Particle physics in a superconductor

A superconducting condensate can display analogous behavior to the Higgs field

By **Alexej Pashkin** *and* **Alfred Leitenstorfer**

The recent discovery of the Higgs boson has created a lot of excitement among scientists. Celebrated as one of the most fundamental results in experimental physics (*1*), the observation of this particle confirms the existence of the associated Higgs field that plays a pivotal role in the Standard Model of particle physics. Because of the Higgs boson's large mass (about 125 GeV), it could be detected only in the world's largest and most powerful accelerator the Large Hadron Collider at CERN, Geneva. Although it sounds strange, the theoretical proposal of the Higgs mechanism was actually inspired by ideas from condensed matter physics, which typically works at much lower energies (a few electron volts or less). In 1958, Anderson discussed the appearance of a coherent excited state in superconducting condensates with spontaneously broken symmetry (*2*). Later, this approach was advanced by

Nambu (*3*). The existence of superconducting condensates has been firmly established. In contrast, unambiguous experimental evidence for the coherent excited state (called the Higgs mode) had been missing. On page 1145 of this issue, Matsunaga *et al.* (*4*) report direct observation of the Higgs mode in the conventional superconductor niobium nitride (NbN) excited by intense electric field transients.

Conventional superconductivity appears in metals when the phases of electronic wave functions lock to each other, forming a macroscopic quantum state that conducts current without energy dissipation. It can be described by a complex order parameter $\Phi(\mathbf{k}) = |\Phi(k)|\exp(i\phi)$, which acquires a nonzero value only in the superconducting state. A result of this description is that a superconducting phase transition must lead to a spontaneous breaking of symmetry. Consequently, the energy of the system shows a minimum at a certain value of the radial amplitude $|\Phi(k)|$, which is, how-
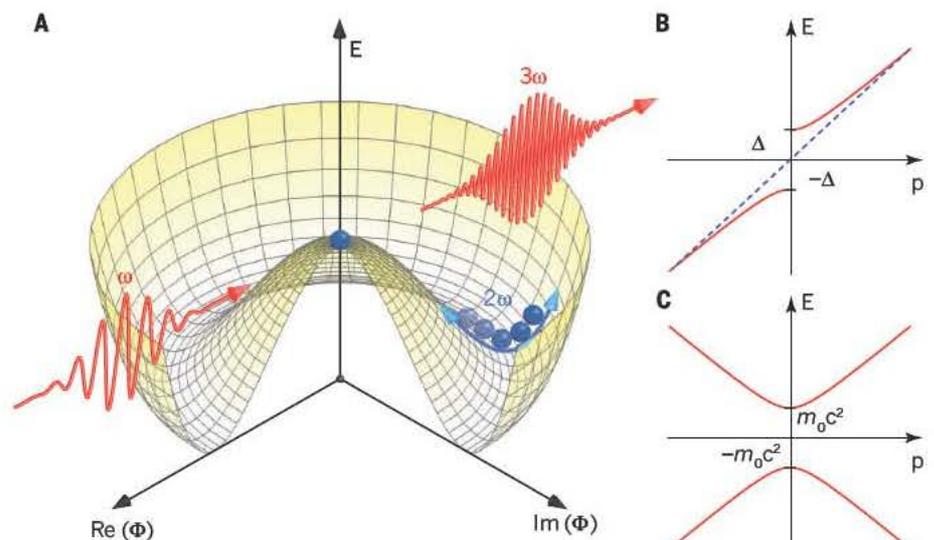
The Higgs amplitude mode. (A) Energy of a system as a function of the complex order parameter Φ in a state with spontaneously broken symmetry. The Higgs mode corresponds to the amplitude oscillations of Φ shown by the blue arrow. The excitation by a light pulse at half the resonance frequency starts a coherent oscillation of the order parameter. The induced superconducting current is nonlinear and leads to emission of the third harmonic of the excitation wave. **(B)** Energy of quasi-particles as a function of their momentum near the Fermi energy of a normal metal (dashed blue line) and a superconductor with energy gap 2Δ (solid red line). **(C)** Energy of a relativistic particle-antiparticle system with rest mass m_0 as a function of its momentum.

ever, independent of the phase φ (see the figure, panel A). Thus, only a displacement of $|\Phi(k)|$ comes with a restoring force that establishes the Higgs mode at a finite frequency of $2\omega_\Delta$.

