On the coexistence of Landau levels and superconductivity

Pacholski, M.J.

Summary

Landau levels are quantum states originating from the periodic cyclotron motion of charged particles, in particular electrons, in the magnetic field. They occur in a multitude of materials, leading to phenomena such as the quantum Hall effect in two-dimensional systems, and the chiral magnetic effect in Weyl semimetals. These effects are of interest, as they constitute a manifestation of topology in condensed matter systems.

Some thirty years ago, the physicists Anderson, Schrieffer and Gor'kov proposed that Landau levels could appear in superconductors, in particular in the high-temperature superconductors. A superconductor tries to expel the magnetic field (the so-called Meissner effect), but in high-temperature superconductors the field can still penetrate in the form of vortices. This proposal led nowhere, because it was soon understood that the vortices will strongly scatter the electrons, thereby fully destroying the Landau levels.

The main contribution of this thesis is the discovery that the Landau levels do remain stable if the charged particles have a so-called chiral symmetry. The chiral symmetry protects the Landau levels from the scattering by vortices. Because the protection is a consequence of a mathematical theorem in topology (the Atiyah-Singer index theorem), one speaks of a topological protection.

We investigate two types of particles with chiral symmetry, which appear in a Weyl superconductor (chapter 2) and in a Fu-Kane superconductor (chapter 5). In both systems these are massless particles, in the Weyl superconductor they move in three dimensions, in the Fu-Kane superconductor in two dimensions (on the surface of a topological insulator).

The presence of Landau levels gives rise to superconducting counterparts of the quantum Hall effect and the chiral magnetic effect, as we describe in chapters 3 and 4. An unexpected finding is the appearance of an electrical current parallel to the magnetic field, with a quantized magnitude. This current exists in the absence of any electric field, it is purely an equilibrium effect. All of this is marked contrast with the known chiral magnetic effect, which only exists out of equilibrium.

Chapter 6 diverges from the topics discussed above, by solving a more technical problem: the computer simulation of massless particles (Dirac fermions) on a lattice. We develop a method to avoid the well known fermion doubling problem (the problem that the discretization of a differential equation on a lattice causes a doubling of the massless particles). This method makes it possible to simulate on a computer the massless particles studied in the other chapters of the thesis.