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Advances in Physics

INSERT

Thursday **26 JANUARY 2006** Morning 1 hour 30 minutes

INSTRUCTIONS TO CANDIDATES

- This insert contains the article required to answer the questions in Section A.

This insert consists of 8 printed pages.

Scientific Spin-Offs

Blue Skies and Spin-offs

'Blue skies' projects are those whose outcomes cannot be predicted when they are set up. Just as the clear blue sky seems to extend to infinity with no end in sight, so in 'blue skies' research the eventual outcome cannot be seen. Much of the most exciting research in particle physics and astronomy comes into this category. It is confidently expected that important new discoveries will be made in this work. Although it is hoped to achieve certain definite goals, such as detecting the elusive Higgs boson, this research does not have the same practical purpose as would be expected in engineering research.

One outcome of fundamental research which can be almost guaranteed is the emergence of new technologies. These unintended technological developments or 'spin-offs' are inevitable, given the amount of ground-breaking work that must be done to produce more effective apparatus.

PTFE and the Manhattan Project

One of the best-known examples of a spin-off is PTFE [poly(tetrafluorethene)] found in every kitchen as the Teflon non-stick coating on saucepans. It is also the industrial polymer of choice whenever a material with low friction, or high electrical resistance, or one which is chemically inert, is needed.

The structure of PTFE is similar to polythene [poly(ethene)] but with the hydrogen atoms replaced by fluorine atoms. Another common polymer, PVC, has the same structure as polythene with one-quarter of the hydrogen atoms replaced by chlorine atoms. Because polymers extend by rotation of the bonds between carbon atoms, the large chlorine atoms make the molecular chain of PVC stiffer than polythene. In much the same way, the fluorine atoms make PTFE much stiffer again. For both PVC and PTFE, the presence of the 'foreign' atoms replacing the hydrogen atoms makes the polymer more unreactive, for two reasons. First, the chlorine and fluorine atoms are harder to remove chemically, because they form very strong bonds with the carbon atoms. Secondly, the chlorine and fluorine atoms also block off access to the carbon-carbon bonds which form the 'spine' of the polymer, so chemical attack there is hindered.

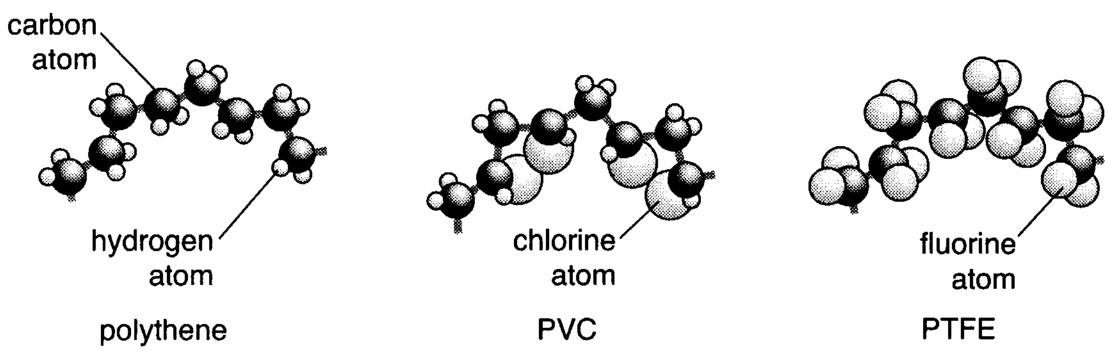

Fig. 1

PTFE is often mentioned as a spin-off from space exploration, and it did find use there in spacesuits. However, it was discovered accidentally much earlier. In 1938, chemist Roy Plunkett was working on chlorofluorocarbons (CFCs), which were then being developed as safe chemicals to replace ammonia and sulphur dioxide in refrigerators. In one experiment, a cylinder which should have contained the gas tetrafluorethene was found to be coated inside with an unreactive waxy solid which turned out to be PTFE.

Although this unreactive polymer did find use in space exploration, the first major application of PTFE was in the Manhattan Project (the development of the atomic bomb in the second world war). To produce a bomb, uranium must be enriched to contain a higher fraction of the fissile isotope U-235 than is found in natural uranium, which is almost all U-238. One successful method adopted was to produce the compound uranium hexafluoride (UF_6), which is a gas more than ten times as dense as air.

Molecules of the hexafluoride compound with the lighter U-235 travel faster than those of the hexafluoride of the more common U-238. This means that $^{235}UF_6$ will diffuse faster than $^{238}UF_6$ through holes in a membrane. As a consequence, the vapour diffusing through the holes is enriched in U-235. The difference in diffusion speeds is very small indeed, so large-scale apparatus with many stages was needed.

