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Controlling vortex motion and vortex kinetic friction

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Abstract

We summarize some recent results of vortex motion control and vortex kinetic friction. (1) We describe a device [J.E. Villegas, S. Savel'ev, F. Nori, E.M. Gonzalez, J.V. Anguita, R. Garcìa, J.L. Vicent, Science 302 (2003) 1188] that can easily control the motion of flux quanta in a Niobium superconducting film on an array of nanoscale triangular magnets. Even though the input ac current has zero average, the resulting net motion of the vortices can be directed along either one direction, the opposite direction, or producing zero net motion. We also consider layered strongly anisotropic superconductors, with *no* fixed spatial asymmetry, and show [S. Savel'ev, F. Nori, Nature Materials 1 (2002) 179] how, with asymmetric drives, the ac motion of Josephson and/or pancake vortices can provide a net dc vortex current. (2) In analogy with the standard macroscopic friction, we present [A. Maeda, Y. Inoue, H. Kitano, S. Savel'ev, S. Okayasu, I. Tsukada, F. Nori , Phys. Rev. Lett. 94 (2005) 077001] a comparative study of the friction force felt by vortices in superconductors and charge density waves.

Keywords: Vortex dynamics; Vortex ratchets; Spatial and temporal asymmetry; Friction

Here we summarize some recent results [1–3] obtained for vortices in superconductors and charge density waves.

1. Superconducting reversible diode that controls the motion of flux quanta

Co-authors: J.E. Villegas, E.M. Gonzalez, J.V. Anguita, R. Garcia, J.L. Vicent

We describe [1] a device that can easily control the motion of flux quanta in a Niobium (Nb) superconducting film grown on an array of nanoscale triangular pinning potentials (Fig. 1). Even though the input ac current has zero average, the resulting net motion of the vortices can be directed *along either one direction, the opposite direction, or producing zero net motion*. This controllable vortex diode effect is due to the asymmetry of the fabricated magnetic pinning centers, producing a net dc motion in one direction. The remarkable *reversal in the direction of the rectified current* is due to the *interaction* between the vortices trapped on the magnetic nanostructures and the interstitial vortices (Fig. 1). The applied magnetic field and input current strength can tune both the polarity and magnitude of the rectified current. All the observed features are explained and modeled theoretically [1,4,5] considering the interactions between particles (Fig. 2). This is the first fabricated ratchet system showing strong effects due to the *correlated motion of the interacting particles*, responsible for its current inversion.

Other recent novel ways to control vortex motion are described in [6–8].

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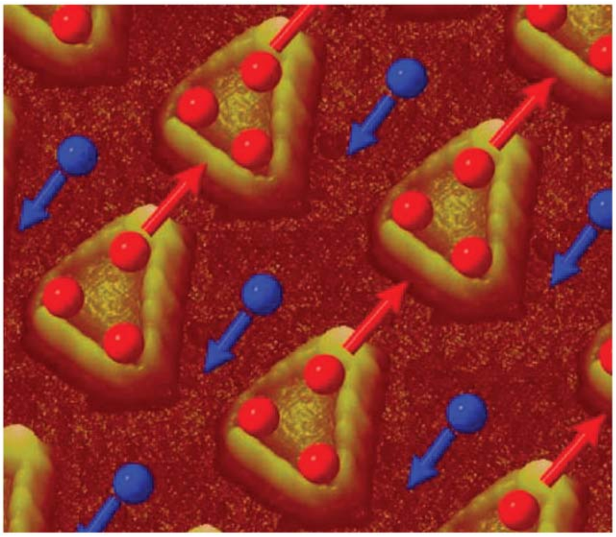

Fig. 1. Schematics of the vortex motion in a Niobium film on nano-scale-magnetic triangles [1].

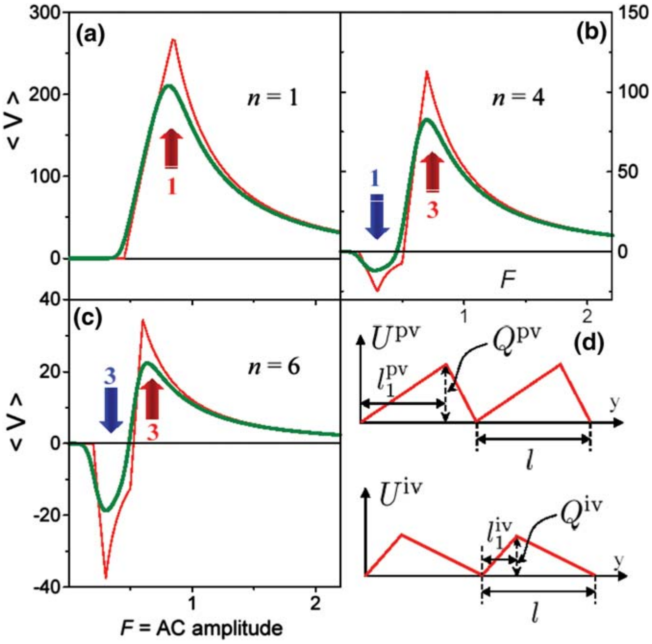

Fig. 2. (a)–(c) The calculated net dc velocity $\langle V \rangle$ versus AC amplitude F, obtained for different effective asymmetry values, using a simple model describing the mixture of pinned (pv) and interstitial (iv) vortices. Red curves are for $T = 0$ and green curves for finite T. The pinned vortices move on the asymmetric potential $U^{pv}(y)$ shown in (d top), while the interstitial vortices feel the potential $U^{iv}(y)$ shown in (d bottom). The latter potential is weaker, inverted, and originates from the interaction of the interstitial vortices with the pinned vortices [1]. (For interpretation of the references in colour in the figure legends 2 and 3 the reader is referred to the web version of this article.)

