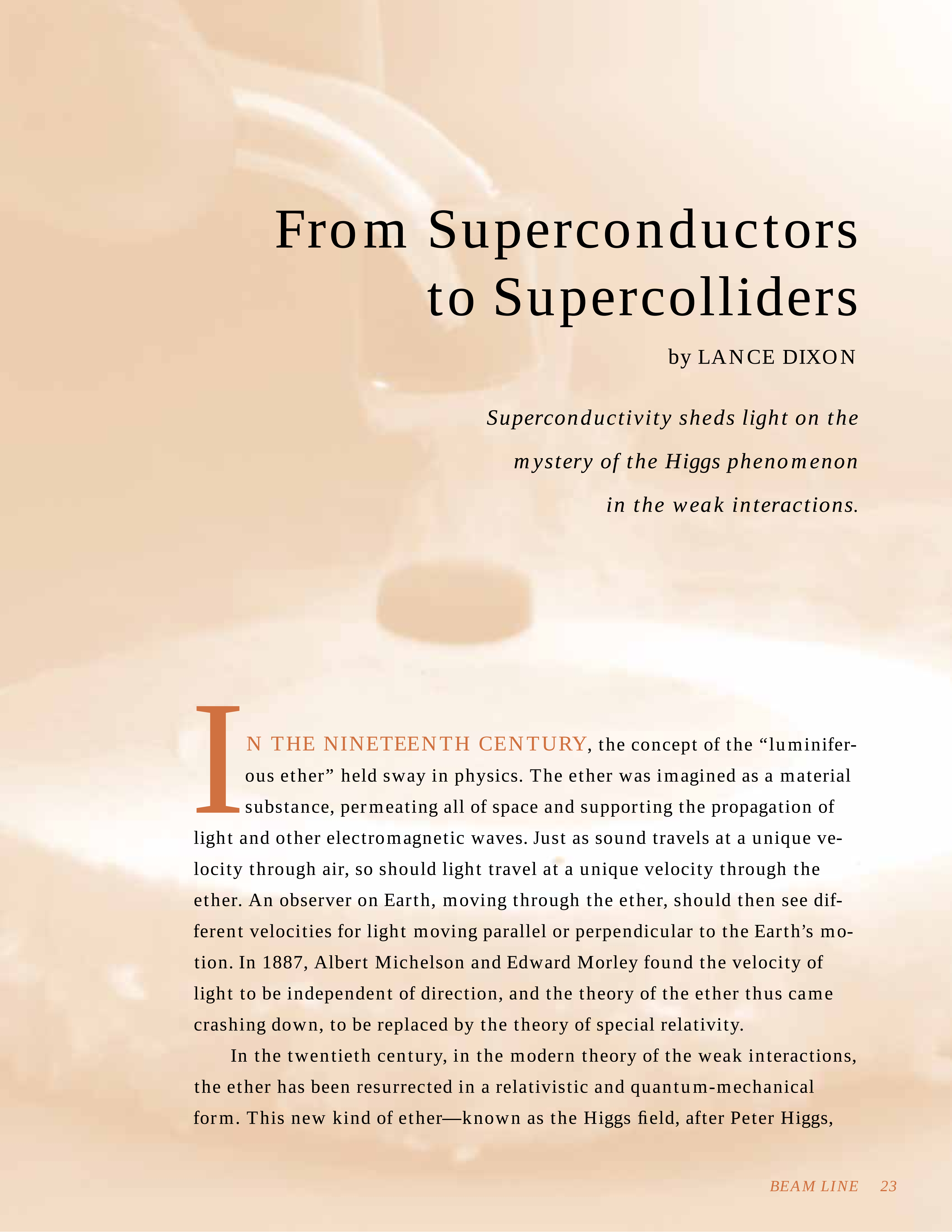

From Superconductors to Supercolliders

by LANCE DIXON

Superconductivity sheds light on the mystery of the Higgs phenomenon in the weak interactions.

