Revolutions in modern physics

The development of quantum theory and the theory of relativity fundamentally changed our understanding of how nature operates and led to the development of a wide range of new technologies, including technologies that revolutionised the storage, processing and communication of information.

Develop your understanding of these modern theories by:

- **Examining observations of relative motion, light and matter that could not be explained by existing theories.**
- **Investigating how the shortcomings of existing theories led to the development of the special theory of relativity and the quantum theory of light and matter.**
- **Evaluating the contribution of the quantum theory of light to the development of the quantum theory of the atom.**
- **Examining the standard model of particle physics and the Big Bang theory.**

Explore modern physics through such contexts as black holes, dark matter, space travel and the digital revolution and technologies, such as photo radar, fibre optics, DVDs, GPS navigation, lasers, modern electric lighting, medical imaging, nanotechnology, semiconductors, quantum computers and particle accelerators, and astronomical telescopes such as the Square Kilometre Array.

Investigate and apply an understanding of relativity, black body radiation, wave/particle duality, and the quantum theory of the atom, to make and/or explain observations of a range of phenomena, such as atomic emission and absorption spectra, the photoelectric effect, lasers, and Earth's energy balance.

Acknowledgements:
See page one for acknowledgements of the support and contributions of individuals and organisations to the Revolutions in Modern Physics section of this book.

References:

Resources used in preparing explanations and background information for the Revolutions in Modern Physics section of this book may also be useful support with additional information and detail:

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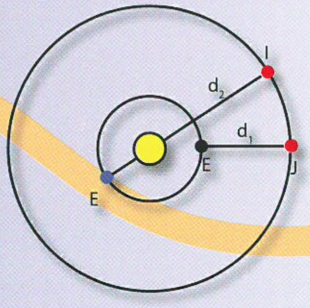
- Bertozzi, William (1964), "Speed and Kinetic Energy of Relativistic Electrons", American Journal of Physics 32 (7): 551–555, Bibcode:1964 AmJPh..32..551B, doi:10.1119/1.1970770
- David H. Frisch and James A. Smith, Measurement of the Relativistic Time Dilation Using Muons, American Journal of Physics, 31, 342, 1963
- J. Bailey et al, 'Measurements of relativistic time dilatation for positive and negative muons in a circular orbit', Nature 268, 301 - 305 (28 July 1977)
- Mikkjal Gulklett, Relativistic Effects in GPS and LEO, cct.gfy.ku.dk/thesis/Speciale1.pdf

Historical tim

1600

1676

Ole Roemer calculates a value for the velocity of light of 227000 km s^{-1}



1700

1727

James Bradley measures the velocity of light as 300000 km s^{-1}

1800

1818

Augustin-Jean Fresnel presents his work on a special kind of lens – now called a Fresnel Lens.

1850

1678

Christian Huygens proposes that light behaves as a wave.

1801

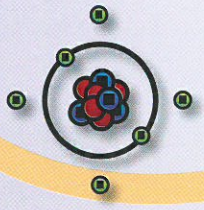
Thomas Young's double slit experiment leads to acceptance of the wave nature of light.

1839

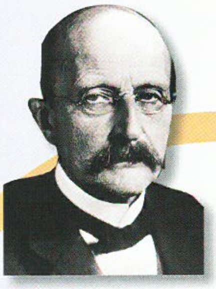
Edmund Bequerel notes that certain materials produce small amounts of electric current when exposed to light.

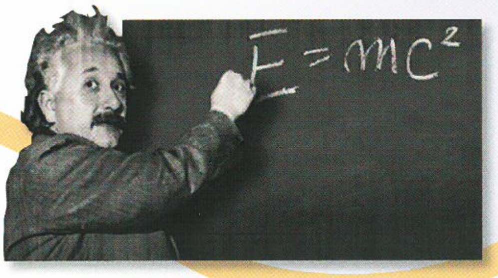
1897

J.J. Thomson discovers the electron and finds a value for charge to mass ratio for electron.



1900





1898

Marie Curie first uses the term radioactivity to describe unknown energy beams.

1900

Max Planck develops a theory to explain the spectrum from black-body radiation.

1905

Einstein concludes from Maxwell's work that light could only exist while it was moving and publishes his work on Special Relativity and that $E = mc^2$

1916

Einstein presents his theory of General Relativity.

1920

1923

Cecilia Payne determines that the Sun is 90% hydrogen. She was made to recant what she had written, but a few years later was proved correct.

$$R_{ab} - \tfrac{1}{2} R g_{ab} = \frac{8\pi G}{c^4} T_{ab}.$$

1917

Arthur Eddington investigates gravitational lensing of photons during an eclipse. The deflection of photons around distant stars supports Einstein's theory of General Relativity.

line of light

1885

Balmer showed that the lines seen on the hydrogen spectrum could be calculated using the mathematical formula:

$$\lambda = 91.16[1/2^2 - 1/n^2]$$

1887

Heinrich Hertz and Phillip Lenard make observations of light affecting the voltage of his spark-gap apparatus. Lenard continued this work on photoemission and was awarded the Nobel Prize in 1905.

1860

James Clerk Maxwell developes his equations for electricity and magnetism and proposes that light consists of magnetic and electric fields travelling through space.

1887

The Michelson-Morley experiment fails, helping support the constancy of the speed of light in Special Relativity.

1895

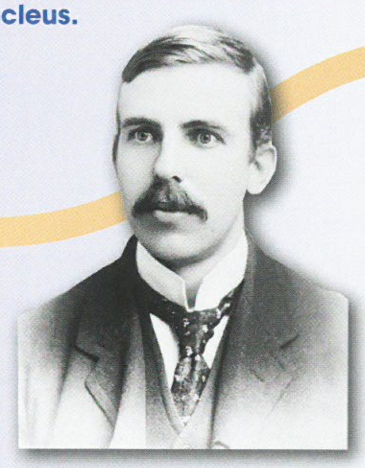
Becquerel and Marie Curie discover radioactivity.

1905

Einstein states that light is bundles of electromagnetic energy, called quanta. The photoelectric effect is used as proof that light has a particle nature. Einstein was awarded the Nobel Prize for this work in 1921.

1911

Ernest Rutherford suggests that the atom has all of its positive charge at its centre which he named the nucleus.



1910

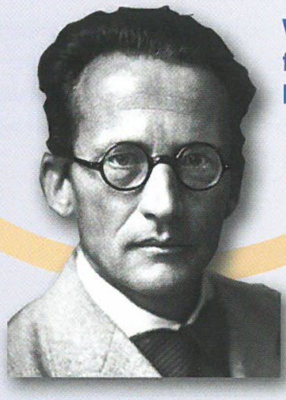
Robert Millikan determines a value for the charge on an electron (oil drop experiment).

1913

Niels Bohr determines an energy state model for hydrogen.

1924

Louis de Broglie postulated the wave nature of matter, suggesting that if light can have both a particle and a wave nature, then perhaps electrons can as well.



1925

Erwin Schrödinger develops his wave equation in which the electron is only allowed standing wave patterns.

1927

Werner Heisenberg puts forward his Uncertainty Principle.

1928

Paul Dirac predicts the existence of an electron-like particle with a positive charge.

Historical tim

1930

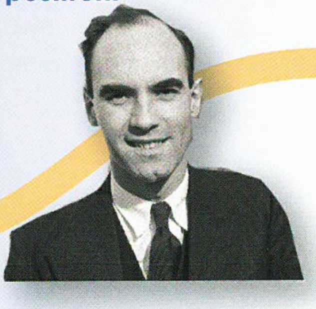
Wolfgang Pauli postulates the existence of a particle, later called the neutrino.

1933

Carl Anderson observes Dirac's particle and names it the positron.

1933

Hideki Yukawa proposes that nuclear particles are held together by a force caused by a particle. He calls the particle a nuclear force meson and predicts its mass ≈ 300 × mass e^- (later called pi-meson.)



1932

James Chadwick discovers the neutron.

1934

Enrico Fermi finds that slow neutrons can be captured by a nucleus much more readily than the fast neutrons that others were using.

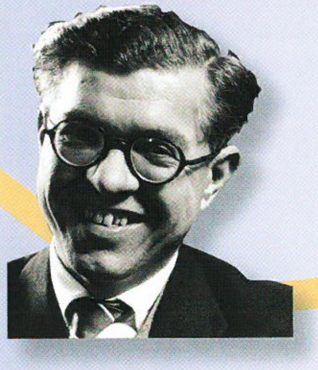
1950

1947

pi-meson found – fits the particle predicted in 1933 by Hideki Yukawa.

1956

Reines and Cowan discover the neutrino.



1946

Fred Hoyle suggests the heavier elements in the Universe, from carbon to iron, are synthesised by nuclear fusion (stellar nucleosynthesis) in pre-supernova type stars.

1947

Richard Feynman and Julian Schwinger develop the theory of quantum electrodynamics.

1970

1967

Steven Weinberg and Abdus Salam incorporate Higgs mechanism into Glashow's theory to produce the modern form.

1970

Current formulation finalised on the experimental confirmation of the existence of quarks at Stanford Linear Accelerator Centre. These were observed initially in 1968.

1977

Bottom quark discovered at Fermi lab

1974

Charm quark and tau lepton discovered at SLAC.

line of light

1940

1935

D. Anderson and Seth Neddermeyer discover a particle they call a muon.

μ

1938

Otto Hahn, Lisa Meitner and Robert Frisch split uranium nuclei into smaller fragment nuclei, but they don't realise it.

1937

J.C. Street and E.C. Stevenson confirm existence of the muon in a cloud chamber experiment.

1941

Rossi-Hall experiment – for the first time muons are used to observe time dilation/length contraction predicted by Special Relativity.

1960

1961

Sheldon Glashow combines electromagnetism and weak theory to produce the electroweak theory.

1964

Higgs particle theorised.

1964

Gell-Mann and Zweig suggest that Hadrons are composed of smaller particles – naming them quarks.

1964

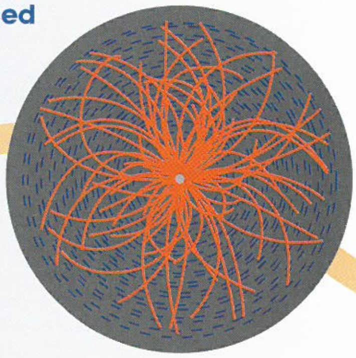
Arno Penzias and Robert Wilson accidentally discover a signal being received from all directions in the Universe suggesting that it was coming from a region in space far greater in size than our galaxy, thought to be left over from the Big Bang. NASA put a satellite into orbit around the Earth in 1989 to study this radiation. Results indicated it was emitted by a black body at a temperature of 2.735 K.

1990

2000

2000

Tau neutrino discovery announced after analysis of results from 1978



1994

Top quark discovered at Fermi lab – mass ≈ 185 × mass of proton.rel

2013

Higgs boson tentatively confirmed to exist by CERN using the LHC – brought about by further collision energy increases. The LHC energy has increased to 7 TeV of energy per proton in each direction. This is 7 times that of its predecessor at the Fermilab in the USA.

Waves and photons explained

Notes

The modern understanding of light

Any form of electromagnetic radiation exhibits properties that combine characteristics of discrete particles (i.e. energy is transferred in "bundles") and characteristics of waves (the best model to describe diffraction and interference).

Physicists accept the dual nature of light. They define light as a collection of one or more photons propagating through space as electromagnetic waves.

This dual nature is known as wave-particle duality. It is not an "either/or" situation. Duality means that the characteristics of both waves and particles are present at the same time. A photon will behave as a particle and/or as a wave depending on the experiment.

Photons

The light particle is known as a photon and it comes into existence when energy is released from an atom. In a simple atomic model, electrons orbit a nucleus made up of protons and neutrons. The electrons occupy separate energy levels, or orbitals. Each orbital can accept only a discrete amount of energy. If an atom absorbs some energy an electron in an orbital close to the nucleus (a lower energy level) can jump to an orbital that is farther away from the nucleus (a higher energy level). The atom is now said to be excited. This excitement generally does not last very long and the electron falls back into the lower energy level. A packet of energy, called a photon, is released. This emitted energy is equal to the difference between the high and low energy levels and, depending on its frequency, might be seen as light.

Waves

The wave form of light can be understood as energy that is created by an accelerating or oscillating charge. This produces an oscillating electric field and an oscillating magnetic field, hence the name electromagnetic radiation. Note that the two fields oscillate perpendicular to each other as shown in figure 12.1. Light is only one form of electromagnetic radiation. All forms are classified on the electromagnetic spectrum by the number of complete oscillations per second that the electric and magnetic fields undergo. This is called the frequency and has the unit cycles per second or hertz (Hz). The amount of energy depends on the frequency of the radiation. Gamma rays, the highest frequency radiation, are the most energetic photons in the electromagnetic spectrum.

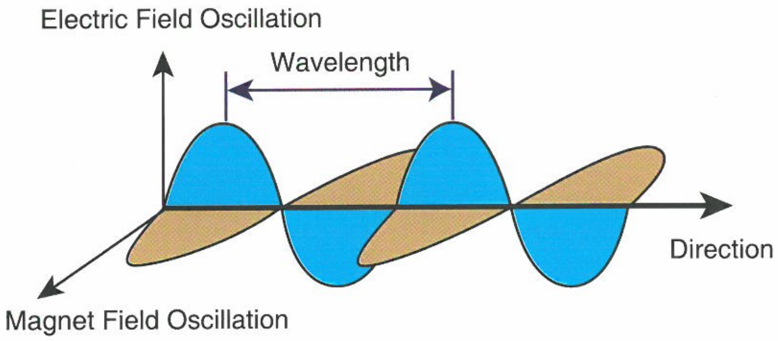
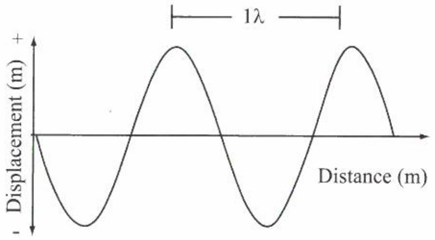


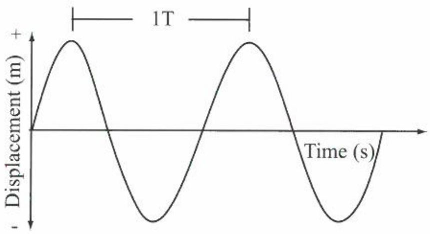
Figure 12.1: Electromagnetic radiation

Notes

Summary

- Light exhibits many wave properties; however, it cannot be modelled only as a mechanical wave because it can travel through a vacuum.
- Current understanding of the nature of electromagnetic radiation (emr), including light, states that emr has both wave and particle characteristics.
- Low energy electromagnetic radiation seems to be most noticeably wavelike and high energy electromagnetic radiation seems to be most noticeably particle-like.
- We can represent waves by a sine curve on a displacement-distance graph, or, if looking only at the motion of one point of the wave, on a displacement-time graph.





- A particle of electromagnetic radiation is called a photon. A photon has a discrete amount of energy called a quantum of energy. Each photon energy has its own characteristic frequency, found by using the formula:
  $E = hf$
- The following formulae apply to electromagnetic radiation whether we picture it as waves or particles.
  $f = \frac{1}{T}$ $c = \lambda f$

Term	Symbol	Definition	Unit
Energy	E	Photon energy	J
Wavelength	λ	The distance between two adjacent points in a wave which are in phase	m
Frequency	f	The number of crests or troughs which pass a point or per unit time, or the number of cycles per second	s^{-1}
Period	T	The time taken for one complete cycle, or the time taken for one complete wave to pass a given point	s
Speed of light	c	The speed of light is 3.00×10^8 m s^{-1}	m s^{-1}
Amplitude	a	The maximum displacement of a particle from its mean position	m
Planck's constant	h	6.63×10^{-34} J s	J s

- A wave model explains a wide range of light-related phenomena, including reflection, refraction, dispersion, diffraction and interference; a transverse wave model is required to explain polarisation.
- Electromagnetic waves are transverse waves made up of mutually perpendicular, oscillating electric and magnetic fields.
- Oscillating charges produce electromagnetic waves of the same frequency as the oscillation; electromagnetic waves cause charges to oscillate at the frequency of the wave.
- Energy and matter exhibit the characteristics of both waves and particles. Young's double slit experiment is explained with a wave model but produces interference and diffraction patterns even when one photon at a time or one electron at a time are passed through the slits.

Waves and photons explained

Notes

Reflection, refraction and diffraction

Reflection is when the wave bounces off a surface. The laws of reflection determine the wave's direction after reflection. When a sound wave is reflected, you hear an echo if the reflecting surface is sufficiently far away.

Refraction is when waves bend as they pass from one medium to another. The change in direction is caused by a change in the speed of the wave as it enters a new medium.

Diffraction occurs when a wave passes through a narrow opening (aperture). The greatest diffraction results when the width of the opening that the wave passes through is similar to the wavelength of the wave. Diffraction also occurs at the edges of an obstacle. In this case, waves of greater wavelength tend to diffract more noticeably.

The electromagnetic spectrum

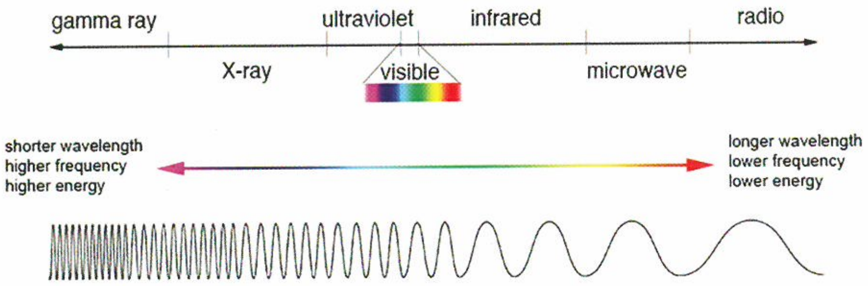


Figure 12.2: Electromagnetic spectrum (Picture credit: NASA)

Radio waves can be produced by electrons accelerating through conducting wires. They are used in radio and television communication systems.

Microwaves are also generated by electronic devices. Because of their short wavelengths, they are well suited for radar systems and for studying the atomic and molecular properties of matter. Microwaves interact with the molecular rotation energy levels in a molecule and can lead to molecules vibrating and causing an increase in temperature. Microwave ovens rely on this property.

Infrared waves are produced by molecules vibrating and are readily absorbed by most materials. Infrared (IR) energy absorbed by a substance appears as internal energy because the energy agitates the atoms of the object, increasing their vibrational or translational motion, which results in a temperature increase. Infrared radiation has practical and scientific applications in many areas, including physical therapy, IR photography, and vibrational spectroscopy.

Visible light is the most familiar form of electromagnetic radiation. It is the part of the electromagnetic spectrum that the human eye can detect. Light is produced by the rearrangement of electrons in atoms and molecules. The sensitivity of the human eye depends on wavelength, being a maximum at a wavelength of about 5.5×10^{-7} m.

Ultraviolet waves (UV) are also produced by the rearrangement of electrons in atoms and molecules. The Sun is an important source of UV light, which is the main cause of sunburn. Sunscreen lotions are transparent to visible light but absorb most UV light.

X-rays: The most common source of X-rays is the deceleration of high-energy electrons bombarding a metal target. X-rays are used as a diagnostic tool in medicine, as a treatment for certain forms of cancer and are also used to study crystal structure (because X-ray wavelengths are comparable to the atomic separation distances in solids - about 0.1 nm).

Gamma rays are electromagnetic waves emitted by radioactive nuclei (such as 60_{Co} and 137_{Cs}) and during certain nuclear reactions. High-energy gamma rays are a component of cosmic rays that enter the Earth's atmosphere from space. They are highly penetrating and produce serious damage when absorbed by living tissues.

Experiment 12.1: Making waves

Background

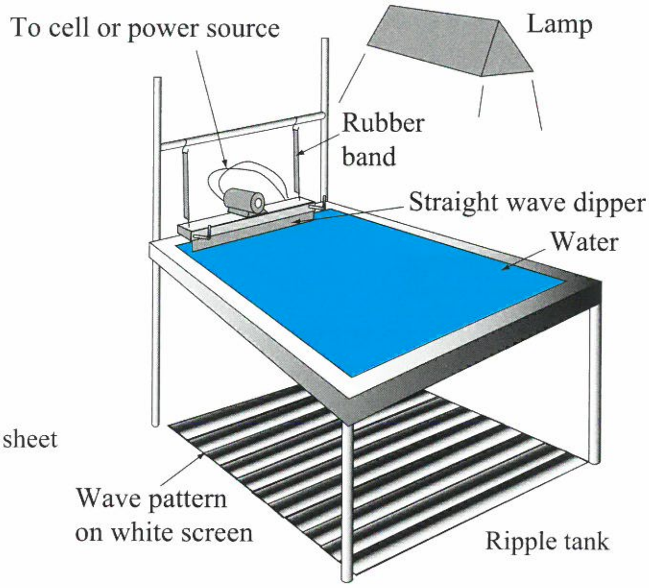
Mechanical waves are affected by various barriers, boundaries, apertures and media. When waves strike barriers they can be reflected. When they pass through apertures or pass edges their direction changes due to diffraction. When they pass from one medium to another, their velocity changes and so may change direction due to refraction. When two different waves collide they interfere. You can observe and study these wave properties using water waves.

Aim

This is a qualitative investigation designed to investigate various wave properties.

Equipment

- white paper
- stroboscope
- rheostat
- power supply
- leads
- ripple tank kit, including
    - motor
    - vibrator bar
    - dippers
    - reflectors
    - barriers and small Perspex sheet
    - overhead light



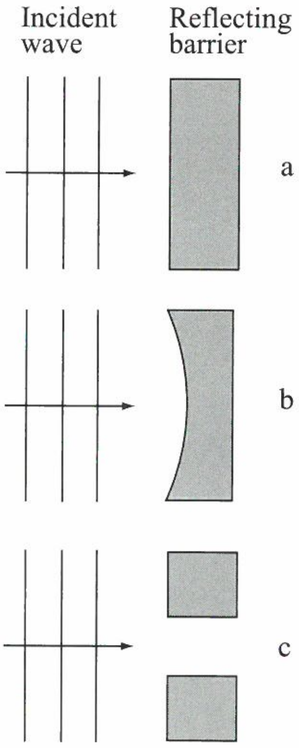
Pre-lab

- Set up the equipment as shown in the diagram.
- Place a lamp 50 cm above the tank.
- Arrange the equipment to show an image of ripple tank on a white backing.
- Add water to 5 mm depth in the tank. Adjust the tank to ensure it is level.

Lab notes

- Adjust the rheostat and observe the relationship between frequency of the vibrator and wavelength. Draw and describe what you observe.
- Place a flat barrier in the tank and observe "head on" reflection. Draw and describe what you observe.
- The diagram at right provides an outline which could be redrawn in your laboratory notebook and completed.

Notes



Experiment 12.1: Making waves

Notes

- Move the barrier so that the waves now strike it at an angle. Again describe and draw what you observe.
- Remove the barrier and replace it with a concave surface. Use the diagram as a guide to describe and draw what you observe.
- Turn the barrier around so that it is now a convex reflector. Describe and draw what you observe.
- Remove the barrier. Place the Perspex sheet into the tank to create a a shallow region. Draw a diagram to show the effect of the shallow water upon waves normal to it.
- Turn the sheet so that the waves are now incident at an acute angle. Draw what you observe.
- Place two barriers in the tank to create a small aperture. Draw what you observe.
- Use the rheostat and increase the wavelength. Again draw what you observe.
- Increase the aperture and repeat the previous two steps. Draw appropriate diagrams to show the observed effects.
- Remove one of the barriers and observe what occurs at the end of the remaining barrier. Describe and draw what you observe.
- Replace the bar with a dipper to create circular waves.
- Repeat all the previous steps using circular waves. Draw your observations.
- Remove the dipper, and replace it with two dippers. Draw what you observe.

Post-lab discussion

1. In which of the above experiments did you observe reflection?
2. In which of the above experiments did you observe refraction?
3. In which of the above experiments did you observe diffraction?
4. In which of the above experiments did you observe interference?
5. What is the general relationship between wavelength and diffraction?
6. How does this relationship explain the fact that sound travels around corners? Which wavelengths of sound would you expect to hear most easily around a corner?
7. Under what conditions would you expect sound waves to interfere?
8. Under what conditions would you expect sound waves to create a stable interference pattern similar to that created in your experiment? Describe what this pattern might sound like to a stationary observer, and to an observer who moves through the pattern.

Investigation 12.2: A short history of light

Notes

A Short history of light

500BC: Ancient Greek and Hindu philosophers viewed light as one of five fundamental elements.

400BC: Empedocles postulated that light is produced within the eye and that it interacts with the light that objects give off.

300BC: Greek philosopher Euclid published *Optica*. He described the law of reflection and questioned the origin of light within the eye.

55BC: Lucretius hypothesised that light is made up of particles from the Sun.

400: Buddhist philosophers Dignāga and Dharmakirti theorised that light is a stream of energetic particles, similar to our idea of photons today.

984: Ibn Sahl derived what will later be known as Snell`s Law in Baghdad. Not being an European, no one even considered giving him credit for it.

1011-1021: Alhazen wrote his seven-volume treatise on optics. He wrote "from each point of every colored body, illuminated by any light, issue light and color along every straight line that can be drawn from that point". He described his idea of the anatomy of the eye.

1621: Willebrord Snellius derived, but did not publish, a version of Snell`s law. He was posthumously awarded the credit.

1637: René Descartes published the first theory of refraction of light. This theory treated light as a wave phenomenon. It assumed that light travels faster in dense media (by analogy with sound). He independently derived Snell`s Law and was accused of plagiarism, despite the fact that Snell never published his work. Descartes got credit, but only in France.

1676: Ole Roemer calculated the speed of light using the timing of the eclipses of Jupiter's moons.

1680: Christiaan Huygens introduced the ether, a medium that light was thought to travel through.

1675: Newton published his *Hypothesis of Light*, which viewed light as particles that he called corpuscles. He explained refraction by allowing the particles to behave like a localised wave

1803: Thomas Young showed through experimentation that light passing through a double slit showed interference and thus wave properties. The wave explanation of Young's double slit demonstration was initially rejected until other physicists, including Fresnel and Poisson, showed that light was able to undergo diffraction, a property of waves.

1821: Augustin-Jean Fresnel showed mathematically that light can only be polarised if it is a transverse wave.

1847: Michael Faraday discovered that the plane of polarisation of light can be rotated by a magnetic field. This leads to the realisation that light is actually a high frequency electromagnetic wave.

Investigation 12.2: A short history of light

Notes

1860s: James Clerk Maxwell developed a theory of electromagnetism and showed that electromagnetic waves would travel through space at the speed of light implying that light was an electromagnetic wave.

1870: Daniel Colladon and Jacques Babinet demonstrated the first application of total internal reflection. This discovery is used in modern fibre optic cable.

1887: Albert Michelson and Edward Morley attempt unsuccessfully to detect the ether.

1900s: Max Planck resolved the 'Ultraviolet Catastrophe' mathematically by treating the light emitted by a blackbody as discrete particles, called quanta.

1900: Lord Kelvin is quoted to have said "There is nothing new to be discovered in physics now, All that remains is more and more precise measurement."

1905: Albert Einstein resolved a longstanding issue with the photoelectric effect by treating light as a particle. These particles were later called photons.

1924: Louis de Broglie showed that not only are waves capable of acting like particles, but particles can behave like waves.

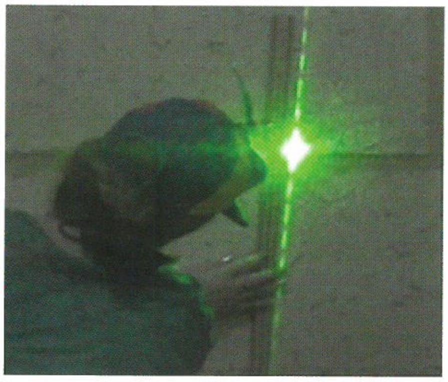
The task

The following scientists and philosophers contributed to our understanding of light today. For each write a short paragraph noting their contribution. Beside each denote with a P or a W to describe how they envisaged light – as particles (P) or as a wave (W).

