Do pentaquarks really exist?

Results from a growing number of experiments at laboratories around the world are casting doubt on the recent discovery of particles containing five quarks

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In 2003 evidence for a novel family of particles called pentaquarks was reported by researchers working on a number of different experiments. The prospect of such a particle – which contains four quarks and one antiquark – has generated a huge amount of interest among theorists because, if confirmed, it would prove that quarks experience powerful correlations that had not been anticipated (see *Physics World* June 2004 pp25–30).

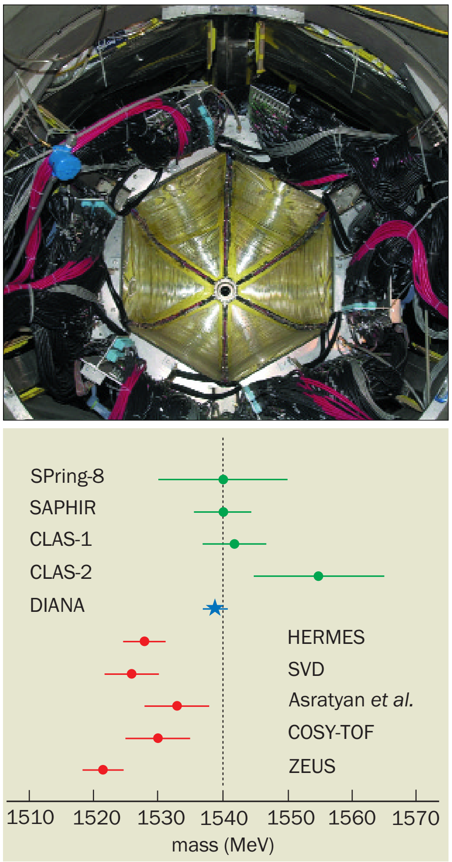
Last year, however, the experimental pendulum swung the other way: several experiments with large data samples saw no evidence for the claimed pentaquark. As 2005 begins, we anxiously await news from what could prove to be a definitive experiment with the CLAS detector at the Jefferson Laboratory in Virginia.

Novel combination

Most particles are either mesons, which contain a quark and an antiquark, or baryons, which comprise three quarks. A proton, for example, is a baryon that contains two "up" quarks and one "down" quark, while a positive kaon is a meson that contains an up quark and a "strange" antiquark. But the theory of the strong force – quantum chromodynamics (QCD) – allows for other types of baryons, providing that the number of quarks minus the number of antiquarks is a multiple of three. In particular, it allows for particles containing four quarks and one antiquark.

The pentaquarks reported in 2003 contained two up quarks, two down quarks and a strange antiquark. Such a particle is said to possess positive strangeness. The trouble is that the novel particle should decay into two lighter particles (i.e. a baryon and a meson) so quickly that these exotic states would effectively be unobservable. Indeed, it was the absence of baryons with positive strangeness that, in part, helped to establish the quark model in the first place.

Particle physicists think of the lifetime of a particle in terms of its "width", which is basically the spread in its rest energy or mass: the larger the width, the shorter the lifetime. Conventional baryons that decay by the action of the strong force have widths of the order of hundreds of MeV, but the claimed pentaquarks turn out to have widths of less than 10 MeV. It is perhaps this feature of pentaquarks that creates the most tantalizing challenge from the perspective of QCD: while it is possible to interpret the pentaquark as a combination of four quarks and an antiquark, the challenge is to explain why it survives of the order of 100 times longer than expected.



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Mass shift – several experiments have found evidence for a pentaquark with a mass of about 1540 MeV, such as the CLAS detector at the Jefferson Laboratory (top). But new results are forcing researchers to question these data. This plot, for example, shows that the value found for the mass of the θ^+ pentaquark may depend on the experimental approach used: the nK^+ data are shown by green circles, while the pK^0 data are shown by red circles (the horizontal lines represent the measurement errors). The DIANA experiment uniquely connects the two channels and is denoted by a blue star (from Q Zhao and F E Close 2004 arXiv.org/abs/hep-ph/0404075).