IN THE NINETEENTH CENTURY, the concept of the "luminiferous ether" held sway in physics. The ether was imagined as a material substance, permeating all of space and supporting the propagation of light and other electromagnetic waves. Just as sound travels at a unique velocity through air, so should light travel at a unique velocity through the ether. An observer on Earth, moving through the ether, should then see different velocities for light moving parallel or perpendicular to the Earth's motion. In 1887, Albert Michelson and Edward Morley found the velocity of light to be independent of direction, and the theory of the ether thus came crashing down, to be replaced by the theory of special relativity.

In the twentieth century, in the modern theory of the weak interactions, the ether has been resurrected in a relativistic and quantum-mechanical form. This new kind of ether—known as the Higgs field, after Peter Higgs, one of the first to postulate it—is supposed to permeate all of space, and to be responsible for giving mass to the *W* and *Z* bosons, carriers of the weak force, and to the quarks and leptons that constitute all matter. What is this new ether made out of? Why should we believe it exists, and how does it give mass to elementary particles? How is it related to the Higgs particle, the main quarry of present and planned supercolliders? The answers to these questions, where known, are not that easy to describe. Fortunately, though, there is a fruitful and precise analogy between the Higgs mechanism for generating the *W* and *Z* masses and the phenomenon of superconductivity. In this analogy, the entire Universe is a superconductor, not for electromagnetism but for the weak interactions. The abstract quantum fields associated with a yet-undetected Higgs particle (or particles) are made more concrete in the analogy; they are represented by the concerted motions of many ordinary electrons in a solid. These parallels have been known for a long time; indeed they inspired many particle physicists in the late 1950s and 1960s, as the Higgs mechanism was being incorporated into models of the weak interaction. As we'll see, the analogy could operate at more than one level; it is certainly valid at a descriptive, phenomenological, or macroscopic level, but it might also work at a deeper one.

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Before turning to superconductivity, let's take a glimpse at what we have learned about the weak interactions in the one hundred years since Henri Becquerel discovered them. The most obvious property of the weak force is, naturally, its weakness. For example, a neutrino can easily pass through the entire Earth without interacting. The electroweak theory, initially developed by Sheldon Glashow, Steven Weinberg, and Abdus Salam in the 1960s, explains the weak interactions in terms of a triplet of particles called vector bosons, the electrically charged W^+ and W^- and neutral *Z* bosons. These particles are analogous to the photon (the quantum of light) which carries electromagnetism. The photon is exactly massless because of a certain symmetry, called gauge invariance. The corresponding symmetry in the electroweak theory is said to be spontaneously broken by the Higgs mechanism, giving a mass to the *W* and *Z* bosons. We'll use the superconductor analogy to explain what that last sentence really means!

The weakness of the weak interactions is due to the large *W* and *Z* masses, almost one hundred times the proton mass. In the scattering of a neutrino off a nucleon, there is not enough energy to make a real *W* or *Z* particle. However, the uncertainty principle of quantum mechanics allows a "virtual" *W* or *Z* to be produced, but only for a short time, related to its large mass; this results in a very small probability for the scattering to occur. Another way of saying the same thing is that the field of the *W* or *Z* only extends a tiny distance away from the neutrino (see below), thus making it hard for the neutrino to find a quark in the nucleon to interact with. Nowadays, real *W*'s and *Z*'s are produced routinely at particle accelerators, and their properties agree extremely well with theoretical predictions; yet the Higgs mechanism remains the most poorly tested part of the theory. The minimal version of the mechanism predicts a single new particle, the Higgs boson, but this version is probably just a surrogate for more complicated dynamics. One of the prime rationales for building new supercolliders (using superconducting magnets!) is to shed light on the mystery of the Higgs sector.

