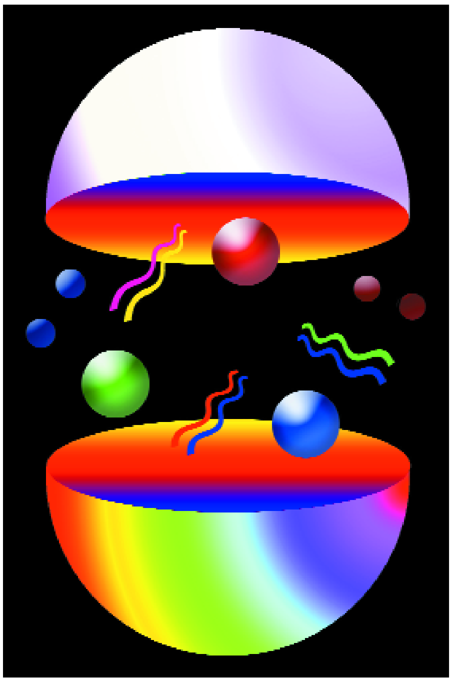
The gravity of hadrons

Researchers have calculated the masses of several particles by exploiting a connection between string theory and QCD

From **Nick Evans** in the Department of Physics, University of Southampton, UK



Duality could simplify our understanding of the way quarks are bound in hadrons such as neutrons.

IAN MACVICAR

In recent years particle physicists have realized that many theories they previously thought were distinct are actually copies of one another that describe the same physical phenomena. The most remarkable example of this "duality" has been the connection between string theory and the Standard Model of particle physics.

String theory describes the subatomic world in terms of lengths and loops of infinitesimal strings that exist in higher spatial dimensions than our familiar three. Different vibrations or modes of these strings represent different particle properties, and at long distances the strings appear as if they are indeed point-like. Crucially, these modes require the curved space–time of general relativity, which is a theory of gravity. String theory is thus viewed as a candidate for a "theory of everything" that unites gravity with the three other fundamental forces of nature: electromagnetism plus the weak and the strong nuclear forces.

The hugely successful Standard Model describes these three forces in terms of gauge theories, in which the interactions between elementary particles are mediated by "gauge bosons". For example, in the gauge theory of electromagnetism – quantum electrodynamics or QED – charged particles such as electrons interact via the exchange of photons. Gravity, however, is not included in the Standard Model.

Although there is no firm evidence for string theory or for higher dimensions, duality proposes that strings might offer a new description of the gauge theory of the strong force: quantum chromodynamics (QCD).

Strongly coupled

In QCD the interactions between the six known quarks (up, down, charm, strange, bottom and top) are mediated by massless gluons. However, unlike the forces of electromagnetism and gravity – which decrease rapidly with distance – the strong nuclear force gets *stronger* the further two quarks are separated. Indeed, the interaction between widely separated quarks is so strong that the quarks can never be freed from one another, and are instead confined into protons, neutrons and other hadrons. On the other hand, the strong interaction switches off completely at very short distances.

This "asymptotic freedom" makes the equations of QCD extremely difficult to solve, and it is only recently that advances in computing capabilities have enabled researchers to thoroughly test the theory (see *Physics World* July pp22–23). But in 1997 Juan Maldacena of the Institute for Advanced Study in Princeton conjectured that the physics of quarks and gluons could be equally well described in terms of the space–time geometry, black holes and gravity waves of a "dual" string theory. This dual theory is weakly coupled, rather than strongly coupled like QCD, which means we know how to calculate observables such as particle masses using it. In other words, Maldacena's duality suggested that everything about the QCD particle spectrum might be calculable from the dual theory with no more than a pencil and paper!

Early work on this correspondence between QCD and string theory was performed with a mathematical relative of QCD that included only gluons, in order to make the calculations simpler. This dual theory, which automatically includes gravity, contains strings that exist in four spatial dimensions. As you move in the fourth direction of this "anti-de-Sitter" space–time, lengths in the remaining three directions increase (see *Physics World* May 2003 pp35–38).

To the surprise of many theorists, the extra dimension in this dual gravitational theory turns out to account for the different length scales in QCD. For example, the density of strings at different places in the fourth dimension can tell you that QCD is asymptotically free. Other strings with different vibrations or motions, for instance, can describe the properties of states in which two or more gluons are bound together. The duality therefore provides a strict mapping between each QCD state and a particular dual string.

