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March 2004

Features



The physics of elementary particles

by Peter Kalmus



The realisation that the great diversity of the world stems from a handful of elementary particles acting under the influence of a few fundamental forces was one of the triumphs of twentieth century physics. But the path to this realisation was not straightforward, and at one point physicists were faced with a bewildering collection of "fundamental particles" – more than there are elements in the chemical table! It has taken an understanding of mathematical symmetry combined with experiments into conditions similar to those soon after the "Big Bang" to bring physicists to the elegant understanding of today.

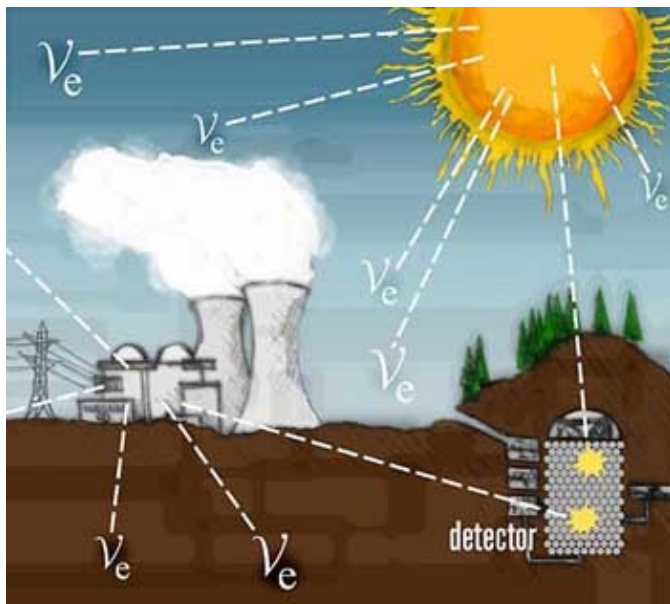
From simplicity to diversity

The physics of elementary particles



In the early 1930s the entire universe appeared to have been built using only three elementary building blocks: the protons and the neutrons which were the constituents of nuclei, and the electrons which complete the atoms. The electrons were bound into the atoms by *electromagnetism*, since they were attracted by the opposite charge of the nuclear protons, but in order to ensure that the nuclei did not disintegrate because of the mutual repulsion of their constituent protons, a new short-range force, the *strong interaction*, was required.

This simple picture did not last long. *Antiparticles*, which had some properties (such as mass) equal and others (such as charge) opposite to normal particles, were predicted and later discovered. Experiments on radioactive *beta decay*, where one element spontaneously converts into another with the emission of an electron, appeared to violate the laws of conservation of energy and momentum. To conserve these quantities it was postulated that an additional particle, named the *neutrino*, was emitted, which carried away the missing energy and momentum.



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The neutrino did not feel either the electromagnetic or the strong force, and hence escaped undetected in these beta decay experiments. It would be created by another new short-range force, the *weak interaction*, which was so feeble that neutrinos on average could penetrate light-years of material such as iron before having a significant chance of interaction; they were therefore thought to be undetectable. However, in the 1950s the huge flux of neutrinos coming from radioactive material in nuclear reactors led to their detection. Since then neutrinos from various sources – accelerators, reactors, the Sun, supernova SN1987A, cosmic ray interactions – have been observed in many experiments.

Also in the 1950s and 1960s, experiments using cosmic rays, and later the new large accelerators, showed that if particles such as protons hit nuclei with sufficient energy, then additional new particles could be created by converting some of the collision energy into particle mass), according to the wellknown equation $E=mc^2$. These particles were unstable and decayed rapidly into more stable forms, either in around 10^{-23} seconds by the strong interaction, or at a more leisurely pace, say in 10^{-8} seconds or 10^{-10} seconds by the weak interaction.

By the 1970s the number of so-called "elementary particles" exceeded the number of chemical elements!

Back to simplicity

Fortunately the present situation is again much simpler. There now appear to be only two classes of elementary building blocks, called *quarks* and *leptons*. Quarks feel the strong interaction, leptons do not. In our normal surroundings where kinetic energies per particle are low, we have only two of each. Electrons and neutrinos are leptons. However, the proton and neutron are no longer elementary, but are made up of two types or "flavours" of quark called *up* (u) and *down* (d). Each contains three quarks: the proton is made up of two "up" and one "down"; the neutron of one "up" and two "down". The electric charges are $+2/3$ for up and $-1/3$ for down (relative to the electron charge of -1), so, as we would expect, the neutron has no charge, and the proton a positive charge of 1.

At higher energies, this simple pattern of two leptons and two quarks is repeated, but only twice, leading to three generation of quarks and leptons, as shown in the diagram below. Also, every quark and lepton has an *antiparticle*, so we end up with six each of quarks, antiquarks, leptons and antileptons.

