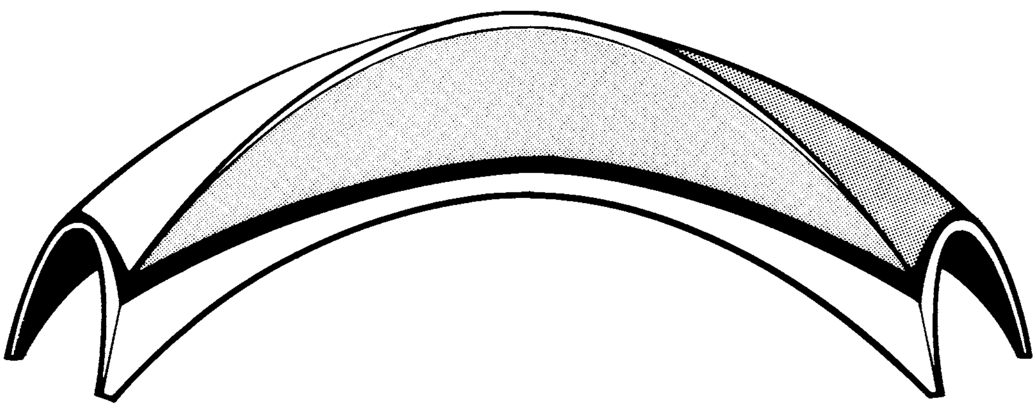
UNIVERSITY OF ABERDEEN

DEPARTMENT
OF
PHYSICS



Wave Particle Duality

Activity Day
For
Advanced Higher Physics

25th November 2003

Wave-particle duality for Advance Higher Physics

CONTENTS

NOTE FOR STUDENTS

Please read enough of the instructions for each experiment you try BEFORE you start the experiment so that you know what you are expected to do and how you will go about doing it.

Particles, Waves and Bits of String

Background

The remarkable discoveries of Newton and other scientists in the 17th century triggered off the development of a technological revolution, particularly here in the Britain. By the 19th century, the triumph of science seemed clear for all to see. There seemed to be nothing that science could not do or explain and many scientists firmly believed that, within just a few decades, an understanding of the structure of the Universe itself would be within their grasp[1]. According to their beliefs, the Universe was a mechanism like a perfect machine, every part of it linking into every other part with the precision of a Swiss clock.

This over confident view of our understanding of nature was to be rocked to its core during the early part of the 20th Century. Profound new discoveries[2] of the fundamental nature of matter were to show that the classical edifice of science was built on very shaky foundations. The "new" science that replaced the old was to be called *Quantum Physics* and it described a world that was fundamentally chaotic. In this world energy could flash into and out of existence - for no particular reason - breaching the most sacred of classical physics principles - "the conservation of energy". The deterministic certainties of the old classical physics were to be replaced with uncertainties, particles moving, not according to Newton's laws, but according to "probability waves" that according to some interpretations could exist in an infinite number of "parallel Universes". Today we are still struggling to come to terms with this weird, strange and sometimes bizarre picture of how our Universe really works.

Lecture

In the lecture today, I shall attempt to convey some of the fundamental ideas of quantum physics - of wave particle duality, quantum interference and some of the newest theories that attempt to explain the very structure of our Universe.

Dr Geoff Dunn

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1 One of the reasons for believing this was because of the work of James Clerk Maxwell (one of the most brilliant and influential physicists of the 19th century and a lecturer here at Aberdeen University) who produced the first *unification theory* showing the electrostatic and electromagnetic forces were really "two sides of the same coin".

2 Here at Aberdeen University, G. P. Thomson showed the wave nature of electrons experimentally, for which he won the Nobel Prize in Physics.

Wave particle duality helps us characterise materials!

This sheet is intended as a background to the instruments you will visit in the Meston Building. The instruments are used on a daily basis for the characterisation of a range of materials - cements, polymers, catalysts, semiconductors, biomaterials....

X-ray Diffraction (XRD)

Our powder X-ray diffraction machine depends on the fact that we can treat X-rays as both particles and waves.

The basis of the method is that, much as light is diffracted when it passes through a diffraction grating, X-rays are diffracted as they pass through a crystal. This is because:

(a) the distances between atoms are around the same as the wavelength of X-rays ($0.5\text{-}2 \times 10^{-10}$m);

(b) the atoms in a crystal are arranged in an ordered manner.

So, the X-rays arrive from the tube on the left hand side of the instrument and are diffracted (as waves) from the sample. The diffracted X-rays are then counted by the detector at the right hand side - this depends on them being particles! From this experiment, we can tell what is in our samples, how much and what specific form it takes.


The Bruker D8 Advance XRD

A similar experiment is *neutron diffraction*; the experiment is *a lot* bigger, but depends on neutrons behaving as waves. The UK neutron diffraction facility is at the Rutherford Appleton Laboratory, Oxon.

