“Millikan oil drops” as quantum transducers between electromagnetic and gravitational radiation

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Abstract

Pairs of Planck-mass-scale drops of superfluid helium coated by electrons (i.e., “Millikan oil drops”), when levitated in the presence of strong magnetic fields and at low temperatures, can be efficient quantum transducers between electromagnetic (EM) and gravitational (GR) radiation. A Hertz-like experiment, in which EM waves are converted at the source into GR waves, and then back-converted at the receiver from GR waves back into EM waves, should be practical to perform. This would open up observations of the gravity-wave analog of the Cosmic Microwave Background from the extremely early Big Bang, and also communications directly through the interior of the Earth.

1 Introduction

The problem of generating gravitational radiation in the laboratory has historically been an exceedingly difficult one because of the extreme smallness of Newton’s constant $G$ and the extreme largeness of the speed of light $c$. This paper explores situations in which the introduction of yet another physical constant, namely Planck’s constant $h$, due to its extreme smallness, can under certain circumstances lead to the efficient generation, as well as detection, of gravity waves. Under these circumstances, the reciprocity principle (i.e., time-reversal symmetry) demands the existence of nonnegligible back-actions of a quantum measuring device upon incident gravitational radiation fields. This leads to the possibility of generating, as well as detecting, gravity waves in a symmetric manner.
The quantum approach being suggested here is in stark contrast to the classical, test-particle approaches being taken in contemporary, large-scale gravity-wave experiments, which are based solely on classical physics. The back-actions of classical measuring devices such as Weber bars and large laser interferometers upon the incident gravitational fields that are being measured, are completely negligible. Hence they can only detect gravity waves from powerful astronomical sources such as supernovae [1], but they certainly cannot generate these waves.

Specifically, the quantum physics of Planck-mass-scale “Millikan oil drops” consisting of electron-coated superfluid helium drops at milli-Kelvin-scale temperatures in the presence of Tesla-scale magnetic fields, will be explored to see if radiative couplings mediated by such drops are large enough to be experimentally interesting. We shall see that numerical estimates based on quantum mechanics lead to the conclusion that efficient quantum transducers between electromagnetic and gravitational waves consisting of pairs of such drops should indeed be possible to implement in table-top-scale experiments. Such experiments, some of which will be described below, have become practical to perform because of advances in dilution refrigerator technology, and I am planning to perform them with my colleagues at the new 10th campus of the University of California at Merced. These experiments will explore some interesting new physics lying at the interface of quantum mechanics and general relativity, in which gravitational radiative effects on macroscopically coherent, charged quantum systems, and their reciprocal effects back on gravitational radiation fields, should become observable.

The paper is organized as follows: Sections 2 and 3 introduce the ratio of coupling constants of gravity to electricity for two electrons in the vacuum, which ratio also applies to the radiative powers emitted by these electrons when they are set into motion. Section 4 introduces the Planck mass scale in the context of the low temperature physics of macroscopically coherent, charged quantum matter. Maxwell-like equations for weak gravitational radiation fields that result from linearizing Einstein’s equations are introduced in Section 5, and the boundary conditions and the solutions of these equations for the reflections of gravity waves from superconductors and quantum Hall fluids are discussed. In Sections 7 and 8, “Millikan oil drops” are described in more detail, and their role as quantum transducers in a Hertz-like experiment to generate and detect gravitational radiation is discussed. Section 9 examines the quantum conditions for these drops to exhibit a Mössbauer-like response to radiation fields. In Section 10, time-reversal symmetry is applied to the differential scattering cross-section, and an estimation of the total cross-section based on the Maxwell-like equations introduced in Section 5 is made for a pair of Mie-resonant drops. A common misconception that the drops are too heavy to move appreciably, which ignores the role of the equivalence principle, is corrected in Section 11. The final three sections present numerical considerations to show the feasibility of the Hertz-like experiment, and discuss its possible applications.
2 Forces of gravity and electricity between two electrons

Let us first consider, using only classical, Newtonian concepts (which are valid in the correspondence-principle limit and at large distances asymptotically, as seen by a distant observer), the forces experienced by two electrons separated by a distance $r$ in the vacuum. Both the gravitational and the electrical force obey long-range, inverse-square laws. Newton’s law of gravitation states that

$$|F_G| = \frac{G m_e^2}{r^2} \quad (1)$$

where $G$ is Newton’s constant and $m_e$ is the mass of the electron. Coulomb’s law states that

$$|F_e| = \frac{e^2}{r^2} \quad (2)$$

where $e$ is the charge of the electron. The electrical force is repulsive, and the gravitational one attractive.

Taking the ratio of these two forces, one obtains the dimensionless ratio of coupling constants

$$\frac{|F_G|}{|F_e|} = \frac{G m_e^2}{e^2} \approx 2.4 \times 10^{-43} \quad (3)$$

The gravitational force is extremely small compared to the electrical force, and is therefore usually omitted in all treatments of quantum physics.

3 Gravitational and electromagnetic radiation powers emitted by two electrons

The above ratio of the coupling constants $G m_e^2/e^2$ is also the ratio of the powers of gravitational (GR) to electromagnetic (EM) radiation emitted by two electrons separated by a distance $r$ in the vacuum, when they undergo an acceleration $a$ and are moving with a speed $v$ relative to each other, as seen by a distant observer.

From the equivalence principle, it follows that dipolar gravitational radiation does not exist. Rather, the lowest order radiation permitted by this principle is quadrupolar, and not dipolar, in nature. General relativity predicts that the power $P^{\text{quad}}_{GR}$ radiated by a time-varying mass quadrupole tensor $D_{ij}$ of a periodic system is given by

$$P^{\text{quad}}_{GR} = \frac{G}{45c^5} \left\langle \partial^2 D_{ij} \right\rangle = \omega^4 \frac{G}{45c^5} \left\langle D^2_{ij} \right\rangle \quad (4)$$

where the triple dots over $\bar{D}_{ij}$ denote the third derivative with respect to time of the mass quadrupole-moment tensor $D_{ij}$ of the system (the Einstein summation convention over the spatial indices $(i, j)$ for the term $\bar{D}^2_{ij}$ is being used here), $\omega$
is the angular frequency of the periodic motion of the system, and the angular brackets denote time averaging over one period of the motion.

Applying this formula to the periodic orbital motion of two point masses with equal mass \( m \) moving with a relative instantaneous acceleration whose magnitude is given by \( |a| = \omega^2 |D| \), where \( |D| \) is the magnitude of the relative displacement of these objects, and where the relative instantaneous speed of the two masses is given by \( |v| = \omega |D| \) (where \( v << c \)), all these quantities being measured by a distant observer, one finds that Equation (4) can be rewritten as follows:

\[
P^{(\text{quad})}_{GR} = \kappa \frac{2}{3} \frac{G m^2}{c^3} a^2 \quad \text{where} \quad \kappa = \frac{2 \nu^2}{15 c^2}.
\]

(5)

The frequency dependence of the radiated power predicted by Equation (5) scales as \( v^2 a^2 \sim \omega^6 \), in agreement with triple dot term \( \ddot{D}_{ij}^2 \) in Equation (4).

It should be stressed that the values of the quantities \( a \) and \( v \) are those being measured by an observer at infinity. The validity of Equations (4) and (5) has been verified by observations of the orbital decay of the binary pulsar PSR 1913+16 [1].

Now consider the radiation emitted by two electrons undergoing an acceleration \( a \) relative to each other with a relative speed \( v \), as observed by an observer at infinity. For example, these two electrons could be attached to the two ends of a massless, rigid rod rotating around the center of mass of the system like a dumbbell. The power in gravitational radiation that they will emit is given by

\[
P^{(\text{quad})}_{GR} = \kappa \frac{2}{3} \frac{G m^2}{c^3} a^2,
\]

(6)

where the factor \( \kappa \) is given above in Equation (5). Due to their bilateral symmetry, these two identical electrons will also radiate quadrupolar, but not dipolar, electromagnetic radiation with a power given by

\[
P^{(\text{quad})}_{EM} = \kappa \frac{2 e^2}{3 c^3} a^2,
\]

(7)

with the same factor of \( \kappa \). The reason that this is true is that any given electron carries with it mass as well as charge as it moves, since its charge and mass must co-move rigidly together. Therefore two electrons undergoing an acceleration \( a \) relative to each other with a relative speed \( v \) will emit simultaneously both electromagnetic and gravitational radiation, and the quadrupolar electromagnetic radiation which it emits will be completely homologous to the quadrupolar gravitational radiation which it also emits.

