Foreword

The enigmatic problem of *"perpetuum mobile"* has attracted a lot of attention over the years, starting already in the Middle Ages. Indeed, *perpetual* motion implies a lack of energy dissipation which is a very unusual situation in science. Two key cases of nondissipating motion on a macroscopic scale are well known:

- the *flow of electrical current in superconductors* and
- the *propagation of light* (and other electromagnetic waves as well) *in vacuum*.

If a current is induced in a superconducting ring that is meters or kilometers in size, it circulates there forever. When we enjoy the romantic glimmer of a distant star in the night, the light from it has arrived after traveling for billions of years, a nice experimental proof of dissipation-free propagation. An important difference here is that the first system deals with current in *condensed matter,* the second one with the propagation of electromagnetic fields in *vacuum*. In the first case, the energy dissipation is forbidden by the existence of the coherent *quantum* state of the condensate of the charged Cooper pairs carrying the current, while in the second case there is not too much to interact with for the light propagating in vacuum, as prescribed by the *classical* Maxwell's equations.

Whereas propagating light interacts with matter or gravitational waves and represents the basis for optical devices and experiments, the *frictionless flow of supercurrent* interferes with *nanosize objects* in the superconductor such as tunnel barriers, surfaces, interfaces, or the so-called *fluxons* or *vortices*, quantized magnetic flux of extremely small magnitude $\Phi_0 = h/2e \approx 2.06 \times 10^{-15}$ Wb, that are induced by an applied current, a magnetic field, or thermal fluctuations. On the one hand, an appropriate nanotechnology is required to master *fluxon behavior* – for instance through designing appropriate pinning potentials to localize the fluxons (vortices) – and retain the frictionless supercurrent that is necessary for a number of superconducting applications. This forms one of the main objectives of *fluxonics*. On the other hand, it offers a wide range of options for improved or even novel fluxonic concepts, especially since the necessary tools for "nanoengineering" superconducting materials are readily available nowadays.

Generally, the superconducting condensate is described by the "order parameter" that obeys the Ginzburg–Landau (GL) equations (*Nobel Prize in Physics, 2003*). The boundary conditions for these, strongly influencing the solutions, are imposed at the physical sample boundaries, thus implying that the properties of confined fluxons can be tailored by applying specific surface configurations. This creates a unique opportunity for the *"quantum design" of the physical properties of the confined condensates and fluxons* through the application of specially defined nanomodulated boundary conditions, which can be additionally tuned using, for instance, magnetic templates, electrical fields, or even optical signals. The imposed nanomodulation can therefore lead to the practical implementation of the confined fluxon patterns possessing the specific properties needed for applications in fluxonics ranging from passive and active elements to qubits for quantum computing.

It is the intention of this book to highlight and discuss the state-of-the-art and recent progress in this field, as well as to highlight current problems with “Superconductors at the Nanoscale”. This includes:

– the visualization and understanding of fluxons (vortices) and their interaction on the nanoscale, in nanostructured superconductors, as well as in novel types of superconductors;
– progress in controlling *static* fluxon configurations as well as the *dynamic* properties (up to THz frequencies) of fluxons in nanoscale superconductors;
– the behavior of different types of fluxons (Abrikosov vortices, kinematic vortices, and Josephson vortices) in mesoscopic, nanostructured, and/or layered superconductors;
– the impact of the combination of superconductors with other materials, like ferromagnetic layers, on the nanoscale, and;
– progress in nanoscale superconducting electronics such as SQUIDs, THz emitters, or photonic detectors.

For a better general understanding, the topic of superconductivity is introduced in an extended Tutorial that provides a brief history and a scientific overview of the physics of superconductivity.

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