PARTICLE PHYSICS

Theory with a twistor

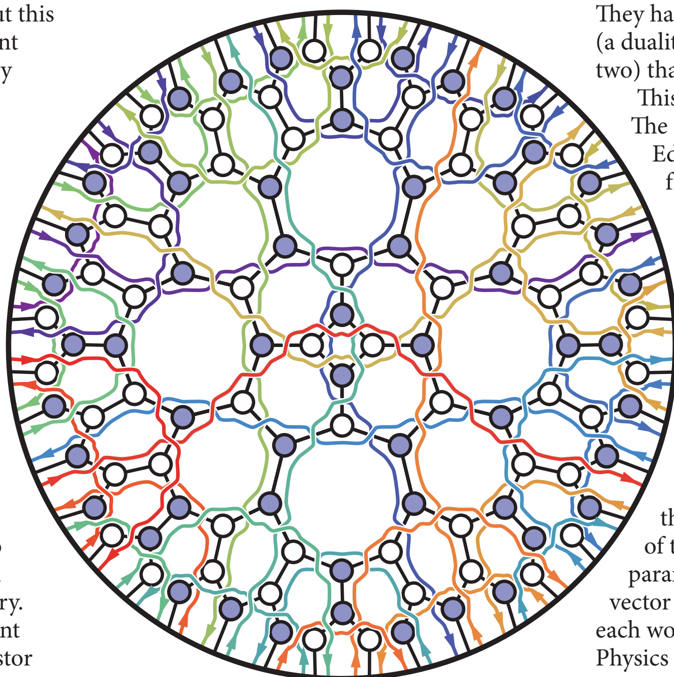
A reworking of the theory of particle interactions — the same theory but rendered in a new form based on twistor geometry — is likely to have wide implications for physics, including the reformulation of gravity.

Andrew Hodges

News of developments in fundamental physics tends to focus on reporting discoveries that go beyond, or overturn, accepted theories. For instance, the dark matter problem — of reconciling the apparent distribution of galactic mass with the standard model of particles — does indeed suggest that there are highly surprising things yet to be found. But this is not the only story. Just as important is the development of a revolutionary new description of what is already well established.

The culmination of a decade of such developments in fundamental physics suggests that methods in use since the 1940s are now under challenge. The theories are not wrong, but they benefit from complete reformulation. A glance at a preprint[1] from a group led by Nima Arkani-Hamed, entitled 'Scattering amplitudes and the positive Grassmannian', will reveal strange new pictures of particle interaction. They are networks connecting white and dark vertices, with a chromatic finale (pictured) to the 154-page opus that resembles an artwork from the Tate Modern gallery. What these pictures actually represent is even stranger: propagators in 'twistor space', a concept unfamiliar to all but a few physicists.

But the pictures are rooted in practicality, not speculation. Experiments involving particle collisions suffer from a major practical problem: to see something new and unexpected, you must have an effective and reliable description of the old and predicted. Yet the 'background' of particle collisions predicted by standard theory is extremely complicated and hard to work out. In principle, the theory of particle collisions was solved in the late 1940s, and generations of physicists have come to see Richard Feynman's diagrams, of 'virtual' particles mediating interactions, as a picture of reality. But Feynman's virtual particles are purely mathematical, not directly observed. Furthermore, the mathematics becomes quite impractical for the gluons and quarks of subnuclear events — millions of diagrams must be summed before a physically meaningful description emerges. Since the 1980s, it has been clear that the answers are far simpler than the formalism, and new methods have shown how to derive them more directly.



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A buzzword describing these new methods is 'on-shell', which means dealing only with the geometry of real fields, not virtual fields. Other crucial words are 'helicity', and the 'spinors', which represent states of pure helicity. Spinors, which are like square roots of vectors, are not new — their mathematics goes back to the nineteenth century, and they entered centrally into quantum mechanics with Dirac's equation for the electron. Dirac worked hard to keep the electron described as a single object, but from the perspective of the modern standard model it splits naturally into a left-handed and a right-handed part. The spinors describing these two parts are simpler, and in fact drive the simplification underlying the modern approach to scattering theory.

Twistors, introduced by Roger Penrose in the 1960s, extend such spinor geometry into a new picture of space-time. While spinors give a sort of square root of vectors, and so of directions, twistors give a sort of square root for space-time itself. In 1972, Penrose wrote down and evaluated the first twistor diagrams for particle scattering[2]. They had those same white and dark vertices (a duality which expresses this splitting into two) that now appear in the new work[1].

This journey has taken many years. The critical juncture was in 2003, when Ed Witten brought together insights from string theory, knowledge of twistor geometry, and an appreciation of the practical needs of scattering calculation[3]. With this stimulus, Penrose's twistor diagrams enjoyed a renaissance. In 2005, I showed how they fitted into Witten's new theory, and then in 2009, Arkani-Hamed and colleagues[4] built on this to create a new calculus for scattering theory, in which a central role is taken by the classical geometrical concept of the 'Grassmannian', a space that parameterizes all linear subspaces of a vector space. (Arkani-Hamed and Witten each won a US$3 million Fundamental Physics prize last year).

