Photon-Assisted Vortex Depairing in Two-Dimensional Superconductors

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We propose a novel quantum detection mechanism for photon absorption in a two-dimensional superconductor that exhibits a vortex-unbinding transition. Well below the transition, absorption of a single photon of energy hf can result in the creation of a vortex-antivortex pair, which can be broken apart in an applied current, thus transferring a single flux quantum Φ_0 across the film. This results in a quantum-limited voltage responsivity $\Phi_0/hf=1/2ef$, and may account for some reports of enhanced non-bolometric detection of infrared radiation in thin granular superconducting films.

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In recent years, there has been a series of observations of anomalously large responses to infrared radiation in thin granular superconducting films.[1-6] Although superconducting tunnel junctions are well known to provide excellent quantum-limited photodetection, the mechanism of detection in these granular films has remained somewhat elusive. Qualitative ideas of vortex flow have been mentioned as possible explanations,[5,6] but a more quantitative theory has been lacking. We propose that some of these observations may follow from the novel properties of two-dimensional (2D) superconductors.[7-11]

The key to understanding the transport properties of a 2D superconductor lies in the vortices, each with quantized flux Φ_0, that can be present even in the absence of an external magnetic field. A 2D superconductor can consist of a homogeneous film of thickness $d \lesssim \xi$ (the Ginzburg-Landau coherence length), in which the vortices are the usual Abrikosov vortices with a "normal core" $\approx \xi$ in radius. Alternatively, a 2D Josephson-coupled array,[11] either a regular array of junctions or a more random granular assembly, can exhibit similar behavior associated with intergranular Josephson vortices. In this case, there is no vortex core as such, but the corresponding length scale is the characteristic grain size (or lattice spacing) a_0.

In either case, a vortex with a given polarity is attracted to an antivortex (i.e., one with the opposite helicity) with an energy that is essentially logarithmic with distance[9] (neglecting renormalization effects[10]):

$$U(r) \approx 2\pi K_0 \ln(r/a_0), \quad \text{for } a_0 \ll r \ll \Lambda . \tag{1}$$

Here a_0 is the effective vortex-core scaling length, and the transverse penetration depth $\Lambda=\lambda^2/d$ can be substantially greater in a thin film or granular array than the bulk magnetic penetration depth λ. In addition, for small distances there is a core energy[10] which is of order the prefactor $2\pi K_0$. This prefactor, which sets the scale for the vortex energy, can be expressed as[7-11]

$$2\pi K_0 = \Phi_0^2 d/2\pi\mu_0\lambda^2 = \Phi_0 d a_0 J_0 , \tag{2}$$

where $J_0 = n_s e\hbar/2ma_0$ is essentially the mean-field critical current density. For a homogeneous superconductor, $2\pi K_0 \approx 4\pi\mu_0 H_c^2 \xi^2 d$, which is the condensation energy $\mu_0 H_c^2/2$ over a volume of order $\xi^2 d$.

Just below the mean-field critical temperature T_{c0} of a 2D superconductor, these vortex pairs are common equilibrium excitations. In fact, they are so common that they overlap each other and act to screen the attractive intervortex force, leading to the presence of vortices that are effectively free. Since current-driven motion of these vortices is dissipative, the superconductor is actually resistive in this regime. As the temperature is lowered further and more vortex pairs freeze out, there is a second critical temperature $T_c \approx 2\pi K_0/4k_B$, the Kosterlitz-Thouless phase transition, below which the vortices are effectively bound and the resistance goes to zero.[10] Even then, the vortex pairs can be torn apart by application of a large enough transport current J, which reduces the depairing distance to a value $r_c \approx (J_0/J)a_0$ and lowers the depairing energy to a value[10]

$$U_0(J) \approx 2\pi K_0 \ln(J_0/J) . \tag{3}$$

Via a thermally activated vortex-escape process, this yields a nonlinear resistance of the form[10]

$$R(I) \propto \exp[U_0(J)/2k_B T] \approx (J/J_0)^{(\pi K_0/k_B T)} . \tag{4}$$

These power-law I-V curves, which have been observed experimentally in a variety of 2D superconductors,[9,10] provide a direct indication of the presence of the logarithmic vortex-pair interaction.

We propose that a single photon of energy hf can supply this vortex-depairing energy, producing a pair of free vortices, which can then be swept to the sides of the film by the transport current. This will produce a collected

TABLE I. Corresponding quantities for photodetectors.

	e-h pair	Vortex pair
Carriers	$\pm e$	$\pm \Phi_0$
Measured quantity	Current pulse e	Voltage pulse Φ_0
Quantum responsivity	$R_i = e/hf$ [A/W]	$R_v = \Phi_0/hf$ [V/W]
Pair-breaking threshold	$V = 2\Delta/e$	$I = I_c$
Photon-assisted step	$\Delta V = hf/e$	$\Delta I_{\text{core}} = hf/\Phi_0$ [a]