Electron Diffraction, electron microscopy

Electrons can behave like waves and so can be used in a similar manner to X-rays. The wavelength of the electrons is related to velocity,

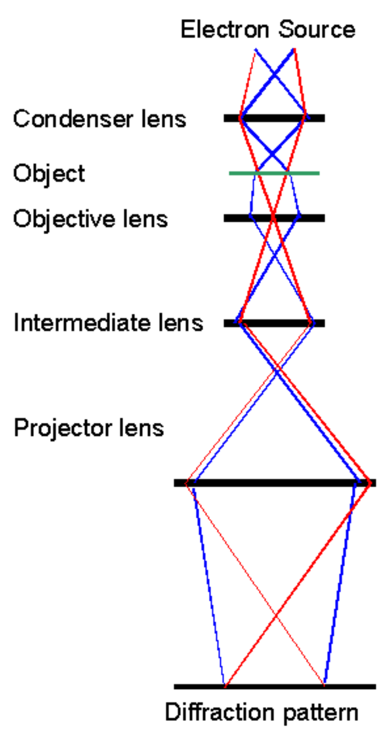
$$\lambda = h/mv \qquad \text{(de Broglie)}$$

and the velocity is controlled by the accelerating voltage in the electron gun. In fact, electron diffraction was used to confirm de Broglie's equation which was the basis for his doctoral thesis.

G. P. Thomson won the Nobel prize for demonstrating electron diffraction in the department of Natural Philosophy (the old name for physics) at Aberdeen.

Thomson, and also Davisson at Bell Labs., measured electron diffraction patterns which revealed that a 100 keV electron had a wavelength of $\sim 3.9 \times 10^{-12}$m. You can check this using de Broglie's relationship and the formula for kinetic energy.

The set up for an electron microscope is a "simple" lens system - see diagram. However, rather than conventional glass lenses, we use *electromagnetic lenses*. In the diagram on the right, the diffraction pattern is recorded at the bottom. However, by changing the focus of the lenses, we can see a highly magnified image of the sample. The magnification can be enough in some microscopes to "see" atoms.

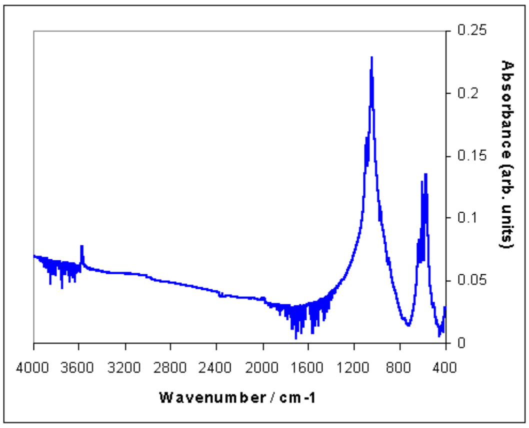


Planck'#s constant $h = 6.626 \times 10^{-34}$ Js   mass of electron $m_e = 9.109 \times 10^{-31}$ kg $1\text{eV} = 1.602 \times 10^{-19}$ J

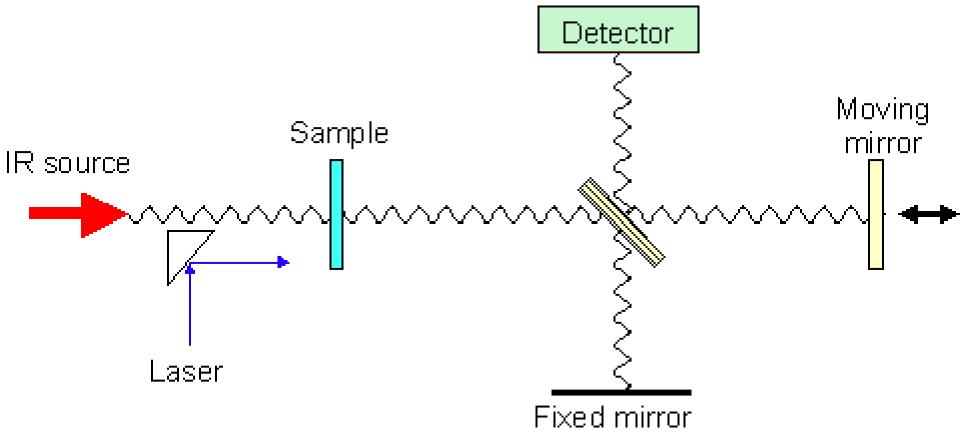
Fourier Transform Infrared Spectroscopy (FTIR)

This is not quite an example of wave/particle duality, but it is a nice example of waves, optics and interactions with materials.

Spectroscopic techniques rely on the fact that, given the correct conditions, materials will absorb or emit energy. The spectra produced are thus a plot of absorption or emission (y axis) as a function of energy - but traditionally, since we can write $E = hc/\lambda$, we use λ^{-1} as the x-axis, in unit of cm^{-1}, called *wavenumbers*.
In all materials, the atoms are not held firmly apart but behave as though they are attached by springs (and indeed we can derive some interesting physics from this concept!). The springs can bend, compress and stretch, and depending on the atoms at each end of the spring we get characteristic vibrations. The more different atoms, the more vibrations. For a linear molecule with "n" atoms, there are 3n-5 vibrational modes, if it is nonlinear, it will have 3n-6 modes. For example, water (H_2O), has 3 atoms, and is non linear: therefore it has $(3\times3)-6 = 3$ modes of vibration - symmetric stretch, asymmetric stretch and bend.
In solids, atoms vibrate at $\sim10^{12}$-10^{13}Hz. Different groups will give characteristic frequencies of vibration, and therefore we can assign the peaks in the spectrum to different groups.



