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Do mirrors for gravitational waves exist?

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ABSTRACT

Thin superconducting films are predicted to be highly reflective mirrors for gravitational waves at microwave frequencies. The quantum-mechanical *non-localizability* of the negatively charged Cooper pairs, which is protected from the localizing effect of decoherence by an energy gap, causes the pairs to undergo *non-picturable*, *non-geodesic* motion in the presence of a gravitational wave. This non-geodesic motion, which is accelerated motion *through* space, leads to the existence of mass and charge supercurrents inside the superconducting film. On the other hand, the decoherence-induced *localizability* of the positively charged ions in the lattice causes them to undergo *picturable*, *geodesic* motion as they are carried along *with* space in the presence of the same gravitational wave. The resulting separation of charges leads to a virtual plasma excitation within the film that enormously enhances its interaction with the wave, relative to that of a neutral superfluid or any normal matter. The existence of strong mass supercurrents within a superconducting film in the presence of a gravitational wave, dubbed the "Heisenberg–Coulomb effect," implies the specular reflection of a gravitational microwave from a film whose thickness is much less than the London penetration depth of the material, in close analogy with the electromagnetic case. The argument is developed by allowing classical gravitational fields, which obey Maxwell-like equations, to interact with quantum matter, which is described using the Bardeen–Cooper–Schrieffer (BCS) and Ginzburg–Landau theories of superconductivity, as well as a collisionless plasma model. Several possible experimental tests of these ideas, including mesoscopic ones, are presented alongside comments on the broader theoretical implications of the central hypothesis.

1. Introduction

Experiments at the frontiers of quantum mechanics and gravitation are rare. In this paper we argue for a claim that may lead to several new types of experiment, namely, that a superconducting film whose thickness is less than the London penetration depth of the material can specularly reflect not only electromagnetic (EM) microwaves, as has been experimentally demonstrated [1,2], but gravitational (GR) microwaves as well. The basic motivation for our approach lies in the well-known fact that Einstein's field equations lead, in the limits of *weak* GR fields and *non-relativistic* matter, to gravitational Maxwell-like equations [3], which in turn lead to boundary conditions for gravitational fields at the surfaces of the superconducting films homologous to those of electromagnetism. All radiation fields, whether electromagnetic or gravitational, will be treated classically, whereas the superconductors with which they interact will be treated quantum mechanically. Thus, in this paper we adopt a *semi-classical* approach to the interaction of gravitational radiation with matter.

Not enough effort has been made to investigate the ramifications of the gravitational Maxwell-like equations for the interaction of GR waves with matter, perhaps because the so-called "electromagnetic analogy" has been so hotly contested over the years [4]. In any case, we believe that these equations provide a helpful framework for thinking about the response of non-relativistic matter to weak, time-varying gravitational fields, especially that of macroscopically coherent quantum charge and mass carriers, namely, the Cooper pairs of conventional, type I superconductors. We argue here that the electromagnetic analogy manifested in the Maxwell-like equations implies that type I superconductors can be surprisingly efficient mirrors for GR waves at microwave frequencies.

In Section 2, we introduce the two basic claims upon which the larger argument rests. Together, these two claims open the door to an enormously enhanced interaction between a GR microwave and a type I superconductor, relative to what one would expect in the case of a neutral superfluid or, indeed, any normal metal or other classical matter. The first claim is that a GR microwave will generate quantum probability supercurrents, and thus mass and

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electrical supercurrents, inside a type I superconductor, due to the quantum-mechanical *non-localizability* of the Cooper pairs within the material.

The non-localizability of Cooper pairs, which is ultimately due to the Uncertainty Principle (UP), causes them to undergo *non-picturable*, *non-geodesic* motion in the presence of a GR wave. This non-geodesic motion, which is accelerated motion *through* space, leads to the existence of mass and charge supercurrents inside a superconductor. By contrast, the localizability of the ions within the superconductor's lattice causes them to undergo *picturable*, *geodesic* motion, i.e., free fall, in the presence of the same wave. The resulting relative motion between the Cooper pairs and the ionic lattice causes the electrical polarization of the superconductor in the presence of a GR wave, since its Cooper pairs and ions carry not only mass but oppositely signed charge as well.

Furthermore, the non-localizability of the Cooper pairs is "protected" from the normal process of localization, i.e., from decoherence, by the characteristic energy gap of the Bardeen–Cooper–Schrieffer (BCS) theory of superconductivity. The decoherence of entangled quantum systems such as Cooper pairs (which are in the spin-singlet state) is the fundamental cause of the *localizability* of all normal matter [5]. Indeed, this "classicalizing" process must occur within any spatially extended system before the idea of the "universality of free fall" [6] can be meaningfully applied to its parts. After all, the classical principle behind the universality of free fall, the Equivalence Principle (EP), is a strictly *local* principle [7].