- Empedocles (400BC).
- Euclid (300BC).
- Lucretius (55BC).
- Dignāga and Dharmakirti (400).
- Ibn Sahl (984).
- Alhazen (1011-1021)
- Willebrord Snellius (1621).
- René Descartes (1637).
- Ole Roemer (1676).
- Christiaan Huygens (1680).
- Isaac Newton (1675)
- Thomas Young (1803).
- Augustin-Jean Fresnel (1821)
- Michael Faraday (1847).
- James Clerk Maxwell (1860s)
- Daniel Colladon and Jacques Babinet (1870)
- Albert Michelson and Edward Morley (1887).
- Max Planck (1900s).
- Albert Einstein (1905).
- Louis de Broglie (1924).

Experiment 12.3: Finding the width of cotton thread

Background



Diffraction is the bending of a wave, including light around an object or through an opening. Light is diffracted by very small diameter objects, such as cotton thread, human hair or a slit in a piece of paper. In this experiment when the light wave is diffracted by the cotton thread, it creates an interference pattern. The distance between successive dark bands in the interference pattern is related to the size of the object that caused the scatter, in this case the thread. By measuring the distance between the dark bands you can calculate the width of the cotton thread.

Equipment

- laser pointer
- adhesive tape
- a room that can be darkened
- cardboard (10 cm × 15 cm)
- 8 cm of a fine cotton thread
- retort stand and clamp
- ruler

Lab notes

1. Make a frame to hold the cotton by cutting a 1 cm by 4 cm rectangle inside the piece of cardboard.
2. Tape each end of the 8 cm of fine cotton, as tightly as you can, across the middle of the inside rectangular cutout in the cardboard.
3. In a dark room, place a desk or table about 2 metres from a blank wall.
4. Using the retort stand and clamp hold the frame containing the cotton on the desk or table. Shine a laser pointer at the wall from just behind the cotton, making sure it hits the cotton along the way. You will see the light scatter to the sides as you hit the hair with your laser pointer.
5. Measure the distance in centimetres from your cotton to the wall.
6. Check the wavelength of light produced by your laser pointer. A red laser pointer will be about 650 nanometers and a green one will be about 532 nanometers. Usually this is listed on the laser pointer itself.
7. Measure the average distance between the "dark" lines by measuring the distance across the dark lines from the centre then dividing this value by the number of lines.

Post-lab discussion

Use the following equation to determine the thickness of the thread. Make sure that all of your measurements are in the same units, in this case centimetres.

$$d = \frac{\lambda L}{x}$$

where:

d is the diameter of the thread.

λ (lambda), is the wavelength of the laser, note that 650 nanometres = 0.000065 cm.

L is the distance to the wall (cm)

x is the average distance (cm) between the "dark" lines.

Further investigation:

Repeat the experiment to determine the thickness of a human hair.

Notes

Experiment 12.4: Observing light sources

Notes

Background

The range of photons emitted by a source is called its spectrum. Spectra can be classified as absorption or emission spectra. These can be further classified as line, band or continuous.

Aim

To observe various spectra using a direct-vision spectroscope.

Pre-lab

- Practise using a direct-vision spectroscope until you understand where the slit has to be pointed in order for you to see a useful image.
- Look through the hand held spectroscope at a light source. Adjust the slit and eyepiece to obtain a clearly focussed spectrum.

Caution: Do not look ***directly*** *at the Sun with your eyes or through the spectroscope.*

Part 1: Observing light sources

Lab notes

- View the following light sources through the spectroscope, observe and record the spectra produced.

  sodium vapour lamp neon lamp fluorescent lamp
  incandescent lamp bright blue sky

Post-lab discussion

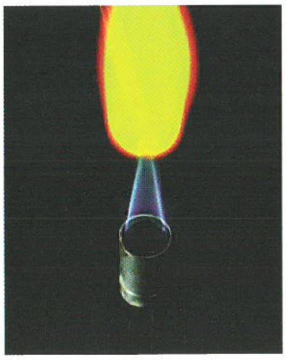
1. Draw a spectrum of each of the light sources. Label the colours seen.
2. Comment of similarities between the spectrum of the sodium lamp, neon lamp, and the fluorescent light tube.
3. Comment of similarities and differences between the solar spectrum and the incandescent lamp spectrum.

Caution: these salts are toxic if ingested. Wash your hands after handling them.

Part 2: Observation of the spectra of heated compounds

Lab notes

- Adjust the flame of a Bunsen burner until it is very pale blue.
- Using a platinum or nichrome wire, heat a loopful of sodium chloride in the flame until it fuses and vaporises. Record your observations.
- Repeat using calcium chloride, strontium nitrate and barium nitrate. Use a different loop for each salt.



Post-lab discussion

1. Draw diagrams of the spectra observed through the spectroscope, labelling the colours seen.
2. Comment on the similarities of the flame colours of calcium and strontium nitrate. Can you separate the two salts on the basis of their spectral colours?
3. What are the main differences between the spectrum of the sodium vapour lamp and the spectrum of sodium chloride?
4. What is the difference between a continuous emission spectrum and a line emission spectrum? Identify each with reference to your experiment.
5. It is possible to produce a spectrum for each element by using an electric discharge or arc between two electrodes that contain a sample of the element. Using this method how could you determine which elements are present in a mixture of substances?
6. Calculate the frequency and wavelength of a photon resulting from an electron in the hydrogen atom moving from one energy level to another with an energy difference of 10.21 eV.
7. How do scientists gain information about the composition of distant stars?

Experiment 12.5: Line spectra

Background

After gaining energy (e.g. from high-temperature atomic collisions, or by absorbing a photon) an atom quickly loses this energy by emitting one or more photons.

Equipment

- gas discharge tubes
- an induction coil and DC power pack
- direct vision spectroscopes
- darkened room

Pre-lab

- Mount the gas discharge tube vertically using a retort stand and clamp.
- Connect the high voltage terminals of the induction coil to the discharge tube terminals.
- Connect the primary terminals of the induction coil to the DC terminals of the power pack. Set the power pack to the required voltage and turn on. Be sure to follow the manufacturers' safety rules.

Lab notes

- Examine the light emitted by the tubes through a direction vision spectroscopes. Record your observations.
- Choose one tube and estimate the wavelength and frequency of each line in its visible spectrum. This may done by using the wavelength markings on the display in the spectroscope if these are provided. If not, find out the approximate frequency or wavelength range for each colour in the spectrum and estimate the characteristics of the visible lines that way.

Post-lab discussion

1. Sketch the emission spectrum for each tube you observed. Label line colours clearly.
2. Consider the element for which you estimated the wavelengths and frequencies of the lines. Work out the photon energies involved and construct a partial energy level diagram for that element. Show clearly the size and direction of each transition responsible for a spectral line.
3. Why is this a partial energy level diagram?
4. Are any of the lines that you observed the result of transitions to or from ground state? Explain.

Notes

Experiment 12.6: Band spectra

Notes

Background

Gaseous atoms create line spectra by emitting or absorbing light at particular frequencies or wavelengths. Compounds behave differently, by emitting or absorbing many frequencies or wavelengths – in effect, creating bands rather than lines.

Equipment

- coloured filters
- solutions of coloured salts (copper sulfate, nickel sulfate, cobalt chloride, very dilute potassium permanganate) or vegetable dyes, in parallel-sided glass or plastic containers
- white light source
- direct vision spectroscopes
- darkened room

Pre-lab

- Set up the white light lamp so it shines toward the viewing location.
- Check where the spectroscope has to be placed to obtain a bright, clear spectrum.

Lab notes

- While one group member observes the spectrum from the white light source, another member inserts a filter or sample of coloured liquid between the lamp and the spectroscope. Note changes in the spectrum when the coloured material is introduced, and record your observations. While still observing the spectrum, have the filter or solution sample removed.
- Repeat this for filters or solutions of a range of colours.

Post-lab discussion

1. Did you observe emission or absorption spectra? How can you tell?
2. Choose any two different coloured materials and explain how they caused the spectrum that you observed.
3. Line spectra can be used to identify individual elements by matching the locations and brightness of several lines. Could band spectra be used in a similar way? Explain.

Experiment 12.7: Detecting infrared radiation

Background

Most television remote control units work using invisible infrared radiation. Infrared radiation has longer wavelengths than visible light and is affected differently by obstacles in its path.

Notes

Aim

To investigate diffraction, absorption and transmission of beams of visible and infrared radiation.

Equipment

- television set and remote control unit
- hand mirror
- clear glass or plastic container with flat, parallel sides
- electric torch
- flour or baby powder
- water

Pre-lab

- Prepare a table to record your results.
- Find a place that allows a direct line, between 2 to 3 metres, from you to the television set.
- Darken the room.
- With the television off, check that you can see the light from the torch reflecting from the screen.
- Check that the remote control also works from your chosen position.

Lab notes

- Get your lab partner to stand directly in front of the screen, about halfway between you and the television. Operate the remote control "on" button and record the result. Shine the torch beam at the television and record the result.
- Get your lab partner to stand off to one side, about halfway between you and the television, holding the hand mirror. Point the torch at the mirror, and move the mirror around until it shines on the screen. Now point the remote control at the mirror, operate the remote control "on" button and record the result.
- Repeat this using just the lab partner's body (that is, without the mirror).
- Get your lab partner to blow a small amount of flour or baby powder into the air between you and the television. Try to turn on the television through the cloud; then repeat, using the torch. Record your results.
- More than half fill the container with water. Hold the water directly in front of the torch, then the remote control, while pointing at the television. Record your results.
- Get your lab partner to hold one hand between you and the television, at several distances from the remote control unit. Record when the hand obstructs the infrared beam and the visible light beam.

Post-lab discussion

1. Make general statements about the observed behaviours of infrared and visible beams.
2. Explain your observations in terms of the relative wavelengths of infrared and visible light.
3. Why would television manufacturers use infrared rather than visible light beams in their remote control units?
4. Infrared sensors can locate people in total darkness, but do this best when the air temperature is low. Explain.
5. Infrared sensors can locate the seat (hottest part) of a fire, but have difficulty detecting hot objects in rain, cloud or fog. Explain.

Experiment 12.8: Detecting ultraviolet radiation

Notes

Background

Human eyes are not able to see ultraviolet (UV) light as a colour. We can however see the result when UV light shines on a fluorescent material.

Aim

To use fluorescence to detect ultraviolet light.

Equipment

- two clear, plastic cups
- waterproof markers
- one litre of tap water
- one litre of tonic water
- black backdrop material (cloth, paper or felt, roughly A4 size)
- access to direct sunlight or a source of UV radiation ("black light")

Safety note*: UV is harmful if it shines directly into your eyes.*
If you use a black light source, use a shield to protect your eyes from direct UV emissions.

Pre-lab

- Label the plastic cups "tonic" and "water."
- Nearly fill each cup with tonic water or water as required.
- Place the cups in direct sunlight, or place a UV source above the cups, so that sunlight, or UV radiation, strikes the liquid surface in both cups.

Lab notes

- Hold a backdrop behind the cups to increase contrast. Looking through the sides of the cups, observe the surfaces of the liquids.
- Record your observations.

Post-lab discussion

1. Which material is fluorescent? What is your evidence?
2. How do you know that the cup is not fluorescent?
3. Tonic water contains water, sugar and quinine. Suggest how you could determine which one or more of these ingredients causes the fluorescence.
4. Many common substances are fluorescent. If you are using a black light source, test a range of objects and record the results. Do all fluorescent objects glow with the same colour? If so, what colour is it?
5. If you used sunlight, describe how you would test whether the position of the Sun in the sky makes a difference.

Extensions:

- If time permits, you can see how UV light is affected by passage through glass, Perspex, or cellulose acetate (used to make some overhead transparencies).
- How could you test the efficiency of sunscreens of different SPF values?

Investigation 12.9: Light intensity

Measuring light intensity

You can use a photographic light meter or a 35 mm camera with in-built exposure meter to compare light intensities.If you are using a light meter be sure to use the diffusing screen accessory. If you are using a camera you will obtain more reliable results if you use a diffusing screen in front of the lens. A piece of frosted glass or a piece of greaseproof paper will both work. The film's exposure is controlled by the shutter speed and the f-stop number which is a measure of the lens aperture size. For a given fixed shutter speed the f-number needed for correct film exposure is an indirect measure of the light intensity. In fact, the light intensity I is directly proportional to the square of the f-number f. For example, if light intensity increased by a factor of 4 then the f-number would have to increase by a factor of 2.

$$I = \text{constant} \times f^2$$

If you are using a photographic light meter, set the film speed to 400 ASA, hold up the meter to the light source and determine the f-number required at a shutter speed of $\frac{1}{60}$ s. By always using the same film speed and shutter speed settings the square of the f-number (f^2) will be your measure of light intensity.

If you are using a camera with an in-built exposure meter, set the film speed to 400 ASA and the shutter speed to $\frac{1}{60}$ s. Point the camera at the light source and determine the f-number needed for correct exposure. By leaving the film speed and shutter speed settings fixed, the square of the f-number (f^2) will be your measure of the light intensity.

Notes

Part 1: Comparing light sources

Background

The aim of this activity is to compare the relative intensities of several light sources. Read the section above on Measuring light intensity before you start.

Equipment

- Photographic light meter or a camera with in-built exposure meter
- light sources, e.g. various sizes of incandescent lamps, spotlights etc.
- metre rule or tape measure
- darkish room

Pre-lab

Position the light measuring device a fixed distance from the brightest lamp.
Select a shutter and film speed that gives you an exposure of f/16.

Lab notes

Keeping both the distance and the film speed fixed, determine the f-numbers needed for the other lamps. Record your results in a suitable chart.

Post-lab discussion

1. Plot a suitable graph of the square of the f-number (f^2) vs lamp type.
2. Which lamp gave the highest intensity?
3. Does the most intense lamp have to be the most efficient? Explain.

Investigation 12.9: Light intensity

Notes

Part 2: Variation of light intensity with distance

Background

The further you are from a lamp the less intense is its light. In this activity you are to investigate how the intensity of the light varies with the distance from the light source. Read the section above on page 153 'measuring light intensity' before you start.

Equipment

- Photographic light meter or 35 mm camera with in-built exposure meter
- 100 W, 240 V incandescent lamp or a compact fluorescent lamp of about 15 W
- metre rule or a tape measure
- darkish room

Pre-lab

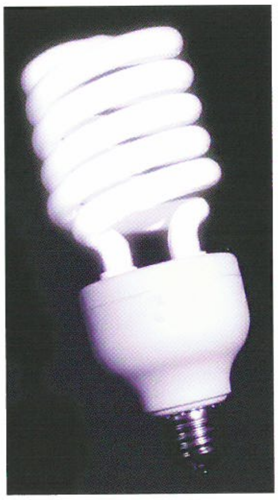
- Draw up a table for recording your results.
- Position the light measuring device approximately 1 m from the lamp.
- Select a shutter speed and film speed that gives you an exposure of approximately f/16.

Lab notes

- Vary the distance d between the lamp and device so that the exposure is exactly f/16. Record the distance in your table.
- Determine and record the distance that will give an exposure of f/11.
- Repeat this for the other f-numbers in the table.

Post-lab discussion

1. Plot a suitable graph of the square of the f-number (f^2) vs distance d.
   Comment on the general shape of the graph.
2. Plot a graph f vs $\frac{1}{d^2}$.
   Comment on the general shape of this graph.
3. Find a simple mathematical relationship between f and d.



Part 3: Turning up the volts

Background

Increasing the voltage applied to a lamp will usually make it brighter. Devise and conduct an experiment that investigates how the intensity varies with the applied voltage. Read the section above on on page 153 'measuring light intensity' before you start.

Equipment

- photographic light meter or camera with in-built exposure meter;
- metre rule
- power pack, 0 - 12 V
- voltmeter, 0 - 15 V
- 12 V, 36 W incandescent lamp
- rheostat, 0 - 11 W
- connecting leads

Pre-lab

Plan your investigation.

Post-lab discussion

Be sure to present your findings in an appropriate way.

Investigation 12.10: Fluorescence

Equipment

- UV 'black light' source
  *(**CAUTION:** do not look directly at the light source when it is turned on)*
- a range of fluorescent materials such as: the minerals fluorite or calcite; soap powder
- quinine sulfate or fluorescine solution; motor oil; vaseline smeared on paper; zinc sulfide; highlighter pens of various colours

Pre-lab

- A darkened room works best.

Safety note: UV is harmful to the unprotected eye. Make sure that no-one can see the UV lamp directly when it is turned on.

Lab notes

- Compare the colours of the materials when viewed under white light and when viewed under ultraviolet light.
- Explain what happens in terms of photons and energy levels.

Post-lab discussion

1. Explain the difference between 'fluorescence' and 'phosphorescence'.
2. Were any of the materials that you observed phosphorescent? How do you know?
3. What makes a UV lamp more potentially harmful to your eyes than a normal bright lamp?
4. Some insects that feed on nectar and pollen from certain flowers have eyes that can detect UV light. Are the flowers on which they feed likely to be fluorescent, or non-fluorescent? Explain.

Notes

Problem set 12.1: Waves and photons

Notes

1. What is meant by stating that light is transmitted as an electromagnetic wave?

2. (a) Two light sources are described as coherent. What does this mean?
   (b) Would the light from two identical incandescent lamps be coherent? Explain.

3. The energy of an electron depends on its velocity. All photons in air have the same velocity. How is it that photons in the visible spectrum with different colours can have different energies?

4. A red LED emits light with a frequency of 3.85×10^{14} Hz. What energy would be associated with the photons produced?

5. The photons in a beam of electromagnetic radiation have an energy of 1.00×10^{-17} J. What will be the photon frequency and to what part of the electromagnetic spectrum does it belong?

6. A long range surveillance radar unit operates at a frequency of 1.30 MHz.
   (a) What is the energy of one quantum of electromagnetic radiation emitted from this radar?
   (b) What would be the wavelength of a photon in this beam?
   (c) What would be the velocity of an electron that has the same kinetic energy as the energy of an individual photon in this radar beam?

7. A microwave oven has a power rating of 1100 W and operates at a frequency of 2650 MHz.
   (a) Calculate the wavelength of the radiation produced.
   (b) What is the energy of each photon produced?
   (c) A cup of water is heated in this microwave oven for 2.50 minutes in preparation for making a cup of coffee How many photons are produced by the oven in this time assuming 100% efficiency?

8. An individual laser diode emits radiation of wavelength 905 nm at a peak power of 34 W and a pulse length of 150 ns.
   (a) To which part of the electromagnetic spectrum does this radiation belong?
   (b) What is the energy of a photon produced under these conditions?
   (c) How many photons are in each pulse?

9. Television antennas are mounted in the horizontal and not the vertical plane. Explain why this is done?

10. A microwave transmitter transmits a 1.52×10^{9} Hz signal at an average power of 5.00 W. The microwaves are emitted in pulses of duration 1.50 μs, the time between pulses being 4.00 ms.
    (a) Calculate the wavelength emitted.
    (b) What is the energy of each photon?
    (c) How many photons are emitted by the transmitter each second?
    (d) Calculate the power output of each pulse of radiation.

11. A green laser of wavelength 435 nm is used to burn data onto plastic DVDs and CDs. Calculate the energy transferred to the disc by such a laser beam if it produces 3.25×10^{18} photons every second and it is focused on the disc for 1.2 ms.

12. A 1.00 W ruby laser emits monochromatic light of wavelength 694 nm.
    (a) What is the energy per photon in the beam produced by this laser?
    (b) What is the intensity of the laser beam if its cross sectional area is 10.0 mm^2?
    (c) The average intensity of sunlight at the Earth's surface is about 1000 W m^{-2}. Compare the intensity of this laser beam with the average intensity of sunlight.

Notes

13. The human eye is adapted to seeing, most clearly, colours in the middle of the visible spectrum. The retina can detect yellow light with a wavelength of 6.00×10^{-7} m at a minimum power of only 1.70×10^{-8} W. What is the minimum number of photons per second that the human eye can detect at this wavelength?

14. One of the ABC radio stations in Perth transmits on the AM band at a frequency of 720 kHz using a 50.0 kW transmitter. This transmission is continuous over any 24 hour period.
    (a) At what wavelength does it transmit?
    (b) Estimate how much energy it sends out per 24 hour broadcast period.

15. The air traffic control tower at Perth Airport monitors the movement of all aircraft in the vicinity of that airport. It uses radar that emits microwaves with an average energy per photon of 2.00×10^{-24} J.
    (a) What is the frequency of these microwaves?
    (b) What is the wavelength of these microwaves?
    (c) How does the energy, frequency and wavelength of these microwaves compare with those of visible light? Give your answers as higher, lower or greater or smaller.

16. A method for determining water depth in oceans, up to around 70 metres, can be found by shining an intense beam of laser light pulsed at around 900 pulses per second from an aircraft vertically onto the surface of the water and measuring the difference in the time taken to receive back the pulses reflected from bottom and surface of the water. The device uses a beam splitter to split a green laser beam into a green beam and an infrared beam. The infrared beam is reflected from the surface and the green beam from the bottom. The green light has a wavelength of 532 nm in air, which decreases by 25% in water.
    (a) Why is a green and not infrared laser used to reflect from the bottom?
    (b) Why does this beam need to have a high intensity and what is meant by "high intensity"?
    (c) What is the wavelength of this green laser light in water?
    (d) What is the frequency of this light beam in water?
    (e) If the difference in time between receiving the two reflected pulses is 3.8 µs, estimate the depth of the water.
    (f) If the pulses are all 1.00 µs long, what is the power of each green photon?

17. Yellow incandescent filament lamps can be used in outside areas to help control insects at night. A globe in one such lamp is rated with a power output of 75.0 W and the frequency of the maximum intensity photons it emits is 5.28×10^{-16} Hz with. This globe gets very hot when operating.
    (a) Explain why the temperature of this globe will increase.
    (b) Draw a graph of what you think the distribution of blackbody radiation from this globe would look like. Make sure you clearly indicate colours on the relevant axis.
    (c) Calculate the wavelength of the highest intensity photons.
    (d) Calculate the energy, in eV and joules, of the photons with the greatest intensity.
    (e) How many such photons would be emitted by this globe per second?
    (f) Why would it not be possible to determine the number of photons from experimental measurement?

Photoelectric effect explained

Notes

The photoelectric effect is the process of emission of electrons from a metal surface when that surface is irradiated with light in the range from infrared to ultraviolet. It is classed as a low energy phenomenon.

Heinrich Hertz (1887) noticed, in his experiments with electrical discharge, that electrodes more readily produced an arc when they were irradiated with UV light.

Observations made and experiments conducted on these effects were in direct conflict with Maxwell's Electromagnetic Wave Theory, which assumed that the production, transmission and absorption of electromagnetic radiation could be described by using the properties of continuous waves.

Planck postulated light is radiated or absorbed in packets (called them quanta), the energy of which is proportional to their frequency: $E = hf$

Albert Einstein used this to explain the photoelectric effect and why it did not obey the wave theory. He published a paper in 1905, for which he received the Nobel Prize in 1921, in which he explained the emission of photoelectrons being caused by light having discrete quantised packets of energy (following on from the Quantum Theory of Planck) and behaving as particles, not waves. His explanation of the photoelectric effect was therefore that of a particle collision.

Experimental evidence shows:

1. For photoelectrons to be emitted from a metal surface there is a minimum frequency (energy) needed in the incident radiation below which no photoelectric emission will occur. This frequency is called the threshold frequency for that metal. It is different for all metals.

   e.g. Caesium – yellow – 5.16×10^{14} Hz
   Potassium – green – 5.53×10^{14} Hz
   Calcium – violet – 6.93×10^{14} Hz
   Magnesium – ultraviolet – 8.83×10^{14} Hz

2. The kinetic energy of the emitted photoelectrons is independent of the intensity of the incident light.

3. An increase in intensity of the incident radiation causes more photoelectrons to be emitted. The photoelectric current is directly proportional to the intensity of the incident light provided its frequency is above the threshold frequency.

4. The higher the frequency of the incident radiation above the threshold frequency the greater the number of photoelectrons emitted.

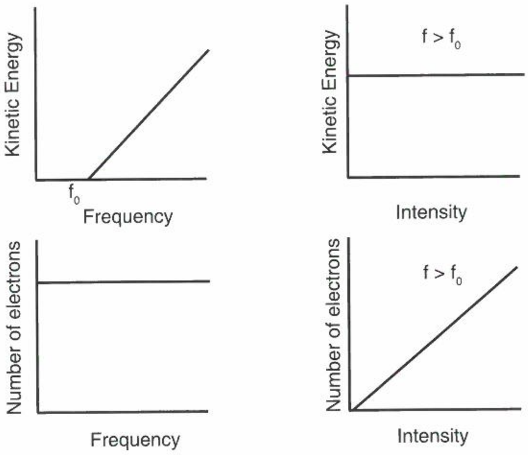


Figure 12.3:Characteristics of the photoelectric effect

The table below gives the work function for a number of surfaces - both in joules and in electron volts. The threshold frequency for each surface is also included.

Notes

Element	W (Joules)	W (eV)(V)	f_0 (frequency) (Hz)	λ_0 (wavelength) (nm)
Sodium	3.8×10^{-19}	2.40	5.8×10^{14}	520
Caesium	3.0×10^{-19}	1.88	4.5×10^{14}	666
Lithium	3.7×10^{-19}	1.88	5.6×10^{14}	560
Calcium	4.3×10^{-19}	2.69	6.5×10^{14}	462
Magnesium	4.3×10^{-19}	3.69	8.9×10^{14}	337
Silver	7.6×10^{-19}	4.75	11.14×10^{14}	263
Platinum	10.0×10^{-19}	6.75	15.1×10^{14}	199

Experiment 12.11: The photoelectric effect

Notes

In 1905, during his "miracle year," Albert Einstein published five papers. These included special relativity, which dealt with space and time, as well as general relativity, which related mass and energy through the equation $E = mc^2$. However, Einstein won his only Nobel Prize for work he did that same year on the photoelectric effect.

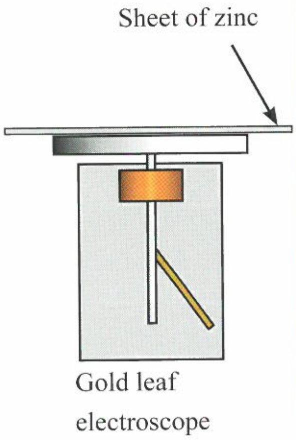
At the time, it was known that light shining on certain materials could knock out electrons to produce a current. It stood to reason that the stronger the light, the greater the current. Researchers also found that how much of a kick the electrons got (or how much kinetic energy they had) depended on the color of the light. Many scientists expected a stronger light would also release an electron with greater energy.

It took Einstein's brilliance to understand why the color (or frequency) of the light played such a key role in determining how much energy the electrons came away with. The consequences of this insight, along with the contributions of many other scientists, lead to the development of quantum mechanics, which is the basis for the modern electronic world.

This experiment introduces you to the photoelectric effect and guides you to recreate the type of data Einstein interpreted.

Equipment

- piece of zinc metal
- short lead/wire
- source of visible light (incandescent lamp)
- source of ultraviolet light - carbon arc lamp or a strong "black light" or laser pointer/pen
- sandpaper or steel wool
- plate of glass
- electroscope (gold leaf)



Lab notes

1. Rub the piece of zinc with a piece of sandpaper or steel wool. This removes oxides to expose the metal.
2. Discharge the electroscope by touching your finger to the electrode.
3. Using a very short lead/wire, attach the zinc to the electroscope.
4. Darken the room.
5. Shine the light from an ultraviolet source onto the zinc.
6. Observe the effect on the electroscope leaves.
7. Discharge the electroscope and shine visible light onto the zinc.
8. Observe the effect of shining the ultraviolet source through a pane of glass that transmits mostly visible range light, but hardly any ultraviolet light.
9. Charge the electroscope positively using a charged glass rod and observe the effect of shining ultraviolet light on the zinc.
10. Charge the electroscope negatively using a charged polythene rod and observe the effect of shining the ultraviolet light on the zinc.

Post lab discussion

1. Compare the effect of the ultraviolet source and the visible source.
2. compare the effect of shining the ultraviolet source through a pane of glass that transmits mostly visible range light, but hardly any ultraviolet light.
3. Ultraviolet light shining on a piece of zinc results in a charge separation. This charge causes the leaves of a negatively charged electroscope to separate further and causes the leaves of a positively charged electroscope to come together. This indicates the charge is negative or, more specifically, consisting of electrons. Visible light does not result in this charge being developed in the zinc.

Problem set 12.2: The photoelectric effect

Notes

1. The photoelectric effect was explained by Einstein, using the idea of Planck, that light consisted of photons with discrete energies dependent on their frequency. Explain how the photoelectric effect is used as evidence for the particle nature of light.