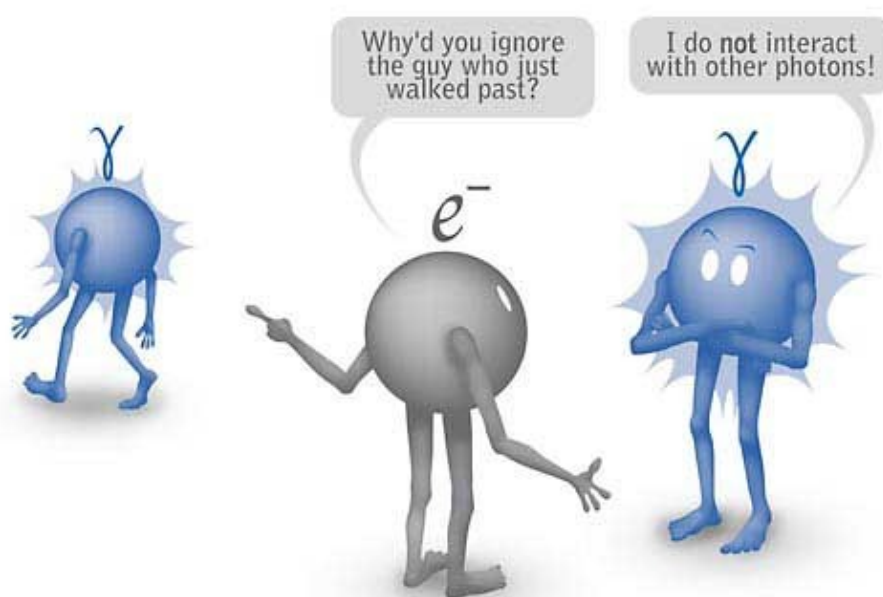
Leptons (do not feel strong force)			Quarks (feel strong force)			Also antiquarks antileptons
electron	e^-	-1	up	u	$+2/3$	
electron-neutrino	ν_e	0	down	d	$-1/3$	6 antileptons
						6 quarks
						6 antiquarks

Feel the forces

We expect all particles to feel the gravitational force, which is, however, fantastically weak in comparison with the others. For example, the electromagnetic force between a proton and an electron is 10^{40} times stronger than the gravitational force. All particles feel the weak force. Quarks and charged leptons also feel the electromagnetic force, and quarks feel the strong force.

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The forces through which the building block particles interact are transmitted by the exchange of another type of object. The force-carriers are *bosons*. The carrier of electromagnetism is the *photon*. Gravity is believed to be transmitted by particles called *gravitons*, but these have not yet been detected.



The objects which carry the colour force between quarks and hence glue them into hadrons are called *gluons*. Unlike photons, gluons can interact with each other. As a consequence of this, the force increases with distance, and quarks are confined inside hadrons, so that free individual quarks have not been observed. Gluons were first discovered in 1979 at the DESY laboratory in Germany.

The theory of strong interactions, known as *quantum chromodynamics* (QCD), is well-developed and consistent with experiments, although it is not easy to test it very precisely.

Initially it was thought that a charged carrier, called W for weak, was responsible for the weak force. But in the 1960s, theorists achieved the surprising feat of unifying the apparently disparate phenomena of the electromagnetic and weak forces into a single mathematical framework. Electromagnetism has a classical inverse square law (like Newton's classical law of gravitational attraction), and infinite range. In contrast, the weak interaction under normal circumstances is very feeble and is confined to sub-nuclear distances. Protons in the solar core collide many times a second, but on average a particular proton will only convert into a neutron (a necessary stage in the conversion of hydrogen into helium) after around five billion years of collisions. Hence it can be calculated that the Sun is only half way through its hydrogen burning, thereby providing both the environment and the time-scale for biological evolution on Earth.

In electroweak theory, there are four mediating objects. The massless photon transmits the electromagnetic force and the weak force is transmitted by three massive particles: the charged W^+ and W^- particles and the neutral Z^0 particle, which have masses about 100 times that of the proton. The intrinsic strengths of these carriers are identical, but the massive nature of the W and Z particles limits their range to very short distances, a consequence of the uncertainty principle of quantum mechanics. In collisions at relatively low energies, the particles do not approach each other sufficiently closely for W or Z exchange to occur. However, at very high energies, say 100 times the proton rest mass, close encounters are common, showing electroweak unification. The most spectacular experimental verification of this theory was the discovery of the W and Z particles at CERN in 1983. Electroweak theory has now been tested to high accuracy.

Symmetries

Symmetries play a significant role in particle physics. In mechanics, in electromagnetism, and in strong interaction physics, there is no intrinsic difference between left and right. A process and its mirror image occur at the same rate. Similarly, observable processes would occur with the same probabilities if all particles were changed into their corresponding antiparticles. At the microscopic level, the laws for a process and its *time-reversed process* should also be equivalent. For macroscopic systems, time reversal does not hold, but this is a consequence of its statistical improbability rather than of basic laws.



