Lattice window on strong force

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A long-awaited breakthrough has been made in lattice quantum chromodynamics — a means of calculating the effect of the strong force between sub-atomic particles that could, ultimately, unveil new physics.

The fundamental particles called quarks exist in atom-like bound states, such as protons and neutrons, that are held together by the strong force. The heavier varieties of quark, such as the bottom quark, can disintegrate to produce other, lighter particles, and the pattern of the decay rates is constrained, but not determined, in the theory of fundamental particles, the standard model. That pattern, especially the part involving the bottom quark, is sensitive to new physical phenomena. But although accurate measurements of the rates have been made, the window on new physics has been obscured. This is because the binding effect of the strong force between quarks modifies the decay rates: unless correction factors can be accurately worked out, the data cannot be fully interpreted for signs of any physics that is as yet unknown. This has been the case for almost 40 years. But at last, Davies *et al.* report an advance in lattice quantum chromodynamics, a method of calculating the effect of the strong force, that promises the calculational precision required (C. T. H. Davies *et al. Phys. Rev. Lett.* **92,** 022001; 2004).

The standard model describes all observed particles and their interactions. Particles interact by exchanging other particles that convey force. For example, in an atom, electrons bind to protons by swapping photons with one another. This is the electromagnetic force, described by the theory of quantum electrodynamics (QED). In a proton, two types of quark, called 'up' and 'down', are bound together so tightly, by exchanging particles called gluons, that this is known as the strong force. Its associated theory is quantum chromodynamics, or QCD. In the standard model there is a third force, the weak force, which is the mediator of radioactive β-decay. Another example of the weak force in action is the decay of a heavy bottom quark into an up quark, through the emission of a *W* particle (which then itself decays to an electron and an anti-neutrino; Fig. 1a).

Despite its success, the standard model leaves many questions unanswered. For example, although the observable Universe is made of matter and there is no evidence for significant quantities of antimatter, equal amounts of both should have been created in the Big Bang. When matter and antimatter meet, they annihilate each other: if a small asymmetry between matter and antimatter did not exist at the time of the Big Bang, there would be no matter in the Universe today. So how did that asymmetry arise?