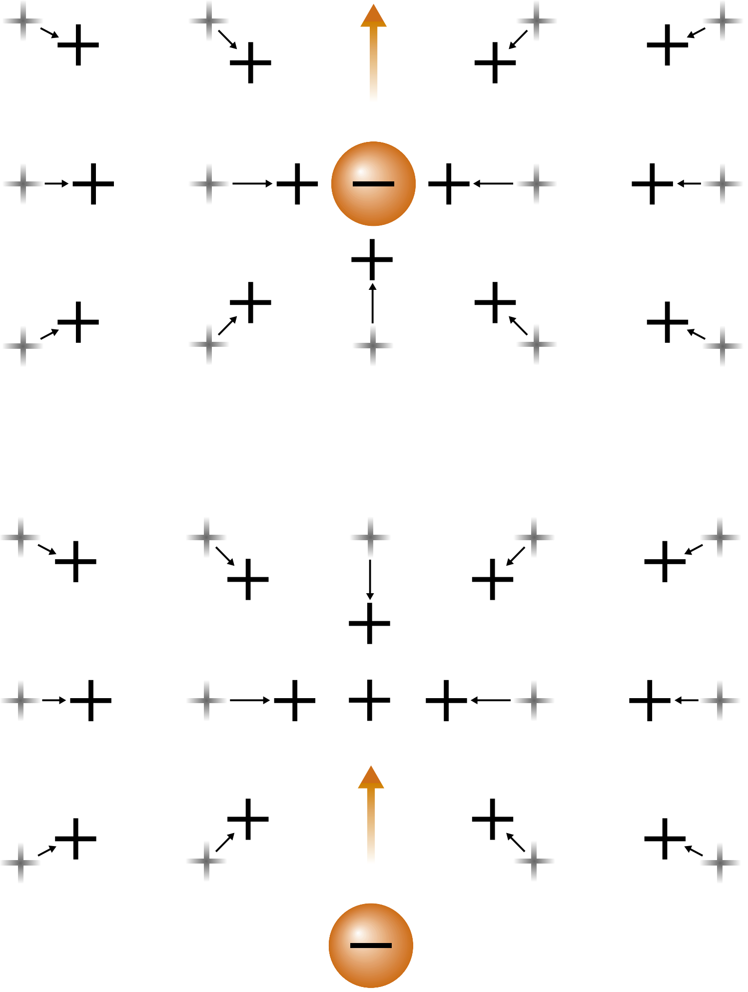
SUPERCONDUCTIVITY is itself a pretty remarkable phenomenon. Cool a chunk of lead or niobium down to a few degrees above absolute zero and its electrical resistance completely vanishes. Once an electrical current is established in a ring of superconducting material, it circulates essentially forever without an external power source. Magnets wound from superconducting wire have huge advantages over conventional magnets for many applications, ranging from magnetic resonance imaging to the bending magnets in modern proton storage rings such as the Fermilab Tevatron and the Large Hadron Collider to be built at CERN. Superconductors also expel external magnetic fields (the Meissner effect). The photograph on the next page shows a superconductor expelling the field of a permanent magnet and thereby levitating the magnet. This effect may eventually find practical application in magnetically-levitated high-speed trains, for example.

A superconductor only works below some critical temperature T_c. Above T_c thermal effects disrupt the mechanism and the material becomes "normal." Conventional metallic superconductors have critical temperatures ranging from a few to tens of degrees kelvin. In the past decade, however, a new class of ceramic materials has been discovered, which superconduct well above the boiling point of liquid nitrogen (77 degrees kelvin). Because liquid nitrogen is much cheaper to produce and store than liquid helium, there is considerable interest in developing commercial devices from these high-T_c superconductors. The critical temperature for the weak interactions, viewed as a superconductor, is a quadrillion degrees kelvin (10^{15} K) making this truly the ultimate high-T_c superconductor! Above this temperature, the masses of the W and Z bosons, and all the quarks and leptons, should vanish. Testing this conclusion in the laboratory would require heating a sample of the Universe to 10^{15} K in order to make it go normal. One has to go back to the first instants of the Big Bang to achieve those conditions. In an accompanying article in this issue, Eric Sather describes how the predominance of matter over antimatter that we observe today may have originated as the Universe cooled through this electroweak phase transition. Since that moment, the Universe has been stuck firmly in the superconducting phase.

The mechanism of superconductivity in conventional superconductors has been well understood since the pioneering work of John Bardeen, Leon Cooper and J. Robert Schrieffer (BCS) in the mid 1950s. At room temperature these materials are metals—they have conduction electrons which are not localized on any particular atom but roam around the entire material, while the remaining positive ions stay fixed in a crystal lattice. A suggestive name for this collection of electrons is the Fermi sea. Like water molecules in the ocean, the electrons are free to move, but different electrons must occupy different locations, so the sea fills up to some level. Also like the ocean, the depths are calm, and all the action is at the surface.

