Test of the superluminality of supercurrents induced by a local electric field in a superconducting-core coaxial cable

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In our Physica E paper "Do mirrors for gravitational waves exist?" [1], we predicted that superluminal mass supercurrents will be induced by a gravitational (GR) plane wave which is incident upon a large, square superconducting (SC) plate. It is the *superluminality* of these quantum mass supercurrents that leads to the surprising prediction that the SC plate will act like a mirror which can reflect the incident GR wave. Specular reflections from SC spheres could then lead to geometrical cross sections for the scattering of GR radiation. This is the basis for our proposed Hertz-like experiment, in which pairs of charged SC spheres with a certain charge-to-mass ratio would efficiently convert EM radiation into GR radiation, and vice versa. As we continue to ready the gravitational-wave Hertz-like experiment, it would be helpful to have firm evidence that superluminal mass currents are indeed possible within a SC system. Here we propose a simple proof-of-principle experiment that will allow us to test this basic claim (see Figure 1).

In the proposed experiment, supercurrents are induced by a local electric field, whereas in the case of GR-wave mirrors they will be induced a GR wave. Although the interaction between the matter and radiation is more complex in the GR case, the crucial condition in each case is the production of superluminal supercurrents by the incident wave. In both cases this possibility arises from the globally coherent, macroscopic quantum state occupied by the Cooper pairs, with a well-defined quantum phase established everywhere inside the body. The resulting globally coherent condensate wavefunction renders the Cooper pairs fundamentally indistinguishable from one another within the entire SC system. When a charge pulse whose characteristic energy is lower than the BCS energy gap of the SC arrives at point A, the nonlocalizability and indistinguishability of the Cooper pairs imply that the same pulse will be instantaneously (or at least superluminally) registered at point B. For it is fundamentally impossible to tell, even in principle, whether momentum has been transferred to the Cooper pairs which are at A, or to the Cooper pairs which are at B, by the action of a locally applied electric field.

