Using abrupt changes in magnetic susceptibility within type-II superconductors to explore global decoherence phenomena

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Abstract

A phenomenon of a periodic staircase of macroscopic jumps in the admitted magnetic field has been observed, as the magnitude of an externally applied magnetic field is smoothly increased or decreased upon a superconducting (SC) loop of type-II niobium–titanium wire that is coated with a non-SC layer of copper. Large temperature spikes were observed to occur simultaneously with the jumps, suggesting brief transitions to the normal state, caused by en masse motions of Abrikosov vortices. An experiment that exploits this phenomenon to explore the global decoherence of a large SC system will be discussed, and preliminary data will be presented. Although further experimentation is required to determine the actual decoherence rate across the SC system, multiple classical processes are ruled out, suggesting that jumps in magnetic flux are fully quantum mechanical processes that may correspond to large group velocities within the global Cooper pair wavefunction.

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(Some figures may appear in color only in the online journal)

1. Instability regions in type-II superconductors

When the magnitude of an externally applied magnetic field incident on a closed loop of a type-II superconductor (such that the field has a non-zero component parallel to the axis of the loop) exceeds the first critical field \(H_{c1}\), Abrikosov vortices of Cooper pair electrons will form, allowing some flux lines to penetrate the sample. When the field is increased with time, the motion of the Abrikosov vortices can give rise to a slight increase in thermal energy and therefore a slight increase in temperature. Since the London penetration depth

\[
\lambda_L(T) = \lambda_L(0)[1 - (T/T_c)^4]^{-1/2},
\]

where \(T\) is the sample temperature and \(T_c\) the superconducting (SC) critical temperature, increases with the positive change in temperature, lines of magnetic flux from the applied field push further into the sample. In addition, the critical current density

\[
j_c(T) = j_c(0)(1 - T/T_c)
\]

decreases, an effect that creates an electric field via the London equation

\[
E = \frac{\partial}{\partial t}(\Lambda j).
\]

This electric field can lead to another temperature increase, and the process will repeat in a cascading effect until the magnetic flux line densities in the two regions are such that

\[
B_{out} = B_{in} + \mu_0 H_{c1},
\]
where $B_{\text{out}}$ is the field magnitude just outside of the loop, and $B_{\text{in}}$ is the field magnitude inside the loop. This process, which restores the condition given in (4), is henceforth referred to as a ‘flux jump’. The increase in temperature that accompanies a flux jump drives the sample, or part of the sample, to a normal state in most cases [1], resulting in the collapse of the global Cooper pair wavefunction state that spanned the entire SC electron gas before the flux jump occurred. While the flux jumps are thermal effects that are not discontinuous, the rate of increase of the magnetic induction inside the loop during a flux jump will be assumed throughout this paper to satisfy

$$B_{\text{in}}(t) \gg B_{\text{out}}(t),$$

where $\dot{B}$ is the ramping rate of the externally applied field.

Due to the phenomenon of ‘flux creep’, in which lines of magnetic flux pass, via Abrikosov vortices, from the outside of the loop, where the field is higher, to the inside of the loop, but do not raise the temperature so as to cause a flux jump, condition (4) can be satisfied without the occurrence of flux jumps for small ramping rates $\dot{B}_{\text{in}}$. There exists a maximum ramping rate for which the adiabatic flux creep process is stable, below which no flux jumps will occur, which is given by [2]

$$\dot{B}_{\text{in}} < \frac{8 \mu_0 j_1 h}{\pi^2 C},$$

where $\mu_0$ is the permeability of free space, $j_1 = E \frac{\partial E}{\partial t}$, where $E$ is the electric field induced in the flux creep process, $h$ is the heat transfer coefficient and $C$ is the heat capacity of the sample.

While it can be assumed that flux jumps will occur when the condition in (6) is not met (by using larger ramping rates that are above this threshold) and this has been reproducing verified by our experiments, an individual flux jump is a quantum-mechanical process, and the time at which one will occur cannot be reliably predicted a priori. This is due to the fact that a flux jump represents a change between quantum states (via persistent current modes), much like spontaneous emission in a two-level atom.

