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RECOGNISING ACHIEVEMENT

ADVANCED GCE

PHYSICS B (ADVANCING PHYSICS) 2865/01

Advances in Physics

Tuesday 27 January 2009

ADVANCE NOTICE ARTICLE

May be opened and given to candidates upon receipt.

CUP/T62586

INSTRUCTIONS TO CANDIDATES

- Take the article away and read it through carefully. Spend some time looking up any technical terms or phrases you do not understand. You are ***not*** required to research further the particular topic described in the article.
- For the examination on Tuesday 27 January 2009 you will be given a fresh copy of this article, together with a question paper. You will not be able to take your original copy into the examination with you.
- The values of standard physical constants will be given in the *Advancing Physics* Data, Formulae and Relationships booklet. Any additional data required are given in the appropriate question.

INFORMATION FOR CANDIDATES

- Questions in Section A of Paper 2865, Advances in Physics, will refer to this *Advance Notice* article, and may give additional data related to it.
- Section A will be worth about 60 marks
- Section B will consist of two questions. These will ***not*** be based on the *Advance Notice* article. Section B will be worth about 30 marks.
- Four marks are available for the quality of written communication assessed over the whole paper.
- This document consists of **8** pages. Any blank pages are indicated.

SP (CM/CG) T62586/5

Turn over

Synchrotrons

Early particle accelerators

Rutherford's discovery of alpha particles, and his subsequent use of them, with Geiger and Marsden, to probe the nucleus of the gold atom, is justly well-known. He also used alpha particles as projectiles to bombard a number of different targets, including nitrogen gas. This was particularly interesting, for it produced the very first artificial nuclear change, turning nitrogen into oxygen and ejecting a proton.

To produce more effective nuclear probes, Rutherford realised it would be necessary to have particles with greater energy than that typically obtained in alpha or beta emission. Cockcroft and Walton, using an ingenious arrangement of transformers and capacitors, had already managed to produce a 200 kV potential difference down an evacuated vessel nearly two and a half metres long. By accelerating protons down this vessel into a lithium target, they were able to disintegrate lithium nuclei into alpha particles. This was the original 'atom-smashing' machine, although the reaction is now best understood in terms of the proton being absorbed by the lithium nucleus to become a very unstable beryllium nuclide, rather than the protons smashing apart the nucleus.

Greater particle energies were soon obtained with a natural extension to Cockcroft and Walton's accelerator: a linear accelerator or LINAC, where the ions to be accelerated pass through a series of cylindrical tubes (Fig. 1).