It follows that the ratio of gravitational to electromagnetic radiation powers emitted by the two-electron system is given by the same ratio of coupling constants as that for the force of gravity relative to the force of electricity, viz.,

\[
\frac{P^{(\text{quad})}_{GR}}{P^{(\text{quad})}_{EM}} = \frac{G m^2}{e^2} \approx 2.4 \times 10^{-43}.
\]

(8)
Thus it would seem at first sight to be hopeless to try and use any two-electron system as the means for coupling between electromagnetic and gravitational radiation.

Nevertheless it must be emphasized here that although this dimensionless ratio of coupling constants is extremely small, the gravitational radiation emitted from the two electron system must in principle exist, or else there must be something fundamentally wrong with the experimentally well-tested inverse-square laws given by Equations (1) and (2).

4 The Planck mass scale

However, the ratio of the forces of gravity and electricity of two “Millikan oil drops” (to be described in more detail below; see Figure 1) needs not be so hopelessly small 5.

Suppose that each “Millikan oil drop” has a single electron attached firmly to it, and contains a Planck-mass amount of superfluid helium, viz.,

\[ m_{\text{Planck}} = \sqrt{\frac{\hbar c}{G}} \approx 22 \text{ micrograms} \]  

where \( \hbar \) is Planck’s constant/2\( \pi \), \( c \) is the speed of light, and \( G \) is Newton’s constant. Planck’s mass sets the characteristic scale at which quantum mechanics (\( \hbar \)) impacts relativistic gravity (\( c, G \)). (Planck obtained this mass by means of
dimensional analysis.) Note that the extreme smallness of \( \hbar \) compensates for the extreme largeness of \( c \) and for the extreme smallness of \( G \), so that this mass scale is mesoscopic, and not astronomical, in size. This suggests that it may be possible to perform some novel nonastronomical, table-top-scale experiments at the interface of quantum mechanics and general relativity, which are accessible in the laboratory. Such experiments will be considered here.

The forces of gravity and electricity between the two “Millikan oil drops” are exerted upon the centers of mass and the centers of charge of the drops, respectively. Both of these centers coincide with the geometrical centers of the spherical drops, assuming that the charge of the electrons on the drops is uniformly distributed around the outside surface of the drops in a spherically symmetric manner (like in an \( S \) state). Therefore the ratio of the forces of gravity and electricity between the two “Millikan oil drops” now becomes

\[
\left| \frac{F_G}{F_e} \right| = \frac{G \frac{m^2_{\text{Planck}}}{e^2}}{G \frac{(hc/G)^2}{e^2}} = \frac{hc}{e^2} \approx 137.
\]

(10)

Now the force of gravity is approximately 137 times stronger than the force of electricity, so that instead of a mutual repulsion between these two charged, massive objects, there is now a mutual attraction between them. The sign change from mutual repulsion to mutual attraction between these two “Millikan oil drops” occurs at a critical mass \( m_{\text{crit}} \) given by

\[
m_{\text{crit}} = \left( \frac{e^2}{\hbar c} \right) m_{\text{Planck}} \approx 1.9 \text{ micrograms}
\]

(11)

whereupon \( |F_G| = |F_e| \), and the forces of gravity and electricity balance each other in equilibrium. The radius of a drop with this critical mass of superfluid helium, which has a density of \( \rho = 0.145 \text{ g/cm}^3 \), is

\[
R = \left( \frac{3m_{\text{crit}}}{4\pi \rho} \right)^{1/3} \approx 1.9 \text{ micrometers}.
\]

This is a strong hint that mesoscopic-scale quantum effects can lead to non-negligible couplings between gravity and electromagnetism that can be observed in the laboratory.

The critical mass \( m_{\text{crit}} \) is also the mass at which there occurs a comparable amount of generation of electromagnetic and gravitational radiation power upon scattering of radiation from the pair of “Millikan oil drops,” each with a mass \( m_{\text{crit}} \) and with a single electron attached to it. The ratio of quadrupolar gravitational to the quadrupolar electromagnetic radiation power is given by

\[
\frac{P_{GR}^{(\text{quad})}}{P_{EM}^{(\text{quad})}} = \frac{GM^2_{\text{crit}}}{e^2} = 1,
\]

(12)

where the factors of \( \kappa \) in Equations \( \[\text{6}\] \) and \( \[\text{7}\] \) cancel out, if the center of mass of the drop co-moves rigidly together with its center of charge. This implies that
the scattered power from these two charged objects in the gravitational wave channel will become equal to that in the electromagnetic wave channel. Note that a pair of larger drops, whose masses have been increased beyond the critical mass, will still satisfy Equation (12), provided that the number of electrons on these drops is also increased proportionately so that the charge-to-mass ratio of these drops remains fixed, and provided that the system is placed in a strong magnetic field and cooled to low temperatures so that it remains in the ground state.

5 Maxwell-like equations that result from linearizing Einstein’s equations

In order to understand the calculation of the scattering cross section of the “Millikan oil drops” to be given below, let us start from a very useful Maxwell-like representation of the linearized Einstein’s equations of standard general relativity that describes weak gravitational fields coupled to matter in the asymptotically flat coordinate system of a distant inertial observer [6]:

\[ \nabla \cdot \mathbf{E}_G = -\frac{\rho_G}{\varepsilon_G} \]  

(13)

\[ \nabla \times \mathbf{E}_G = -\frac{\partial \mathbf{B}_G}{\partial t} \]  

(14)

\[ \nabla \cdot \mathbf{B}_G = 0 \]  

(15)

\[ \nabla \times \mathbf{B}_G = \mu_G \left( -\mathbf{j}_G + \varepsilon_G \frac{\partial \mathbf{E}_G}{\partial t} \right) \]  

(16)

where the gravitational analog of the magnetic permeability of free space is given by

\[ \mu_G = \frac{4\pi G}{c^2} = 9.31 \times 10^{-27} \text{ SI units} \]  

(17)

and where the gravitational analog of the electric permittivity of free space is given by

\[ \varepsilon_G = \frac{1}{4\pi G} = 1.19 \times 10^9 \text{ SI units.} \]  

(18)

Taking the curl of the gravitational analog of Faraday’s law, Equation (14), and substituting into its right side the gravitational analog of Ampere’s law, Equation (16), one obtains a wave equation, which implies that the speed of gravitational radiation is given by

\[ c = \frac{1}{\sqrt{\varepsilon_G \mu_G}} = 3.00 \times 10^8 \text{ m/s}, \]  

(19)

which exactly equals the vacuum speed of light. In these Maxwell-like equations, the field \( \mathbf{E}_G \), which is the gravito-electric field, is to be identified with the local acceleration \( \mathbf{g} \) of a test particle produced by the mass density \( \rho_G \), and the field
\( \mathbf{B}_G \), which is the gravito-magnetic field produced by the mass current density \( j_G \) and by the gravitational analog of the Maxwell displacement current density \( \varepsilon_G \partial \mathbf{E}_G / \partial t \), is to be identified with the Lense-Thirring field of general relativity.

In addition to the speed \( c \) of gravity waves, there is another important physical property that these waves possess, which can be formed from the gravito-magnetic permeability of free space \( \mu_G \) and from the gravito-electric permittivity \( \varepsilon_G \) of free space, namely, the characteristic impedance of free space \( Z_G \), which is given by \[ Z_G = \sqrt{\frac{\mu_G}{\varepsilon_G}} = 2.79 \times 10^{-18} \text{ SI units}. \] (20)

As in electromagnetism, this characteristic impedance of free space plays an important role in all radiation problems, such as in a comparison of the radiation resistance of gravity-wave antennas to the value of this impedance in order to estimate the coupling efficiency of these antennas to free space. The numerical value of this impedance is extremely small, but the impedance of all material objects must be “impedance matched” to this extremely small quantity before significant power can be transferred efficiently from gravity waves to these objects, or vice versa.