2. An experiment on the photoelectric effect was conducted and the maximum energy of the emitted photoelectrons measured at two different frequencies. When a wavelength of 4.00×10^{-7} m was used the maximum energy of the emitted electrons was 1.40×10^{-19} J and with an incident wavelength of 3.00×10^{-7} m the energy was 3.06×10^{-19} J. From these data derive a value for Planck's constant.

3. Green light with a frequency of 6.7×10^{14} Hz is incident on a caesium metal surface with a work function 2.14 eV. What is the maximum kinetic energy of an electron emitted from this surface as a result of this collision?

4. The work function of aluminium is 4.08 eV.
   (a) What does the term "work function" mean in this context?
   (b) What is the maximum wavelength of photons incident on this surface that will cause photoelectrons to be emitted?

   An aluminium surface is irradiated with ultraviolet radiation of frequency 2.39×10^{15} Hz.
   (c) Calculate the maximum kinetic energy of the photoelectrons emitted from this surface under these conditions.

5. Whether electrons are, or are not, emitted from a metal surface that is illuminated by light depends on certain factors. State how, if at all, the following properties or factors affect the emission of photoelectrons from a metal surface.
   (a) The thickness of the piece of metal.
   (b) The area of surface illuminated.
   (c) The length of time for which the surface is illuminated.
   (d) The type of metal the surface is made from.
   (e) The wavelength of the incident light.
   (f) The intensity of the incident light beam.
   (g) The cleaniness of the surface.

6. A nickel surface, work function of 5.01 eV, in an evacuated chamber is irradiated with light of wavelength of 325 nm.
   (a) What stopping potential will prevent the emitted photoelectrons from travelling between the pair of plates in the chamber?
   (b) The intensity of the incident light is doubled but the frequency remains constant. What effect will this have on the stopping potential? Explain your answer.

Problem set 12.2: The photoelectric effect

Notes

7. The threshold frequency for aluminium is 1.25×10^{14} Hz.
   (a) Calculate the work function of aluminium in both joules and electron-volts.
   An aluminium surface was then irradiated with blue light with a frequency of 6.95×10^{14}Hz and the resultant emitted electrons analysed. Calculate, showing all working:
   (b) The wavelength of the incident blue light.
   (c) The energy of the incident photons in both joules and electron-volts.
   (d) The maximum kinetic energy of the emitted photo-electrons
   (e) The maximum velocity of the emitted photo-electrons.

8. The surface of a piece of cadmium is irradiated with electromagnetic radiation of wavelength 287 nm. Photoelectric emission stops when a reverse potential of 3.68 V is applied between the anode and cathode of the photoelectric cell.
   (a) From this data calculate the work function of cadmium in joules.
   (b) Calculate the maximum velocity of electrons emitted.

9. An experiment is conducted where the surfaces of both platinum and sodium are irradiated with blue light of wavelength 465 nm. Photoelectrons are found to be emitted from the sodium surface but not the platinum surface.
   (a) Explain why this different effect has occurred with the two metal surfaces.
   Explain the effect each of the following changes would have on the photoelectric current for each of the metals.
   (b) The intensity of the incident beam is increased.
   (c) The blue light was replaced with a light of much longer wavelength.
   (d) The blue light was replaced with a light of much shorter wavelength.
   (e) A small reverse potential is applied between the anode and cathode of the photoelectric tube.

10. Ultraviolet light with a wavelength of 3.55×10^{-7} m from a mercury vapour lamp strikes a clean metal surface with a work function of 2.64×10^{-19} J and causes photoelectrons to be emitted.
    (a) What is the frequency of the incident ultra-violet radiation?
    (b) What is the energy of a single photon incident on this surface?
    (c) What is the maximum kinetic energy any photoelectron emitted from this surface can have?
    (d) What is the longest wavelength of radiation that will eject photoelectrons from this surface?

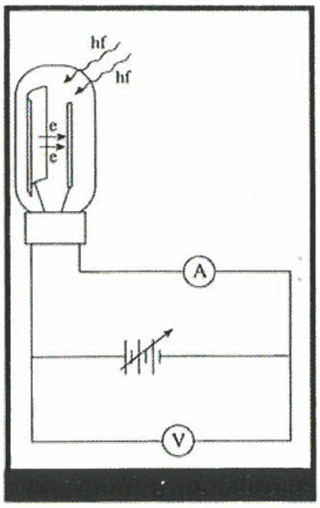
11. One type of smoke detector contains a photocell, a device that reacts to the amount of light falling on it, and a small permanent light source. If smoke enters the detector, reducing the intensity of light falling on the photocell below a minimum value, the current change in the circuit will set off the alarm. How does the presence of smoke affect the emitted photoelectrons? Does it change their number or their energy or both? Explain.

12. The following data comes from an experiment using a photocell coated with magnesium. The frequency of the incident light was varied and the maximum kinetic energy of the emitted photoelectrons was determined at each frequency.

Notes

Frequency	Kinetic energy (J)
1.0×10^{15}	6.0×10^{-18}
1.2×10^{15}	1.9×10^{-19}
1.4×10^{15}	3.3×10^{-19}
1.6×10^{15}	4.6×10^{-19}
1.8×10^{15}	5.3×10^{-19}
2.0×10^{15}	7.2×10^{-19}

(a) Plot a graph of kinetic energy against frequency.
(b) From the graph determine each of the following.
  (i) The threshold frequency of magnesium.
  (ii) An experimental value for Planck's constant.
  (iii) The work function of magnesium.



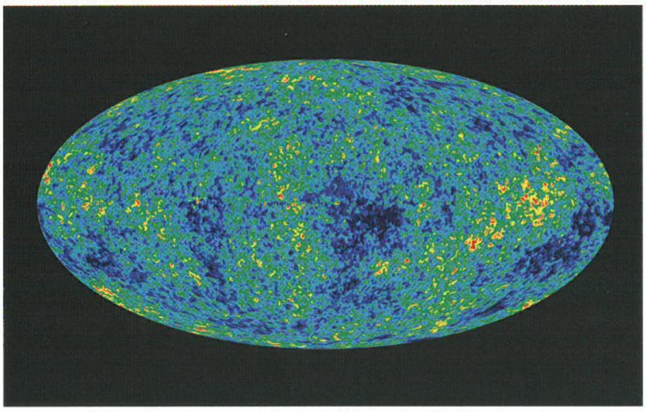
Black body radiation and radio astronomy

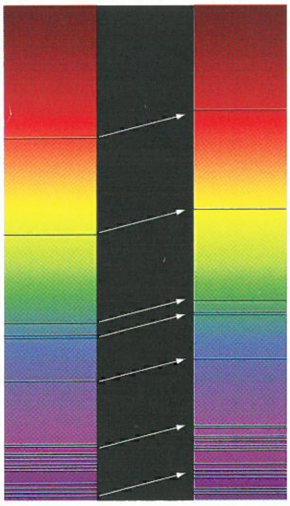
Black Body Radiation

Objects emit thermal radiation which, depending on the emitting body's temperature, can be in the infrared, visible or ultraviolet part of the electromagnetic spectrum. This radiation is produced by the vibrational motion of the atoms and molecules in that object; the hotter the object, the greater the vibration, and hence the higher the frequency of emitted radiation. However, this reasoning would suggest that if you were to create a fire hot enough you would be able to heat an object to a temperature where it could produce X-rays or even gamma rays.

But it is not possible to generate more and more powerful forms of electromagnetic radiation. This limit was a great puzzle at one time; why a sufficiently heated body does not cross over the threshold so that it produces ultra-violet radiation (the "ultraviolet catastrophe"). It was Max Planck who discovered the limits imposed by quantum mechanics. The amount of energy that a photon can receive from heating due to combustion cannot be greater than the quantised energy allowed when vibrating molecules jump to a lower energy level. This energy can be no more than is acquired when molecular bonds are broken in the combustion process. The quantised nature of thermal radiation also explains why radiation from a cool object is not able to increase the temperature of a warmer object.

Astronomers use the relationship between temperature and colour to determine the surface temperatures of stars. **Red stars are cooler than orange stars, which are in turn cooler than blue stars** (as shown in the image). If we study the spectrum emitted by the Sun and plot its intensity against wavelength we obtain a graph very similar to that from a tungsten filament light globe, with the greatest intensity from both being yellow light with a wavelength of around 5×10^{-7} m. The operating temperature of a tungsten filament is around 5800 K so we can conclude that the surface temperature of the Sun must also be around 5800 K. This idea can be applied to most other stars. Measurement of the maximum-intensity wavelength in their spectrum enables their surface temperatures to be determined. The latest research on black body radiation, with the potential to give a greater insight into the formation of the Universe, is the use of radio astronomy to study the 3 K background radiation found throughout the cosmos. This is thought to be radiation, highly red-shifted, that was produced by the Big Bang.





Doppler Effect and Redshift

You can hear the Doppler effect whenever a vehicle with a siren recedes from you: the sound of the siren falls in pitch as the sound source moves further away increasing the distance between one wavefront and the next. Redshift is the term used to describe the change in light wavelength (or frequency) from a fast-receding object. The redshifts of galaxies increase as their distances from us increase, leading to the idea of an expanding Universe. The diagram shows the redshift of the light from a distant galaxy.

Determining the Elemental Composition of Stars

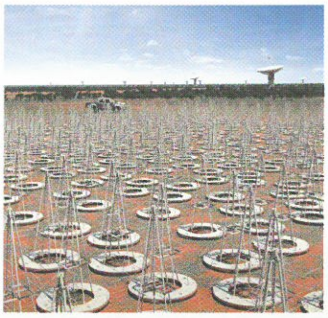
Astronomers can determine the elemental composition of stars and other matter in space by studying their emission or absorption spectra. Each distinct line in such a spectrum is characteristic of the elemental atoms emitting or absorbing the light. The Sun, consist mainly of the lighter elements hydrogen and helium, while older and hotter stars can contain higher proportions of heavier elements.

Black body radiation and radio astronomy: comprehension questions

The SKA

The Square Kilometre Array (SKA) is a multi-billion dollar international project to build the world's largest radio telescope. Co-located primarily in South Africa and Western Australia, the SKA will be a collection of hundreds of thousands of radio antennas with a combined collecting area equivalent to approximately one million square metres, or one square kilometre. The project is one of the largest scientific endeavours in history and will be many times more sensitive and much faster at surveying galaxies than any current radio telescope. The incredible flow of data from the telescope will be supported by supercomputers faster than any current facility and one trillion times the computing power that helped put us on the Moon.

The SKA will collect radio waves, a form of light invisible to the human eye, to give us a unique view of the Universe we live in. It will use three different configurations of radio antennas – Australia's Murchison region will host the low-frequency antennas that look a little like Christmas trees, whilst the mid to high frequency 'dishes' will be based in South Africa's Karoo desert. Construction of the SKA will be completed in two phases, with Phase 1, 10% of the telescope, due to begin later this decade and early science expected early next decade.



Background image: *The SKA low frequency antennas that will be constructed in Western Australia. Credit: SKA Office.*

The SKA is aiming to solve five fundamental and long-standing mysteries of the Universe.

1. **How did the first stars, galaxies and black holes form?**
   With its incredible sensitivity, the SKA will look back 13 billion years in time to the Universe's Dark Ages. At this point in the Universe's infancy, the opaque plasma created by The Big Bang recombined to form the first neutral particles which coalesced into the first stars and galaxies.
2. **Is Einstein's Theory of Relativity correct?**
   Eintstein's famous Theory of Relativity predicts that moving objects cause ripples in the fabric of the Universe, spacetime. These fluctuations are called gravitational waves and, since the most powerful sources are so distant, they are extremely weak by the time they reach Earth and have eluded scientists for nearly a century. The SKA's extraordinary sensitivity will allow us to indirectly study gravitational waves from powerful cosmic processes, such as a pair of orbiting black holes.
3. **Are we alone in the Universe?**
   The extreme sensitivity of the SKA is also expected to reveal new planets outside our solar system – exoplanets – some of which may be capable of supporting life. The SKA may even detect transient signals from extraterrestrial life itself, proving that we are not alone in the Universe.
4. **What is dark matter and dark energy?**
   More than three-quarters of all matter in the Universe cannot be directly observed because it does not absorb, emit or reflect light. We call this 'dark matter' and its nature remains one of the greatest mysteries in the Universe. Mass distribution in the Universe is also affected by an enigmatic force that pulls matter apart, which we call 'dark energy'. The rapid survey speed of the SKA will produce detailed maps of the mass and motions in millions of galaxies, helping us to figure out the nature and abundance of dark matter and dark energy in the Universe and to refine our cosmological models.
5. **What drives cosmic magnetic fields?**
   Magnetic fields exist through the entire Universe and affect the way stars form and galaxies evolve. Most sources of cosmic magnetism produce very weak emissions, which makes them very hard to detect. The sensitivity and survey speed of the SKA will revolutionise the study of cosmic magnetism by detecting these weak emissions from billions of distant galaxies, creating three-dimensional maps of cosmic magnetism throughout the Universe.

Comprehension questions

1. Explain what is meant by 'redshift'. How does redshift occur in an expanding Universe?
2. The frequencies the SKA is expected to receive will be very low. Explain.
3. Consider the 'Doppler Effect' redshift diagram on page 164, which spectrum represents a receding galaxy? Explain.

Chapter 13: Quantum theory

Qantum theory explained

Notes

Main points

- Atomic phenomena and the interaction of light with matter indicate that states of matter and energy are quantised into discrete values
- At the atomic level, electromagnetic radiation is emitted or absorbed in discrete packets called photons. The energy of a photon is proportional to its frequency. The constant of proportionality, Planck's constant, can be determined experimentally using the photoelectric effect and the threshold voltage of coloured LEDs.
- A wide range of phenomena, including black body radiation and the photoelectric effect, are explained using the concept of light quanta.
- Atoms of an element emit and absorb specific wavelengths of light that are unique to that element; this is the basis of spectral analysis.
- The Bohr model of the hydrogen atom integrates light quanta and atomic energy states to explain the specific wavelengths in the hydrogen spectrum and in the spectra of other simple atoms; the Bohr model enables line spectra to be correlated with atomic energy-level diagrams.
- At the atomic level, energy and matter exhibit the characteristics of both waves and particles. Young's double slit experiment is explained with a wave model but produces the same interference and diffraction patterns when one photon at a time or one electron at a time are passed through the slits.
- Applications of quantum physics (including lasers, photovoltaic cells) have influenced society.

Mathematical formulae

The speed of an electromagnetic wave is a product of its wavelength and frequency:

$$c = f.\lambda$$

The energy of a photon is proportional to its frequency.

$$E = hf = \frac{hc}{\lambda}$$

The kinetic energy Ek of an electron ejected from a metal by an energetic photon is given by:

$$E_K = hf - W$$

Where W is the work function of the metal

Atoms of an element emit and absorb specific wavelengths of light that are unique to that element; this is the basis of spectral analysis

$$\Delta E = hf, \quad E_2 - E_1 = hf$$

The de Broglie wavelength is related to the particles momentum as follows:

$$\lambda_{dB} = \frac{h}{mv}$$

Constants

The speed of light in vacuum (defined)

$c = 299{,}792{,}458 \text{ m s}^{-1}$

Planck's constant (measured)

$h = 6.62606896 \times 10^{-34} \text{ J s} = 4.13566733 \times 10^{-15} \text{ eV s}$

Introduction

Notes

Quantum physics (or quantum mechanics) and general relativity are amongst the most important 'discoveries' of the past century. General relativity presents a picture of the very big (space-time and gravity), while quantum physics presents a picture of the very small (atoms and sub-atomic particles).

The popular literature surrounding quantum physics has led to many weird and wonderful ideas. It is believed to be responsible for all sorts of strange occurrences such as quantum entanglement, particles kilometres apart able to communicate instantaneously, hypothetical cats that are dead and alive at the same time and photons that are capable of going in two directions at one time and being able to interfere with each other.

But quantum physics is also responsible for the technological advances that make modern life possible. Without quantum physics there would be no transistors, and hence no personal computers, no lasers, and hence no Blu-ray players. It is fundamental to our understanding of chemistry and biology. It is the basis for a huge range of technologies and applications used in everyday life, including lasers, CDs, DVDs, solar cells, fibre-optics, digital cameras, photocopiers, bar-code readers, fluorescent lights, LED lights, computer screens, transistors, semi-conductors, super-conductors, spectroscopes, MRI scanners, etc.

History

Quantum mechanics developed over many decades beginning at the turn of the 20th century, around the same time that Albert Einstein published his theories of relativity. Unlike relativity, however, the origins of quantum mechanics cannot be attributed to any one scientist. Rather, multiple scientists contributed to a foundation of three revolutionary principles that were gradually verified experimentally and gained wide acceptance. These three principles are:

1. **Wave/particle duality:** Experiments showed that light behaved as a wave: it bounces off walls and bends around corners, and crests and troughs of waves can add together or cancel out. Quantum theory revealed that light can sometimes behave as a particle.
2. **Quantised properties:** Properties, such as energy, position and momentum, are realised in specific, discrete quantities, much like steps on a ladder or a digital readout that "clicks" from number to number. This challenged the belief that such properties should exist on a smooth, continuous spectrum.
3. **Matter waves:** Matter can also behave as a wave. This was contrary to the understanding gathered from decades of experiments showing that matter (such as atoms and electrons) exists as particles.

Max Planck

Around the turn of the 20th century German physicist Max Planck sought to explain black body radiation. He proposed that in a solid, the electrons emitted or absorbed radiation only in discrete packets with the energy in each packet being proportional to the frequency of the radiation. He described mathematically the energy of these packets: $E = hf$ where f is the frequency of the radiation and h, is Planck's constant. However, the process by which radiation was emitted and absorbed remained a mystery for some time.

Planck's ideas helped to explain other mysteries of physics. Planck, along with Einstein, later developed the idea that we accept and use today, that light exists as photons that have particle-like behaviour. This accounts for both black body radiation and the photoelectric effect which could not be satisfactorily explained using existing theories of the time.

Qantum theory explained

Notes

Albert Einstein

In 1905, Einstein published a paper where he described light as "energy quanta." This quantum of energy could be absorbed or generated only as a whole when an atom "jumps" between quantised energy states. Under this model, Einstein's "energy quanta" contained the energy difference of the jump and, when divided by Planck's constant, the frequency of light carried by those quanta. It also explained how light could eject electrons off metal surfaces, a phenomenon known as the "photoelectric effect."

Twenty years after Einstein's paper the term "photon" was popularised for describing energy quanta thanks to the 1923 work of Arthur Compton. It had become clear that light could behave both as a wave and a particle, placing light's "wave-particle duality" into the foundation of quantum mechanics.

Niels Bohr

Scientists had observed that when hydrogen gas was heated above a specific temperature light was emitted light at distinct frequencies (now called emission lines). Further increase in temperature made no change to the emission lines. No visible light is emitted below this temperature. This was totally unexpected and could not be explained by classical physics.

In 1913 Niels Bohr, using Ernest Rutherford's 1911 "planetary" model of the atom, proposed that electrons were restricted to orbits around an atom's nucleus and could jump from one orbit to another. The orbits represent distinct energy levels and an electron that absorbs the right amount of energy jumps to a higher energy level. When this 'excited' electron falls back to its original energy level it emits the same amount of energy, creating an emission line. The concept of quantised properties explained so much that it became a founding principle of quantum mechanics.

Louis de Broglie

In 1924, a French physicist named Louis de Broglie hypothesised that, if light has both a particle and a wave nature, then matter (such as electrons) also has both types of properties.

De Broglie proposed that the wave nature of the electron determined the allowed orbits in Bohr's theory. He used a simple wave model to show that electron orbits must fit a whole number of wavelengths around the orbit. By doing this they undergo constructive interference and are stable whereas the electron waves in non-allowed orbits undergo destructive interference and cancel out. The concept that matter can also behave as a wave is the third founding principle of quantum mechanics.

Deriving the De Broglie Wavelength

De Broglie derived his wavelength equation as follows:

1. Einstein's famous equation relating matter and energy:
   $E=mc^2$ where: E = energy, m = mass and c = speed of light
2. Planck's equation elates energy to frequency:
   $E=hf$ where: h = Plank's constant (6.62607×10^{-34} J s) and f = frequency
3. De Broglie believed particles and waves have the same properties, he hypothesised that the two energies would be equal: $mc^2=hf$
4. Because real particles do not travel at the speed of light, De Broglie substituted velocity (v) for the speed of light (c). $mv^2=hf$
5. Substitute v/λ for f. The final expression relates the de Broglie wavelength and particle momentum.
   $mv^2 = \frac{hv}{\lambda}$ and $\lambda_{dB} = \frac{h}{mv}$

Werner Heisenberg and Erwin Schrödinger

In 1925, two scientists working independently and using separate lines of mathematical thinking applied de Broglie's reasoning to explain how electrons behaved within the atoms. In Germany, physicist Werner Heisenberg developed 'matrix mechanics' and Austrian physicist Erwin Schrödinger developed a similar theory called 'wave mechanics.' Later it was shown that these two approaches were equivalent.

The Heisenberg-Schrödinger model of the atom in which each electron acts as a wave (sometimes referred to as a 'cloud') around the nucleus of an atom replaced the Rutherford-Bohr model. In this model, electrons obey a 'wave function' and occupy 'orbitals' rather than orbits. Unlike the circular orbits of the Rutherford-Bohr model, atomic orbitals have a variety of shapes ranging from spheres to dumbbells to daisies.

The uncertainty principle

In 1927, Heisenberg made another major contribution to quantum physics now known as 'Heisenberg's uncertainty principle'. He reasoned that since matter acts as waves, some properties, such as an electron's position and speed, are 'complementary' meaning that there is a limit to how well the precision of each property can be known. The limit is related to Planck's constant. It was reasoned that the more precisely an electron's position is known, the less precisely its speed can be known, and vice versa.

Quantum Energy Levels

Electron Transitions

Bohr's model or description of the structure of the hydrogen atom explains that the electron can only exist at certain energy levels. These energies in a hydrogen atom can be calculated fairly accurately. This is more difficult for more complex atoms and compounds. Even so, many of the energy levels in these more complicated atoms and molecules have been determined.

When in what is known as the' ground state', the electrons in a compound are in the lowest energy orbitals possible. When a photon is absorbed by the compound an electron jumps from a low energy orbital to an unoccupied spot in a higher energy orbital. The compound is said to be in an excited state. When an electron falls back to the vacant low energy orbital a photon is released. If the energy difference is in the appropriate range visible light will be observed. If the energy difference is greater, an invisible ultra-violet photon or X-ray will be emitted.

One way of illustrating energy levels is to visualise them as steps on a ladder or shelves in a bookcase. Electrons can sit on shelves but not between shelves. To move from a lower level to a higher level, an electron must gain an amount of energy equal to the difference between the two levels. This can involve absorption of a photon. To move from a higher to a lower level, the electron will lose energy by emitting a photon with energy equal to the difference between the levels:

$$E_{photon} = E_{high} - E_{low}$$

The frequency (or wavelength) can be found as follows:

$$f = \frac{c}{\lambda} = \frac{E}{h}$$

Also: $E = hf = \frac{hc}{\lambda}$

Qantum theory explained

Notes

Hydrogen spectra

When white light is shone on a sample of hydrogen gas, the hydrogen atom absorbs energy and an electron jumps to a higher energy level, see Figure 13.1. The light that passes through the hydrogen gas can be analysed and a continuous spectrum with black lines at 656, 468, 434, and 410 nm is observed. This indicates that these wavelengths have been absorbed and this spectrum is known as an absorption spectrum, see Figure 13.2. Similarly, when the light emitted from a hydrogen atom in an excited state, an emission spectrum is observed. All elements have characteristic emission spectrums and characteristic absorption spectra.

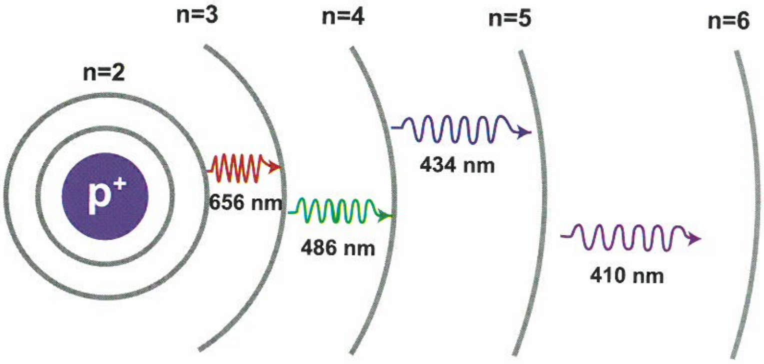


Figure 13.1: The emission of light by a hydrogen atom.

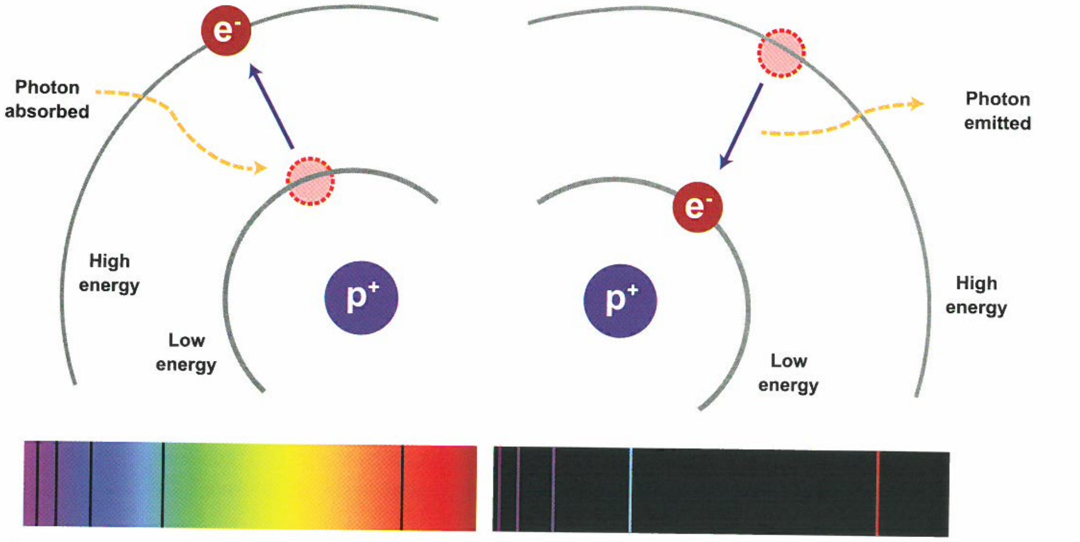


Figure 13.2: Hydrogen Absorption Spectrum (left) and emission spectrum (right).

Investigations 13.1: Applications of quantum mechanics

Background

X-rays

High energy particles, X-rays and gamma rays can deliver enough energy to expel tightly held electrons from the inner orbitals of an atom causing ionisation. Electrons in higher energy orbitals are able to 'fall' into the lower orbital releasing energy in the form of an X-ray photon. The energy of this photon is characteristic of the atom from where it originated. The term X-ray fluorescence is applied to this phenomenon. The wavelength of this fluorescent radiation can be calculated from Planck's Law:

$$\lambda = \frac{hc}{E}$$

The fluorescent radiation can be analysed either by sorting the energies of the photons (energy-dispersive analysis) or by separating the wavelengths of the radiation (wavelength-dispersive analysis). Once sorted, the intensity of each characteristic radiation is directly related to the amount of each element in the material. This is the basis of X-ray fluorescence analysis.

Task 1

X-ray analysis

X-ray fluorescence analysis and X-ray diffraction analysis are two very powerful and widely used material compositional and structural analysis techniques. Describe the two different techniques and their capabilities. Describe the X-ray detection systems used for each system. One method relies on the quantum nature of light, the other on the wave nature; discuss.

Task 2

Applications of quantum mechanics

Many applications of quantum physics have influenced society.