At the heart of the instrument is a Michelson interferometer. Infrared radiation is passed through the sample and towards the beam splitter, where half the radiation if reflected from a fixed mirror and the other half from a moving mirror (which moves ~2μm). When the two beams are recombined at the detector, an interference pattern is produced.



Wave functions

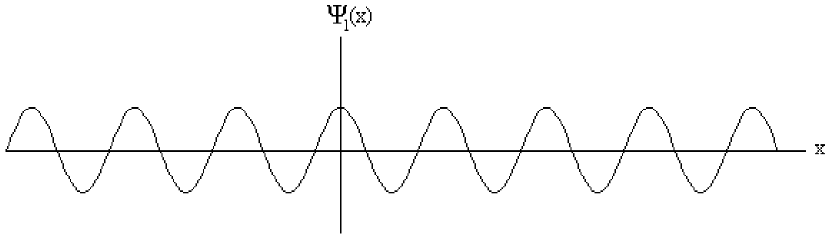
The advent of Quantum Mechanics resolved the problem of whether things such as electrons or protons or light waves are 'waves' or 'particles'. Quantum mechanics describes these objects by wave functions that are the solutions of a fundamental equation due to Schrödinger. The wave function contains all the information that we can have about the object. The object is not a particle, nor is it a wave; however it does have properties that traditional terminology would describe as 'wave-like' or 'particle-like'.

Wave-packets

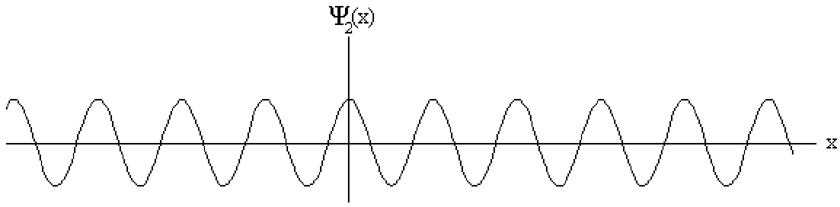
To avoid using the word 'particle', we will talk about an electron. However our 'object' could be anything.
The simplest wave function to describe is the one that the Schrödinger equation produces for an electron moving freely with a fixed momentum, *p*. The wave function is like a travelling wave and the property of the wave that relates to the momentum of the electron is its wavelength, λ.
The connection between *p* and λ was proposed by De Broglie and takes the form

$$p = \frac{h}{\lambda}$$

where h is Planck's constant. Although we cannot show the moving wave, we can illustrate the character of the wave function, $\Psi(x,t)$, by taking a snapshot of it as it passes. It looks like a cosine function:

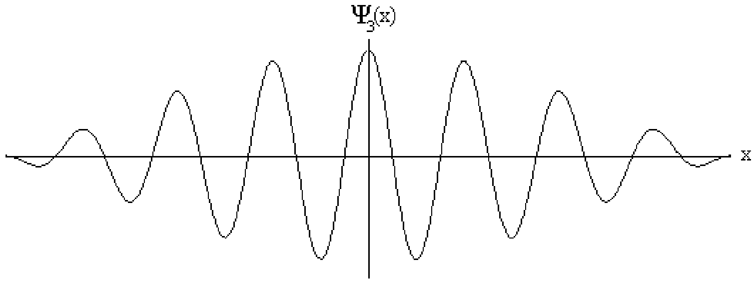


By 'freezing' the wave we lose the information about which way the wave is moving (to the left or the right) but that need not concern us now.
Since the momentum is *inversely* proportional to the wavelength, a faster electron will be described by a wave with a shorter wavelength.



A further aspect of the quantum mechanical description is that the *amplitude* of the wave at position x is related to the probability of the electron being at position x.
Here we meet our first problem. Since the cosine waves shown above extend from $-\infty$ to $+\infty$, we have to ask "If this wave represents our total knowledge about the electron, then where is it?"

Because the wave shown has a precise wavelength, we have precise knowledge of the momentum of the electron (the De Broglie relationship). But, because the waveform extends from $-\infty$ to $+\infty$ without change in form, we have no knowledge at all about where the particle is. This observation is at the root of the famous Heisenberg Uncertainty Principle, which says that you cannot know both the position and momentum of a particle simultaneously. If we are going to acquire a better idea of where the electron is, we must give up our precise knowledge of its momentum, i.e. the wavelength of the wave function.
The wave function that describes a localised particle should have a significant amplitude in a restricted region of space, and be small outside that region. It could look like the function below, which is a called a wave-packet.



How do we construct a wave-packet?

Activity 1.