A difficulty in the process was that uranium hexafluoride, being extremely reactive, attacked the main seals in the miles of piping and pumps. General Leslie Groves, the director of the wartime Manhattan Project, heard about the unreactive PTFE, so that was used to coat the pipe seals in the pipes and pumps. It worked. After the war, commercial uses of Teflon were developed, principally as an electrical insulator where resistivity even higher than that of PVC was required.

Particle Physics and Modern Medicine

Large particle accelerators, particularly the Large Electron-Positron collider (LEP) at CERN and Fermilab's Tevatron, have been successful in probing deep into matter. In so doing, they have provided evidence for our theoretical model of matter, but have been very expensive. So expensive, in fact, that the planned SuperConducting Supercollider in the USA, with which we hoped to clarify our understanding of why matter has mass, was abandoned. Its planned investigations have now been left to the new CERN project, the Large Hadron Collider, which is more modest in scope, although still needing billions of Euros in funding.

To probe ever deeper into matter, it is necessary for the particles used in this research to reach higher and higher kinetic energies – of the order of TeV, where 1 TeV = 10^{12} eV. Unfortunately, to accelerate particles to reach these very high energies, huge particle accelerators are needed.

To achieve these high energies, a singly-charged particle such as a proton or its antiparticle, the antiproton, effectively needs to be accelerated through a p.d. of 10^{12} V. This is impossible to accomplish in one step. In Fermilab's Tevatron, not far from Chicago, the two largest accelerators use combinations of electric and magnetic fields to reach these energies.

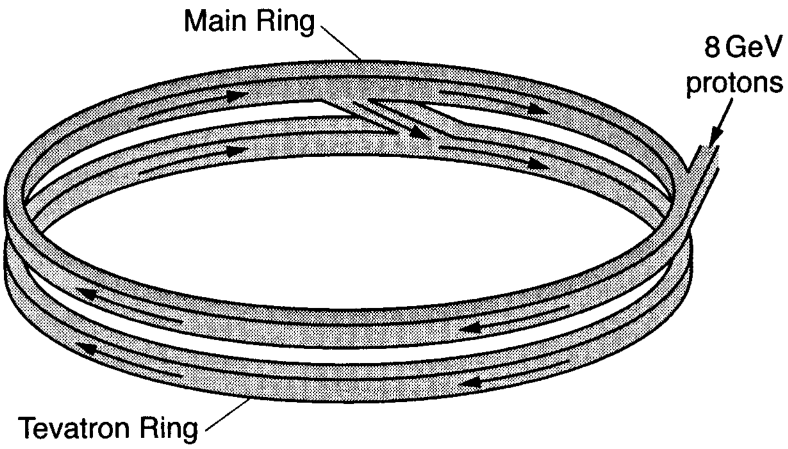

Fig. 2

Protons enter the Main Ring from earlier accelerators at an energy of 8 GeV, travelling at 99% of the speed of light. The protons are then accelerated further in the ring by pulses of electric field, and they are kept moving in the circular path by large magnetic fields. This Main Ring uses electromagnets wound with copper wire, which produce magnetic fields up to 1.8 T. Protons emerge from the Main Ring with energies of 150 GeV and are passed into the Tevatron Ring at 99.998% of the speed of light (Fig. 2 above).

The speed of light, *c*, is the maximum possible, so it might seem pointless to try to accelerate these protons further. However, Einstein's Theory of Special Relativity shows that the total energy *E* and momentum *p* can increase further without any great increase in speed. This is illustrated in the following table, where the speed *v* of the proton is shown as a percentage of the speed of light, *c*.

v/c (percentage)	momentum p / 10^{-20} N s
10%	5
20%	10
30%	16
40%	22
50%	29
60%	38
70%	49
80%	67
90%	100
99%	350
99.9%	1100
99.99%	3500
99.999%	11000
99.9999%	35000

Table 1

It can be seen that once the speed v is more than about 20% of the speed of light, the momentum of the proton is no longer given by $p = mv$. Close to the speed of light, very tiny changes in v are associated with great changes in momentum. Because momentum p and total energy E are related by the equation $E^2 = (pc)^2 + E_{rest}^2$, where the rest energy $E_{rest} = mc^2$, the energy of these protons is very large indeed. This makes the expensive construction of huge accelerators worthwhile.

The job of the Tevatron Ring is to accelerate the protons to energies of 1000 GeV (1 TeV), which is about 1000 times their rest energy. As the momentum of the orbiting protons increases, so the centripetal force needed to keep them moving in a circular path of the same radius as the Main Ring increases. This means that very strong magnetic fields are needed. Magnetic fields stronger than those in the Main Ring cannot be produced by conventional means, due to the heat dissipated in the coils. The need to produce very large magnetic fields in the Tevatron Ring without excessive power consumption stimulated the development of superconducting electromagnets. The superconducting magnets in the Tevatron Ring produce magnetic fields of flux density 4.5 T, about a million times larger than the Earth's field. Still greater flux densities are difficult to make as the steel and iron cores of the electromagnets saturate, so that increased current or more turns do not give rise to much increase in flux.