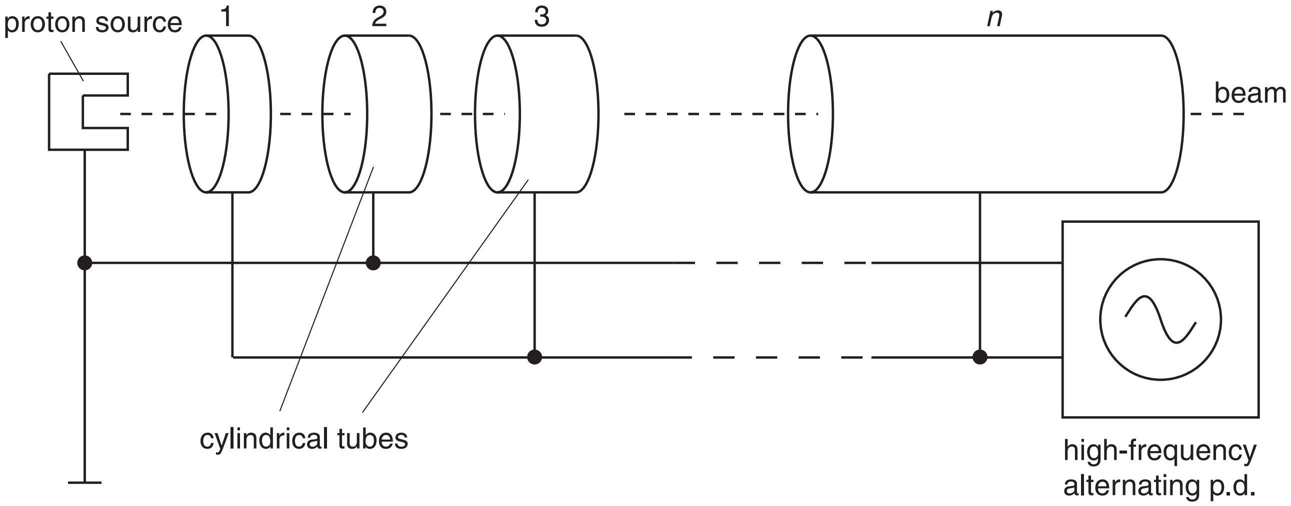


Fig. 1

The p.d. between adjacent tubes is limited by the available p.d. A linear accelerator overcomes this problem by having a large number of accelerating stages. For an ion to be continually accelerated, it is necessary that the p.d.s between adjacent tubes reverse as the particles pass through, ensuring that the electric field continues to accelerate the ion. The length of the gap between adjacent tubes is constant, but the length of the tubes increases along the accelerator path, to ensure the alternating p.d. matches the position of the accelerating ions. Using such an instrument in 1931, Ernest Lawrence and David Sloan produced mercury Hg^+ ions with an energy of 1.26 MeV using a 10 MHz source with a voltage output of 40 kV. This type of accelerator is still used, particularly for accelerating massive ions such as those used by Lawrence and Sloan, but the limitations of length meant that another approach became popular.

Lawrence's cyclotron

Ernest Lawrence had the idea of accelerating ions over a greater distance by using a magnetic field to bend the paths into a circle. His cyclotron consisted of two 'dees', each being half of a hollow cylinder, with a magnetic field vertically though the dees (Fig. 2).

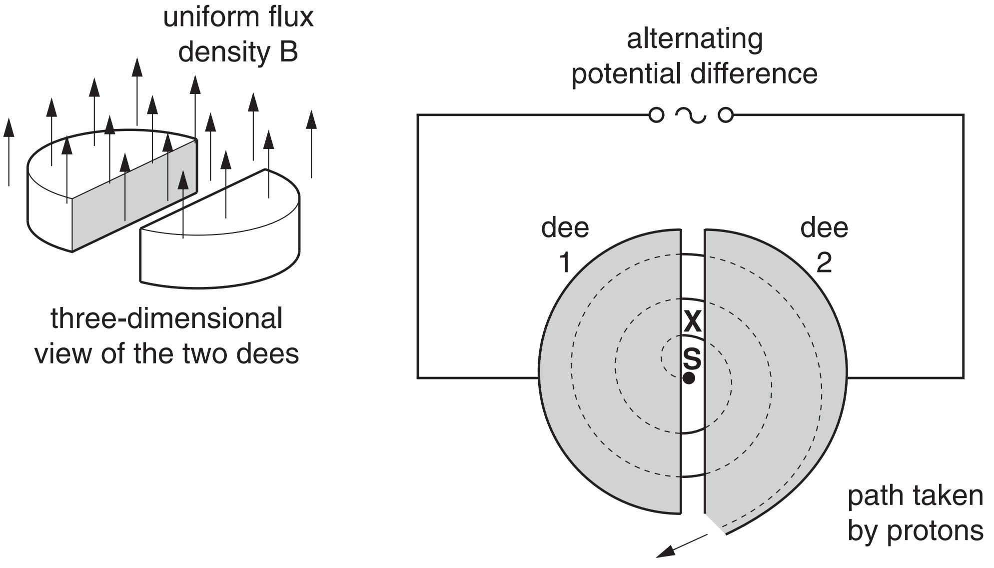


Fig. 2

The ions are injected into the centre of the dees, at the point marked **S**. They are attracted first to dee 1, which has the opposite sign of charge to the ions and then, as the alternating p.d. reverses the charges on the dees, they are attracted to dee 2, and so on. The working of the cyclotron relies on Lawrence's realisation that the frequency of rotation of a particle is independent of the radius of the orbit: as the particle velocity increases, so does the radius of its orbit. The particle momentum p varying with the radius of orbit R according to the equation $p = BqR$. Each orbit takes the same time, keeping the particle in step with the alternating field as it spirals outwards. To increase the particle energy, it is necessary to increase the size of the dees and (more difficult) the size of the magnet. Lawrence's first design was only 10 cm across, but he soon built one 69 cm in diameter.

