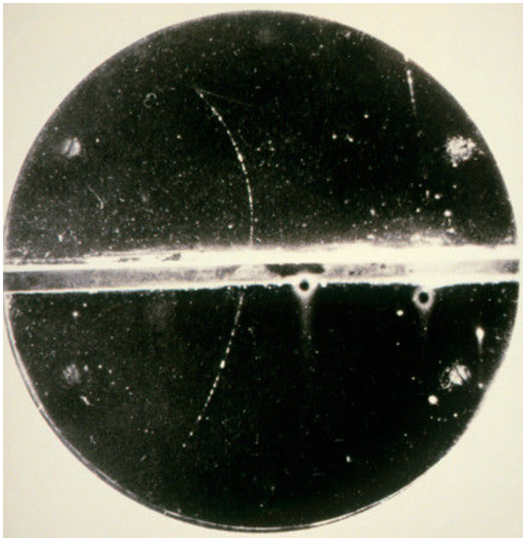
Bishop Heber High School

Practical Physics I

Lower Sixth

Autumn term 2011



The discovery photograph of the positron, the positive version of the electron and the first antimatter particle to be discovered. The cloud chamber photo was taken in 1932 by US physicist Carl Anderson. It shows the track of a positive particle that enters the chamber from below. The particle is known to be positive because of the way it bends in the chamber's magnetic field; it is known to be moving up the picture because it loses energy and so curves more in the magnetic field after traversing the 6 mm thick lead plate in the middle. The track is too faint to be caused by a proton–it is exactly like an electron's track–and so it had to be the predicted positron.

CARL ANDERSON / SCIENCE PHOTO LIBRARY

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Errors

In practical work in AS and A2 physics, you should be prepared to

- identify the source of uncertainties in an experiment.
- calculate the fractional or percentage error from the size of the measurement and the absolute error on it.
- combine the uncertainties of different measurements when you evaluate something which depends on a number of quantities. It is very unlikely that you will have to do a full calculation of the total error, but you may be asked, for example, to identify which individual measurement contributes the biggest uncertainty.

Sources of uncertainty and absolute errors

Any measurement has a statistical uncertainty associated with it. It is generally a combination of both the reading error on a measuring instrument and the uncertainty to do with the way you are performing the measurement. For example, the reading error on a 1 m ruler is at best 0.5 mm. If you are using it to measure the depression of another ruler, you might reasonably assign a total uncertainty of 3 mm, to account for the fact that you may not have the measuring ruler absolutely vertical. An error of this kind is an absolute error, and has the dimension of the quantity you are measuring.

Systematic errors may also be built in to the experiment, for example the ruler above may have an actual length of say 99 cm when you have assumed to be 1 m, or an ammeter may show a non-zero reading when disconnected from an electric circuit. Such uncertainties may not alter the reliability of your readings, but they may well affect the accuracy of a calculated quantity.

Fractional or percentage errors

These are dimensionless and are calculated using the formula

$$\text{fractional error} = \frac{\text{absolute error}}{\text{size of measurement}}.$$

Combination of errors

- If you make two measurements of the same type x and y, for example the length and breadth of a table, then absolute error on the sum $x + y$ or difference $x - y$ of x and y is equal to the sum of absolute errors on x and y.
- If you make measurements of any two quantities x and y, then fractional error on the product xy or quotient x/y is equal to the sum of fractional errors on x and y.
- If a power law holds

$$\text{fractional error on } x^k = k \times \text{fractional error on } x.$$

Determining relationships by plotting graphs

When a certain relationship exists between two variables y and x, its form can sometimes be determined by plotting a suitable graph. You should be familiar with the following cases.

Linear

If $y = mx + c$ a graph of y against x should be a straight line with gradient m and y-intercept c.
NB y is only proportional to x if $c = 0$.

Exponential

If $y = Ae^{-mx}$, where A is a constant, then taking natural logs of both sides gives

$$\ln y = \ln A + \ln(e^{-mx}) = \ln A - mx.$$

Hence a graph of $\ln y$ against x should be a straight line of gradient $-m$ and intercept $\ln A$. Examples of such relationships are found in radioactive decay and in electric circuits containing capacitors.

Polynomial

If $y = Ax^m$, then taking natural logs of both sides gives

$$\ln y = \ln A + \ln(x^m) = \ln A + m \ln x.$$

Hence a graph of $\ln y$ against $\ln x$ should be a straight line of gradient m and intercept $\ln A$. Examples include the variation of the period of a simple pendulum with length ($m = 0.5$) and the energy stored in a stretched spring with extension ($m = 2$).

Errors obtained from graphs

When it is believed that a linear relationship exists between two quantities plotted on a graph, a straight line of best fit should be drawn through the points, which passes as close to all the points as possible.

You can draw error bars for each point so that the length of the line on either side of the point represents the absolute error you have assigned to the individual measurements. The line of best fit should pass through about two-thirds of the error bars, if you have assessed the errors realistically (and if a linear relationship holds).

It is common to extract the gradient or the intercept since they often correspond to something interesting. You can evaluate the error on them by drawing another fit line, making it as steep or shallow as possible, so that it still passes through the error bars. The difference between the values so obtained for the gradient and intercept, and those of the best-fit line correspond to the absolute errors.

Index

Writing up A-level practicals

During your practical lessons over the next year or two we require you to perform the practical, produce some results, and do some processing of the data. Possibly even evaluating a quantity which appears to have no relevance! You will then usually answer some questions relating to possible errors.