In more than 10 experiments worldwide, researchers have found evidence for a pentaquark state known as $\theta^+(1540)$, where 1540 is the mass of the particle in MeV (see, for example, A R Dzierba *et al.* 2004 arXiv.org/abs/hep-ex/0412077). Several of these, such as the LEPS experiment at the SPring-8 facility in Japan, reported a signal in the decay channel $\theta^+ \rightarrow K^+n$, where K is a kaon and n is a neutron. In this "photoproduction" reaction, a beam of photons is directed at a stationary target such as deuterium or carbon-12, and researchers effectively count the number of times a positive kaon plus a neutron is produced.

Other experimental groups, such as the DIANA collaboration at the ITEP laboratory in Moscow and the CLAS team, saw the same narrow state in reactions that produced neutral kaons and protons: $\theta^+ \rightarrow K^0p$. And although not seen at other experiments, the NA49 collaboration at CERN claimed evidence for a heavier version of the θ^+ called the $\Xi^{--}(1860)$, which contains two strange quarks, two down quarks and one up antiquark. Similarly, researchers working on the H1 experiment at the DESY laboratory in Germany claimed to have seen a "charmed" cousin of the θ^+ pentaquark, which is made up of two up quarks, two down quarks and one charm antiquark.

Experimental doubts

At first sight these results are impressive. However, in 2004 a series of theoretical criticisms and, perhaps more significantly, negative experimental searches began to appear. These include "hadroproduction" experiments at Fermilab, Los Alamos and Brookhaven, in which beams of protons, nuclei and kaons are bombarded with other hadrons; "electroproduction" experiments at the HERA accelerator at DESY, in which electron beams are used; and high-statistics studies of the decay of the Z boson using the now dismantled LEP accelerator at CERN.

Moreover, there appear to be inconsistencies with the experiments reporting evidence for pentaquarks. For instance, one of the potential pentaquark peaks has a width that appears to be much larger than the upper limit of 1 MeV inferred from other data, and there are also some tantalizing variations in the reported mass of the θ^+. For the nK^+ signals it is unambiguous that any θ^+ state must have a strangeness of +1, but signals seen in pK^0 decays could come from strangeness +1 or −1, and could therefore be due to a θ^+ or a conventional state known as the Σ^+.

In some experiments the narrow state has been assumed to be θ^+ on the grounds that no narrow Σ^+ is known at such masses. However, one has to note that until recently there was no evidence for a narrow θ^+ either; the absence of an established Σ^+ therefore proves little about the interpretation of such a narrow state. Furthermore, there appears to be a systematic mass shift between signals in the nK^+ and pK^0 data, with the former suggesting a slightly higher mass for the Θ^+ than the latter (see figure).

Special signal

The first and subsequent sightings of the Θ^+ pentaquark have tended to be in photoproduction experiments. Indeed, the signal with the best statistical significance comes from experiments in which high-energy photons collide with protons to produce a pion, a kaon and a Θ^+, which then decays into a neutron and a positive kaon (nK^+). This decay has a peak with a statistical significance of seven standard deviations at a mass of 1550 ± 10 MeV and a width that is smaller than the resolution of the detector. Could it be that there is something special about photoproduction that aids the appearance of the Θ^+, whereas hadroproduction is disfavoured?

If photoproduction is special, then the Θ^+ should be clearly visible in dedicated high-statistics experiments that are currently under way at the CLAS spectrometer at the Jefferson Laboratory. It had been hoped that the first of these experiments would be ready to report results last summer, but this has been delayed. A positive signal from this experiment in 2005 would be very significant; a negative result could be potentially even more so.

Claims for the existence of pentaquarks have inspired intense studies of the theory and phenomenology of QCD in the so-called strong-interaction regime. In particular, it has led to the discovery that the strong regime may contain unexpected correlations among groups of two or three quarks and antiquarks. These experiments have thus opened up new lines of theoretical investigation that may survive even if their original inspiration – the exotic Θ^+ pentaquark – turns out to have been a chimera.