Describe the application and operation of the following technologies highlighting the importance of quantum theory:

1. Photo-voltaic cells.
2. Lasers.

Notes

Investigations 13.2: Microwaves

Notes

Background

This quantum energy level model does not only apply to the electrons within an atom. Atoms and molecules can also contain energy by way of molecular vibrations and/or rotations. Molecules have discrete energy levels and can jump between the different levels giving off photons. Infrared radiation originates from changing vibrational states within a molecule. When a molecule jumps from a high energy vibrational mode (or state) to a low energy mode an infrared photon is emitted. Similarly, microwave radiation is emitted when a molecule changes its rotational energy state

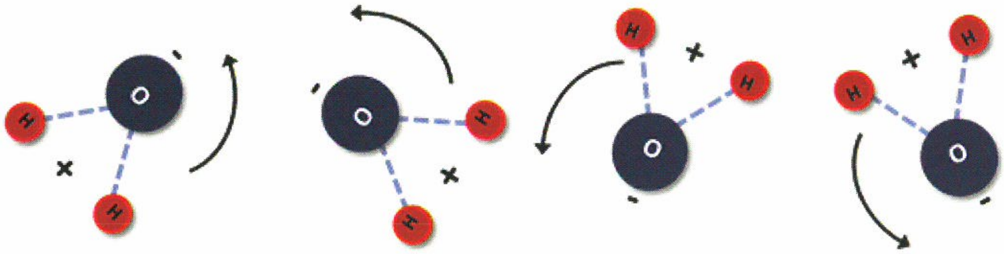


Figure 13.2: Schematic of a rotating water molecule. The oxygen has a net negative charge creating an electric dipole that oscillates due to the rotation of the water molecule.

The task

A modern application of microwave radiation is the everyday microwave oven. Microwaves are electromagnetic radiation associated with a corresponding change in the rotational energy level or state of a molecule. For a molecule to absorb a microwave photon it must have a rotating electric dipole. Water is a good example of a dipolar molecule. Although water molecules don't have an overall charge, their oxygen atom is slightly negative and their hydrogen atoms are slightly positive (the molecule has a positive and negative pole so is called polar). This means that in an electric field water molecules rotate to align with the field. When subjected to microwaves the electric field of a molecule will point upwards and then downwards about 2.5 billion times every second.

A. Microwave Ovens
- Using appropriate physics understanding, explain how a microwave oven works.
- What substance is most suitable for heating in a microwave oven?
- Why is it difficult to heat dry rice in a microwave oven?
- Discuss the statement: 'Frozen food should not be thawed in a microwave oven'

B. State and explain two other applications of microwave radiation.

Experiment 13.3: Quantum interference

Equipment

- Laser
- Needle
- Tape
- White card paper or cardboard
- 2 retort stands and clamps
- A room that can be darkened

Lab notes

1. Push a tiny hole in the card or cardboard with your needle.
2. Stand the card or cardboard upright in a retort stand and clamp at least 3 m away from the wall you will project your laser onto.
3. Mount your laser pointer in a second retort and clamp.
4. Predict what you expect to see when the laser light is directed through the hole. Turn the laser on and adjust its position and angle so that the light passes through the hole in the card and onto the wall. Record your observations. Do your observations match your prediction?
5. Push another hole in your card right next to the first one so that they are as close together as possible without creating one large hole.
6. Predict what you expect to see when the laser light is directed through both of the holes. Adjust your laser so that it passes through both holes. Observe and record the shapes created on the wall. Do your observations match your prediction?
7. Predict what you expect to see if you now cover one of the holes and use the laser setup as in step 6. Cover one of the holes with a small piece of paper, leaving the other open. Observe and record how the projected image on the wall changes. Do your observations match your prediction?

Post lab discussion

1. Explain why you should see a single blob of light from the laser when it was passing through one hole.

2. Explain why you should see a striped blob of light when it was passing through both holes.

3. Explain why you should have noticed that the stripes disappeared when you covered one of the holes.

Notes

Experiment 13.4: Measuring Planck's constant

Notes

Max Planck

The Planck constant plays a central role in understanding the properties of matter and energy. It is a cornerstone of the theory of quantum mechanics. Named after German physicist Max Karl Planck (1858–1947), the Planck constant tells us how the energy of individual photons relates to the wavelength of their radiation:

$$E_p = hc/\lambda$$

Where

E_p is the energy of a single photon (in joules), h is the Planck constant, c is the speed of light in a vacuum, and λ is the wavelength of the radiation.

How light emitting diodes work

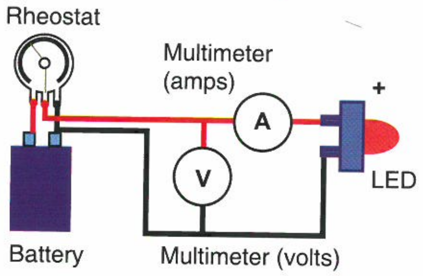
Light emitting diodes or LEDs are produced by the junction of two 'doped' semiconductor materials, one of which has an excess of electrons (n-type) and the other a lack of electrons (p-type). When an electrical current passes through this junction, energy is released in the form of photons. The energy of each photon determines the colour of the light emitted. The amount of energy can be tailored by modifying the chemical composition of the semiconductor materials. LEDs can emit light in specific colours, such as red and green in the visible region of the electromagnetic spectrum, or beyond into the ultraviolet and infrared regions.

The wavelength determines the colour of the light emitted. For example, green-emitting LEDs typically produce light with a wavelength of around 567 nanometres. Each colour of LED has a different threshold voltage at which electrons start being produced. Measuring this voltage, together with known values for the emission wavelengths, provides a way to determine a value for the Planck constant.

Equipment

- Four LEDs emitting different colours - red, orange, green and blue. Make sure the LEDs have a clear, colourless casing surrounding the LED, so that the colour is determined by the device itself, not from the coloured casing.
- A battery pack or pure DC power supply capable of delivering 0–3 V.
- Rheostat or 1 kΩ potentiometer
- A voltmeter and an ammeter or two multimeters, or a data logger with voltage and current probes

Lab notes



1. Set up the circuit as shown in the diagram. Connect the ammeter in series with the LED to measure the current through it, and connect the voltmeter in parallel to the LED to measure the voltage across it. The applied voltage can be adjusted by using the potentiometer or the rheostat.

2. Change the voltage in steps of 0.05 V from 0 V to 3 V, and measure the resulting electrical current. Note that when the current flowing through the LED is small, the LED might not light up, but the ammeter can still measure the current. To protect the LED, take care to keep the current below 5 mA.

Post lab discussion

Notes

1. For each LED, plot a graph of current vs voltage. On each graph, find the straight line of 'best fit' to join up the points that slope up from the x-axis. If the points lie close to the line, a linear relationship holds between the applied voltage and the current in this region of the graph.
2. Determine the activation voltage (Va) from the collected data for each LED. It can be read from the graph by extrapolating a straight line through the current vs voltage graphs for each coloured LED where they intercept the x-axis.
3. Tabulate your findings in a table similar to the following:

LED colour	Wavelength, λ (nm)	Frequency, f $f=c/\lambda$	Activation voltage, V_a

4. Graph activation voltage (vertical axis) vs frequency (horizontal axis). Determine the slope of the graph, which is Planck's constant. How does your value compare with the accepted value for the Planck constant of 6.626×10^{-34} J s?

Problem Set 13: Quantum theory

Notes

1. The light from stars can be analysed by digitising and enhancing the spectrum produced by passing the starlight through a diffraction grating. The observed continuous spectrum contains distinct black lines.

   (a) Explain how these black lines are produced.

   Astronomers can use these lines to predict the elemental composition of the observed stars by comparison with line emission spectra produced by various elements under laboratory conditions.

   (b) Explain how this method gives accurate predictions of the elements in the observed stars.

   (c) What are two essential criteria needed to produce the line emission spectra.

2. White light is incident on a solution of chromium(III) chloride in a beaker and the resultant transmitted spectrum analysed.

   (a) Explain why the chromium(III) chloride solution appears green.

   (b) Give the name of the type of spectrum produced in the transmitted beam.

3. Aurora Australis, in the Southern Hemisphere, and Aurora Borealis, in the Northern Hemisphere, produce brilliant patterns of light in the upper atmosphere at the extreme latitudes of the magnetic poles of the Earth. This light is produced as a result of interactions between the magnetic field of the Earth, charged particles produced by solar winds and molecules and atoms of gas in the Earth's atmosphere.

   The predominant green colour has a wavelength of 557.7 nm and is a result of electron transitions between the $n = 3$ and $n = 2$ energy levels of oxygen.

   (a) Calculate the difference in energy between these two levels in both joules and electron volts.

   (b) Is this an example of fluorescence of phosphorescence? Explain.

4. An energy level diagram (not to scale) for the hydrogen atom is shown on the right. Consider each of the following downward transitions:

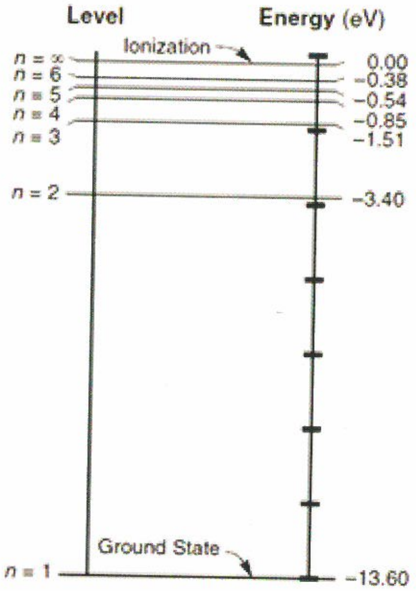
   (i) E2 to E1 (ii) E4 to E2
   (iii) E3 to E2 (iv) E5 to E3

   Calculate the following for each of these transitions.

   (a) The frequency of the emitted photon.

   (b) The section of the electromagnetic spectrum to which the emitted photon belongs.
   A purple line in the visible emission spectrum of hydrogen has a wavelength of 434 nm.

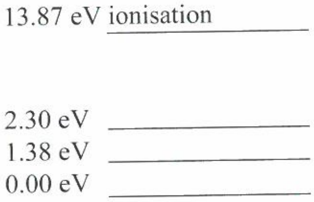
   (c) Between which two levels must this electron fall to emit this photon?
   Note: $1\text{eV} = 1.6 \times 10^{-19}$ J



5. An electron undergoes a transition from a higher to a lower energy level of 2.35 eV and in so doing emits a photon with an energy of 4.00×10^{14} Hz. In which energy level was this electron before it undertook this transition?

6. Explain why the spectrum from a gas such as hydrogen only shows the emision of certain wavelengths on excitation and why this same gas is capable of absorbing only some of these wavelengths.

7. At right is a diagram representing some of the energy levels in a caesium atom.
A beam of electrons with energy of 2.80 eV is incident on a gaseous sample of caesium in a sealed container.
   (a) What are the possible energies that electrons in the emerging beam can have?
   (b) What are the possible energies of any photons emitted?
   (c) What energy bombarding electrons would be needed to ionise a sample of caesium gas?
This sample of caesium was bombarded with photons forming a continuous spectrum containing all energies between 1.00 eV and 14.5 eV.
   (c) What difference would be observed in this photon beam, after it emerged from the caesium sample?



Notes

8. Light-emitting diodes are semiconductor devices that emit light when a potential difference is applied across the junction of their semiconductor. A minimum potential difference is needed across this junction before they will emit light, and the colour emitted is determined by the value of this voltage. The applied potential raises the energy of the electrons in the semiconductor to an excited state and when they return to the ground state this energy is released as photons.
In an experiment it was found that a potential difference of 2.06 V across the diode junction resulted in light of wavelength 600 nm being produced.
   (a) Calculate the energy (in joules) absorbed by an electron in the ground state when this potential difference is applied.
   (b) What is the wavelength of the emitted photon?
   (c) Use this data to estimate a value for Planck's constant.

9. The wavelength of the red line in the Balmer (visible) series of the spectrum of atomic hydrogen is 656.3 nm. What is the difference in energy between the two energy levels responsible for this line.

10. Ground state helium atoms are irradiated with photons and it is noticed that the longest wavelength absorbed from the incident spectrum is 5.84×10^{-8} m. Calculate, in joules and electron volts, the energy difference between the ground state and this excited state of Helium.

11. Show that the separation of the energy levels of an excited atom is related to the wavelength, λ, of a photon released in the electron transition between these levels by the formula
$E = 1.24 \times 10^{-6}/\lambda$

12. Three lines are observed on the emission spectrum from the first two excited states of a particular gas. The shortest wavelength of these was 1.042×10^{-7} m and one other was 1.235×10^{-7} m.
   (a) What is the wavelength of the third line observed in this spectrum and to what part of the visible or near visible spectrum does it belong?
   (b) Draw a labelled diagram showing these two energy levels for this atom.

13. Gaseous helium has a first excitation energy of 21.2 eV and an ionisation energy of 24.6 eV.
   (a) When electrons with an energy of 22.0 eV are fired at a sample of helium gas in a sealed tube photons are emitted that all have the same energy. What is the energy and wavelength of these photons and to what part of the electromagnetic spectrum do they belong?
   (b) What would you expect to occur to theses gas atoms or to observe in the emitted spectrum if these incident electrons had an energy of 26.0 eV? Explain your answer.
   (c) A beam of photons with a range of energies up to 26.0 eV was incident on this sample of helium. How would the transmitted beam differ from this incident beam and what is the maximum energy photon that might now be emitted?

Applications of special relativity

What gives gold its colour?

In discussions of special relativity, you occasionally encounter a claim like, "The effects of special relativity only matter to particle physicists and others working with extreme energies and velocities. Relativity has no consequences in everyday life." Well, these days, anybody who relies upon the Global Positioning System (GPS) to navigate their car or the airliner in which they're travelling uses both special and general relativity, because without correction for their effects, GPS would be so inaccurate as to be useless. But GPS is a recent innovation, and the relativistic corrections are both complicated and hidden from the user in the software in the receiver and on board the satellites. But there's an effect of special relativity which was observed, if not understood, by the ancients: the yellow gleam of gold.

With an atomic number of 79, gold is in the last row of the periodic table containing stable elements, and only four stable elements (mercury, thallium, lead, and bismuth) have greater atomic number. With 79 protons in its nucleus, the electrons of the gold atom are subjected to an intense electrostatic attraction. Using the naïve Bohr "solar system" model of the atom for the moment, electrons in the 1s orbital, closest to the nucleus, would have to orbit with a velocity v of 1.6×10^8 m s^{-1} to have sufficient kinetic energy to avoid "falling into" the nucleus. This is more than half the speed of light. At theses speeds the momentum of the electron increases causing a relativistic contraction of its orbit.

The colour of metals such as silver and gold is mainly due to absorption of light when a d electron jumps to an s orbital. For silver, the 4d→5s transition has an energy corresponding to ultraviolet light, so frequencies in the visible band are not absorbed. With all visible frequencies reflected equally, silver has no colour of its own; it's silvery. In gold, however, relativistic contraction of the s orbitals causes their energy levels to shift closer to those of the d orbitals (which are less affected by relativity). This, in turn, shifts the light absorption from the ultraviolet down into blue visual range. A substance that absorbs blue light will reflect the rest of the spectrum: the reds and greens which, combined, result in the yellowish hue we call golden.

Special relativity is also responsible for gold's resistance to tarnishing and other chemical reactions. Chemistry is mostly concerned with the electrons in the outermost orbitals. With a single 6s electron, you might expect gold to be highly reactive; after all, cæsium has the same 6s outer shell, and it is the most alkaline of natural elements: it explodes if dropped in water, and even reacts with ice. Gold's 6s orbital, however, is relativistically contracted toward the nucleus, and its electron has a high probability to be among the electrons of the filled inner shells. This, along with the stronger electrostatic attraction of the 79 protons in the nucleus, reduce the "atomic radius" of gold to about half of that for cæsium with its 55 protons and electrons. The gold atom is almost 50% heavier, yet only a little over half the size of cæsium giving gold its high density. Only the most reactive substances can tug gold's $6s^1$ electron out from where it's hiding among the others. The colour of gold and its immunity to tarnishing and corrosion are consequences of special relativity.

GPS systems

The Global Positioning System (GPS) is based on an array of 24 satellites, each carrying a precise atomic clock, orbiting the Earth. Using a hand-held GPS receiver which detects radio emissions from any of the satellites which happen to be overhead, users of even moderately priced devices can determine latitude, longitude and altitude to an accuracy currently reaching 15 metres, and local time to 50 billionths of a second. GPS has applications in aircraft navigation, oil exploration, wilderness recreation, bridge construction, sailing, and interstate trucking.

But in a relativistic world, things are not simple. The satellite clocks are moving at 14,000 km h^{-1} in orbits that circle the Earth twice per day, much faster than clocks on the surface of the Earth, and Einstein's theory of special relativity says that these rapidly moving clocks tick more slowly, by about seven microseconds (millionths of a second) per day.

Also, the orbiting clocks are 20,000 km above the Earth, and experience gravity that is one–quarter that on the ground. Einstein's general relativity theory says that gravity curves space and time, resulting in a tendency for the orbiting clocks to tick slightly faster, by about 45 microseconds per day. The net result is that time on a GPS satellite clock advances faster than a clock on the ground by about 38 microseconds per day.

To determine its location, the GPS receiver uses the time at which each signal from a satellite was emitted, as determined by the on-board atomic clock and encoded into the signal, together the with speed of light, to calculate the distance between itself and the satellites it communicated with. The orbit of each satellite is known accurately. Given enough satellites, it is a simple problem in Euclidean geometry to compute the receiver's precise location, both in space and time. To achieve a navigation accuracy of 15 metres, time throughout the GPS system must be known to an accuracy of 50 nanoseconds, which simply corresponds to the time required for light to travel 15 metres.

But at 38 microseconds per day, the relativistic offset in the rates of the satellite clocks is so large that, if left uncompensated, it would cause navigational errors that accumulate faster than 10 km per day! GPS accounts for relativity by electronically adjusting the rates of the satellite clocks, and by building mathematical corrections into the computer chips which solve for the user's location. Without the proper application of relativity, GPS would fail in its navigational functions within about 2 minutes.

Experimental evidence for time dilation

One of the first experiments to provide evidence of time dilation was done over seventy years ago by detecting muons Muons are particles created when incoming cosmic rays collide with air molecules in the outer reaches of the atmosphere. A constant stream of these particles travels towards the surface of the Earth at speeds very close to the speed of light. They are unstable particles, with a "half-life" of about 1.5 microseconds, which means that if you start with a thousand, 1.5 microseconds later you will have about 500 and so on.

In 1941, a detector placed near the top of Mount Washington (at 2000 m above sea level) measured muon flux of about 570 per hour. It would be expected that the number of muons would decrease as they fall, so if we move the detector to a lower altitude we expect it to detect fewer muons.

Knowing the half-life, and given that 570 per hour hit a detector near the top of Mount Washington, it would be expected that about 35 muons per hour would survive down to sea level. But with the detector at sea level about 400 muons per hour were detected! How do we explain the difference? The reason they didn't decay is that in their frame of reference, much less time had passed. The actual speed of the muons is about 0.994c, which corresponds to a time dilation factor of about 9. This means that in the time it takes to travel form the top of Mount Washington to sea level (6 microseconds), the time registered on the muons internal clock is about 0.67 microseconds (6/9) microseconds. In this time, only about one-quarter of them would decay leaving ¾ or about 430 to reach the detector.

Length contraction also plays its part. From the muon's point of view Mount Washington is less than 240m high. This explains why they can cover the distance so quickly.

In 1979 scientists carried out an experiment using a particle accelerator at CERN. They reported a similar experiment with muons accelerated to speeds 0.9994c. Trapped in a particle accelerator, muons were observed in the lab to have 29.3 times their rest half-life, completely consistent with time dilation.

Chapter 14: Special relativity

Special relativity explained

Notes

Main points

- Observations of objects travelling at very high speeds cannot be explained by Newtonian physics. These include the dilated half-life of high-speed muons created in the upper atmosphere, and the momentum of high-speed particles in particle accelerators.
- Einstein's special theory of relativity predicts significantly different results to those of Newtonian physics for velocities approaching the speed of light.
- The special theory of relativity is based on two postulates: that the speed of light in a vacuum is an absolute constant, and that all inertial reference frames are equivalent.
- Motion can only be measured relative to an observer; length and time are relative quantities that depend on the observer's frame of reference.

Equations:

The frequency f, wavelength λ, and wave speed v are related by the equation: $v = f\lambda$

The relationship between mass and energy is: $E = mc^2$

In a nuclear reaction: $E = \Delta m\, c^2$

The factor v/c is often referred to as β where: $\beta = \frac{v}{c}$

The Lorentz factor: $\gamma = \frac{1}{\sqrt{1 - \beta^2}}$

If L_0 is the length of an object measured by an observer in the objects reference frame and L is the length as measured by the observer in a stationary reference frame then the two measurements are related as follows: $L = L_0 / \gamma$

$t = \gamma t_0$

Here t_0 is the time as measured in the frame of the moving 'light-clock' and t is the time as measured by the stationary observer.

Relative velocities: $u' = \frac{u - v}{1 - \frac{uv}{c^2}}$ $\qquad u = \frac{u' + v}{1 - \frac{u'v}{c^2}}$

Relativistic energy and momentum: $E_k = \gamma mc^2$ $\qquad p = \gamma mv$

To find a photon's momentum p, we can combine Planck's formula (E = hf) and Einstein's mass/energy formula ($E = mc^2$):

$$p = mc = \frac{e}{c} = \frac{hf}{c} = \frac{h}{\lambda}$$

Special relativity

For a long time many scientists assumed that there must be some kind of substance through which light propagated similar to that observed with waves in water and with sound waves. They called this unknown substance the 'ether'. In 1887 Albert Michelson and Edward Morley carried out an experiment in which they tried to show the motion of Earth relative to the ether by measuring changes in light speed in different directions. To their surprise they found no change in the light speed regardless of the relative motion between Earth and the source of light or the ether.

Their experiment was a 'failure' but this 'failure' enabled scientists to abandon their ideas of the theory of 'ether' and to think differently. Without the ether theory there was now no absolute reference frame to determine what is at rest and what is moving. At this point Einstein started his work on special relativity.

Notes

Albert Einstein

Albert Einstein was born in Ulm, Germany on March 14, 1879. As a child, Einstein developed a curiosity for understanding the mysteries of science. Moving to Italy and then to Switzerland, he graduated from high school in 1896. In his later years, Einstein would write about two events that had a marked effect on his childhood. One was an encounter with a compass at age five, where he marvelled at the invisible forces that turned the needle. The other was at age 12, when he discovered a book of geometry which he read over and over.

In 1905, while working as a patent clerk in Bern, Switzerland, Einstein had what came to be known as his "Annus Mirabilis" or "miracle year". It was during this time that he obtained his doctorate degree and published four of his most influential research papers, including the special theory of relativity. This theory and his now world famous equation "$E = mc^2$" revolutionised our understanding of the Universe. In 1915, Einstein completed his general theory of relativity and in 1921 he was awarded the Nobel Prize in Physics for his explanation of the photoelectric effect.

Today, the practical applications of Einstein's theories include the development of modern electronics, GPS systems, lasers, and medical imaging techniques. Recognized as TIME magazine's "Person of the Century" in 1999, Einstein coupled his intellect with strong passion for social justice and dedication to pacifism, and gave the world both knowledge and pioneering moral leadership.

Einstein's special theory of relativity

The special theory of relativity changed forever ideas about space and time, energy and mass. The theory reveals to us that one person's interval of space is not the same as another person's, and time runs at different rates for different observers travelling at different speeds. A moving clock appears to run slower and a moving object measures shorter in its direction of motion. It also tells us that the momentum of a moving object increases exponentially as its velocity increases until, at the speed of light, it becomes infinite. The theory leads to the idea that energy and mass, once thought to be two distinctly different properties, are equivalent and interchangeable.

The reason that these predictions are not obvious in everyday observations is that the effect at everyday speeds for average size objects that we tend to deal with is very small. The effects only really become apparent at speeds approaching that of light itself.

The postulates of Einstein's special relativity

Einstein's theory is based on two simple postulates:

1. The laws of physics are the same in all inertial frames of reference.
2. The speed of light in vacuum has the same value in all inertial frames of reference.

The first postulate implies that there is equivalence between all inertial frames. An inertial frame is a place in space that is not experiencing any accelerating forces. It includes objects at rest and those moving at constant velocity – but then we need to ask, what does 'at rest' mean? There is no way of knowing this. There is no experiment that we can perform to determine our velocity or to ascertain whether we are at rest. All we can do is measure our velocity relative to some other object or reference frame. As we watch a train rush by we could say it has a velocity of 100 km h^{-1}. But an observer on a similar train passing in the opposite direction who suddenly looks out the window will see the first train pass at 200 km h^{-1}. An observer in an aircraft travelling overhead will observe a completely different velocity, as would someone on the surface of the moon peering down through a powerful telescope. The Earth moves across the solar system at high speed but we have no way of knowing this as we sit at our desk where we imagine we are 'at rest'.

Notes

There is also no such thing as an absolute reference frame. A fixed point in space in one frame is a moving point for another frame. People in two frames moving relative to each other will not agree about who is moving and at what velocity.

The first postulate was understood before Einstein. Einstein's revolutionary contribution is the new concept of the universality and constancy of the speed of light. The second postulate is the one that forces us to change the laws of physics as they were known before Einstein's relativity.

The universal speed limit

Surprising properties of light were discovered in the late nineteenth century. These properties form the basis of the theory of special relativity.

Experiments performed with radio and light waves emitted by pulsars, with light emitted from particles in accelerators, or with the light of gamma-ray bursts all show that the speed of the electromagnetic radiation does not depend on the frequency of the radiation, or on its polarisation, or on its intensity. After starting together and travelling together for thousands of millions of years across the Universe, light beams with different properties still arrive side by side. Other experiments show that the speed of light is the same in all directions of space.

But this invariance of the speed of light is puzzling. We all know that in order to throw a ball as fast as possible, we run as we throw it. We know instinctively that the ball's speed with respect to the ground is higher than if we do not run. We also know that hitting a tennis ball more forcefully makes it travel faster. But light behaves differently.

Experiments show that light emitted from a moving lamp has the same speed as light emitted from a resting one. One way to prove this is to look at the sky. The sky shows many examples of binary stars, stars that rotate around each other along ellipses. In some of these systems, we see the ellipses (almost) edge-on so that each star periodically moves towards and away from us. If the speed of light would vary with the speed of the source, we would see bizarre effects, because the light emitted from some positions would catch up with the light emitted from other positions. We would not be able to observe the elliptical shape of the orbits. However, such strange effects are not seen and perfect ellipses are observed. In other words, light in a vacuum will never travel faster than the speed of light. Experiments and theory show that no object can reach the speed of light. The speed of light is the universal speed limit; it is the maximum speed in nature. The velocity v of any physical system in nature is bound by c. The existence of an invariant limit speed c is not as surprising as we might think but, nevertheless it leads to many interesting results: it leads to observer-varying time and length intervals, to an intimate relation between mass and energy, to the existence of event horizons and to the existence of antimatter.

The complete theory of special relativity is contained within these statements.

- All light beams have the same speed.
- The speed of light in vacuum is invariant (it doesn't change).
- The speed of light is a universal limit speed.

Space and time

Because of Einstein's theory of relativity we can now say that space and time are related to each other by a common factor, the speed of light. Because it has the same value in all frames of reference it does not matter whether you are stationary with reference to a light source, travelling toward it or travelling away – the speed at which light reaches you is always the same. The constant velocity of light is used in our modern definitions of both time and distance.

Light moves extremely rapidly but with a finite speed. Today the speed of light is specified with a precision of nine significant figures. The metre is now defined in terms of the speed of light. Since 1983 the metre has been defined by international agreement as the distance travelled by light in vacuum during a time interval of 1/299,792,458 of a second. This makes the speed of light exactly 299,792.458 km s^{-1}.

Time is also defined in terms of the properties of light. One second is defined as the duration of 9 192 631 770 periods of the wavelength of light emitted by caesium-133 produced by electron transitions between the two hyperfine levels of the ground state of that atom.

Some astronomical distances are defined by their relationship to the speed of light. An example is the light year – the distance traversed by a photon in one year of travel through vacuum. The light that we see from our nearest neighbour star, Proxima Centauri, was transmitted 4.2 years ago so Proxima Centauri is 4.2 light years from Earth. Light produced by the Sun takes approximately 8 minutes to reach the Earth, so the diameter of the Earth's orbit around the Sun is about 16 light minutes.

Space-time

Space-time (also known as the space–time continuum) is a model that combines space and time into a single model. The Universe is usually interpreted from a Euclidean space perspective where space consists of three dimensions often described on a Cartesian system with x, y and z axes. In space-time a "fourth dimension" is introduced to enable time information to be included. Any event can now be described by knowing its location in space and the time at which it occurred. By multiplying time by the speed of light the time dimension will have the same units as the space dimensions.

