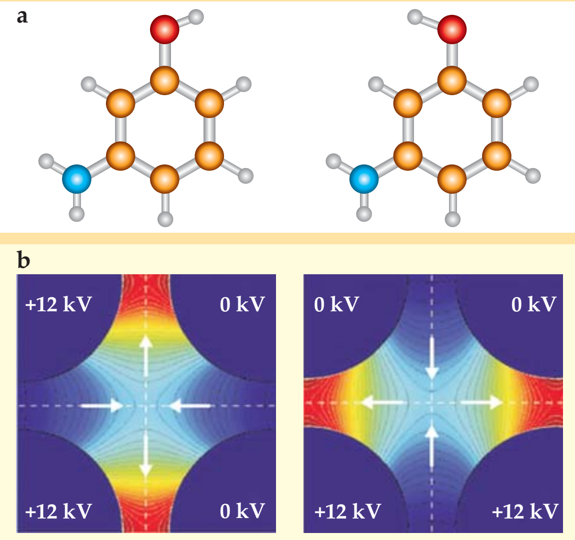

(a) The conformers of 3-aminophenol: *trans*-3AP (left) and *cis*-3AP (right). Carbon atoms are shown in yellow, nitrogen in blue, oxygen in red, and hydrogen in white. Only the position of the uppermost H atom differs between the two structures, but that variation is enough to give them different electric dipole moments. **(b)** The electric-field configurations used to separate the 3AP conformers. Regions of high electric field are shown in red, and regions of low electric field are shown in blue. The white arrows indicate the directions of the focusing and defocusing forces on the molecules. The frequency of switching between the two configurations determines which conformer is transmitted. (Adapted from ref. 1.)

be useful for studying molecular structure using x-ray or electron diffraction. The use of x rays to determine the shape of a single structure has been demonstrated (see PHYSICS TODAY, January 2007, page 19). As Küpper explains, the benefit of a constantly renewed beam of identical molecules is that "you can irradiate the samples with intense x-ray pulses and sum up the images for as long as you want—in principle, every image will look the same, because each fresh sample looks the same, even in real space."

Küpper and colleagues' method achieves only a partial separation because molecules in high rotational states don't feel the focusing and defocusing forces as strongly as those in low rotational states. That problem can be lessened, but not entirely eliminated, by decreasing the rotational temperature of the beam. And biomolecules of interest—such as the amino acid phenylalanine, which has at least six conformers with well-separated dipole moments—are not easy to coax into a molecular beam. Says David Pratt of the University of Pittsburgh, "As usual, the devil is in the details. But I am optimistic that the technique will be broadly applicable."

Johanna Miller

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Collider data show evidence for a meson made of four quarks

It's not obvious from quantum chromodynamics what sorts of unusual mesons and baryons experimenters should expect.

In the six decades since the discovery of the pion, more than a hundred other meson species have been found. Most decay by the strong nuclear interactions and therefore live less than 10^{-22} s. So one sees them only as resonant peaks in scattering cross sections or energy distributions. But until now they all had one thing in common: Every known meson was characterized by a combination of quantum numbers—charge, spin, parity, strangeness, charm, and the like—that could be accounted for simply by a quark–antiquark ($q\bar{q}$) pair.

Now the Belle collaboration at the KEKB electron–positron collider in Tsukuba, Japan, has reported impressive evidence for the first manifestly exotic meson—a meson that clearly requires more quarks than just a $q\bar{q}$ pair.[1] Dubbed $Z^\pm(4430)$, the new charged meson has a mass of 4.43 GeV, about four and a half times that of the proton. Particle physicists welcome such exceptions as clues to elusive ramifications of quantum chromodynamics, the accepted theory of the strong interactions of quarks and the hadrons (baryons and mesons) they make up.