However, all classical material objects, such as Weber bars, have such a high dissipation and such a high radiation resistance that they are extremely poorly impedance-matched to free space. They can therefore neither absorb gravity wave energy, nor emit it efficiently \[ [3] [8]. Hence it is a common belief that all materials, whether classical or quantum, are essentially completely transparent to gravitational radiation. Quantum materials, such as superconductors, however, can be exceptions to this general rule, since they can have a strictly zero dissipation which arises from an energy gap (the BCS gap) in the material, as evidenced by the persistent currents in annular rings of superconductors that have been projected to last longer than the age of the Universe \[ [9].

6 Specular reflection of gravity waves from superconductors and other quantum fluids

One important consequence of the zero-resistance property of superconductors is that a mirror-like reflection should occur at a planar vacuum-superconductor interface. This reflection is similar to that which occurs when an incident electromagnetic wave propagates down a transmission line with a characteristic impedance \( Z \), which is then terminated by means of a resistor \( R \) whose value is close to zero. The reflection coefficient \( R \) of the wave from such a termination is given by

\[ R = \left| \frac{Z - R}{Z + R} \right|^2 \rightarrow 100\% \text{ when } R \rightarrow 0 , \] (21)

which approaches arbitrarily close to 100% when the resistance vanishes.

From the Maxwell-like Equations (13) - (16), and the boundary conditions that follow from them, it follows that there should exist an analogous reflection
of a gravitational plane wave from a planar vacuum-superconductor interface, whose Fresnel-like reflection coefficient $R_G$ is given by

$$R_G = \frac{|Z_G - R_G|^2}{|Z_G + R_G|^2} \to 100\% \text{ when } R_G \to 0 . \quad (22)$$

This counter-intuitive result is due to the fact that the superconductor possesses a strictly zero dissipation, and therefore an equivalent mass-current resistance $R_G$ that should also be strictly zero, as compared to the characteristic impedance of free space $Z_G = 2.79 \times 10^{-18}$ SI units given by Equation (20).

Although the gravitational impedance of free space $Z_G$ is an extremely small quantity, it is still a finite quantity. However, the resistance of a superconductor is strictly zero. Arbitrarily long-lasting persistent mass currents in annular rings of superconductors that accompany long-lasting persistent electrical currents are the evidence for this experimental fact, which can be understood theoretically on a microscopic basis using the BCS theory of superconductivity [9].

Hence it follows that nearly perfect reflection of gravity waves should occur from a superconductor at temperatures well below its transition temperature. Therefore nearly perfect mirrors for gravitational radiation in principle should exist. Curved superconducting mirrors can focus this radiation, and Newtonian telescopes for gravity waves can therefore in principle be constructed. In the case of scattering of gravity waves from superconducting spheres, the above specular-reflection condition implies hard-wall boundary conditions at the surfaces of these spheres, so that the scattering cross section of these waves from a pair of large spheres should be geometric, i.e., hard-sphere, in size.

Not only superconductors, but also quantum Hall fluids moving frictionlessly on a plane, could possibly exhibit nearly perfect reflectivity to normally incident gravitational plane waves. This follows from the fact that these fluids in their quantum Hall plateaus are also perfectly dissipationless, just like superconductors [10]. For example, in the integer effect, the transverse quantum Hall resistance is quantized in integer multiples of $h/e^2$, where $h$ is Planck’s constant and $e$ is the electron charge, but the longitudinal quantum Hall resistance, which is responsible for dissipation, is strictly zero. This arises from the energy gap of the quantum Hall system, which is proportional to the cyclotron frequency of the electrons in the Tesla-scale magnetic fields used in quantum Hall experiments.

However, one cannot tell whether these statements about specular reflection of gravitational radiation from superconductors or quantum Hall fluids are true or not experimentally, without the existence of a source and a detector for such radiation. The quantum transducers based on “Millikan oil drops” to be discussed in more detail below may provide the needed source and detector.

The counter-intuitive prediction of specular reflection of gravity waves from superconductors may possibly also follow from the recent potentially very important discovery [11] (which of course needs independent confirmation) that in an angularly accelerating superconductor, such as a niobium ring rotating with a steadily increasing angular velocity, there seems to be a large enhancement of
the gravito-magnetic field, perhaps arising from a macroscopically constructive quantum interference effect due to the macroscopically coherent nature of the quantum mechanical phase of the electrons in niobium, which in turn arises from the condensate of many Cooper pairs of electrons in this superconductor. As a result of the angular acceleration of the niobium ring, there seems to arise a steadily increasing gravitational analog of the London moment in the form of a very large $B_G$ field inside the ring, which is increasing linearly in time. The gravitational analog of Faraday’s law, Equation (14), then implies the generation of loops of the gravito-electric field $E_G$ inside the hole of the ring, which can be detected by sensitive accelerometers. The gravito-magnetic field $B_G$ is thus inferred to be many orders of magnitude greater than what one would expect classically due to the mass current associated with the rigid rotation of the ionic lattice of the superconducting ring. These observations have recently been confirmed by replacing the electromechanical accelerometers with a laser gyro [12].

A tentative theoretical interpretation of these recent experiments is that the coupling constant $\mu_G$ which couples the mass currents of the superconductor to the gravito-magnetic field $B_G$ is somehow greatly enhanced due to the presence of the macroscopically coherent quantum matter in niobium. This enhancement can be understood phenomenologically in terms of a gravito-magnetic enhancement factor $\kappa_G^{(\text{magn})}$, which enhances the gravito-magnetic coupling constant inside the medium as follows:

$$\mu_G' = \kappa_G^{(\text{magn})} \mu_G$$  \hspace{1cm} (23)

where $\kappa_G^{(\text{magn})}$ is a positive number much larger than unity. This gravito-magnetic enhancement factor $\kappa_G^{(\text{magn})}$ is the gravitational analog of the magnetic permeability constant $\kappa_m$ of ferromagnetic materials in the standard theory of electromagnetism.

The basic assumption of this phenomenological theory is that of a linear response of the material medium to weak applied gravito-magnetic fields [13]; that is to say, whatever the fundamental explanation is of the large observed positive values of $\kappa_G^{(\text{magn})}$, the medium produces an enhanced gravito-magnetic field $B_G$ that is directly proportional to the mass current density $j_G$ arising from the motion of the ionic lattice of the superconductor. For weak fields, this is a reasonable assumption. However, it should be noted that this phenomenological explanation based on Equation (23) is different from the theoretical explanation based on Proca-like equations for gravitational fields with a finite graviton rest mass, which was proposed by the discoverers of the effect in Ref. [11]. Nevertheless, it is natural to consider introducing the phenomenological Equation (23) to explain the observations, since a large enhancement factor $\kappa_G^{(\text{magn})}$ due to the material medium is similar to its analog in ordinary magnetism, which explains, for example, the large ferromagnetic enhancement of the inductance of a solenoid by a magnetically soft, permeable iron core with permeability $\kappa_m >> 1$ that arises from the alignment of electron spins inside the
iron. This spin-alignment effect leads to the large observed values of the magnetic susceptibility of iron. Just as in the case of the iron core inserted inside a solenoid, where the large enhancement of the solenoid’s inductance disappears above the Curie temperature of iron, it was observed in these recent experiments that the large gravito-magnetic enhancement effect disappears above the superconducting transition temperature of niobium.

If the tentative phenomenological interpretation given by Equation (23) of these experiments turns out to be correct, one important consequence of the large resulting values of \( \kappa_G^{(\text{magn})} \) is that again a mirror-like reflection should occur at a planar vacuum-superconductor interface, where the refractive index of the superconductor has an abrupt jump from unity to a value given by

\[
n_G = \left( \kappa_G^{(\text{magn})} \right)^{1/2}.
\]

However, it should be immediately emphasized here that only positive masses are observed to exist in nature, and not negative ones. Hence gravitational analogs of electric dipole moments do not exist. It follows that the gravitational analog \( \kappa_G^{(\text{elec})} \) of the usual dielectric constant \( \kappa_e \) for all kinds of matter, whether classical or quantum, in the Earth’s gravito-electric field \( E_G = g \), cannot differ from its vacuum value of unity, i.e.,

\[
\kappa_G^{(\text{elec})} \equiv \varepsilon'_G / \varepsilon_G = 1,
\]

exactly. Hence one cannot screen out, even partially, the gravito-electric DC gravitational fields like the Earth’s gravitational field using superconducting Faraday cages. In particular, the local value of the acceleration \( g \) due to Earth’s gravity is not at all affected by the presence of nearby matter with large \( \kappa_G^{(\text{magn})} \), a fact which follows from the Maxwell-like Equations (13) – (16).