The aims of the experiments are to supplement the theory taught in lessons, to give you some insight into experimental physics and also to help you to develop skills which will help you in the practical examination. We have tried to make this workbook fairly complete, and you will not usually need to make copious notes or draw diagrams. You will simply answer the questions asked by filling in the blanks in this booklet. Since the demands on you in this respect are relatively low, we do demand high standards from you. Please take care and learn from your mistakes–do not simply glance at the mark you have gained from the previous practical (instead, see where you dropped marks, and ensure you do not repeat these errors).

The apparatus in the actual practical examination will be set up for you ready to use. In the lessons, we do not have the time to do this, and you will have to set up the apparatus yourself (and put it away properly for the next person to use!) We need you to fill in the index above each week with the date on which you did a particular practical and after marking we shall insert a mark for it.

You will be marked on the following points, if applicable:

- Results table (probably in columns) with headings including appropriate unit
- All figures to an appropriate accuracy, probably 3 s.f.
- Graphs with appropriate scales (no scales of 3, cannot be doubled and still fit on axis). Minimum acceptable size: $8\,\text{cm} \times 8\,\text{cm}$
- Accuracy of point plotting from results table, appropriate line of best fit
- LARGE gradient triangle shown on graph, length of Δy and Δx marked on with units
- Gradient calculation must be shown ($\Delta y/\Delta x$) including units throughout, NB some may be negative
- Estimated of possible errors in quantities, BE REALISTIC
- Your answers on how to reduce errors, how you ensured accuracy in your experiment

We want you to enjoy practical work but also ensure you are continually improving since it is a very important skill and furthermore a rich source of very straightforward marks!

1 Specific charge of the electron

In this experiment, you will determine the ratio of an electron's mass to its charge. This is known as the 'specific charge' of the electron ('specific' is a special word in physics, meaning 'per unit mass', e.g. specific heat capacity or occasionally 'per unit something else'). The specific charge is therefore the charge divided by the mass, and is measured in $\mathrm{C\,kg^{-1}}$. Historically, it was hard to measure the charge of the electron (Millikan, 1909) and so the specific charge was measured first (J.J. Thomson, 1897).

1.1 Assembly

Caution: High voltage is used in this experiment. Complete all assembly steps before plugging in or turning on the power supply.

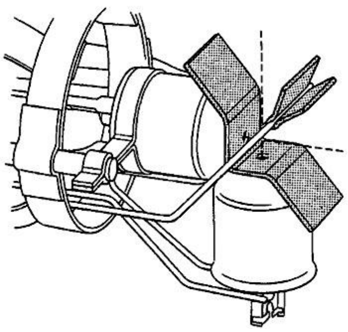
To mount the tube in the stand, begin by squeezing the jaws. With slight pressure, the jaws will open enough to allow the insertion of the tube. When the tube is securely in place, release the pressure on the jaws and slide the jaw clamps forward, locking the tube in position.

The Helmholtz coils must also be assembled into the stand. They can easily be mounted in the holes in the base using the plastic sleeve which slides along the rod. There are two sockets on each coil, which must face outwards to allow connexions to be made. Connect a low voltage power supply[1] to each of the sockets marked A, with the Z sockets interconnected.

1.2 Producing cathode rays

The electrons you will use will be produced 'boiling' them off a coil of heated metal wire, similar to a lightbulb filament. This is known as thermionic emission. They are then dragged away from the metal surface by a positive anode and accelerated through a large potential difference. The anode has a small hole in it, and some of the electrons pass through this and continue as a beam of fast-moving electrons known as a cathode ray.

The double beam tube used in this experiment has two electron beams, one which fires out across the tube and the other one, at right angles to the first beam, up towards the top of the tube. The beam is selected via the connexions close to the cathode. The first task is to connect the low voltage (6.3 V a.c.) to the correct terminals on the back of the tube, so that the filament in the upward pointing electron gun glows.

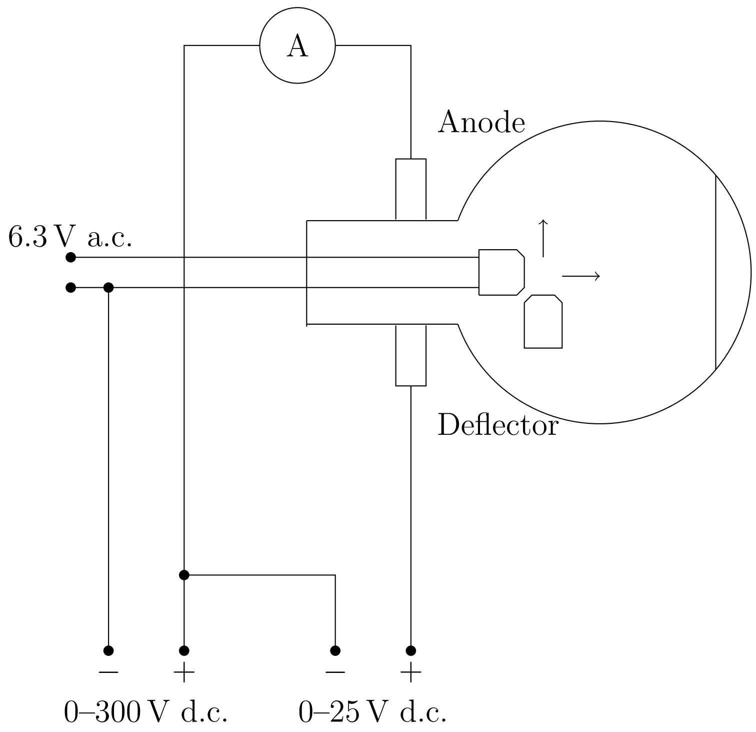


Just outside each gun muzzle there is a pair of plates for deflecting the beam by an electric field. One plate of each pair is attached directly to the gun muzzle which supports it. The other plate of each pair is connected inside the tube to the second side terminal on the tube. If the beam fails to make a clear spot then try a small potential difference to the deflecting plates.