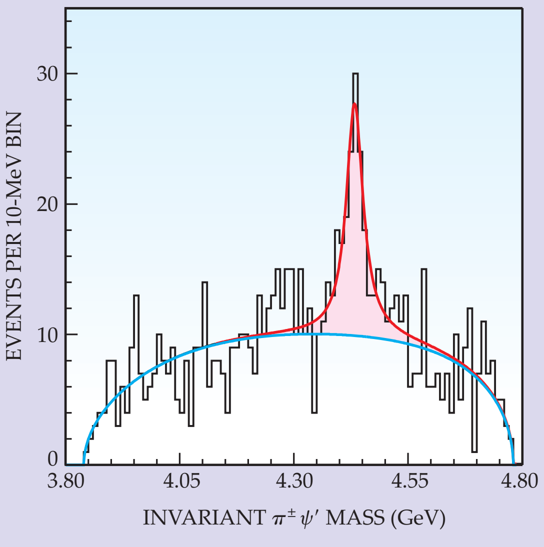
The giveaway was the new meson's observed decay mode. From among the debris of a billion e^+e^- collisions recorded by Belle since 1999, group members Soo-Kyung Choi and Stephen Olsen have unearthed a resonant peak of some 170 events indicating the strong-interaction decay of a 4.43-GeV meson to a $\pi^\pm$ and a ψ' (see the figure on page 19). With a mass of 3.69 GeV, the electrically neutral ψ' is a well-established "charmonium" meson. That is, it's a bound state of the heavy charmed quark (c) and its antiquark ($\bar{c}$). Almost twice as heavy as the proton, the c quark was discovered in the mid-1970s.

Because quarks cannot change character (called flavor) in strong-interaction decays, it's clear that the parent $Z^\pm$ already contained a $c\bar{c}$ pair. But c and $\bar{c}$ have equal and opposite charges ($\pm 2e/3$). So they alone can't account for the charge of the $Z^\pm$ manifested by its charged-pion decay product. Therefore, in addition to the $c\bar{c}$ pair, the new meson must also harbor two of the light quarks that make up more familiar particles like protons and pions. For the Z^+, it's an up quark (u) with charge $+2e/3$ and an antidown quark ($\bar{d}$) with charge $+e/3$.

The figure shows a distribution of invariant mass—the total energy of the two putative decay products in the reference frame of their center of mass. In the absence of lifetime broadening and experimental error, the histogram would exhibit a zero-width spike at the mass of the parent particle. Taking account of measurement uncertainties, the fit to the invariant-mass peak yields an intrinsic width of about 45 MeV. That's unusually narrow for so heavy a meson in the absence of a selection rule that inhibits strong-interaction decay. The narrowness, by itself, is suggestive of an exotic state.

KEKB, like the similar PEPII collider that recently ceased operation at SLAC, is called a B factory. That's because when its beams are tuned to a particular resonant collision energy, a large fraction of all e^+e^- collisions produce a pair of the very heavy B mesons. The Belle analysis has thus far found the $Z^\pm$ peak only in collisions in which a charged or neutral B decays to a K meson plus the ψ' and the charged pion. So the experimenters had to consider and rule out the possibility that the $\psi'\pi$ invariant-mass peak might be a kinematic artifact reflecting resonant interaction between the K and π.

The Belle group determined that its $Z^\pm(4430)$ signal, found in its search through 700 million B decays, has a statistical significance of 6.5 standard deviations. Theoretical issues aside, the experimental case for the $Z^\pm$ is widely regarded as more convincing than was the ephemeral evidence in 2003 for the now largely discredited $\Theta^+(1530)$, which was for a time hailed as the first exotic baryon—a so-called pentaquark requiring five quarks instead of the canonical three (see PHYSICS TODAY, September 2003, page 19). Three quarks couldn't account for the simultaneous positive charge and positive strangeness of the supposed $\Theta^+(1530)$.



Evidence for the existence of a manifestly exotic meson—a meson that can't be simply a quark–antiquark bound state—is the peak at 4.43 GeV in the invariant-mass distribution of the pion and the ψ' charmonium meson from the decays $B \to \psi'\pi^\pm K$ of charged and neutral B mesons from the KEKB collider in Japan. The red and blue curves indicate fits for the resonant peak and its background. The data analysis attributes to the peak a statistical significance of 6.5 standard deviations and an intrinsic width of about 45 MeV. (Adapted from ref. 1.)

Quantum chromodynamics

Hitherto, the absence of exotic mesons whose quantum numbers require $qq\bar{q}\bar{q}$ or exotic baryons requiring $qqqq\bar{q}$ seemed plausible within quantum chromodynamics. But unambiguous predictions are notoriously difficult to calculate from QCD. The theory asserts that quarks of any flavor come in three precisely equivalent sorts, called colors. Quark color is the strong-interaction analogue of electric charge. (See the article by Frank Wilczek in PHYSICS TODAY, August 2000, page 22.) QCD does identify $q\bar{q}$ and qqq as the lowest-energy color-singlet configurations—that is, states with the requisite color symmetry for forming free particles. But the theory, as currently understood, cannot rule out mesons and baryons made, respectively, of four- and five-quark color singlets.