Medical applications of particle accelerators

Besides pure scientific research into the structure of matter, particle accelerators have been applied to medicine since their invention. It is touching that the cyclotron's designer, Ernest Lawrence, realised that the high energies produced by the machines among which he worked were well suited for treating tumours. He arranged for his mother, who had been diagnosed with terminal cancer, to be treated with a high-energy X-ray tube constructed by David Sloan. The treatment was successful, and Mrs Lawrence lived into her 80s.

Most medical applications of particle accelerators use the accelerator beam directly. The beams can be used for radiotherapy or, as in the case of cyclotrons, to produce nuclear changes in a target material, generating radioisotopes such as those used for PET scans. In radiotherapy, particle beams do have the property that the quality factor of the radiation is greater than that of X-rays, which is 1, the lowest value possible.

The Effects of Special Relativity

A drawback of the cyclotron was found when particles were accelerated to large fractions of the speed of light. The momentum of particles at these high velocities is no longer given by $p = mv$. Einstein's Theory of Special Relativity shows that the equation should be $p = \gamma mv$, where

$\gamma = \dfrac{1}{\sqrt{1 - \dfrac{v^2}{c^2}}}$. When v is very close to c, γ becomes very large.

The charge of the particle does not change, so at these very high velocities the momentum needed to keep the particle moving in a circle, and hence the centripetal force, is far higher than would be given by $F = \dfrac{mv^2}{R}$. The result is that Lawrence's finding that the frequency of the particle orbits is unchanged is no longer true, although the cyclotron equation for the particle momentum $p = BqR$ still applies, provided that the relativistic momentum $p = \gamma mv$ is used.

The relativistic constant γ for these particles gives information about their total energy: $\gamma = \dfrac{\text{total energy}}{\text{rest energy}}$. The rest energy E_{rest}, by Einstein's famous equation, is given by $E_{\text{rest}} = mc^2$. For sufficiently large values of γ, the total particle energy is enough for collisions to liberate enough energy to create massive particles. Particle physicists maintain that the considerable expense and technical difficulty of constructing modern particle accelerators is made worthwhile by considering the possible products of collisions between particles of very high values of γ.

Synchrocyclotrons, with varying frequency to keep the particles moving from dee to dee, were constructed to compensate for relativistic effects at high velocities, but these were soon replaced by the circular accelerators used today – synchrotrons.

Synchrotrons

A synchrotron does not have the dee-shape of its predecessors. It is essentially a large torus – a doughnut-shape – although in practice it is likely to consist of straight sections joined by curved sections, in a huge, smoothed-out polygon. The charged particles, already accelerated to quite high velocities, are injected into the torus, and once in there they are continually accelerated to very high energies by electric fields, while magnetic fields exert the forces needed to curve the paths around the corners (Fig. 3).

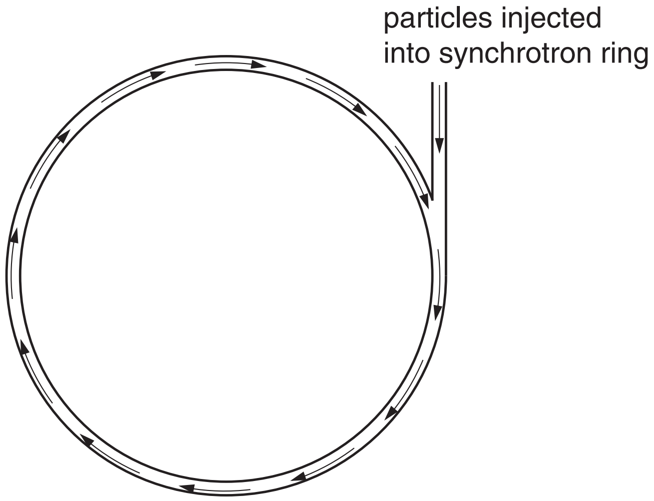


Fig. 3

To explore the structure of matter, physicists want high particle energies. To keep these particles moving in a circular orbit of a manageable radius, very large magnetic fields are needed, of the order of several tesla. Only superconducting magnets are capable of producing magnetic fields of this size, which makes large accelerators very expensive and technically very challenging to build.