[a]This will be somewhat less for the thermally mediated process, and further reduced for a granular superconductor.

flux Φ_0, or equivalently an integrated voltage pulse, leading to a time-average voltage responsivity R_v for a flux of N photons per second given by

$$R_v = V/P = N\Phi_0/Nhf = \Phi_0/hf = 1/2ef\,. \qquad (5)$$

This process is analogous to photoproduction of an electron-hole pair in a semiconductor. In fact, it is more than an analogy; it reflects a formal duality between electricity and magnetism in 2D.[12] This duality has been noted by other researchers—the theory of vortices in 2D superconductors (and superfluids) can be formally mapped onto the 2D Coulomb gas,[8] for example, and dual relations are well known in circuit theory.[13] If one exchanges current with voltage and charge with flux, Eq. (5) is transformed into the standard expression for quantum-limited current responsivity $R_i = e/hf$ in a photoconductor. This is also the limiting responsivity in a superconducting tunnel junction [superconductor-insulator-superconductor (SIS)] biased near the gap voltage $2\Delta/e$.[14] Some of the corresponding quantities in the two dual detection modes are listed in Table I.

We will assume initially that all of the photon energy hf goes into unbinding the vortex pair. Then if J is close to J_0 we have

$$hf \approx 2\pi K_0(1 - J/J_0) = \Phi_0 d a_0 (J_0 - J) = \Phi_0 \Delta I_{\text{core}}\,, \qquad (6)$$

where $I_{\text{core}} = J d a_0$ is the current that flows through the superconductor on the scale of the vortex core. This can also be written in terms of the total current $I = Jwd$ through a film of width w as

$$\Delta I = (J_0 - J) dw \approx (hf/\Phi_0) w/a_0\,, \qquad (7)$$

where ΔI is the total additional current that would be needed to produce the vortex-antivortex pair in the absence of the photon. This yields a photon-assisted current step in the I-V curves, as is indicated schematically in Fig. 1(a), which is analogously dual to the photon-assisted voltage step[14] that occurs in the SIS tunnel junction via a photoconductive mechanism [Fig. 1(b)].

The remaining critical issue in this picture is the microscopic mechanism of photon absorption and vortex-pair creation. We suggest that there are two distinct regimes for vortex-pair creation. First, for frequencies below the energy gap in the superconductor, direct absorption by breaking of Cooper pairs is suppressed, and direct quantum absorption to produce a vortex pair should be possible. For frequencies large compared to the gap, however, it is unlikely that a superconducting vortex pair is an available direct excitation, and in any case direct Cooper-pair breaking is likely to dominate. Even so, we suggest that vortex-pair creation may still be the final result.

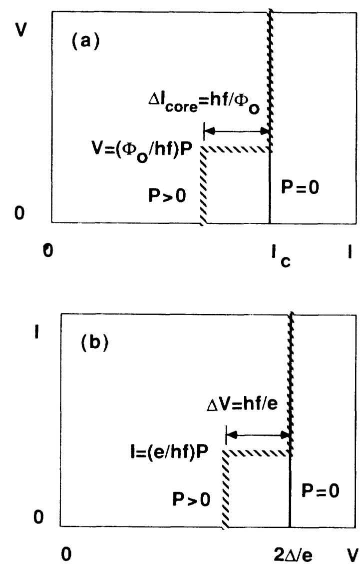

FIG. 1. Sketch of ideal I-V curves for photodetection by (a) a 2D superconductor and (b) a superconducting tunnel junction. Note that I and V are reversed in (a) and (b). The solid lines are for no incident radiation; the dashed lines are for a time-averaged power P of photons with quantum energy hf.

Consider a photon which is absorbed at a spot in a 2D superconductor, producing nonequilibrium local heating of the electrons. This will act to reduce the local value of the energy gap and the critical current on the scale of a_0, and if the critical current density is lowered to below J, this will create a gap instability, driving the local energy gap to zero. The local current will then be forced to divert around that spot, creating a current configuration similar to that in Fig. 2(a). This configuration, in turn, is similar to the net flow in Fig. 2(b), consisting of a closely spaced vortex-antivortex pair, oriented properly in the presence of the transport current for separation by the transverse Lorentz force. Therefore, we suggest that photon-induced local heating will act to nucleate such a vortex pair.