At the heart of the experiment inside the sample cage of a dilution refriger-

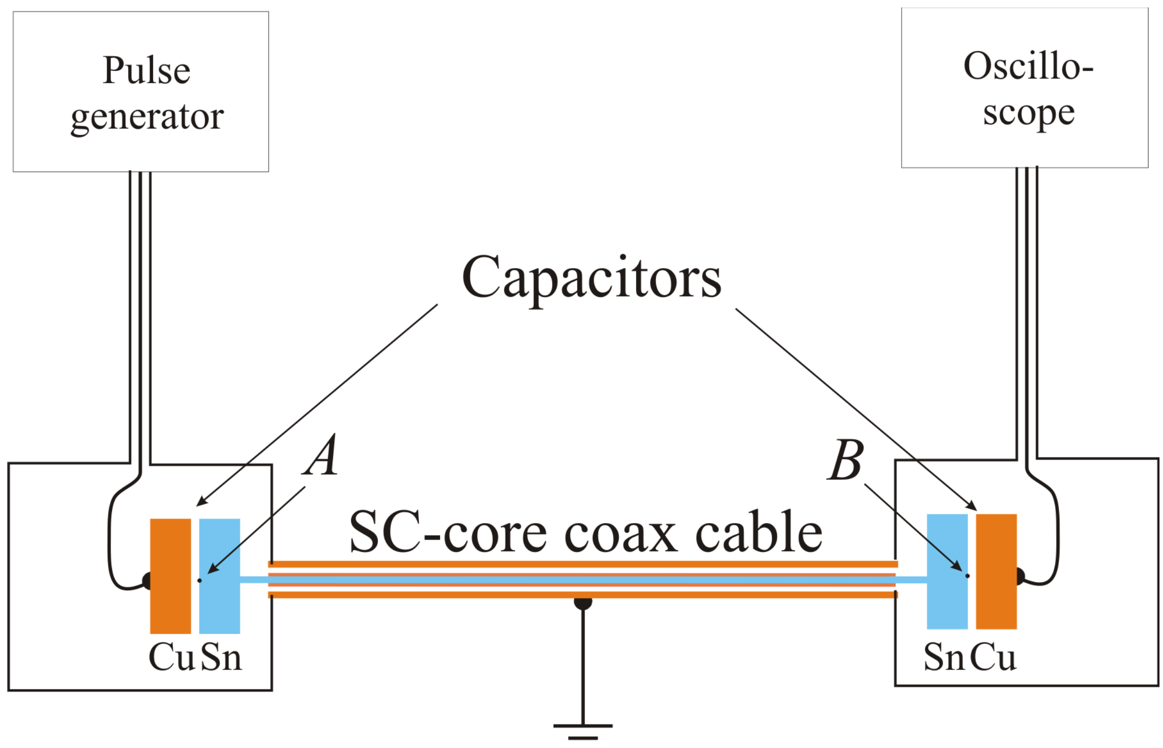

Figure 1: Experiment to test the prediction of superluminal pulse propagation of Cooper pairs in a coax cable with a superconducting (SC) core. A pulse generator induces pulses of charge inside a capacitor at point A. One plate of the capacitor is a normal metal (copper (Cu) in *orange*); the other plate is a SC (tin (Sn) in *blue*) and is connected to the SC core (in *blue*) of a coax cable. Pulses of charge arriving at the capacitor at point B are detected by a fast oscilloscope.

ator is a long coaxial cable (with a total length of roughly 5 meters, which will be coiled in order to fit inside the sample cage), with an inner conductor whose central core is a SC such as tin (indicated in *blue*). This SC core of the inner conductor is overlaid with a normal metal sheath such as copper (indicated in *orange*) [2], so that the Cooper pairs can escape from the SC core into this normal sheath, where they can then break up into normal electrons that propagate along the outer, normal surface of the inner conductor. The outer conductor of the coax is also made out a normal metal such as copper (in *orange*). Thus a normal electromagnetic pulse can propagate "luminally," i.e., at the speed of light within the dielectric of the coax, down the cable. (The dielectric of the cable will be chosen to be Teflon which has a dielectric constant of around 2.) This "luminal" pulse will serve as a means of calibrating the timing measurements for determining the speed of propagation of the "superluminal" pulses which are predicted to exist according to our paper [1].

The SC core of the inner conductor is joined (using SC solder joints, for example) at both ends of the cable to the two SC plates (indicated in *blue*) of two capacitors (i.e., an input capacitor on the left, and an output capacitor on the right). The SC plates (in *blue*) are separated from the normal copper plates (in *orange*) by dielectric spacers in order to form capacitors. A pulse generator at room temperature produces a train of nanosecond-scale finite-bandwidth pulses, such as smooth, Gaussian-like pulses, which propagate down a cryogenic SMA cable into the sample cage through an SMA connector into the interior of a Faraday-cage-like electronics box containing the input capacitor on the left. A similar configuration of a Faraday-cage-like electronics box containing the output capacitor will be used on the right. Thus a given charge pulse originating from the pulse generator will be delivered by means of electrostatic induction to point A of the SC plate of the input capacitor, and the charge pulse arriving at point B of the SC plate of the output capacitor will be monitored by means of a fast scope [3].

The total charge per pulse induced by the pulse generator near point A of the input capacitor will be partitioned into two types of charge, viz., type (i) charge that flows as a normal electrical current along the normal outer surface of the inner conductor of the coax cable, and type (ii) charge that flows as a supercurrent within the central SC core of the inner conductor. Charges of type (i) are normal electrons that result from a pair-breaking process, in which the Cooper pairs that emerge radially from the central SC core into the normal sheath surrounding the core of the cable, are broken up into normal electrons, and end up flowing along the outer surface of the inner conductor as a normal electrical current. Such charges will be associated with the "luminal" pulse. Charges of type (ii) are Cooper pairs that remain unbroken, staying inside the central SC core and flowing within this core from point A to point B as a supercurrent. Such charges will be associated with the "superluminal" pulse.