The case for four-quark mesons is much the stronger of the two. In recent years the Belle collaboration and BaBar, its equivalent at SLAC's PEPII, have discovered half a dozen charmonium mesons that don't fit expectations for straightforward $c\bar{c}$ bound states.[2] Because the c quark is so massive, QCD theorists have availed themselves of nonrelativistic approximations to predict the masses and other properties of excited $c\bar{c}$ states with impressive reliability. But the half-dozen new ones don't fit the picture. The $Z^\pm(4430)$ is the first that's manifestly exotic. The others, though putatively exotic, lack the telltale electric charge.

With regard to the $Z^\pm(4430)$ and the other wayward charmonium states, two different four-quark hypotheses have gotten attention. At least some of the states might be "mesonic molecules," loosely bound pairs of ordinary $q\bar{q}$ mesons barely held together by the QCD analogue of van der Waals forces. More exciting is the notion for which the term *tetraquark* is reserved. That hypothesis takes the exotic states to be color singlets formed by the binding of a strongly coupled qq diquark with a $\bar{q}\bar{q}$ antidiquark. Not being color

singlets, the individual diquarks that make up the tetraquark could not exist as free particles. But there's abundant empirical evidence from the spectrum of hadron masses and from scattering phenomena that certain kinds of diquarks are strongly coupled. These favored diquarks are the ones that are antisymmetric under exchange of any of the three quark labels: color, flavor, or spin orientation.

The mesonic-molecule hypothesis is particularly plausible when the mass of the meson in question is very close to the kinematic threshold for decay to a pair of daughters that might be its molecular constituents. And indeed, theorist Jonathan Rosner at the University of Chicago has pointed out that the $Z^{\pm}$ mass is close to the sum of the masses of a particular pair of D mesons that might be forming a mesonic molecule.[3] Every D meson carries a single c (or $\bar{c}$) quark.

University of Rome theorist Luciano Maiani favors the idea that $Z^{\pm}(4430)$ and the other problematic charmonium states are tetraquarks. On that basis, he and coworkers have assigned to each of them a specific diquark–antidiquark bound state and predicted the existence of additional charmonium tetraquarks yet unseen.[4] In particular, they predict that experimenters will find two different neutral siblings of the $Z^{\pm}$ with masses within a few MeV of 4430. That prediction follows from the strict adherence to isotopic-spin symmetry expected of tetraquarks. Mesonic molecules, by contrast, could exhibit significant violation of that approximate symmetry, which is an elaboration of the charge independence of the strong interactions. Maiani and company also predict more distant tetraquark relatives of the $Z^{\pm}(4430)$, with masses up to 4.6 GeV. Some of those, they argue, should have an unusual affinity for decaying into baryon–antibaryon pairs.

Fooled again?

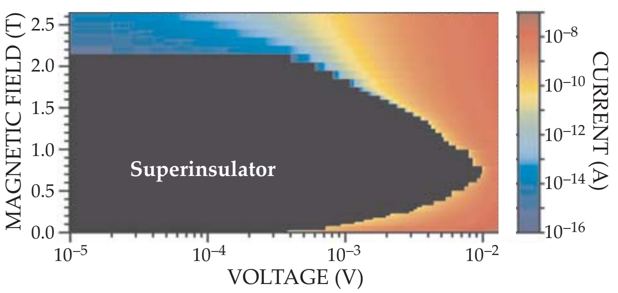
The tetraquark quantum states adduced to account for the observed and predicted charmonium exotics all have the diquark and antidiquark in an *s*-wave state of zero relative orbital angular momentum. Higher orbital states would weaken the already precarious binding. When evidence of the $\Theta^{+}(1530)$ pentaquark baryon was reported in 2003, Wilczek and MIT colleague Robert Jaffe considered that it might be a bound state of two diquarks plus a

physics update

Supplementary material related to these items can be found at www.physicstoday.org.

