid is finite.

The second is that there are some forces acting on the sides of the current balance, because the field of the solenoid is not everywhere parallel to its axis (see figure 62). An allowance for this can only be made by measuring the field perpendicular to the axis at points away from the middle of the solenoid.

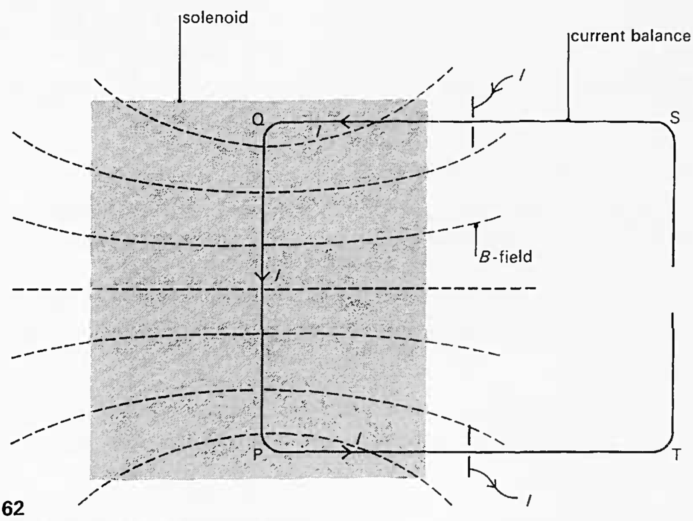



**Figure 62**
The magnetic field in the region of the current balance.

**Apparatus** for experiment 7.15 (1)

You may require:

1003/5 ammeter (10 A)

1079 flat solenoid

1036 current balance

1054 copper wire, bare, about 22 s.w.g.

176 12 volt battery

541/1 rheostat (10–15 Ω)

1000 leads

access to a balance accurate to 10 mg

## 2 Further absolute electrical measurements

You may like to see how you can go on to measure other electrical quantities absolutely once you have measured current absolutely. In principle, you now know how to make sure that the markings on an ammeter's scale are correct without having to trust its maker. You *could* test an ammeter every time you used one, though it would be time-consuming to do so. We suggest that you merely remind yourself, whenever you take a reading with an ammeter in the following experiments, that you could have found the current without using the ammeter at all, employing only a current balance and such mechanical apparatus as metre rules and clocks.

### *Absolute values of B-field, flux, and voltage*

Pass a steady direct current $I$ of about 1 A through a solenoid and a resistance, as in figure 63. Having measured the number of turns per unit of length $N_0$ in the solenoid winding, you can write down the $B$-field in the centre of the solenoid, using

$$B = \mu_0 N_0 I$$

where $\mu_0 = 4\pi \times 10^{-7}\ \mathrm{N\ A^{-2}}$.

(As indicated in the previous part of the experiment, $B$ at the centre of a solenoid which is not indefinitely long will be smaller than this value by a small amount.)

If you now measure the dimensions of the solenoid's cross-section, you can use the cross-sectional area $A$ to write down the flux $\phi$ crossing its centre, using

$$\phi = BA.$$

To measure a voltage absolutely, it is possible to use the voltage induced in a coil of $n$ turns wrapped around the middle of the solenoid, when the flux $\phi$ changes at a known rate, using

$$V = n\ \mathrm{d}\phi/\mathrm{d}t.$$

The necessary changing flux can be obtained by passing an alternating current through the coil. Clearly, the current must be adjusted so that the rate of change of flux in the coil at some instant is known. This can be done by extending the previous work, in which a direct current was passed.

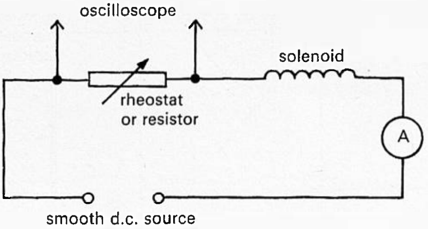



**Figure 63**
A circuit for measuring flux.

An oscilloscope is added across the resistance, as shown in figure 63. A resistance of 1 to 10 Ω, capable of carrying the required current, is suitable. Passing direct current as before (keeping to the current for which the flux has already been calculated), the oscilloscope trace will 'jump' vertically up the screen when the oscilloscope is connected to the steady potential difference across the resistor. Note the number of graticule divisions across which the trace is deflected. (It may be convenient to vary the current or the resistance so that the deflection is a whole number of divisions – say five divisions at a sensitivity of 2 V $cm^{-1}$. If the current is altered, the flux must be recalculated.) The observed oscilloscope deflection is now known to correspond to a definite flux in the solenoid, and if the resistance and oscilloscope sensitivity remain constant, you can work out the flux corresponding to any other deflection.

The flux in the solenoid can now be made to vary by replacing the direct current source with an alternating current source. A transformer or variable voltage supply working at 50 Hz is suitable.

The potential difference across the resistance in figure 63 now varies as shown in figure 64, which illustrates the appearance of the oscilloscope trace. It is convenient to vary the amplitude of the alternating supply until the peak to peak variation is the same as the deflection of the trace in the d.c. part of the experiment. Then, provided that the resistance across which the varying p.d. is being taken is sufficiently near to being a pure resistance, the peak to peak current variation in the solenoid is the same as the previous steady value. It follows that the peak to peak variation of flux in the solenoid is also the same as the previous steady value, which has been calculated.

Setting the time base at one of its calibrated positions, so that the screen contains about one complete cycle, the greatest rate of change of flux $d\phi/dt$, which occurs as the trace passes through zero, can be calculated from the greatest slope of the trace, as indicated in figure 64.

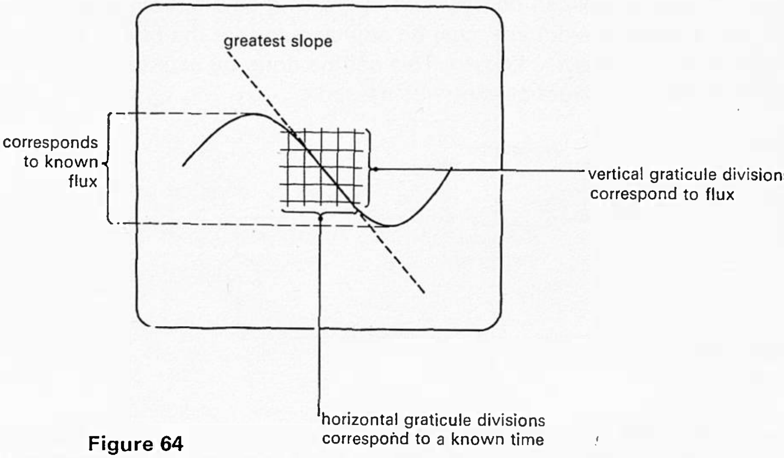



**Figure 64**
Measurement of the rate of change of flux.

Now wind about $n = 10$ turns of insulated wire around the outside of the solenoid, at its middle, and take twisted leads from this coil to the second oscilloscope input. The alternating induced voltage can be displayed together with the previous trace indicating changes of flux. The greatest induced voltage occurs, of course, when the rate of change of flux is greatest, and is given by

$$V = n\ \mathrm{d}\phi/\mathrm{d}t$$

so that you can calculate the greatest induced voltage, in volts. Tracing back the calculations, you will find that no quantity entered them other than measurements of distance or of time, or of counted turns, except for the direct current $I$ you began with, and that too can be measured absolutely as in the first part of the experiment.

*Absolute value of resistance*

Knowing the value, in volts, of the greatest induced voltage now displayed on one oscilloscope trace, you can work out how many volts correspond to one graticule spacing on the oscilloscope, at the sensitivity being used for the induced voltage display. The value of a resistance $R$ can now be found, by using this information to measure the voltage across a resistor when a known current $I$ flows in it. Because the voltage you can now measure absolutely is a small one, the resistance must also be small. A low resistance shunt, such as converts a 100 μA meter into a 1 A meter, is suitable.

To measure the voltage across it, the low resistance $R$ is inserted in series with a direct current source, a rheostat, and an ammeter (1A). See figure 65. Leads across $R$ go to the oscilloscope input, which has just been used to observe a known induced voltage, set at the same sensitivity. The current can be altered until the steady oscilloscope deflection is the same as the maximum, and known, induced voltage gave beforehand. See figure 66. Alternatively, the oscilloscope can be supposed to give deflections proportional to voltage (an easily tested point), and the voltage can be deduced from the deflection at some known current $I$. Then $R$ is given by

$$R = V/I$$

and $I$ can, as in the first part, be measured absolutely in principle, so $R$ is known absolutely.

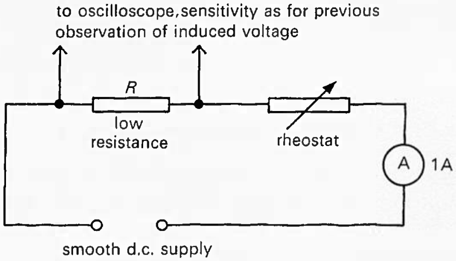



**Figure 65**
A circuit for the absolute measurement of resistance.

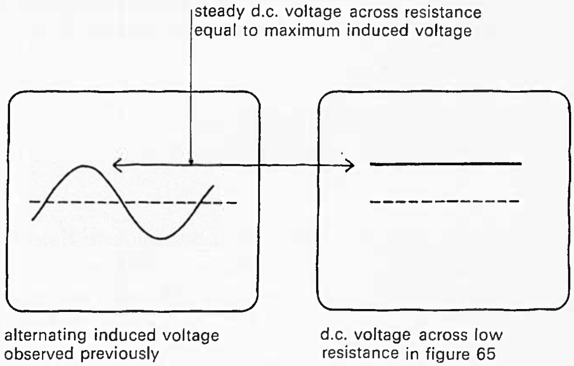



**Figure 66**
Oscilloscope displays: the absolute measurement of resistance.

**Apparatus** for experiment 7.15 (2)

You may require:

1003/5 ammeter (10 A)

1079 flat solenoid

1036 current balance

1054 copper wire, bare, about 22 s.w.g.

176 12 volt battery

541/1 rheostat, 10–15 Ω (but a non-inductive resistor is preferable)

1037 set of solenoids

27 transformer

92X reel of 26 s.w.g., PVC covered, copper wire

1003/4 shunt for ammeter (1 A) or other 0.1 Ω resistor

1057 a.c. ammeter

1007 double-beam oscilloscope

1000 leads

## 7.7 Behaviour and energy balance of a direct current motor dynamo

You will need to select some lines of investigation and measurement from those suggested below. You may also be able to think of other things to do.

*Motor experiments*

The fractional horsepower motor has four input terminals: two for the rotor (armature) and two for the coils providing the field in which the rotor turns. It is best to give these separate 0–12 volt d.c. supplies, though they can be connected in parallel to one supply.

*Do not* connect the rotor to a 12 volt supply unless the field coils are also connected and the rotor can turn, or it will draw a large current and might be damaged.

1 *Torque and rotor current.* With 12 V supplies to field and rotor, see how the rotor current changes when the motor delivers different measured torques. The torque may be applied and measured using a band brake round a motor pulley, as in figure 67.

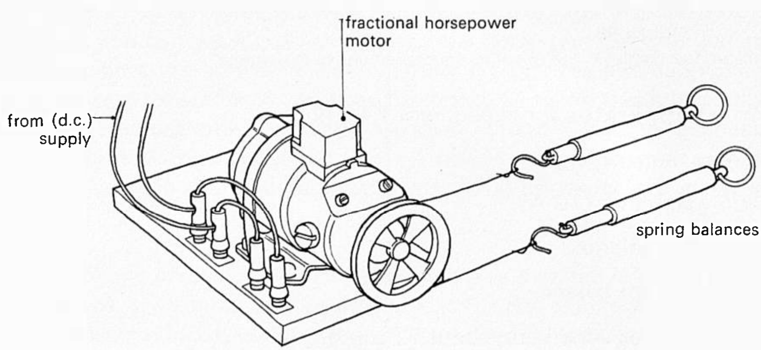



**Figure 67**
A band brake for torque measurement.

If the rotor pulley has radius $r$, and the balances read $F_1$ and $F_2$, the torque is $r(F_1 - F_2)$.

Remember that the rotor delivers some torque in turning against air and bearing friction.

Predict whether a smaller field current will give a larger or smaller torque for the same rotor current, and test your prediction.

2 *Energy balance.* Use ammeters and voltmeters to measure the power supplied to the rotor, and also to the field coils.

If you can measure the motor speed $s$ in revolutions per second, with a band brake as in 1 the mechanical power $P$ delivered to the brake is given by

$$P = 2\pi r(F_1 - F_2)s$$

$P$ is in watts if $F$ is in newtons, $r$ in metres, and $s$ in revolutions per second.

The speed $s$ could be measured with a stroboscope, or with a photodiode and oscilloscope, as in figure 68.