The Matlab program **Demo1** shows how adding a number of cosine waves with slightly different wavelengths produces a wave function that is limited in spatial extent.
You should observe the inverse relationship between the range of wavelengths and the width of the wave-packet, ie. the wider the range, the narrower the packet width.
The wave-packet representation of the particle gives us some idea about where the particle is, but the range of wavelengths in the wave function means that the particle no longer has a well-defined momentum. To gain some knowledge about its position, we have had to sacrifice some knowledge about its momentum.

Activity 2.

In the second activity we will be more quantitative about the trade-off between our knowledge of position and momentum.
The Heisenberg Uncertainty Principle

To form wave functions that can properly describe localised particles, we have to add waves together with a continuous range of wavelengths rather than a few separate wavelengths as we did in activity 1. In essence, the addition becomes an integration. This integration is performed by the program used in the second activity.

The **Demo2** program constructs the wave-packet from a continuous range of input wavelengths. Instead of reporting the range of λ, the program reports the range of the quantity $1/\lambda$, which we will call $\Delta\left(\frac{1}{\lambda}\right)$, since that is more convenient for the calculation that follows. As before you will find that as the range of wavelengths becomes greater, the width of the wave-packet decreases.

Task:

Take the width of the first lobe of the wave-packet (between the first zeros either side of x=0) as a measure of the uncertainty, Δx, in the position of the particle represented by the wave-packet.

The uncertainty in the momentum, Δp, may be obtained from the De Broglie relation and the value of $\Delta\left(\frac{1}{\lambda}\right)$ reported by the program. Since h is constant,

$$\Delta p = h\ \Delta\left(\frac{1}{\lambda}\right)$$

From the values for the individual wave-packets, find the relationship between Δx and Δp. You should be able to verify that

$$\Delta x \times \Delta p \approx h$$

So, the more precisely you know the position the less precisely you know the momentum, and vice versa.

Concluding remarks

As we said, the waves that we have been discussing emerge naturally as the solutions of Schrödinger's equation in quantum mechanics. Not only does the theory account for interference phenomena in relation to objects that we used to call particles, but it also places restrictions on the knowledge we can have about the positions and momenta of these objects.

Random events

Introduction

When light impinges on a detector, the energy does not arrive in a continuous stream but in 'packets'. The packets are the same in principle as the wave-packets that we discussed for electrons (or other objects) but now the width of the packet indicates the region of space in which the electromagnetic energy of the light is concentrated. A wave-packet of electromagnetic energy is called a photon; it embraces properties that traditional terminology would describe as 'wave-like' or 'particle-like'.

With a sensitive detector and very low intensity illumination it is possible to do a 'photon counting' experiment in which the random arrival of individual photons is recorded. The photons do not arrive in a uniform stream. The number arriving in a small time interval (say 1 ns) will vary in different samples of the same interval. The result for one interval provides a first estimate of the average number per interval. We can improve this estimate by counting a number of intervals and averaging the results (or counting for a longer time, which amounts to the same thing).

The question we are going to investigate is: "How does the uncertainty in the average count rate depend on the number of intervals counted?"

We are not in a position to demonstrate the statistics of wave-packet counting, for photons or electrons. However, there are many other situations that display random behaviour with the same essential features. We will focus on one.

Signal recovery by averaging

When a signal is detected electronically it takes the form of a voltage or current. Because the electrons in electronic components, such as resistors, are engaged in random thermal motion there are always unwanted random currents, called ***noise***, that add to or subtract from the desired signal current. Detection problems arise when the noise is much greater than the desired signal.
The signal shown in figure 1 is a so-called 'echo' signal of the type that spinning protons induce in the detector coils of magnetic resonance body scanners. The figure below shows how the echo would appear if there were no noise.

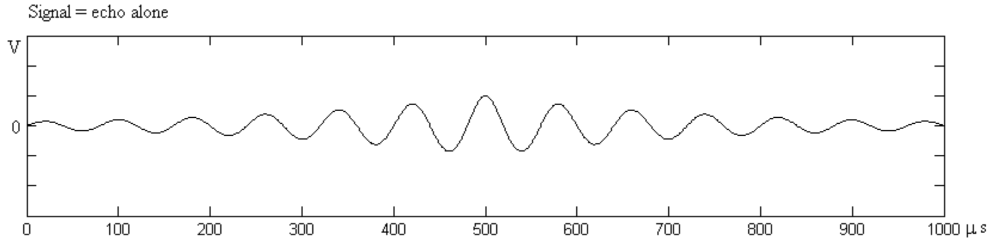


FIG. 1

Figure 2 shows how the signal appears when there are fluctuating noise voltages that greatly exceed the echo voltage. On the basis of this graph it is impossible to say that an echo is present.