As the temperature is lowered, an attractive interaction between conduction electrons near the surface of the Fermi sea binds them into "Cooper pairs." It is somewhat surprising that a pair of electrons should attract, since the electrostatic (Coulomb) force between two like-sign charges is repulsive. In a metal this force is reduced, or screened, at longer distances: Other conduction electrons feel the charges of the two electrons in question, and move out of the way; this leaves a positive charge behind that makes the charges of each electron look less negative. Screening reduces the strength of the Coulomb force, but it remains

A high-T_c ceramic superconductor levitates a magnet. (Courtesy Science Kit & Boreal Laboratories)



Top: An electron moving through a solid polarizes the lattice of positive ions towards it.

Bottom: A second electron is attracted to the excess of positive charge.

repulsive. The attractive interaction results instead from collective motions of the lattice of positive ions, whose modes of oscillation are called phonons. One electron polarizes the lattice by attracting the positive ions toward it; a second electron is then attracted to this build-up of positive-charge, as illustrated by the figure on the left. The net sum of the screened Coulomb repulsion and the lattice (phonon) mediated attraction can be attractive, and in that case it turns out that a Cooper pair will always form at sufficiently low temperature.

Superconductivity does not result merely from the formation of Cooper pairs, but rather from getting a significant fraction of them to occupy a single quantum state, a phenomenon known as Bose condensation. By themselves, electrons are forbidden from Bose condensing because they are fermions, not bosons—the Pauli exclusion principle states that no two of them (let alone a macroscopic number) can occupy the same state. In effect, the exclusion principle holds up the Fermi sea. (In an atom, it similarly explains why the electrons don't all collapse onto the lowest energy atomic orbital.) On the other hand, a Cooper pair is a boson (see the box on the next page), and the Pauli exclusion principle does not apply to bosons. Instead, bosons prefer to occupy the same, lowest energy state, if the temperature is low enough. The term condensation refers to the sudden onset of the new phase as the temperature is lowered to the critical temperature T_c, reminiscent of the condensation of vapor into liquid. If you are trying to visualize what is happening to the Fermi sea, a better picture is the freezing of its surface. In a single quantum state, all the electrons must move in lockstep, like a sheet of ice floating on the surface. In reality, a complicated dance is going on, as individual electrons try to stay out of each other's way, yet as pairs they move together.

How does the macroscopic occupancy of a single quantum state endow a superconductor with its remarkable properties? In an ordinary metal, the electrical current is carried by a large number of electrons, with no quantum-mechanical relation to each other. Electrical resistance is generated when individual electrons (like individual water molecules) moving with the current scatter off impurities or phonons, dissipating energy into the Fermi sea. Energy can be lost in arbitrarily small units because there are empty quantum states nearby for the electrons to scatter into, and because no other electron "cares" what happens to a given electron. In contrast, in a superconductor, current is carried by the Bose condensate of doubly-electrically-charged Cooper pairs, flowing in quantum-coherent unison, like the rigid ice sheet described earlier. Local effects are simply unable to stop its progress, and so the electrical resistance is precisely zero.

As the temperature rises, more and more of the electrons are kicked into excited states instead of the Bose condensate ground state (the ice sheet melts). However, the condensate can carry all the current with perfect conductivity, and so its depletion does not matter much until it disappears altogether at the critical temperature.

The Meissner effect—expulsion of a static magnetic field—requires this perfect conductivity. In response to an externally applied magnetic field, perpetual eddy currents circulate in the superconductor, producing an internal magnetic field that exactly cancels the applied one. An ordinary metal also generates eddy currents in response to an applied magnetic field, but these die out quickly owing to electrical resistance, and then the magnetic field penetrates. (One can observe the effects of these currents by placing a slab of aluminum vertically in a strong vertical magnetic field—it can take seconds for the slab to fall, as it tries to keep the magnetic field lines from penetrating!)