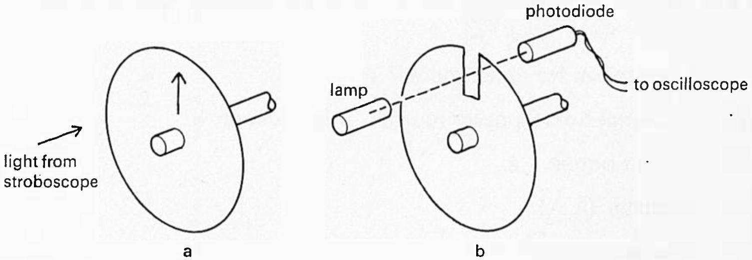



**Figure 68**
Arrangement for measuring motor speed.

Another way is to have a contact on the shaft made once per revolution, and to use a scaler to count electrical pulses from the contact.

Draw up an energy balance-sheet for the motor. You will need to know the resistance of the rotor to include an item for energy dissipated in the rotor. Can you identify the power needed to turn the rotor against air and bearing friction? Remember that the field coils could in principle be replaced by a permanent magnet which uses up no energy.

3 *Speed–torque curve.* Plot a graph of motor speed against torque delivered, for a fixed field coil current. Explain why torque *decreases* with increase of speed.

*Dynamo experiments*

4 *Induced voltage across rotor.* Run the machine as a motor, with an ammeter and voltmeter measuring current to, and p.d. across, the rotor. Cut off the rotor supply at full speed, leaving the meters in circuit. Explain what you see happening.

5 *Induced voltage and speed.* Turn the rotor with a hand drive (geared hand drill), and measure the p.d. across the rotor at various speeds. What is the voltage–speed relationship? Predict how the induced voltage at a given speed will change if the field current is reduced, and test your prediction.

6 *Induced voltage and field current.* Make measurements to show that the induced voltage across the rotor at a fixed speed rises at first with field current, but then tends to level off. Try to explain, remembering that there are limits to the extent to which iron can be magnetized.

7 *Current drawn and power delivered to dynamo.* Try turning the dynamo rapidly, using a hand drill, and then draw a large current from the dynamo. Can you feel a difference? Explain. Given a second d.c. motor-dynamo, you could use one to drive the other. It is possible to devise means of measuring the torque transmitted.

**Apparatus** for experiment 7.7

| | |
|---|---|
| 150 | fractional horse-power motor *1 but ideally, 2* |
| 176 | 12 volt battery *2* |
| 1003/4 | ammeter (1 A) |
| 1003/5 | ammeter (10 A) |
| 1004/2 | voltmeter (10 V) *2* |
| 541/1 | rheostat (10–15 ohms) *2* |
| 10A | ball of cord |
| 81 | newton spring balance (10 N) *2* |
| 134/2 | xenon flasher |
| | *or* |
| 130/2 | photodiode assembly with light source |
| | *and* |
| 64 | oscilloscope |
| 507 | stop watch or stop clock |
| 1055 | geared hand drill |
| 1054 | rubber pressure tubing to join 5 mm shafts |
| 1054 | steel rod, 5 mm diameter, 50 mm long |

Part Three

# Notes on some other experiments

## Electron collisions with atoms

The following three experiments concern the effects of collisions between electrons and atoms. Commercial gas-filled valves are used and the electrons are produced at a heated cathode, then accelerated through a potential difference which can be varied. The processes occurring in these tubes are not simple. Complications arise from the many other effects that occur. Because of this the results you obtain may not be as clear cut as you expect.

### 2.26 Ionization by electron collision

**a** Xenon

**b** Argon

**c** Helium

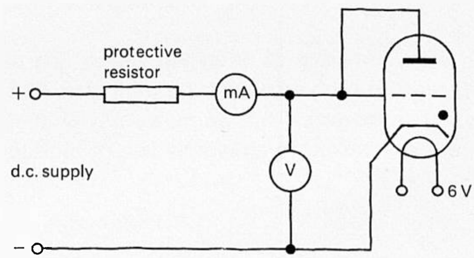



**Figure 69**
A circuit diagram for experiment 2.26.

Electrons from the hot cathode are accelerated by the potential difference, and the larger the p.d., the higher the kinetic energy of the electrons. The anode and the grid of the valve are connected together so that the tube is being used as a diode. Any change in the number of electrons or ions travelling across the tube will show up as a change in the milliameter reading.

#### Apparatus

1049 thyratrons and thyratron base
59 l.t. variable voltage supply
*and*
1064 low voltage smoothing unit
1005 multi-range meter (25 V range)
*or*
1004/3 voltmeter (100 V)
27 transformer
1040 clip component holder
1000 leads

**a**

1049 xenon thyratron EN91 or 2D21
1003/2 milliammeter (10 mA)
1051 protective resistor (1000 Ω)
*or*
1017 resistance substitution box

**b**

1049 argon thyratron 884
1003/3 milliammeter (100 mA)
1051 protective resistor (100 Ω, 5 W)

**c**

1049 helium thyratron 6K25
1003/4 ammeter (1 A)
541/1 rheostat (10–15 Ω) (protective resistor)

## 2.28 Detection of ions

The plate in the thyratron is made slightly negative with respect to the electron source so that only positive ions (and no electrons) reach the plate. See figure 70.

### Apparatus

1049 thyratron base and EN91 thyratron
59 l.t. variable voltage supply
1064 low voltage smoothing unit
1005 multi-range meter
*or*
1004/3 voltmeter (100 V)
27 transformer
1033 cell holder with two U2 cells
1001 galvanometer (internal light-beam)
*or*
1002 microammeter (100 μA)
1040 clip component holder
1051 resistor (10 kΩ)
1000 leads

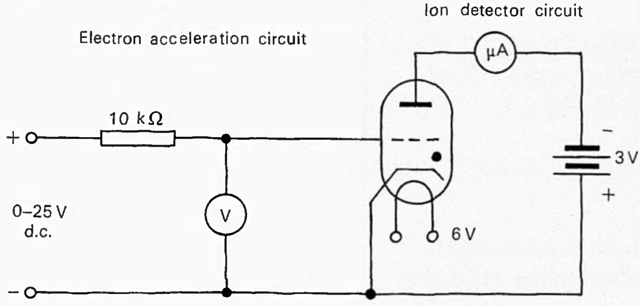



**Figure 70**
A circuit diagram for experiment 2.28.

## 2.29 Excitation of xenon

The flow of current through the galvanometer keeps the plate slightly negative with respect to the accelerating grid. The galvanometer detects electrons which have enough energy to pass beyond the accelerating grid, and a reduction in its reading suggests that some electrons are losing energy by collision. See figure 71.

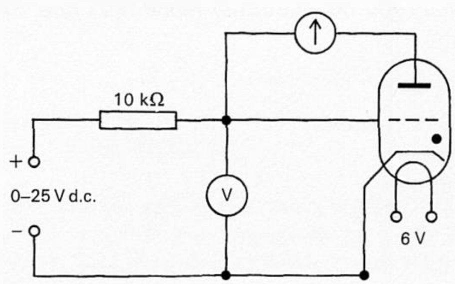



**Figure 71**
A circuit diagram for experiment 2.29.

### Apparatus

As experiment 2.28.

## Experiments with a parallel plate capacitor

In all the capacitor experiments remember that you are a reasonably good conductor of electricity, so that if you are very close to the capacitor plates, you will change the capacitance of the arrangement.

### 3.4 Reed switch and a parallel plate capacitor

**Apparatus**

1010 reed switch
1009 signal generator
1025 capacitor plates with 16 polythene spacers ($10 \times 10 \times 1.5$ mm) *1 pair*
15 h.t. power supply (for 25 V smooth d.c.)
*or*
59 l.t. variable voltage supply
*and*
1064 low voltage smoothing unit
1004/3/2 voltmeter (100 V) and (10 V)
1001 galvanometer (internal light-beam)
1017 resistance substitution box
158 class oscilloscope
501 metre rule
32 1 kg weight
1000 leads

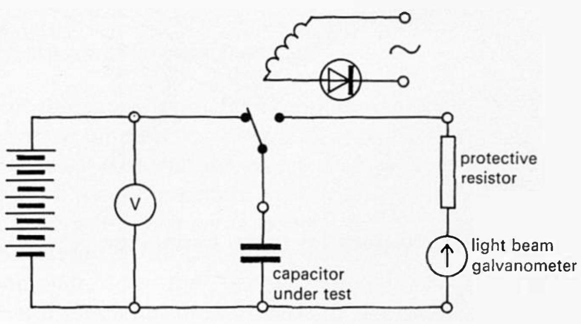



**Figure 72**
A basic reed switch circuit.

Practical details for the switch appear under 'Reed switch' in Part One, page 17. The signal generator should be used to drive the reed switch at as high a frequency as possible, no lower than 300 Hz. A protective resistor of about 100 kΩ should be placed in series with the galvanometer. See figure 72.

The parallel plate capacitor is assembled by placing small insulating spacers between the metal plates. The spacers are all the same thickness so if the same numbers are used at each corner the plates should be the same distance apart at all points. See figure 73.

**a** $Q \propto V$. Is the charge $Q$ on a capacitor plate proportional to the potential difference $V$ between the plates? Record values of the galvanometer current for various voltages and plot a suitable graph to determine the answer. Do not disturb the plates during this experiment.

**b** $Q \propto 1/d$. Is the charge $Q$ on a capacitor plate proportional to the reciprocal of the plate separation $d$? Different values of $d$ can be obtained by using different numbers of the spacers at each corner of the plates.

**c** $Q \propto A$. Is the charge $Q$ on a capacitor plate proportional to the area of overlap of the plates? The area can be changed by sliding the top plate sideways. Position the spacers so as to keep the plate separation constant. A weight will have to be placed on the top plate to keep it level. This weight should be present throughout the experiment.

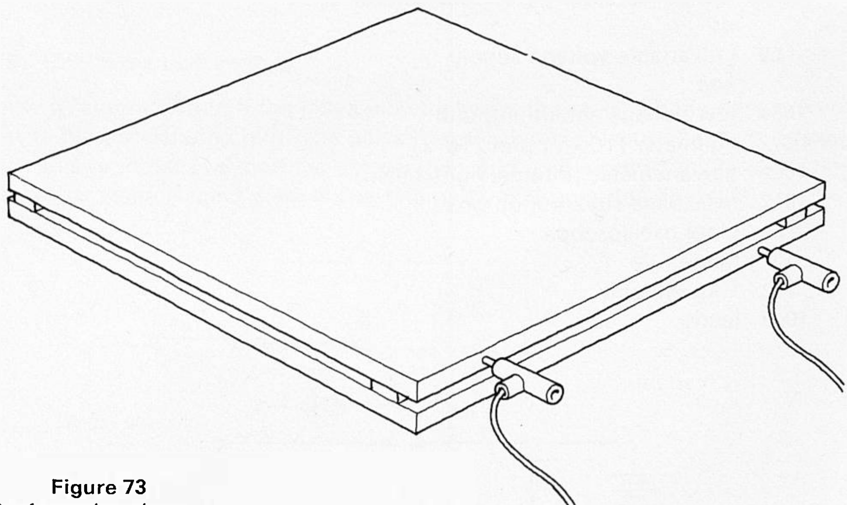


**Figure 73**
A pair of capacitor plates.

### 3.5 Electrometer and parallel plate capacitor

#### Apparatus

| | |
|---|---|
| 1006 | electrometer with probe rod |
| 1051 | capacitor, polystyrene, 0.01 μF (see below) |
| 65 | metal plates with insulating handles *1 pair* |
| 1003/1 | meter to match electrometer, unless provided |
| 14 | e.h.t. power supply |
| 1005 | multi-range meter |
| 1033 | cell holder with U2 cell (1.5 V) |
| 1051 | preset, 5 kΩ or more |
| | *in* |
| 1041 | potentiometer holder |
| 503–5 | retort stand base, rod, and boss 2 |
| 501 | metre rule |
| 1000 | leads |

See 'Electrometer' in Part One, page 13, for details of how to use the electrometer. Unless the electrometer includes a built-in charge range of 0–$10^{-8}$ C, connect a 0.01 μF capacitor (low leakage type) directly across the electrometer input, as shown in figure 74. Do not have it connected by leads which touch the bench. The electrometer can be calibrated using the 1.5 V cell, potentiometer, and multi-range meter (used as a voltmeter).