Now Arkani-Hamed's group has developed this insight into a far more complete picture. A striking feature is an elegant connection with pure mathematics which geometers have been pursuing for quite different reasons. The concept of the 'positive Grassmannian', it turns out, means that there is a direct link with the simple structure of permutations.

Forty years ago, Penrose's hope was not just that twistor geometry would improve the description of accepted theory, but that such a radical paradigm shift would suggest quite new physical theories. As a rough analogy, consider the four-dimensional geometry of Einstein and Minkowski which at first gave a simpler and more complete picture of Maxwell's classical electrodynamics — but actually made possible the modern picture of elementary particles and forces, unimaginable in 1900. As Penrose indicated in 1972, twistor theory was intended to change everything, including gravity and its relation to mass.

Here also there are new developments. A preprint[5] from David Skinner, again building on a long sequence of ideas and discoveries, has adapted Witten's 2004 work to get a new practical handle on gravitational scattering amplitudes. These are even more notoriously difficult to calculate from standard theory than those of sub-nuclear particles and forces. Again, this is not a new theory of gravity — it is the standard theory, but in a completely new form. It has an emergent idea: greater simplicity will arise by including the cosmological constant (or 'dark energy') and abandoning Minkowski's flat space-time as the background. There is much interest in this geometry because of the way it now emerges from observations of the early Universe, but this is a new indication that it may also play a fundamental role in describing scattering amplitudes. The cosmological constant has a beautiful and elegant expression in twistor geometry — which will now attract much attention. ❐

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ROBERT C. RICHARDSON

Cool new world

Robert Coleman Richardson, who discovered superfluidity in helium-3 together with David M. Lee and Douglas D. Osheroff in 1971, has died at the age of 75. Their work sparked a global effort to characterize and understand superfluid helium-3, and the resulting boom in ultra-low temperature physics laid the groundwork for the study of quantum materials that display macroscopic quantum effects.

These days, commercial dilution refrigerators with base temperatures of 10 mK do not even require (external) cryogens. And starting from these temperatures, nuclear demagnetization refrigerators routinely reach 10 μK and below. But back in 1966, when Richardson first arrived at Cornell University as a research associate, low temperature physics was very much a do-it-yourself enterprise. In fact, Lee convinced Richardson to work on the proposed Pomeranchuk refrigerator to cool to 1 mK with no guarantee that they would ever succeed. At the time, however, there was no other way to get to such temperatures, and they wanted to reach the temperature of the nuclear magnetic ordering transition in solid helium-3.

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The basic idea was to cool helium-3 by squeezing it. Zero-point motion of the fermionic helium-3 atoms means that helium-3 remains a liquid at absolute zero. The solid phase only exists under pressure. Given that the entropy of the solid is greater than that of the liquid phase below 0.3 K, a mixture should cool upon compression as the liquid solidifies, theorized Isaak Pomeranchuk in 1950.

Fortunately, the Pomeranchuk principle did work, as demonstrated by Yuri Anufriyev in Moscow and then by John Wheatley's group at the University of California at San Diego, as well as by the Cornell group. Osheroff's design improvements on the first-generation cooling cell soon led to measurements of kinks in the pressure versus time curve of helium-3 near 2 mK. These glitches — first noted as "glitch" and "glitch prime", but now labelled 'A' and 'B' — marked changes in the heat capacity, heralding some kind of phase transition, but in the early days, it was unclear whether those transitions were in the solid or liquid phase.

In their first publication of the phenomenon, Osheroff, Richardson and Lee interpreted the A transition as being related to the magnetic ordering in the solid (*Phys. Rev. Lett.* **28,** 885–888; 1972). But there was strong skepticism from the community. It became paramount to do NMR measurements, which could discriminate between solid and liquid phases based on the magnitude of the susceptibility. After a number of technical set-backs, Osheroff finally identified the B phase as a superfluid. Then it became clear that the A phase was a different superfluid. There would be yet another superfluid, the C phase, in a magnetic field.

Part of the excitement was because helium-3 follows Fermi–Dirac statistics, so the atoms cannot Bose condense. Instead, the fermions need to first pair up, and the resulting Cooper pairs then condense into a degenerate ground state with no viscosity. These superfluids are highly unconventional, having *p*-wave pairing with non-zero spin and angular momentum.

Even while other experimental groups probed these exotic new phases and theoreticians were trying to explain the results, Richardson resumed his initial path towards measuring the much-anticipated magnetic phase transition in solid helium-3. With his student William Halperin, they finally found the ordering temperature of helium-3 nuclei at 1.17 mK. Richardson would continue his low temperature efforts at Cornell, eventually establishing a micro-Kelvin laboratory, and editing the laboratory bible *Experimental Techniques in Condensed Matter Physics at Low Temperatures*. In 1996, he, Osheroff and Richardson shared the Nobel Prize.

MAY CHIAO