By contrast, the gravitational analog of Ampere’s law combined with the analog of the Lorentz force law

\[
F_G = m \left( E_G + 4v \times B_G \right),
\]

where \( F_G \) is the force on a test particle with mass \( m \) and velocity \( v \) (all quantities as seen by the distant inertial observer), leads to the fact that a repulsive component of force exists between two parallel mass currents travelling in the same direction, which is the opposite to the case in electricity, where two parallel electrical currents travelling in the same direction attract each other \[6\]. A repulsive gravito-magnetic gravitational force necessarily follows from the negative sign in front of the mass current density \( j_G \) in Equation (16), which is necessitated by the conservation of mass, since upon taking the divergence of Equation (16), and combining it with Equation (13) (whose negative sign in front of the mass density \( \rho_G \) is fixed by Newton’s law of gravitation, where all masses attract each other), one must obtain the continuity equation for mass, i.e.,

\[
\nabla \cdot j_G + \frac{\partial \rho_G}{\partial t} = 0,
\]
where $j_G$ is the mass current density, and $\rho_G$ is the mass density. Moreover, the negative sign in front of the mass current density $j_G$ in the gravitational analog of Ampere’s law, Equation (16), implies an anti-Meissner effect, in which the lines of the $B_G$ field, instead of being expelled from the superconductor, as in the usual Meissner effect, are pulled tightly into the interior of the body of the superconductor.

However, it should again be stressed that what is being proposed here in the above phenomenological scenario does not at all imply an “anti-gravity” effect, in which the Earth’s gravitational field is somehow partially screened out by the so-called “Podkletnov effect”, where it was claimed that rotating superconductors reduce by a few percent the gravito-electric field $E_G = g$, i.e., the local acceleration of all objects due to Earth’s gravity, in their vicinity. Experiments attempting to reproduce this effect have failed to do so [11]. The non-existence of the “Podkletnov effect” would be consistent with the above phenomenological theory, since longitudinal gravito-electric fields cannot be screened under any circumstances; however, transverse radiative gravitational fields can be reflected by macroscopically coherent quantum matter.

Very large values of $\kappa_G^{(\text{magn})}$ for superconductors would imply that the index of refraction for gravitational plane waves in these media would be considerably larger than unity, i.e.,

$$n_G = \left(\kappa_G^{(\text{magn})}\right)^{1/2} >> 1.$$  \hspace{1cm} (28)

The Fresnel reflection coefficient $R_G$ of gravity waves normally incident upon the vacuum-superconductor interface would therefore become

$$R_G = \left|\frac{n_G - 1}{n_G + 1}\right|^2 \to 100\%,$$  \hspace{1cm} (29)

which would again approach unity. Again, this would imply specular reflection of these waves from superconducting surfaces. It should be noted that large values of the gravito-magnetic permeability-enhancement factor $\kappa_G^{(\text{magn})}$, of the index of refraction $n_G$, and of the reflectivity $R_G$, are not forbidden by the principle of equivalence.

## 7 “Millikan oil drops” described in more detail

Let the oil of the classic Millikan oil drops be replaced with superfluid helium ($^4\text{He}$) with a gravitational mass of around the Planck-mass-scale, and let these drops be levitated in the presence of strong, Tesla-scale magnetic fields.

The helium atom is diamagnetic, and liquid helium drops have successfully been magnetically levitated in an anti-Helmholtz magnetic trapping configuration [14]. Due to its surface tension, the surface of a freely suspended, isolated, ultracold superfluid drop is atomically perfect, in the sense that there are no defects (such as dislocations in an imperfect crystal) which can trap and thereby localize the electron. When an electron approaches a drop, the formation of an
image charge inside the dielectric sphere of the drop causes the electron to be attracted by the Coulomb force to its own image. As a result, it is experimentally observed that the electron is bound to the outside surface of the drop in a hydrogenic ground state. The binding energy of the electron to the surface of liquid helium has been measured using millimeter-wave spectroscopy to be 8 Kelvin [15], which is quite large compared to the milli-Kelvin-scale temperatures for the proposed experiments. Hence the electron is tightly bound to the outside surface of the drop so that the radial component of its motion is frozen, but it is free to move tangentially and thus to become delocalized over the surface.

Such a “Millikan oil drop” is a macroscopically phase-coherent quantum object. In its ground state, which possesses a single, coherent quantum mechanical phase throughout the interior of the superfluid [16], the drop possesses a zero circulation quantum number (i.e., contains no quantum vortices), with one unit (or an integer multiple) of the charge quantum number. As a result of the drop being at ultra-low temperatures, all degrees of freedom other than the center-of-mass degrees of freedom are frozen out, so that there results a zero-phonon Mössbauer-like effect, in which the entire mass of the drop moves rigidly as a single unit in response to radiation fields (see below). Therefore, the center of mass of the drop will co-move with the center of charge. Also, since it remains adiabatically in the ground state during perturbations due to these weak radiation fields, the “Millikan oil drop” possesses properties of “quantum rigidity” and “quantum dissipationlessness” that are the two most important quantum properties for achieving a high coupling efficiency for gravity-wave antennas [8].

Note that two spatially separated “Millikan oil drops” with the same mass and charge have the correct bilateral symmetry in order to couple to quadrupolar gravitational radiation, as well as to quadrupolar electromagnetic radiation. The coupling of the drops to dipolar electromagnetic radiation, however, vanishes due to symmetry. When they are separated by a distance on the order of a wavelength, they should become an efficient quadrupolar antenna capable of generating, as well as detecting, gravitational radiation.

8 A pair of “Millikan oil drops” as a transducer

Now imagine placing a pair of levitated “Millikan oil drops” separated by approximately a microwave wavelength inside a black box, which represents a quantum transducer that can convert gravitational (GR) waves into electromagnetic (EM) waves. See Figure 2. This kind of transducer action is similar to that of the tidal force of a gravity wave passing over a pair of charged, freely falling objects orbiting the Earth, which can in principle convert a GR wave into an EM wave [5]. Such transducers are linear, reciprocal devices.

By time-reversal symmetry, the reciprocal process, in which another pair of “Millikan oil drops” converts an EM wave back into a GR wave, must occur with the same efficiency as the forward process, in which a GR wave is converted into an EM wave by the first pair of “Millikan oil drops.” The time-reversed process
Figure 2: “Charged quantum fluid” is a quantum transducer consisting of a pair of “Millikan oil drops” in a strong magnetic field, which converts a gravity (GR) wave into an electromagnetic (EM) wave.

is important because it allows the generation of gravitational radiation, and can therefore become a practical source of such radiation. The radiation reaction or back-action by the EM fields upon the GR fields via these coherent quantum mechanical drops leads necessarily to a non-negligible reciprocal process of the generation of these fields. These actions must be mutual ones between these two kinds of radiation fields.

This raises the possibility of performing a Hertz-like experiment, in which the time-reversed quantum transducer process becomes the source, and its reciprocal quantum transducer process becomes the receiver of GR waves. See Figure 3. Faraday cages consisting of nonsuperconducting metals prevent the transmission of EM waves, so that only GR waves, which can easily pass through all classical matter such as the normal (i.e., dissipative) metals of which standard, room-temperature Faraday cages are composed, are transmitted between the two halves of the apparatus that serve as the source and the receiver, respectively. Such an experiment would be practical to perform using standard microwave sources and receivers, since the scattering cross-sections and the transducer conversion efficiencies of the two “Millikan oil drops” turn out not to be too small, as will be shown below.
Figure 3: A Hertz-like experiment, in which EM waves are converted by the lower-left quantum transducer ("Charged quantum fluid") into GR waves at the source, and the GR waves thus generated are back-converted back into EM waves by the upper-right quantum transducer at the receiver. Communication by EM waves is prevented by the normal (i.e., nonsuperconducting) Faraday cages.
Let a pair of levitated “Millikan oil drops” be placed in strong, Tesla-scale magnetic fields, and let the drops be separated by a distance on the order of a microwave wavelength, which is chosen so as to satisfy the impedance-matching condition for a good quadrupolar microwave antenna.