[1]The old power supplies work much better, as they supply a much better smoothed and fully rectified d.c.

In general, optimal operating voltages are as follows:
Filament voltage: 6.3 V a.c., 30 mA
Anode voltage: 0 to 300 V d.c., 30 mA
Deflector voltage: 0 to 25 V d.c.

Now make the other connexions to the tube, using the circuit diagram below as a guide.



Once all the connexions have been made, make sure the anode voltage is zero (the control knob should be turned anticlockwise as far as possible), before turning on the power supply to the metal filament.

Allow at least one minute for the filament to heat up, then gradually increase the voltage to the anode. The length of the electron beam depends on this voltage; about 100 V is required to make the beam reach across the bulb. The path of the electron beams is green, because the electrons are travelling through a residual amount of helium gas.

The anode current should always be monitored–keep the current as low as possible, whilst retaining good intensity and path length. Proper electrical connexion should at this stage be tested by deflecting the beam with a magnet. The negative lead should be connected to the common filament and cathode socket. If these connexions are incorrect, the a.c. filament current will make the beam 'fan out' slightly.

If the beam seems too diffuse or fuzzy, try applying a slight voltage between the deflector plates. This has the effect of producing a converging electric field which focuses the electrons and produces a tighter beam. While a deflector voltage of 25 V is suggested, higher voltages may be applied.

1.3 Effect of a magnetic field

Charged particles experience a force in a magnetic field which is proportional to their charge Q, their speed v and the strength of the field B:

$$F = QvB.$$

For an electron, $Q = e$.

This force is always perpendicular to the motion, and so, in a uniform field, charged particles will travel in circular (or spiral) paths. Helmholtz coils are two coils of radius R which are arranged a distance R apart. This provides a fairly uniform field in between the coils. Try turning on the Helmholtz coils, and adjusting the coils' current until the electrons travel in a circle. You might need to fiddle with the coil / beam tube alignment to make sure the electrons' path is a circle rather than a spiral.

1.4 Measurements

Set the Helmholtz coil current to a value so that it will not get too hot, and a good range of beam path radii can be generated by changing the accelerating voltage. Record this value, and give an estimate of the error

____

You are going to change the accelerating voltage and measure the beam radius.

Accelerating voltage / V	Beam radius /	(Beam radius)^2 /

Record the number of turns n on the Helmholtz coils:

____

What do you think the error would be?

____

Measure the radius R of the Helmholtz coils, and give an estimate of your error:

____

1. How did you measure the beam radius?

2. What is the accuracy of your method?

3. Plot a graph of the accelerating voltage V on the y-axis and the square of the beam radius r^2 on the x-axis.

4. Work out the gradient on your graph, and record it here, with a unit:

4. ____________

According to theory, the gradient G of your graph is related to the specific charge e/m of the electron by

$$\frac{e}{m} = \left(\frac{5}{4}\right)^3 \frac{R^2}{\mu_0^2 n^2 I^2} G,$$

where I is the current in the Helmholtz coils, R is the radius of the coils, n is the number of turns, and μ_0 is the permeability of free space, $4\pi 10^{-7}\,\mathrm{H\,m^{-1}}$.

5. Work out the value your gradient gives for the electron's specific charge.

6. What do you think the largest source of error in this experiment is and why?

2 Absorption of γ radiation

High-energy photons (γ-rays) are emitted in radioactive decays of excited nuclei. Such nuclei can form as a result of beta decay, for example:

$$^{60}_{27}\mathrm{Co} \longrightarrow \mathrm{electron} + \mathrm{antineutrino} + {^{60}_{28}\mathrm{Ni}^{**}}(\text{excited state})$$

and

$$^{60}_{28}\mathrm{Ni}^{**} \longrightarrow {^{60}_{28}\mathrm{Ni}^{*}} + \gamma\text{-ray photon } (1.17\,\mathrm{MeV})$$

$$^{60}_{28}\mathrm{Ni}^{*} \longrightarrow {^{60}_{28}\mathrm{Ni}}(\text{ground state}) + \gamma\text{-ray photon } (1.33\,\mathrm{MeV}).$$

The half life of the first decay is 5.27 year, and the last two are almost instantaneous.

From a simple theory for the interaction of a beam of photons with matter, the number of photons per second (the intensity) traversing a thickness d of the material is given by

$$I = I_0 e^{-\mu d},$$

where I_0 is the incident photon intensity.

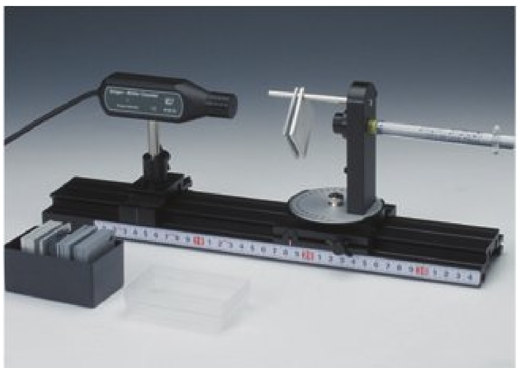
Unless otherwise indicated, you and your partner should take separate sets of measurements, and do the graphical work and calculations independently. You should however work together in making the observations and compare your results. This will allow you to check for mistakes in your work.

2.1 Setting up

First, connect the Geiger-Müller (G-M) tube to the Philip Harris ratemeter, switch it on and set it up so that the microphone clicks for each decay event.