While the onset of a flux jump cannot be predicted ahead of time to arbitrary accuracy, one can detect the onset of a flux jump after it has occurred by measuring the abrupt change in magnetic field created by the change in persistent currents. For example, prior to the first flux jump, a persistent current will flow around the outside edge of a SC ring in order to preserve the absence of magnetic flux lines within the closed loop (ignoring for the moment the flux creep process). As the field continues to increase, so will the persistent current. When a flux jump occurs, a persistent current will be established on the inside edge of the ring to, again, preserve the number of flux lines that have entered the closed loop, until the next flux jump occurs. The sudden increase in the persistent current along the inside edge, coupled with the sudden decrease in the persistent current along the outside edge, allows for straightforward measurement of the flux jump process via a magnetic field sensor or pickup coil that is placed coaxially with the closed loop. Modeling the loop as a pure magnetic dipole, the change in field at a distance $d$ from the loop is given by

$$\Delta B = \frac{\mu_0 r^2}{4d^2} \Delta I,$$

where $r$ is the radius of the loop. $\Delta I$, which should take into account the changes in persistent currents on both the inside and outside edges of the SC loop, will depend on the ramping rate $\dot{B}$ and the critical fields of the superconductor. A detailed, quantitative analysis can be found in [1]. Since the rate of increase of the admitted magnetic flux line density $B_{\text{in}}$ tends to be large, the back-emf in a pickup coil, in accordance with Faraday’s law, is typically straightforward to detect with an oscilloscope.

An interesting situation arises when one considers a closed loop of a SC wire that experiences a large change in magnetic field $\dot{B}$ upon only a part of the system. In this particular experiment, a SC wire was formed such that one coil was wound, then a second coil wound with 3 m of wire in between the two coils, and the wire routed back to the first coil and joined at the starting point to form a complete, coherent SC loop. One coil (henceforth referred to as the ‘low-field SC coil’) was placed in a region where the ramping rate $\dot{B}$ was small, namely near the null of a quadrupolar anti-Helmholtz field, while the other (the ‘high-field SC coil’) was placed in a region of high ramping rate, below the lower limit of the anti-Helmholtz pair, where the axial field is maximal. Thus, the high-field SC coil would experience flux jumps for certain ramping rates, while the low-field coil would not if each were a separate, closed coil. However, this is not the case, since the two-coil system is made from a single, coherent SC loop. Therefore, any changes in persistent currents that arise from the flux jumps induced in the high-field coil, as well as any collapse of the global Cooper pair wavefunction, must also affect the low-field coil.

Since the Cooper pair wavefunction must be single valued everywhere along a continuously connected SC system [3], a collapse of the wavefunction is a global event even when it is triggered locally, e.g. by a flux jump that drives a section of the wire above the SC critical temperature. The question arises: can one determine how quickly the wavefunction collapse occurs in the low-field coil if it is triggered in the high-field coil? Furthermore, can one determine how quickly the persistent currents disappear when the coherent SC connection is broken by a flux jump within the high-field coil? The answers to these questions involve considerations of relativity, since a global collapse of the wavefunction triggered by a local event implies instantaneous action at a distance.

2. Large group velocities within superconductors

In 1905, Einstein published his historic paper on special relativity. Shortly afterwards, Sommerfeld [4] answered criticisms of Einstein’s work, namely that the phase and group velocities of electromagnetic waves can become

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4 The adiabatic condition in (6) was observed experimentally by the author SJM, in that flux jumps did not occur for certain ramping rates that satisfied this inequality. In addition to this condition however, it was observed that flux jumps would reappear below a certain ramping rate $\dot{B}$, suggesting that flux jumps are not absent for all field ramping rates below the upper bound on the right side of (6), but for a range of rates between an upper and a lower bound. However, we feel that this discovery requires more careful scrutiny than has been done at the time of writing this and any novel results obtained therein will be reported elsewhere.
superluminal, since these two kinds of velocities can exceed the vacuum speed of light inside a dielectric medium. Note that Einstein considered wave propagation solely in the vacuum, whereas his critics considered wave propagation in media.

Sommerfeld pointed out that while it is true that both the phase and the group velocities in media can in fact exceed \( c \), the front velocity, defined as the velocity of a discontinuous jump in the initial wave amplitude from zero to a finite value, cannot exceed \( c \). It is Sommerfeld’s principle of the non-superluminality of the front velocity that prevents a violation of Einstein’s basic principle of causality in special relativity, i.e. that no effect can ever precede its cause (see [5]).

In subsequent work, Sommerfeld and Brillouin [4] showed that the ‘front’ is accompanied by two kinds of ‘precursors’, now known as the ‘Sommerfeld’, or the ‘high-frequency’, precursor, and the ‘Brillouin’, or the ‘low-frequency’, precursor. These precursors are weak ringing waveforms that follow the abrupt onset of the front, but although they can precede the gradual onset of the strong main signal, they can never precede the onset of the front. One can therefore view the precursor phenomenon as a kind of ‘shock-wave’ response to the collision between the analytic portions of the waveform with the non-analytic, discontinuous front of the waveform. Such ‘shock-wave’ waveforms, however, can never pass through the front and somehow come ahead of the front. This then is the meaning of the Einstein causality.