Four dimensional space is difficult to visualise and even more difficult to draw on a two-dimensional screen or piece of paper. To simplify we can show just a single space dimension, such as distance in one direction which we could call 'x' and a time axis in the same units as the 'x' axis. For example if 'x' is measured in metres and time in seconds then time can be multiplied by the speed of light 'c' to give units of metres.

Figure 14.2 shows a space-time plot for a car travelling at 20 m s^{-1} (about 72 km h^{-1}). Notice that the horizontal axis is severely squashed. If the two axes were scaled equally the horizontal axis would be about 1500 km long.

For particles travelling at speeds close to the speed of light we can produce an equally scaled plot as shown in Figure14.3. This graph shows the space-time trajectories of two particles – one travelling at 0.95c and another at 0.99c. The solid line represents the speed of light so all events that we can experience will occur in the space-time region below this line. The space-time plot for the car in the previous figure is shown also – its space-time line is virtually horizontal.

The factor v/c is often referred to as β where: $\beta = \dfrac{v}{c}$

Notes

Special relativity explained

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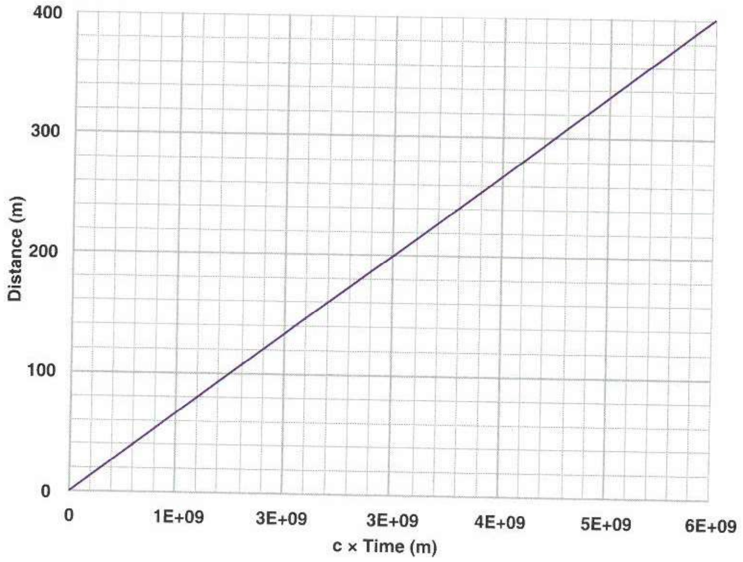


Figure 14.2: A simple space-time plot for a car travelling at 20 m s^{-1} (about 72 km hr^{-1}).

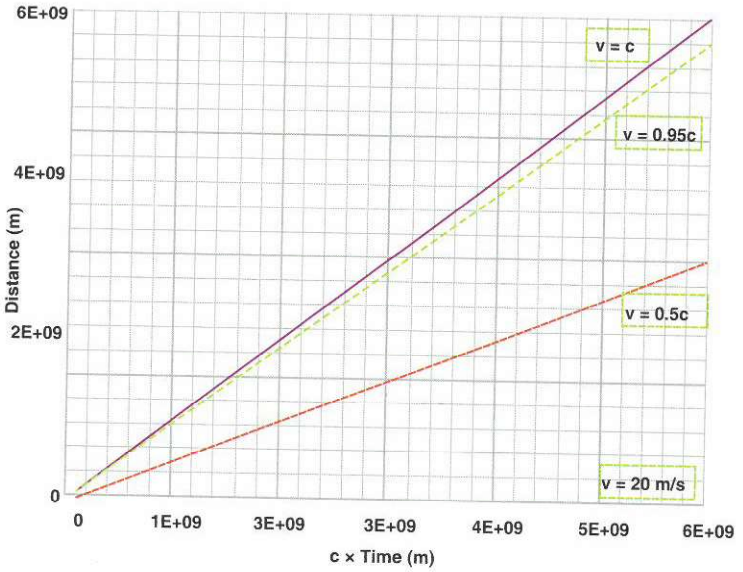


Figure14.3: The space-time trajectories of two particles – one travelling at 0.95c and another at 0.99c. The solid line represents the speed of light.

Hermann Minkowski

A mathematically rigorous description of space time was developed by mathematician Hermann Minkowski in the early 20th century. Now known as 'Minkowski space' or 'Minkowski space-time' this model comprises a four-dimensional manifold where the space-time interval between any two events is independent of the inertial frame of reference in which they are recorded. Although initially developed for Maxwell's equations of electromagnetism, the mathematical structure of Minkowski space-time was shown to be useful when adapted to Einstein's theory of special relativity, and is the most common mathematical structure on which special relativity is formulated. Because it treats time differently Minkowski space differs from simple four-dimensional Euclidean space. The model has significantly simplified a large number of physical theories.

Mass and energy

Mass can be defined as the measure of how much matter an object or body contains - the total number of sub-atomic particles (electrons, protons and neutrons) in the object. But also mass can be defined by Newton's second law, $F = ma$. It can be seen as the resistance to acceleration specifying the amount of force required to cause a body to accelerate.

Energy is the measure of a system's ability to make changes or in mechanics, the ability to perform "work". It exists in many forms: potential, kinetic, thermal etc. The law of conservation of energy tells us that energy can neither be created nor destroyed; it can only be converted from one form to another. It is the total amount of energy that is conserved. If you drop a rock from a bridge the rock has kinetic energy the moment it starts to move. Just before you dropped the ball, it had only potential energy. As the rock moves, the potential energy is converted into kinetic energy. Likewise, when the rock hits the ground, some of its energy is converted to thermal energy. If you find the total energy for the system, you will find that the amount of energy for the system is the same at all times.

The unification of energy and mass

The concept of mass has been fundamental to physics. Its definition goes back to Galileo and Newton who said that mass was that property of a body that enables it to resist externally imposed changes to its motion. Newton used mass to define momentum and force: he defined a body's momentum as $p = mv$ (where v is its velocity), and he defined force in terms of an object's acceleration: $F = ma$.

This definition of mass was applied in a straightforward way for almost two centuries. Then Einstein arrived on the scene and, in his theory of special relativity, he changed this way of thinking forever. Undoubtedly the most famous equation ever written is $E=mc^2$. This equation says that energy is equal to the mass of an object times the speed of light squared. This means that energy and mass are interchangeable – they are manifestations of the same thing. Since the speed of light is constant, an increase or decrease in the system's mass is proportional to an increase or decrease in the system's energy. The law of conservation of energy and the law of conservation of mass can be combined to give one law, the law of conservation of energy.

It is often stated that an object's mass increases as it approaches the speed of light. For example, consider a proton accelerated in a particle accelerator. The following occurs:

1) Energy must be added to the system to increase its speed.
2) More of the added energy goes towards increasing the particle's resistance to acceleration.
3) Less of the added energy goes into increasing the particle's speed.
4) Eventually, the amount of added energy required to reach the speed of light would become infinite. The proton never reaches the speed of light no matter how much energy is added. The speed of light can be considered the universal speed limit.

In step 2, the system's resistance to acceleration is a measurement of an object's mass, which increases when the object speeds up. This is called relativistic mass. It should be noted that many physicists have stopped using this concept of mass and now consider this effect in terms of an increase in momentum and energy. The Newtonian definition of mass still holds for a body at rest, and so has come to be called the body's *rest mass*, often denoted m_0.

Energy and Momentum

In classical mechanics, kinetic energy E_k and momentum p are expressed as

$E_k = ½mv^2$

$p = mv$

Special relativity explained

Notes

These relationships work well at low speeds and for objects of average mass, but at high speed we need to apply the relativistic corrections:

$$E_k = \gamma mc^2$$

$$p=\gamma mv$$

Where γ is the Lorentz factor as described on page 180.

In some relativity textbooks, the so called "relativistic mass" $m = \gamma m_0$ is used as well. Many authors prefer to use the expressions of relativistic energy and momentum to express the velocity dependence in relativity, which provide the same experimental predictions.

Relativistic energy and momentum increase significantly at speeds approaching the speed of light and at these speeds enormous amounts of energy are required. Therefore no massive particle can ever reach the speed of light.

Photons

We have seen that as we accelerate a massive particle up to the speed of light we find that the energy increases rapidly with little change in the particle's velocity. Einstein's formula predicts that, at the speed of light, the energy of the particle would become infinitely great. In other words, it would require an infinitely large amount of energy to accelerate the particle to the speed of light. This is, quite obviously, impossible so how then does a photon manage to travel with the speed of light? The answer is that photons have zero 'rest' mass, which means that the energy of a photon is all kinetic energy. If a photon is forced to come to rest in some absorbent material, it simply ceases to exist.

If individual photons have a definite energy and are able to behave like particles, we should expect them to carry momentum. It is natural to think that light carries energy as the Earth receives tremendous amounts of solar energy from the Sun. Einstein had used the hypothesis that light could be regarded as a stream of individual packets of energy to explain the 'photo-electric effect', the fact that light shining on a metal surface can cause electrons to be ejected. Einstein showed that, if Planck's law of black-body radiation is accepted, photons must also carry momentum $p=h/\lambda$. This photon momentum was observed experimentally by Arthur Compton, for which he received the Nobel Prize in 1927.

To find a photon's momentum we can combine Planck's formula ($E = hf$) and Einstein's mass – energy formula ($E = mc^2$):

$$p = mc = \frac{e}{c} = \frac{hf}{c} = \frac{h}{\lambda}$$

Notes

Simultaneity

How do we know two events happen at the same time? When we see a flash of lightning we know its associated sound, thunder, will arrive shortly after. This time delay is a result of the different rates at which the information is conveyed to us – the flash of lightning travels at the speed of light, the thunder at a pedestrian pace equal to the speed of sound. The time delay can be used to calculate how far away a lightning strike is from the place where we are located.

If we observe two events at locations where we know the distance to our point of observation we can carry out a simple calculation to determine if the two events are simultaneous – that is, did they happen at exactly the same time? But this is not so easy in Einstein's world. Whether or not two events occur simultaneous depends upon your frame of reference. The time order of events that are close together in time but distant in space can be different in different frames.

It was common for Einstein to create simple thought experiments to help illustrate the concepts of his theories. One such thought experiment illustrates the point of simultaneity. Examples similar to this are discussed in many textbooks.

Imagine a train moving with uniform high velocity. A light source located in the centre of the train transmits a light pulse in all directions. A detector (or clock) at the front and rear of the train record the moment a pulse of light is detected. Marie, an observer on board the train recognises that the pulses strike each detector simultaneously. At this moment an observer named Albert on a 'stationary' platform observes the train pass by just as the light pulses are emitted.

As light travels out from the source, according to Albert, the stationary observer, it must be travelling at the speed of light in both directions. After the pulses are emitted the rear of the train has moved closer to the source and therefore has less distance to travel. The forward going pulse has further to travel. Albert perceives that the light pulse has reached the rear detector first and he concludes that the two pulse detection events are not simultaneous.

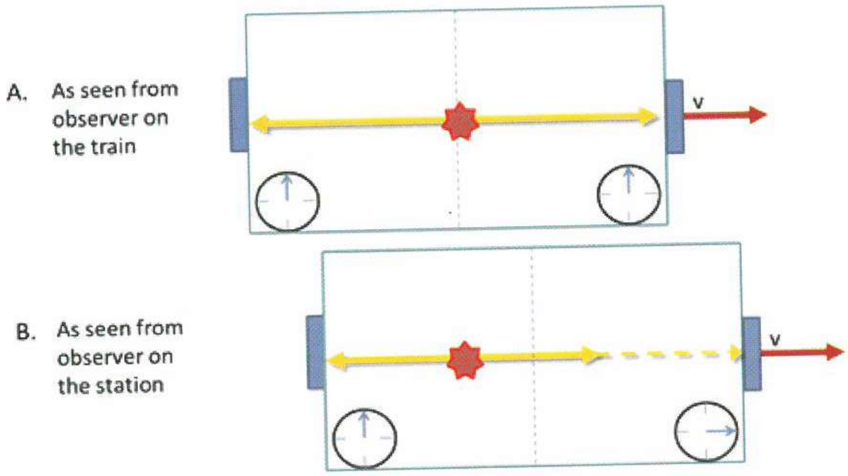


Figure 14.4: A light source located in the centre of the train transmits a light pulse in all directions. An observer on the train sees the pulses strike each detector simultaneously. A stationary observer sees the light pulse reach the rear detector first.

Special relativity explained

Notes

This thought experiment demonstrates that the two events that appear to be simultaneous to one observer do not appear to be simultaneous to another observer. In other words, two events that are simultaneous in one reference frame in general do not appear to be simultaneous in a second frame moving relative to the first. Simultaneity is not an absolute concept but rather one that depends on the state of motion of the observer.

Einstein's thought experiment demonstrates that two observers can disagree on the simultaneity of two events. Visualising events in space-time can help us understand this concept. Imagine you are looking at a row of trees in an orchard. Standing at a position at the end of the row you can see the trees in a line in front of you and you could say they all share the same y-coordinate. From another vantage point, say some distance perpendicular to the line, we can see the trees separated by 2 metres. But if you think of time as just another "direction" you can believe that your time coordinate could have one value in one reference frame, and another value in a different frame.

Time dilation and length contraction follow from this in a straightforward way. And they are much easier to visualise if you can see that time is another "direction", and therefore is relative to the observer, just like position is.

Discussion: Sound waves

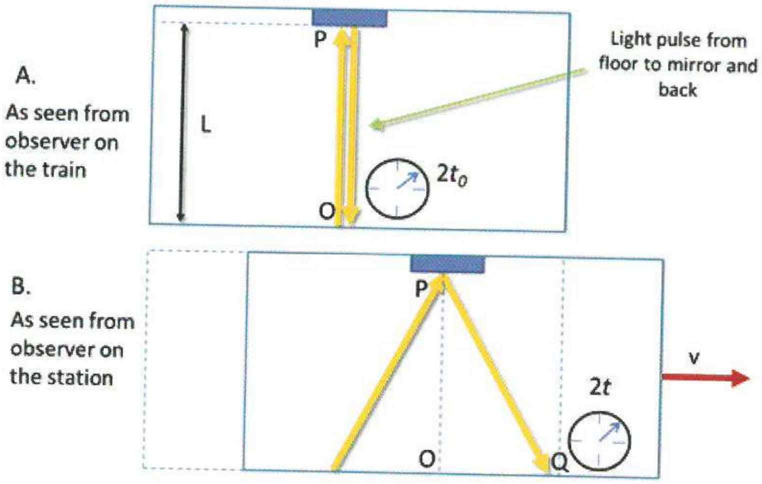
Consider the previous experiment but with the light source replaced by a sound source. When the sound reaches the two detectors a flash of light is given off. Will the two observers agree on the simultaneity of the sound pulse? Discuss.

Time dilation

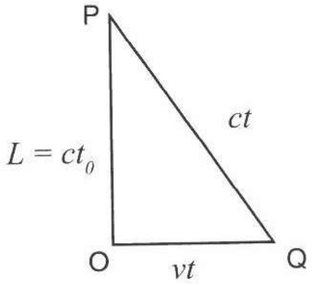
Another typical thought-experiment is the analysis of the "light-clock". The basic idea of a light-clock is to use the distance travelled by a pulse of light and the known speed of light to mark out intervals of time. The following example is discussed in many textbooks and can be used to derive the time dilation formula. The thought experiment proceeds as follows:

Albert, inside a train carriage, sets up an experiment where he directs a pulse of light to a mirror on the roof of the train. The beam returns to its starting position and the time for the return trip is measured. This is shown in part 'A' of the following diagram.

The next step in this experiment is to imagine the train moving at high velocity through the station from left to right and consider how the light pulse would appear to Marie who is standing on the platform of a railway station. She would observe the path of the light pulse as two diagonal paths as shown in part 'B'.



The triangular path OPQ is shown below. Knowing that for constant velocity - distance = velocity multiplied by time - we can determine the length of the sides of the triangle: From part A the length L is equal to the velocity of light *c* multiplied by the time taken, t_0: That is, $L = ct_0$. Similarly the diagonal edge of the triangle is *ct* and the base of the triangle is *vt* as shown. Note that t_0 is known as the 'proper time' and is the time measure in the frame containing the light clock, in this case the train carriage and *t* is the time measured relative to the proper time. The length of the light path PQ as viewed by Marie on the platform is longer than the path PO as observed by Albert in the train carriage. The speed of light *'c'* is the same for both observers so therefore time as measured by Albert, the moving observer, must be ticking 'slower' than time as observed for Marie, the stationary observer.



Notes

If we analyse the triangle using Pythagoras' theorem we get:

$$(ct)^2 = (vt)^2 + (ct_0)^2$$

$$(ct_0)^2 = (ct)^2 - (vt_0)^2$$

$$t_0 = t\sqrt{1 - \frac{v^2}{c^2}} \qquad t = t_0 \frac{1}{\sqrt{1-\beta^2}}$$

Using $\gamma = \frac{1}{\sqrt{1-\beta^2}}$ we get: $t = \gamma.t_0$

Here t_0 is the time as measured in the frame of the moving 'light-clock' and t is the time as measured by the stationary observer. γ is the Lorentz factor and will be described in the next section.

The Lorentz Transform

Hendrik Lorentz (18 July 1853 – 4 February 1928) was a Dutch physicist who shared the 1902 Nobel Prize in Physics with Pieter Zeeman for the discovery and theoretical explanation of the Zeeman Effect - the splitting of a spectral line into several components in the presence of a static magnetic field. He also derived the transformation equations subsequently used by Albert Einstein to describe space and time. The Lorentz transform adapted from his work is a way of comparing observations from different reference frames. It is a way to bring observers of different velocities at different places together so they can 'compare notes'. It takes into account the fact that the speed of light is constant, and finite, but distance and time are not constant.

For example, if you are observing a building from the front entrance and a friend two streets away observes the same building how do you compare your observations about the size and shape of the building? You need to make an adjustment, some sort of a transform, to reflect your different viewpoints. In special relativity this becomes complicated since neither distance nor time are constant between observers moving relative to each other.

In the Lorentz transform measurements in the direction of motion are adjusted by a factor γ (gamma) known as the Lorentz factor. Its value is given by:

$$\gamma = \sqrt{1 - \frac{v^2}{c^2}} \qquad = \frac{1}{\sqrt{1-\beta^2}}$$

Where *v* is the relative velocity of the two reference frames and *c* is the speed of light. Gamma is always greater than one because *v* is always less than *c*.

Special relativity explained

Notes

The following graph is a plot of gamma and 1/gamma for speeds up to the speed of light.

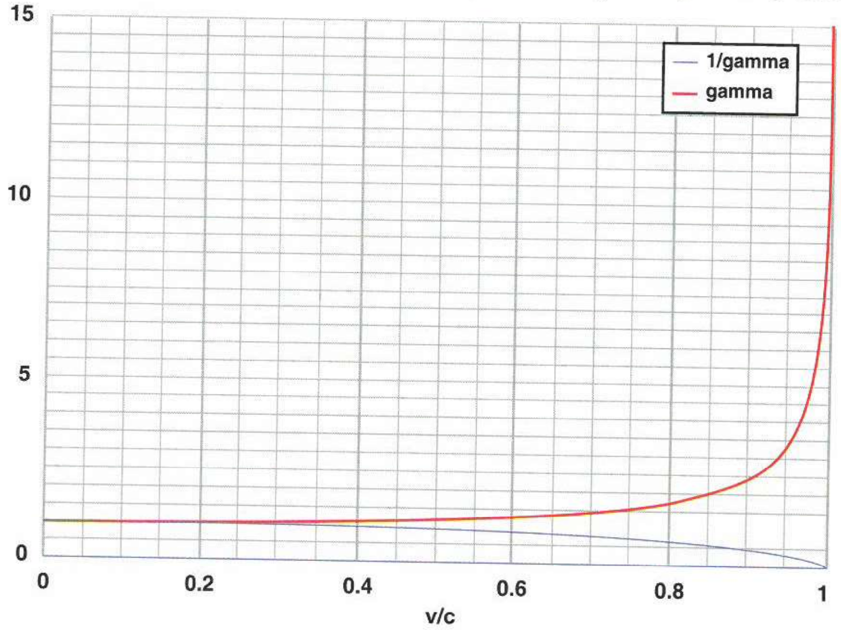


Figure 14.6: A plot of gamma and 1/gamma for speeds up to the speed of light

The relativity of length

As objects move through space-time, space as well as time changes. As an object travels at relativistic speeds it contracts or gets shorter. The term "length contraction" appears in many textbooks but what does it mean? Do fast-moving objects really shrink? Or does an object only appear to shrink, or does the observer only "perceive" a contraction?

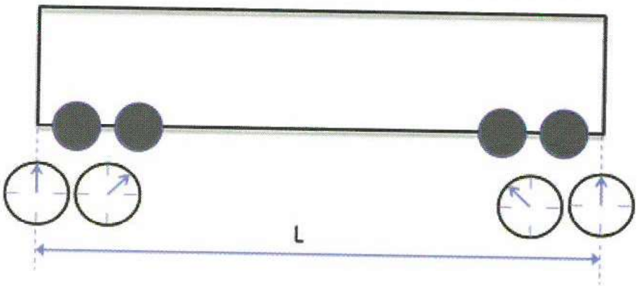


Figure14.7 Measuring the length of a moving train by locating its front and back at the same time

Figure14.7 shows the difficulty of trying to measure the length of a moving train by locating its front and back at the same time. Because simultaneity is relative and it enters into length measurements, length should also be a relative quantity. It is.

A suitable thought experiment is to compare the length of the train with a known external length such as the length of a tunnel.

Marie is on the train, with synchronised clocks placed at each end. Albert is on the station. By carefully setting up the clocks Marie sees the front clock strike noon as the train exits the tunnel and the back clock strike noon as the train enters the tunnel. To Marie the clocks strike noon simultaneously and she concludes that the train fits exactly in tunnel. For Albert the back clock strikes noon first and the front clock a little later so he concludes that the train is shorter than the tunnel.

The key to understanding this is to ask how, exactly, one might measure the length of a moving object. We can do another thought experiment using the example of a very fast train and determine how we can measure its speed. We need a set of stationary clocks spread out at known positions. The measurement of length consists of recording the simultaneous positions of the two ends of the train – we may need multiple observers to do this. The instructions might be to report in if you see either end of the train at your location at precisely noon. We can work out, by knowing who reported in, where the ends of the train were at the chosen time.

Moving objects are length–contracted – they appear shorter to an observer in a stationary frame of reference. Note that length contraction occurs only along the direction of relative motion.

If L_0 is the length of train measured by an observer in the train and L is the length as measured by the observer in a stationary reference frame then the two measurements are related through the formula used in most textbooks:

$$\frac{L}{L_0} = \sqrt{1-\beta^2}$$

$$L = L_0 / \gamma$$

Thoughts on length and time

Does a moving object really shrink? Reality is based on observations and measurements. If the results are always consistent and if no error can be determined, then what is observed and measured is real. In that sense, the object really does shrink. However, a more precise statement is that motion affects the measurement and thus reality. To an observer on the ground the train does shrink. In another observer's reality the amount of shrinking may be different. And for observers on the moving train the reality is that everything is as normal.

The relativity of velocities

No two objects can have a relative velocity greater than c. But what if a spacecraft traveling at 0.9c and it fires a missile which it observes to be moving at 0.8c with respect to it!? Velocities must transform according to the Lorentz transformation, and that leads to a rather non-intuitive result called Einstein velocity addition.

To analyse this situation we can consider two observers in relative motion with respect to each other who are both observing the motion of the missile. How do they measure the velocity of the object relative to each other if the speed of the object is close to that of light? We can consider a reference frame S' moving at a speed v relative to S. The missile has a velocity u' measured in the S' frame. The velocity u is the speed of the missile relative to frame S.

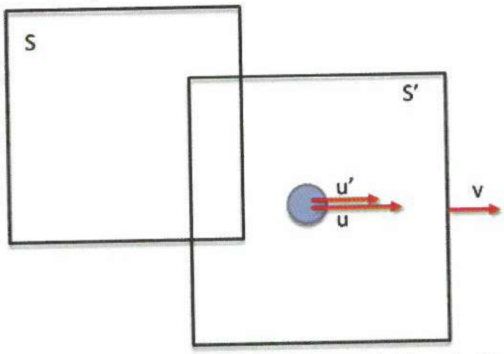


Figure 14.8: A reference frame S' is moving at a speed v relative to S. The missile shown by the blue circle has a velocity u' measured in the S' frame. The velocity u is the speed of the missile relative to frame S.

Then $u' = \dfrac{u - v}{1 - \dfrac{uv}{c^2}}$ and $u = \dfrac{u' + v}{1 - \dfrac{u'v}{c^2}}$

When v is much less than the speed of light c the denominator in the equation for u' approaches unity, and so $u' = u - v$, which is the Galilean velocity transformation equation. It is exactly what we would expect in the non-relativistic case. However, when u approaches the speed of light the equation becomes:

$$u' = \frac{c - v}{1 - \dfrac{cv}{c^2}} = \frac{c - v}{1 - \dfrac{v}{c}} = \frac{c\left(1 - \frac{v}{c}\right)}{1 - \dfrac{v}{c}} = c$$

From this result, we see that the speed of a particle travelling close to the speed of light measured by an observer in frame S is also measured as c by an observer in S'. This result is independent of the relative motion of S and S'. This s consistent with Einstein's second postulate, that the speed of light must be c relative to all inertial reference frames. Furthermore, we find that the speed of an object can never be measured to be greater than c.

What can two observers agree on?

Two observers do agree on:
(1) their relative speed of motion with respect to each other
(2) the speed of any ray of light, and
(3) the simultaneity of two events which take place at the same position and time in some frame.

We have seen several measurements that the two observers do not agree on:
(1) the time interval between events that take place in one of the frames,
(2) the distance between two fixed points in one of the frames,
(3) the velocity of a moving particle, and
(4) whether two events are simultaneous or not.

Experiment 14.1: Measuring the speed of light

Notes

Background

Visible light is one form of electromagnetic radiation (emr). Other forms exist that we cannot detect with our eyes, including infrared, ultraviolet and microwave radiations. All forms of emr travel at the same speed in vacuum, and almost the same speed in air.

Microwave ovens contain a device that emits microwaves of a single frequency. Note that many ovens contain a diffuser whose job is to break up the standing waves. This will make the pattern harder to detect.

Electromagnetic waves interact with materials in different ways, depending on the nature of the material and the frequency of the electromagnetic wave. Microwaves work well for cooking because their energy can be efficiently absorbed by molecules commonly found in food, including water, sugars, and fats. The absorbed microwave energy is converted to thermal energy and this cooks the food.

In this experiment you will use some of the properties of waves to estimate the speed of light. These properties are interference and the relationship between a wave's speed, its frequency, and its wavelength. Interference is what happens when multiple waves interact. In a microwave oven, interference occurs between waves that are reflected from the inside surfaces of the oven. The interference patterns can create "hot" and "cold" spots in the oven-areas where the microwave energy is higher or lower than average. This is why many microwave ovens have rotating platters to promote more even cooking of the food.

The spacing of the hot spots will be equal to one-half of the wavelength of the microwaves. Microwave ovens produce microwaves in a special configuration, called a standing wave. A standing wave is a wave that so perfectly fits its container that the wave pattern looks like it is standing still.

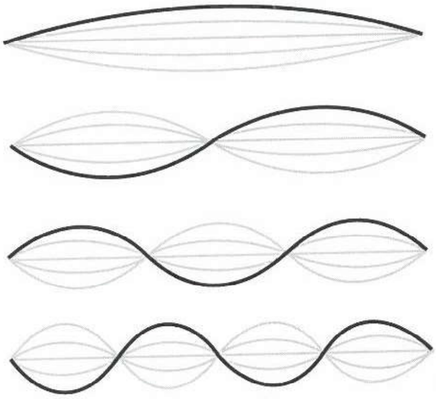


Figure14.1: Standing Wave patterns

The distance between hot-spots is equal to half of the wavelength of the microwaves. You will be able to measure the distance between the hot spots by measuring the distance between melted sections in chocolate. The frequency of the microwaves can be found on a label on the back of the oven. The frequency f, wavelength λ, and wave speed v are related by the equation:
$v = f\lambda$.