Giant piezoresistance. A new experiment, conducted by scientists from France, Switzerland, and the UK, has recorded the largest-ever change brought about in a bulk material's electrical resistance by straining the material at room temperature. Called piezoresistance, the phenomenon is often exploited in sensors. In simple metal-foil piezoresistors, the kind used to examine the integrity of a concrete wall or to monitor a prosthetic limb, the change in resistance per unit of strain (a ratio referred to as the gage factor) has a typical value of about 2. For silicon-based piezoresistors, the kind used in cell phones and airbag accelerometers, the gage factor is usually about 100. The new experiment uses a silicon–aluminum hybrid material in which the arrangement of the components, not their composition, is of paramount importance. The metal—in this case aluminum—is effectively a current shunt; applying a mechanical stress to the device deflects current toward or away from the shunt and thereby alters the device's resistance. For appropriate geometric configurations, the researchers, led by Alistair Rowe of the École Polytechnique in Palaiseau, France, measured a gage factor of nearly 900, the largest ever seen at room temperature in a bulk material. Giant piezoresistive structures could be good news for the designers of microelectromechanical devices in which the measurement of ultra-small accelerations or atomic-scale deflections is important. Alternatively, higher sensitivity to movement can be translated into lower power requirements when battery energy is at a premium, as in cell phones. (A. C. H. Rowe et al., *Phys. Rev. Lett.* **100**, 145501, 2008.) —PFS

A superinsulating state. In conventional superconductivity, electrons combine into Cooper pairs, and those pairs collectively enter into a single quantum state in which current can flow with zero electrical resistivity; there is no current dissipation and no Joule heating of the material. A multinational collaboration led by Valerii Vinokur of Argonne National Laboratory in the US and Tatyana Baturina of the Institute of Semiconductor Physics in Russia recently reported on an analogous but opposite situation in which electrical current is vanishingly small, effectively zero. The group studied a thin film of superconducting titanium nitride. Below critical values of temperature and applied voltage, the system went through an abrupt transition from an insulator with normal, linear resistivity to one with apparently infinite resistivity. What's more, the transition could be crossed by tuning a magnetic field for a given threshold voltage, as shown in the figure. As with a superconductor, the superinsulator has zero Joule loss—but now because there is no current rather than no resistance. The experimental system was successfully modeled and analyzed as an array of superconducting islands or droplets connected by Josephson weak links. The researchers conjecture that such a network is also essential to the superconductor-to-insulator transition in thin films. (V. M. Vinokur et al., *Nature* **452**, 613, 2008.) —PFS



Guiding light. In the pursuit of a quantum computer, the photon is a leading candidate for the quantum bit, or qubit. Working models of photonic circuits, however, have been unscalable arrangements of bulky mirrors and beamsplitters sitting atop a square-meter-sized table. Now scientists at the Center for Quantum Photonics at the University of Bristol in the UK have printed several dozen photonic circuits onto a silicon wafer. The research team created waveguides by first depositing a doped layer of silica onto the wafer, then patterning 3.5-micron-wide ridges into the silica. Two waveguides are coupled when they approach each other and then diverge, as shown in the figure, allowing evanescent waves to overlap. Using such directional couplers, the researchers not only fabricated on-chip beamlone strange antiquark.[5] In that case, however, Bose statistics forbids an *s*-wave between the two diquarks. “But because the experimental evidence for the pentaquark at first seemed so compelling,” recalls Jaffe, “we speculated that maybe forming the favored antisymmetric diquark pays so well that a pair of them can bear the insult of being in a *p*-wave.”

The supposed pentaquark was first sighted in collisions between photons and nuclei at a synchrotron light source and at a nuclear-physics accelerator. When follow-up searches were carried out with higher statistics at particle-physics accelerators, the pentaquark signal was gone. Old particle-physics hands had wondered why, if the $\Theta^+(1530)$ really did exist, they had not found it decades ago when they were searching in the same energy regime for positively charged baryons with positive strangeness.[6]

The B factories, by contrast, allow experimenters to find hadronic states they probably couldn’t have unearthed earlier. The 5.3-GeV B mesons created there in great profusion are just about as heavy as mesons ever get. They decay (by flavor-changing weak interactions) preferentially into mesons that carry charmed quarks. It’s among such decays that theorists expect exotic mesons to be found—if they exist.