It is well known that the phase velocity of electromagnetic waves can become superluminal under certain circumstances. A simple example is the superluminality of the phase velocity of an electromagnetic wave traveling within a rectangular waveguide in its fundamental TE\(_{01}\) mode. Another, more impressive, example is the superluminality of the phase velocity of x-rays in all materials. As was first noted by Einstein, the superluminality of the phase velocity of x-rays in all kinds of crystals leads to the phenomenon of total external reflection of x-rays impinging at grazing incidence from the vacuum upon the surface of any kind of crystal [5]. Hence the superluminality of the phase velocity has physically observable consequences.

However, one cannot send a true signal faster than light by means of a superluminal phase velocity, since the phase velocity is the velocity of the crests (i.e. the phase fronts) of a continuous-wave, monochromatic, electromagnetic wave. Since the amplitude and phase of a continuous wave do not change with time, there can be no information contained within such an infinite waveform. As in radio, one must introduce a time-dependent modulation of the continuous ‘carrier’ waveform (using either AM or FM modulation), i.e. a genuine change in the carrier waveform, before any true signal can be sent via the carrier wave.

While it is well known that phase velocities can become superluminal, it is less well known that group velocities can also become superluminal. There is a common misconception that the group velocity is the ‘signal’ velocity of physics, which relates a cause to its effect, and therefore that it cannot propagate faster than light. However, the group velocity is not the velocity that relates a cause to its effect. Only Sommerfeld’s front velocity can fulfill this role.

One experimentally observed example of the occurrence of superluminal group velocities is that individual photons tunnel superluminally through a tunnel barrier [6]. There have been numerous other observations of superluminal group velocities of laser pulses propagating superluminally and transparently through various kinds of dielectric media with optical gain [7]. A recent example of superluminal group velocities is the observation of the superluminal and transparent propagation of laser pulses within optical fibers which possess stimulated Brillouin gain [8].

Nevertheless, Sommerfeld showed that it is the front velocity, and only the front velocity, that relates a cause to its effect in special relativity. He introduced the theta function

\[
\Theta(t) = \begin{cases} 
0 & \text{for all times } t < 0, \\
1 & \text{for all times } t \geq 0 
\end{cases}
\]

in order to modulate any kind of continuous carrier wave. The instant \( t = 0 \) corresponds to the sudden turn-on of the carrier wave, initiated, for example, by the pushing of the ‘ON’ button of a continuous-wave radio-frequency signal generator. This ‘push-button’ kind of signaling guarantees that no effect can precede its cause. The light-cone structure of spacetime in relativity follows from the propagation of these ‘push-button signals’ at the front velocity, and not from the propagation of smooth, analytic ‘wavepacket signals’ at the group velocity, such as the superluminal propagation of a Gaussian wavepacket within a transparent dielectric medium with a gain mechanism. Hence the ‘signal’ velocity of physics, in the fundamental sense of a physical ‘signal’ that connects a cause to its effect, is given by the front velocity, and not by the group velocity.

When a flux jump occurs, the Cooper pair wavefunction collapses across the entire SC system, and thus a global change in phase accompanies a flux jump. However, note that one is not directly measuring the collapse of the wavefunction, but the change in supercurrent density (in this particular experiment, via a back-emf voltage induced in a pickup coil due to the changing magnetic flux). Thus, it is not the change in global phase \( \nabla \phi \) which is an observable, but a change in the value of the current density \( j \). The two are related via the minimal coupling rule by

\[
j = \frac{\hbar}{m^*} \left( \frac{\hbar}{i} \nabla \phi - q^* A \right)
\]

where the general form of the Cooper pair wavefunction is \( \psi = \sqrt{\rho} e^{i\phi} \), \( A \) is the magnetic vector potential, and \( m^* \) and \( q^* \) are the mass and charge of a Cooper pair, respectively. Thus, while the two terms on the right side of (9) may undergo changes via an instantaneous action-at-a-distance process, the observable \( j \) remains unchanged until after the luminal or sub-luminal ‘wavefront’ (the signal that propagates from the high-field SC coil to the low-field SC coil immediately following the onset of a flux jump, which travels with velocity \( v \leq c \)).

A simplified picture is shown in figure 1 where, for simplicity and without loss of generality, the decoherence event occurs between the two coils which have been relabeled ‘Coil A’ and ‘Coil B’ to establish symmetry. While the decoherence event may create a change in global phase and a change in the electromagnetic vector potential at the two coils
on the space axis, no faster-than-light signals can be sent since these quantities cannot be freely manipulated at the origin or measured at the coils. A change in the current density \( j \) can be detected at either coil, but the measurement must take place inside the light cone of the initial decoherence event at the origin of the spacetime diagram if it is to be observed.