The superconducting coils in the electromagnets in the Tevatron Ring are made of wire consisting of tiny filaments of an alloy of niobium and titanium embedded in a matrix of copper, to form the wire shown in cross-section in Fig. 3.

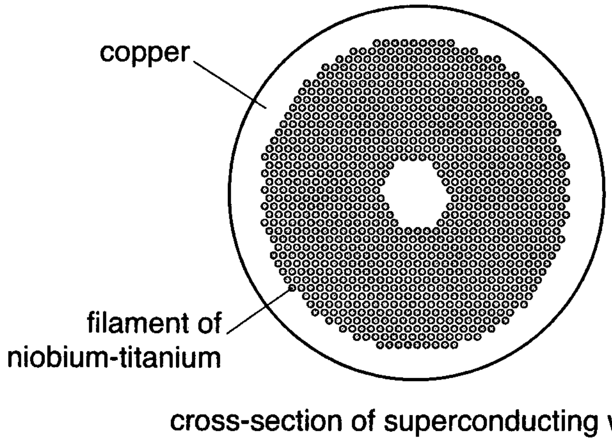

Fig. 3

At temperatures below 10 K, the resistivity of the niobium-titanium filaments, normally rather high, becomes zero. Since the wire is now superconducting, no power supply is required to maintain the current, because there will be no p.d. across the coils. Once there is a current in the coil, it will continue without the need for additional power, so the supply is disconnected.

In this composite cable, the surrounding copper, normally one of the best conductors, actually carries no current at all. The function of the copper is that of a ductile matrix holding the superconducting strands in place. However, should the temperature rise above 10 K, the niobium-titanium ceases to be a superconductor. The magnetic flux collapses, and the energy stored in the field is dissipated by induced currents in the copper. This heats the copper, evaporating the liquid helium used to cool the niobium-titanium and perhaps melting the wire. Great care is taken that this does not happen.

The Tevatron Ring contains enough superconducting wire to go more than twice around the world. This research stimulated other developments needing strong magnetic fields, including MRI (Magnetic Resonance Imaging) scanners.

In an MRI scanner, the patient lies inside a huge superconducting electromagnet, producing fields greater than one tesla in strength, as shown in Fig. 4.

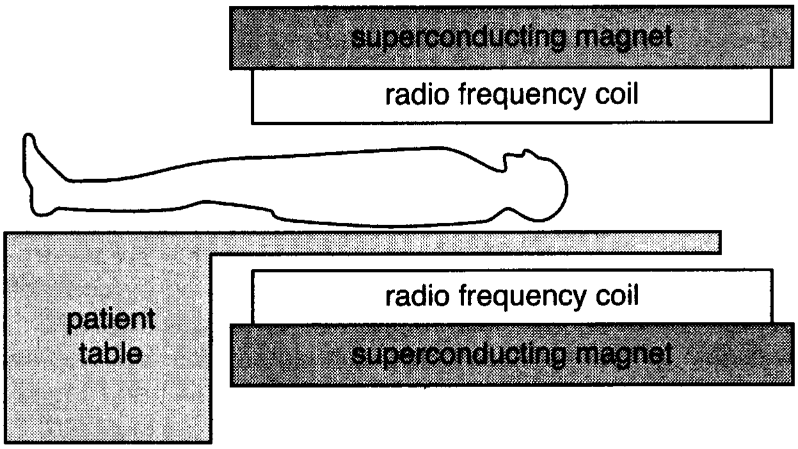

Fig. 4

The procedure works by a phenomenon called Nuclear Magnetic Resonance. In this process, nuclei of atoms with odd nucleon numbers – predominantly hydrogen – become lined up by the strong magnetic field. A smaller, oscillating field is applied from the radio frequency coil, and this causes hydrogen nuclei to 'flip' into a different alignment. The energy required for this flip is about 2×10^{-7} eV, and photons of this energy are to be found in the radio frequency range of the electromagnetic spectrum, typically at about 50 MHz.

The hydrogen nuclei resonate with the applied radio frequency field, and sensors detect the absorption of energy from the radiation. The hydrogen nuclei in the body are in different environments, so the scan gives the radiographer a detailed map of the tissues of the body, as shown in Fig. 5. MRI scanning has advantages over the use of X-rays in that it is less risky for the patient, and it gives better distinction between soft tissues.

Fig. 5