Superconductor responds to nano-scale change

The critical temperature of superconducting lead can be controlled by changing its thickness by a single atomic layer

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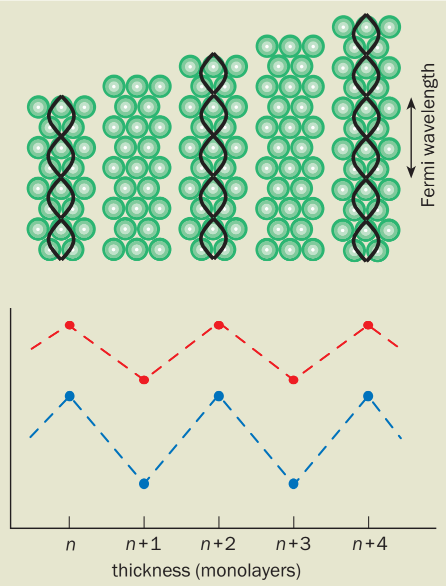
Imagine measuring the electrical resistance of a perfect rectangular copper bar as you reduced its thickness, layer by atomic layer. What would happen? Initially, the resistance would increase smoothly as the cross-section of the bar became smaller, although the electrons in the bar would remain free to move in any direction. But at some point, when the thickness reached the nanometre range, the motion of the electrons in the vertical direction would be restricted.

This confinement can give rise to extraordinary physical properties. Now Qi-Kun Xue of the Chinese Academy of Sciences in Beijing and co-workers have found that the superconducting transition temperature – the temperature below which the resistance drops to zero – of thin films made of lead varies with the number of atomic layers in the film (Y Guo *et al.* 2004 *Science* **306** 1915).

Super states

The motion of electrons in a thin film corresponds to the textbook example of quantum particles in a box, and is best understood by treating the electrons as waves rather than particles. When confined within such an ultrathin layer, the electrons can only be in certain "quantum well" states that correspond to standing waves across the thickness of the film, similar to the standing waves along the length of an organ pipe.

In fact, only a small fraction of the huge number of electrons in a material is involved in physical processes such as conductivity: these are the electrons with the highest energy, or Fermi energy. This energy translates into a wavelength, with short wavelengths corresponding to high energies and vice versa, which means that the Fermi energy has an associated "Fermi wavelength".



Thick and thin – for certain thicknesses of a superconducting thin film, a quantum-well state can form that corresponds to a standing-wave pattern of electron waves with the Fermi wavelength (*n* is an integer). A peak then appears in the density of states at the Fermi level (red), and since these electrons govern the physical properties of the film, a peak also appears in the superconducting critical temperature (blue).

In a thin layer of material, these crucial electrons can only form quantum-well states when the thickness of the film matches an integer multiple of half the Fermi wavelength. Only then is there a large density of electron states at the Fermi energy. If this condition is not met, the density of states will be lower and it will therefore oscillate as a function of the thickness of the film.

Due to this quantum size effect, the electronic properties of the metal are significantly altered, and the addition or removal of a single atomic layer of material may give rise to abrupt variations in the physical properties. However, to demonstrate these quantum size effects experimentally we need to be able to control the thickness of the films with an accuracy of a single atomic layer (monolayer).

Ultimate control

Xue and co-workers have now achieved this ultimate control over the properties of thin films. By growing ultrathin lead films on a silicon surface at a temperature of 145 K, they have demonstrated that monolayer variations in the thickness of a thin lead film gives rise to variations in its superconducting critical temperature of up to 0.5 K.

The Fermi wavelength of lead is 0.4 nm, which is approximately four monolayers, so the oscillation period should be about two monolayers. Photoemission experiments carried out on a film containing between 20 and 30 atomic layers at a temperature of 75 K clearly revealed a monolayer-by-monolayer oscillation in the electron density of states near the Fermi level. It is therefore expected that many physical properties, such as the critical temperature, will also show such oscillating behaviour.

The Bardeen–Cooper–Schrieffer theory, which describes superconductivity in terms of "Cooper pairs" of electrons, states that the superconducting transition temperature depends exponentially on the electron density at the Fermi energy. When Xue and co-workers measured the resistance of their lead films, they indeed found that the transition temperature oscillates between about 6 K and 6.5 K with the expected period of two atomic layers.

Crucial for the success of this experiment has been the ability to grow ultra-smooth films of lead that have exactly the same thickness. Any local fluctuations in thickness