One might wonder whether the instantaneous change in the vector potential could be measured via the Aharonov–Bohm effect in which, for example, an electron acquires a phase in the presence of a non-zero vector potential, but in the absence of a local magnetic field. However, recall that the Aharonov–Bohm experiment allows one to measure the line integral \( \oint A \cdot dl \), which is equal to the magnetic flux (obvious after an application of Stokes’ theorem), and not the vector potential \( A \) itself. Thus, the phase incurred through the Aharonov–Bohm effect would not be measurable until the flux changes, which is due to a change in \( j \), which, as discussed, can only occur on a time scale less than or equal to \( 1/c \), where \( l \) is the distance between the coils, again forbidding any faster-than-light signaling.

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Appendix. Preliminary experimental data

A preliminary experiment was conducted in which the abrupt change in magnetic field \( B_\text{in} \) was measured (via voltage signals in nearby pickup coils) within both the high-field and low-field SC coils during a flux jump. Attempts were made to measure the difference in time between the leading edges of each signal to determine the delay in arrival between the two voltage signatures. For specific experimental parameters, see the footnote.5

5 The high- and low-field SC coils were composed of a wire with a single-filament, 470 \( \mu \text{m} \) diameter NbTi superconducting channel and a 150 \( \mu \text{m} \) layer of copper cladding. The SC coils were roughly identical, each with diameters of 3 cm, heights 2 cm and 50 turns of wire. The pickup coils had the same diameters and heights and 150 turns of 26 AWG, enameled copper wire. The pickup coils were placed directly above the SC coils. The length of wire between the SC coils was 3 m. The base temperature of the Oxford Instruments model DR200 dilution refrigerator was 35 mK. This temperature increases during ramping of the magnetic field due to changes in current in the wires connecting the anti-Helmholtz coils to an external power supply (Oxford Instruments model IPS120-10), but the temperature stayed well below 1 K for the duration of the experiment. The maximum ramping rate \( B_\text{ramp} \) was 39 mT min\(^{-1}\) due to constraints on this power supply. A digital oscilloscope (model TDS2024B) was used to monitor the voltage signals in each pickup coil and control experiments were run to account for offsets in signal arrival time due to any differences in overall length between the two signal cables.

Several voltage signatures were recorded with the pickup coils at different time scales. The voltage signals were highly reproducible and multiple data sets were averaged to reduce noise levels. Each voltage signal was observed to coincide with an increase in local temperature, as measured by temperature sensors placed on each SC coil. The flux jump phenomena along with the accompanying temperature increases can be seen experimentally in figure A.1.

Figure A.2 shows a typical, complete voltage signal as measured by the pickup coil connected to the oscilloscope during a ramp-up of the magnetic field (i.e. \( B_\text{ramp} > 0 \)). The reason for the different polarity in the voltage signals is that the SC coils were oppositely oriented in order to rule out any false signals due to direct detection of the flux jump in the high-field SC coil by the pickup coil at the low-field SC coil. The flux jump causes a temperature increase in the high-field SC coil that, in turn, causes the persistent currents to flow into the copper cladding instead of through the SC channel, where there are ohmic losses. However, it is assumed that, over the short time scales in which the flux jump occurs, the currents continue to flow through the SC channel in the low-field SC coil, where there are no ohmic losses. Thus, the current decay rate is expected to be larger in the high-field coil, which is
The first is the time scale related to the inductance to resistance (L/R) ratio, over which currents would decay in a purely classical circuit. This is a realistic model for the currents during a flux jump in the high-field SC coil, since the currents travel through the copper cladding. The inductance of the (individual) SC coils is approximately 440 µH, and the resistance is estimated (and verified through a four-lead measurement) to be approximately 2 mΩ using the geometry of the wire and the temperature-dependent value of electrical resistivity for copper. Although a voltage signal can be theoretically seen due to the change in current magnitude before one characteristic time constant has passed, one can see immediately that this time constant is of the order of hundreds of ms, which is many orders of magnitude larger than the actual measured time decay, and therefore it is not likely that this is the mechanism under which the voltage signal was generated.

The second alternative considered is phonon interaction in the copper cladding when a flux jump takes place. Since the collapse of the Cooper pair wavefunction is stimulated in the high-field SC coil, the time for a phonon to travel from the high-field SC coil to the low-field SC coil bears consideration. This time is simply characterized by 1/v_c, where l = 3 m is the distance between the two coils and v_c ≈ 5000 m s⁻¹ is the sound velocity through copper at cryogenic temperatures. It is apparent that the time for this to occur is of the order of hundreds of microseconds, an order of magnitude longer than the measured time delay.

