Creation of superconducting vortices by angular momentum of light

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We investigate a superconducting state irradiated by a laser beam with spin and orbital angular momentum. It is shown that superconducting vortices are created by the laser beam due to heating effect and transfer of angular momentum of light. Possible experiments to verify our theory are also discussed.

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Interaction of light with condensed matter systems has offered a new approach to control and study them in an ultrafast manner. Various aspects of superconductors under light illumination have been investigated such as response of an Abrikosov vortex [5, 6], superconducting single photon detectors [7, 8], excitation of Higgs modes [9, 10], laser created Josephson junctions [11], manipulation of a vortex [12], and excitation of phonons [13, 14] which are fundamentally and technologically important. Most of the previous works have considered energy transfer of light. One of the consequences is the local increase of electron temperature. This effect is captured by the hot spot model where the temperature varies in space [20, 21]. As a result, the superconductivity can be locally suppressed or destroyed around the hot spot. On the contrary, in this work, we focus on the angular momentum of light.

Light has spin and orbital angular momentum. The spin angular momentum is given by circular polarization. On the other hand, the orbital angular momentum is given by spatial structure of the light: the phase structure of the light is winding and hence the intensity is zero at the center of the beam (along the propagation axis), analogous to superconducting vortices. This type of light is dubbed optical vortices [22, 23]. There have been various demonstrations of orbital angular momentum transfer, e.g., to classical particles [24, 25] or excitons [26]. It also has been demonstrated that spin angular momentum of circularly polarized light can be used to reverse magnetization [27].

Since the relevant length scales of superconductors and optical vortices are the same (\sim 1 \mu m), it can be expected that orbital angular momentum of light can be imprinted on superconductors.

In this paper, we investigate a superconducting state irradiated by a laser beam with spin and orbital angular momentum. It is shown that superconducting vortices are created by the laser beam due to heating effect and transfer of angular momentum of light. Possible experiments to verify our theory are also discussed.

We consider a two dimensional superconductor irradiated by a laser beam with spin and orbital angular momentum as shown in Fig. 1. We assume that photon is completely absorbed by the superconductor without any reflection and transmission of the light. The dynamics of the superconductor can be described by the Ginzburg-Landau theory.

The Ginzburg-Landau free energy of this system reads

\[ F = \int \left\{ \alpha \left[ T(r,t) - T_c \right] |\psi|^2 + \gamma \left( \nabla + \frac{i e}{\hbar} A \right)^2 |\psi|^2 \right\} d^2r, \] (1)

where \( T_c \) is the transition temperature of the superconductor. Due to the heating effect of the laser beam, the temperature \( T \) depends on space and time [20, 21]. The time dependent Ginzburg-Landau (TDGL) equation is given by

\[ \frac{\partial \psi}{\partial t} = \tau(r,t) \psi + (\nabla + iA)^2 \psi \] (2)

with \( \tau(r,t) = \frac{T(r,t) - T_c}{(T_\infty - T_c)} \) and \( T(r,t) = T_\infty + \Delta T(r,t) \). Here, \( T_\infty \) and \( \Delta T(r,t) \) denote the temperature far from the laser beam and the variation of the temperature by the laser beam, respectively. The typical time scale of the TDGL equation is ps. The length is normalized by the superconducting coherence length \( \xi \sim 1 \mu m \). We consider a laser pulse of the form \( A = \frac{2 \pi}{\lambda} \vec{E} \delta(t) \). Here, \( \omega \) is the frequency of the laser beam. With the initial condition \( \psi(r,0) = \psi_\text{b} \) (constant), and neglecting \( A^2 \) term assuming a weak electric field, we then obtain

\[ \frac{\partial \psi}{\partial t} = \tau(r,t) \psi + \nabla^2 \psi + i(\nabla \cdot A) \psi_\text{b}, \] (3)

We expand the order parameter in a Fourier series as

\[ \psi = \sum_n e^{i n \theta} \psi_n(r), \]
We use two types of laser beams: left circularly polarized Gaussian and Bessel beams. The Bessel beam carries orbital angular momentum. First, consider a left circularly polarized Gaussian beam

\[ E = E_0 \exp \left( -\frac{r^2}{2\sigma^2} \right) \left( \begin{array}{c} 1 \\ i \end{array} \right) \]  

(4)

with a constant \( E_0 \) and the radius of the beam \( \sigma \), and \( \Delta T(r, t) = T_b \exp \left( -\frac{r^2}{2\sigma^2} \right) \delta(t) \). The variation of the temperature is assumed to be proportional to the intensity of the beam with a proportionality coefficient \( T_b \). Then, the TDGL equation becomes

\[ \frac{\partial \psi_n}{\partial t} = \tau(r, t) \psi_n + \nabla^2 \psi_n, \quad n \neq 1, \]  

(5)

\[ \frac{\partial \psi_1}{\partial t} = \tau(r, t) \psi_1 + \nabla^2 \psi_1 + \frac{2e E_0 \xi}{\hbar \omega^2 r} \exp \left( -\frac{r^2}{2\sigma^2} \right) \psi_0 \delta(t) \]  

(6)

with \( \nabla^2 = \frac{\partial^2}{\partial r^2} + \frac{1}{r} \frac{\partial}{\partial r} - \frac{n^2}{r^2} \). Therefore, we find \( \psi_n = 0 \) for \( n \neq 0, 1 \).