The largest synchrotron operating at the time of writing, Fermilab's Tevatron, is 2.0 km in diameter, and uses superconducting magnets of maximum field strength 4.2 T to keep the high-energy ions moving in circular paths. The new 8.6 km diameter Large Hadron Collider at CERN, which should be fully operational by the time this article is published, will have magnetic fields up to 8.3 T. The larger diameter ring together with the stronger magnetic fields will allow particles to be accelerated to higher energies than in the Tevatron. Although the speed of the particles does not seem appreciably greater in the Large Hadron Collider than in accelerators using conventional electromagnets, the very great particle energies obtained when the velocity approaches the speed of light make the expense and technical difficulty of using superconducting magnets worthwhile.

Synchrotron radiation

This phenomenon was first observed in 1946 in a 70 MeV synchrotron. The machine was not fully shielded, and the torus itself was transparent. When a technician was checking for sparking in the tube (carefully using a mirror to look around the shielding) he saw a bright arc of light.

This phenomenon had been predicted earlier by the quantum physicist Julian Schwinger, and it was a problem for synchrotrons as it involved a loss of energy from the system. The basic reason for the radiation is very simple. In an aerial, when you accelerate electrons by oscillating them to and fro, electromagnetic waves are radiated. In the same way, electromagnetic radiation is emitted when charged particles are accelerated by going round a curve. For particles travelling at very high speeds, this radiation emerges along the tangent to the circular path (Fig. 4) and is polarised. The frequency of radiation produced is the frequency of rotation of the particles and multiples of this fundamental frequency.

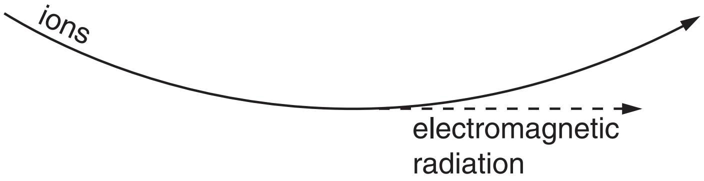
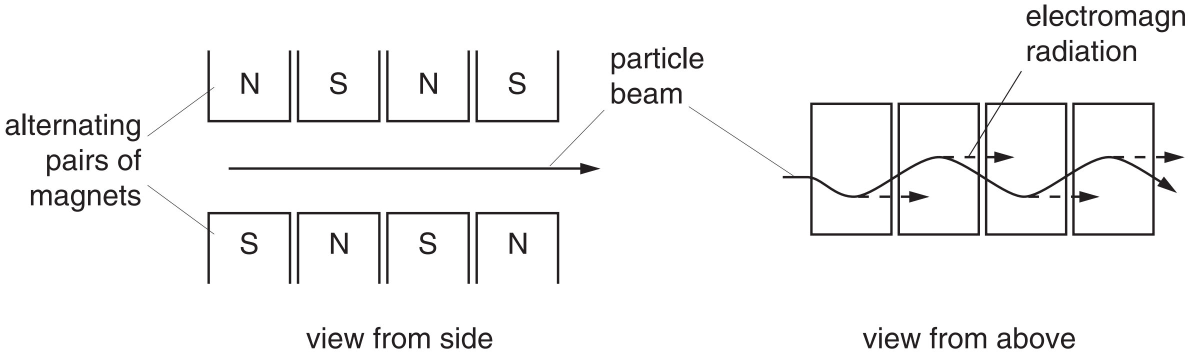


Fig. 4

This effect was used by Ernest Lawrence. He knew that his cyclotron emitted radio waves, so he slept at home with his radio tuned to the frequency emitted. Whenever the hiss on his radio stopped, he knew that his cyclotron was not running, and he would go and check up on it.

The frequency of the radiation emitted depends on the radius of curvature as well as the speed of the particles. The frequencies of the electromagnetic radiation emitted by synchrotrons can be tuned over a very large range, from infrared to ‘hard’ (high energy) X-rays. Tuning is achieved with ‘undulators’ or ‘wigglers’, which use alternating pairs of magnets to force the particles in the beam to oscillate from side to side as they move along (Fig. 5).