Experiment 14.1: Measuring the speed of light

Notes

Aim

To measure the speed of EMR using microwaves

Equipment

- microwave oven
- two plates, or one plate and a shallow bowl
- bread and butter or margarine, or a large slab of chocolate or other low-melting material
- metre rule

Pre-lab

- Remove the turntable from the microwave oven.
- Cover the turntable spindle (the the rotating parts) using an inverted plate or the shallow bowl.
- Balance the other plate on top of the inverted one.
- Completely cover all the pieces of bread with butter or margarine (not necessary if using chocolate).
- Arrange the buttered bread on the plate so there are no large gaps between them; or place the chocolate slab so that none overhangs the edge of the plate.

Lab notes

- Turn on the oven and observe the butter or chocolate. As soon as it starts to melt, turn the power off and remove it from the oven. This should take only a few seconds.
- The butter or chocolate should begin to melt in bands or rows. Measure and record the distance between the centres of two adjoining rows.
- Check the manufacturer's plate on the back of the oven. Record the frequency of the microwaves in MHz or GHz. If this is not given you will need to do some research.

Post-lab discussion

1. Determine the wavelength of the microwaves produced in the oven.
2. Use the wavelength and the frequency to determine the wave speed.
3. Estimate your uncertainty in measuring the wavelength. Does your measured value agree (within experimental uncertainty) with the accepted value of the speed of emr?
4. Why do microwave ovens have a turntable to rotate the food as it cooks?
5. Other devices that use microwaves include mobile telephones and radar. Is there any hazard in using these devices?

Investigation 14.2: Plotting a space-time graph

Notes

Background

Space-time graphs are usually constructed for fast-moving particles, but you probably have limited access to these.

The task

Consider an everyday journey, such as your normal trip to school. Make a space-time graph of this journey. Make the x-axis 'space-time' in units of 'light-minutes'. (A light minute is the distance travelled by light in one minute. It is found by taking the time in minutes multiplied by the speed of light). The y-axis will the distance travelled in metres or kilometres whichever is more convenient.

Plan your work carefully. You need to work out (and record) the answers to some apparently simple questions.

- (i) How do you define your starting and finishing points?
- (ii) Will you be working with scalar quantities, or vector quantities? Why?
- (iii) How will you find out the distance (or displacement) travelled?
- (iv) Will you be using your speed or your velocity to create your graph?
- (v) Does it matter that for some parts of the journey, you travel at constant speed, while for other parts you are accelerated (or decelerated)?
- (vi) How do you determine the values to use on the x- and y-axes?
- (vii) The speed of light is expressed to nine decimal places. Are error bars important for your graph? Why?

Post-lab discussion

After you have created your graph, use it to answer these questions, using calculations where appropriate.

1. What is the gradient of your graph? What is the maximum gradient it could have? How do you know?
2. How do you find your instantaneous velocity from the graph? How do you find your average velocity? Explain your answer.
3. What is the maximum value of β from your graph?
4. What is the minimum value of β from your graph?
5. If the horizontal axis used the same scale as the vertical axis, how wide would your graph need to be?

Problem Set 14.1: Special relativity explanation questions

Notes

1. (a) What is meant by the term "inertial reference frames"
   (b) Are two vehicles moving at different but constant velocities in the same inertial reference frame?

2. State Einstein's postulates in his special theory of relativity.

3. The term "proper time" is used in special relativity. What is meant by this term?

4. Light does not undergo any effects like length contraction and time dilation so is it subject to the theories of special relativity?

5. A photon has energy but does not obey Einstein's mass/energy equation $E = mc^2$. Explain.

6. Two trains are moving at different but constant velocities. Are there any conditions under which they are in the same inertial reference frame? Do two non-inertial reference frames imply that one frame is accelerating?

7. Two spaceships are launched from the same place at the same time in opposite directions, both eventually reaching a velocity of 0.70c, in their respective directions. The technicians at the launch site on see both of these spaceships as travelling away from them at 0.70c. When the second spaceship is viewed from the first and vice versa what would the velocity of the other ship be? Numerically it would appear that the speed at which either ship is moving away from the other is 1.40c. Discuss the validity of this supposition.

8. Given a jet fighter can fly at supersonic speed (say Mach 3) does design allowance need to be incorporated to accommodate any shrinkage in length? Would this be necessary in spacecraft design if the spacecraft could travel at near light speed? Explain.

9. Is the density of the material from which a relativistic space ship is constructed itself relative?

10. Alpha Centauri is a star 4.367 light years from Earth. A time traveller taking this journey at near light speed in a starship was confused by the fact that it he made the journey in less than 4 years based on his clock. How would you explain this situation to the traveller? How would this dilemma be viewed by an observer on Earth?

11. Explain if or how the density of a material is affected when it is travelling at relativistic velocities.

12. A diagram of a beam of light bouncing off mirrors shows that time in a moving spacecraft must run slow as seen by a stationary observer.
    (a) Explain why there must be length contraction.
    (b) Is this contraction real or an optical illusion?

13. When an object travels at near light speed we talk about the effects of time dilating relative to an observer in a different reference frame and length contracting to approach zero as its velocity approaches light speed. Why is it that light itself not subject to these two effects?

14. Special relativity considers the speed of light as being constant in all reference frames. How does this explain refraction of a beam of light by a glass prism when this is said to occur because the velocity of the light has decreased?

15. You are the pilot of a spaceship and are looking for a safe runway on which to land. You see one on a planet you are passing when travelling at 0.70c and measure it to be 2.2 km long and 600 m wide. What are the actual dimensions of this landing strip as measured on the ground?

16. You are in a spaceship with no windows, radios or other means to check outside. How would you determine if the spaceship is at rest or moving at constant velocity?
    A. by determining the apparent velocity of light in the spaceship
    B. by checking your precision watch- if it's running slow, then the ship is moving.
    C. by measuring the lengths of objects in the spaceship. If they are shorter, then the ship is moving
    D. you should give up because you've taken on an impossible task.

    Explain your choice.

17. It is said that Einstein, in his teenage years, asked the question: "What would I see in a mirror if I carried it in my hands and ran with the speed of light?" How would you answer this question?
    A. The mirror would be totally black
    B. You would see the same thing as if you were at rest
    C. The image would be distorted
    D. None of the above

    Explain your choice.

18. You are riding in a spaceship travelling at 0.6c when you shine your headlights into the distance. Another spaceship is travelling toward you and a scientist on board measures the speed of the light beam coming from your spaceship. What will he observe?

Notes

Problem Set 14.2: Special relativity calculation questions

Notes

1. At what velocity is a spaceship travelling if a clock on it runs at a rate which is one-half the rate of a clock at rest relative to the spacecraft?

2. Calculate the speed of a spaceship that is measured by an observer at rest at 0.70 of its actual length.

3. Calculate the momentum of a spacecraft with a rest mass of 2.5 tonne travelling at a velocity of 0.92c.

4. Two vehicles, both travelling at 0.80c, are moving apart from each other in exactly opposite directions. Calculate the velocity of one vehicle relative to the other.

5. A spacecraft is moving past a stationary observer at 0.92c. How long is one second of proper time on the spacecraft as measured by the stationary observer?

6. A train with a length measured at rest of 200 m is approaching a mountain tunnel of length 160 m. An observer at rest relative to the train sees that all of the train is inside the tunnel at the same time. Calculate the speed at which the train is approaching the tunnel.

7. A spacecraft is travelling to a distant galaxy 250 light years from Earth at 0.995c. How long would this spacecraft take to reach this galaxy
   (a) relative to the occupants of the spacecraft?
   (b) relative to an observer on Earth?

8. While you are on Earth, you observe that the spaceship Centauri-1 travels past you at 0.994c in 30 ns. This spacecraft is normally stored in a hanger at the local intergalactic base. What is the minimum length this hanger would need to be to completely enclose the Centauri-1?

9. The half-life of a π-meson (pion) is 26 μs and it travels at a velocity of 0.95c towards Earth. What is its lifetime measured relative to a stationary point on Earth?

10. Two manned spaceships, Enterprise and Discovery, are launched so that they finish up travelling in exactly opposite directions away from each other. Enterprise has a velocity of 0.70c relative to Earth in its direction and Discovery a velocity of 0.85c relative to Earth in its direction.
    (a) What velocity would an observer on Earth see each of their velocities as being?
    (b) From the reference frame of an occupant of Discovery, at what velocity would they say the Earth was moving away from them at?
    (c) An occupant of Enterprise says Discovery was moving away from them at a velocity of 1.55c. Explain why this person is wrong and give a better value for the separation velocity. You must show all equations used and calculations performed.

11. Our solar system is part of is the Milky Way galaxy which is generally considered to have a diameter of around 1.2×10^5 light years. If a particle travelling at a velocity of 0.98c entered this galaxy, how long would it take to traverse the diameter in the reference frame of:
    a) the particle b) a stationary observer

12. Identical clocks are placed with you on Earth and in a spaceship travelling away from you at a velocity of 0.95c and at a particular instant they are both showing 9.00 am. When your clock shows a time of 12.00 midday, what time would the astronaut observe on his clock?

13. A space fighter, with a length of 600 m, leaves its mothership and moves away from it at a constant velocity of 0.8c. The mothership needs to communicate with the fighter so it sends out a laser beam carrying the signal to the fighter. The crew on the fighter and the communications officer on the mothership both record zero time at the instant the laser beam arrives at the rear of the fighter.
    (a) Can each of these frames of reference be considered inertial frames?
    (b) How long after this would the beam reach the front of the fighter as measured by the crew on the fighter?
    (c) How long after this would the beam reach the front of the fighter as measured by the communications officer on the mothership?

    On reaching the front of the fighter the laser beam is reflected back through the fighter in the direction from which it came. The reflected laser beam is again viewed by both the crew on the fighter and the communications officer on the mothership.
    (d) Using the initial time as when the laser beam first reached the rear of the fighter, how long would it be before it again reached the rear as measured by the crew on the fighter?
    (e) Using the initial time as when the laser beam first reached the rear of the fighter, how long would it be before it again reached the rear as measured by the communications officer on the mothership?

14. Two identical spacecraft leave the Earth at the same velocity but in directly opposite directions. If the velocity of each spacecraft was 0.84c, what value would an observer on Earth obtain when she calculated their relative velocities?

15. You are standing on Earth observing a dogfight between two fighter jets. One of them, flying at 3.5 times the speed of sound, fires a missile at 700 m s^{-1} when directly overhead of your position. Calculate the velocity of the missile as observed by you using each of the following.
    (a) Classical physics principles. (b) Relativity theory.

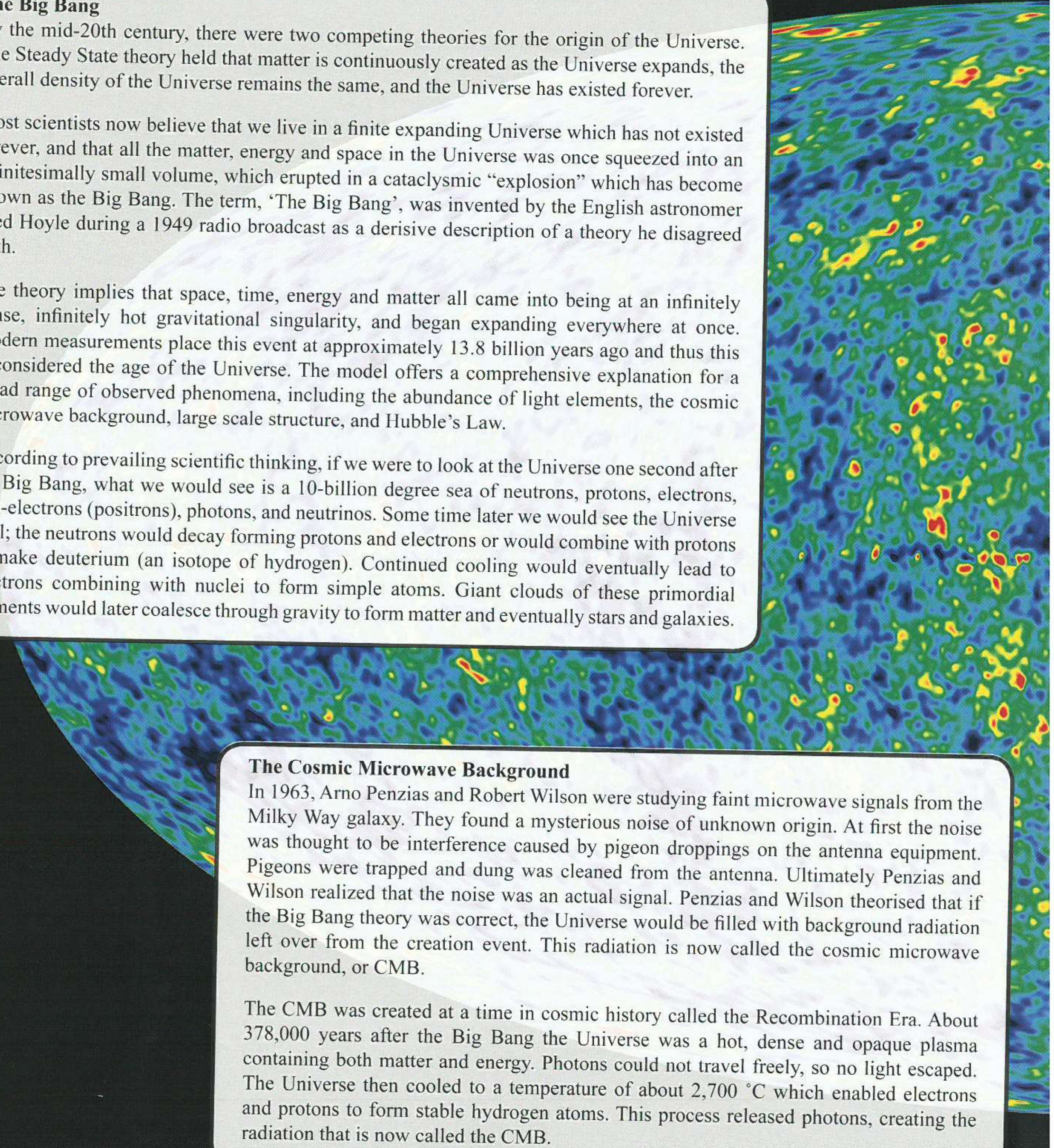
16. A radioactive nucleus travelling away from you at 0.25c in your frame of reference undergoes decay and emits a beta particle in the direction of its travel at 0.65c relative to the remaining nucleus. What is the velocity of the emitted beta particle relative to you?

17. What is the relativistic mass of a space vehicle traveling at 2.25×10^8 m s^{-1} if it has a rest mass of 3400 kg?

18. A train that has a proper length of 158 m and a rest mass of 8.00×10^5 kg is traveling at 0.925c. What is its mass and length as measured by a stationary observer?

19. Einstein said that mass and energy are the same and as a particle's velocity increases so does its mass. At what speed would a particle be travelling for its rest mass to increase to three times its rest mass?

The birth of the Universe



The Big Bang

By the mid-20th century, there were two competing theories for the origin of the Universe. The Steady State theory held that matter is continuously created as the Universe expands, the overall density of the Universe remains the same, and the Universe has existed forever.

Most scientists now believe that we live in a finite expanding Universe which has not existed forever, and that all the matter, energy and space in the Universe was once squeezed into an infinitesimally small volume, which erupted in a cataclysmic "explosion" which has become known as the Big Bang. The term, 'The Big Bang', was invented by the English astronomer Fred Hoyle during a 1949 radio broadcast as a derisive description of a theory he disagreed with.

The theory implies that space, time, energy and matter all came into being at an infinitely dense, infinitely hot gravitational singularity, and began expanding everywhere at once. Modern measurements place this event at approximately 13.8 billion years ago and thus this is considered the age of the Universe. The model offers a comprehensive explanation for a broad range of observed phenomena, including the abundance of light elements, the cosmic microwave background, large scale structure, and Hubble's Law.

According to prevailing scientific thinking, if we were to look at the Universe one second after the Big Bang, what we would see is a 10-billion degree sea of neutrons, protons, electrons, anti-electrons (positrons), photons, and neutrinos. Some time later we would see the Universe cool; the neutrons would decay forming protons and electrons or would combine with protons to make deuterium (an isotope of hydrogen). Continued cooling would eventually lead to electrons combining with nuclei to form simple atoms. Giant clouds of these primordial elements would later coalesce through gravity to form matter and eventually stars and galaxies.

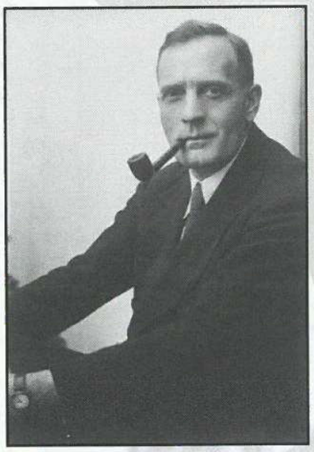
The Cosmic Microwave Background

In 1963, Arno Penzias and Robert Wilson were studying faint microwave signals from the Milky Way galaxy. They found a mysterious noise of unknown origin. At first the noise was thought to be interference caused by pigeon droppings on the antenna equipment. Pigeons were trapped and dung was cleaned from the antenna. Ultimately Penzias and Wilson realized that the noise was an actual signal. Penzias and Wilson theorised that if the Big Bang theory was correct, the Universe would be filled with background radiation left over from the creation event. This radiation is now called the cosmic microwave background, or CMB.

The CMB was created at a time in cosmic history called the Recombination Era. About 378,000 years after the Big Bang the Universe was a hot, dense and opaque plasma containing both matter and energy. Photons could not travel freely, so no light escaped. The Universe then cooled to a temperature of about 2,700 °C which enabled electrons and protons to form stable hydrogen atoms. This process released photons, creating the radiation that is now called the CMB.

The Expanding Universe

In 1925, the American astronomer Edwin Hubble stunned the scientific community by demonstrating that there was more to the Universe than just our Milky Way galaxy and that there were in fact many separate islands of stars - thousands, perhaps millions of them, and many of them huge distances away from our own. Then, in 1929, Hubble announced a further dramatic discovery. Using improved telescopes, Hubble observed that the light coming from these galaxies was shifted a little toward the red end of the spectrum, which indicated that the galaxies were moving away from us. When the source of a wave is moving toward an observer the wavelength is shortened (called 'blue shift') and when the source is moving away from the observer the wavelength is lengthened ('red shift'). Hubble observed that the emission spectra of distant galaxies were all red-shifted, and the further away they were the greater the red shift.


Edwin Hubble

After a detailed analysis Hubble concluded that the galaxies and clusters of galaxies were in fact flying apart from each other at a speed that was in direct proportion to its distance. This is known as Hubble's Law. A galaxy that is twice as far away as another is receding twice as fast, one ten times as far away if receding ten times as fast, etc. The law is usually stated as $v = H_0 D$, where v is the velocity of recession, D is the distance of the galaxy from the observer and H_0 is the Hubble constant which is around 22 km/s/million light years.

Individual galaxies themselves are not expanding but space itself is expanding. Imagine a balloon inflating, if tiny dots are painted on the balloon to represent galaxies, then as the balloon expands so the distance between the dots increases and the further apart the dots the faster they move apart. In such an expansion the Universe continues to look more or less the same from every galaxy.

Comprehension task

Draw a time line starting at the Big Bang to show when and how matter evolved from sub-atomic particles to heavy nuclei.
At points along the time line, there are great changes in the nature of the Universe and the matter in it. Explain what caused these changes.

Chapter 15: The standard model

The standard model explained

Notes

Main points

- The Big Bang theory describes the early development of the Universe, including the formation of subatomic particles from energy and the subsequent formation of atomic nuclei.
- A variety of evidence supports the Big Bang theory, including cosmic background radiation, the abundance of light elements and the red shift of light from galaxies that obey Hubble's law.
- Alternative theories exist, including the Steady State theory, but the Big Bang theory is the most widely accepted theory today.
- The standard model is used to describe the evolution of forces and the creation of matter in the Big Bang theory.
- The expansion of the Universe can be explained by Hubble's law and cosmological concepts, such as red shift and the Big Bang theory.

The big questions are, "What is the world made of?" and "What holds it together?"

- The standard model is the most complete explanation of the fundamental particles and interactions to date.
- The standard model is based on the premise that all matter in the Universe is made up from elementary matter particles called quarks and leptons; quarks experience the strong nuclear force, leptons do not.
- The world is made of six quarks and six leptons. Everything we see is a conglomeration of quarks and leptons.
- Baryons are composite particles made up of quarks.
- Names and descriptions are only a small part of any physical theory; the concepts, rather than physics vocabulary, are the critical elements.
- A particle's state (set of quantum numbers) can affect how it interacts with other particles.
- Lepton number and baryon number are conserved in all reactions between particles; these conservation laws can be used to support or invalidate proposed reactions.
- There are four fundamental forces, and force carrier particles are associated with each force.
- The standard model explains three of the four fundamental forces (strong, weak and electromagnetic forces) in terms of an exchange of force carrying particles called gauge bosons; each force is mediated by a different type of gauge boson.
- High-energy particle accelerators are used to test theories of particle physics, including the standard model.
- The magnitude of the force experienced by a particle travelling in a magnetic field depends on the charge of the particle, the velocity of the particle and the strength of the field.

Physicists have developed a theory called the standard model that explains what the world is made of, and what holds it together. Developed since the middle of the 20th century, the theory holds that all matter in the Universe is made up of combinations of elementary particles called quarks and leptons. It describes all of the particles and the interactions between. It explains the strong, weak and electromagnetic forces as a result of the exchange of various types of force carrier particles between the elementary matter particles. All the known matter particles are composites of quarks and leptons, and they interact by exchanging force carrier particles.
The Standard Model has been verified by experiments; all the particles predicted by this theory have been found. But it does not explain everything. For example, gravity is not included in the Standard Model. Dark energy and dark matter are not yet understood, but are believed to be cosmological properties required to explain the expanding Universe.

Structure within the atom
Protons and neutrons vibrate within the nucleus, and quarks vibrate within the protons and neutrons.
Figure 15.1 is quite distorted. If we drew the atom to scale and made protons and neutrons a centimetre in diameter, then the electrons and quarks would be smaller than the diameter of a human hair and the entire atom's diameter would be greater than the length of thirty football fields; 99.999999999999% of an atom's volume is just empty space!

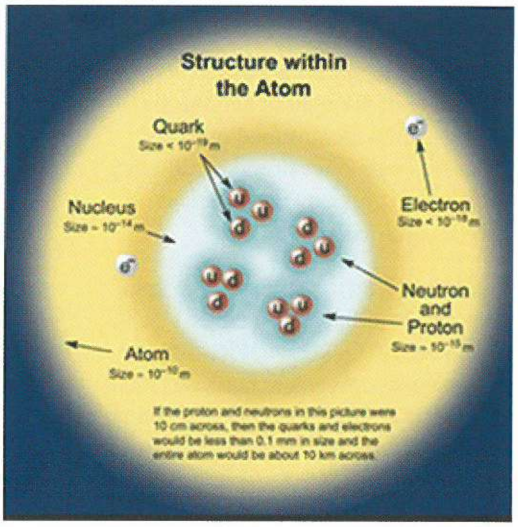


Figure 15.1: This is the modern atom model. Electrons are in constant motion around the nucleus, protons and neutrons vibrate within the nucleus, and quarks vibrate within the protons and neutrons (ParticleAdventure.org).

While an atom is tiny, the nucleus is ten thousand times smaller than the atom and the quarks and electrons are at least ten thousand times smaller than that. We don't know exactly how small quarks and electrons are; they are definitely smaller than 10^{-18} metres, or they might literally be points, but we just do not know. It is also possible that quarks and electrons are not fundamental after all, and will turn out to be made up of other, more fundamental particles ... and on it goes. Relative sizes are shown in Figure 15.2.

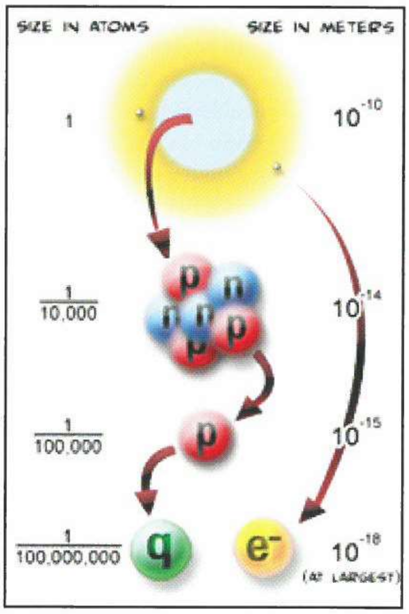


Figure 15.2

Physicists are constantly look for new particles. When they find a new particle, they find out its properties, trying to find patterns that tell us what the fundamental building blocks of the Universe are, and how they interact. We now know of about two hundred particles most of which aren't fundamental. These particles are named using letters from the Greek and Roman alphabets. Of course, the names of particles are but a small part of any physical theory. You should not be discouraged if you have trouble remembering them. Take heart: even the great Enrico Fermi once said to his student (and future Nobel Laureate) Leon Lederman, "Young man, if I could remember the names of these particles, I would have been a botanist!"

The standard model explained

Notes

The Pauli Exclusion Principle

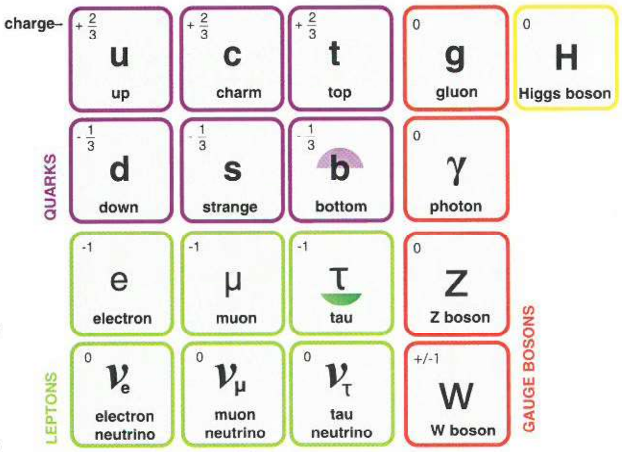
We can use these quantum particle properties to categorise the particles we find. Physicists once thought that no two particles in the same quantum state could exist in the same place at the same time. This is called the Pauli Exclusion Principle, and it explains much about chemistry. But certain particles do not obey this principle. Particles that do obey the Pauli Exclusion Principle are called fermions, and those that do not are called bosons.

Imagine a large family of identical fermion siblings spending the night at the Fermion Motel, and another large family of identical boson siblings spending the night at the Boson Inn. Fermions behave like squabbling siblings, and not only refuse to share a room but also insist on rooms as far as possible from each other. On the other hand, boson siblings prefer to share the same room.

Fermions and bosons

These are the matter particles consisting of six quarks and the six leptons. They are grouped together under this name because they all obey the Pauli Exclusion Principle and all have an anti-particle.

A fermion is any particle whose spin is an odd half-integer (such as 1/2, 3/2, and so forth). Quarks and leptons, as well as most composite particles, such as protons and neutrons, are fermions. For reasons we do not fully understand, having odd half-integer spin means that fermions obey the Pauli Exclusion Principle (i.e. two fermions cannot co-exist in the same state at same location at the same time).



charge–	$+\frac{2}{3}$ **u** up	$+\frac{2}{3}$ **c** charm	$+\frac{2}{3}$ **t** top	0 **g** gluon	0 **H** Higgs boson
QUARKS	$-\frac{1}{3}$ **d** down	$-\frac{1}{3}$ **s** strange	$-\frac{1}{3}$ **b** bottom	0 **γ** photon	
	-1 **e** electron	-1 **μ** muon	-1 **τ** tau	0 **Z** Z boson	GAUGE BOSONS
LEPTONS	0 ν_e electron neutrino	0 ν_μ muon neutrino	0 ν_τ tau neutrino	+/-1 **W** W boson	

Figure 15.3: Quarks, leptons and bosons (ParticleAdventure.org)

Bosons have an integer spin (0, 1, 2...). All force carrier particles are bosons, as are those composite particles with an even number of fermion particles (such as mesons).

Matter and antimatter

For every type of matter particle we know, there exists a corresponding antimatter particle, or antiparticle. The antiparticle is identical in mass to the particle from which it derives its name but opposite in sign. The antiparticle of the electron is called a positron. Antiparticles behave just like their corresponding matter particles, except they have opposite charges. For instance, a proton is electrically positive whereas an antiproton is electrically negative. When a matter particle and antimatter particle meet, they annihilate into pure energy.