Natural symmetry

In the 1950s it was found that for weak interactions the first two of these symmetries – the left–right and the charge symmetries – do not hold. In fact, they are as wrong as possible! The strict mirror image of beta decay is not observed unless at the same time particles and antiparticles are interchanged, and even this combined symmetry (called CP) is violated in some rare processes. This violation is not understood, but is believed to an essential condition for the vast preponderance of matter over antimatter in our universe.

Electroweak theory and QCD have been incorporated into what is known as the *standard model* of particle physics. Although this model works very well it suffers from a number of defects. There are rather a lot of arbitrary numbers which are not intrinsic to the theory but have to be obtained from experiment. The theory predicts nonsensical results at energies slightly higher than now available – equivalent to processes having a probability greater than 1! In addition, the theory requires that the W and Z particles, like the photon, should be massless. A mechanism which gives mass to the particles by allowing them to interact with a field was first suggested by Peter Higgs. This would have a carrier object – the *Higgs boson*, which, so far, has not been detected.

Neutrino physics

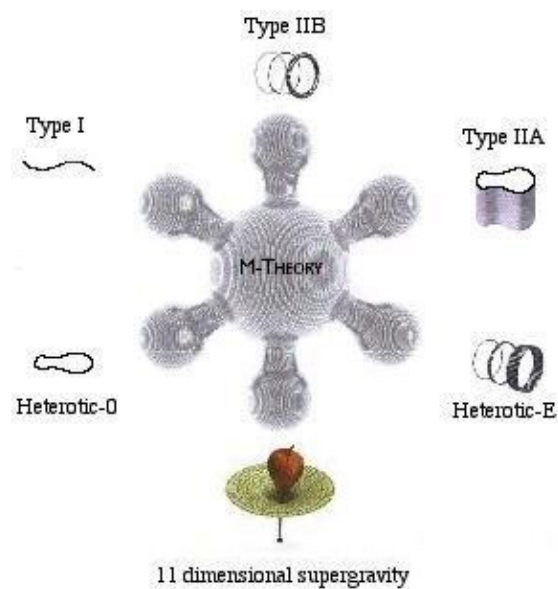
This has been one of the most exciting areas in particle physics in recent years. In the late 1960s, Raymond Davis discovered that the number of neutrinos reaching the Earth from the Sun was only about one third of the number expected from theoretical calculations of fusion reactions. The experiment was a very difficult one, but it was continued for many years and the calculations of reactions in the Sun were refined. Later

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experiments, using different detection techniques which were sensitive to different energies of solar neutrinos, all showed deficits. One suggested solution to this solar neutrino problem was that the neutrinos generated in the Sun (which are electron neutrinos, see the table above) transformed into one or both of the other neutrino types, which would not be recorded in the experiments. Such neutrino mixing or oscillations requires neutrinos to have a non-zero mass.

In the 1990s, several very large underground detectors, buried deep underground to shield them from unwanted radiation, investigated solar neutrinos and also neutrinos of much higher energies originating from decays of atmospheric cosmic rays. Another important experiment measured the flux of electron-neutrinos at a central location around 140 to 210 km from a large number of nuclear reactors in Japan. A consistent picture has now emerged. Neutrino mixing occurs. Raymond Davis, and Masatoshi Koshiba, the pioneer of Kamiokande, shared the 2002 Nobel Prize, together with X-ray astronomer Riccardo Giacconi.

Particle theory



The network of string theories and M-theories.

Image courtesy of Stephen Hawking

In this short summary, very little has been written about the theoretical advances in particle physics. There are mathematical schemes which unite the strong interaction with electroweak theory. These are known as *grand unified theories*, or GUTs. Another theory, *supersymmetry*, unites the building blocks – the quarks and the leptons – with the force carriers. This requires new partner particles for all these objects, none of which have so far been discovered. *Superstring* theories, and their recent extension, *M-theories*, which require supersymmetry, are exciting and fashionable. They treat particles as excitations of tiny strings. This avoids objectionable infinities which arise when particles are treated as point objects. Superstring theories do, however, require more than the usual three space and one time dimension. The unobserved dimensions are assumed to be *compactified* – curled up so that they are too small to be observable, just as an overhead telephone wire appears from a distance to be only one-dimensional. Superstring theories have the potential to provide a quantum theory of gravity and to unite gravity with the other forces, and there is much activity in this field.