2. Experimentally realizable devices for controlling the motion of magnetic flux quanta in anisotropic superconductors

Co-authors: D. Cole, S.J. Bending, A. Grigorenko, T. Tamegai

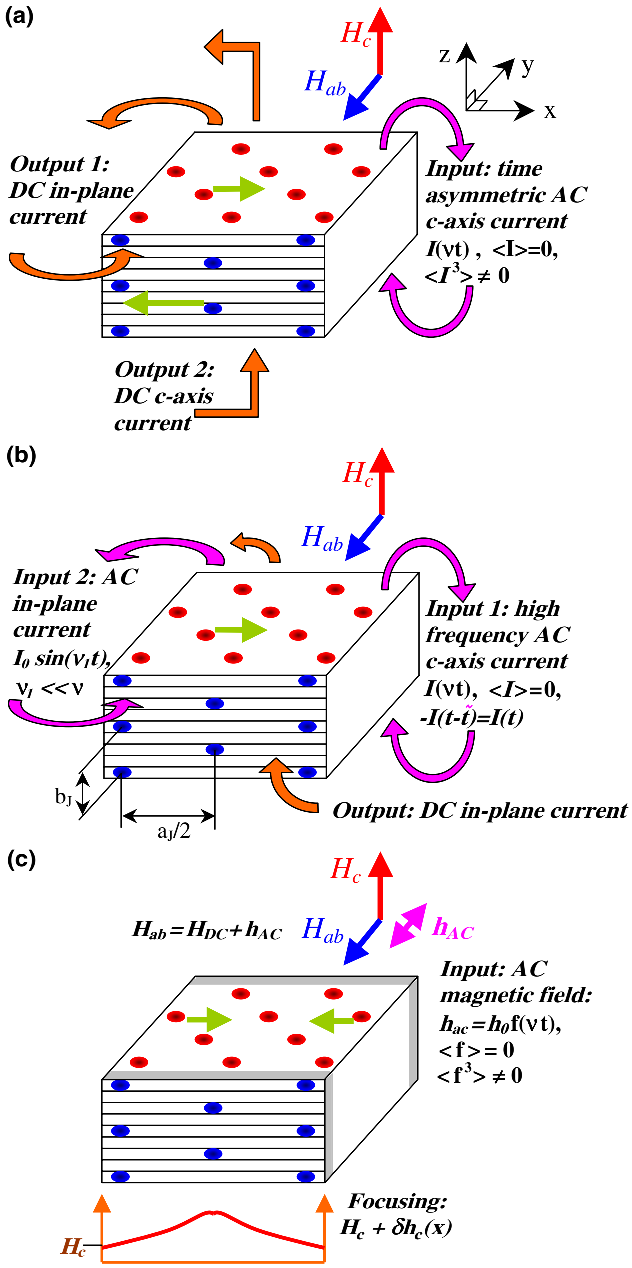

Fig. 3. Schematic diagram of three experimentally-realizable devices [2] designed for controlling the vortex motion. These use extremely anisotropic superconductors, like Bi2212, placed in magnetic fields tilted away from the c-axis, where there are two vortex subsystems consisting of PV stacks, indicated by red circles, and JVs, shown in blue. The vortex pump in (a) transforms the input time-asymmetric AC current flowing along the c-axis into in-plane and out-of-plane DC vortex currents marked by dashed green lines. The degree of temporal asymmetry of the zero-averaged $\langle I(t) \rangle = 0$ input current $I(t)$ can be quantified by its third moment $\langle I^3(t) \rangle \neq 0$. The vortex diode in (b) rectifies the applied in-plane current using the time-averaged spatially-asymmetric effective potential generated by the high-frequency oscillating JVs. The vortex lens in (c) employs an applied time-asymmetric AC magnetic field to either increase or decrease the vortex density at the center of the sample. The two irradiated edge regions with enhanced pinning, shown in gray, prevent sideways leakage of PVs.

A new generation of microscopic ratchet systems are currently being developed for controlling the motion of electrons and fluxons, as well as for particle separation, electrophoresis, and surface modification in materials. Virtually all of these use spatially-asymmetric potential energies in order to control its transport properties. We propose [2] completely new types of ratchet-like systems that *do not require spatially asymmetric potentials* in the samples. As specific examples of this new general class of ratchets, we propose devices that control the motion of flux quanta in superconductors and could address a central problem in many superconducting devices, including qubits; namely, the removal of trapped magnetic flux that produces noise.