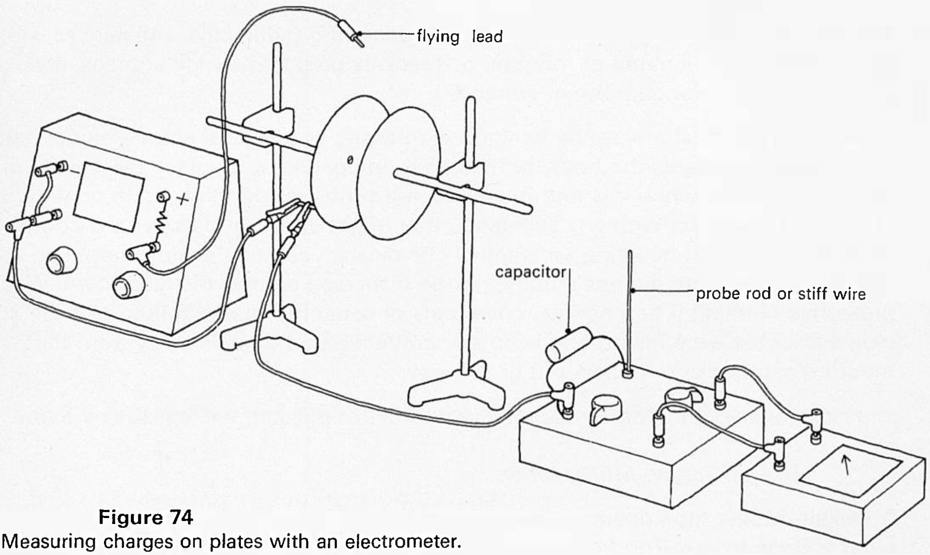



**Figure 74**
Measuring charges on plates with an electrometer.

**a** $Q \propto V$. Put the capacitor plates about 10 mm apart and use voltages in the range 0 to 500 V to see whether the charge $Q$ on a capacitor plate is proportional to the potential difference $V$ between the plates. The multi-range meter can be used to measure the voltage of the e.h.t. supply. (If it is used, it must be connected to the supply throughout, since it draws some current and reduces the supply voltage.) The plates can be charged by touching a flying lead from the e.h.t. supply momentarily to one plate. Then the charge is measured by moving the electrometer so that a probe rod or stiff wire in its input terminal touches the plate.

**b** $Q \propto 1/d$. With a constant voltage of a few hundred volts, measure the charge on a capacitor plate for plate spacings of 5 to 25 mm. Also take a measurement when the plates are a long way apart, say half a metre. Is the charge $Q$ on a plate proportional to the reciprocal of the plate separation $d$?

## Experiments with radiations from radioactive materials

*Handling radioactive substances*

Radioactive substances should be handled with the same care and treated with the same respect as one would use with dangerous chemicals such as concentrated acids. The following are some simple commonsense precautions which you must observe when using radioactive substances.

You may find yourself using either naturally occurring radioactive substances, such as compounds of uranium or thorium, or specially prepared sealed sources, such as americium 241, strontium 90, or cobalt 60.

Sealed sources must always be handled with tongs or a special source holder, and never pointed towards the body, or held near any part of it. Replace the source in its lead-lined box when it is not in use. Do not probe inside the source, or allow it to come into contact with any substance that might attack or dissolve the source or its container. When handling radioactive chemicals, you must ensure that they cannot be taken into anyone's body, nor be dispersed around the laboratory. Wear protective clothing if appropriate, cover cuts or scratches, use a spill tray, wash your hands after the experiment, and keep any contaminated objects away from the mouth. Keep books or papers out of the way.

If used properly, none of the radioactive sources suggested will cause any harm.

*Use of Geiger–Müller tubes*

A Geiger–Müller tube operates over a limited range of voltages. You should ask what voltage to use. Too high a voltage can damage the tube. At too low a voltage it will work ineffectively or not at all. Operating instructions for the use of a scaler with a Geiger–Müller tube will be found in Part One under 'Scaler' (page 26).
The GM tube MX 168 contains ferromagnetic material, and there is some danger of breaking it accidentally when using the tube near a magnet, if the magnet attracts the tube and they come sharply into contact.

### 5.1 The magnetic deflection of beta particles

#### Apparatus

130/1 scaler
130/3 GM tube holder
130/5 thin window GM tube
195/2 pure beta source
196 source holder
50/3 magnet, Eclipse Major
*or*
92I mild steel yoke
*and*
92B Magnadur magnet
503–6 retort stand base, rod, boss, and clamp *2*
1M lead block *2*

The scaler should be adjusted to record beta particles arriving at the GM tube (see under 'Scaler', page 26). Then arrange the apparatus so that you can see the effect of allowing beta particles to pass through a magnetic field. Can you detect any deflection of beta particles in a magnetic field? Would your results indicate that beta particles carry no charge, a positive charge, or a negative charge?

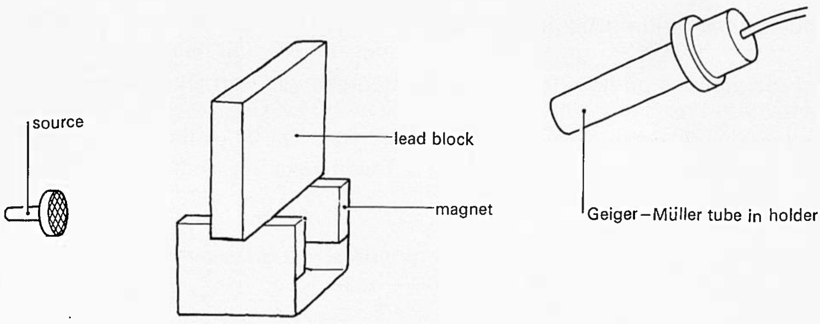



**Figure 75**
Arrangement of the apparatus for the magnetic deflection of beta particles.

## 5.2 The number of ions produced by an alpha particle

### Apparatus

### 5.2a Measuring the ionization current

1006 electrometer with $10^9$ Ω input resistor
1008 ionization chamber
195/3 pure alpha source
15 h.t. power supply
1003/1 milliammeter (1 mA)
196 source holder
1000 leads

### 5.2b Counting alpha particles from the source

*Add:*
130/4 solid state detector and preamplifier
130/1 scaler
503–6 retort stand base, rod, boss, and clamp *2*
507 stop watch or stop clock

If the ions which are produced by alpha particles as they go through the air can be collected, the current which they cause can be measured and it is then possible to estimate the number of ions formed. The steps in the argument are as follows.

Measure the current due to the ions.
The charge on an ion is of the same order of magnitude as the charge on

an electron, so the number of ion pairs produced every second can be estimated. These are the ion pairs (a positive and a negative ion) produced by all the alpha particles which go into the collecting (ionization) chamber. Knowing the activity of the alpha source, you can estimate the number of alpha particles produced every second.

The number of ion pairs produced by one alpha particle can thus be estimated.

For instructions on how to use the electrometer see Part One, page 13.

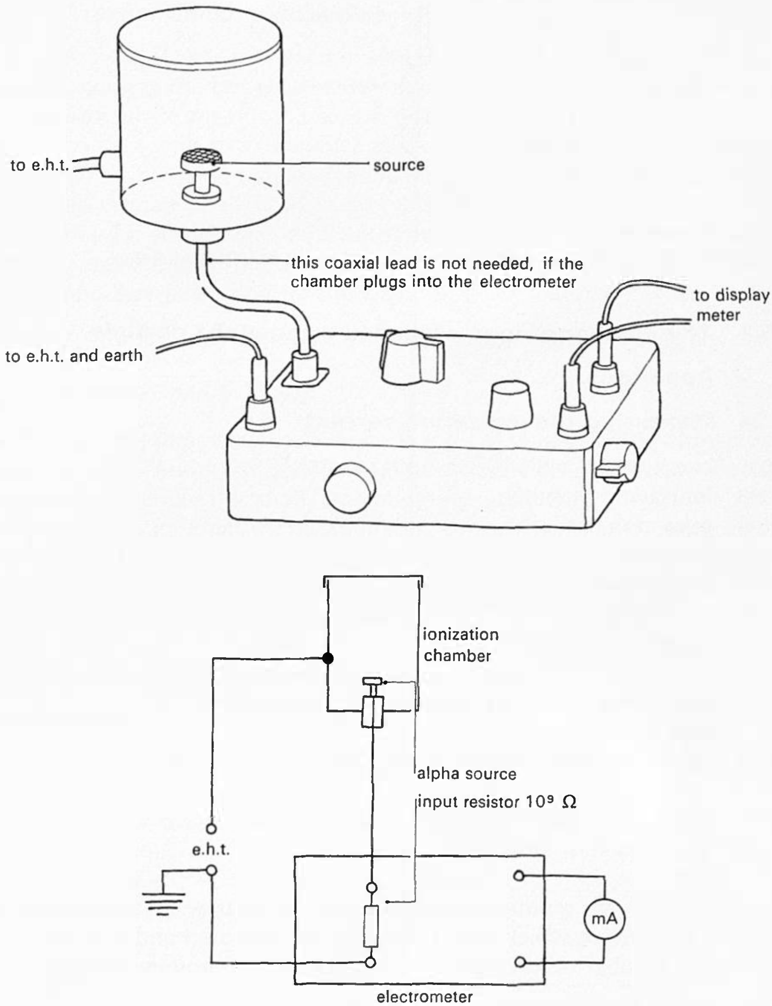



**Figure 76**
Measurement of the ionization produced by alpha particles.

Mount the source in the ionization chamber and connect it to the electrometer input as shown. The ions which are produced by the alpha particles can be swept out of the chamber by applying a p.d. from the h.t. power supply. Increase the p.d. until all the ions which are being produced are being collected. (How will you know when this is happening?) If the electrometer has been calibrated, you can deduce the p.d. $V$ across its input from the indication on its output meter. This p.d. will be up to 1 V, and is the result of the ionization current flowing through the input resistor $R$. If you know $R$, you can find the ionization current $I$, using $I = V/R$.

An activity of one curie is $3.7 \times 10^{10}$ disintegrations each second and the alpha source may be marked 5–10 μCi (say 7 μCi). The activity of the source can be checked. (See the subsidiary experiment at the end of this one.) The charge on an electron is $1.6 \times 10^{-19}$ C.

With this information you should be able to calculate the number of ions produced by an alpha particle.

### *Alpha particle energy*

Your result for the number of ions produced by an alpha particle can be used to give a value for the energy an alpha particle has on emission. The ionization energy of nitrogen ('air') is 14 electronvolts. An alpha particle may not be 100 per cent efficient at causing ionization; there may be collisions which transfer only a part of the alpha particle's energy, sometimes imparting kinetic energy, sometimes causing excitation instead of ionization. The average energy lost by an alpha particle for each ionization will not be less than 14 eV. Experiments suggest an average of about 30 eV. The energy of the alpha particle is the energy needed to make one ion pair multiplied by the number of pairs it produces.

Calculate the energy of an alpha particle emitted by the source
(1 eV $= 1.6 \times 10^{-19}$ J).

There are several sources of error in this experiment. For example, do all the alpha particles produced by the source go into the chamber? Where do they do? Does it matter how big the ionization chamber is? What would happen if it were made smaller and smaller? (What experiments could be done to check what effect the size of the chamber has?)

### *Subsidiary experiment to 5.2b: Activity of the alpha source*

Set the detector a small distance $r$ (say 20 mm) from the foil in the source holder and determine the count-rate, in counts per second.

If the count-rate is $C$, then in one second, $C$ disintegrations send alpha particles into an area of $\pi d^2/4$ at a distance $r$ where $d$ is the diameter of the detecting surface. If we assume that all directions of emission are equally probable, the total number of disintegrations per second, $N$, is given by

$$N = \frac{C}{\pi d^2/4} \times 4\pi r^2 = \frac{16Cr^2}{d^2}.$$

(Since alpha particles emitted backwards into the source holder do not emerge at all, an area $2\pi r^2$ or even less might replace the area $4\pi r^2$ if one wants to find the observable activity of the source.)

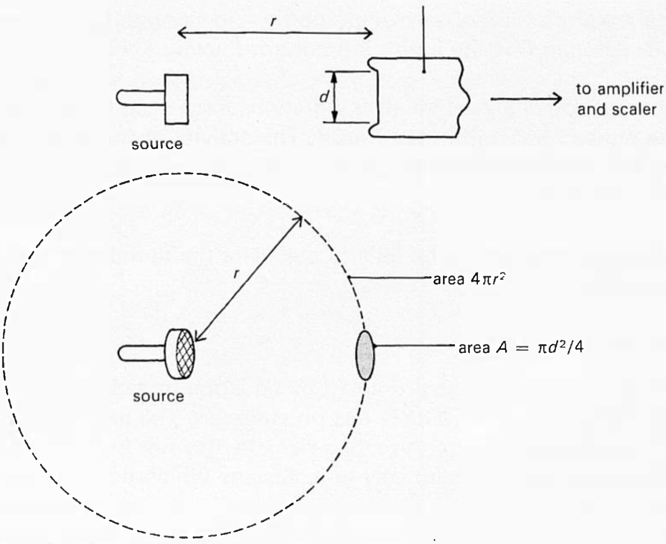



**Figure 77**
The radiation reaching the solid state detector.

## 5.3 The cloud chamber tracks of alpha, beta, and gamma rays

### Apparatus

28 diffusion cloud chamber with weak radium source
47 illuminant
27 transformer
19/1/2 $CO_2$ cylinder and dry ice attachment
1056 methylated spirit (or ethanol)
195/1 pure gamma source
*or*
195/3 pure alpha source (see below)
196 source holder
133 camera (optional)
171 photographic accessories kit (optional)
1054 film and monobath developer (optional)

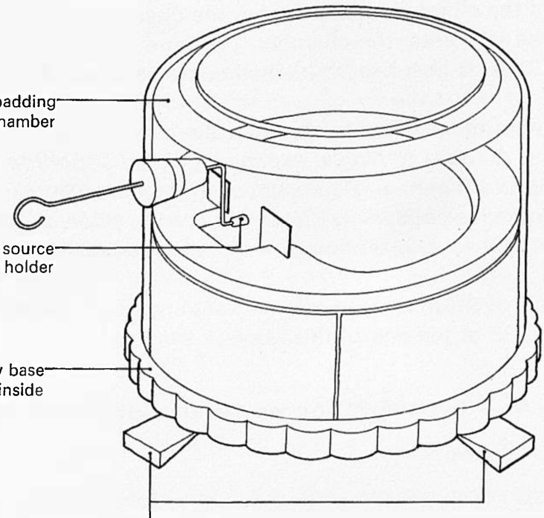



**Figure 78**
A diffusion cloud chamber.

Instructions for using the chamber appear under 'Diffusion cloud chamber' in Part One, page 30.