The branching ratio that determines what fraction of the total induced charge near A ends up after the partitioning process as type (i) charges, and what fraction ends up as type (ii) charges, will be determined roughly by the ratio of the capacitance of the cable for an effective length of cable corresponding the pulse width of a given charge pulse, relative to the capacitance of the capacitor at B at the end of the cable. For a given charge pulse of a duration on the order of a nanosecond, which corresponds to an effective length of cable of roughly 20 cm, this leads to an effective cable capacitance of 16 picofarads. For an output capacitor with a plate radius of 1 centimeter, and a gap of 0.3 millimeters, with Teflon as the dielectric, this leads to a capacitance of 18 picofarads. Therefore, in this case, we expect the branching ratio to be on the order of unity. Thus we expect to see a "double pulse," one "luminal" and the other "superluminal," appearing on a scope trace triggered by the pulse generator, with approximately equal voltage amplitudes for the two types of charge pulses.

If the group velocity of the superluminal type (ii) charge pulse is very much larger than the speed of light [4], then the separation in time between the type (i) and type (ii) pulses will be determined mainly by the time delay of the "luminal" pulse, which, for a 5 meter long cable, should be around 24 nanoseconds (assuming an index of 1.4 for Teflon). This should be easily resolvable using our present oscilloscopes, which have rise times on the order of 5 nanoseconds. We conclude that the experiment which we propose here is feasible to perform.

One control experiment would be to warm up the apparatus above the SC transition temperature, in which case, one expects the "superluminal" component of the double pulse to disappear, and only a "single pulse," viz., only the "luminal" pulse, to remain. Another possible control experiment would be to apply a magnetic field that is larger than the critical field to the cable, in which case, again one expects only a "single pulse," viz., only the "luminal" pulse, to remain. One may also wish to use two parallel SC-core coax cables connected in parallel to the input and output capacitor configurations. Then one can ramp the magnetic field through a hysteresis loop and determine whether the cables are superconducting or not, by monitoring the presence or absence of trapped flux inside the SC circuit. This would be an *in situ* method to establish the presence or absence of superconductivity in our SC samples.

A positive result from this "superluminality" experiment would imply that not only is there superluminal transfer of charge occurring from A to B, but that superluminal transfer of mass is also occurring from A to B. This is because each Cooper pair which is being transferred from A to B carries with it not only charge but also mass. Superluminal mass motions in superconductors must exist if superluminal charge motions in them were to be demonstrated to exist. Thus one of the crucial claims of our Physica E paper would have been successfully demonstrated. On the other hand, if this claim were to be falsified by experiment, there would be little point in going ahead with the Hertz-like experiment.

References

[1] S.J. Minter, K. Wegter-McNelly, R.Y. Chiao, Physica E **42** (2010) 234–255.

[2] This type of SC coax cable is available from a Japanese company,."Coax Co., Ltd."

[3] Note that in both the superluminal and luminal cases, a positively charged pulse at A must appear as a flipped, negatively charged pulse at B. This follows from the conservation of charge.

[4] Starting from the Ginzburg-Landau (G-L) theory of superconductivity, and using the DeWitt minimal coupling rule, we showed that the supercurrent density induced by electromagnetic and gravitational fields is given by the expression

$$\mathbf{j} = \frac{1}{m} \operatorname{Re} \left(\psi^* \left\{ \frac{\hbar}{i} \nabla - q\mathbf{A} - m\mathbf{h} \right\} \psi \right) \tag{1}$$

where ψ is the condensate wavefunction, q is the charge of a Cooper pair, m is its mass, $\mathbf{A}$ is the EM vector potential, and $\mathbf{h}$ is DeWitt's gravitational vector potential. This is a generalization of the London equation $\mathbf{j} = \Lambda\mathbf{A}$ for superconductors, in order to include supercurrents induced by gravitational fields. We also showed that the velocity of the Cooper pairs is given by

$$\mathbf{v} = \frac{\mathbf{j}}{\psi^*\psi} \tag{2}$$

In the special case where there is the absence of radiation fields, and where the cubic nonlinearity in the G-L equation is negligible, there exists a plane wave solution of the form $\psi = \sqrt{n}\exp(i\mathbf{k}\cdot\mathbf{r})$ of this equation. Then the probability current density given in (1) becomes

$$\mathbf{j} = \frac{\hbar}{2mi}(\psi^*(i\mathbf{k})\psi - \psi(-i\mathbf{k})\psi^*) = n\frac{\hbar}{m}\mathbf{k} = n\mathbf{v} \ .$$