In the last few years theorists have turned this new theoretical tool to the question of whether we can describe the physics of real QCD. But in order to fully account for the plethora of particles that we know to be bound by the strong nuclear force, the dual theory has to be extended so that it includes quarks.

Something from nothing

The most versatile construction for including quarks in the gravitational dual was developed by Andreas Karch and co-workers at the University of Seattle in 2002. Using the same mapping rules between QCD and strings developed for the gluon-only dual theory, the researchers included a new sector of strings in the gravity theory that had the correct properties, such as mass, to describe quarks. The next step was to find out whether the quarks triggered the vacuum of the gluon-only theory to fill with quark–antiquark pairs.

Asymptotic freedom has dramatic consequences for the way QCD describes the vacuum. You might think that the vacuum would simply be empty, but according to the uncertainty principle empty space can borrow a little energy for very short periods of time. Einstein's famous mass–energy relation then tells us that this energy can be used to create particles such as a quark–antiquark pair.

The strength of the attraction between distant quarks means that these "virtual" particles become real and long-lived. The vacuum therefore fills rapidly until the quarks are so close together that asymptotic freedom kicks in and the production of further quark pairs is no longer energetically favourable. The signal we have for this cut-off behaviour is simply the proton mass, which is 100 times larger than the combined mass of its constituent quarks (two up quarks and a down quark) due to their interactions with the mire of vacuum quark pairs.

In 2004 James Babington and co-workers at Humboldt University in Berlin along with the present author (and, in a parallel analysis, Martin Kruczenski and co-workers at the Perimeter Institute in Canada) showed that one of the extra string distributions introduced by Karch and co-workers corresponds to a non-zero density of quark–antiquark pairs in the dual theory. In other words, the gravitational description indeed appeared to describe the QCD vacuum, and theorists could begin to study hadrons for the first time.

The first hadron we looked at was a type of meson called a pion, which is a bound state of either an up or down quark plus an antiquark. In QCD such a state corresponds to a small area of space where the quark–antiquark density is greater than it is in the vacuum. But the gravitational theory describes the pion as an area of space in which there is an excess in the density of *strings* that travels through anti-de-Sitter space like a wave. The gravitational technique again turned out to be a success, reproducing, for example, the experimental observation that the pion mass depends on the square root of the mass of the constituent quarks.

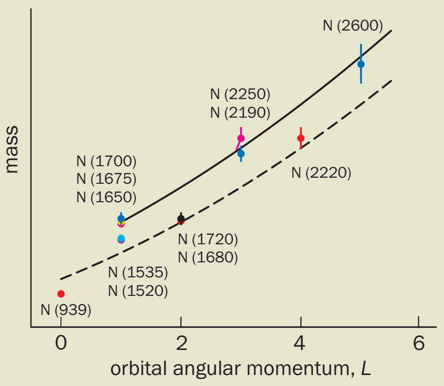
These results were all obtained in simple gravitational duals that contained only one type of quark. But formally deriving the string theory of a more realistic gravitational dual of QCD – one that includes up, down and strange quarks, for example – has turned out to be hard. Recently, however, Stanley Brodsky of Stanford University, Josh Erlich of Seattle University and Leandro De Rold of the University of Barcelona independently took a more practical approach and simply guessed what the gravitational dual would look like (arXiv.org/abs/hep-ph/0501128 and arXiv.org/abs/hep-ph/0501218).

The models all consist of the same anti-de-Sitter space–time of Maldacena's original duality. But they also include a set of strings that are put in "by hand", which have the right properties to play the role of the mesons of full QCD. While not completely rigorous, these models of QCD's dual have proved remarkably predictive. For example, they can predict the strength of pion self-interactions and their decay constants to within 30%.

Baryonic dual

Brodsky and co-workers have now made another important step forward by including "fermionic" strings in the gravitational dual (*Phys. Rev. Lett.* **94** 201601). All particles are either fermions or bosons depending on the value of their internal angular momentum, or spin: particles with half-integer spins, such as the proton and neutron, are fermions; while particles with integer spins, such as pions, are bosons. The exclusion principle only allows one fermion to exist in any particular state, so a fermionic string reproduces this behaviour by only permitting one quanta of energy per oscillation. Brodsky's strings therefore have the properties to describe the spectrum of baryons – particles that contain three quarks and are therefore fermions.