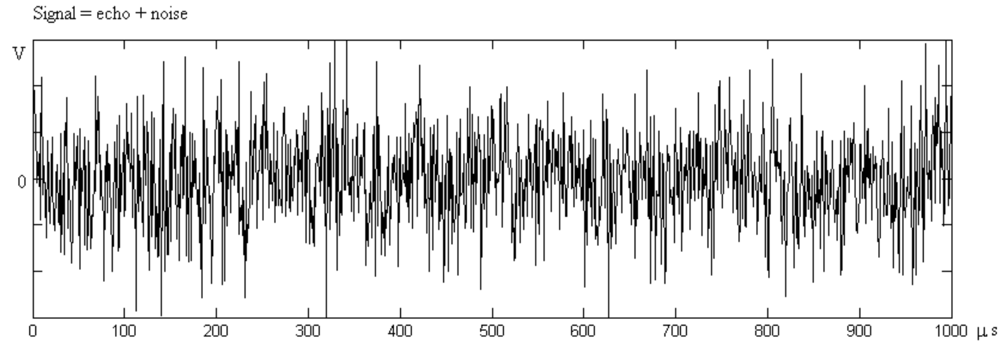


FIG. 2

Since the echo is the response to a stimulus, it can be repeated as often as desired.
If the stimulus is repeated, the echo will always occur in the same way but the random fluctuations will be different for each repetition. This creates the prospect of adding up several repetitions of the signal; the echo should be the same each time but the random noise voltage at any instant will be sometimes positive and sometimes negative and so should be partially self-cancelling. The average value of all the additions should begin to look like the echo signal.

All of which brings us back to our original question: "How does the uncertainty in the average echo signal depend on the number of repetitions counted?"

Signal-to-noise ratio

As a measure of the quality of the echo signal we use the signal-to-noise ratio (SNR), which is defined as:

$$\text{SNR} = \frac{\text{maximum amplitude of the echo}}{\text{rms amplitude of the noise}}$$

The root mean square (rms) amplitude is a standard method of putting a number on the extent of the fluctuations in a fluctuating quantity.

Activity 3

By running the Matlab program Demo3 you can simulate the results of averaging several repetitions of the signal.

Demo 3a simply averages the echo (without noise) and produces the obvious result that the average is the same as any one realisation of the signal.

Demo 3b does the same operation for noise alone. Here the result is different and shows that adding random values that can be positive or negative, while not producing a zero result, does produce an average that is smaller than one realisation of the noise.

Demo 3c simulates an actual experiment in which the signal is invisible in one realisation. By averaging several repetitions, the signal remains the same but the noise reduces. So the SNR (signal-to-noise ratio, remember) improves.

You should draw a graph of SNR versus the number (N) of averages to show how the SNR increases with N. Values of N between 1 and 256 are suitable.
In doing this you will uncover a universal truth about the averaging of random events.

Conclusion

If a measured quantity is subject to random fluctuations, repeating the measurement N times will reduce the uncertainty in the result by a factor of $\sqrt{N}$. This law of diminishing returns applies equally to photon counting and MRI brain scanning.

Counting Photons – More is Better

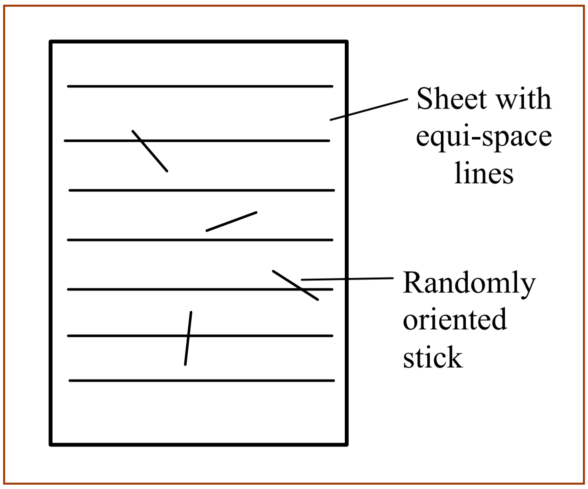
Context

Counting photons is what you do when your source of radiation is weak. It may be weak starlight or comparatively weak X-ray scattering in a diffraction experiment to determine crystal or molecular structure. It's a feature of such photon counting that if you repeat the experiment and count the same thing for the same amount of time, you don't get the same count. Counting photons has a built in randomness. This is quite different from, say, counting the number of people in this room. Everyone who does it should get exactly the same result. Our experiment is intended to illustrate the idea that the longer you count a random variable, the better it is known. For instance, if you're counting X-ray photons to measure the intensity of an X-ray reflection, the longer you count the more accurately you'll determine the intensity. If you're scanning your counter through a reflection to determine at what angle it is located, the more photons you collect at each point in the scan the better you'll locate the angle of a reflection.

The experiment

Counting photons requires expensive kit, precautions to exclude stray light and other practical difficulties. You won't be surprised to find that we're going to illustrate the idea in quite a different way. The experiment is called "Buffon's needles", after an 18th century Frenchman who thought of it long before the idea of randomness was given its modern mathematical treatment.

You need a sheet of paper on which parallel lines are drawn with a spacing equal to the length of the short sticks you'll have. Buffon used needles, as you'll have guessed. You then throw a stick onto the sheet and record if it crosses a line or not. This is the 'count'. You repeat this experiment many times, counting the number of sticks that cross a line and the total number of sticks you've thrown down at random, i.e. you obtain a number for the fraction, f, of sticks that lie across a line. You'll find that this number jumps about and it won't agree in detail with what your neighbour finds.