Tracks should appear within thirty seconds of setting up the cloud chamber with the radium source, and they can be made sharp by rubbing the top of the chamber with a duster, which provides an electric field in the chamber.

**a** The main tracks visible in the chamber are those of alpha particles. How far do they travel? Do they all travel the same distance? What might you suppose about the energy of the alpha particles emitted by the source?

**b** The alpha particles can be observed by arranging the source so it is immediately behind one of the aluminium foils in the chamber. Tracks of beta particles can then be observed by carefully adjusting the position of the illuminant. They are much fainter than those of alpha particles and more care is needed to see them. The aim is to illuminate the sensitive layer and to keep the light off the floor of the chamber. A slit over the illuminant and a convex lens to obtain a parallel beam of light might help. The right position will be found by trial and error and this part of the experiment is best done in a darkened room.

**c** Tracks produced by gamma rays can be seen by bringing the gamma source up to the cloud chamber. A source holder should be used. Close the hole in the side of the chamber with an uncut cork, after first removing the radium source.

Americium 241 can be used as a gamma source, though intended as a 'pure' alpha source. It produces a little weak gamma radiation, and may simply be placed on the top of the cloud chamber so that the chamber wall absorbs the alphas, and the gamma rays enter the chamber. The pure gamma source, item 195/1, can also be used. This is best kept in its lead container, put near the chamber.

Compare the results you get with the photographs in Gentner, Maier-Leibnitz, and Bothe, *An atlas of typical expansion chamber photographs* (reference 6), or Lewis and Wenham, *Radioactivity* (reference 19). A smaller selection of photographs appears in *Classical scientific papers – physics* (reference 1) on page 369. An explanation of the tracks starts on page 360.

Details of these reading references are given in *Students' book,* Unit 5. See also page 135 at the end of this book.

## 5.4 The penetrating power of alpha, beta, and gamma rays

### Apparatus

| | |
|---|---|
| 195/ 1/2/3 | pure gamma, pure beta, pure alpha sources |
| 196 | source holder |
| 130/1 | scaler |
| 130/3 | GM tube holder |
| 130/4 | solid-state detector and preamplifier |
| 130/5 | thin window GM tube |
| 130/6 | gamma GM tube (not essential) |
| 507 | stop watch or stop clock |
| 503–6 | retort stand base, rod, boss, and clamp *2* |
| 501 | metre rule |
| 1052 | absorbers for alpha, beta, and gamma rays (see below) |
| 1055 | vernier callipers (or micrometer screw gauge) |

The collection of absorbers (item 1052) should contain cigarette paper, ordinary paper, thin glass and Perspex sheets, aluminium cooking foil, aluminium sheet of several thicknesses to cover a range of 1 to 5 mm, and lead sheet or blocks to cover a range of 5 to 20 mm thicknesses.

This experiment has a number of possible parts from which you will have to choose:
**a** Range of alpha particles in air.
**b** Range of beta particles in aluminium.
**c** 'Half-thickness' of lead for gamma rays.
**d** Relation between absorber thickness and radiation transmitted.
**e** Relation between source to detector distance and intensity received.

In all these experiments a count will be detected even when no radioactive source is present. You will have to make corrections for this background count in order to find the true count-rate produced by the radioactive source.

Instructions on the use of the scaler appear on page 26 in Part One.

### a Range of alpha particles in air

Alpha particles are so easily absorbed that, unless the right detector is used, they fail to get past the outer cover of the detector. For this reason either a very thin end-window Geiger–Müller tube or a solid-state detector must be used.

Determine the range in air of the alpha particles. Figure 79 is a graph, showing the range in air of alpha particles with different energies. What are the energies of the alpha particles from your source? (If you used a GM tube you will have to make allowances for the effect of the end-window. The window of a MX 168/01 tube is equivalent to about 17 mm of air, that of a MX 168 tube to about 30 mm.) Find out what thickness of different materials will just absorb alpha particles.

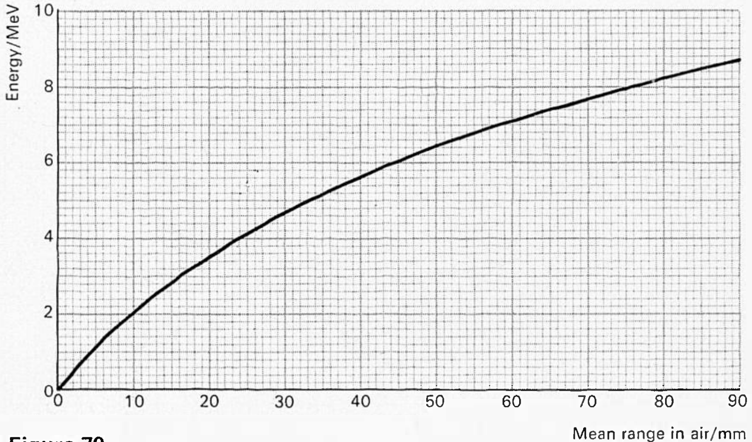



**Figure 79**
The mean range in air of alpha particles of different energies.
*From Gentner, W., Maier-Leibnitz, H., and Bothe, W. (1954)*. An atlas of typical expansion chamber photographs, *Pergamon.*

### b Range of beta particles in aluminium

How far do beta particles travel in air? Because beta particles are not the same 'things' as alpha particles, it does not follow that beta particles which travel further in air than alpha particles necessarily have more energy than the alpha particles. Find the maximum energy of the beta particles from your source. To do this, you can, keeping the distance from the source to the detector fixed, interpose varying thicknesses of aluminium and determine the range of the radiation in aluminium. Figure 81 shows the range in aluminium of beta particles of different energies. Find the maximum energy of the beta particles from your source. You should remember that the beta particles you observe have travelled not only through aluminium but through the end-window of the Geiger–Müller tube and through air as well.

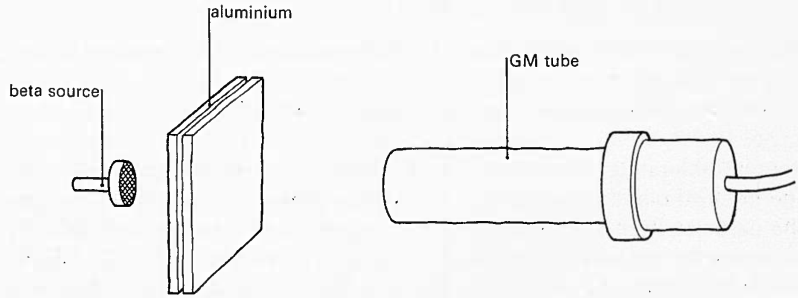



**Figure 80**
Apparatus for determining the range of beta particles in aluminium.

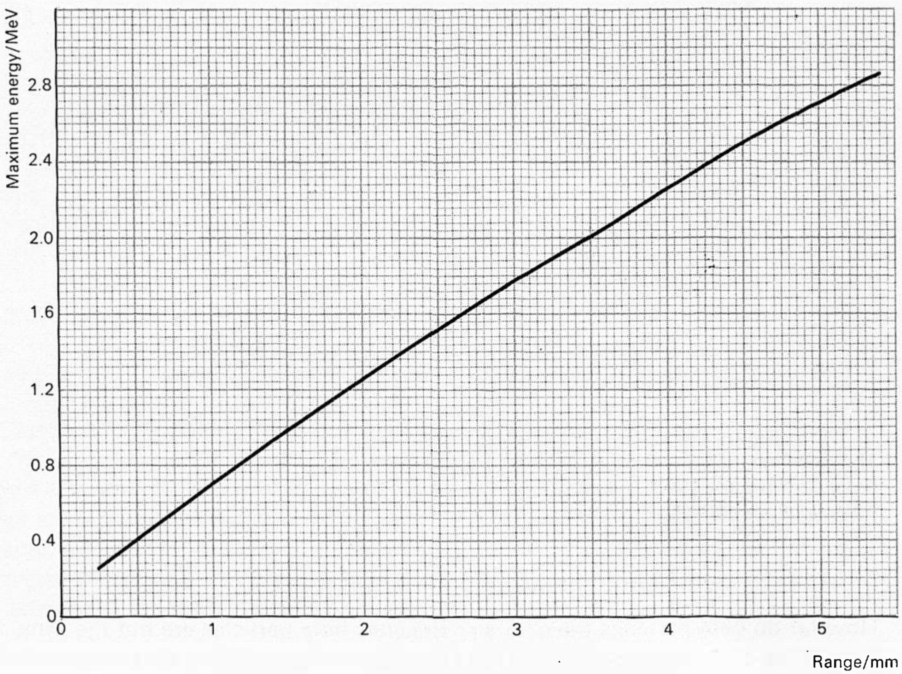



**Figure 81**
The range–energy curve for beta particles in aluminium.
*From Katz, L., and Penfold, A. S. (1952) 'Range–energy relations for electrons and the determination of beta–ray end-point energies by absorption.'* Rev. Mod. Phys. ***24***, *28*.

## c 'Half-thickness' of lead for gamma rays

Find the energy of the gamma radiation emitted from your source. To do this, you can, keeping the distance from the source to the detector fixed, interpose varying thicknesses of lead and find how the count-rate changes with thickness of lead.

Figure 82 shows the half-thickness of lead for gamma radiations of different energies. The half-thickness is the thickness which will reduce the count-rate to one half of its original value.

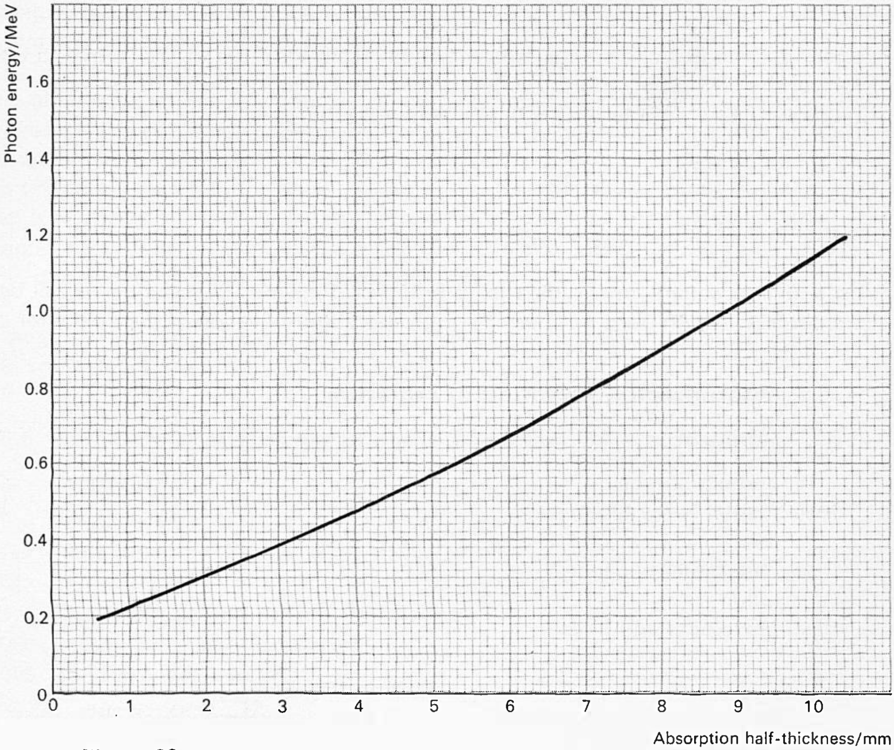



**Figure 82**
The half thickness–energy curve for gamma radiation in lead.
*From Davisson, C. M., and Evans, R. D. (1952) 'Gamma–ray absorption coefficients.'* Rev. Mod. Phys. ***24**, 79.*

### d Relation between absorber thickness and radiation transmitted

See if you can find a relationship between the count-rate and the thickness of absorber introduced between a detector and a source at a fixed separation. Try gamma or beta radiations.

### e Relation between source to detector distance and intensity received

The gamma ray count-rate decreases as the distance from the source increases. See if you can find out *how* the intensity decreases. Does it vary inversely with the distance, or inversely with the square of the distance, or exponentially, or what? An end-window Geiger–Müller tube or a shielded tube designed for gamma rays can be used. Whichever tube you use, measuring the distance without involving a zero error is difficult. If, therefore, there is an inverse square law dependence (say), then the relation between count-rate and distance will have the form:

$$\textit{count-rate} \propto \frac{1}{(d+e)^2}$$

where $d$ is the actual distance measured (say from the front of the source to the front of the GM tube, with the tube's protective cover in place) and $e$ is the (unknown) zero error in $d$. It is better to rewrite this as

$$(d+e)^2 \propto \frac{1}{\textit{count-rate}}$$

so that $$(d+e) \propto \frac{1}{\sqrt{\textit{count-rate}}}.$$

If the inverse square law holds, than a graph of $d$ against $1/\sqrt{\text{count-rate}}$ will be a straight line, which does not pass through the origin because of the zero error $e$.