Unfortunately, the school currently has no scalar, which would allow decay events to be counted. However, it is possible to connect the terminals marked 'chart output' to a computer via its microphone input. The waveform can then be recorded, displayed and analysed using the open source software Audacity `http://audacity.sourceforge.net/` allowing the number of decay events to be counted (though this is somewhat laborious at present).

Now set up the source holder (**without** the radioactive source at this stage) on the measurement track, and put the G-M tube in position about 10 cm away from the source holder. Connect the ratemeter to a computer as described, and open Audacity.



2.2 Background count

Firstly, you need to measure the background radiation in the laboratory (due to cosmic rays, rocks). Make sure the experiment is set up as it will be carried out (minus the source). The apparatus should be positioned so that the source will point towards a wall, away from people.

With the ratemeter's microphone on, record the 'chart output' signal from the ratemeter for a good 3 minutes (you can select 3 minutes of audio later). You might find that you need to have the laptop unplugged from the mains (the 50 Hz mains supply introduces a lot of unwanted noise into the signal, which may swamp the detector pulses). I also found that moving the mouse produced noises, so leave it alone whilst measuring.

Once the measurement has finished, you need to count the audio pulses. Select exactly 3 minutes of audio recording, and amplify this (`effects > amplify`, default settings are usually adequate). Record the number of pulses in each minute:

Minute 1	Minute 2	Minute 3	Total

1. What is the number of background counts per second?

1. ____________

2. Look again at your results. How accurately do you know the background rate (to which significant figure are you confident and why)?

____

2.3 Lead absorption

You have a selection of coated lead plates (10×1 mm, 5×2 mm). You should check the thickness of the plates using a screw-gauge micrometer, to see whether it differs significantly from the advertised values. Record you workings and conclusions below.

____

____

____

____

Now ask for the γ source.

CAUTION This experiment involves the use of radioactive materials. There must be absolutely no eating or drinking, applying of make-up. The cup-type source should only be handled by means of the stem, and kept at least 10 cm away from the hand; large forceps are ideal. Do not point the source at anyone, neither look at the active surface (behind the wire mesh). Minimize the time the source is unshielded (i.e. outside of its lead pot and hardwood container).

The source was manufactured by a different company from the measurement track, with the result that the source must at present be held in by blu-tack!

3. Ask for assistance in getting the source into the holder from its box.
4. You now need to record the ratemeter output, and fill in the count rate for various thicknesses of lead in the table.

Thickness/mm	Count rate/s^{-1}	Corrected rate I/s^{-1}	$\ln(I/s^{-1})$
0.0			

5. Put the source away (but leave the lead in position for now if you can, in case you need to check a reading) and work out the corrected readings (measured counts – background) and the final column on your calculator.
6. Plot a graph of $\ln I$ on the y-axis against the thickness of lead on the x-axis.
7. Work out the gradient of your graph. Show all your working on the graph, but copy the result here.

7. ____________

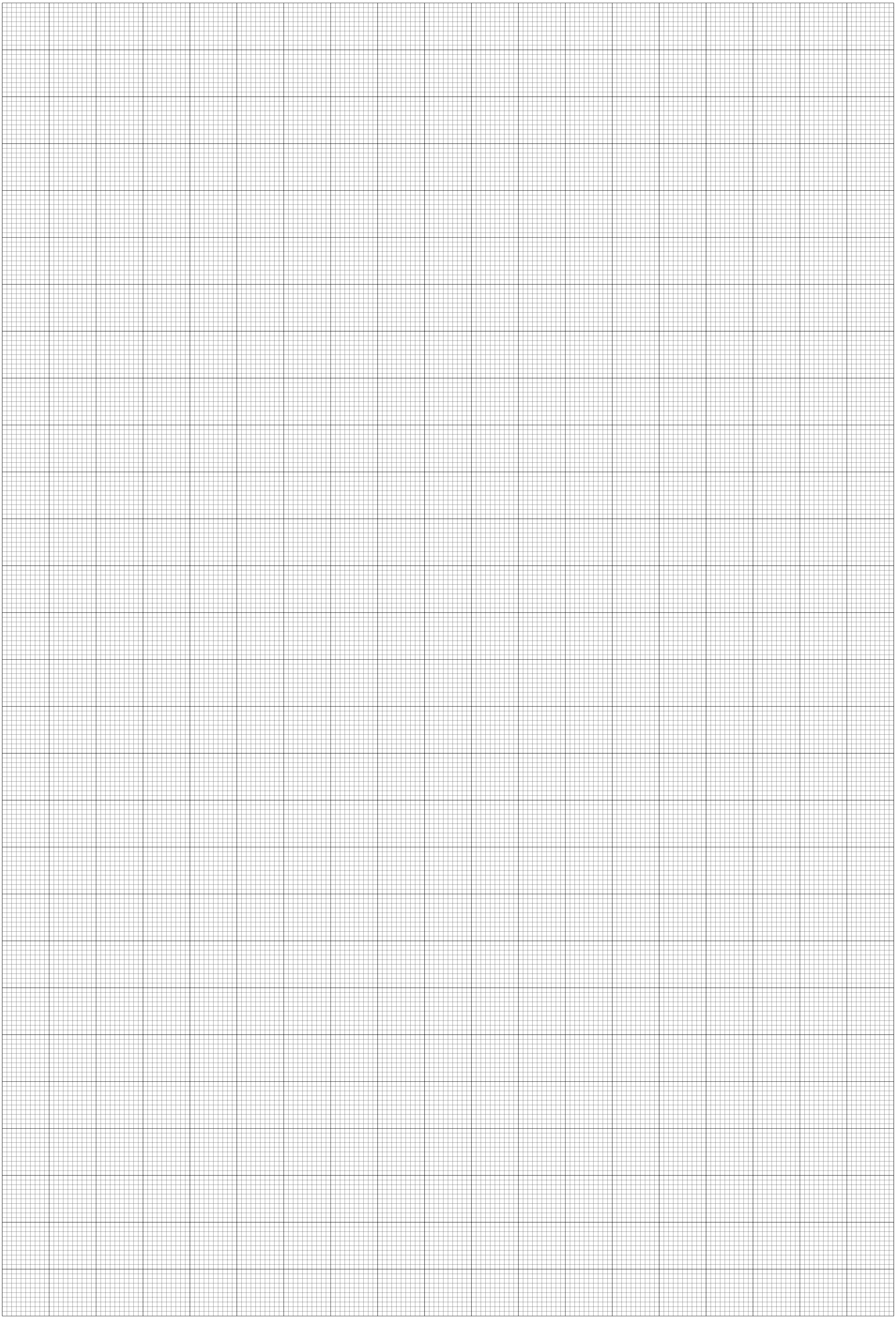
It can be shown that your gradient is a measure of μ, the absoption coefficient of lead. The textbook value of μ for 1.17 MeV–1.33 MeV photons in lead is $\approx 20\,\mathrm{m}^{-1}$.