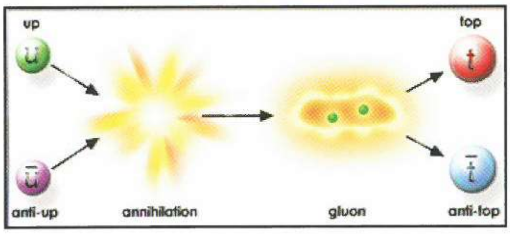


Figure 15.4: Fermions and Bosons (ParticleAdventure.org)

The Universe appears to be composed entirely of matter. If antimatter and matter are exactly equal but opposite, then why is there so much more matter in the Universe than antimatter? Well ... that is a question that keeps physicists up at night.

The usual symbol for an antiparticle is a bar over the corresponding particle symbol. For example, the "up quark" u has an "up" antiquark" designated by $\overline{u}$, pronounced u-bar. The antiparticle of a quark is an antiquark, the antiparticle of a proton is an antiproton, and so on. The antielectron is called a positron and is designated e+.

Quarks

There are six quarks. They are never found alone but as combinations of two or three in particles called hadrons. Three quarks having charge of +2/3 are called up, charm and top; and three having charge -1/3 are called down, strange and bottom. The up and down quarks together account for both the proton and neutron.

All matter from galaxies to mountains to molecules is made from quarks and leptons. But that is not the whole story. Quarks behave differently than leptons, and for each kind of matter particle there is a corresponding antimatter particle. Quarks are one type of matter particle. Most of the matter we see around us is made from protons and neutrons, which are composed of quarks.

There are six quarks, but physicists usually talk about them in terms of three pairs: up/down, charm/strange, and top/bottom. (Also, for each of these quarks, there is a corresponding antiquark.) Quarks have the unusual characteristic of having a fractional electric charge, unlike the proton and electron, which have integer charges of +1 and -1 respectively. Quarks also carry another type of charge called colour charge, which we will discuss later. The most elusive quark, the top quark, was discovered in 1995 after its existence had been theorized for 20 years.

The naming of quarks.
In 1964, Murray Gell-Mann and George Zweig suggested that hundreds of the particles known at the time could be explained as combinations of just three fundamental particles. Gell-Mann chose the name "quarks,"pronounced "kworks," for these three particles, a nonsense word used by James Joyce in the novel Finnegan's Wake. In order to make their calculations work, the quarks had to be assigned fractional electrical charges of 2/3 and minus 1/3. Quarks are never observed by themselves, and so initially these quarks were regarded as fiction. Experiments have since convinced physicists that not only do quarks exist, but there are six of them, not three.

There are six 'flavors' of quarks which just means different kinds. The two lightest are called up and down. The third quark is called strange. It was named after the "strangely" long lifetime of the K particle, the first composite particle found to contain this quark. The fourth quark type, the charm quark was discovered in 1974 almost simultaneously at both the Stanford Linear Accelerator Centre (SLAC) and at Brookhaven National Laboratory.

The fifth and sixth quarks 'top' and 'bottom' were sometimes called 'truth' and 'beauty'. The bottom quark was first discovered at Fermi National Lab (Fermilab) in 1977. The top quark was discovered last, also at Fermilab, in 1995. It is the most massive quark. It had been predicted for a long time but had never been observed successfully until then.

Hadrons

These are particles made up of two or more quarks, are capable of existence on their own (as opposed to in combination) and can interact strongly with each other. Quarks only exist in groups with other quarks and are never found alone. Composite particles made of quarks are called **Hadrons**. Only a very small part of the mass of a hadron is due to the quarks in it.
Although individual quarks have fractional electrical charges, they combine such that hadrons have a net integer electric charge. Another property of hadrons is that they have no net colour charge even though the quarks themselves carry colour charge.

There are two classes of hadrons: baryons and mesons:

- A baryon is any hadron made of three quarks (qqq). Protons are baryons, made of two up quarks and one down quark (uud). So are neutrons (udd).
- A meson is a hadron made from a quark and its anti-quark. One example of a meson is a pion (+), which is made of an up quark and a down anitiquark. The antiparticle of a meson just has the quark and antiquark switched, so an antipion (-) is made of a down quark and an up antiquark. Mesons, made of a particle and an antiparticle, are very unstable.

Notes

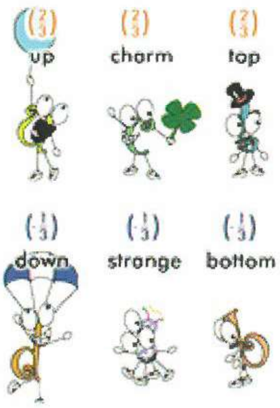


Figure 15.5: Six quarks (ParticleAdventure.org)

The standard model explained

Notes

The K meson lives much longer than most mesons, which is why it was called "strange" and gave this name to the strange quark, one of its components.

Leptons

The other group of matter particles is the leptons. There are six leptons, three being electrically charged and three being neutral. Leptons appear to be point-like particles without internal structure. The best known lepton is the electron (e-). The other two charged leptons are the muon and the tau, which like electrons are charged but with a lot more mass. The other leptons are the three types of neutrinos. These have no electrical charge, very little mass, and are very hard to detect.

Each pair of leptons is intimately connected to a pair of quarks – the electron and its neutrino are connected to the up and down quarks, the muon and its neutrino to the strange and charm quarks and the tau and its neutrino to the top and bottom quarks.

Leptons are solitary particles. Each lepton has a corresponding antilepton. The heavier leptons, the muon and the tau, are not found in ordinary matter at all. This is because when they are produced they very quickly decay, or transform, into lighter leptons. Sometimes the tau lepton will decay into a quark, an antiquark, and a tau neutrino. Electrons and the three kinds of neutrinos are stable.

When a heavy lepton decays, one of the particles it decays into is always its corresponding neutrino. The other particles could be a quark and its antiquark, or another lepton and its antineutrino.

Physicists have observed that some types of lepton decays are possible and some are not. In order to explain this, they divided the leptons into three lepton families: the electron and its neutrino, the muon and its neutrino, and the tau and its neutrino. The number of members in each family must remain constant in a decay; a particle and an antiparticle in the same family "cancel out" to make the total of them equal zero. Although leptons are solitary, they are always loyal to their families!

Lepton type conservation

Leptons are divided into three lepton families: the electron and its neutrino, the muon and its neutrino, and the tau and its neutrino. The terms "electron number," "muon number," and "tau number" to refer to the lepton family of a particle. Electrons and their neutrinos have electron number +1, positrons and their antineutrinos have electron number -1, and all other particles have electron number 0. Muon number and tau number operate analogously with the other two lepton families.

One important thing about leptons, then, is that electron number, muon number, and tau number are always conserved when a massive lepton decays into smaller ones. Let's take an example decay. A muon decays into a muon neutrino, an electron, and an electron antineutrino (*see left*)

	muon		muon neutrino		electron		e^- antineutrino
equation	μ		ν_μ	+	e^-	+	$\bar{\nu}_e$
electron number	0	=	0	+	1	+	-1
muon number	1	=	1	+	0	+	0
Tau number	0	=	0	+	0	+	0

As you can see, electron, muon, and tau numbers are conserved. These and other conservation laws are what we believe define whether or not a given hypothetical lepton decay is possible.

Neutrinos

Neutrinos are a type of lepton. Since they have no electrical or strong charge they almost never interact with any other particles. Most neutrinos pass right through the earth without ever interacting with a single atom of it.

They are produced in a variety of interactions, especially in particle decays. In fact, it was through a careful study of radioactive decays that physicists hypothesized the neutrino's existence. For example:

- In a radioactive nucleus, a neutron at rest (zero momentum) decays, releasing a proton and an electron.
- Because of the law of conservation of momentum, the resulting products of the decay must have a total momentum of zero, which the observed proton and electron clearly do not. (Furthermore, if there are only two decay products, they must come out back-to-back.)
- Therefore, we need to infer the presence of another particle with appropriate momentum to balance the event.
- We hypothesize that an antineutrino was released; experiments have confirmed that this is indeed what happens.

Because neutrinos were produced in great abundance in the early Universe and rarely interact with matter there are a lot of them in the Universe. Their tiny mass but huge numbers may contribute to total mass of the Universe and affect its expansion.

Gauge bosons

Gauge bosons are massless and are referred to as the force carriers because they are the particles responsible for mediating the strong and weak interactions. Particles subject to either the strong or the weak interaction exchange bosons as they interact. The W-positive, W-negative and Z0 mediate the weak interactions between the different flavours of quarks and leptons, the eight gluons mediate the strong force between the quarks and the photon mediates the electromagnetic interaction.

Photons

Photons are different from the other bosons and particles because they do not have a rest mass and travel at the speed of light. Depending on its energy a photon can be transformed into a particle/anti-particle pair. Conversely, a collision between a particle and its anti-particle will result in the annihilation of those particles and the formation of photons. The relationship between the mass and energy interchanged can be calculated from Einstein's equation E = mc2, where all of the energy becomes mass or all of the mass will become energy.

Flavour

An alternative name is generation. Flavour is a property that separates the different types of leptons and quarks. Each of the charged leptons and its associated neutrino has a distinct flavour, as do the three flavours of quarks, with two per flavour for both. The first flavour of both leptons and quarks (the electrons, protons and neutrons) does not undergo decay, with the electrons orbiting the atomic nuclei containing the protons and neutrons which are composed of up and down quarks. The second flavour (charm and strange quark; muon and muon neutrino) and third flavour (top and bottom quark; tau and tau neutrino) have short half-lives and are only observed in very high energy particle accelerators. The masses of the particles in each successive flavour are greater than that of corresponding particles in the flavour before. This is why successive flavours were discovered only when more powerful particle accelerators were built.

The standard model explained

Notes

The four interactions

Matter is made of quarks and leptons but what holds all these particles together?

Matter exists because of the ways in which the fundamental particles interact. These interactions include attractive and repulsive forces, decay, and annihilation. There are four fundamental interactions between particles, and all forces in the world can be attributed to these four interactions. Any force you can think of - friction, magnetism, gravity, and so on - is caused by one of these four fundamental interactions.

How do things interact without touching! How do two magnets “feel” each other’s presence and attract or repel accordingly? How does the Sun attract the Earth? Generally the answers given to these questions are “magnetism” and “gravity,” but how do these interactions work? At a fundamental level, a force is not just something that happens to particles, it is a thing that is passed from one particle to another.

Interactions that affect matter particles arise from an exchange of force carrier particles, a different type of particle altogether. What we normally think of as “forces” are actually the effects of force carrier particles on matter particles. We see examples of attractive forces in everyday life (such as magnets and gravity), and so we generally take it for granted that an object’s presence can just affect another object. The deeper question, “How can two objects affect one another without touching?” leads us to propose that the invisible force could be an exchange of force carrier particles. Particle physicists can explain the force of one particle acting on another to incredible precision through the exchange of force carrier particles.

One important thing to know about force carriers is that a particular force carrier particle can only be absorbed or produced by a matter particle which is affected by that particular force. For instance, electrons and protons have electric charge, so they can produce and absorb the electromagnetic force carrier, the photon. Neutrinos, on the other hand, have no electric charge, so they cannot absorb or produce photons.

The electromagnetic force

The electromagnetic force causes like-charged things to repel and oppositely-charged things to attract. Many everyday forces, such as friction, and even magnetism, are caused by the electromagnetic force. For instance, the force that keeps you from falling through the floor is the electromagnetic force which causes the atoms making up the matter in your feet and the floor to resist being displaced.

The carrier particle of the electromagnetic force is the photon. Photons of different energies span the electromagnetic spectrum of x rays, visible light, radio waves, and so forth. Photons have zero mass, as far as we know, and always travel at the “speed of light”, c, which is about 300,000,000 metres per second in a vacuum.

Atoms usually have the same numbers of protons and electrons. They are electrically neutral, therefore, because the positive protons cancel out the negative electrons. Since they are neutral, what causes them to stick together to form stable molecules? The answer is that the charged parts of one atom can interact with the charged parts of another atom. This allows different atoms to bind together, an effect called the residual electromagnetic force. This is what allows atoms to bond and form molecules, allowing the world to stay together and create the matter you interact with all of the time. All the structures of the world exist simply because protons and electrons have opposite charges!

The Strong Nuclear Force

What then binds the nucleus together? The nucleus of an atom consists of a bunch of protons and neutrons crammed together. Since neutrons have no charge and the positively-charged protons repel one another, why doesn’t the nucleus blow apart?

We cannot account for the nucleus staying together with just electromagnetic force. What else could there be?

Notes

To understand what is happening inside the nucleus, we need to understand more about the quarks that make up the protons and neutrons in the nucleus. Quarks have electromagnetic charge, and they also have an altogether different kind of charge called colour charge. The force between colour-charged particles is very strong, so this force is called ‘the strong force’. The strong force holds quarks together to form hadrons, so its carrier particles are called gluons because they so tightly “glue” quarks together.

Colour

‘Colour’ or ‘colour charge’ is a label and has nothing to do with actual colour. It is a name given to the three states of quarks labelled red, blue and green. Anti-quarks are labelled anti-red, anti-blue and anti-green. Gluons, which hold quarks together, are also coloured. When a gluon is emitted or absorbed by a quark the quark may change colour (state) but the large composite particle is always colourless. In order to be colourless, baryons (protons and neutrons), are comprised of three quarks, and must therefore have one of each colour. Mesons are comprised of two quarks, and must comprise a quark/anti-quark pair.

Quarks and gluons are colour-charged particles, they exchange gluons in strong interactions. When two quarks are close to one another, they exchange gluons and create a very strong colour force field that binds the quarks together. The force field gets stronger as the quarks get further apart. Quarks constantly change their colour charges as they exchange gluons with other quarks.

There are three colour charges and three corresponding anti-colour (complementary colour) charges. Each quark has one of the three colour charges and each antiquark has one of the three anti-colour charges. Just as a mix of red, green, and blue light yields white light, in a baryon a combination of “red,” “green,” and “blue” colour charges is colour neutral, and in an antibaryon “anti-red,” “anti-green,” and “anti-blue” is also colour neutral. Mesons are colour neutral because they carry combinations such as “red” and “anti-red.”

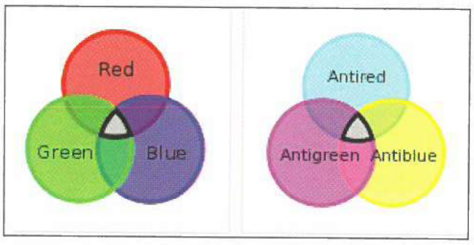


Figure 15.7: Three colours or anti-colours combine to be colourless.

Because gluon-emission and -absorption always changes colour, and -in addition - colour is a conserved quantity - gluons can be thought of as carrying a colour and an anti-colour charge. Since there are nine possible colour-anti-colour combinations we might expect nine different gluon charges, but it works out that there are only eight combinations.

Colour-charged particles cannot be found individually. For this reason, the colour-charged quarks are confined in groups (hadrons) with other quarks. These composites are colour neutral.

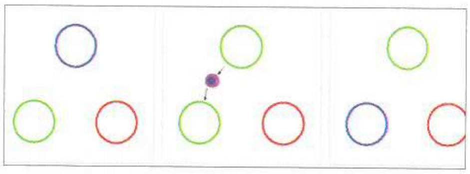


Figure 15.8: A. A hadron with three quarks (red, green, blue) before a colour change

B. Blue quark emits a blue-antigreen gluon

C. Green quark has absorbed the blue-antigreen gluon and is now blue; colour remains conserved

The development of the Standard Model’s theory of the strong interactions reflected evidence that quarks combine only into baryons (three quark objects), and mesons (quark-antiquark objects), but not, for example, four-quark objects. Now we understand that only baryons (three different colours) and mesons (colour and anti-colour) are colour-neutral. Particles such as ud or uddd that cannot be combined into colour-neutral states are never observed.

The standard model explained

Notes

Residual strong force

The strong force binds quarks together because quarks have colour charge. But that still does not explain what holds the nucleus together, since positive protons repel each other with electromagnetic force, and protons and neutrons are colour-neutral. So what holds the nucleus together? The answer is that, in short, they don't call it the strong force for nothing. The strong force between the quarks in one proton and the quarks in another proton is strong enough to overwhelm the repulsive electromagnetic force. This is called the residual strong interaction, and it is what "glues" the nucleus together.

The Weak Force

Weak interactions are responsible for the decay of massive quarks and leptons into lighter quarks and leptons. When fundamental particles decay we observe the particle vanishing and being replaced by two or more different particles. Although the total of mass and energy is conserved, some of the original particle's mass is converted into kinetic energy, and the resulting particles always have less mass than the original particle that decayed. The only matter around us that is stable is made up of the smallest quarks and leptons, which cannot decay any further.

When a quark or lepton changes type (a muon changing to an electron, for instance) it is said to change flavour. All flavour changes are due to the weak interaction. The carrier particles of the weak interactions are the W+, W-, and the Z particles. The W's are electrically charged and the Z is neutral.

Gravity

What about gravity? Gravity has been considered one of the fundamental interactions, but the Standard Model cannot satisfactorily explain it. This is one of those major unanswered problems in physics today. In addition, the gravity force carrier particle has not been found. Such a particle may someday be found: the graviton.

Fortunately, the effects of gravity are extremely tiny in most particle physics situations compared to the other three interactions, so theory and experiment can be compared without including gravity in the calculations. Thus, the Standard Model works without explaining gravity.

Experiment 15.1: Detecting the world - wavelength and resolution

Background

When using waves to detect the physical world the quality of the image is limited by the wavelength you use. Our eyes are attuned to visible light, which has wavelengths of about 0.5 micrometres which means that we can resolve objects larger than about a micrometre. However, the wavelength of visible light is too long to analyse anything smaller than a cell. To observe things under higher magnification, you must use waves with smaller wavelengths. That's why scientists use scanning electron microscopes when studying sub-microscopic things such as viruses. However, even the best scanning electron microscope can only show a fuzzy picture of an atom.

A good example of the wavelength vs. resolution issue is a swimming pool. If you have a swimming pool with waves which are 1 metre apart (a 1 metre wavelength) and push a stick into the water, the pool's waves just pass around the stick because the large wavelength ensures that the waves are not affected by such a tiny target. What physical effect is responsible for this?

All particles have wave properties. So, when using a particle as a probe, we need to use particles with short wavelengths to get detailed information about small things. As a rough rule of thumb, a particle can only probe down to distances equal to the particle's wavelength. To probe down to smaller scales the probe's wavelength has to be made smaller.

Notes

Lab notes

Part A

Use a pool or a ripple-tank to investigate the relationship between wavelength and resolution. Set up the tank according to the instructions, and begin generating waves.

Insert a thin upright wire into the water, downstream from the wave source – does the wire affect the wave pattern? Would you know the wire was there if you could only observe the wave pattern downstream? Repeat with thicker wires, rods and tubes etc. and with different wavelengths, to obtain a relationship between wavelength and resolution (the ability to observe a small object).

Part B

Different sized balls can be used to obtain an image of an object. With an object placed on the ground use balls to surround the object and then remove the object to observe the 'image' created. How does the size of the balls affect the detail of the image?

Investigation 15.2: Detecting the world - particle beams

Background

Most of the experiments that have given rise to our current conception of particle physics have occurred relatively recently. But the story of how physicists experiment to test and create theories in modern particle physics is one which starts less than a hundred years ago. In 1909 a man named Ernest Rutherford set up an experiment to test the validity of the prevailing theory of the atom. In doing so he established a way, by using particle beams, that for the first time physicists could "look into" tiny particles they couldn't see with microscopes.

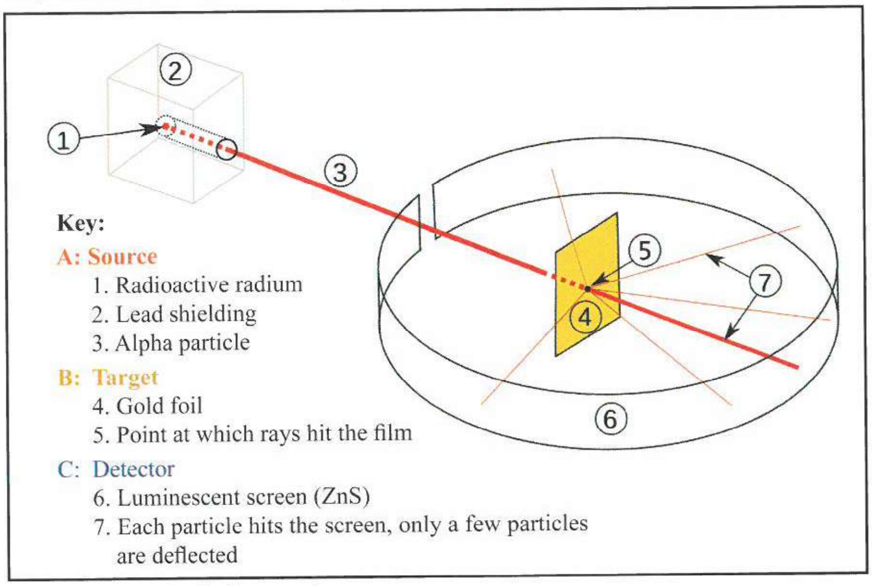


Figure 15.1: Rutherford's experiment

Rutherford's experiment is shown in Figure 15.1. The alpha particles were expected to pass right through the very thin gold foil and make their marks in a small cluster on the screen. If atoms were permeable, neutral balls, then the alpha particles should simply pass through the gold foil and strike the back of the screen. But much to everyone's surprise, some of the alpha particles were deflected at large angles to the foil; some even hit the screen in front of the foil. The deflection of the particles is shown in Figure 15.2.

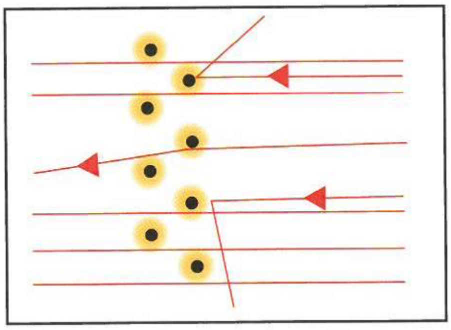
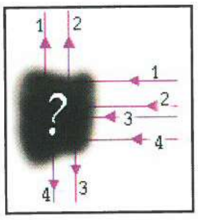


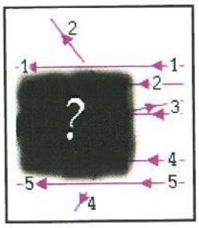
Figure 15.2: Target, gold foil atoms, magnified

Notes

(a)



(b)



Almost all particle physics experiments today use the same basic elements that Rutherford did:

- A source (in this case, a beam of alpha particles)
- A target (the gold atoms in the foil)
- A detector (the zinc sulfide screen)

In addition, Rutherford established the practise of "seeing" into the sub-atomic realm by using particle beams and particle physicists today follows his experimental lead by inferring the actual nature of particles and interactions from the frequently counterintuitive results they find.

The task

In the pictures (left), there is a target hidden by a black cloud. To figure out the shape of the target, we shot some beams into the cloud and recorded where the beams came out. Can you figure out the shape of each target? What assumptions have you made when deciding the shape?

In modern laboratories, experimenters use computers to analyse and visualise the data.

In terms of the experimental setup above, describe how you, personally, perceive the world. Note that you have more than one way to 'observe' your surroundings.

(a) If the target is the object that you observe, what is the source?
(b) How does the 'detector' work?
(c) What are the limitations to what you can perceive?
(d) How can (or do) you use technology to improve your perception of the world?

Investigation 15.3: Accelerators

Background

Notes

The physicists tool: The accelerator

Physicists can't use visible light to explore atomic and sub-atomic structures because the wavelengths are too long. However, since particles have wave properties, physicists can use particles as their probes. In order to see the smallest particles, physicists need a particle with the shortest possible wavelength, but most particles in the natural world have fairly long wavelengths. So how do physicists decrease a particle's wavelength so that it can be used as a probe?

A particle's energy and its wavelength are inversely related. High-energy physicists apply this principle when they use particle accelerators to increase the energy of a probing particle, thus decreasing its wavelength. Steps:

- Put your probing particle into an accelerator.
- Give your particle lots of energy by speeding it up to very nearly the speed of light.
- Since the particle now has a lot of energy, its wavelength is very short.
- Slam this probing particle into the target and record what happens.

Mass and energy

Quite often, physicists want to study massive, unstable particles that have only a fleeting existence (such as the very massive top quark.) However, all that physicists have around them in the everyday world are very low-mass particles. How does one use particles with lesser mass to obtain particles of greater mass?

Albert Einstein's famous equation $E = mc^2$ says that mass is just a form of energy. To produce particles with a greater mass, all one has to do is put the low-mass particles into an accelerator, give them a lot of kinetic energy (i.e. speed them up), and then collide them together. During this collision, the particle's kinetic energy results in the formation of new massive particles. It is through this process that we can create massive unstable particles and study their properties.

What makes particles go in a circle?

To keep any object going in a circle there needs to be a constant force on that object towards the centre of the circle. In a circular accelerator an electric field makes the charged particle accelerate, while large magnets provide the necessary inward force to bend the particle's path in a circle.

The presence of a magnetic field does not add or subtract energy from the particles. The magnetic field only bends the particles' paths along the arc of the accelerator. Magnets are also used to direct charged particle beams toward targets and to "focus" the beams, just as optical lenses focus light.

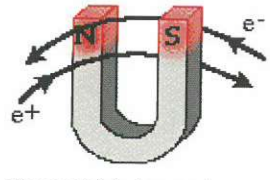


Figure 15.3.1: A magnet bends the direction of a moving charged particle

The Force a Magnetic Field Exerts on a moving Charged Particle

The magnitude of the force experienced by a particle travelling in a magnetic field depends on the charge of the particle, the velocity of the particle, the strength of the field, and, importantly, the angle between their relative directions. The right hand rule can show the direction of the force on a positive charge in a magnetic field. Point your index finger along the direction of the particle's velocity. If your middle finger points along the magnetic field, your thumb will point in the direction of the force.

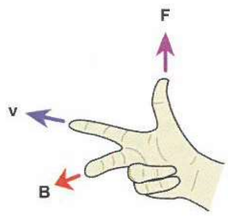


Figure 15.3.2 Right hand rule

Note: For negative charge reverse the direction of the velocity (or use your left hand).

Key Equations:

The force on a charged particle: $F_B = qvB \sin \Theta$

where q is the charge of the particle, v is the velocity of the particle, B is the magnetic field value and Θ is the angle between the velocity vector and the magnetic field vector. Note that where the direction of the particle and the direction of the magnetic field are perpendicular then

$$F_B = qvB$$

also, recall that to make a charged particle traverse a circular path of radius r a centripetal force: $F_C = F_B$ is required.

$$\frac{mv^2}{r} = qvB$$

Investigation 15.3: Accelerators

Measuring charge and momentum

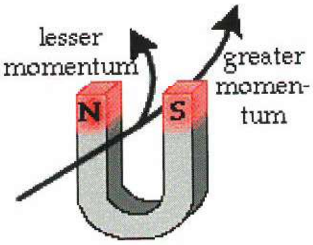


Figure 15.3.4: A magnet is used to bend the path of a particle.

One important function of the detector is to measure a particle's charge and momentum. For this reason, the inner parts of the detector, especially the tracking device, are in a strong magnetic field. The signs of the charged particles can easily be read from their paths, since positive and negative particles that are initially traveling in the same direction curve in opposite directions in the same magnetic field.

The momenta of particles can be calculated since the paths of particles with greater momentum bend less than those of lesser momentum. A particle with greater momentum spends less time in the magnetic field or has greater inertia than the particle with lesser momentum.

To summarise, physicists use accelerators to "peek" into the structure of particles. Detectors collect data which is then analysed by computers and then by people.

Detectors

Rutherford used zinc sulfide to test for the presence of invisible alpha particles and used this knowledge to determine the path of alpha particles. To look for these various particles and decay products, modern physicists have designed multi-component detectors that test different aspects of an event. Each component of a modern detector is used for measuring particle energies and momenta, and/or distinguishing different particle types.
Following each event, computers collect and interpret the vast quantity of data from the detectors and present the extrapolated results to the physicist. Modern detectors consist of many different pieces of equipment each of which tests for a different aspect of an event. These many components are arranged in such a way that physicists can obtain the most data about the particles spawned by an event. The reason that detectors are divided into many components is that each component tests for a special set of particle properties. These components are stacked so that all particles will go through the different layers sequentially. A particle will not be evident until it either interacts with the detector in a measurable fashion, or decays into detectable particles.