## 5.5 Photographic detection of radiation

### Apparatus

16 radium source
1054 dental X-ray film
*or*
1054 fast bromide paper
*and*
1054 developer and fixer

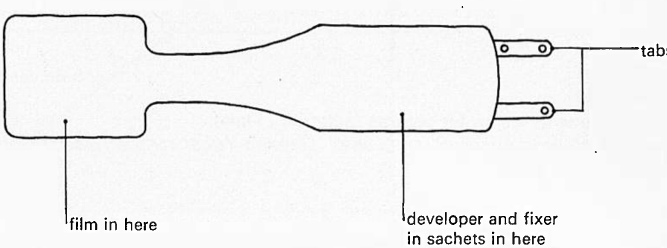



**Figure 83**
Dental X-ray film.

Use of the dental X-ray film, which contains its own developer and fixer, avoids the need for a darkroom but involves some expense. The source should be placed face down on the film pack for twenty to thirty minutes. The film is contained in the flat end of the sachet. To develop it, hold the sachet upright by gripping the top, the part between the tabs, with the thumb and forefinger of one hand. Using the other hand, pull the tab with *one hole* completely out of the sachet. This releases the developer, which should be eased down to the film section by gentle pressure. Wait thirty to forty-five seconds. Then pull the tab with the *two holes*. This releases the fixer which again should be eased down to the film section by gentle pressure. Wait thirty to sixty seconds. The sachet should then be opened over a sink by peeling the plastic apart from the top. Remove the film and rinse it under cold running water for a few seconds before viewing. A longer washing time is needed if the film is intended to be permanent.

As an alternative, the source can be placed face down on the sensitive surface of fast bromide paper ('hard' paper is better than 'soft'), again for about half an hour, after which the paper is developed. Work in a darkroom with a suitable safe light. With the paper, the alpha particles produce nearly all the effect. If the sensitive paper is wrapped in black paper, the alphas are stopped, and the exposure time becomes much longer (some hours). The film is faster, and develops an exposed patch, due mainly to betas, in a reasonable time.

It is possible, but very time-consuming, to repeat Becquerel's work using sensitive paper and salts of uranium.

## 5.6 Large angle scattering of alpha particles

### Apparatus

| | |
|---|---|
| 28 | diffusion cloud chamber |
| 47 | illuminant |
| 27 | transformer |
| 19/1/2 | $CO_2$ cylinder and dry ice attachment |
| 1056 | methylated spirit or ethanol |
| 1055 | gold foil (see below) |

See 'Diffusion cloud chamber' in Part One, page 30, for operating instructions.

The foil should be placed inside the chamber and it is essential to mount it on a support of low thermal conductivity to avoid disturbing the temperature gradient in the chamber. There is some advantage in making the foil support cylindrical, so that the source can be placed near the axis of the cylinder, and having it of such thickness and density that α-particles will not penetrate it. The foil support is placed near the centre of the chamber and the source is moved forward so that it is near the axis of the support. The illumination should be adjusted so that tracks can be seen on both sides of the foil.

It is necessary to watch the chamber for a considerable time (fifteen minutes at least). Most particles appear to go straight through the foil, but a few are visibly deflected, occasionally through a large angle.

Instructions for mounting the foil on its support are given in *Teachers' guide* Unit 5, with experiment 5.6.

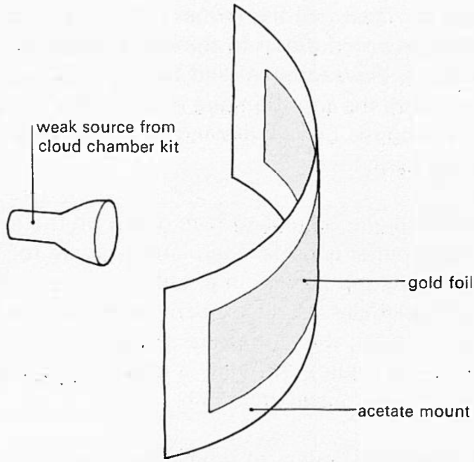



**Figure 84**
The large-angle scattering of alpha particles.

## 5.7 Collisions between pucks in two dimensions

### Apparatus

| | |
|---|---|
| 95 | Edinburgh $CO_2$ pucks kit |
| 161 | gantry for $CO_2$ pucks kit |
| 19/1/2 | $CO_2$ cylinder and dry ice attachment |
| 134/1 | motor-driven stroboscope |
| 133 | camera |
| 171 | photographic accessories kit |
| 1054 | film, monobath developer/fixer |
| 1054 | P 153 daylight printing paper, paper developer, and fixer |
| | slide projector |

See 'Stroboscopic photographs' in Part One, page 22, for instruction on this technique and on film development and the use of daylight printing paper.

Gentner, Maier-Leibnitz, and Bothe, *An atlas of typical expansion chamber photographs* (reference 6 in the *Students' book,* Unit 5) shows many photographs of nuclear particles colliding. A particularly interesting one is shown in figure 29 of the book where, after the collision, an angle of nearly 90° is formed between the paths of the two particles involved in the collision. The 90° angle is a characteristic of an elastic collision between particles of equal mass, one of which was initially at rest. This can be verified with the frictionless pucks. By suitable loading of pucks, try reproducing the angles shown in other photographs (for example, figures 28, 30, 31, and 32) which involve particles of unequal masses, such as an alpha particle and a hydrogen nucleus (a proton).

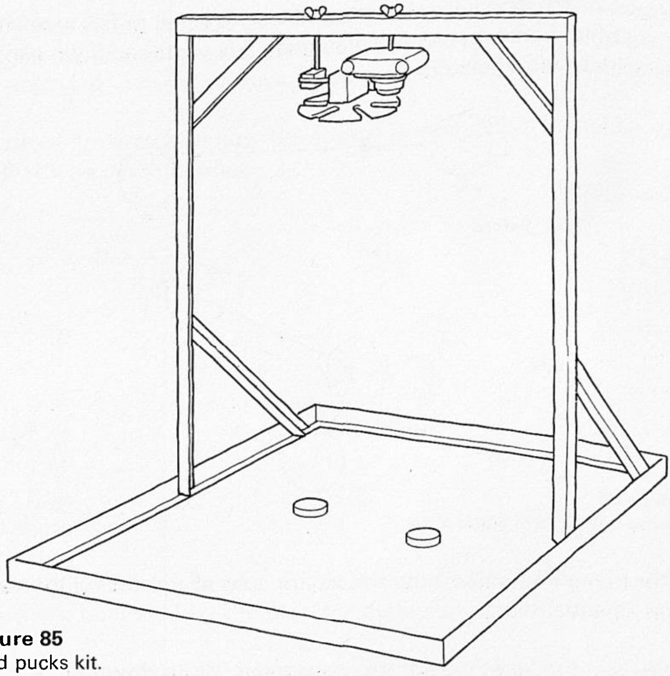


**Figure 85**
The gantry and pucks kit.

If only angles are required, there is no need for stroboscopic photographs to be taken. If, however, you want to make some calculations on momenta, then stroboscopic photographs will be required so that you can measure the velocities of pucks.

The distance of the camera above the table should be adjusted until the table fills the field of view. If a xenon flasher is used you should work in the dark and arrange for the path of the pucks to be illuminated by the light from the flasher.

If the motor stroboscope is used, the slide projector should be arranged to illuminate the pucks. The rotating disc of the stroboscope should be placed close to the lens of the camera.

The speed of the stroboscope needs adjusting so that successive views of the pucks are neither too far apart nor too close together. This will depend on the speed with which the pucks are pushed, and you will have to make adjustments to suit your particular experiment.

The right-angled collision which occurs when a moving object hits a stationary object of equal mass can be deduced theoretically, as follows.

The vector sum of the momenta after the collision is equal to the momentum before the collision. Since the masses are equal, this vector addition can be done with the velocities. See figure 86.

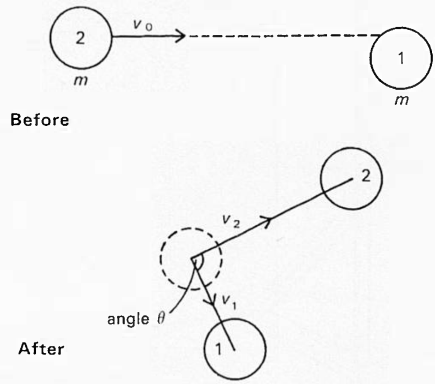



**Figure 86**
Collision of pucks which have equal mass.

Draw a vector triangle to show how the vector sum of $v_1$ and $v_2$, the velocities after collision, is equal to $v_0$.

Assume, now, that the kinetic energy is conserved. Write down an equation between kinetic energies before and after collision. You can then make use of Pythagoras' Theorem to prove that the vector triangle must have angle $\theta = 90°$.

## 5.8 Knock-on of protons by alpha particles

### Apparatus

28 diffusion cloud chamber
47 illuminant
27 transformer
19/1/2 $CO_2$ cylinder and dry ice attachment
1056 methylated spirit (or ethanol)
195/3 pure alpha source
1053 expanded polystyrene sheet, 10 mm thick
1053 pins, 20 mm long 4
1053 polythene sheet (very thin)
1055 cork borer

Hydrogen contains the lightest of all nuclei. What is the mass of a hydrogen nucleus (a proton) compared with that of an alpha particle?
Polythene contains a lot of hydrogen and can also be made into very thin sheets. (Why is this important if we want to see the effect of an alpha-particle hitting a hydrogen nucleus?) In this experiment alpha particles are fired at a thin sheet of

polythene. What would you expect to happen in a collision between alpha particles and hydrogen nuclei? You could revise your knowledge of collisions, using dynamics trolleys or a linear air track if you are not sure.

Figure 87 gives the details of how the source is mounted in its holder with a thin sheet of polythene over the front.

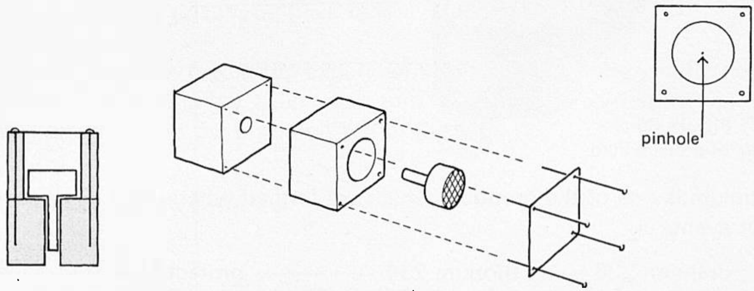



**Figure 87**
Details of the source mount.

The source in its holder is placed on the floor of the cloud chamber close to the position normally occupied by the cloud chamber source.

A small pin-hole is made at A, in the centre of the polythene, so as to allow an occasional alpha particle to pass through and provide a comparison between an alpha particle track and one caused by a proton. You may have to wait several minutes for the cloud chamber to settle down after putting in the source before seeing anything other than the occasional alpha particle track.

In what way is the track of a proton different from that of an alpha particle?

## 5.9 Decay and recovery of protactinium

### Apparatus

130/1 scaler
130/3 GM tube holder
130/5 thin window GM tube
1055 polythene bottle (50 cm$^3$)
1056 uranyl nitrate
1056 concentrated hydrochloric acid
1056 iso butyl methyl ketone (2-methyl butan-3-one)
*or*
1056 amyl acetate
503–6 retort stand base, rod, boss, and clamp
507 stop watch or stop clock

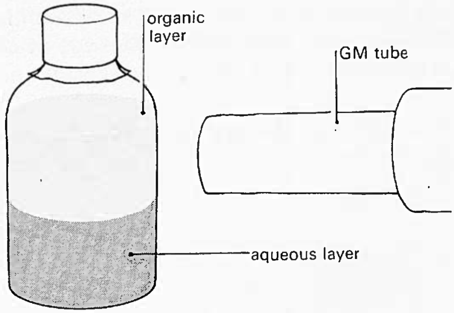



**Figure 88**
The decay of protactinium.

Protactinium is one of the products which are formed when uranium decays. The chain of events is:

$$\text{uranium 238} \xrightarrow[\text{alpha}]{} \text{thorium 234} \xrightarrow[\text{low energy beta}]{} \text{protactinium 234} \xrightarrow[\text{energetic beta}]{}$$

The uranium 238 decays very slowly indeed. The thorium 234 decays much more quickly but it still takes twenty-four days for half of it to go. The protactinium 234 decays still more quickly – fast enough for its decay to be easily detectable in a short experiment.

The decay of the protactinium on its own can be detected by separating it from the thorium, using an organic solvent which removes the protactinium from an acid solution but leaves its parent thorium behind. A convenient way to do the experiment is to mix all the chemicals in a polythene bottle. After the bottle has been shaken the organic solvent now containing the protactinium floats to the top of the remaining aqueous layer and the activity of the protactinium can be detected in the organic layer. (It emits beta particles which can pass through the wall of the bottle.)