The third alternative is not entirely different from the second, in that a heat transfer time scale will be calculated; however, this will be a fully classical treatment using the diffusion equation

\[
\frac{\partial T}{\partial t} = \alpha \nabla^2 T = \frac{\partial^2 T}{\partial z^2},
\]

where \( T \) is the temperature of the sample, and \( \alpha \) is the thermal diffusivity of copper. We consider only one spatial dimension \( z \) in the Laplacian operator due to the wire geometry of the sample.

At temperatures near \( T = 0 \), the thermal diffusivity satisfies [9]

\[
\alpha \approx 30 \text{ m}^2 \text{ s}^{-1}.
\]

Using an (approximated) homogeneous initial condition across the length of the wire and an inhomogeneous boundary condition at the high-field SC coil (where we define \( z = 0 \), we have

\[
T(z, t = 0) = 0
\]

\[
T(z = 0, t) = T_c,
\]

which is valid for the short time scales over which a flux jump occurs.

The Green’s function for this model is found by spatially differentiating the heat kernel, and is given by

\[
G(z, t) = \frac{z}{\sqrt{4\pi\alpha t}} \exp \left( -\frac{z^2}{4\alpha t} \right)
\]

and the solution to the diffusion problem is the convolution of \( G \) with the boundary condition (A.4) leading to

\[
T(z, t) = T_c \int_0^t G(z, t - s) \, ds.
\]
This integral can be evaluated analytically, and thus the temperature of the wire is given by
\[ T(z, t) = T_c \text{erfc} \left( \frac{z}{2 \sqrt{\alpha t}} \right) \equiv T_c \left[ 1 - \text{erf} \left( \frac{z}{2 \sqrt{\alpha t}} \right) \right], \quad \text{(A.7)} \]
where the error function is defined as
\[ \text{erf}(x) \equiv \frac{2}{\sqrt{\pi}} \int_0^x \exp(-x^2) \, dx. \quad \text{(A.8)} \]

Using the typical value of the critical temperature of \( T_c \approx 10 \, \text{K} \) for NbTi \([10]\), we wish to find the time at which \( T = 7.5 \, \text{K} \), corresponding to where the persistent currents disappeared in the preliminary experiment depicted in figure A.1. For the full distance \( z = l = 3 \, \text{m} \), this time scale is of the order of seconds. However, the excess wire between the two coils was itself made into loops, and if one ignores Kapitza resistance and assumes that the heat can travel from one section of the wire to another via a loose contact, a more conservative distance of \( z = 25 \, \text{cm} \) should be used instead. Note that it is not assumed that Kapitza resistance can be ignored when calculating the \( L/R \) time constant, or in the phonon-interaction model. For this smaller fixed distance of \( z \), the time required for the temperature at the low-field SC coil to reach 7.5 K is of the order of tens of ms, still multiple orders of magnitude above the measured time.

Thus, while many other potential theoretical and experimental research avenues exist on this topic, one can be guided by the likelihood that this process is fully quantum mechanical in nature, and the theoretical description outlined in section 2 may be a valid starting point for future research.

References

[1] Mints R G and Rakhmanov A L 1981 Rev. Mod. Phys. 53 551
[2] Mints R G 1996 Phys. Rev. B 53 12311
[3] Byers N and Yang C N 1961 Phys. Rev. Lett. 7 46
[4] Brillouin L 1960 Wave Propagation and Group Velocity (Pure and Applied Physics Series) (New York: Academic)
[5] Chiao R Y 2011 Superluminal phase and group velocities: a tutorial on Sommerfeld’s phase, group and front velocities for wave motion in a medium, with applications to the ‘instantaneous superluminality’ of electrons arXiv:1111.2402v1
[6] Steinberg A M, Kwiat P G and Chiao R Y 1993 Measurement of the single-photon tunneling time Phys. Rev. Lett. 71 708
[7] Boyd R W and Gauthier D J 2002 ‘Slow’ and ‘fast’ light Progress in Optics vol 43, ed E Wolf (Amsterdam: Elsevier) pp 497–530
[8] Zhang L, Zhan L, Qian K, Liu J M, Shen Q S, Hu X and Luo S Y 2011 Superluminal propagation at negative group velocity in optical fibers based on Brillouin lasing oscillation Phys. Rev. Lett. 107 093903
[9] Jensen J E et al 1980 Selected Cryogenic Data Notebook (Upton, NY: Brookhaven National Laboratory)
[10] Blatt F J 1992 Modern Physics (New York: McGraw-Hill)