Now let a beam of electromagnetic waves in the Hermite-Gaussian TEM\(_{11}\)
mode [17], which has a quadrupolar transverse field pattern that has a substantial overlap with that of a gravitational plane wave, impinge at a 45° angle with respect to the line joining these two charged objects. Such a mode has been successfully generated using a “T”-shape microwave antenna [8]. As a result of being thus irradiated, the pair of “Millikan oil drops” will be driven into relative motion in an anti-phased manner, so that the distance between them will oscillate sinusoidally with time, according to an observer at infinity. Thus the simple harmonic motion of the two drops relative to one another (as seen by this observer) produces a time-varying mass quadrupole moment at the same frequency as that of the driving electromagnetic wave. This oscillatory motion will in turn scatter (in a linear scattering process) the incident electromagnetic wave into gravitational and electromagnetic scattering channels with comparable powers, provided that the ratio of quadrupolar radiation powers is that given by Equation (12), i.e., is of the order of unity, which will be case if the charge-to-mass ratio of the drops is the same as that of a single electron on a drop with a critical mass \(m_{\text{crit}}\). The reciprocal scattering process will also have a power ratio of the order of unity. Pairs of large superfluid drops with many electrons on them can be used as scatterers, as long as their charge-to-mass ratio is consistent with Equation (12).

The Mössbauer-like response of “Millikan oil drops” will now be discussed in more detail. Imagine what would happen if one were to replace an electron in the vacuum with a single electron which is firmly attached to the outside surface of a drop of superfluid helium in the presence of a strong magnetic field and at ultralow temperatures, so that the system of the electron and the superfluid, considered as a single quantum entity, would form a single, macroscopic quantum ground state [18]. Such a quantum system can possess a sizeable gravitational mass. For the case of many electrons attached to a large, massive drop, where a quantum Hall fluid forms on the outside surface of the drop in the presence of a strong magnetic field, there results a Laughlin-like ground state, which is the many-body state of an incompressible quantum fluid [19]. The property of quantum incompressibility of such a fluid is equivalent to the property of “quantum rigidity,” which is the first necessary requirement for achieving high efficiency in gravitational-radiation antennas, as was pointed out in [8]. Like superfluids and superconductors, this fluid is also dissipationless. This fulfills the condition of “quantum dissipationlessness,” which is the second necessary requirement for the successful construction of efficient gravity-wave antennas [8].
In the presence of strong, Tesla-scale magnetic fields, an electron is prevented from moving at right angles to the local magnetic field line around which it is executing tight cyclotron orbits. The result is that the surface of the drop, to which the electron is tightly bound, cannot undergo low-frequency liquid-drop deformations, such as the oscillations between the prolate and oblate spheroidal configurations of the drop which would occur at low frequencies in the absence of the magnetic field. After the drop has been placed into Tesla-scale magnetic fields at milli-Kelvin-scale operating temperatures, both the single- and many-electron drop systems will be effectively frozen into the ground state, since the characteristic energy scale for electron cyclotron motion in Tesla-scale fields is on the order of Kelvins. Due to the tight coupling of the electron(s) to the outside surface of the drop, also on the scale of Kelvins, this would effectively freeze out all low-frequency shape deformations of the superfluid drop.

Since all internal degrees of freedom of the drop, such as its microwave phonon excitations, will also be frozen out at sufficiently low temperatures, the charge and the entire mass of the “Millikan oil drop” will co-move rigidly together as a single unit, in a zero-phonon, Mössbauer-like response to applied radiation fields with frequencies below the cyclotron frequency. This is a result of the elimination of all internal degrees of freedom by the Boltzmann factor at sufficiently low temperatures, so that the system stays in its ground state, and only the external degrees of freedom of freedom of the drop, consisting only of its center-of-mass motions, remain.

The criterion for this zero-phonon, or Mössbauer-like, mode of response of the electron-drop system is that the temperature of the system is sufficiently low, so that the probability for the entire system to remain in its ground state without even a single quantum of excitation of any of its internal degrees of freedom being excited, is very high, i.e.,

\[
\text{Prob. of zero internal excitation} \approx 1 - \exp\left(-\frac{E_{\text{gap}}}{k_B T}\right) \to 1 \text{ as } \frac{k_B T}{E_{\text{gap}}} \to 0,
\]

where \(E_{\text{gap}}\) is the energy gap separating the ground state from the lowest permissible excited states, \(k_B\) is Boltzmann’s constant, and \(T\) is the temperature of the system. Then the quantum adiabatic theorem ensures that the system will stay adiabatically in the ground state of this quantum many-body system during adiabatic perturbations, such as those due to weak, externally applied radiation fields with frequencies below the cyclotron frequency. By momentum conservation, since there are no internal excitations to take up the radiative momentum transfer, the center of mass of the entire system must undergo recoil in the emission and absorption of radiation. Thus the mass involved in the response to radiation fields is the entire mass of the whole system.

For the case of a single electron (or many electrons in the case of the quantum Hall fluid) in a strong magnetic field, the typical energy gap is given by

\[
E_{\text{gap}} = \hbar \omega_{\text{cycl}} = \frac{\hbar e B}{mc} >> k_B T,
\]

where \(\omega_{\text{cycl}} = eB/mc\) is the electron cyclotron frequency. This inequality is valid
for the Tesla-scale fields and milli-Kelvin-scale temperatures in the experiments being considered here.

10 Estimate of the scattering cross-section

Let $d\sigma_{a\rightarrow\beta}$ be the differential cross-section for the scattering of a mode $a$ of radiation of an incident gravitational wave to a mode $\beta$ of a scattered electromagnetic wave by a pair of “Millikan oil drops” (Latin subscripts denote GR waves, and Greek subscripts EM waves). Then, by time-reversal symmetry

$$d\sigma_{a\rightarrow\beta} = d\sigma_{\beta\rightarrow a} .$$

(32)

Since electromagnetic and weak gravitational fields both formally obey Maxwell’s equations (apart from a difference in the signs of the source density and the source current density; see Equations (13) - (16)), and since these fields obey the same boundary conditions, the solutions for the modes for the two kinds of scattered radiation fields must also have the same mathematical form. Let $a$ and $\alpha$ be a pair of corresponding solutions, and $b$ and $\beta$ be a different pair of corresponding solutions to Maxwell’s equations for GR and EM modes, respectively. For example, $a$ and $\alpha$ could represent incoming plane waves which copropagate in the same direction, and $b$ and $\beta$ scattered, outgoing plane waves which copropagate together in a different direction. Then for a pair of drops with the same charge-to-mass ratio as that for critical-mass drops with single electrons, there is an equal conversion into the two types of scattered radiation fields in accordance with Equation (12), and therefore

$$d\sigma_{a\rightarrow b} = d\sigma_{a\rightarrow\beta} ,$$

(33)

where $b$ and $\beta$ are corresponding modes of the two kinds of scattered radiations.

By the same line of reasoning, for this pair of drops

$$d\sigma_{b\rightarrow a} = d\sigma_{\beta\rightarrow a} = d\sigma_{\beta\rightarrow\alpha} .$$

(34)

It therefore follows from the principle of reciprocity (i.e., detailed balance or time-reversal symmetry) that

$$d\sigma_{a\rightarrow b} = d\sigma_{a\rightarrow\beta} .$$

(35)

In order to estimate the size of the total cross-section, it is easier to consider first the case of electromagnetic scattering, such as the scattering of microwaves from a pair of large drops with radii $R$ and a separation $r$ on the order of a microwave wavelength (but with $r > 2R$). The diameter $2R$ of the drops can be made to be comparable to their separation $r \approx \lambda$, (e.g., with $2\pi R = \lambda$ for the first Mie resonance), provided that many electrons are added on their surfaces, so that their charge-to-mass ratio is maintained to be the same as that of a single electron on a critical-mass drop (this requires the addition of 20 thousand electrons for the first Mie resonance at $\lambda = 2.5$ cm, where $R = 4$ mm), and therefore Equation (12) still holds for these large drops.
For an incident EM wave of a particular circular polarization, even just a single, delocalized electron in the presence of a strong magnetic field is enough to produce specular reflection of this wave (see Appendix A). Therefore for circularly polarized light, the two drops behave like perfectly conducting, shiny, mirrorlike spheres, which scatter light in a manner similar to that of perfectly elastic hard-sphere scattering in idealized billiards. The total cross section for the scattering of electromagnetic radiation from this pair of large drops is therefore given approximately by the geometric cross-sectional areas of two hard spheres

$$\sigma_{\alpha \rightarrow \text{all} \beta} = \int d\sigma_{\alpha \rightarrow \beta} \simeq \text{Order of } \pi R^2$$  \hspace{1cm} (36)

where $R$ is the hard-sphere radius of a drop. This hard-sphere cross-section is much larger than the Thomson cross-section for the classical, localized single free-electron scattering of electromagnetic radiation.