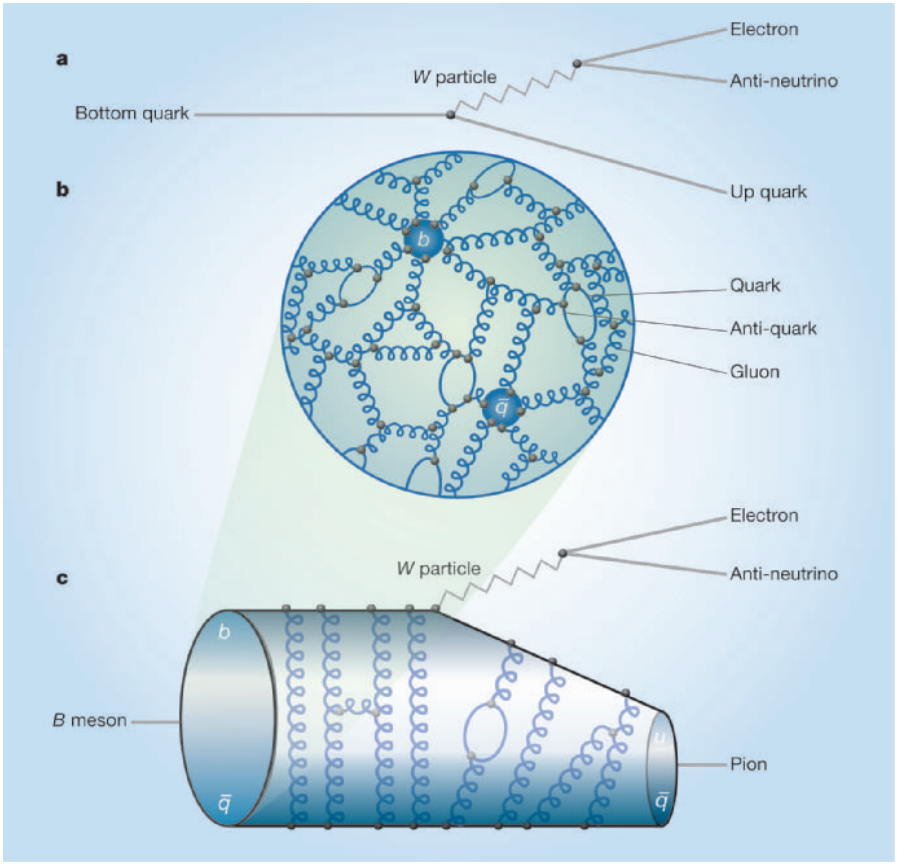

Figure 1 **Bottom's up.** a, **An idealized representation of the decay of a free bottom quark into an up quark. In the standard model of particle physics, the process occurs through the weak force, mediated by a *W* particle, and also produces an electron and an anti-neutrino.** b, **In the real world, however, there is no such thing as a free quark. Instead, a bottom quark exists in a bound state with other quarks — such as in a *B* meson, bound by the exchange of gluons to an anti-quark. Gluons and quark pairs are constantly emitted then reabsorbed; only a fraction of this 'sea' of particles is shown here.** c, **So the realistic picture of the decay of a bottom quark is complex. The *B* meson — a bottom quark and anti-quark pair — becomes a pion (an up quark and an anti-quark), but the route is obscured by the mass of gluons and quarks (of which, again, only a fraction are shown). Calculating the details of the process is fiendishly complicated. But new advances in lattice quantum chromodynamics mean that precise theoretical correction factors can be worked out, and the problem effectively reduced to the simple process shown in** a.

If heavy particles that existed in the early Universe decayed preferentially into matter over antimatter, that could have created the matter excess. In the standard model, two types of quark, bottom and strange, do decay asymmetrically. But this effect alone is far too small to account for the asymmetry. However, there are many theories that predict the existence of other, massive particles that could readily produce the asymmetry. And because of the connection between asymmetry and mass, these theories also address other puzzles, such as why electrons are almost 10,000 times lighter than bottom quarks.

Searching for evidence of these particles can be done directly or indirectly: powerful accelerators, reaching ever higher energies, could create these mysterious particles; or there is the precision approach of looking for subtle deviations in the properties of known particles, influenced by the unknown. If

deviations are found, their pattern and magnitude, much like a fingerprint, would identify the new physical phenomena responsible. To see such deviations in the decay rates of quarks, a measurement precision at the level of 1–2% is required, and this is becoming achievable experimentally. But the necessary correction factors, allowing for the binding effect of the strong force between quarks, have been riddled with uncertainties at the 20% level.

Consider the rate at which a bottom quark transforms into an up quark (Fig. 1a). In principle, it is an easy measurement to make: produce a known number of bottom quarks and count how many times one of them disintegrates and an up quark is produced. However, bottom quarks always come paired with lighter anti-quarks, in particles called *B* mesons (Fig. 1b). The bottom quark and the anti-quark constantly exchange gluons, within the bounds of Heisenberg's uncertainty principle, binding them strongly together. So experimenters must study the decays of *B* mesons, not free quarks (Fig. 1c). In measuring the decay rate, correction factors must be used to compensate.

The uncertainties in these correction factors are due to the great strength of the strong force. Similar corrections arise in QED, through the constant exchange of photons. But because the electromagnetic force is so much weaker than the strong force, the quantum corrections are tiny. A detailed calculation of any electromagnetic process can be performed by adding up a sufficient number of quantum corrections, and consequently the theory of QED has been verified down to the tenth decimal place.

Not so QCD, where there is an additional complication: unlike photons, the gluons have a property called colour, which means that not only do the quarks in a meson constantly exchange gluons, but those gluons can constantly exchange other gluons as well. Pairs of quarks and anti-quarks also make fleeting appearances. The quantum corrections that allow for this swarm of gluons and quarks are very large, so adding them all up is unfeasible. As a result, QCD calculations involving the strong force cannot be made as precisely as those for QED processes.