Before we can return to the weak interactions, we need to know that there are two important length scales in a superconductor. The first measures how efficiently the condensate expels a magnetic field. In fact, the expulsion is not quite complete (see the figure on the next page). There is a thin layer of depth λ, called the London penetration depth, over

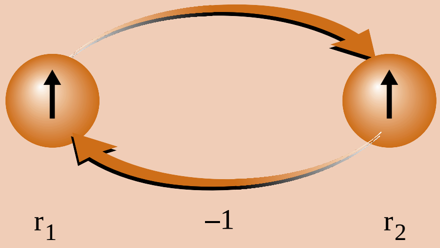
Fermions, Bosons and Cooper Pairs

ELECTRONS ARE CALLED fermions because they carry 1/2 unit of the basic quantum of angular momentum (Planck's constant, $\hbar$), and therefore they obey Fermi-Dirac statistics, which means that the quantum-mechanical wave function ψ for n electrons has to be antisymmetric under the exchange of each pair of electrons. For example, under the exchange of electrons 1 and 2, ψ picks up a minus sign,

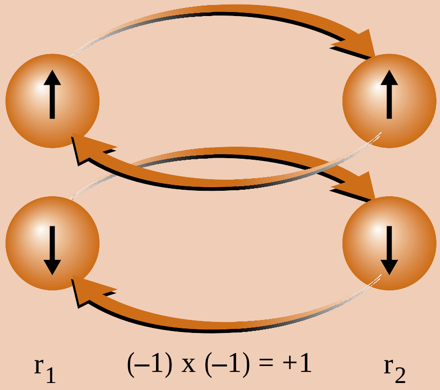
$$\psi(r_1,s_1;r_2,s_2;\,.\;.\;.;\,r_n,s_n) = -\psi(r_2,s_2;r_1,s_1;\,.\;.\;.;r_n,s_n),$$

where r_i and s_i label the positions and spins of the electrons.

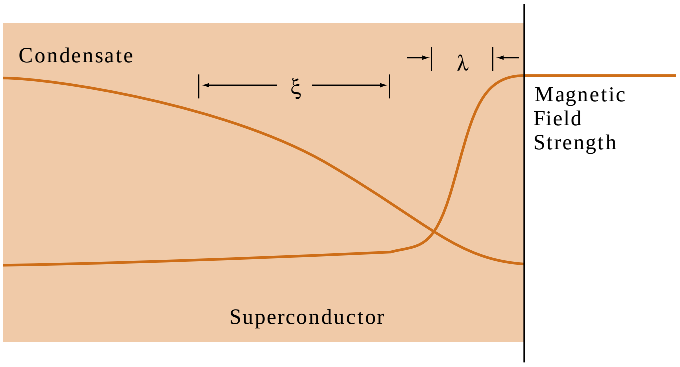
A particular consequence of these rules is the Pauli exclusion principle, that no two electrons can occupy exactly the same state. This means that they cannot condense directly. However, a pair of electrons, in any quantum state, must have an integer unit of angular momentum—the two spin 1/2's can add to make either 0 or 1, and the orbital angular momentum is always an integer. Thus the pair of electrons is a boson, obeying Bose-Einstein statistics, which requires the wave function to be symmetric under the exchange of any pair of bosons. The figures below illustrate how a system of two electron pairs can be symmetric under exchange of the pairs, yet antisymmetric under exchange of individual electrons. In a Cooper pair—the lowest quantum state for a pair of electrons with a phonon-mediated attraction—the electrons have zero orbital angular momentum, and are antisymmetric in spin (spin 0). Thus a Cooper pair has zero total angular momentum. This did not have to be the case, and indeed there is mounting evidence that for high-T_c superconductors the pairs that condense have spin 2, not 0.



The wave function for two electrons with the same spin (denoted by ↑) at different locations r_1 and r_2, must pick up a minus sign when r_1 and r_2 are exchanged.



The wave function for two pairs of electrons, at r_1 and r_2, picks up two minus signs when the pairs are exchanged. (Opposite spins within each pair are also required by Fermi-Dirac statistics.)



