Particle physics

Liberating quarks and gluons

Frank Wilczek

An extraordinary new state of matter, the quark–gluon plasma, may have been produced. In collisions between high-energy heavy nuclei, conditions like those 0.01 seconds after the Big Bang are reproduced — though only on a small scale and briefly. Temperatures of 10^{12} K or more are achieved, roughly ten million times that at the surface of the Sun, or ten thousand times that in the solar core. Theorists predict that under these conditions there is a drastic change in the structure of nuclear matter. The usual description in terms of baryons (such as protons and neutrons) and mesons (such as pions) must be abandoned in favour of a description involving the truly fundamental particles, quarks and gluons. Experiments last year have provided the first substantial evidence that such a change in fact occurs[1–3].

To put these developments in perspective, let me sketch some of the background. Quantum chromodynamics (QCD) is the modern theory of the strong interaction[4] — the most powerful force of nature, responsible for holding atomic nuclei together, and for most of what goes on in high-energy accelerators. QCD is verified by dozens or perhaps hundreds of experimental tests[5,6]. But it is a most peculiar theory: its fundamental particles, the quarks and gluons, have never been observed in isolation. Indeed, the theory predicts that they never will be.

According to QCD, particles that carry uncompensated colour charge call forth such strong forces that they spontaneously ionize empty space. One might say that they cause a colour lightning storm. When the storm subsides, all the colour charges have been neutralized. The strongly interacting particles that experimenters can actually observe are composites of several quarks and gluons, arranged into structures with compensating colour charges, so that they are neutral overall. The most important types are baryons, which can be constructed from three quarks; antibaryons, constructed from three antiquarks; and mesons, constructed from a quark and an antiquark.

Quarks and gluons themselves carry uncompensated colour charge, and therefore, according to QCD, cannot exist in isolation — they are 'confined'. Nevertheless, to modern physicists quarks and gluons are quite real and tangible objects, no less than (say) electrons. Indeed, quarks and gluons have quite distinct signatures (Fig. 1). They can do so, despite being confined, because of the special nature of the forces among them. The powerful confinement forces only come into play when colour charges are taken far apart from one another, and they take some time to set in. When the colour balance is disturbed by sudden, small-scale motions, to begin with the colour forces are much weaker. This property of QCD is called asymptotic freedom. In a high-energy collision, the key events that control the large-scale flow of energy and momentum are brief, violent accelerations of the particles. Because of asymptotic freedom, these events occur almost as if the quarks and gluons were free and unconfined, so the energy and momentum distribution follows a pattern imprinted by the quarks and gluons (Fig. 1).

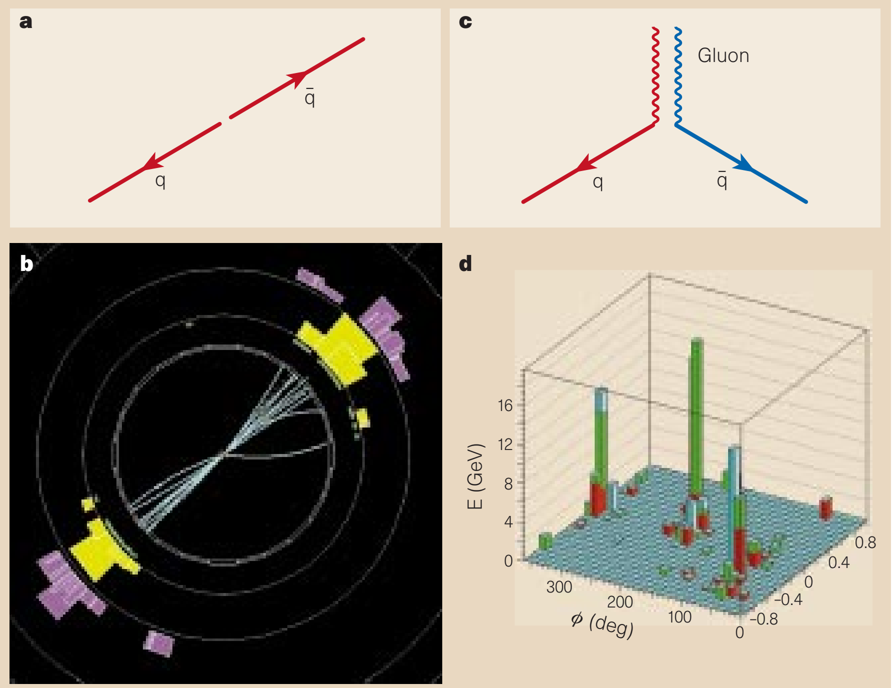

Figure 1 **Realization of quarks and gluons as jets. A Z-boson decay into quark and antiquark** (a) **is reflected in the jets of compound particles observed** (b). **When the Z-boson instead decays into quark, antiquark and gluon** (c), **the observed energy and angle distribution of the products** (d) **again follows the pattern set by the underlying quarks and gluons. (Parts b and d from ref. 9.)**