However, if, as one might expect on the basis of the prevailing (but possibly incorrect) opinion that all gravitational interactions with matter, including the scattering of gravitational waves from all types of matter, is completely independent of whether this matter is classical or quantum-mechanical in nature on any scale of size, and that therefore the scattering cross-section for the drops would be extremely small as it is for the classical Weber bar, then by reciprocity, the total cross-section for the scattering of electromagnetic waves from the two-drop system must also be extremely small. In other words, if “Millikan oil drops” were to be essentially invisible to gravitational radiation as is commonly believed, then by reciprocity they must also be essentially invisible to electromagnetic radiation. To the contrary, if it should turn out that the quantum Hall fluid on the surface of these drops should make them behave like superconducting spheres, then the earlier discussion in connection with Equation (22) would imply that the total cross-section of these drops will be like that of hard-sphere scattering, so that they certainly would not be invisible.

In order to check the above hard-sphere scattering cross-section result, we propose to first perform in a preliminary experiment a measurement of the scattering cross section for quadrupolar microwave radiation off of a pair of large “Millikan oil drops” (see Figure 4). A standard oscillator at 12 GHz emits microwaves which are prepared in a quadrupolar TEM$_{11}$ mode and directed in a beam towards these drops. The intensity of the scattered microwave beam generated by the pair of drops is then measured by means of a standard 12 GHz heterodyne receiver, which receives a quadrupolar TEM$_{11}$ mode. The purpose of this experiment is the check if the scattering cross-section is indeed as large as the geometric cross-section predicted by Equations (22) and (36). As one increases the temperature, one should observe the disappearance of this enhanced scattering cross section above the quantum Hall transition temperature or the superfluid lambda point, whichever comes first.
Figure 4: Schematic of apparatus to measure the scattering cross-section of quadrupolar microwaves from a pair of “Millikan oil drops” (not to scale).
11 A common misconception corrected

In connection with the idea that an EM wave incident on a pair of drops could generate a GR wave, there arises a common misconception that the drops are so heavy that their large inertia will prevent them from moving with any appreciable amplitude in response to the driving EM wave amplitude. How can they then possibly generate copious amounts of GR waves? This objection overlooks the major role played by the principle of equivalence in the motion of the drops, as will be explained below.

According to the equivalence principle, two tiny inertial observers, who are undergoing free fall, i.e., who are freely floating near their respective centers of the two “Millikan oil drops,” would see no acceleration at all of the nearby surrounding matter of their drop (nor would they feel any forces) due to the gravitational fields arising from a gravity wave passing over the two drops. However, when they measure the distance separating the two drops, by means of laser interferometry, for example, they would conclude that the other drop is undergoing acceleration relative to their drop, due to the fact that the space between the drops is being alternately stretched and squeezed by the incident gravity wave. They would therefore further conclude that the charges attached to the surfaces of their locally freely-falling drops would radiate electromagnetic radiation, in agreement with the observations of the observer at infinity, who sees two charges undergoing time-varying relative acceleration in response to the passage of the gravity wave.

According to the reciprocity principle, this scattering process can be reversed in time. Under time reversal, the scattered electromagnetic wave now becomes a wave which is incident on the drops. Again, the two tiny inertial observers near the center of the drops would see no acceleration at all of the surrounding matter (nor would they feel any forces) due to the electric and magnetic fields of the incident electromagnetic wave. Rather, they would conclude from measurements of the distance separating the two drops, that it is again the space between the drops that is being alternately squeezed and stretched by the incident electromagnetic wave. They would again further conclude that the masses associated with their locally freely-falling drops would radiate gravitational radiation, in agreement with the observations of the observer at infinity, who sees two masses undergoing time-varying relative acceleration in response to the passage of the electromagnetic wave.

From this general relativistic viewpoint, which is based upon the equivalence principle, the fact that the drops might possess very large inertias is irrelevant, since in fact the drops are not moving at all with respect to the local inertial observer located at the center of drop. Instead of causing motion of the drops through space, the gravitational fields of the incident gravitational wave are acting directly upon space itself by alternately stretching and squeezing the space in between the drops. Likewise, in the reciprocal process the very large inertias of the drops are again irrelevant, since the electromagnetic wave is not producing any motion at all of these drops with respect to the same inertial observer. Instead of causing motion of the drops through space, the electric and magnetic
fields of the incident electromagnetic wave are again acting directly upon space itself by alternately squeezing and stretching the space in between the drops. The time-varying, accelerated motion of the drops as seen by the distant observer that causes quadrupolar radiation to be emitted in both cases, is due to the time-varying curvature of spacetime induced both by the incident gravitational wave and by the incident electromagnetic wave. It should be remembered that the space inside which the drops reside is therefore no longer flat, so that the Newtonian concept of a radiation-driven, local accelerated motion of a drop through a fixed, flat Euclidean space, is therefore no longer valid.

12 The strain of space produced by the drops for a milliwatt of GR wave power

Another common objection to these ideas is that the strain of space produced by a milliwatt of an electromagnetic wave is much too small to detect. However, in the Hertz-like experiment, one is not trying to detect directly the strain of space, but rather the power that is being transferred by the gravitational radiation fields from the source to the receiver.

Let us put in some numbers. Suppose that one succeeded in completely converting a milliwatt of EM wave power into a milliwatt of GR wave power at the source. How big a strain amplitude of space would be produced by the resulting GR wave? The gravitational analog of the time-averaged Poynting vector is given by

\[ \langle S \rangle = c \langle t_{\mu\nu} \rangle = \frac{\omega^2 c^3}{8\pi G} h_+^2 \]

where \( \langle t_{\mu\nu} \rangle \) are certain components of the time-averaged stress-energy tensor of a plane wave and \( h_+ \) is the dimensionless strain amplitude of space for one polarization of a monochromatic plane wave. For a milliwatt of power in such a plane wave at 30 GHz focused by means of a Newtonian telescope to a 1 cm\(^2\) Gaussian beam waist, one obtains a dimensionless strain amplitude of

\[ h_+ \simeq 2 \times 10^{-24}. \]

This strain is indeed exceedingly difficult to directly detect. However, it is not necessary to directly measure the strain of space in order to detect gravitational radiation, just as it is not necessary to directly measure the electric field of a light wave, which may also be exceedingly small, in order to be able to detect this wave. Instead, one can measure directly the power conveyed by a beam of light by means of bolometry, for example. Likewise, if one were to succeed to completely back-convert this milliwatt of GR wave power back into a milliwatt of EM power at the receiver, this amount of power would be easily detectable by standard microwave techniques.
13 Signal-to-noise considerations

The signal-to-noise ratio expected for the Hertz-like experiment depends on the current status of microwave source and receiver technologies. Based on the experience gained from the experiment done on YBCO using existing off-the-shelf microwave components [8], we expect that we would need geometric-sized cross-sections and a minimum conversion efficiency on the order of a few parts per million per transducer, in order to detect a signal. The overall signal-to-noise ratio depends on the initial microwave power, the scattering cross-section, the conversion efficiency of the quantum transducers, and the noise temperature of the microwave receiver (i.e., its first-stage amplifier).

Microwave low-noise amplifiers can possess noise temperatures that are comparable to room temperature (or even better, such as in the case of liquid-helium cooled paramps or masers used in radio astronomy). The minimum power \( P_{\text{min}} \) detectable in an integration time \( \tau \) is given by

\[
P_{\text{min}} = \frac{k_B T_{\text{noise}} \Delta \nu}{\sqrt{\tau \Delta \nu}}
\]

where \( k_B \) is Boltzmann’s constant, \( T_{\text{noise}} \) is the noise temperature of the first stage microwave amplifier, and \( \Delta \nu \) is its bandwidth. Assuming an integration time of one second, and a bandwidth of 1 GHz, and a noise temperature \( T_{\text{noise}} = 300 \text{ K} \), one gets \( P_{\text{min}}(\tau = 1 \text{ sec}) = 1.3 \times 10^{-25} \) Watts, which is much less than the milliwatt power levels of typical microwave sources.