Shake the bottle for 10 to 15 seconds and then place it at once beside the GM tube so that the window of the tube is opposite the top half of the bottle, as in figure 88. As soon as the layers have separated, the scaler can be started, and counts can be taken at 10-second intervals without stopping the scaler. Alternatively, a 10-second count can be taken every half minute. A ratemeter is an acceptable substitute.

Plot a graph of count-rate against time to show the pattern of the decay. There will be a count even when you do not put a source in front of the tube. This 'background' count should be determined and allowed for when plotting the count-rate due to the protactinium alone.

Determine the half-life of protactinium from your graph. The half-life is the time taken for half the substance to decay, and is the same time as that taken for the count-rate to decrease by a factor of two. Start at several points and see how long the count-rate takes to drop by half in each case.

The thorium from which the protactinium has been removed is left in the aqueous layer in the lower half of the bottle. Protactinium will immediately start to be produced again as the thorium decays, and the growth curve of protactinium can be plotted. You should try this if you have time.

To observe the recovery, repeat the experiment with the GM tube window opposite the lower layer, or, for a better count-rate, turn the GM tube so that its window faces upwards and stand the bottle on top of the tube.

## 5.10 The decay of radon

### Apparatus

1006 electrometer, with $10^{11}$ Ω input resistor
1008 ionization chamber
1066 'thoron' generator
1003 meter to match electrometer
15 h.t. power supply
1000 leads

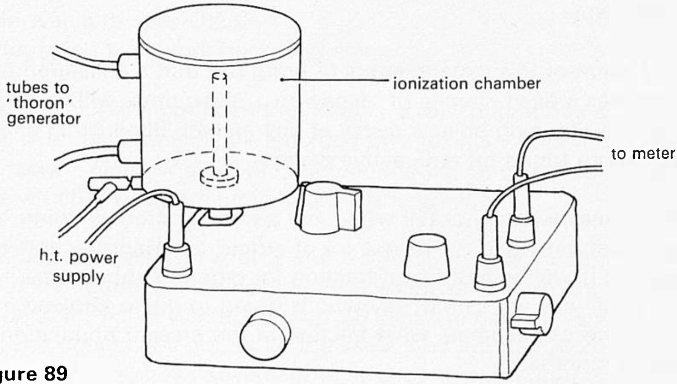



**Figure 89**
The decay of radon.

Radon 220 is one of the products which are formed when thorium 232 decays. The chain of events is:

thorium 232→ radium 228→ actinium 228→ thorium 228→ radium 224→ radon 220→

Radon 220 is a gas while the other materials earlier in the chain are solids. Because radon 220 is a radioactive gas, the chemicals which give rise to radon 220 should be kept in a closed container. A convenient system is to store them in a plastic bottle so that the radon can be puffed out when needed.

Radon 220 is an alpha emitter, and though alpha particles are strongly ionizing they can easily be stopped. One way to measure the activity in a school laboratory is to measure the ionization current, which will be proportional to the rate at which alpha particles are emitted.

If ions are formed in the ionization chamber, the applied p.d. sweeps them to the extension rod and to the walls of the chamber. A current thus flows across the $10^{11}\ \Omega$ resistor and its effect is amplified and recorded on the meter. Apply a p.d. of about 100 V, turn the input switch to R, and then pass radon 220 into the ionization chamber by gently squeezing the thoron bottle until the meter shows a full-scale deflection. If too much gas is allowed into the chamber, the ionization current will be too large and the pointer of the meter will go off the scale. You will then have to wait until it comes back again before taking readings. Record the meter reading every 15 seconds and plot a graph of meter readings against time.

Determine the half-life of radon 220 from your graph. Start at several points and see how long the reading takes to drop by half in each case.

## 5.11 Radioactive decay analogue

### Apparatus

1055 dice *100*
1054 graph paper

The particular point of this experiment is to bring out that a collection of objects, each of which has a fixed chance of 'decay' in a given time, will, as a result of random selection of which objects decay at any instant, diminish in amount in the exponential pattern found for radioactive decay.

In radioactive decay we cannot tell when any particular atom is going to decay. All we can say is that, provided we have a lot of atoms, a certain fraction will decay in, say, one second. It will be a different fraction for different substances.
In much the same way we cannot say who is going to die in England in the next year. However, we *can* estimate what fraction of the present population will die in the next twelve months.

If you throw a die you have one chance in six of throwing, say, a three (provided the die is not loaded). If you can throw the die six times, or throw six dice once, do you think you will get one 6, one 5, one 4, etc.? Suppose you threw the die a lot of times, what fraction of the throws would result in, say, a five? Provided you throw enough times or have enough dice for one throw you can predict the fraction with reasonable certainty. Throwing the dice is then analogous to radioactive decay. If we throw a lot of dice we cannot be sure which ones will turn up a five but we can estimate what fraction of the total number will show a five. If we remove this fraction as if they have 'decayed' and then throw the remainder, and so on, the decay process imitates radioactive decay, to some extent.

Throw the dice and remove and count those that fall with, say, a five upwards. Throw the remaining dice again and remove and count those which 'decay'. Continue this process for about ten throws. Plot a graph of the number of dice decaying (or the number left behind) against the number of the throw. The graph is a curve which shows that the decay rate gets less and less. The points fluctuate and you will need to draw the line which best represents the decay. How could you obtain experimental results which would give a smoother curve? The graph is similar in shape to that obtained for the capacitor discharge experiment in Unit 3 when an exponential discharge was obtained. What test can you apply to see if this dice graph is exponential? Read experiment 5.9, page 117, and then see if you can work out the 'half-life of your dice'. Also see if you can work out the half-life from the fact that about 5/6 of the dice are left after each throw (work out arithmetically what fraction should be left after 1 throw, 2 throws, and so on).

## 5.12 Random variation of count-rate

### Apparatus

| | |
|---|---|
| 130/1 | scaler |
| 130/3 | GM tube holder |
| 130/5 | end window GM tube |
| 16 | radium source, or pure gamma, or pure beta source |
| 196 | source holder |
| 507 | stop watch or stop clock |
| 503–6 | retort stand base, rod, boss, and clamp |

Experiments in which the count of the number of disintegrations of a radioactive material in a fixed time interval are recorded give results which fluctuate. This experiment takes a closer look at the fluctuations which can occur when counting the particles which result from radioactive disintegration.

Arrange the distance between source and GM tube to give a count-rate which is approximately 50 counts per second. For the whole of this experiment keep the source and detector fixed. Record at least 50 separate counts, each for a period of 10 seconds. The counts will not all be the same, and in order more easily to see the way in which they vary, it is convenient to arrange them in groups which cover a range of, say 10 counts. For example, you might tabulate results as in table 5.

| Range | Number of results falling in range |
|---|---|
| 471–480 | 2 |
| 481–490 | 5 |
| 491–500 | 7 |
| 501–510 | 15 |
| and so on | |

**Table 5**

The results should then be shown on a histogram.

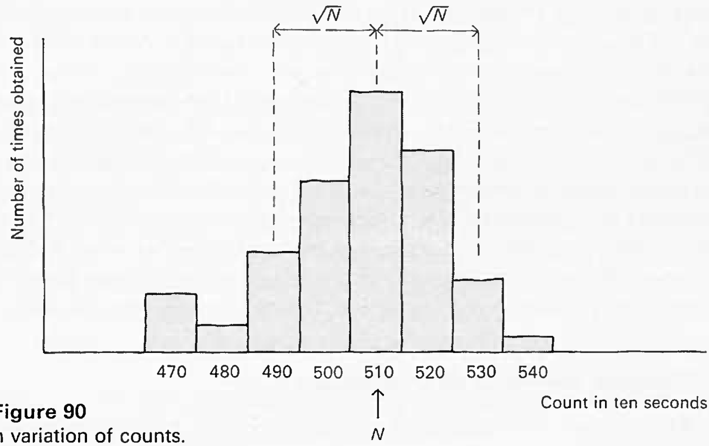



**Figure 90**
The random variation of counts.

Is there a 'true' value for the number of counts which occur in ten seconds? Could the spread of results which you have be the result of variations in the time?

A useful quantity which is used to describe the scatter of results is the standard deviation. In the case of radioactivity, this is approximately equal to the square root of the average count. Thus, if a count of 100 was recorded the standard deviation would be $\sqrt{100}$ or 10, and the result expressed as $100 \pm 10$. What is, roughly, the standard deviation for the counts you recorded? What fraction of your results lies within plus and minus one standard deviation on either side of your mean result? What fraction lies within plus and minus two standard deviations? If you only had one result how good a clue to its reliability would be the standard deviation?

Suppose, for example, that a count of 100 in 1 minute is recorded, on one occasion, and 10 000 in 100 minutes on another occasion. Both give the same count-rate. Is one result more reliable than the other?

You may find it helpful to look at the uses made of similar ideas by a biologist, in Eggleston, *Thinking quantitatively I: Descriptions and models* and *Thinking quantitatively II: Statistics and experimental design*.

## Transformers

### 7.11 Investigations of transformer action

The notes and diagrams which follow are not intended as instructions, but as preliminary suggestions of things you might try. The job of deciding what experiment to do, and how to do it, is as much a part of the art of experimental physics, as is skill in actually doing it.

A transformer is quite a simple object. It has two coils, both wrapped around an iron core. An alternating current in one coil (the primary) produces an alternating flux in the iron, and some, perhaps nearly all, of this flux links the second coil (the secondary). An alternating induced voltage appears across the secondary, and alternating current can be taken from it.

In these investigations, you can use ready-made coils, each of which can be used with either 120 or 240 turns in circuit. You can also wind coils of your own from plastic-covered wire, which is convenient for coils with up to, say, 50 turns.

For the iron core, you can either use pairs of laminated iron C-cores which fit together to make a complete ring, or you can use a steel rod, such as a mild steel retort stand rod (rods made of aluminium or of stainless steel are not suitable).

You can compare alternating voltages with an oscilloscope, and measure alternating currents with a.c. ammeters. Rheostats or lamps can be used as loads connected to the transformer.

Very many investigations are possible and some are indicated in outline in the illustrations which follow (figures 91 to 99). You can investigate the effect on the current in one coil of various arrangements of the core, or of current drawn from the other coil. You can see what are the effects of altering the numbers of turns in coils on the voltages across them, the currents in them, and the flux in the core. You can see how the flux in the core, measured by the voltage across a small coil wrapped around it, varies with the current in the coil producing the flux, and with the number of turns in that coil. You can investigate how the amount of flux in the core varies with the length and thickness of the core, or look at the effect of having the core in a closed ring or in some arrangement which is not closed in a ring. When you alter the core arrangement, the current in the primary may change, and you may need to provide a way of adjusting it to a constant magnitude, so as to observe only the effect of changes to the iron parts of the transformer.

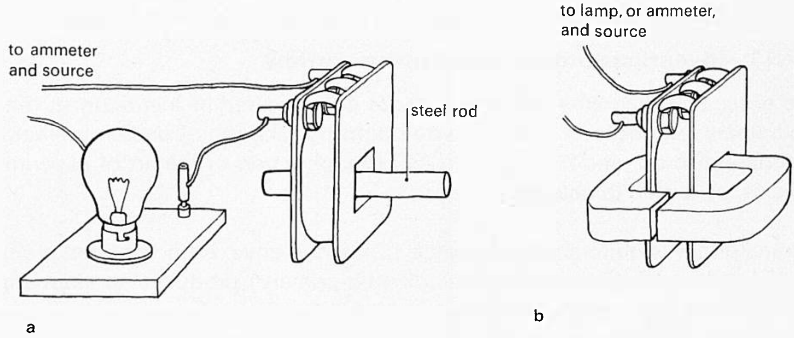



**Figure 91**
The effects, on the current in a coil, of inserting an iron core.

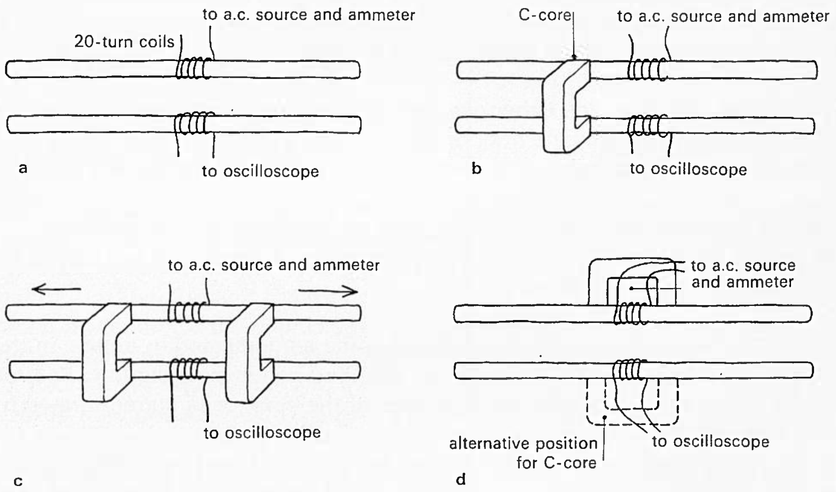



**Figure 92**
Simple transformer systems with variations to the iron core.
**a** Two steel rods not joined.
**b** A C-core as a bridge between the rods.
**c** Two C-core bridges – effect of length of iron in the iron ring linking the coils.
**d** Other places for a C-core bridge.