Next, consider a left circularly polarized Bessel beam of the form

\[ E = E_0 J_m(kr) e^{im\theta} \left( \begin{array}{c} 1 \\ i \end{array} \right) \]  

(7)

and \( \Delta T(r, t) = T_b (J_m(kr))^2 \delta(t) \). Here, \( J_m \) is the Bessel function of the first kind and order \( m \). \( k \) is the wave number of the beam.

The TDGL equation reads

\[ \frac{\partial \psi_n}{\partial t} = \tau(r, t) \psi_n + \nabla^2 \psi_n, \quad n \neq m + 1, \]  

(8)

\[ \frac{\partial \psi_{m+1}}{\partial t} = \tau(r, t) \psi_{m+1} + \nabla^2 \psi_{m+1} + \frac{2e E_0 k}{\hbar \omega} J_{m+1}(kr) \delta(t). \]  

(9)

We see \( \psi_n = 0 \) for \( n \neq 0, m + 1 \).

In the numerical calculation, we set \( \delta(t) \to \frac{1}{2t_0} \Theta(t_0 - |t|) \) with \( t_0 = 10^{-3} \), \( \psi_0 = 1, \) \( T_\infty/T_e = 0.9, \) and \( \frac{2\xi E_0}{\hbar \omega} = 10 \) which corresponds to \( E_0 = 5kV/m, \) \( \omega=0.25\text{THz}, \) and \( \xi=1\mu m \). We also use \( \sigma = 1 \) for the Gaussian beam and \( k = 1, m = 1 \) for the Bessel beam. We have solved the TDGL equations with the boundary condition \( \psi_n(r \to \infty, t) = 0 \) by the Crank-Nicolson method numerically. In the following, the numerical results are shown at \( t = 2t_0 \).

Figure 2 shows the order parameters as a function of \( r \) for various \( T_b \). It is seen that the bulk component \( \psi_0 \) is reduced over the laser width (\( \sigma = 1 \)) as shown in Fig. 2(a). The order parameter with vorticity one \( \psi_1 \) is induced by the laser beam as shown in Fig. 2(b).

Away from the laser beam, this component goes to zero. The TDGL equation for \( \psi_1 \) contains the derivative of the electric field. Thus, \( \psi_1 \) has a peak around the edge of the beam. These components are reduced with the increase

\[ \text{FIG. 2: (Color online) The order parameters as a function of } r \text{ for various } T_b \text{ under the left circularly polarized Gaussian beam.} \quad (a) \psi_0, \quad (b) \psi_1. \]

\[ \text{FIG. 3: (Color online) The order parameters as a function of } r \text{ for various } T_b \text{ under the left circularly polarized Bessel beam.} \quad (a) \psi_0, \quad (b) \psi_2. \]
of $T_b$. Here, we have considered a left circularly polarized beam. For a right circularly polarized beam, the results are identical except for the replacement $\psi_1 \rightarrow \psi_{-1}$.

Figure 3 depicts the order parameters as a function of $r$. It is seen that the bulk component is reduced, reflecting the spatial profile of the Bessel function as seen in Fig. 3 (a). Since $J_1(0) = 0$, $\psi_0$ is not so reduced at the center of the beam $r = 0$. The order parameter with vorticity 2 is induced by the laser beam as shown in Fig. 3 (b). Since $J_1(r)$ is an oscillating function of $r$, these components also oscillate. In particular, $\psi_2$ changes its sign. This is because heating acts on both $\psi_0$ and $\psi_2$ but $\psi_2$ is also affected by $\nabla \cdot \mathbf{A}$ term which changes its sign, as seen from Eq.(9). It is remarkable that these components have ring-shaped spatial profiles. The irradiation of optical vortices makes it possible to create vortices with vorticity more than one, so-called giant vortices. Vortex with vorticity more than one is usually unstable and split into vortices with vorticity one.

As for the generation of the order parameters with vorticity, two mechanisms work: (i) heating breaks superconductivity locally; (ii) angular momentum of light is transferred to the superconductor. These mechanisms play a role analogous to local breakdown of superconductivity by magnetic field and flux quantum trapped in the vortex core.

Now, let us discuss possible experiments to verify our prediction. Since a laser beam can create a superconducting vortex, laser illumination around the center of the superconductor of finite size can create superconducting quantum interference device as shown in Fig. 4 (a). This way, one can measure vorticity or magnetic flux at the vortex transferred from the light. In the mixed phase under the temperature gradient, the vortices experience the force proportional to the temperature gradient. When the vorticities of the vortices have the same (opposite) sign, the interaction between them is repulsive (attractive). Thus, the total force acting on the vortices and hence their velocities approaching the laser spot depend on the angular momentum of light, as shown in Fig. 4 (b), which can be used to check our theory. In particular, vortices with opposite vorticities, i.e., vortices and antivortices, can be pair annihilated. Therefore, it is also possible to eliminate vortices by laser beam, similar to laser-induced demagnetization in magnets. The electric states at the vortex core also reflect vorticity which can be measured by scanning tunneling microscope.

Our results are also applicable to type I superconductors where vortices cannot be generated by magnetic field. Vortices in chiral p-wave superconductors can host Majorana fermions. When our results are applied to chiral p-wave superconductors, Majorana fermions can be controlled by a laser beam.

We have neglected the nonlinear terms with respect to the order parameter and vector potential, which lead to couplings between different components of the order parameter ($\psi_n$). Thus, other components than those considered in this paper are also generated in the presence of the nonlinear terms. However, these components are less dominant.

In summary, we have investigated a superconducting state irradiated by a laser beam with spin and orbital angular momentum. We have shown that superconducting vortices are created by the laser beam due to heating effect and transfer of angular momentum of light. Experimental setups to verify our theory are also discussed.

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