The second of the two claims presented in Section 2 is that the mass supercurrents induced by a GR wave are much stronger than what one would expect in the case of a neutral superfluid or any normal matter, due to the electrical polarization of the superconductor caused by the wave. This is what we refer to as the "Heisenberg–Coulomb (H–C) effect." The magnitude of the enhancement due to the H–C effect (derived in Section 7) is given by the ratio of the electrical force to the gravitational force between two electrons,

$$\frac{e^2}{4\pi\varepsilon_0 G m_e^2} = 4.2\times10^{42}, \tag{1}$$

where e is the electron charge, m_e is the electron mass, ε_0 is the permittivity of free space, and G is Newton's constant. The enormity of Eq. (1) implies the possibility of an enormous back-action of a superconductor upon an incident GR wave, leading to its reflection.

Of the four fundamental forces of nature, viz., the gravitational, the electromagnetic, the weak, and the strong forces, only gravity and electricity have long range, inverse-square laws. The pure number obtained in Eq. (1) by taking the ratio of these two inverse-square laws is therefore just as fundamental as the fine structure constant. Because this number is so large, the gravitational force is typically ignored in treatments of the relevant quantum physics. But as we shall see below, a semi-classical treatment of the interaction of a superconductor with a GR wave must account for both the electrodynamics and the gravito-electrodynamics of the superconductor, since both play an important role in its overall response to a GR wave.

In Section 3, we consider the interaction between an EM wave and a thin metallic film having an arbitrary, frequency-dependent complex conductivity. We determine the relevant boundary conditions using Faraday's and Ampere's laws in order to derive general expressions for the transmissivity and reflectivity of a thin film. In Section 4, we show that, in the case of a superconducting film, the BCS theory implies that EM waves at microwave frequencies will be specularly reflected even from films whose thickness is less than the London penetration depth of the material, or, equivalently (at sufficiently low frequencies), less than the material's plasma skin depth, as has been experimentally observed [1,2]. We show, furthermore, that the frequency at which reflectivity drops to 50%, what we call the "roll-off frequency" ω_r, depends only on the ratio of the speed of light c to a single parameter, the length scale l_k associated with the kinetic inductance L_k of the film's Cooper pairs [8], which in turn depends on the plasma skin depth δ_p. In the electromagnetic case, the microscopic size of δ_p leads to a microscopic value for l_k and thus to the possibility of specular reflection over a wide range of frequencies (including microwave frequencies) in the EM case.

In Section 5, we review the Maxwell-like equations for linearized Einsteinian gravity and highlight the fact that any normal matter, with its inherently high levels of dissipation, will necessarily be an inefficient reflector of GR waves because of its high impedance relative to the extremely low "gravitational characteristic impedance of free space" Z_G (2.8×10^{-18} in SI units). Superconductors, on the other hand, are effectively *dissipationless* at temperatures near absolute zero because of their quantum-mechanical nature [2]. The fact that a superconductor's effectively *zero* impedance can be much smaller than the very small quantity Z_G allows it to reflect an incoming GR wave, much as a low-impedance connection or "short" at the end of a transmission line can reflect an incoming EM wave.

In Section 6, we appeal to the Maxwell-like equations introduced in Section 5, to the identicality of the boundary conditions that follow from them, and to the linearity of weak GR-wave optics, in order to introduce GR analogs of the earlier EM expressions for the reflectivity and roll-off frequency. As in the EM case, the GR roll-off frequency $\omega_{r,G}$ can be expressed as the ratio of the speed of light c to a single parameter. In this case, however, the relevant parameter is the length scale $l_{k,G}$ associated with the *gravitational* kinetic inductance $L_{k,G}$ of the Cooper pairs. In this section we treat the superconductor as if it were a neutral superfluid, i.e., as if its Cooper pairs were electrically neutral particles interacting with one another and with the ionic lattice exclusively through their mass. Although this assumption is unphysical, it leads to a result in agreement with conventional wisdom, namely, that the gravitational plasma skin depth $\delta_{p,G}$ and the kinetic inductance length scale $l_{k,G}$ will be astronomical in size ($\sim10^{13}$ and $\sim10^{36}$ m, respectively). Such enormous values imply that $\omega_{r,G}$ will be effectively zero, and thus that superconductors cannot function as mirrors for GR microwaves in laboratory-scale experiments.

In Section 7, we show why the approach taken at the end of the previous section, in accord with conventional wisdom, is wrong. Superconductors *can* function as laboratory-scale mirrors for GR microwaves because of the H–C effect. When one takes into account the electrical charge separation induced within a superconductor by a GR wave (due to the BCS-gap-protected non-localizability of its Cooper pairs), the ratio given in (1) enters into the analysis in such a way as to keep $l_{k,G}$ microscopic and to raise $\omega_{r,G}$ to the level of ω_r. Thus the H–C effect greatly enhances the reflection of a GR wave from the surface of a superconductor—by 42 orders of magnitude!—relative to what one would expect from a neutral superfluid, a normal metal, or any normal matter.

Because both charge supercurrents and mass supercurrents are generated by an incoming GR wave (and by an incoming EM wave), it is also necessary to consider whether superconducting films are not mirrors but rather transducers, i.e., converters, of GR radiation into EM radiation (in the case of an incident GR wave), or vice versa (in the case of an incident EM wave). In Section 8, we take up this particular question and show that transduction in both directions is too weak to decrease reflection by any appreciable amount. In Section 9, however, we show that energy