Behavior of the magnetic field and the superconducting condensate near the surface of a superconductor to which an external magnetic field has been applied.

which the magnetic field drops exponentially to zero. The value for λ depends on the material, but a tenth of a micron is typical. In this same region, the magnetic field perturbs and reduces the condensate. The second length scale, called the coherence length ξ, governs how fast the condensate snaps back to its bulk value once the magnetic field has gone to zero. (Here you can imagine the stiffness of that ice sheet in response to some deformation, if you like.) Depending on the material, the coherence length can be either longer or shorter than the magnetic field penetration length; these two classes of superconductors (known as type I and type II) turn out to have quite different magnetic properties. In any case, it is this response of the condensate to a local disturbance that is the superconductor analog of the Higgs particle.

Finally, we have to accept that in quantum field theory, distance scales and energy-momentum scales are related through the uncertainty principle, and particles and fields become one and the same. A particle of mass M has associated with it a Compton wavelength given by $\hbar/Mc$, where $\hbar$ is Planck's constant and c is the speed of light. The Compton wavelength tells how fast the field of a particle falls off with distance. For example, the exponentially falling penetration of the magnetic field into a superconductor means that the photon has acquired a mass $M_\gamma = \hbar/\lambda c$. (The expert reader will object that this is not a true photon mass, because the condensate is nonrelativistic, and the electric field behaves differently from the magnetic field. But it's close enough for our purposes.)

AT LAST we are ready to draw the analogy between a superconductor and the Higgs mechanism. We imagine that there is a Bose condensate permeating all of space, the occupied quantum state of some boson that carries a charge under the weak interactions, just as the Cooper pairs carry an electric charge ($2e$). A quark or lepton carries both weak and electromagnetic charges, so it produces fields of W's, Z's and photons around it. But the condensate responds to these W and Z fields by producing currents that conspire to cancel out the fields—expel them from the vacuum—except for a tiny region near the quark or lepton. That region is of order the W Compton wavelength, which we know to be 0.0025 fermi. By comparison, a proton is roughly a fermi (10^{-15} meters) across. The photon field, on the other hand, is not screened and extends to infinite distances (unless the quark or lepton happens to be inside a real superconductor!). Using the inverse of the penetration length as a measure of efficiency, the Higgs mechanism is about a billion times more efficient at screening the weak interactions than an ordinary superconductor is at screening electromagnetism. The screening is so efficient that it is hard to imagine the weak analogs of electrical currents, arising from the motion of a bunch of quarks and

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leptons. The W and Z fields fall to zero even before the next particle in the bunch is reached, for any bunch we can conceive of making in the laboratory.

In principle, a quark or lepton should also be able to "kick" the condensate, producing the exponentially decaying field of the Higgs particle itself, whose decay length (the coherence length) is also tiny. (Because we don't know the mass of the Higgs particle, or particles, we don't know this precise length. Whether it is large or small should control the qualitative nature of the Higgs sector—"weakly-coupled vs. strongly-coupled." The analogous ratio of the coherence length to the penetration length similarly controls many properties of superconductors.) If the condensate were kicked hard enough, in a violent collision, a real Higgs particle could pop out. In practice, it is believed that the light quarks and leptons (which are all that we can easily fashion into particle beams), couple only very weakly to the Higgs, and most proposals for making the Higgs particle involve perturbing the condensate indirectly, by means of vector boson fields (the W, Z, photon, or even gluon), much as the magnetic field perturbs the condensate in a superconductor.

We have seen that the phenomenon of superconductivity closely parallels the Higgs mechanism for W and Z mass generation, and that the two important length scales in a superconductor, λ and ξ, when reinterpreted in the electroweak context, become the Compton wavelengths, or inverse masses, of the W boson (λ) and of the Higgs boson (ξ). However, the analogy so far has been at the macroscopic or phenomenological level. We did not ask what the Higgs condensate is made of. Likewise, we made no reference to the details of the BCS electron-pairing mechanism, beyond the fact that it generates a condensate. Indeed, in 1950, seven years in advance of the BCS theory, Vitaly L. Ginzburg and Lev D. Landau were able to accurately describe many phenomena of superconductivity without recourse to a microscopic theory. Their key advance was to account for the quantum-mechanical nature of the Bose condensate, and its ability to be deformed, by introducing a complex wave function $\psi(x)$, whose magnitude-squared $|\psi(x)|^2$ they interpreted as the local density of the condensate at a point x.