The collective Higgs mode appears only in a Lorentz-invariant relativistic theory (5), which is usually associated with high-energy particle physics. Obviously, the energy scale in superconductors is far below the level where relativistic effects play a noticeable role. Why, then, does the Higgs mode appear in this case? The reason is that the superconducting energy gap opens up in the spectrum of quasi-particles at the Fermi energy. Electrons with properties modified by their environment are termed quasi-particles in condensed matter physics, and the Fermi level denotes the energy limit up to the point that their quantum

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states are occupied at zero temperature. Whereas the energy of quasi-particles in a normal metal depends linearly on their momentum in this region, it acquires a form analogous to the relativistic case in the superconducting state. The gap energy $2\Delta = 2\hbar\omega_\Delta$ plays the role of the rest mass of a particle-antiparticle pair (see the figure, panels B and C). Mathematically, this situation results in a formal identity of the Dirac Hamiltonian of Lorentz-invariant quantum theory and the BCS Hamiltonian used in the microscopic description of superconductivity developed by Bardeen, Cooper, and Schrieffer.

The Higgs amplitude mode in superconductors does not come with a dipole moment. Therefore, it cannot couple to electromagnetic radiation directly. Nonetheless, using the formalism of Anderson's pseudospins, Matsunaga *et al.* demonstrate that there exists a quadratic coupling between light and the Higgs mode that should result in resonant excitation at half the resonance frequency ω_Δ. To prove this prediction, Matsunaga *et al.* irradiated a superconducting NbN sample with intense light pulses with central frequencies from

0.3 to 0.8 THz (1.2 meV to 3.3 meV). Such energies correspond to the low superconducting transition temperature of 15 K in NbN. They fall into the terahertz spectral region, where both microwave and optical sources were once rather limited in amplitude. This problem has been solved recently with the development of tabletop terahertz sources based on femtosecond laser amplifiers. Optimized nonlinear conversion schemes now deliver unprecedented peak electric fields of terahertz light beyond 1 MV/cm (6) or even 100 MV/cm in the multi-terahertz region (7).

Matsunaga *et al.* have observed two manifestations of the Higgs mode. First, they used a delayed broadband probe terahertz pulse to trace the dynamics of the order parameter (the superconducting energy gap). By careful measurements at different excitation frequencies and gap energies tuned by temperature, they convincingly demonstrate that the order parameter oscillates at twice the terahertz driving frequency, confirming their initial report (8). Second, in accordance with the theoretical prediction by the authors, the superconducting current induced in the sample should oscillate at the third harmonic of the excitation. The experiment clearly detects the terahertz field emitted by this current and its resonant character with respect to the superconducting gap energy.

The results reported by Matsunaga *et al.* show that superconductors exhibit a strong "quantum" nonlinearity that originates from spontaneous breaking of symmetry and the resulting Higgs mode. Novel high-field terahertz technology is now actively used to study such quantum nonlinearities in solids (9–12). Quite generally, the goal is to gain insight into strongly coupled low-energy excitations of complex matter by investigating their nonlinear dynamics with subcycle temporal resolution. This powerful new approach will continue to provide information that is inaccessible to conventional techniques based on linear analysis in the spectral domain.

REFERENCES

1. A. Cho, *Science* **337**, 141 (2012).
2. P. W. Anderson, *Phys. Rev.* **110**, 827 (1958).
3. Y. Nambu, *Phys. Rev.* **117**, 648 (1960).
4. R. Matsunaga *et al.*, *Science* **345**, 1145 (2014).
5. M. Varma, *J. Low Temp. Phys.* **126**, 901 (2002).
6. J. Hebling, K. L. Yeh, M. C. Hoffmann, B. Bartal, K. A. Nelson, *J. Opt. Soc. Am. B* **25**, B6 (2008).
7. A. Sell, A. Leitenstorfer, R. Huber, *Opt. Lett.* **33**, 2767 (2008).
8. R. Matsunaga *et al.*, *Phys. Rev. Lett.* **111**, 057002 (2013).
9. S. Leinß *et al.*, *Phys. Rev. Lett.* **101**, 246401 (2008).
10. B. Zaks, R. B. Liu, M. S. Sherwin, *Nature* **483**, 580 (2012).
11. F. Junginger *et al.*, *Phys. Rev. Lett.* **109**, 147403 (2012).
12. O. Schubert *et al.*, *Nat. Photonics* **8**, 119 (2014).

Department of Physics, University of Konstanz, 78457 Konstanz, Germany. E mail: alfred.leitenstorfer@uni konstanz.de