Magnetic Flux Periodicity of *h/e* in Superconducting Loops

February 23, 2008 (H23). This month's "*Nature Physics*" published a Letter under the provocative title above [1]. The letter, by a team of the Mannhart group at the University of Augsburg, Germany, present theoretical results mainly derived from the doctoral dissertation of Florian Loder, the first author. They start with the Bogoliubov–de Gennes equations for the pairing Hamiltonian and calculate the energy spectrum of eigenenergies for the *d*-wave BCS model.

In superconducting rings, the electrical current responds to a magnetic flux by having a periodicity of *h*/2*e*, where the ratio of Planck's constant and the elementary charge defines the magnetic flux quantum *h*/*e*. The well-known *h*/2*e* periodicity is a hallmark for electronic pairing in superconductors and is considered evidence for the existence of Cooper pairs. Does, *vice versa*, the existence of Cooper pairs or the *h/2e* flux quantization necessarily imply the *h/2e* periodicity of the energy or screening current in superconducting loop?

The authors show that, in contrast to this long-held belief, rings of many superconductors bear an *h*/*e* periodicity of the total energy and total screening current. These superconductors include the high-temperature superconductor Sr_2RuO_4, the heavy-fermion superconductors, as well as all other unconventional superconductors with nodes (zeros) in the energy gap, and conventional *s*-wave superconductors with small gaps.

The authors argue that the BCS (Bardeen–Cooper–Schrieffer) theory of superconductivity implies that for loops of such superconductors the ground-state energies and consequently also the supercurrents are generically *h*/*e* periodic. A numerically calculated example for a mesoscopic square loop is shown in Figure 1. The abscissa is in units of *h/e*. The ordinates for energy and current are in arbitrary units. At any temperature, including $T = 0$, the condensation energies, the screening current densities, the kinetic inductances and the penetration depths of rings of nodal superconductors are *h*/*e* periodic, the relative intensity of the *h*/*e* Fourier component decreasing with 1/*d*. The same properties are predicted for loops of *s*-wave superconductors with small gaps such as rings with diameters smaller than ξ, the coherence length. A possible experimental test would be an Al ring with diameter $d < \xi = 1.6$ μm.

Complicated real-space distributions of the probability density (function of state) $|\Psi|^2$ lead to complicated current distributions, with local currents flowing opposite to the main screening current. Such magnetic-flux-induced local currents affect many properties of unconventional superconductors. Of particular importance are a resulting enhancement of the London penetration depth and a weakening of the radio frequency shielding.

According to the authors, their predictions are strict, free of fitting parameters and are therefore open to stringent experimental tests. The *h*/*e* periodicity of the supercurrent is a fundamental property of loops formed by unconventional superconductors. The flux quanta penetrating the ring remain *h*/2*e*, but their kinetic energy is different.

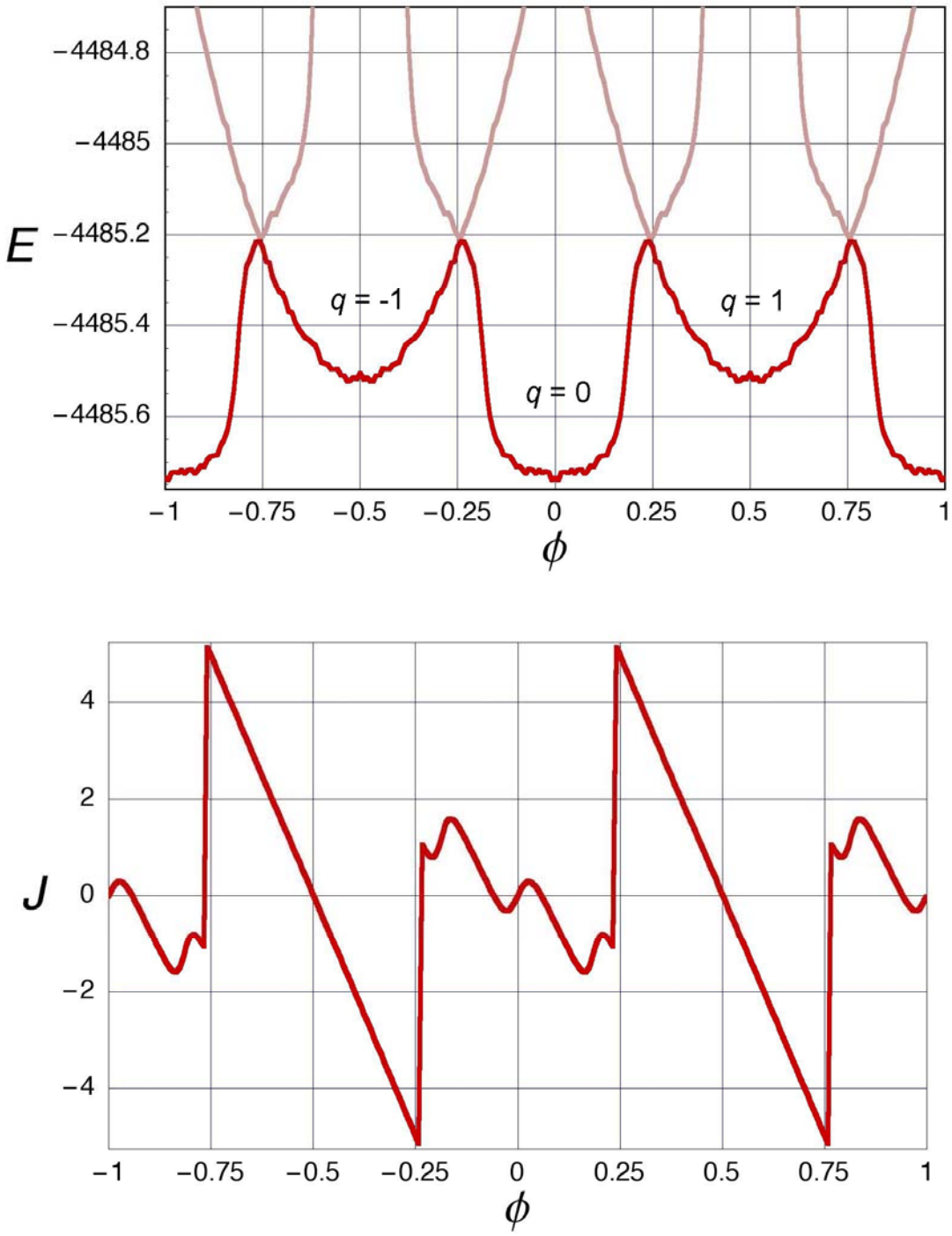

Fig. 1. Calculated flux dependence of total energy *E* and total circulating current *J*.

[1] F. Loder, A.P. Kampf, T. Kopp, J. Mannhart, C.W. Schneider and Y.S. Barash, *Nature Physics* **4**, 112-115 (2008).