In a quark–gluon plasma, liberation of quarks and gluons is taken to a new level. At low particle densities, each coloured particle is bound up with its neutralizing partners, inside some ordinary hadron (Fig. 2a). At high particle densities the hadrons start to overlap, and cease to exist as meaningful individuals. Indeed, a particle needing a mate no longer finds it necessary to stay married to a particular partner, since there are always plenty of eligible singles nearby (Fig. 2b). The meaningful units are then quarks and gluons, not hadrons.

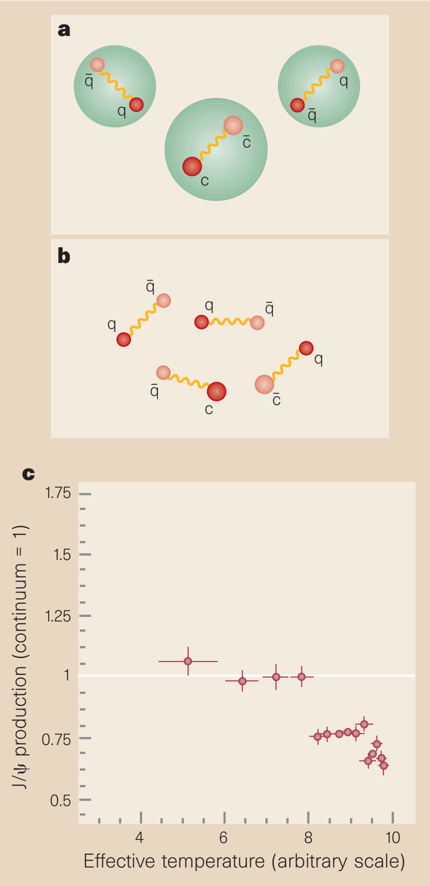

Figure 2 **Confinement and deconfinement. When the surrounding quarks and gluons are contained in colour-neutral hadrons** (a), **the charm quark and antiquark that make up a J/ψ particle must also stay paired, so that their colour charges cancel out. But if the surrounding quarks and gluons run free** (b), **the components of the J/ψ readily make and break bonds with other particles, and the J/ψ particles dissociate much more quickly. A rapid decrease in J/ψ production with effective temperature has been seen by the NA50 experiment[10] at CERN** (c).

Theorists calculate that this drastic change in the structure of matter sets in over a narrow range of temperatures centred around 10^{12} K. To gauge the change, it is instructive to compare the degrees of freedom — the number of different particles that energy can go to. On the hadronic side of the transition, the important particles at these temperatures are just the pions (the other hadrons being too heavy). These are spinless particles and come in three types — with positive, negative or zero electric charge. On the quark–gluon side, there are three colours of quarks of three different types (up, down and strange — the other quarks are too massive to play a part) and each has two possible spin directions. Taking into account antiquarks, we find $3 \times 3 \times 2 \times 2 = 36$ quark degrees of freedom. In addition, there are eight gluons each with two possible spin directions — thus 54 degrees of freedom altogether, compared with the previous three. A direct consequence is that a given input of energy will raise the temperature of a quark–gluon plasma much less than it would the hadronic gas, as the energy has to be shared by many more particles.

Despite the dramatic nature of these predicted changes, it is not easy to establish experimentally that one has produced a quark–gluon plasma. Difficulties arise because the number of particles reaching the detectors after a heavy ion collision is extremely large, and because the plasma, even if produced, has only a fleeting existence in a very small region.

The experimenters are like inspectors who must examine the residue of a great explosion to determine if it was due to conventional or nuclear weapons (or perhaps a meteorite). Ambitious responses to this challenge are being mounted at CERN and at Brookhaven, where the heavy-ion accelerator RHIC will come into operation next summer.