Thus the speed v associated with the current density j is

$$v = \frac{\hbar}{m}k \ .$$

Now, the dispersion relation for de-Broglie matter waves is given by

$$\omega = \frac{\hbar k^2}{2m} \ ,$$

which leads to

$$v_{\text{group}} \equiv \frac{d\omega}{dk} = \frac{\hbar}{m}k$$
$$v_{\text{phase}} \equiv \frac{\omega}{k} = \frac{1}{2}\frac{\hbar}{m}k \ .$$

Hence the velocity $\mathbf{v}$ given in (2), which is associated with the probability current density $\mathbf{j}$ given in (1), is the *group* velocity, and not the *phase* velocity, of a Cooper pair. The physical meaning of $\mathbf{j}$ is that it is the quantum transport current density of Cooper pairs. Such currents transport both the charge q and the mass m of the Cooper pairs within the SC. In general, the non-relativistic quantum mechanics of macroscopically coherent wavefunctions of superconductors can lead to superluminal group velocities, but the front velocity, which is responsible for relativistic causality, can never exceed c. Use of the relativistic Dirac equation instead of the non-relativistic Schrödinger equation does not change this conclusion, since the Wigner time for the Dirac equation has also been shown to lead to superluminal group velocities, for example, in the case of electron tunneling. Gaussian wave packet solutions with superluminal group velocities for both the Dirac and Schrödinger equations lead to the superluminal transport of a quantum particle (such as the electron in tunneling), so that superluminal mass currents must be possible in general. In the specific case of superluminal supercurrents induced by incident gravitational radiation predicted in [1], we quote from page 246, section 7:

> '...the group velocity of a Cooper pair given by (69) is predicted to be superluminal, even for extremely small values of the dimensionless strain h_+ of an incident GR wave [33]. Using (71), (73), and (78) to solve for $|\mathbf{v}/c|$, one finds that
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> $$\left|\frac{\mathbf{v}}{c}\right| = \frac{1}{c}\frac{\Xi}{\Xi - 1}\left|\mathbf{h}\right| = \frac{1}{2}\frac{\Xi}{\Xi - 1}\left|h_+\right| \ . \qquad (101)$$
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> Even for an arbitrarily chosen, extremely small value of $|h_+| \approx 10^{-40}$ (which, for a 6 GHz GR wave, corresponds to an incident power flux on the order of 10^{-16} W m^{-2}), the value given in (96) leads to a velocity roughly one hundred times the speed of light. This apparent violation of special relativity suggests that the response of a superconductor to a GR-wave field will in general be nonlinear, invalidating our assumption of linearity in (75).
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> 'However, group velocities much larger than c (infinite, even) have been experimentally demonstrated [39]. In particular, photon tunneling-time measurements confirm the "Wigner" transfer time, which is a measure of an effective group velocity broadly applicable to all quantum scattering processes. Wigner's analysis [40] assumes a *linear* relation between the initial and final states of a quantum system, and yields a transfer time that is proportional to the derivative of the phase of the system's transfer function with respect to the energy of the incident particle. In the present context, this implies that the Wigner time will be zero, since the phase of the Cooper-pair condensate remains constant everywhere, and stays unchanged with time and energy, due to first-order time-dependent perturbation theory (i.e., assuming that no pair-breaking or any other quantum excitation is allowed [15]). Returning to Figure 1, the Wigner time implies that an observer located at the center of mass of the superconductor who spots a Cooper pair at point B during the passage

of the wave will see the pair disappear and then *instantaneously* reappear at point A. This kind of *simultaneity* (as seen by the observer at the center of mass of the system) is a remarkable consequence of quantum theory, but it does not violate special relativity, nor does it invalidate the assumption of linearity.'