A few important things to note:

- Charged particles, such as electrons and protons, are detected both in the tracking chamber and the electromagnetic calorimeter.
- Neutral particles, such as neutrons and photons, are not detectable in the tracking chamber; they are only evident when they interact with the detector. Photons are detected by the electromagnetic calorimeter, while neutrons are evidenced by the energy they deposit in the hadron calorimeter.
- Each particle type has its own "signature" in the detector. For example, if a physicist detects a particle only in the electromagnetic calorimeter, then she is fairly certain that she observed a photon.

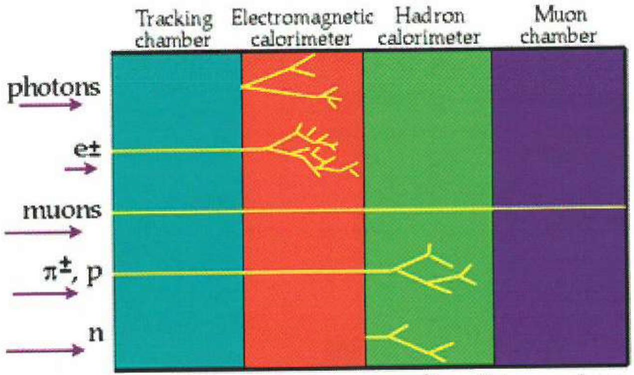


Figure 15.3.5: The interaction of various particles with the different components of a detector. Neutrinos are not shown on this chart because they rarely interact with matter, and can only be detected by missing matter and energy.

Accelerators solve two problems. Since all particles behave like waves, physicists use accelerators to increase a particle's energy, thus decreasing its wavelength. Second, the energy of speedy particles is used to create the massive particles that physicists want to study. Basically, an accelerator takes a particle, speeds it up using electromagnetic fields, and bashes the particle into a target. Surrounding the collision point are detectors that record the many pieces of the event.

Notes

How to obtain particles to accelerate

How do physicists get the particles they want to study?

- Electrons: Heating a metal causes electrons to be ejected. A television, such as a cathode ray tube, uses this mechanism.
- Protons: They can easily be obtained by ionizing hydrogen.
- Antiparticles: To get antiparticles, first have energetic particles hit a target. Then pairs of particles and antiparticles will be created via virtual photons or gluons. Magnetic fields can be used to separate them.

Accelerators speed up charged particles by creating large electric fields which attract or repel the particles. This field is then moved down the accelerator, "pushing" the particles along, as shown in Figure 15.3.6

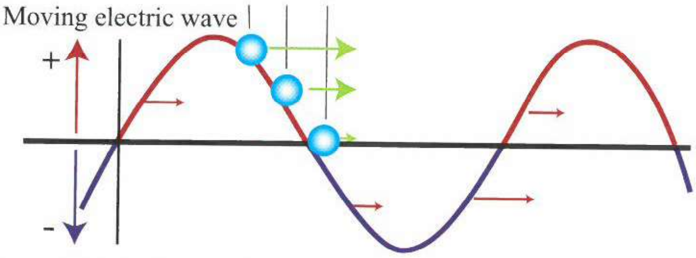


Figure 15.3.6: In a linear accelerator the field is due to travelling electromagnetic (E-M) waves.

Task 1

Accelerator design

There are several different ways to design these accelerators, each with its benefits and drawbacks.

(a) Research and describe the following target arrangements:
  - Fixed target
  - Colliding beams

(b) What are the advantages and disadvantages of each target arrangement?

(c) Research and describe the following accelerator layouts:
  - Linac
  - Synchrotron

(d) What are the advantages and disadvantages of each layout?

Task 2

Major accelerators

Explore the basic plans of the world's major accelerators and the differences in accelerator designs. Write a brief synopsis of each of the following, stating their basic design, advantages and main achievements.

- SLAC: Stanford Linear Accelerator Centre, in California
- Fermilab: Fermi National Laboratory Accelerator, in Illinois.
- CERN: European Laboratory for Particle Physics, crossing the Swiss-French border
- BNL: Brookhaven National Lab, in New York
- CESR: Cornell Electron-Positron Storage Ring, in New York.
- DESY: Deutsches Elektronen-Synchrotron, in Germany.
- KEK: High Energy Accelerator Research Organization, in Japan
- IHEP: Institute for High-Energy Physics, in the People's Republic of China

Problem Set 15.1: The standard model

Notes

1. The hundreds of known particles are all made from how many fundamental particles?

2. What are protons and electrons made of?

3. Baryons and mesons are made of quarks. Describe their make up

4. When a muon and an anti-muon collide they can annihilate each other and release their mass-energy as two photons. Assuming that these two photons are identical,
   (a) What will each of their energies be?
   (b) What wavelength will they have?
   (c) Why does there need to be two photons produced and not just one?
   (d) In what directions would they have to travel relative to each other and why?
   (e) In what part of the electromagnetic spectrum are they located?

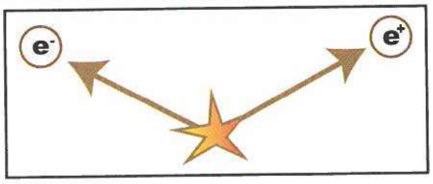
5. Fill in the missing baryons or leptons in each of the following equations. Assume that charge, baryon number and lepton number are all conserved, and that the mass of the reactants cannot be less than the mass of the products.
   (a) $n \rightarrow p + e^- + \_\_\_\_$
   (b) $\_\_\_\_ + n \rightarrow \_\_\_\_ + e^-$
   (c) $\pi^+ \rightarrow \mu^+ \rightarrow + \_\_\_\_$
   (d) $p \rightarrow n + \nu_e + \_\_\_\_$

6. An electron and a positron undergo pair annihilation. If they initially had no kinetic energy, what is the energy of each γ produced by the annihilation.? Why must there be two gamma rays produced?

7. If a magnetic field makes electrons go clockwise, in which direction does it make positrons go?

8. Can an object accelerate while keeping the same speed?

9. An electron and a positron were produced when a particle and its antiparticle collided head-on, perpendicular to this page. The diagram below shows the outcome of the collision. What conservation law appears to have been broken? Explain.
   - charge
   - number of leptons
   - momentum
   - energy



10. Which fundamental interaction is responsible for:
    (a) friction? (b) nuclear bonding? (c) planetary orbits?

11. Which interactions or interactions
    (a) act on neutrinos? (b) has heavy carriers? (c) act on the protons in you?

12. Which force carriers cannot be isolated? Why?

13. Which force carriers have not been observed?

Problem Set 15.2: General revision questions

Notes

1. Protons are accelerated in the LHC to an energy of 7.00 TeV and a velocity of 0.999997c. What is their wavelength under these conditions?

2. In the Australian synchrotron electrons are travelling with an average energy of 3.00 GeV in the main ring.
   (a) What is their average velocity in the main ring?
   (b) What wavelength do they have at this velocity?
   (c) Calculate the relativistic mass of each of these electrons.

3. In an experiment at the LHC at CERN two protons travelling in opposite directions with an energy of 7.00 Tev each are forced to collide. What is the relativistic mass, in kilograms, of each of these protons if they are travelling at 0.999999c?

4. An atomic nucleus decays emitting an alpha particle with a kinetic energy of 4.7 MeV. What is the mass equivalent of this energy?

5. A particular electron gun accelerates an electron from rest to a velocity of 0.965c. Calculate, in both joules and electron volts:
   (a) The rest energy of the electron.
   (b) The energy of the moving electron.
   (c) The kinetic energy of the electron.

6. Electrons in the beam of an X-ray machine are accelerated from rest through a potential difference of 40.0 kV. Calculate:
   (a) The maximum velocity that these electrons can achieve under these conditions.
   (b) The maximum relativistic kinetic energy of an electron in this beam.

7. Protons in a bubble chamber are bombarded with energetic antiparticles known as negative pions. At collision points, a proton and a pion transform into a negative kaon and a positive sigma:

   $$\pi^- + p \rightarrow K^- + \Sigma^+$$

   The rest energies of these particles are
   π^- 139.6 MeV K^- 493.7MeV   P 938.3 MeV Σ^+ 1189.4 MeV

   How much energy is released in this reaction?

8. The element protactinium-236 is known to undergo beta decay to uranium-236 with a half-life of 9.00 minutes. A protactinium-236 nucleus at rest undergoes such a decay and recoils with a velocity of 5200 m s^{-1}. Assuming the anti-neutrino leaves with minimum momentum after decay:
   (a) Calculate the velocity of the ejected beta-particle.
   (b) Is this value reasonable? Justify your answer with an explanation and calculations.

9. In an experiment at the LHC at CERN two protons travelling in opposite directions with energies of 7 Tev each are forced to collide. What is the relativistic mass, in kg, of each of these protons if they are travelling at 0.999999c?

10. A proton in the LHC, circumference 27 km, was accelerated to 99.9999997c.
    (a) Calculate its apparent mass at this speed.
    (b) How long would the path in the LHC appear to the particle?

Problem Set 15.2: General revision questions

Notes

11. In the Synchrotron electrons are accelerated to velocities approaching the velocity of light. On the same set of axes sketch graphs of both the non-relativistic energy and the relativistic energy against the velocity of the electron, with the electron velocity being in units of "c".

12. Stanford University in the USA has a linear accelerator 3.00 km in length and in which electrons are accelerated to 0.9999999997c.
    (a) Calculate the rest energy of an electron in MeV.
    (b) Calculate the relativistic momentum of an electron in this tube and compare it to the non-relativistic momentum.
    (c) Calculate the total energy, in joules and eV, possessed by an electron in this accelerator.

13. In the Australian synchrotron electrons are travelling with an average energy of 3 GeV in the main ring.
    (a) What is their average velocity in the main ring?
    (b) What wavelength do they have at this velocity?
    (c) Calculate the relativistic mass of each of these electrons.

14. A discharge lamp in a stationary reference frame emits light with a wavelength of 240 nm. The same wavelength from a distant galaxy is observed to be Doppler shifted to 600 nm. Is this galaxy moving towards or away from us? Justify your answer with relevant calculations.

15. A spaceship captain was charged for going through a red traffic light. He argued in court that due to his motion the red was Doppler shifted so he saw it as green. Estimate his speed at this time.

16. Beta particles are released from a carbon-14 nucleus when it undergoes decay. One such beta particle is measured to be travelling at 0.89c. Calculate this beta particle's
    (a) relativistic mass.
    (b) kinetic energy on release.

17. When a particle and its antiparticle collide they annihilate each other and all of their mass is converted to a pair of photons.
    (a) Explain why these two photons would be expected to travel in opposite directions.
    In one particular case these two particles are a positron and an electron, each travelling at 0.7c in a research facility. Calculate the total momentum and total energy in each of the following.
    (b) The frame of reference of the research facility.
    (c) The rest frame of the electron.

18. The half-life of a π-meson (pion) is 26 μs and it travels at a velocity of 0.95c towards Earth. What is its lifetime measured relative to Earth?

19. A scientist working in a particle research facility fired pi-mesons (pions) at a speed of 0.950c towards a target in a particle accelerator. Pions are radioactive with a half-life of 2.60×10^{-8} s in their own reference frame.
    (a) How long will their half-life be from the point of view of the physicists?
    (b) How far will the pions travel in the particle accelerator during their lifetime?
    (c) How far will they travel in their own reference frame?

20. The spectrum from a distant galaxy, H15, is measured from Earth and a spectral line of 550 nm is found to be blue shifted to 450 nm.
    (a) Relative to the Earth, in what direction is galaxy H15 moving?
    (b) What is H15's velocity relative to Earth?
    The same spectral line from H15 is measured at 700 nm relative to another galaxy G10.
    (c) In what direction is H15 moving relative to G10?
    (d) What is galaxy H1's velocity relative to G10?

Measurement and uncertainties

The *maximum* uncertainty of a measurement is usually ± 1 scale division. Thus, on a ruler that measures to 1 mm, a reading of 14.5 cm would be shown as **14.5 ± 0.1 cm**. On a *digital* instrument (stopwatch, balance) this is the best you'll get.

On an *analogue* instrument (ruler, thermometer, measuring cylinder) a skilled user may be able to estimate to less than this. For example, a thermometer having a fairly big spacing between the degree markings might be readable to ± 0.2 degree, if you were good at using it, or to ± 0.5 degree if you are not so skilled.

Other factors such as the reliability of the instrument itself are also important.

Example:

- Use a ruler to measure this page to ± 0.1 cm.
- Now measure it to the best (most accurate) value that you can, and show your result accordingly.
- How can we show which of these measurements has the lesser uncertainty (i.e. is 'more accurate')?

Adding or subtracting uncertainties:

If you *add* two measurements, you also add their uncertainties. Thus,

4.5 ± 0.1 cm + 5.5 ± 0.1 cm = **10.0 ± 0.2 cm**.

(Note that a simple rule about significant figures does not apply here; 2 SF + 2 SF but the answer is to 3 SF. *Significant figures give a general idea of uncertainties* instead of the more thorough treatment of uncertainties shown here.)

If you subtract measurements, you also add the uncertainties. Thus,

5.5 ± 0.1 cm - 4.5 ± 0.1 cm = **1.0 ± 0.2 cm**.

If you *multiply or divide* measurements, you convert to % uncertainty, then add these.

Example:

1. A toy car travelled 6.25 ± 0.05 metres in 22.51 ± 0.01 seconds. The speed is distance divided by time. So, we convert to % uncertainty:

$$\frac{\pm 0.05}{6.25} \times 100 = \pm 0.8\%$$

so we can now write the distance as 6.25 cm ± 0.8% .

The % uncertainty in the time is:

$$\frac{\pm 0.01}{22.51} \times 100 = \pm 0.04\%$$

So we can now write the time as **22.51 s ± 0.04%**.

Then when we calculate the average speed of the car, we can show an estimate of the uncertainty of the speed in the answer.

$$\text{speed} = \frac{\text{distance}}{\text{time}} = \frac{6.25\text{ m}}{22.51\text{ s}} = 0.27765...\text{m s}^{-1}$$

$$\text{uncertainty} = 0.8 + 0.04 = \pm 0.84\%$$

$$0.84\% \text{ of } 0.27765 ... = 0.002$$

$$\text{thus the speed is } 0.278 \pm 0.002 \text{ m s}^{-1}$$

Note that a significant figure 'rule of thumb' works in this case. But note also that for actual measurements, showing the uncertainty estimate is much better than just blindly following a rule.

Exercise: Use your measurements of this page (above) to calculate its area, and show the result with an estimate of the uncertainty.

Measurement and uncertainties

Minimising uncertainties by making repeat measurements:

You can reduce the uncertainty in a measurement by making lots of measurements of the same thing, each independent of the others, then finding the mean value and the standard deviation of the distribution. The uncertainty in this case is ± the standard deviation. Another name for standard deviation is 'standard error of the mean'.

For example, a group of students measuring "g" got the following:

Run	1	2	3	4	5	6	7	8	9	10
Value (m s^{-2})	9.36	9.67	9.64	9.41	9.88	10.21	9.55	9.74	9.96	9.92

Calculate the mean and the standard deviation of these values, and hence quote "g" with an estimate of the experimental uncertainty.

Using a spreadsheet to calculate the mean and standard deviation, we get:

Mean = 9.734

St dev = 0.250

We would quote the mean value to be:

9.7 ± 0.2 m s^{-2}, or 9.7 ± 0.3 m s^{-2}; note that either way, the "expected" value of 9.8 m s^{-2} falls within the experimental uncertainty.

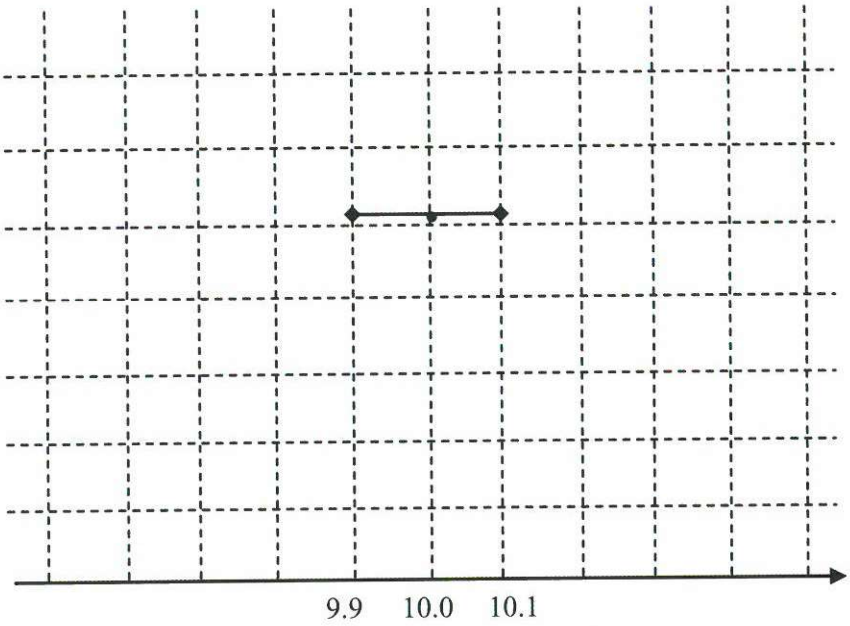
The more values you include, the more likely it is that your mean is close to the expected or actual value.

Why does this reduce the experimental uncertainty? Try using any two or three consecutive values in this table to calculate an average value for "g" and then compare it with the expected value. Note that the standard deviation is a feature of large samples and is not a valid measure for small samples, eg two or three.

Showing uncertainties on a graph:

You can graphically represent uncertainty in a measurement by plotting the value, and then adding 'error bars' that extend along the axis to show the ± values.

For example you would graph a value of 10.0 ± 0.1 m s^{-1} as a dot at 10.0, with a bar extending 0.1 unit in the positive direction (to show that the value could be as high as 10.1) and a bar extending in the negative direction (to show that the value could be as low as 9.9).



When drawing a line of best fit, it is worth keeping in mind that the central dot is not the measurement – anywhere along the bars could be correct. That is what an uncertainty means. A line of best fit should reflect your understanding of the physics of the situation.

Formulae & constants

Motion and Forces in gravitational fields	
Mean velocity	$v_{av} = \frac{s}{t}$ $= \frac{v+u}{2}$
Equations of motion	$a = \frac{v-u}{t}$; $s = ut + \frac{1}{2}at^2$; $v^2 = u^2 + 2as$; $v = u + at$
Force	$F = ma$
Weight force	$F = mg$
Momentum	$p = mv$
Change in momentum (impulse)	$Ft = mv - mu$
Kinetic energy	$E_k = \frac{1}{2}mv^2$
Gravitational potential energy	$E_p = mgh$

Motion and Forces in gravitational fields	
Work done	$W = Fs$ $= \Delta E$
Power	$P = \frac{W}{t}$ $= \frac{\Delta E}{t}$ $= Fv_{av}$
Centripetal acceleration	$a_c = \frac{v^2}{r}$
Centripetal force	$F_c = ma_c$ $= \frac{mv^2}{r}$
Newton's Law of Universal Gravitation	$F = G\frac{m_1 m_2}{r^2}$
Gravitational field strength	$g = G\frac{M}{r^2}$
Kepler's 3rd Law	$\frac{T^2}{r^3} = \frac{4\pi^2}{GM}$
Moment of a force	$\tau = rF \sin\theta$

Formulae & constants

Electricity and magnetism	
Electric current	$I = \frac{q}{t}$
Electric field	$E = \frac{F}{q}$ $= \frac{V}{d}$
Work and energy	$W = Vq$ $= VIt$
Ohm's Law	$V = IR$
Resistances in series	$R_T = R_1 + R_2 + \ldots$
Resistances in parallel	$\frac{1}{R_T} = \frac{1}{R_1} + \frac{1}{R_2} + \ldots$
Power	$P = VI$ $= I^2R$ $= \frac{V^2}{R}$
Magnetic flux	$\Phi = BA$
Electromagnetic induction	$\text{emf} = -N\frac{\Phi_2 - \Phi_1}{t},$ $= \frac{-N\Delta\Phi}{t} = \frac{-NBA}{t}$ $\text{emf} = \ell v B$
AC generator	$\text{emf}_{max} = -2N\ell vB$ $\text{emf}_{max} = -2\pi NBAf$
RMS voltage	$\text{emf}_{rms} = \frac{\text{emf}_{max}}{\sqrt{2}}$
Magnetic force	$F = I$ $F = qvB$
Ideal transformer turns ratio	$\frac{V_s}{V_p} = \frac{N_s}{N_p}$
Force between electrostatically charged objects	$F = \frac{I}{4\pi\varepsilon_\circ} \frac{q_1 q_2}{r^2}$
Magnetic field strength	$B = \frac{\mu}{2\pi} \bullet \frac{I}{r}$

Particles and waves	
Energy of photon	$E = hf = \frac{hc}{\lambda}$
Energy transitions	$E_2 - E_1 = hf$
Wave period	$T = \frac{1}{f}$
Wave equation	$v_{wave} = f\lambda$
Internodal distance	$d = \frac{1}{2}\lambda$

Motion and Forces in electric and magnetic fields	
Electric field	$E = \frac{F}{q}$ $= \frac{V}{d}$
Magnetic force	$F = qvB = \frac{mv^2}{r}$
Photoelectric effect	$E_k = hf - W = hf - hf_\circ$
de Broglie	$\lambda = \frac{h}{p}$
Special relativity	$\ell = \ell_\circ\sqrt{\left(I - \frac{v^2}{c^2}\right)} = \frac{\ell_\circ}{\gamma}$ $t = \frac{t_\circ}{\sqrt{\left(I - \frac{v^2}{c^2}\right)}} = \gamma t_\circ$ $u = \frac{v + u'}{\left(1 + \frac{vu'}{c^2}\right)} \quad u' = \frac{u - v}{1 + \frac{uv}{c^2}}$ $Pv = \frac{Mv}{\sqrt{\left(I - \frac{v^2}{c^2}\right)}} = \gamma mv$ $E = \frac{mc^2}{\sqrt{\left(I - \frac{v^2}{c^2}\right)}} = \gamma mc^2$

Formulae & constants

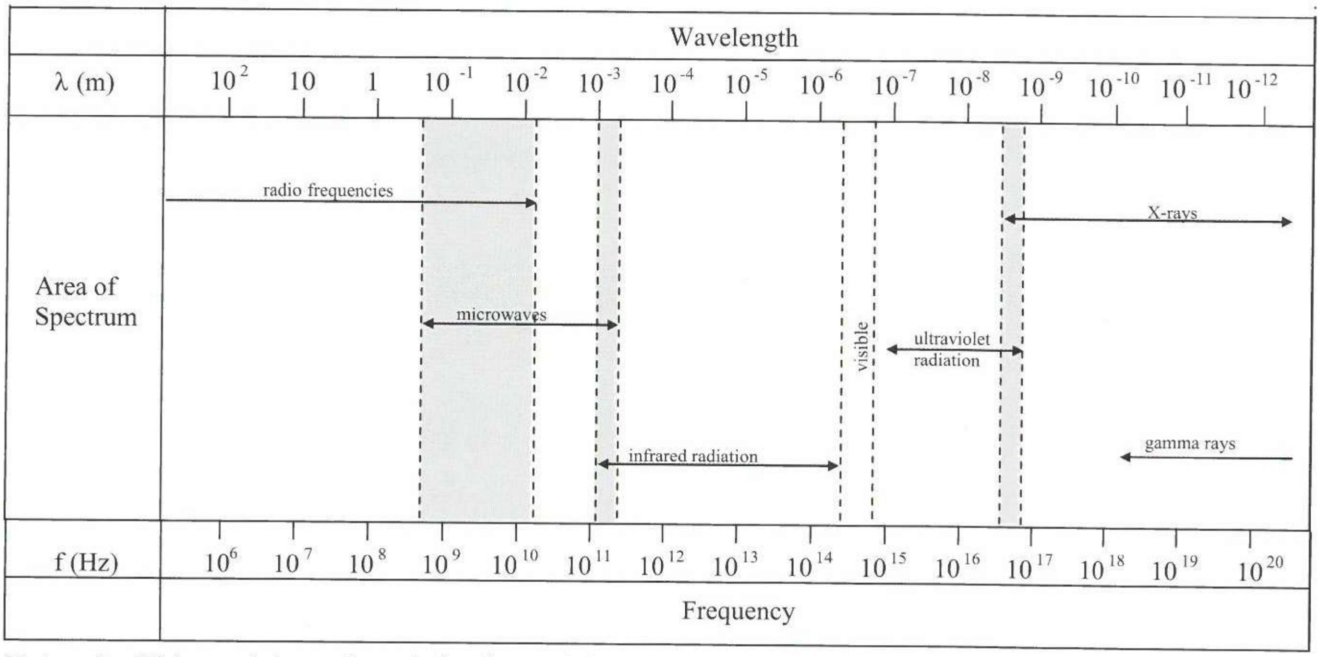
Physical Constants

Speed of light in vacuum or air	c	$= 3.00 \times 10^{8}$ m s^{-1}
Speed of sound in air at 25 °C	v	$=$ 346 m s^{-1}
Permeability of vacuum	μ_o	$= 1.257 \times 10^{-6}$ m kg^{-2}A^{-2}
Permittivity of vacuum	ε_o	$= 8.854 \times 10^{-12}$ m^{-3} kg^{-1}s^{4}A^{2}
Electron charge	e	$= -1.60 \times 10^{-19}$ C
Mass of electron	m_e	$= 9.11 \times 10^{-31}$ kg
Mass of proton	m_p	$= 1.67 \times 10^{-27}$ kg
Mass of alpha	m_α	$= 6.65 \times 10^{-27}$ kg
Planck's constant	h	$= 6.63 \times 10^{-34}$ J s
Universal gravitational constant	G	$= 6.67 \times 10^{-11}$ N m^{2} kg^{-2}
Electron volt	1 eV	$= 1.60 \times 10^{-19}$ J

Physical Data

Mean acceleration due to gravity on Earth	g	$=$ 9.80 m s^{-2}
Mean acceleration due to gravity on the Moon	g_M	$=$ 1.62 m s^{-2}
Mean radius of the Earth	R_E	$= 6.37 \times 10^{6}$ m
Mass of the Earth	M_E	$= 5.98 \times 10^{24}$ kg
Mean radius of the Sun	R_S	$= 6.96 \times 10^{8}$ m
Mass of the Sun	M_S	$= 1.99 \times 10^{30}$ kg
Mean radius of the Moon	R_M	$= 1.74 \times 10^{6}$ m
Mass of the Moon	M_M	$= 7.35 \times 10^{22}$ kg
Mean Earth-Moon distance	3.84×10^{8} m	
Mean Earth-Sun distance	1.50×10^{11} m	
Tonne	1 tonne	$= 10^{3}$ kg $= 10^{6}$ g

Electromagnetic spectrum



Note:
1. This graph is not intended to be used for accurate measurement.
2. Shaded areas represent regions of overlap.
3. Gamma rays and X-rays occupy a common region.

Mathematical expressions

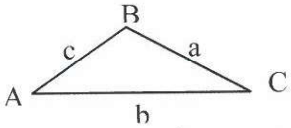
Prefixes of the Metric System

Factor	Prefix	Symbol	Factor	Prefix	Symbol
10^{12}	tera	T	10^{-3}	milli	m
10^{9}	giga	G	10^{-6}	micro	µ
10^{6}	mega	M	10^{-9}	nano	n
10^{3}	kilo	k	10^{-12}	pico	p

Mathematical expressions

$$\text{Given } ax^2 + bx + c = 0, \quad x = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a}$$

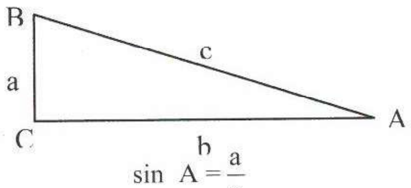
The following expressions apply to the triangle ABC as shown:



$$\frac{a}{\sin A} = \frac{b}{\sin B} = \frac{c}{\sin C}$$

$$a = \sqrt{b^2 + c^2 - 2bc\cos A}$$

The following expressions apply to the right-angled triangle ABC as shown:



$$\sin A = \frac{a}{c}$$

$$\cos A = \frac{b}{c}$$

$$\tan A = \frac{a}{b}$$