Building-blocks of matter

THE outcome of the formative period of particle physics is familiar. Matter is made of quarks and leptons.

Hadrons. Combinations of quarks make hadrons, which are either baryons (which, like electrons, have half-integer spin) or mesons (whose spin is either zero or integral). There are six quarks, with the whimsical names up, down, strange, charm, bottom and top, for each of which there is also an antiparticle with an electric charge which is opposite in sign.

Quarks resemble electrons in having half-integer spin. Why they differ from all other particles of matter in carrying charges that are fractions of the electronic charge is not understood, but the up quark has a charge of $+{}^{2}/_{3}$ units, explaining why two ups and a down (with charge $-{}^{1}/_{3}$) make a proton and also why two downs and an up make a neutron.

Mesons are simpler. For example, the pion (π) consists of pairs of up and down quarks (called u and d in what follows), but not straightforwardly; such a combination would have non-integral charge. Thus the π^- is a combination of an anti-u (written $\bar{u}$) with a d, while the π^+ is the combination of a u and a $\bar{d}$, giving charges of -1 and $+1$ respectively. The π^0, by contrast, is a mixed state of $u\bar{u}$ and $d\bar{d}$ (which is one reason why its decay is 10^8 times more rapid than those of its two partners); the predominant decay products are two energetic photons, recognizable by the electron–positron pairs they eventually produce. For all three, the total spin is zero.

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Computer reproduction of a hadronic decay of a Z^0 particle as seen in the OPAL detector at CERN's Large Electron–Positron collider, LEP.

CERN Photo

The problem with this simple view (as it formed in the early 1960s) is that there are too few quantum numbers to account for the variety of the unstable particles that had then been created by the accelerators. (The Pauli principle is an efficient way of exhausting the capacity of classifiers.) How to resolve that difficulty? With the discovery of the strange particles (in 1947), 'strangeness' was added as an additional quantum number. Until the discovery of the charmed quark in 1975, three quarks seemed sufficient to account for the hadrons then known.

Leptons. Electronic matter is similar, but different. Just as there are three pairs of quarks ((u and d), (s and c), (b and t)), so there are three 'generations' (as they are known in the trade) of leptons — e, μ and τ — and the corresponding neutrinos, ν_e, ν_μ and ν_τ, all of them electrically neutral and supposedly without mass. These particles interact with others of the same generation and also with quarks by means of the 'weak' nuclear force.

While nobody knows why nature accommodates both the electron (e) and its two more massive congeners μ and τ, the theorists are lucky that these particles transform among themselves. Thus the muon is spontaneously transformed into an electron by $\mu^\pm \rightarrow e^\pm + \nu_e + \nu_\mu$. That is the weak force in its pure and simple manifestation.

After quantum electrodynamics, the outstanding triumph of theoretical particle physics is the 'electroweak' theory of Glashow, Salam and Weinberg in the late 1960s. The interacting fields are those of leptons, quarks and of the particles analogous to photons that mediate their interaction.

The surprise is that the mediating field is that of the particles called intermediate vector bosons, or Z^0 and $W^\pm$, predicted before their discovery at CERN in 1983, whose masses are very large. The large mass of these particles is one reason why, at low energy, the 'weak' force is indeed weak. The decay of the $\mu^\pm$, for example, is not a direct conversion, but involves the intermediate (and 'virtual') production of $W^\pm$ (and of ν_μ) followed by its conversion into $e^\pm$ and the electron neutrino. The intervention of particles such as $W^\pm$, whose energy is much greater than that liberated by the conversion of $\mu^\pm$ into $e^\pm$, is allowed in the calculations because of the simple rule of quantum mechanics that any state that is not a pure state (or eigenstate) must be, in principle, a combination

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The ghosts in the machine?

THE great neutrino puzzle has dragged on for a quarter of a century, and is not yet in sight of resolution. The presenting symptom is the deficit of neutrinos emitted by the Sun, first measured by R. Davies Jr by means of an experiment first planned 30 years ago[1] and designed to provide direct evidence of the thermonuclear reactions in and near the Sun's core. It consists of a tank filled with 600 tonnes of the cleaning fluid tetrachloroethylene installed beneath 1,500 metres of overburden in the Homestake mine at the town of Lead in South Dakota.

The relevance of the cleaning fluid is its content of the isotope ^{37}Cl, with which electron neutrinos should infrequently interact to yield radioactive ^{37}Ar by the reaction $\nu_e + {}^{37}\mathrm{Cl} \rightarrow {}^{37}\mathrm{Ar} + e^-$. Atoms of ^{37}Ar are collected every two months or so, when their concentration represents a balance between production and decay. The conversion of ^{37}Cl to ^{37}Ar, which is an endothermic process (as chemists would say), can detect neutrinos only when their energy exceeds 0.8 MeV.

Over a quarter of a century, the measured flux has been consistently only a third of that expected. Expectations are almost independent of the fine details of the solar model, but are almost entirely determined by the rate of conversion of hydrogen and deuterium into heavier elements and thus by the total energy output of the Sun.

This measurement has since been repeated with other pieces of equipment. Of those so far mounted, the Japanese experiment called Kamiokande (based on a tank of 6,000 tonnes of pure water in a deep mine) is the most interesting. It relies on the expected scattering of neutrinos by electrons, which are themselves detectable by a pulse of Cherenkov radiation if their speed is greater than that of light in water.

The experiment has the advantage that it is possible to win directional information about the neutrinos responsible for knocking electrons out of atoms (confirming that those detected do indeed come from the direction of the Sun) as well as to estimate their energy. Because the scattered electrons can be detected only when