8. Work out the percentage error between your result and the accepted value.

9. How could you have improved the accuracy of your values for the count rates? Give a reason why your suggestion would improve matters.

10. What do you think the biggest source of error was in this experiment? How could it be reduced?

11. How could the experimental technique have been improved?



3 Determining Planck's constant

In quantum theory, light exists as a stream of photons, each with energy hf, where h is Planck's constant and f is the frequency of the light.

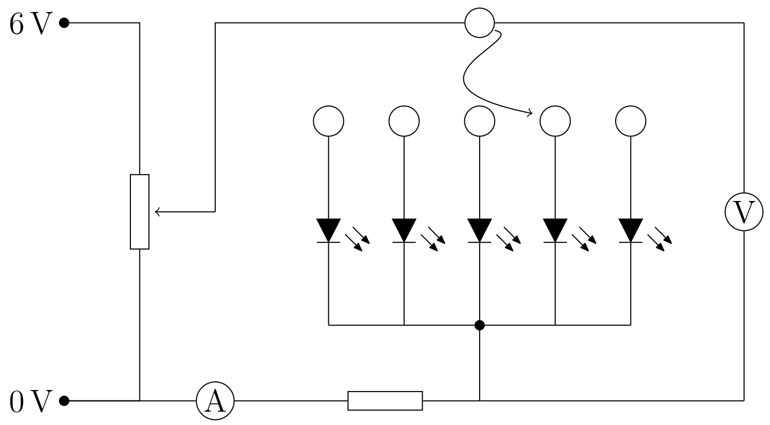
$$E_{\text{photon}} = hf = \frac{hc}{\lambda},$$

where λ is the wavelength of the light.

In this experiment, you will attempt to determine Planck's constant h by using light emitting diodes (LEDs). These are devices, which turn electrical energy into light. Your experiment will measure the electrical energy needed to produce light of different colours of known wavelength in coloured LEDs.

3.1 Apparatus

You need to use a d.c. power supply of 6 V, a voltmeter and a milliammeter. All of the LEDs you will use are in a specially-made box for this experiment, which you need to connect up with the voltage supply and measuring apparatus as shown on the box. The circuit is as follows:



Some data on the LEDs from the manufacturer is below:

Colour	λ/nm	$I_{\max}$/mA
Red	700	25
Orange	627	30
Yellow	590	30
Green	565	25
Blue	430	30

3.2 Measurements

For each LED, you need to take several readings of current and voltage (which will allow you to plot a current-voltage characteristic), by increasing the voltage from zero until the current reaches the manufacturer's recommended maximum current (and no further).

V/V	I/	V/V	I/	V/V	I/

V/V	I/

V/V	I/

V/V	I/

1. Plot the current-voltage characteristics for all of the LEDs on the **same** graph, with voltage on the x-axis and current on the y-axis (take care to label the curves!) On this graph, you need to extrapolate each curve down to the x-axis to find the voltage at which current first starts to flow, and light photons start to be emitted. Use this to fill in the table below.

Colour	λ / nm	$1/\lambda$ / ...	V_{min} / V
Red	700		
Orange	627		
Yellow	590		
Green	565		
Blue	430		

2. Now plot a second graph, this time of the minimum voltage for light emission on the y-axis against the LED wavelength on the x-axis.

3. Work out the gradient, showing your working on the graph.

3. ____________

According to theory, your gradient G is related to Planck's constant by $h = eG/c$, where e is the electronic charge, 1.6×10^{-19} C, and c is the speed of light, $3 \times 10^{8}\,\mathrm{m\,s^{-1}}$.

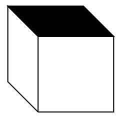
4. What value does your experiment give for h?

4. ____________

5. Comment briefly on this value, and on the quality of your data, on your second graph. What do you think were the biggest sources of error in this experiment?

4 Radioactive decay analogue

In this experiment, you will use an analogue of radioactive decay to learn more about random errors in measurement, and to produce a decay curve for a small number of 'radioactive' particles. The only apparatus you will need are a number of cubes, each with one face identified.



Because radioactive decay is a randomly activated process, the rolling of cubic dice is an appropriate way to study it. Measurement of the rate of radioactive decay is subject (like any other measurement in physics) to random fluctuations, i.e. repeated measurements of the number of nuclei decaying in a given period of time will not all be equal. We aim to study the distribution of these measurements in this experiment.