(not to scale)

Fig. 5

The wiggler is designed to produce a narrow beam of radiation at a controllable frequency. The duration of the electromagnetic pulse produced, and the time between pulses, can also be controlled. This is done by varying the length of the group of ions passing around the synchrotron and the interval between each such group.

Synchrotron radiation has produced a number of methods for studying live and wet tissue samples, giving structural information on all length scales down to atomic resolution. Such techniques have played a crucial role in the development of molecular biology and the understanding of protein structures.

The Diamond Light Source

In January 2007, the Diamond synchrotron (Fig. 6) at Harwell in Oxfordshire started operating. This science facility, the size of 5 football pitches, was constructed purely for the production of electromagnetic radiation and not for the production of high-energy particles. The process starts, as is the usual with synchrotrons, with a linear accelerator (1) producing 100 MeV electrons. These are then accelerated up to 3 GeV by a small, booster synchrotron (2) and fed into the storage ring (3) where they are kept on a circular path and passed through specially designed magnets, which cause them to produce the synchrotron light. This light can then be used in a wide variety of experiments.

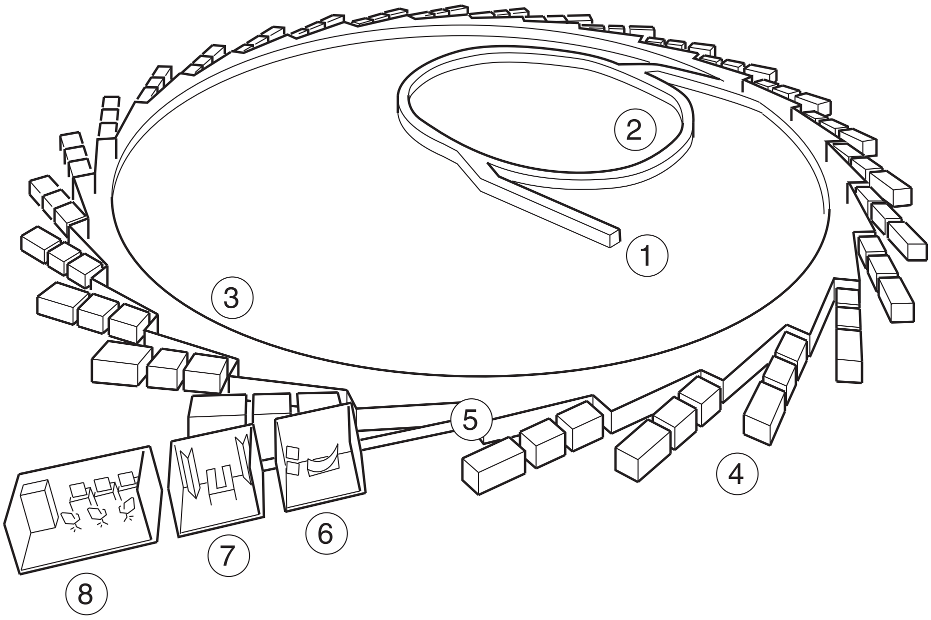


Fig. 6 – the Diamond synchrotron

Research at Diamond takes place in the experimental stations (4) around the storage ring. In March 2008, there were 9 operational experimental stations/beamlines and Diamond has funding in place to increase this number to 22 by 2011. In a given beamline (5), there is an optics 'hutch' (6) containing mirrors and diffraction gratings to filter and focus the beam. The beam then passes into the experimental 'hutch' (7), where the sample is placed surrounded by the detectors and cameras that capture the information. The experiment is monitored from the control cabin (8). Use of the intense polarised radiation from Diamond will give insights into all fields of science. Examples include understanding the structure of a host of biological samples to give us new drugs to fight disease, the structure of new materials in nanotechnology and high temperature superconductivity to advance fields such as material science, electronics and engineering, as well as analysing environmental samples to find solutions to the world's pollution problems.

END OF ARTICLE

Copyright Acknowledgements:

Fig. 6 Source: Diamond Light Source Limited, www.diamond.ac.uk