Now, a short mathematical argument shows that the probability of a stick crossing a line is just $(2/\pi)$. Hence in this case you know what the fraction f should be heading towards and you can use f to estimate π:

$$\text{Estimate for } \pi = 2/f$$

In summary, you're measuring π by a statistical method, just as you're measuring the intensity of an X-ray reflection by a statistical method. In this case you know what the answer is supposed to be (3.14159…) so you can see how well you're doing. At first you get answers like 2 and 4, which are at least in the right ball-park, but as you obtain more counts the answer will improve.

Equipment

You should have:
1) a sheet of A3 paper
2) a pencil
3) a Perspex ruler
4) a bundle of sticks
5) a results scoring sheet
6) a calculator (your own)

What to do

1) Draw a series of parallel lines on the A3 sheet of paper, equal in spacing to the length of a stick.
2) Put the paper on the board (in any orientation)
3) Drop 10 sticks onto the sheet in an attempt to make them fall and lie with a random orientation. You can drop them down all at once, throw them quickly one-at-a-time or 'bomb' the board with vertical sticks, or try other ways. Count the number that cross a line
4) **Write your names on the results sheet**. Fill in the first line of your results sheet, making your first estimate of π
5) Pick up the thrown sticks, rotate the paper at random on the table or on the board (if you are using a board) to help randomise the experiment. Your partner can now throw 10 sticks down. You can vary the number of sticks dropped but you have to try to drop the sticks with a random orientation.
6) Fill in further columns of the results sheet, taking it in turn between you and your partner to put the sticks on the board. For each calculation of f and π, use the **total number** of sticks thrown in all trials and the **total count** of tries that crossed a line. You should find that the result gets close to 3 quite quickly but it takes a long time to get even the next decimal point correctly.
7) When you've tried about 250 times between you, stop. Finally collect the total results from others doing the same thing and add them to yours so you have the result for π for at least 1000 attempts. Is it any more accurate than your result?

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8) Now go to one of the computers in the room. These are running a simulation of the experiment you have just done. The computer lets you simulate the results of 10,000 or 100,000 trials, something no-one has the patience for. In real counting experiments, you might well use electronics to collect 100,000 photons to record the intensity of a Bragg reflection.
9) The program screen "Buffon's needles" should be showing, as illustrated on the next page.

   a. Set the number of *areas* on the computer page to 10 using the up or down arrows near the top right and then press *reset*.

   b. Set the toss size to *10 times* using the arrows just under the *toss* button near the top centre. Press the *toss* button to throw the sticks ten at a time. Notice the value of π obtained, shown on the left. Record the result for 100 throws. Now throw the sticks 100 at a time. Record the result for 1000 throws. Is this result better or worse than the group result you obtained in "7)" above? Finally, simulate 10,000 and 100,000 throws and record your results.

Summary

Screen as it might look after 100 tosses

You can download the program from the URL mentioned on the screen and try this at home. There are other web pages that offer different interactive versions of Buffon's needles.

Conclusion

You have to record a lot of counts to obtain an accurate statistical measurement. Normally this can only be done with the aid of electronics. When counting photons, the percentage accuracy of your measurement improves as $100/\sqrt{N}$, where you count N photons. Counting 100 photons therefore results in an answer with a 10% uncertainty; counting 10,000 photons reduces the uncertainty to 1%.

RESULTS

NAME 1:

NAME 2:

DATE:

RESULTS RECORDED:

No. of sticks dropped 'N'	10	20	40	60	80	100	250	1000
No. crossing a line								
Fraction crossing a line, f								
Estimate for π ($2/f$)								

Computer simulation

No. of throws →	N = 100	N = 1000	N = 10,000	N = 100,000
Computer value for π				

REMINDER

- You choose the number of sticks dropped, N.
- You measure the number of sticks that cross a line

