Interaction of Vortices with Elastic Deformations

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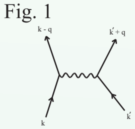
Abstract

When a superconductor is subjected to a magnetic field which is in excess of some critical value, the magnetic flux penetrates the bulk of the material in a form of quantized filaments called vortices. The vortices arrange themselves in a periodic lattice - flux lattice. In the presence of dynamical elastic deformations the ions of the crystal lattice induce electromagnetic fields. Consequently, the flux lattice moves in response to the electromagnetic forces which gives rise to various exciting effects. This poster presents some new effects arising from the interaction of quantized flux with elastic deformations, namely, ignition of a vortex by ultrasound, the possibility of detecting high mechanical stress due to moving dislocations, and decoherence of flux qubits by phonons.

The Phenomenon of Superconductivity

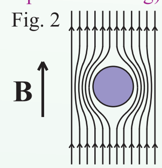
Superconductivity is an electronic state that allows electrons to flow without any resistance. This phenomenon is a consequence of attractive interaction among electrons at the Fermi surface that is mediated by quantized elastic deformations called phonons. Fig.1 shows a typical scattering process of two electrons by exchanging a phonon. The electrons pair up into Bosons called cooper pairs and undergo condensation at the Fermi level.

Fig. 1



Another feature of superconductivity is the Meissner effect first discovered by Meissner and Ochsenfeld in 1933. They found that a magnetic field that initially threads through the normal (non-superconducting) sample is expelled, Fig. 2, when the material underwent a transition into the superconducting state. This transition occurs below a critical temperature T_c.

Fig. 2



In some superconductors the magnetic field penetrates the material in the form of quantized vortices. These objects resemble little tornados with the superconducting electrons flowing around a normal core. The vortices form a lattice shown in Fig. 3. Each vortex carries a unit magnetic flux e/hc. Superconductors with this property are called type-II superconductors.

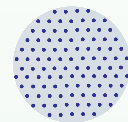
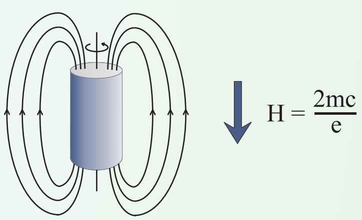


Fig. 3

Ignition of a Vortex by Ultrasound

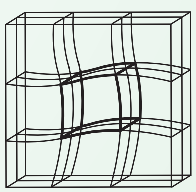
In a rotating reference frame the action of a rotation is equivalent to a magnetic field H = (2mc/e) where is the angular velocity. Thus, a rotating superconductor develops Meissner currents that expel the magnetic flux. In a laboratory frame these currents produce a magnetic dipole, see Fig 4.

Fig. 4



A vortex will enter a superconductor only if the magnetic field exceeds a critical value H_{c1} . For a mechanical rotation this would correspond to an angular velocity of 10^9Hz which is beyond experimental possibility. However, ultrasound can produce a local rotation of the crystal field at a frequency up to 10GHz. Fig. 5 illustrates the local rotation of a crystal cell. Therefore, locally the effective magnetic field can exceed H_{c1} which then ignites a vortex. As the direction of rotation oscillates back and forth, the vortex will enter and exit the superconductor with a frequency of the ultrasound.

Fig. 5



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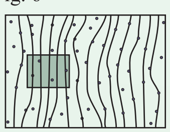
Depinning of Flux by Moving Dislocations

Every realistic solid contains defects. These include point defects, such as vacancies and interstitial atoms, and extended defects, namely dislocations. When a vortex lattice is formed in a superconductor the flux lines become distorted by point defects as shown in the Fig. 6. Within a certain volume, however, the flux lattice will preserve its order. This volume is called a vortex bundle and is represented by the shaded area in Fig. 6. Sending a transport electric current J through the sample can depin the flux lattice due to a transverse force

Fig. 6



$$\mathbf{F} \;\; \frac{1}{c}\mathbf{J}\times\mathbf{B}$$

Dislocations can also act as sources of pinning if their orientation is parallel to the flux lines. A screw dislocation is drawn in Fig 7. The shift in the atomic plain creates a spiral path along the z-direction as one moves in a closed path around the dislocation center. A moving dislocation induces a pattern of electric current, Fig 8. This current produces a transverse force on the vortices which results in depinning and motion of the flux lattice. A moving flux can be detected by measuring the voltage across the superconductor. Since fast moving dislocations are the main cause of material fractures the above scenario can be used as a sensor of mechanical stress.

Fig. 7

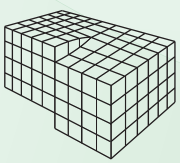
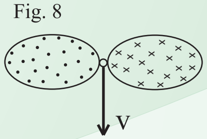


Fig. 8



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Decoherence of Flux Qubits by Thermal Phonons

Flux qubits are macroscopic superconducting devices that can be prepared in a quantum superposition state. Because of their large size they are becoming strong candidates for quantum bits - qubits. A flux qubit consists of a superconducting electrode interrupter by two insulating barriers. Fig. 9 shows two classical states of current flow, clockwise (cw) and counterclockwise, respectively. The arrow indicates the direction of the dipole magnetic filed generated by the current in the loop. Due to quantum interference of the cw and ccw directions the flux qubit is equivalent to a particle in a double-well potential. Putting the flux qubit into a superposition of the ground and first excited states causes an oscillation in the direction of the current flow. If a flux qubit in this state were placed on a solid surface it would produce quantized elastic twists (phonons) as shown in Fig. 10. Consequently the superposition state degrades and is projected into the ground state. This process, called decoherence, poses the greatest challenge in the construction of the quantum computer. Fig. 11 shows some typical particle-phonon processes. The firs two correspond to a single transition while the last one is called a Ramman process in which a phonon is scattered by the particle.

Fig. 9

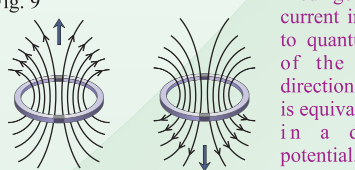


Fig. 10

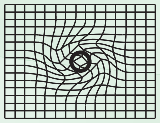
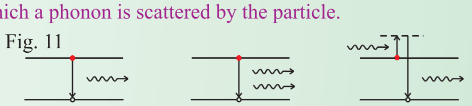


Fig. 11



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