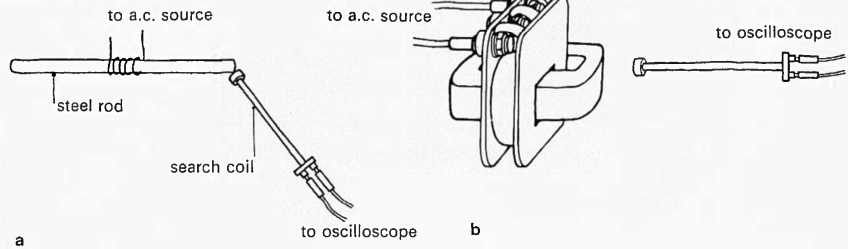



**Figure 93**
Magnetic flux near an iron core.

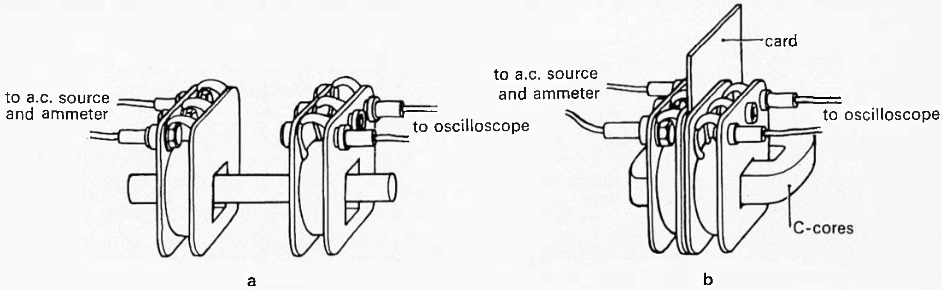



**Figure 94**
Effectiveness of a transformer with modifications to the core.
**a** Spacing of coils along a rod.
**b** Variable thickness of non-magnetic gap (cards) in a C-core.

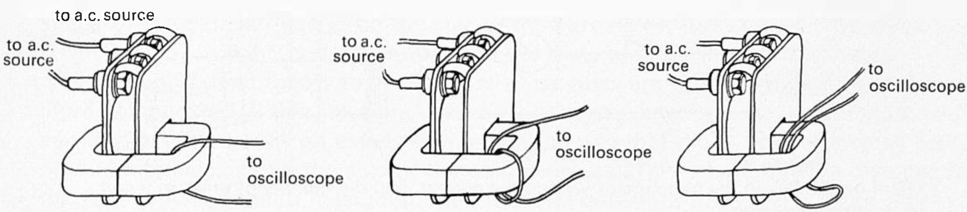



**Figure 95**
Effects of number and placing of secondary turns through a closed C-core. Only a few of the possibilities are shown.

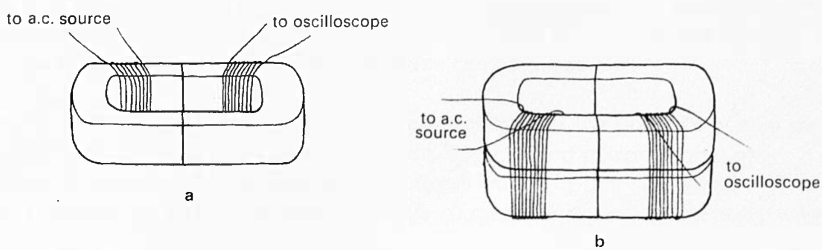



**Figure 96**
The effect on the voltage induced in the secondary coil (and so on the flux in the cores), of using two cores side by side for a fixed primary current. (Twenty-turn coils will do.)

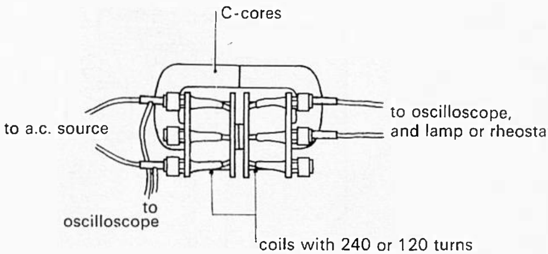



**Figure 97**
The effect, on the voltages across primary and secondary coils, of varying ratios of primary and secondary turns. A load can be connected to the secondary coil, to see if that has any effect on the voltages.

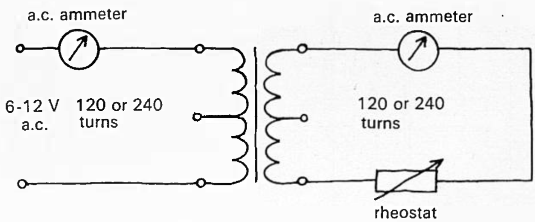



**Figure 98**
Sizes of primary and secondary currents, when current is drawn from the secondary coil, using different ratios of turns.

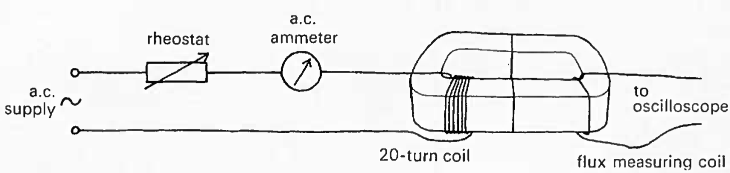



**Figure 99**
Effect on the flux in the iron core of varying the current, and the number of turns, in a coil magnetizing the core.

**Apparatus** for experiment 7.11

You may require:

| | | |
|---|---|---|
| 27 | transformer | |
| 84 | wire strippers | |
| 92X | reel of 26 s.w.g. PVC covered copper wire | |
| 1058 | coil with 120+120 turns | *2* |
| 92G | double C-core and clip | *2* |
| 1057 | a.c. ammeter | *2* |
| 158 | class oscilloscope | |
| 177 | lamp (12 V, 6 W) | *2* |
| 74 | lamp holder (s.b.c.) on base | *2* |
| 1039/1 | search coil | |
| 504 | retort stand rod (steel) | *2* |
| 541/1 | rheostat (10–15 Ω) | |
| 1053 | card | |
| 1000 | leads | |
| | *and possibly* | |
| 1075 | electronics kit (with double-beam switch) | |
| 1033 | cell holder with four U2 cells (for electronics kit) | |

## Quantitative magnetic field investigations

### 7.13 Fields around electric currents

Electric currents in wires produce $B$-fields around them. The strength, direction, and shape of the $B$-field depend on the size of the current, on the shape of the wires (bent, coiled, straight, and so on), and on the distance from the wires. These variations of $B$-field follow rules: some of these rules are simple, while others are more complicated. Some rules are valid only as approximations. As an example, you can find in most books on electromagnetism the rule that the $B$-field of a small coil of wire, at places along the axis of the coil, varies as $1/d^3$, where $d$ is the distance to the coil, provided that $d$ is large enough. Several questions arise. How could one measure such a field? How could one test whether the rule works in some particular situation? How large must $d$ be for the rule to work? In what way does the rule go wrong if $d$ is not large? Given a set of data, what would be the best way to use it to test the rule? How accurate must the data be to make an effective test? Are seeming variations from the rule (which says itself that it does not always apply) genuine or are they the effect of errors of measurement?

Questions of this kind sometimes occupy physicists, and the purpose of this series of investigations is to give you experience in forming and answering such questions. A number of investigations and experiments in this Advanced Physics course (though not all), have been relatively rough, letting you see broadly what happens. The present investigations are more *quantitative* ones: their object is to collect data which are precise enough to test a definite proposed rule, and perhaps to discover its limitations.

You have to choose for yourself what situation to experiment with, what rule to test, and how to use the data to test it. You have to decide what data to collect, and how accurate those data need to be. You have to decide how much data to collect, and the range over which they should vary.

The illustrations (figures 100 to 105) which follow offer suggestions of situations to explore. To save time for thinking about how to do an experiment, they also give some practical details to help you to set up arrangements which will actually work.

The $B$-fields can be measured with one of two sets of instruments: a Hall probe and galvanometer, or a search coil and oscilloscope. The first is used with steady fields, produced by direct currents. The second is used with alternating fields, produced by alternating currents. The maximum voltage induced in the search coil is proportional to the maximum rate of change of $B$ at the search coil, which, *at a fixed frequency*, is proportional to the maximum value of the alternating $B$-field at that place. So, indirectly, the search coil indicates the strength of the $B$-field. The advantage is that it can be made very sensitive by using a high frequency, so that a small $B$-field still has a large rate of change. Notes on these instruments are given in Part One (page 32).

The conductors can be of several kinds. You can use solenoids; a Slinky coil as a solenoid; small, ready wound 120+120-turn coils; coils of any shape you please wound around pegs on a board (the magnetic field board); or wires stretched across the bench.

Direct current can be supplied from a 12 volt battery, controlled by a rheostat and measured by an ammeter. Alternating current up to 5 A or so at 50 Hz can come from a transformer, again using a rheostat and an a.c. ammeter. Higher frequencies can be obtained from the low impedance output of a signal generator, using the gain control on the generator to vary the current. The current is not large, and can be measured with a multimeter, though the meter may not be reliable at high frequencies. When using alternating current, especially at high frequencies, it is worth remembering that the current may not stay the same if the circuit is altered (say, by winding turns more closely) because of the changed self-inductance of the circuit, so that it is wise always to keep a check on the current.

*Some rules to test* (*figure 100*)

**1** The field is uniform across the width of the solenoid, and zero outside.
**2** The field is uniform along a great part of the length of the solenoid.
**3** If the same number of turns is stretched out to a greater length, at fixed current the product of *field* × *length* is constant.
**4** The field at the end of the solenoid is half that at the centre.
**5** If the spacing of the turns and the current are fixed, the field at the centre does not depend on the length of the solenoid, if it is reasonably long.

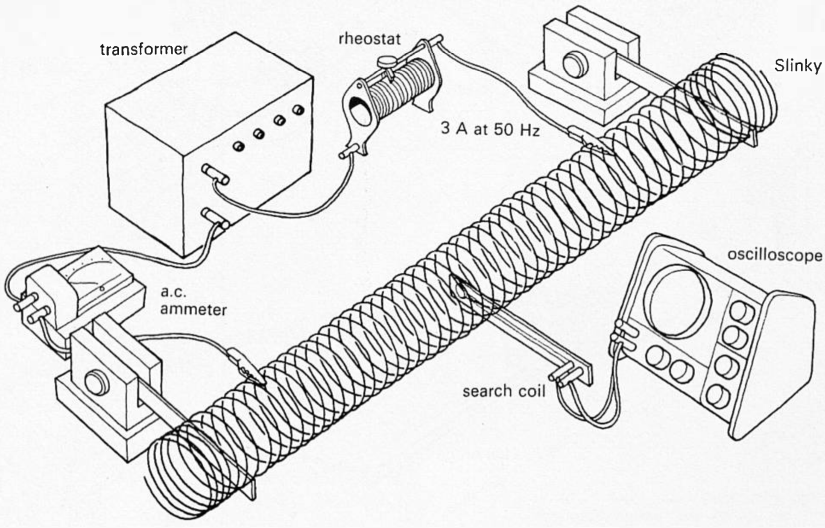



**Figure 100**
Slinky coil used as a solenoid. The Hall probe can be used to investigate the field, if the current is a few amperes d.c. from a 12 volt battery.

*Some rules to test* (*figure 101*)

See **1**, **2**, and **4**, which go with figure 100, and the following:

**1** If the turn-spacings are the same (and the current) the field at the middle of a long solenoid does not depend on its cross-section.
**2** The fields of solenoids within one another add algebraically (this rule needs to be applied cautiously at high frequencies because of voltages induced in one coil by changing flux from the other).
**3** The field at the centre is proportional to *current* × *density of turns* if the solenoid is long.