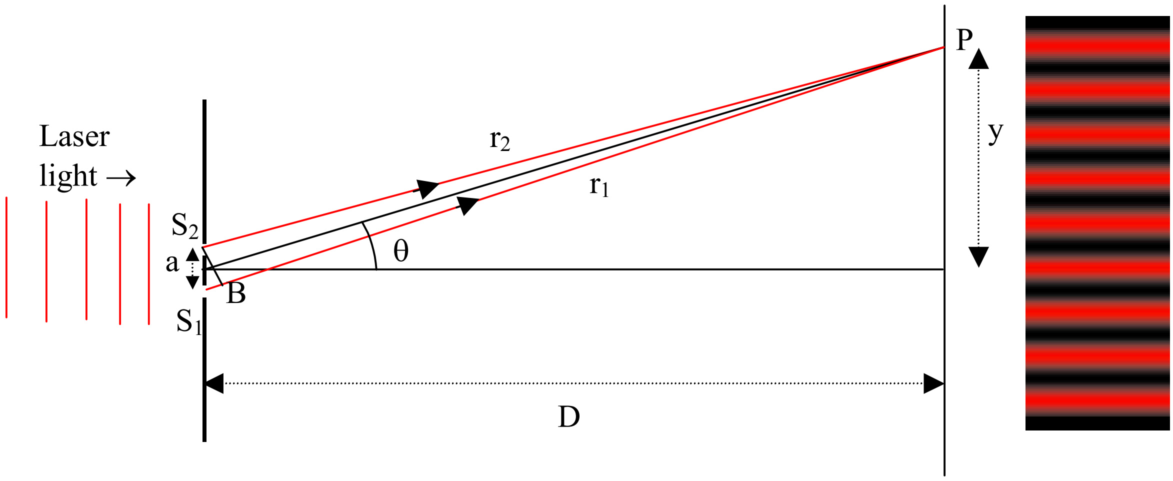
Young's slits experiment

Background

Can you name a famous scientist who was crucial in deciphering Egyptian hieroglyphs, laid the foundations of the Life Assurance industry, made important discoveries in elasticity, optics, physiology and other subjects, was a medical doctor and physician, was fluent in more than a dozen languages, was Humphrey Davy & Michael Faraday's predecessor in the famous Royal Institution, was elected Fellow of the Royal Society when only 20, came to the University of Aberdeen and was very impressed with our equipment? Young is the name, Thomas Young. Some of his contemporaries called him "Phenomenon Young" and they were right. It doesn't bear guessing how many Highers he would have passed if there had been Highers in those days. Young wasn't just good at learning things, he had real insight too. It was he who devised the very elegant experiment requiring very little equipment that shows beyond doubt that light behaves at times like a wave. The experiment is called "Young's slits", though he actually used pin-holes.

Young's idea

Young's experiment is one of the world's great experiments. It is simple, easy to follow the correct theory, gives a clear visual result and gives deep insight. Young's experiment is an archetypal arrangement to illustrate interference. In our version you shine laser light into two closely space slits S_1 and S_2. A long distance D away you have a screen. Look at the screen and, Young said, you will see the characteristic interference pattern of light. What was remarkable is that in Young's day, 200 years ago, no-one knew about the interference of light. It was this experiment that convinced people it really happened.



Illuminated by laser light, the two slits S_1, S_2 become coherent sources a distance 'a' apart. Constructive interference occurs at a point P on a screen when the path lengths of light travelling from the sources to P, i.e. S_1P and S_2P, differ by a whole number ('m') of wavelengths, i.e.

$$m\lambda = S_1P - S_2P = S_1B = a.\sin\theta \approx a\theta \ ,$$

since the fringe pattern will usually be spread over a range of angles that keeps θ small. θ varies as P moves up the screen. 'y' measures the distance of P up the screen.

$$\theta \approx \tan\theta = y/D\,.$$

From the two relationships above, you can see that bright **fringes occur at positions we will call $y_m = D\theta = mD\lambda/a$**. This is what the experiment is about. At the predicted values of *y* on the screen, the illumination will be bright. It's not hard to see that half way in between, there should be no illumination.

The distance between neighbouring fringes is clearly $\Delta y = D\lambda/a$. For example, with $\lambda = 500$ nm, a = 0.5 mm and D = 3 m, the spacing between neighbouring fringes is 3 mm.

Our experiment

What you will do is:

1) Make two, narrow, parallel slits very close together, about 0.1 mm apart.
2) Place the slits in your laser beam and observe on the screen a few metres away that the bright and dark fringes really do occur. Measure how far away the screen is (the distance *D* above) and the distance 'y' between a chosen number *m* of bright or dark fringes. Estimate *a*.
3) Having found values for *y*, *m*, *D* and *a*, use the relationship $\boxed{y = \frac{mD\lambda}{a}}$ to determine the wavelength of the light.

Equipment

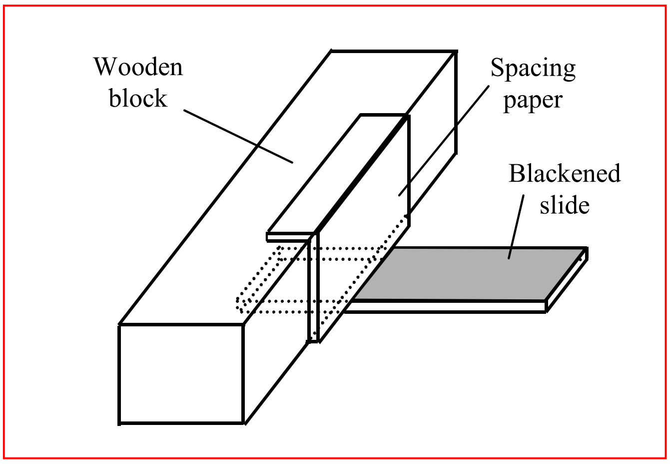
You should have:

1) a laser suitably mounted, with off/on switch at rear and a block for holding slides in the beam as it emerges
2) two microscope slides, blackened on one side
3) a scribing tool
4) a rectangular wooden block and a strip of paper to act as scribing guide
5) two example double slits, mounted in holders
6) a magnifying glass for putting close to your eye (a "loup")
7) a screen on the wall in the form of an A4 sheet of paper
8) a metre stick and perspex ruler
9) a sheet of paper for your results and calculation
10) your own calculator

What to do

1) **Write your names on the results sheet, and the date.** Read through this description of the experiment. There is no need to follow the derivation of the relationship $\boxed{y = \frac{mD\lambda}{a}}$ that we're going to use in detail if you've not met it before, but you should know enough to know what the symbols in it stand for. Before you begin, read the laser safety instructions on the last page.