14 Possible applications

If we should be successful in the Hertz-like experiment, this could lead to important possible applications in science and engineering. In science, it would open up the possibility of gravity-wave astronomy at microwave frequencies. One important problem to explore would be observations of the analog of the Cosmic Microwave Background (CMB) in gravitational radiation. Since the Universe is much more transparent to gravity waves than to electromagnetic waves, such observations would allow a much more penetrating look into the extremely early Big Bang towards the Planck scale of time, than the presently well-studied CMB. Different cosmological models of the very early Universe give widely differing predictions of the spectrum of this penetrating radiation, so that by measurements of the spectrum, one could tell which model, if any, is close to the truth [21]. The anisotropy in this radiation would also be very important to observe.

In engineering, it would open up the possibility of intercontinental communication by means of microwave-frequency gravity waves directly through the interior of the Earth, which is transparent to such waves. This would eliminate the need of communications satellites, and would allow communication with people deep underground or underwater in submarines in the Oceans. Such a new direction of gravity-wave engineering could aptly be called “gravity radio”.

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15 Appendix A: specular reflection of a circularly polarized EM wave by a delocalized electron moving on a plane in the presence of a strong magnetic field

Here we address the question: What is the critical frequency for specular reflection of an EM plane wave normally incident upon a plane, in which electrons are moving in the presence of a strong B field? The motivation for solving this problem is to answer also the following questions: How can just a single electron on the outside surface of a “Millikan oil drop” generate enough current in response to an incident EM wave, so as to produce a re-radiated wave which totally cancels out the incident wave within the interior of the drop, with the result that none of the incident radiation can enter into the drop? Why does specular reflection occur from the surface of such a drop, and hence why does a hard-sphere EM cross-section result for a pair of “Millikan oil drops”?

To simplify this problem to its bare essentials, let us examine first a simpler, planar problem consisting of a uniform electron gas moving classically on a planar dielectric surface. We shall start from a 3D point of view, but the Coulombic attraction of the electrons to their image charges inside the dielectric will confine them in the direction normal to the plane, so that the electrons are restricted to a 2D motion, i.e., to motion in the two transverse dimensions of the plane. The electrons are subjected to a strong DC magnetic field applied normally to this plane. What is the linear response of this electron gas to a weak, normally incident EM plane wave? Does a specular plasma-like reflection occur below a critical frequency, even when just only a single, delocalized electron is present on the plane? Let us first solve this problem classically.

Let the plane in question be the $z = 0$ plane, and let a strong, applied DC $B$ field be directed along the positive $z$ axis. The Lorentz force on an electron is given by

$$\mathbf{F} = e \left( \mathbf{E} + \frac{\mathbf{v}}{c} \times \mathbf{B} \right)$$

(40)

where $\mathbf{E}$, the weak electric field of the normally incident plane wave, lies in the $(x, y)$ plane. (We shall use Gaussian units here.) The cross product $\mathbf{v} \times \mathbf{B}$ is given by

$$\mathbf{v} \times \mathbf{B} = \begin{vmatrix} \mathbf{i} & \mathbf{j} & \mathbf{k} \\ v_x & v_y & 0 \\ 0 & 0 & B \end{vmatrix} = iv_y B - jv_x B.$$  \hspace{1cm} (41)

Hence Newton’s equations of motion reduce to $x$ and $y$ components only

$$F_x = m\ddot{x} = eE_x + \frac{v_y}{c} eB = eE_x + \frac{\dot{y}}{c} eB.$$ \hspace{1cm} (42)

$$F_y = m\ddot{y} = eE_y - \frac{v_x}{c} eB = eE_x - \frac{\dot{x}}{c} eB.$$ \hspace{1cm} (43)
Let us assume that the driving plane wave is a weak monochromatic wave with the exponential time dependence
\[ E = E_0 \exp(-i\omega t) \]  

Then assuming a linear response of the system to the weak incident EM wave, the displacement, velocity, and acceleration of the electron all have the same exponential time dependence
\[ x = x_0 \exp(-i\omega t) \quad \text{and} \quad y = y_0 \exp(-i\omega t) \]  
\[ \dot{x} = (i\omega) x \quad \text{and} \quad \dot{y} = (i\omega) y \]  
\[ \ddot{x} = -\omega^2 x \quad \text{and} \quad \ddot{y} = -\omega^2 y \]  
which converts the two ODEs, Equations (42) and (43), into the two algebraic equations for \( x \) and \( y \)
\[ -m\omega^2 x = eE_x - \frac{i\omega y}{c}eB \]  
\[ -m\omega^2 y = eE_y + \frac{i\omega x}{c}eB. \]  

Let us now add \( \pm i \) times the second equation to the first equation. Solving for \( x \pm iy \), one gets
\[ x \pm iy = e^{\left(\frac{E_x \pm iE_y}{-m\omega^2 \pm \omega \omega_{\text{cycl}}/c}\right)} \]  
where the upper sign corresponds to an incident clockwise circularly polarized EM, and the lower sign to an anti-clockwise one. Let us define as a shorthand notation
\[ z_{\pm} \equiv x \pm iy \]  
as the complex representation of the displacement of the electron. Solving for \( z_{\pm} \), one obtains
\[ z_{\pm} = \frac{eE_{\pm}}{-m(\omega^2 \mp \omega \omega_{\text{cycl}})} \]  
where the cyclotron frequency \( \omega_{\text{cycl}} \) is defined as
\[ \omega_{\text{cycl}} \equiv \frac{eB}{mc}, \]  
and where
\[ E_{\pm} \equiv E_x \pm iE_y. \]  

For a gas of electrons with a uniform number density \( n_e \), the polarization of this medium induced by the weak incident EM wave is given by
\[ P_{\pm} = n_e e (x \pm iy) = n_e e z_{\pm} = \frac{n_e e^2 E_{\pm}}{-m(\omega^2 \mp \omega \omega_{\text{cycl}})} = \chi E_{\pm} \]  

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where the susceptibility of the electron gas is given by
\[ \chi = \frac{n_e e^2}{-m (\omega^2 + \omega \omega_{\text{cycl}})} = -\frac{\omega_{\text{plas}}^2 / 4\pi}{\omega^2 + \omega \omega_{\text{cycl}}} \]  
(54)
where the plasma frequency \( \omega_{\text{plas}} \) is defined by
\[ \omega_{\text{plas}} \equiv \sqrt{\frac{4\pi n_e e^2}{m}}. \]  
(55)
The index of refraction of the gas \( n(\omega) \) is given by
\[ n(\omega) = \sqrt{1 + 4\pi \chi(\omega)} = \sqrt{1 - \frac{\omega_{\text{plas}}^2}{\omega^2 + \omega \omega_{\text{cycl}}}}. \]  
(56)
specular reflection occurs when the index of refraction becomes a pure imaginary number. Let us define as the critical frequency \( \omega_{\text{crit}} \) as the frequency at which the index vanishes, which occurs when
\[ \frac{\omega_{\text{plas}}^2}{\omega_{\text{crit}}^2 + \omega_{\text{crit}} \omega_{\text{cycl}}} = 1. \]  
(57)
Since the index vanishes at this critical frequency, the Fresnel reflection coefficient \( R(\omega) \) from the planar structure for normal incidence at criticality is given by
\[ R(\omega) = \left| \frac{n(\omega) - 1}{n(\omega) + 1} \right|^2 \rightarrow 100\% \text{ when } \omega \rightarrow \omega_{\text{crit}}, \]  
(58)
which implies specular reflection of the incident plane EM wave from the electron gas. This yields a quadratic equation for \( \omega_{\text{crit}} \)
\[ \omega_{\text{crit}}^2 + \omega_{\text{crit}} \omega_{\text{cycl}} - \omega_{\text{plas}}^2 = 0. \]  
(59)
The solution for \( \omega_{\text{crit}} \) is
\[ \omega_{\text{crit}} = \frac{\pm \omega_{\text{cycl}} \pm \sqrt{\omega_{\text{cycl}}^2 + 4\omega_{\text{plas}}^2}}{2}. \]  
(60)
The first \( \pm \) sign is physical, and is determined by the sense of circular polarization of the incident plane wave. The second \( \pm \) sign is mathematical, and originates from the square root. One of the latter mathematical signs is unphysical. To determine which choice of the latter sign is physical and which is unphysical, let us first consider the limiting case when the inequality
\[ \omega_{\text{cycl}} \ll \omega_{\text{plas}} \]  
(61)
holds. This inequality corresponds physically to the situation when the magnetic field is very weak, but the electron density is very high, so that the phenomenon
of specular reflection of EM waves with frequencies below the plasma frequency $\omega_{\text{plas}}$ occurs. Let us therefore take the limit $\omega_{\text{cycl}} \to 0$ in the solution (61). Negative frequencies are unphysical, so that we must choose the positive sign in front of the surd as the only possible physical solution. Thus in general it must the case that the physical root of the quadratic is given by

$$\omega_{\text{crit}} = \pm \omega_{\text{cycl}} + \sqrt{\omega_{\text{cycl}}^2 + 4\omega_{\text{plas}}^2}. \quad (62)$$