In extremely anisotropic layered superconductors placed in a tilted magnetic field, there are two interpenetrating vortex lattices consisting of Josephson vortices (JVs), aligned parallel to the CuO_2 planes, and pancake vortices (PVs), oriented perpendicular to those planes.

We show that, due to the JV–PV mutual interaction and asymmetric driving, the AC motion of JVs and/or PVs can provide a net DC vortex current. This controllable vortex motion can be used for vortex pumps, diodes and lenses (Fig. 3). These proposed devices sculpt the microscopic magnetic flux profile by simply modifying the time dependence of the AC drive, *without* the need of samples with static pinning. Recently, the predicted lensing effect [2] has been experimentally observed [9].

3. Nano-scale friction: kinetic friction of magnetic flux quanta and charge density waves

Co-authors: A. Maeda, Y. Inoue, H. Kitano, S. Okayasu, I. Tsukada

When a massive block slides on a rough surface, the resistive force opposing its motion has two components: one (kinetic friction F_k) from the substrate and an additional (hydrodynamical) viscous force due to the surrounding fluid. Similarly, when tiny magnetic and electrical quanta move inside solids, they also experience a resistive force from both the underlying substrate impurities F_k and the surrounding medium.

In analogy with the standard macroscopic friction, here we briefly summarize a comparative study [3] of the friction force felt by moving magnetic flux quanta (vortices) in superconductors and charge density waves. Using experiments and a model for this data [3], our observations:

1. provide a link between friction at the micro- and macroscopic scales (Table 1);
2. explain the sharpness (roundness) of the static–kinetic friction transition in terms of system sizes (critical-phenomena view) and thermal fluctuations;
3. explains the crossing of the kinetic friction F_k versus velocity V for our pristine (high density of very weak defects) and our irradiated samples (with lower density of deeper pinning defects);
4. extend friction concepts to the realm of driven quasiparticles in solids, including both moving magnetic and electric quanta.

3.1. Duality between the Electric and Magnetic driven lattices

Note that these two examples (magnetic and electric collective transport) are dual to each other. Thus, the equations for kinetic friction for moving vortices or CDWs are the same, after replacing the current density j by the electric field E, and the resistivity ρ by the conductivity. The mapping becomes:

Table 1
Comparison between mechanical friction, friction for vortices in superconductors (SC), and charge density waves (CDW)

System	Mechanical friction	Vortex lattice in SC	Charge density waves
Movable objects	Blocks, films, etc.	Vortices (magnetic quanta)	Electrons (electric quanta)
Driving force	Mechanical force F_d	Lorentz force $\propto j$	Electric force $\propto E$
Static resistance	Static friction F_s	Pinning ($F_{pinning}$)	Pinning ($F_{pinning}$)
Static friction F_s due to	Surface roughness, molecular forces, etc.	Defects, impurities, disorder	Impurities, commensurability of CDW with ions
Critical parameter max (F_s)	Maximum static friction F_s^{max}	Critical current density j_c	Depinning electric field E_T
Dynamic resistance due to substrate	Kinetic friction F_k	Kinetic friction F_k (slow down due to pinning)	Interaction with impurities
Dynamical events	Stick-slip motion	Flux bundle motion	Current (sliding CDW)
Hydrodynamic resistance (due to surrounding "fluid")	Viscosity η, ($P_{dissipated} = \eta V^2$)	Dissipative flux flow $\propto \rho$, ($P_{dissipated} = \rho j^2$)	Dissipative sliding CDW; viscosity $\propto \sigma_{CDW}$, ($P_{dissipated} = \sigma_{CDW} E^2$)
Inertial term	Important	Negligible	Important at high ω
Thermal fluctuations	Not important	Important	Important
History dependence	Yes	Yes	Yes
Elastic theory	Elastic mechanics	Larkin–Ovchinnikov approach	Fukuyama-Lee-Rice approach

If a driven block slides on a rough surface, the resistive force on the block has two components: one due to the interaction with the substrate (standard kinetic friction F_k) and an additional (hydrodynamic) resistance if the driven block is submerged in a fluid (e.g., molasses). Similarly to a massive sliding block driven in molasses, when a vortex moves inside a superconductor, it experiences a resistive force because of the surrounding superfluid interacting with the vortex core. This dissipative flux flow exists even when the sample has zero pinning impurities. This is the reason why this component must be subtracted from the measured resistive force: to obtain the kinetic friction F_k due to the interaction between the vortex and the pinning "substrate". Thus, pinning adds additional friction (denoted here by F_k) to moving vortices. Here, $P_{dissipated}$ is the power (energy/time) dissipated during motion, and ω is the driving frequency.

$$[\text{driving force} \leftrightarrow j \leftrightarrow E], \text{ and}$$
$$[\text{viscous dissipation} \leftrightarrow \rho \leftrightarrow \sigma] \text{ for}$$
$$[\text{mechanical} \leftrightarrow \text{magnetic} \leftrightarrow \text{electric}]$$

driven transport. Therefore, *V–I* curves for superconductors map into *I–V* curves for CDW transport. A more detailed comparison between these driven (mechanical, magnetic and electric) systems is found in Table 1 and in [3].

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