2) You want to scribe two fine slits on the blackened slide, lines about 0.1 mm wide and whose separation is about 0.1 mm. Using the loup (item 6 above) look at the two examples that we have provided of such a pair of lines, mounted in a 35 mm slide holder. You have a sharp scriber for cutting the lines. If you don't want to use such a sharp instrument, call over a demonstrator who will help. Drawing the second line close and parallel to the first can be a bit tricky. Our method of making the lines is this.

   Place the wooden block on top of the slide as a guide for your scriber. Place the piece of paper about 0.1 mm thick to extend the wooden block outward by this thickness. Holding the scriber firmly against the sheet of spacing paper, scribe a line on the black side carefully. Make just one pass with your scriber. Now, **holding the block completely still**, flick away the spacing paper and scribe a second line, which should come out parallel to the first and 0.1 mm away. Drawing the first line you will get the feel of how hard to press: not so hard that you scratch the glass but hard enough to cut the black coating. You have one microscope slide per person. Both of you should draw a couple of pairs of lines on your slide, more if you make a mistake. Examine your slits for regularity through the loup.

3) Put a slide in the holder and move it until a pair of your lines are into the laser beam, which should be pointing at your screen. You should now see the interference pattern on the screen. This is the best part of the experiment – seeing that the interference really does occur! Get your partner to move the slide until your second set of lines are in the beam and see if they, too, produce interference. All should be well unless you have drawn your lines further apart than the width of the laser beam, which is about 0.5 mm.
4) With the perspex ruler, measure how big a distance in mm is spanned by, say, 5 fringes, excluding the fringe you start from. This is y for $m = 5$. Record your answer on your answer sheet.
5) Use the metre stick to estimate **how far away the screen is from your slit** (no great accuracy is needed). This is 'D' in the relationship above. Measuring the separation in mm from the middle of one slit to the middle of the next slit at about the point where the laser beam went through is a bit time consuming. This is 'a' in the formula. It can be done with a travelling microscope or calibrated direct vision microscope if you have time. Assume for the moment that $a = 0.1$ mm.
6) Convert 'a' and 'y' from mm to m and use the relationship $\lambda = ya/mD$ to estimate the laser wavelength. You should get an answer in the right 'ball-park' of 600 nm.
7) You can 'turn the experiment around' and assume the wavelength is 628 nm and measure the small distance a that was difficult to measure: $a = mD\lambda/y$. What do you find for a? Is your answer in the region of 0.1 mm? Having calibrated your slits with one wavelength, you could use them to find the wavelengths of other sources.

8) If you have a safe place to keep your slide, then you can keep it but don't put it anywhere where you might end up with broken glass, such as in your pocket. You can keep the results sheet for this experiment. I hope you are convinced that light interference really does take place as the textbooks say it should.

Laser Safety

Your laser is a He/Ne laser, emitting red light at a power less than 1 mW. Lasers are specified by the power of the light emitted; ordinary lamps by the amount of electricity they consume. Inside the box is the laser tube itself with the necessary excitation source and electronics. It has a normal lifetime of over 20,000 hours, but a lifetime of 0 seconds if you drop it. Please take care.

LASER SAFETY

There are strict Health & Safety at Work rules for anyone using a laser. Our lasers are Class II, the safest of all likely to be met with in a general laboratory. If you were to accidentally get the laser beam or a direct reflection in your eye then your natural blink reflex would protect you. Nonetheless, take great care, for the source is as bright as the sun and better collimated. Your eye could focus a laser beam onto a very small spot of high energy density on your retina. Observe the following safety requirements:

- ☠ **Never look straight into the laser light, either into the direct beam or into the beam after it has been refracted or reflected.**
- ☠ Never lift up the source and wave it around.
- ☠ Take care when putting objects into the laser beam that stray reflections are kept at bench height.
- ☠ Keep the beam directed towards your screen.
- ☠ Always look down on the laser beam; never put you head at bench level.
- ☠ Switch off the laser when not in use.

RESULTS

NAMES:

DATE:

MEASUREMENTS

QUANTITY ↓	1st trial	2nd trial	3rd trial	4th trial
Distance of screen 'D' in m				
No. of fringes measured 'm'				
Distance across *m* fringes 'y' in mm				
Slit separation '*a*' in mm	0.1			
Wavelength 'λ' in nm				628 nm

Make a minimum of 1 trial

RELATIONSHIPS

- Remember that $\boxed{\lambda = \frac{ya}{mD}}$. With all the distances measured in m, the result is in m.
- 1 nm ≡ 10^{-9} m.