The way round this is to use powerful computers to simulate the most probable arrangements of quarks and gluons inside a particle, and from there to estimate the particle's properties. But no computer in existence could keep track of all the quarks and gluons in a meson. The problem can be simplified by imagining space and time not as a continuum, but as a lattice — a four-dimensional grid of discrete points. Quarks and gluons reside at these points. With this restriction, an infinite number of variables is reduced to a finite (although very large) number of variables. This approach is called lattice QCD.

Originally developed in the 1970s, lattice QCD initially enjoyed great success; in the 1980s, it explained why quarks are bound inside protons. But it took almost 20 years to go from predictions of qualitative features to realistic calculations of particle properties. Now, thanks to the increasing speed of computers and, more importantly, to a succession of improvements in the technique, Davies *et al.* have managed to calculate nine different quantities, each a particle property that is determined by the strong force. They have included in their calculation all of the pairs of light quarks and anti-quarks that fluctuate into brief existence inside a quark-based particle (Fig. 1b) — previously these pairs had usually been left out, because they are much more difficult to deal with than gluons, and it has been prohibitively costly in computer time to simulate them. Each property calculated by Davies *et al.* has already been measured in experiment, and — the acid test — all of the calculations are a good match to the data, to within a few per cent.

The authors are now racing to calculate the properties of other particles called *D* mesons, which contain a heavy 'charm' quark. Experiments are already under way with the CLEO-c detector at Cornell University in New York, to measure the properties of these particles to a precision of several per cent. If the lattice calculations are completed by the time the CLEO-c measurements are published, and they agree, it will serve as a powerful validation of lattice QCD and silence the sceptics. Such validation is crucial if similar lattice QCD calculations of correction factors for *B* mesons are to be confidently applied to data from current and future experiments around the world. The success of the lattice approach would also be relevant in other areas of particle physics, and in nuclear physics and astrophysics.

If all goes well, experimentalists and theorists together will soon pull back the strong-force curtain that has confounded them for 40 years and look through the window for the first time. If they see a pattern of quark-decay rates that does not conform to the standard model, the deviations might provide information about new physical phenomena — phenomena that make bottom quarks heavier than electrons and give rise to the asymmetry between matter and antimatter that permits us to exist. ■

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Medicine

Genetic spotlight on a blood defect

Diether Lambrechts and Peter Carmeliet

The causes of defects in the blood system of newborn babies can be hard to establish if the errors are not inherited. An elegant approach has identified a gene that can encourage new blood vessels to grow.

Babies who are born with defects in their vascular system face serious medical and social problems. But we know little about the cause of these blood-vessel anomalies[1,2]. Discovering the genetic basis of such vascular birth defects remains a challenge, as most of these errors are not inherited. Instead, they occur sporadically and affect only certain areas of the body.

On page 640 of this issue, Tian *et al.*[3] report the discovery of the first susceptibility gene for a disorder characterized by diverse defects in the vascular system — Klippel–Trenaunay syndrome (KTS). The authors show that when the gene, called *VG5Q*, is expressed at high levels, new blood vessels are stimulated to grow, suggesting that *VG5Q* is probably responsible for the vascular malformations seen in some patients with KTS. The unusual means by which Tian *et al.* identified and evaluated *VG5Q*, with a combination of human genetics and functional assays, underscores the importance of using similar approaches to identify other factors involved in the formation of new blood vessels (angiogenesis). Such factors could include molecules that are clinically relevant, or potential drug targets.

Blood vessels are lined by special endothelial cells and surrounded by smooth muscle cells. They are formed when founder endothelial cells give rise to a simple network of blood vessels — a 'vascular plexus'— which is subsequently remodelled into a more mature network of large and small vessels[2]. This remodelling allows blood to carry oxygen to growing tissues, and so is essential for fetal development. If remodelling fails to occur normally, the vessels might become deformed, resulting in vascular birth defects. Unlike blood-vessel tumours, in which endothelial cells grow in excess, vessels in vascular malformations have normal numbers of endothelial cells but are improperly formed and remodelled. A few molecules, such as vascular endothelial growth factor and the protein Tie2, have been implicated in vascular birth defects[1,4], but most vascular malformations remain unexplained in terms of the genes and molecules involved.

More than a century ago, the French physicians Maurice Klippel and Paul Trenaunay