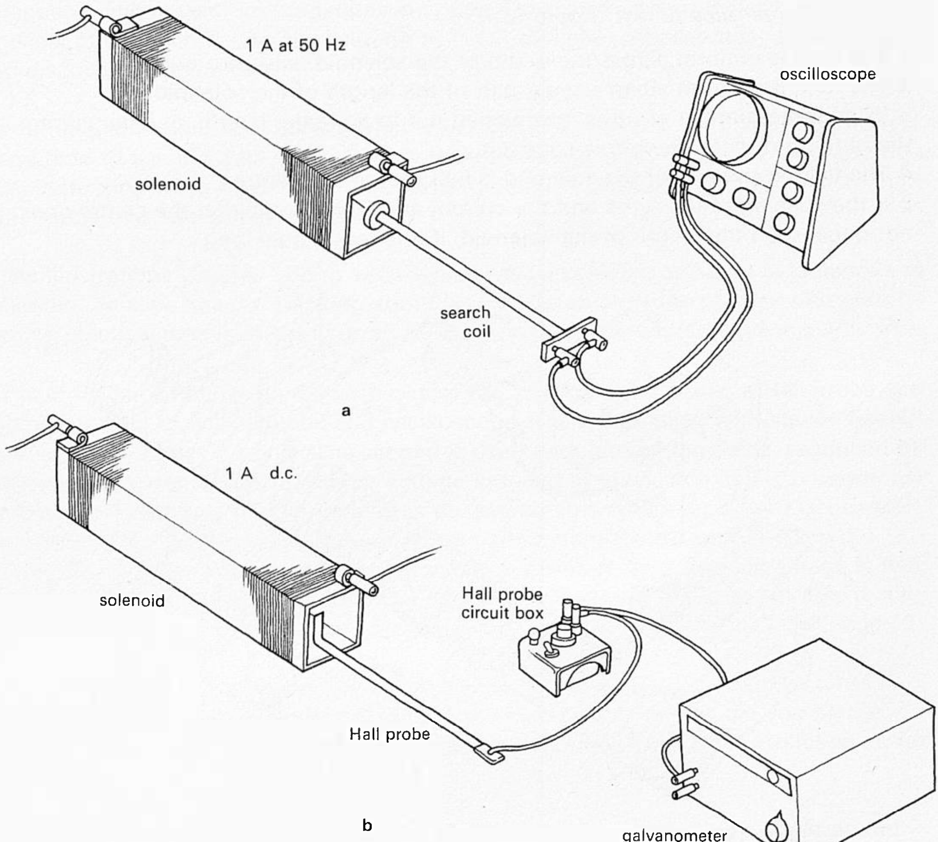



**Figure 101**
Solenoids used with either a search coil and a.c. or with a Hall probe and d.c.

*Some rules to test (figure 102)*

**1** Close to the wire, the *B*-field is perpendicular to the wire.
**2** The field varies as $1/r$, where $r$ is the perpendicular distance to the wire, as long as the wire is long and $r$ is not too large.
**3** There is no field component directed towards, or parallel to, the length of the wire.

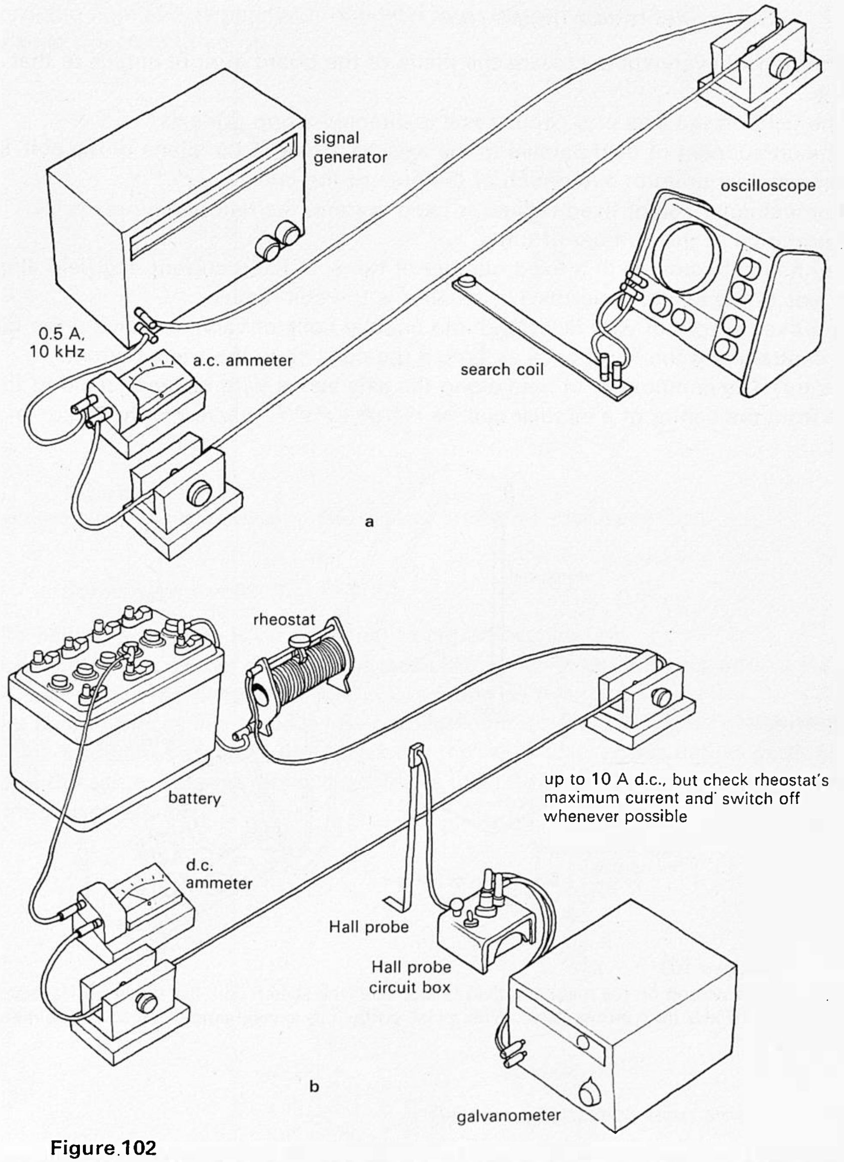



**Figure 102**
Field of a long straight wire, using either a.c. and a search coil or d.c. and a Hall probe. Use a wire which is at least one metre in length.

*Some rules to test (figure 103)*

**1** The $B$-field everywhere crosses the plane of the board at right angles to that plane.
**2** The field on the axis of a circular coil is directed along the axis.
**3** The component of field parallel to the axis, at places in the plane of the coil, is approximately uniform over much of the area of the coil.
**4** For a circular coil of fixed radius, at fixed current, the field at any point is proportional to the number of turns.
**5** For a circular coil, with a fixed number of turns, at fixed current, the field along the axis at the centre varies as $1/r$, where $r$ is the coil radius.
**6** If a fixed length of wire is wound into circular coils of varying radius $r$, the field at the centre along the axis varies as $1/r^2$, if the coils carry the same current.
**7** (*Hard*) The component of field along the axis varies with distance $d$ along the axis from the centre of a circular coil, as $r^2/(d^2+r^2)^{3/2}$, where $r$ is the radius of the coil.

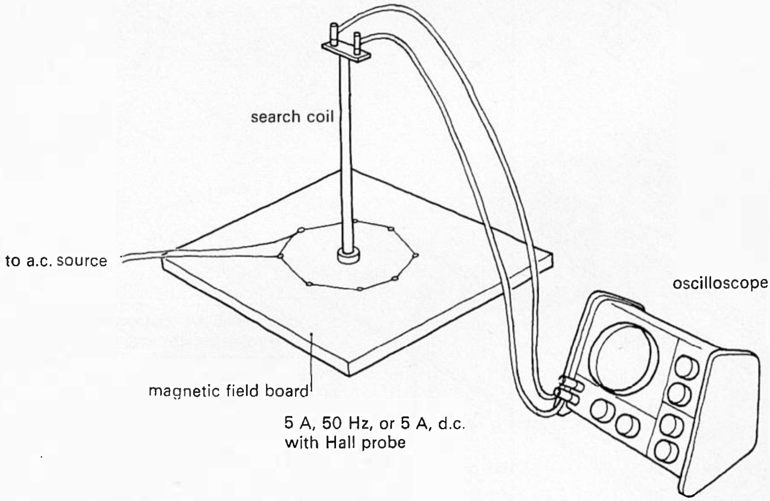



**Figure 103**
Fields of coils wound on the magnetic field board. With the search coil, use either 50 Hz, several amperes, or 10 kHz from an oscillator. With a Hall probe, use several amperes d.c., with a rheostat and battery.

*Some rules to test (figure 104)*

**1** The field of a square coil is rather similar to that of a circular coil (see figure 104 *a*).
**2** Parallel wires carrying equal and opposite currents give zero field (see *b*).
**3** The field of a zig-zag wire is the same as the field of a straight wire carrying the same current in the same general direction; that is, bits of wire carrying current can be resolved like vectors as far as their field producing capacity is concerned (see *c*).

**4** In *d*, the field at X is parallel to the field at Y, but is half as great. (Also, the two fields are opposite in sense.)

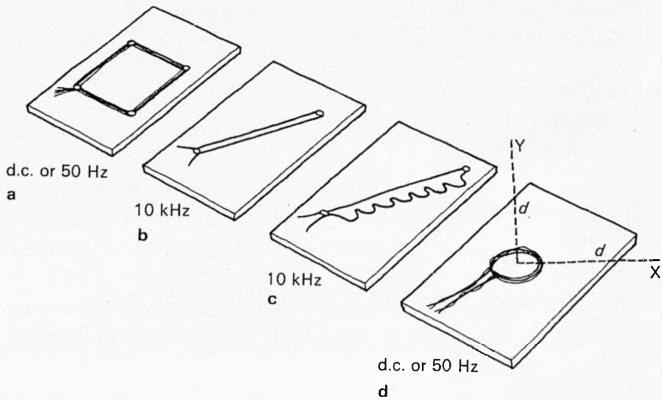



**Figure 104**
Some other arrangements of wires on the magnetic field board. (See figure 103.)

*Some rules to test* (*figure 105*)

**1** The field at *any* place is proportional to *current* × *turns*.
**2** The field on the axis of the coil at places like X lies along the axis, and varies as $1/d^3$, where $d$ is the distance to the coil, as long as $d$ is large.
**3** The field at places like Y, on a line perpendicular to the axis of the coil through the coil, also varies as $1/d^3$, lies parallel to the coil's axis, and is half as great as the field at the same distance along the axis, as in **2**. Again, $d$ must be sufficiently large for the rule to be valid.

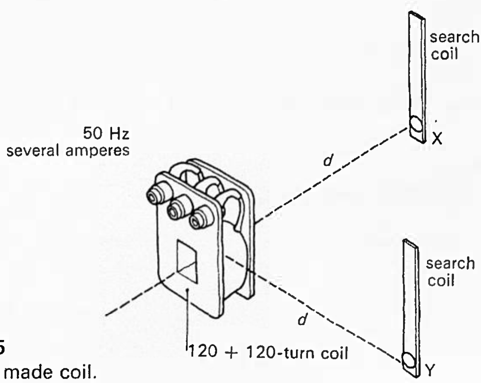



**Figure 105**
Field of a small ready made coil.

**Apparatus** for experiment 7.13

*Field measuring devices: either*

1038 Hall probe and circuit box
1001 galvanometer (internal light-beam)
*or*
1039/1 axial search coil
1039/2 lateral search coil
158 class oscilloscope

*Conductors: one set from the following*

101 large Slinky
30 slotted bases *2*
1053 wooden strips (e.g. rulers) to support Slinky *2*
52K crocodile clips *2*
*or*
1037 set of solenoids
*or*
1042 magnetic field board
92X reel of 26 s.w.g. PVC covered copper wire
*or*
1058 coil with 120+120 turns
*or*
1030 high inductance coil

*Sources of current: one set from the following*

176 12 volt battery
541/1 rheostat (10–15 Ω)
1003/5 ammeter (10 A)
*or*
27 transformer
541/1 rheostat (10–15 Ω)
1057 a.c. ammeter (or 1005 multi-range meter)
*or*
1009 signal generator
1057 a.c. ammeter (or 1005 multi-range meter)

*All require:*

1000 leads

# Book references


Arons, A. B. (1965) *Development of concepts of physics.* Addison-Wesley.

Bennet, G. A. G. (1968) *Electricity and modern physics.* (MKS version.) Edward Arnold.

Born, M. (1951) *The restless Universe.* Dover.

Caro, D. E., McDonell, J. A., and Spicer, B. M. (1962) *Modern physics.* Edward Arnold.

*Classical scientific papers – physics* (1964), Mills & Boon.

Eggleston, J. F. (1971) Nuffield Advanced Biological Science Topic Review *Thinking quantitatively I: Descriptions and models.* Penguin.

Eggleston, J. F. (1971) Nuffield Advanced Biological Science Topic Review *Thinking quantitatively II: Statistics and experimental design.* Penguin.

Gentner, W., Maier-Leibnitz, H., and Bothe, W. (1954) *An atlas of typical expansion chamber photographs.* School edition. Pergamon.

Lewis, J. L., and Wenham, E. J. (1970) Longman Physics Topics *Radioactivity.* Longman.

Millikan, R. A. (1963) Phoenix Science Series *The electron.* University of Chicago Press.

PSSC (1965) *Physics.* 2nd edition. Heath.

Rogers, E. M. (1960) *Physics for the inquiring mind.* Oxford University Press.

# Index

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This book is a collection of notes and information which students may use in the laboratory. It is divided into three Parts. The first, 'Tools', gives information about some of the more important pieces of apparatus which are used in the course and how to operate them; this should enable students to use the instruments by themselves. The second Part, 'Long experiments', gives details, with apparatus lists, of the techniques necessary for doing some of the more difficult experiments in the course, again, so that students may be able to do the work by themselves. The third Part is 'Notes on some other experiments'; these notes, also including apparatus lists, are intended to enable students to make a start on the experiments, but then to develop further work as they wish. The book ends with reading references.

Published by Penguin Education

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