Links with cosmology

The "hot big bang" picture assumes that the early universe was a primordial soup of elementary particles, and today's high energy machines provide collision energies like those which existed when the universe was less than one nanosecond old. Accurate measurement of the fluctuations in the cosmic microwave background, observation of the acceleration of the expansion of the universe, and computer modelling of galaxy formation and clustering have recently provided a consistent view of the universe. The universe is geometrically flat: parallel light rays do not converge or diverge. The observable matter in the universe, i.e. that which can be detected in any part of the electromagnetic spectrum, only accounts for about 5% of the energy density of the universe. Another 25% is cold dark matter and the remaining 70% has been dubbed "dark energy". Neutrinos can only make up perhaps 0.5% of the total.

Candidates for dark matter are WIMPs – weakly interacting massive particles – of which the favourite is the *neutralino*, the lowest mass supersymmetric particle. Searches for WIMPs are in progress in several underground laboratories. Dark energy is even more mysterious. It appears to be like a negative pressure of space, reminiscent of the cosmological constant which Einstein put into his equations to prevent the gravitational collapse of a static universe, before Hubble's discovery that the universe was expanding.

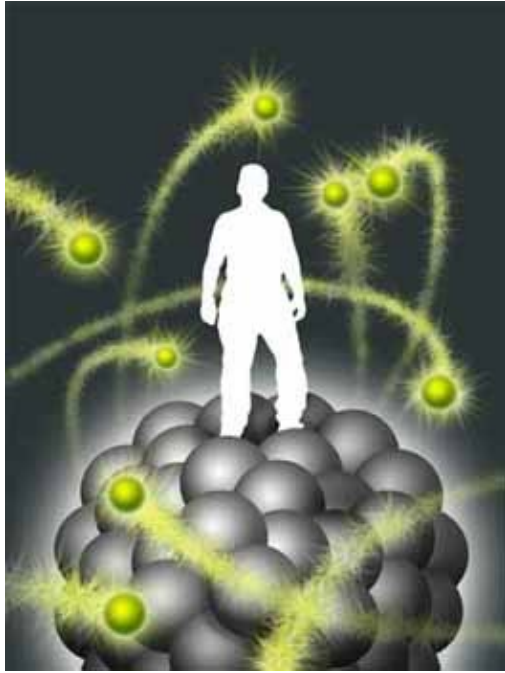
Future prospects

The large hadron collider, LHC, 27km in circumference, colliding proton beams at a total energy of about 15,000 times the proton rest mass, is being constructed at CERN in Geneva, and will start in around 2007. It seems highly probable that the Higgs boson will be discovered with that machine; indeed it might be discovered sooner at the Fermilab Tevatron which has been upgraded. If the Higgs is not found, then some other new physics is certain to emerge, to avoid the excess of probability that would otherwise come from the standard model.

Designs for a large linear electron–positron collider are in advanced stages, and there is hope that one such machine might be approved in a few years' time, and built in Europe, America or Asia as a world–wide collaboration. In the more distant future it may be possible to make intense and well–controlled high energy neutrino beams from decays of muons in a storage ring, although at present many technical problems remain unsolved.

The origin of the vast preponderance of matter over antimatter is likely to be discovered within the next few years. Supersymmetric particles, if they exist, should be found at the LHC. If not found, supersymmetry will presumably be discarded and some alternative theory will take its place.

What else will emerge?



the final frontier

We take for granted that the electron and proton charges are numerically equal, and indeed experimentally they are equal to better than 1 part in 10^{21} . This may not seem surprising. However, leptons and quarks are quite distinct. The numerical charge equality between 3 quarks and an electron cannot be a coincidence. Perhaps at high energies, such as existed in the early universe, leptons and quarks coupled with each other. At lower energies, this symmetry is broken in an analogous way to electroweak symmetry breaking. In 1997 there was excitement when some collisions between positrons and protons at the HERA machine at DESY gave some indication of the existence of such leptoquarks. With more data this interpretation turned out to be wrong, but it still seems likely that in the fairly near future some better understanding will arise of the connection between leptons and quarks.

Superstring theory may also come up with some predictions that can be tested. But although the graviton, the quantum transmitter of the gravitational force, fits well into the superstring picture, it seems unlikely that it will be found in the near future. However, gravitational radiation is predicted from general relativity, and its existence can be inferred from the careful measurements over many years of the change in period of a binary pulsar. Several detectors for gravitational radiation are in the final stages of construction. They are large optical interferometers, with arms 0.6km to 2km in length, looking for the distortion of space caused by violent astronomical events. So the wave properties of gravity will open a new window in astronomy.

There will no doubt be unexpected surprises, as there have been in the past. I predict that particle physics and its links with astrophysics and cosmology will continue to be exciting in the foreseeable future.

About the author

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Peter Kalmus, Emeritus Professor of Physics at Queen Mary, University of London has carried out research in experimental particle physics at accelerators in several countries, and is the author of about 120 publications. He was awarded the Rutherford Medal for the discovery of the W and Z particles, the Kelvin Medal for public understanding of science, and an OBE for services to physics.



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