Unless otherwise indicated, you and your partner should take separate sets of measurements, and do the graphical work and calculations independently. You should however work together in making the observations and compare your results. This will allow you to check for mistakes in your work.

4.1 A set of readings: mean and standard deviation

Take 50 of the small cubes, which represent radioactive nuclei. You need to shake them all up and let them fall onto the desk. All of the cubes which have landed with the black face uppermost are those which have 'decayed' in the time interval of the experiment. Firstly, you need to obtain a set of 10 measurements of the number of nuclei out of 50 which decay in one timestep (start with 50 each time).

Measurement	1	2	3	4	5	6	7	8	9	10
Decays										

1. What is the probability of 1 nuclei decaying in 1 timestep?

   1. ____________

2. How many nuclei do you expect to decay out of 50 in 1 timestep?

   2. ____________

   The mean (or average) $\overline{x}$ is normally the best estimate of the true value of a measured quantity, being at the centre of the distribution of reading values.

3. Calculate the mean of your 10 measurements:

   3. ____________

   We also need a measure of the spread of the measurements. Conventionally, this is σ, the **standard deviation** or 'sigma'. You can quickly estimate a value for σ using the 'range method'[2], i.e. if r is the range of a set of n readings (the difference between the largest and smallest values), then an *estimate* of σ is given by

$$\sigma = \frac{r}{\sqrt{n}}.$$

4. Estimate the standard deviation of your 10 measurements.

4. ____________

4.2 Distribution of means

One way to correct for the effects of random fluctuations is to find the mean of repeated measurements. Theory suggests the following formula for σ_m, the standard deviation of the mean of n measurements,

$$\sigma_m = \frac{\sigma}{\sqrt{n}}.$$

5. Calculate σ_m for your mean.

5. ____________

6. Look at your partners' results and mean. Do your means agree with the equation above for the case $n = 10$? Make a short comment below.

____

____

____

____

4.3 Presenting the final answer

The correct, conventional way to present the result of a repeated measurement is as follows:

$$\text{result} = \overline{x} \pm \sigma_m.$$

In graphical work, error bars normally run from $\overline{x} - \sigma_m$ to $\overline{x} + \sigma_m$
e.g. $R = 4.625 \pm 0.007\ \Omega$.

The error in a measurement is usually given to one significant figure (sometimes two significant figures if the numerical value starts with a 1), and a result and its error should always be given to the same number of decimal places.

7. Give the result of your set of 10 measurements in the format above.

7. ____________

[2]The range method is good for n up to about 12.

8. Give the most accurate result you can (use your partner's results too) in the same format. Show any working.

4.4 Radioactive decay

You are now going to simulate radioactive decay, by removing those dice which 'decay' at each turn, and re-rolling the remaining dice for each timestep. Record your own results in the table below, and then add your results to those of your partner to give a total in the column for this purpose.

Time t	Number remaining x	Pooled results $\sum x$	Mean[3] $\overline{x}$	Estimated spread σ_m
0	50		50	
1				
2				
3				
4				
5				
6				
7				
8				
9				
10				
11				
12				

9. Now plot a graph of $\overline{x}$ on the vertical axis against t on the horizontal axis, and draw a trend line. Your results ought to be quite similar to those expected from radioactive decay. The trend should be the same, and there is also some randomness.

10. Comment on your results. It the trend as you expect? How close are the points to the line of best fit?

A close match between the results from this model and the results from real radioactivity would strongly suggest that individual radioactive atoms decaying at random with a fixed probability in any given time interval. This experiment also helps to 'explain' the downward trend of the decay curve: only dice that are left can 'decay', and as there are fewer of them each time, fewer will decay.

11. How does the pooling of results make your $\overline{x}$ more accurate than your x?

12. This activity raises the interesting question about how long a radioactive source will last. What happens to the last 'atom'? Comment below.

5 Bubble chamber tracks

In this experiment, you will determine some properties of short-lived particles by analysing photographs from a liquid hydrogen bubble chamber. The experiment is based around measurements of film taken from the bubble chamber at CERN particle physics laboratory near Geneva.

Bubble chambers played an important part in discovering particles whose existence played an important part in establishing the quark model in the 1950s–1970s. They are no longer in use at accelerator centres, having been superseded by the faster modern electronic detectors. However, a bubble chamber is currently being used during the search for dark matter (WIMPs).

5.1 Background

The bubble chamber, invented by Donald Glaser in 1952, consists of a tank of unstable (superheated) transparent liquid. Hydrogen is often used[4], at a temperature of about 30 K. This liquid is very sensitive to the passage of **charged** particles, which initiate boiling as a result of the energy they deposit by ionizing the atoms as they force their way through the liquid. Bubbles are formed along the paths of the charged particles, and these tracks of bubbles can be photographed.

5.2 How to read bubble chamber tracks

- Beam particles whose tracks do NOT remain parallel all the way through the picture must have collided with a proton in a hydrogen atom.
- All the paths of charged particles (and we only see charged particle paths) are curved by the magnetic field.
- Positively charged particles' paths curve one way, negatively charged particles' paths the other. (Normally, it is not necessary to be told which way is field pointing - the picture already contains the answer. The little curly tracks are produced by electrons which are knocked out of the atoms by charged particles passing by.)
- The momentum of a particle is proportional to the radius of curvature of the track in the bubble chamber.
- When a particle has used up its energy making bubbles, it stops. So its range is a measure of its energy. In practice, this is useful for identifying protons that have received only a gentle blow from the beam particle, thus not having enough energy to get all the way to the edge of the chamber.
- Other particles (for example pions) may stop; but if they do, they decay in a characteristic way which tells us that they are pions. In such a case, we would know the mass m and its momentum p from the curvature of the track; the energy can then be calculated using: $E^2 = p^2c^2 + m^2c^4$.