The overall fit to QCD data is again reasonable, but Brodsky's new dual theory has a more striking feature: it predicts the existence of baryons that have the same quark content but different amounts of orbital angular momentum and therefore different masses from one another.



Mass agreement – using a "gravitational dual" theory that can also describe QCD, Stanley Brodsky and co-workers were able to predict the masses of certain baryons called nucleons, N. These particles can have a spin angular momentum of $\frac{1}{2}$ (dashed curve) or of $\frac{3}{2}$ (solid curve) and each state can also have various values of *orbital* angular momentum (horizontal axis). For example, the $L = 0$ state is the neutron, N (939), where the number in brackets represent its mass in mega-electron-volts. The observed masses of the nucleons are shown by the points. Importantly, the gravitational-dual theory correctly predicts that states differing by one unit of L on the solid and dotted curves have the same mass.

These particular baryons, which are called nucleons because they consist of combinations of the lightest up and down quarks, have been observed in particle accelerators, but some of the small mass differences between them have not been explained before. The simplest case is the spin-$\frac{1}{2}$ nucleon otherwise known as the neutron, in which the spins of two of the constituent quarks point in opposite directions. But a spin-$\frac{3}{2}$ nucleon in which the spins of all three quarks are aligned also exists, and each nucleon can also have an excited state with a different orbital angular momentum (see figure).

Brodsky's gravitational dual predicts that the spin-$\frac{1}{2}$ state with an angular momentum of 1 should have the same mass (about 2000 MeV) as the spin-$\frac{3}{2}$ state with angular momentum equal to 2. In nature, both of these states lie close to 1700 MeV, supporting the fact that they are degenerate even if the absolute value is a little off. The theory predicts similar mass degeneracies for a type of baryon called the Δ, which also contains up and down quarks.

These results suggest that the gravitational-dual description of QCD may turn out to be an important tool for understanding the full hadronic spectrum we observe in nature. Future work will concentrate on refining these models to capture more detailed features of QCD, including more precise values of the masses of bound states and also the strengths of their interactions. It may be some time before gravitational calculations take over from the precise computations of modern lattice QCD, but the fact that such a radically different picture of quarks exists is an important and ongoing revelation.

HIGHLIGHTS FROM PHYSICSWEB

New look for hydrogen storage

Physicists in the US, Canada and Germany have proposed a novel technique for storing hydrogen. The method involves storing the gas between layers of graphite, and could help in the quest for practical hydrogen-storage devices for fuel cells. John Tse of the University of Saskatchewan and co-workers have shown that thin sheets of carbon atoms spaced between 6–7 Å apart can store hydrogen at room temperature and moderate pressures.

Triple-star status for exoplanet

A planet with a mass similar to that of Jupiter has been discovered orbiting a star in the constellation Cygnus. Maciej Konacki and colleagues found that the new planet orbits the main star of a triple-star system every 3.35 days, which means it is much closer to its parent star than predicted by current theories of planetary formation. More than a hundred extrasolar planets have been found in recent years but this is the first to be discovered in a three-star system.

GPS sheds light on tsunami

An international team has performed the most comprehensive analysis to date of the earthquake that caused the devastating Indian Ocean tsunami in December 2004. The results, based on the movements of more than 60 Global Positioning System (GPS) monitoring stations, indicate that the seafloor rupture was at least 1000 km long and that it propagated extremely quickly. The data rule out the possibility that the earthquake was caused by a slow "aseismic" rupture.

Bubble fusion returns

Researchers at Purdue University in Indiana claim to have found new evidence for nuclear fusion in a table-top device. Yiban Xu and Adam Butt say that firing sound waves into a beaker of acetone that has been "seeded" with neutrons from californium-257 produces bubbles in the liquid. The bubbles then collapse and produce pressures and temperatures thought to be high enough to initiate nuclear reactions. Such "bubble fusion" met with widespread scepticism when it was first reported in 2002.

physicsweb

Read these articles in full, and sign up for free e-mail news alerts, at physicsweb.org