This thermally mediated process will not be 100% efficient at coupling thermal energy into vortex energy, since some of the heat energy is likely to be simply dissipated. However, a rough calculation indicates that for a homogeneous superconductor, assuming that the energy goes into heating the electrons on the scale of the coherence length ξ, this thermal energy is comparable in magnitude to the vortex nucleation energy in Eq. (6). This is

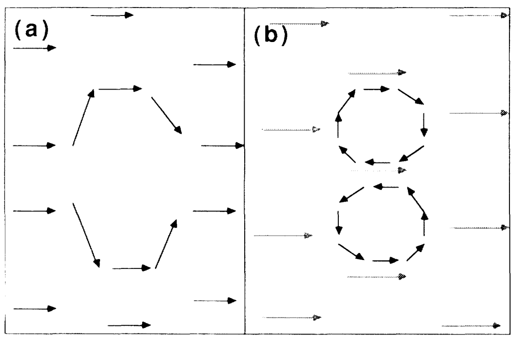

FIG. 2. Schematic distribution of supercurrent flow in a 2D superconductor. (a) Current diverting around the region with depressed superconductivity on the scale of the vortex-core size a_0, which might be induced by an incident photon. (b) Closely spaced vortex pair oriented properly in near-critical applied current for vortex separation. Note that the total current distribution in (b) approximates that in (a).

consistent with the observation that just below T_c, most of the electronic heat capacity of a superconductor is associated with the condensate. Hence, even for the thermally mediated case, ΔI_{core} should be of order hf/Φ_0. For a granular superconductor, ΔI_{core} will be further reduced, approximately by the same amount that J_c is depressed below that of the homogeneous superconductor.

Although we have been focusing on the 2D case, this picture can be extended directly to the 1D and 3D cases, with important implications. In the 1D limit, vortex-pair creation reduces to a phase slip in a long 1D superconducting microstrip, with transverse dimensions $\lesssim \xi$.[15] In fact, although there are some differences in detail, the long microstrip is essentially the electrical dual to the superconducting tunnel junction. In the microstrip, there is a current-induced voltage at I_c due to vortex-pair breaking, whereas in the tunnel junction, there is a voltage-induced current at $2\Delta/e$ due to Cooper-pair breaking. Likewise, in the former there should be photon-assisted current steps of width hf/Φ_0, in analogy to the photon-assisted voltage steps of width hf/e in the latter (see Table I). The 0D limit is a short superconducting microbridge or point contact, which should exhibit the same responsivity.

The 3D limit of a vortex pair is a vortex ring, essentially a vortex closing on itself, which should be an important feature in high-temperature superconducting films, given their very short coherence length.[16] For such a material, it will be difficult to prepare a homogeneous film that is truly a 2D superconductor, but the same phenomena should be present in a 3D sample. A vortex ring should nucleate in much the same way as a vortex pair, with a locally depressed value of the critical current, which may be caused by an incoming photon. In analogy to Eq. (6), the energy that must be supplied by the photon in this case is of order $\Phi_0 a_0^2 (J_0 - J)$ for J near J_0. A current parallel to the axis of a vortex ring will exert a Lorentz force that causes it to expand, in the same way that a vortex-antivortex pair is pulled apart by a current. Ultimately, this will transfer a single flux quantum across the film, leading to the same responsivity Φ_0/hf.

Finally, we suggest that this quantum voltage responsivity Φ_0/hf is likely to be the greatest that one can obtain in a superconducting film or device biased near the critical current. This is because the current-induced breakdown of superconductivity is always related to some sort of phase-slip or vortex process, for which the flux quantum is the relevant quantity. One might think that if the voltage onset at I_c becomes arbitrarily sharp, then a higher responsivity might be possible, but the analogous quantum limits will apply here as in the SIS tunnel junction case.[14] The only exception would be a case whereby a single photon could lead to the nucleation of multiple vortex pairs or phase slips. This might occur, for example, in the 1D case where a single photon could heat up a spot, leading to several phase slips before the spot cooled down.

There have been many observations over the years of enhanced nonbolometric electromagnetic detection in granular thin-film superconductors, from microwaves all the way through the infrared.[1-6] For example, Fujimaki, Okabe, and Okamura[1] reported voltage responsivities as high as 10^8 V/W for 10-GHz radiation incident on granular Sn, and Enomoto and Murakami[3] observed values of order 10^4 V/W above a 1-μm wavelength, increasing with increasing wavelength, in $BaPb_{0.7}Bi_{0.3}O_3$ films. These results approach the quantum limit Φ_0/hf predicted by this theory. Measurements on granular superconducting films of anodized NbN (Ref. 2), Nb/BN cermets (Ref. 4), and YBa_2Cu_3O (Refs. 5 and 6) have indicated enhanced infrared detection and subgap absorption,[17] as well as evidence for a vortex-unbinding transition.[6] The present model has some rather direct implications for the kinds of superconducting films that should exhibit this effect and the optimum modes of operation, and further analysis will be presented separately, together with new experiments designed to test these specific predictions.[18]

In conclusion, we have outlined a model for photon-assisted vortex depairing in current-biased 2D superconductors. At low energies this is likely to occur by a direct quantum process, while above the gap, the dominant mechanism will involve local thermal suppression of J_c. In either case, there should be a quantum-limited responsivity approaching Φ_0/hf. Throughout this analysis, we have been guided by the duality between current flow and flux flow in 2D, and these associations are summarized in Table I. Natural extensions of this picture to other dimensions predict similar behavior involving phase slips in 1D and vortex rings in 3D. This picture should provide a clearer basis for future measurement and analysis of photodetection in thin superconducting films.

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