So much for charged particles. Neutral particles do NOT leave trails of bubbles. However, we can still sometimes glean some clues about their properties:

[4]Hydrogen was popular as it has the simplest nucleus; other nuclei presented problems such as, 'Did the beam particle hit a neutron or a proton?'

- An unstable neutral particle may decay before it leaves the bubble chamber into a pair of lighter particles - one positive and one negative - leaving an easily recognizable letter V (or vee) shape.
- If the tracks from the vee happen to cross again, downstream, the line joining the crossing position to the decay position (the V) points back to the origin of the neutral particle.
- An uncharged particle is often produced when an unstable charged particle decays–usually into a charged particle of the same sign and one or more neutral particles. This shows up in the bubble chamber as a kink (a sudden change into a more curved track).
- The energy and momentum of the uncharged particle(s) which leave at the kink can be inferred by conservation laws from the tracks we do see.
- If you want to examine the picture of a collision very carefully to find small angle kinks, for example it is a good idea to print the picture and look at it from a very low angle.

5.3 Event A

1. (a) How many charged beam particles enter the chamber?

   (a) ____________

   (b) In what direction is the beam moving (from the bottom to the top or vice versa)? Draw arrows on the image to show this.

   (c) If there are any knock-on electrons, label these on the image.

   (d) How many collisions do you see?

   (d) ____________

   (e) How many particles result from each of the collisions?

   (e) ____________

   (f) Identify the charges of these particles, and explain your reasoning.

   ____

   ____

   ____

   (g) What is the charge of the beam particles (assuming collisions are with protons)?

   (g) ____________

   (h) How many kinks do you see?

   (h) ____________

   (i) How many vees do you see?

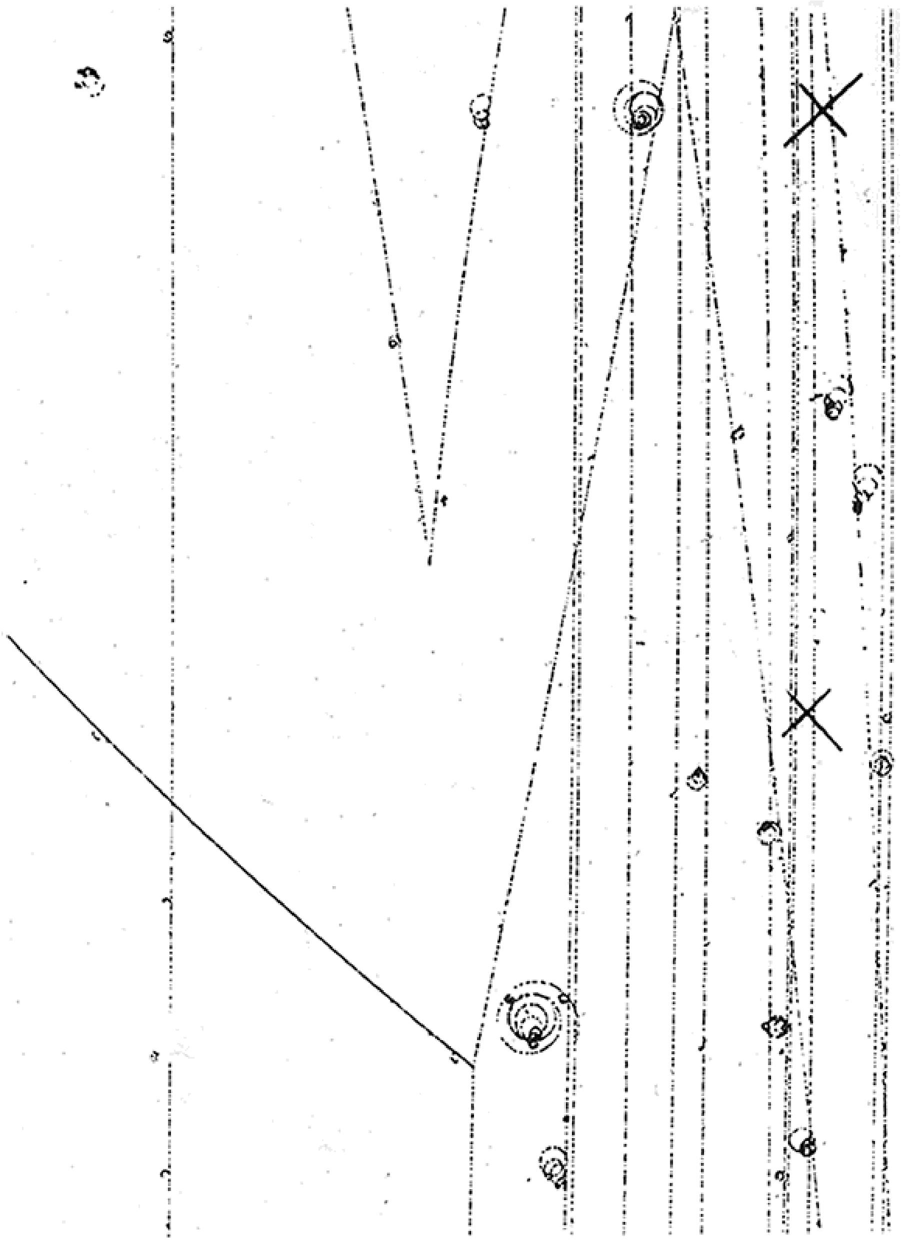
   (i) ____________

   (j) How many particles result from the decays?

