SUPERCONDUCTIVITY

Higgs, Anderson and all that

The Higgs mechanism is normally associated with high energy physics, but its roots lie in superconductivity. And now there is evidence for a Higgs mode in disordered superconductors near the superconductor–insulator transition.

Philip W. Anderson

There have been a number of publications recently — for instance, the work by Daniel Sherman *et al.*[1] in *Nature Physics* — and historically[2] claiming to have discovered the 'Higgs' in superconducting contexts. But many of us thought the Higgs belongs to our multi-gigavolt friends — what is it doing in a superconductor? So, some history: even before the Bardeen–Cooper–Schrieffer (BCS) theory of superconductivity was published in December 1957, a flurry of papers were in preparation[3–5] to solve the apparent gauge invariance difficulty of that theory, which manifests itself in the fact that London's equation comes out of BCS in the non-invariant form $\mathbf{J} = \rho_s\mathbf{A}$ rather than $\mathbf{M} = \nabla \times \mathbf{J} = \rho_s(\nabla \times \mathbf{A})$, where $\mathbf{J}$ is the superconducting current density, $\rho_s = -n_s e^2 / mc$, n_s is the number density of superconducting carriers, e is the elementary charge, m is the carrier's mass, c is the speed of light, $\mathbf{A}$ is the vector potential and $\mathbf{M}$ is the magnetization.

All three of these publications recognized that the trouble lay in the fact that BCS assumed that the pairing strictly involved zero-momentum pairs, which in modern terms means that the order parameter is assumed to be rigidly fixed in space. Therefore, to correct the error one must produce a theory that allows order parameter fluctuations and retains the translational symmetry of the electron gas. Such a theory would (if the pairs were neutral) have a phonon-like mode similar to superfluid liquid He II (later known as a Goldstone mode) and all of these papers showed that if that were the case the dynamics would come out okay. They also showed that there could be, depending on the structure of the pairing interactions, other modes as well (later to be known as Anderson–Bogoliubov modes, and demonstrated to exist in the superfluid phase of ^{3}He). But only I made the point[6] that in the real charged system there is no such mode and the gap is completely empty!

Next, Yoichiro Nambu, who was a particle theorist and had only been drawn into our field by the gauge problem, noticed in 1960 that a BCS-like theory could be used to create mass terms for massless elementary particles out of their interactions. After all, one way to describe the energy gap in BCS is that it represents a mass term for every point on the Fermi surface, mixing the particle with its opposite spin and momentum antiparticle. In 1960 Nambu and Jona-Lasinio developed a theory[7] in which most of the mass of the nucleon comes from interactions — this theory is still considered partially correct.

But the real application of the idea of a superconductivity-like broken symmetry as a source of the particle spectrum came with the electroweak theory — which unified the electromagnetic and weak interactions — of Sheldon Glashow, Abdus Salam and Steven Weinberg. However, that theory had to wait for some crucial steps in the reasoning. One of these was the charm quantum number, which Sheldon Glashow supplied. Another roadblock was the apparent necessity of allowing a number of Goldstone bosons into the theory, which would mean that the theory would be full of massless bosons — which didn't exist! When I heard in 1962 that people considered this a real obstacle, I sent off a short paper[8] saying "forget it — the gap is empty in a real superconductor!". The gauge field — the photon in a superconductor — and the matter field, the Goldstone boson, combine and make massive vector bosons (plasmons for superconductors, W and Z bosons for particles).

Peter Higgs and at least six others grabbed this idea and made a relativistic model of it in 1964 (ref. 9) — I had felt that it was intuitively obvious that it would work relativistically — and added the Higgs particle to it. Neither Nambu nor BCS had had to introduce an extra particle to create the superconducting instability, they just set up the interactions to get it; but Higgs and his friends were punctilious about having the mechanism explicit, so they inserted a 'Mexican hat' energy that required the Higgs field to have a finite mean value and to couple with and give mass to — that is, gap — all the other fermions in the system. In particle theory the rest is history — but not quite.

It was Peter Littlewood and Chandra Varma[2] who first noticed that superconductivity has its Higgs particle too. It is not an actual particle but an Anderson–Bogoliubov collective mode in the pair channel. Oddly enough, in 1958, without discussing it, I had remarked[6] that such a mode existed, but with the oversimplified BCS Hamiltonian it occurred at exactly twice the gap (at the threshold for two-particle excitations) and would be hard to see. I had no idea that it was important, and was barely aware that you could think of it as (in some sense) the amplitude mode for the order parameter. It is not clear that Littlewood and Varma[2] had the right mode (ref. 1 doesn't refer to them) but credit for the idea belongs to them.

There is one further question. If superconductivity does not require an explicit Higgs in the Hamiltonian to observe a Higgs mode, might the same be true for the 126 GeV mode? As far as I can interpret what is being said about the numbers, I think that is entirely plausible. Maybe the Higgs boson is fictitious!

To return to superconductivity, the claim of Sherman *et al.*[1] is that the Higgs mode is lowered below the double-gap threshold near the superconductor–insulator critical point, and that this effect allows its observation — in this case, by optical spectroscopy of disordered superconducting films of NbN and InO. If so, it is an important result, if only because it bears on the nature of the Lagrangian of the Standard Model. ❐

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