The minimal Higgs mechanism in the electroweak theory can be obtained from the Ginzburg-Landau description of superconductivity by replacing their ψ by the Higgs field, usually called ϕ. Just two additional modifications have to be made:

First, the theory must be relativistically invariant—or else Michelson and Morley would be very unhappy with us! A superconductor is not Lorentz invariant, in the sense that (as with any ordinary material) there is a preferred frame where it is at rest. Technically, the necessary alteration to the theory is easily carried out; we just declare the Higgs to be a Lorentz-invariant (scalar or spin-zero) field. Conceptually, though, this change makes it much harder to visualize what kind of "material" makes up the Higgs field.

Second, a single complex value (at each point in space) will not suffice for ϕ; at least two turn out to be required in order to give mass to the triplet of weak vector bosons, W^+, W^- and Z. Of course this vastly oversimplifies the way in which the electroweak theory was really developed.

IF WE ARE TO TRY to extend the Higgs-superconductor analogy to a deeper, microscopic or mechanistic level, we must first ask: Is the Higgs field ϕ of the Standard Model really a fundamental scalar field? Or is it instead a cooperative effect of some more elementary objects—perhaps fermions—as in the BCS theory? Proponents of supersymmetry, a symmetry that transforms fermions into bosons and vice-versa, argue that it is just as natural for there to be fundamental scalars as fermions, and that one of them could and should be the Higgs. Proponents of technicolor argue that no fundamental scalar particle has been detected to date, and that the Higgs is more likely to be a composite particle, a pair of fermions bound together by a new strong gauge interaction. This new force is imagined as a super-strong version of the color force that binds quarks into nuclei, hence the name technicolor.

The jury is still out on which alternative is correct (if either!). Yet it is striking how closely technicolor parallels the BCS theory at the microscopic level. The technicolor interaction is postulated to strongly bind together some new fermions, technifermions, into a state where they are moving at nearly the speed of light. Technifermions would also carry weak charges, so that a Bose condensate of pairs of them would give mass to the W and Z bosons, just as the superconducting electron-pair condensate gives mass to the photon. The BCS theory treats highly non-relativistic electrons that are weakly bound by phonons, so the two mechanisms still sound pretty different. However, remember that the important electrons for the BCS mechanism are those at surface of the Fermi sea. These electrons behave very much like relativistic particles—if they have a little extra momentum, their extra energy is proportional to that, like the relation for a particle moving at the speed of light, $E = pc$, except that the speed of light c gets replaced by something called the Fermi velocity v_F. The technicolor vector bosons and the phonons have this same massless, linear relation as well. The coupling between electrons and phonons may look weak, but like all couplings in relativistic field theories, it depends on the distance-scale. Indeed, both the technicolor and the electron-phonon couplings can be shown to change slowly, from a weak value at "very short" distances (the Planck scale for technicolor, the Debye frequency for BCS) to an arbitrarily strong value at "long" distances (the weak scale for technicolor, the coherence or penetration length for BCS). So they are really very similar phenomena, something that was recognized, even before technicolor was fully developed, by Yoichiro Nambu and Giovanni Jona-Lasinio. Of course, just because the deeper theoretical analogy holds doesn't mean that technicolor is right.

While conventional superconductors are quite well understood today, via the BCS mechanism and many subsequent developments, the recent class of high-T_c ceramic superconductors is much more of a mystery.

In some sense they are at the stage that the weak interactions were at in the 1960s and early 1970s, when the basic phenomenology, the full pattern of symmetry breaking, was not yet clear. Was there a Z boson or not? How were the W and Z masses related? In the case of the new superconductors, the analogous questions are about the charge of the condensate and its angular momentum, or spin. The charge appears to be $2e$, as for conventional superconductors, which means that an electron-pairing mechanism of some kind should be the culprit, but the BCS mechanism is probably too weak to do the job. The spin appears to be two, which means that the new condensate is not rotationally invariant, unlike the BCS condensate and Higgs condensate. As with the Higgs mechanism of the Standard Model, there are many strong opinions about the microscopic physics underlying high-T_c superconductors, but no complete consensus. Only time and experiment will tell.