Already, CERN has seen what might be the first harbinger of the quark–gluon plasma. Charm–quark/charm–antiquark pairs, making up the J/ψ family of particles, seem to find it much more difficult to stay paired once the energy in a fireball exceeds a threshold value (Fig. 2c). This certainly suggests the deconfinement mentioned above. It has been advocated for some time as a signature of the quark–gluon plasma. Even though the issue is muddied by the fact that the J/ψ particles will be buffeted more at higher temperature whether one has hadrons or quark–gluon plasma, nevertheless the apparent sharpness of the threshold, and other details, point towards the plasma. What makes the latest results[3] especially intriguing is that they are the first that sceptical theorists[7] have not been able to explain without invoking a quark–gluon plasma.

A big question left open by these experiments is whether the transition from normal matter to quark–gluon plasma, as a function of temperature, is continuous or truly abrupt. If it is abrupt (in the language of phase transitions, first order), superheating and supercooling are possible, and could trigger explosive instabilities. If such events occurred in the early Universe, they must have appreciably perturbed its evolution.

We anticipate other relics of the quark–gluon plasma created in accelerators. An especially intriguing possibility is that the quark–antiquark condensate which normally fills space could reassemble incorrectly, forming a domain analogous to domains in magnets. When such a domain snaps back into place, it will release a laser-like pion beam[8].

More prosaically, it would be reassuring to see the predicted high specific heat, and the associated increase in multiplicity of particles. In particular, strange quarks and antiquarks are much lighter and therefore much easier to produce than the K mesons in which they are normally confined. So events following the creation of a quark–gluon plasma should be especially strange, in more ways than one. ☐

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Neurobiology

Phantoms of the brain

Jon H. Kaas

The brain often reorganizes itself after damage to some of its sensory inputs, so that neurons that were responsive to the missing inputs come to respond to remaining inputs[1]. After the loss of somatosensory input from the hand, for example, the region of the somatosensory cortex on the opposite side of the brain that is normally responsive to touch on the hand becomes responsive, over months of recovery, to touch on the face or arm[2–6].

When the brain reorganizes in this way, do the newly reactivated neurons signal that the sensations are coming from the location of the stimulated skin, or do they signal instead the location of their original but missing source of activation? This question has been tackled by Karen Davis and colleagues (page 385 of this issue[7]) by recording and stimulating brain responses with microelectrodes placed in the somatosensory thalamus of patients with missing limbs (Fig. 1, overleaf).

People with amputations often have the feeling that the missing limb is still present as a so-called phantom limb[8]. Furthermore, sensations on the missing limb can sometimes be evoked by touching ‘trigger zones’ on other parts of the body. For example, touching the face or remaining upper arm on the side of an arm amputee may produce sensations both of those body parts and of the missing hand[9,10]. A logical interpretation of these trigger zones is that touching the arm or the face activates neurons in the arm or the face territories in the brain, and the territories normally devoted to the hand.

According to this view, this type of brain reorganization is not beneficial, but instead contributes to the misperception that something is touching the phantom hand. Another possibility, however, is that the reactivated neurons devoted to a missing hand or foot become recalibrated by experience so that they come to signal stimuli on remaining body parts such as the hand or face. This, of course, would not explain trigger zones, but it would mean that the extensive brain reorganization that follows amputation is potentially useful.

People without amputations report appropriately localized sensations when sensory representations in the brain are stimulated electrically[11]. As part of a therapeutic procedure for amputees with pain, Davis and co-workers[7] placed microelectrodes in normal parts of the somatosensory thalamus and in that part of the thalamus where neurons previously would have been activated by stimulating the missing limb. The investigators determined the regions of skin where light touch activated neurons recorded at various electrode locations, thereby defining the receptive fields of those neurons; and they electrically stimulated the same or nearby neurons to produce sensations, thus defining sensation fields.

In the normal, undeprived portions of the somatosensory thalamus, neurons had matching receptive fields and sensation fields. But in some amputees, those with notable phantom sensations, stimulating neurons with receptive fields on the stump of the missing limb produced sensations referred to the missing limb (Fig. 1). Thus, the brain had reorganized so that the territory of the missing limb in the thalamus had become responsive to the sensory inputs from the stump of the arm, whereas the activation of neurons in this territory continued to signal sensations on the missing limb.

This does not tell us how or where the sensations are generated, because the activated