   (j) ____________

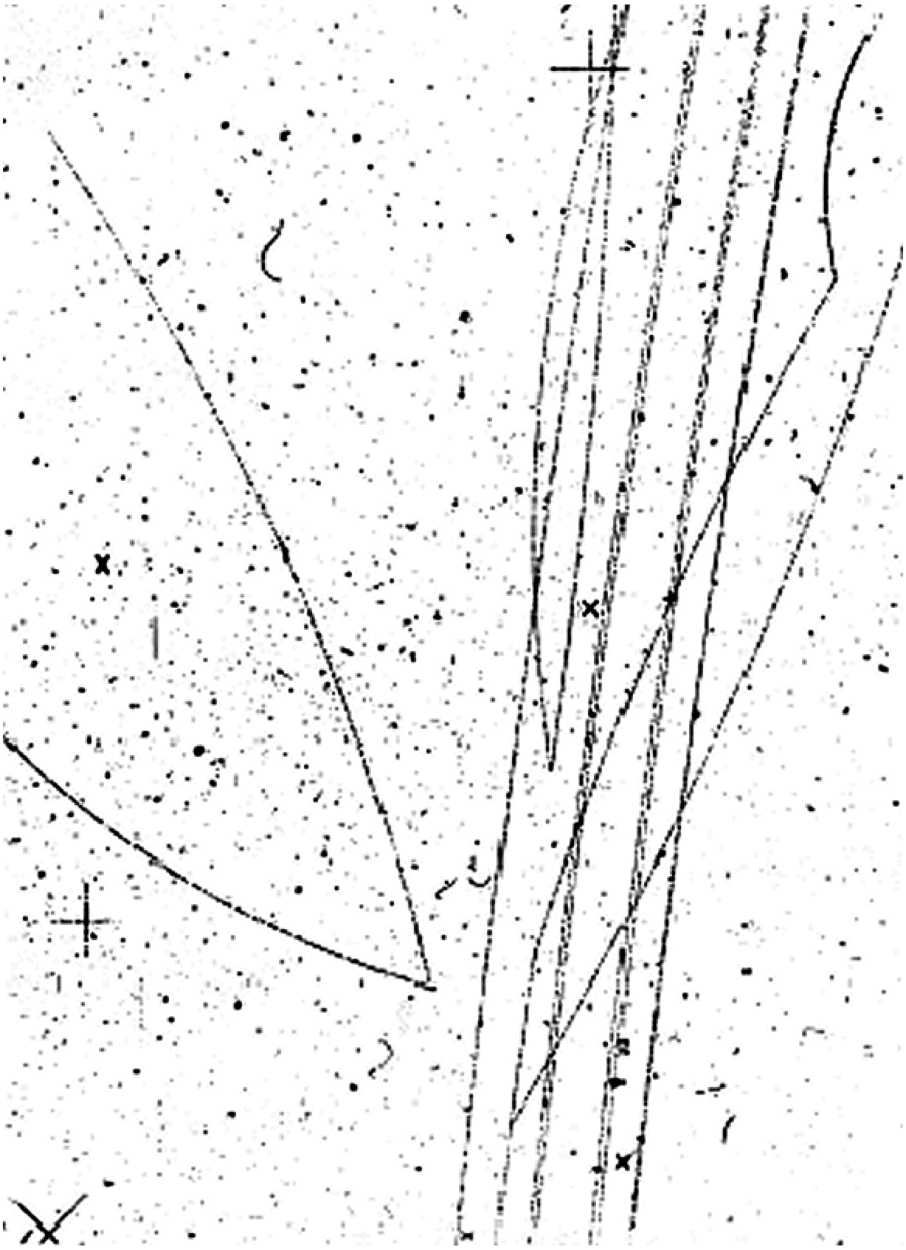
(k) Identify the charges of the particles from decays, and explain your reasoning.

(l) Consider the main collision/interaction. Which of the charged particles from the collision has the lowest momentum? How do you know?



Event A. The crosses are known as fiducials and are marked at positions which are accurately surveyed. They are measured along with events and are essential to the 3D reconstruction process.

5.4 Event B



(a) In what direction is the beam going? Mark this with an arrow on the photograph.

(b) How many beam tracks are there?

(b) ____________

(c) How many collisions are there?

(c) ____________

(d) How many vees are there?

(d) ____________

(e) How many kinks are there?

(e) ____________

(f) What does the fact that you see a track indicate?

(g) How can you tell if two tracks represent particles of the opposite charge?

(h) What physical property of a particle is determined by the curvature of its track?

(h) ____________

(i) What causes a kink?

(j) What causes a vee?

(k) What are the small crosses?

(l) What is the charge of the target particles (remember this is a hydrogen bubble chamber)?

(l) ____________

(m) What is the charge of the beam and how do you know?

(n) In which direction are the neutral particle(s) moving from the kinks?

(o) What needs to happen for a track to kink twice?

(p) What particles can cause a vee?

(q) From which point do the particles that cause the vees come?

5.5 Event C

(a) How many charged beam particles enter the chamber?

(a) ____________

(b) In what direction is the beam moving (from the bottom to the top or vice versa)? Put an arrow on the photograph to show this.

(c) Are there any knock-on electrons? If so, label these on the photograph.

(d) How many collisions do you see?

(d) ____________

(e) How many particles result from each of the collisions?

(f) Identify the charges of these particles.

(g) What is the charge of the beam particles? How do you know?

(h) How many kinks do you see?

(h) ____________

(i) How many vees do you see?

(i) ____________

(j) How many particles result from the decays?

(k) Identify the charges of the particles from decays.

(l) Identify the possibilities particle that decays, forming a vee.

(m) Identify the possibilities for the particle that decays, forming a kink.