PEPII and KEKB were built primarily to study the tiny asymmetry between particles and antiparticles (see PHYSICS TODAY, May 2001, page 17). As a byproduct of that effort, Belle and BaBar have accumulated enormous reserves of B-decay data that could reveal many more new states. “That’s a fantastic resource we’re just beginning to explore,” says Jaffe. “QCD is a beautiful and complete theory, but nobody has been able to solve it for hadronic states. We need all the help we can get to understand the confinement of quarks inside hadrons.”

Bertram Schwarzschild

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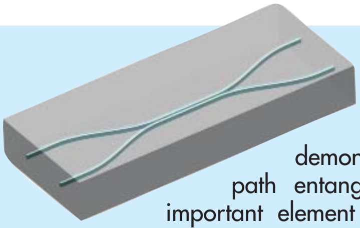
6. See, for example, R. N. Cahn, G. H. Trilling, *Phys. Rev. D* **69**, 011501 (2004).



splitters, interferometers, and even a controlled-NOT gate, but combined those devices into photonic circuits. Among their demonstrated results is a high-fidelity, path entangled state of two photons, an important element for quantum computation. The silica-on-silicon photonic circuits may also be applied to quantum metrology and communication technologies. (A. Politi et al., *Science* **320**, 646, 2008.) —JNAM

Collisions between carbon dioxide molecules can affect greenhouse warming. Visible light coming from the Sun pours down daily and is reflected back from Earth’s surface as IR radiation. Extra warming occurs when some of that IR is absorbed and retained in the atmosphere. Only a trace gas in the atmosphere, CO_2 is far outnumbered by O_2 and N_2 molecules, but its growing presence (mostly due to human activity) and its ability to absorb and trap IR radiation are thought to be instrumental in producing greenhouse effects. The interactions between atoms in a single molecule generate the molecule’s dipole moment and polarizability, two properties that greatly affect how the molecule absorbs or scatters radiation. Going to the next level of complexity, a new study shows in detail how a large class of molecules, including CO_2, absorbs and sometimes scatters light energy during intermolecular collisions. Michael Chrysos and his colleagues at the University of Angers (France) and Saint Petersburg State University (Russia) have derived exact mathematical formulas that can be used to calculate how collisions between so-called linear-rotor molecules modify the molecules’ absorption spectra. During a molecular interaction, a transient supermolecular complex arises with its own degrees of freedom—distinct from those of the constituent molecules—and its own dipole moment or polarizability. The net result is that a broad band of frequencies, including many that are unavailable to single molecules, can be absorbed or scattered. The new study is important for several reasons: It allows exact calculations of how the intercepted IR photon energy is converted to kinetic energy and shared among neighboring gas molecules; it allows for the inclusion of higher-order effects, such as the simultaneous collision of three molecules; and it provides evidence that long-range intermolecular interactions are far more important than short-range ones for absorption, a conclusion in conflict with mainstream assumptions. (M. Chrysos et al., *Phys. Rev. Lett.* **100**, 133007, 2008.) —PFS

Peaks and labyrinths in a magnetic fluid. A ferrofluid is a colloidal suspension of nanometer-sized magnetic particles in a nonmagnetic carrier fluid. As you might expect, it can be easily manipulated with external magnetic fields and often exhibits different patterns and instabilities. For example, when a sufficiently strong magnetic field is applied perpendicular to the flat surface of a ferrofluid, the Rosensweig instability produces a stationary array of peaks protruding above the surface. When a similar field is applied to a ferrofluid droplet immersed in a confined immiscible liquid, the labyrinthine instability produces horizontal fingering as the two fluids interpenetrate. A new experiment reveals a hybrid situation in which those two normally distinct instabilities occur simultaneously. Scientists from Taiwan and Brazil immersed a ferrofluid droplet in a thin layer of a miscible nonmagnetic fluid. The images of the experiment, with a side view in the upper panels and a top view in the lower ones, show what the researchers found after switching on the field. The Rosensweig instability grows rapidly to its greatest amplitude in 0.43 s (left panels), at which time diffusion is already affecting the base of the droplet, decreasing the magnetic body force that sustains the peak against gravity and surface tension. At 1.2 s (middle panels), the peak is clearly decaying as the fingering progresses and after 5 s (right panels) the surface is again flat and radial diffusion dominates. (C.-Y. Chen, W.-K. Tsai, J. A. Miranda, *Phys. Rev. E* **77**, 056306, 2008.) —SGB ■