Let us now focus on the more interesting case where the magnetic field is very strong, but the number density of electrons is very small, so that the plasma frequency is very low, corresponding to the inequality

$$\omega_{\text{cycl}} \gg \omega_{\text{plas}}. \quad (63)$$

There then are two possible solutions, corresponding to clockwise-polarized and anti-clockwise-polarized EM waves, respectively, viz.

$$\omega_{\text{crit},1} = \omega_{\text{cycl}} \quad \text{and} \quad \omega_{\text{crit},2} = 0. \quad (64)$$

Note the important fact that these solutions are independent of the number density (or plasma frequency) of the electron gas, which implies that even a very dilute electron gas system can give rise to specular reflection. The fact that these solutions are independent of the number density also implies that they would apply to the case of an inhomogeneous electron density, such as that arising for a single delocalized electron confined to the vicinity of the plane $z = 0$ by the Coulombic attraction to its image. Both solutions of the quadratic equation (64) are now physical ones, and imply that whether the sense of rotation of the EM polarization co-rotates or counter-rotates with respect to the magnetic-field–induced precession of the guiding center motion of the electron around the magnetic field, determines which sense of circular polarization is transmitted when $\omega > \omega_{\text{crit},2} = 0$, or which sense of circular polarization is totally reflected when $\omega < \omega_{\text{crit},1} = \omega_{\text{cycl}}$, provided that the frequency of the incident circularly polarized EM wave is less than the cyclotron frequency $\omega_{\text{cycl}}$. The interesting solution is the one with the non-vanishing critical frequency, since it implies that there always exists one solution where there is specular reflection of the EM wave, even when the number density of electrons is extremely low, i.e., even when the plasma frequency $\omega_{\text{plas}}$ approaches zero, and even when this number density becomes very inhomogeneous as a function of $z$.

In the extreme case of a single electron completely delocalized on the outside surface of superfluid helium (for example, in an $S$ state on the outside surface of a spherical drop), one should solve the problem quantum mechanically, by going back to Landau’s solution of the motion of an electron in a uniform magnetic field, and adding as a time-dependent perturbation the weak (classical) incident circularly polarized plane wave. However, the above classical solution is sufficient, since it should hold in the correspondence principle limit, where, for the
single delocalized electron, the effective number density of the above classical solution is determined by the absolute square of the electron wavefunction, viz.

\[ n_e = |\psi_e|^2, \text{ and} \]

\[ \int n_e dV = \int |\psi_e|^2 dV = 1. \]  

(65)  

(66)

Here we must take into account the fact that there is a finite confinement distance (around 80 Å) in the z direction of the electron’s motion in the hydrogenic ground state caused by the Coulomb attraction of the electron to its image charge induced in the dielectric, but the electron is completely delocalized in the x and y directions on an arbitrarily large plane (and hence over the large spherical surface of a large drop). The effective plasma frequency of the single electron may be extremely small; nevertheless, total reflection by this single, delocalized electron still occurs, provided that the frequency of the incident circularly polarized EM wave is below the cyclotron frequency. The fundamental reason why even just a single electron in a strong magnetic field can give rise to 100% reflection is that the \( \mathbf{v} \times \mathbf{B} \) Lorentz force leads to an arbitrarily large transverse induced current (i.e., to an arbitrarily large Hall conductivity of the electron on the plane, even though the quantum Hall conductance \( e^2/h \) may be finite), which effectively shorts out the incident circularly polarized EM wave. Thus one concludes that the hard-wall boundary conditions used in the order-of-magnitude estimate given by Equation (36) of the scattering cross-section of microwaves from the drops are reasonable ones. This conclusion will be tested experimentally (see Figure 4).

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The response of the medium must not only be linear in the amplitude of the weak applied gravitational radiation fields, but it must also be causal. Hence the real and imaginary parts of the linear response function $\kappa_{\omega}^{(magn)}(\omega)$, as a function of frequency $\omega$ of the gravity wave, must obey Kramers-Kronig relations similar to those given by Equations (4) and (5) of Ref. [8](a).

M. A. Weilert, D. L. Whitaker, H. J. Maris, and G. M. Seidel, Phys. Rev. Letters 77, 4840 (1996); M. A. Weilert, D. L. Whitaker, H. J. Maris, and G. M. Seidel, J. Low Temp. Phys. 106, 101 (1997). Another method of levitating charged superfluid drops uses a parallel-plate capacitor geometry similar to that used by Millikan in his original oil-drop experiment; see J. J. Niemela, J. Low Temp. Phys. 109, 709 (1997).

C. C. Grimes and T. R. Brown, Phys. Rev. Letters 32, 280 (1974); C. C. Grimes and G. Adams, Phys. Rev. Letters 36, 145 (1976). In the ground state of the system, the electron resides on the outside surface of a superfluid helium drop, and not within the inside volume of the drop. When the electron is forced to be within the interior of the drop, it will form a bubble with a radius of around one nanometer, due to the balancing of an outwards Pauli pressure with the surface tension of the superfluid (see R.
J. Donnelly, *Experimental Superfluidity* (The University of Chicago Press, Chicago, 1967), p. 176 ff). The bubble will then rise to the surface, driven by the Coulomb force of attraction to its own image charge induced in the surface. It will then burst through the surface to uniformly coat the drop with one electron charge on its outside surface. The electron will be in an $S$-state in order to minimize the energy of the system. This then is the ground state of the system.

[16] Note that the quantum-mechanical ground-state wavefunction (or complex order parameter) must remain *single-valued* (according to a distant inertial observer) globally at all times everywhere inside the interior of the system during the passage of a gravity wave. This is another aspect of the “quantum rigidity” of a quantum fluid in its response to the gravity wave.

[17] A. Yariv, *Quantum Electronics*, 1st edition (John Wiley & Sons, New York, 1967), page 223ff.

[18] This single quantum entity can be viewed as if it were a gigantic atom, in which the usual atomic nucleus is replaced by the superfluid helium drop, and the usual electronic cloud surrounding the atomic nucleus is replaced by the electrons on the surface surrounding the drop. The large energy gap (Equation (31)) arising from the large applied magnetic field is what makes this gigantic atom extremely rigid and dissipationless at low temperatures. A pair of such gigantic atoms forms a gigantic diatomic molecule. If the charges and masses of the two drops are slightly different from each other, such a gigantic diatomic molecule will form an entangled state of charge and mass in its ground state.

[19] R. B. Laughlin, Phys. Rev. Letters **50**, 1395 (1983).

[20] The principle of equivalence should apply to all charges and fields in curved spacetime. However, Maxwell’s equations, as usually formulated for standard electromagnetism, are expressed in terms of fields on a flat spacetime. They must be generalized to fields on a *curved* spacetime when interactions with gravitational radiation are considered. The back-action of EM waves propagating in a curved spacetime upon GR waves can in principle arise from the contribution of the Maxwell stress-energy tensor, which is *quadratic* in the EM field strengths, as a source term on the right-hand side of Einstein’s field equations. Such quadratic terms would give rise to second harmonic generation in the conversion of EM to GR waves, but not to first harmonic generation. However, there can in principle arise a *linear* coupling of EM to GR waves when a strong DC magnetic field is present, and Einstein’s equations are linearized in the weak EM and GR wave amplitudes. This linear coupling arises from a mixing term, which consists of a product of the DC magnetic field strength and the EM wave amplitude in the quadratic Maxwell stress-energy tensor that leads to first harmonic generation of GR waves at the same frequency as that of the incident EM waves in a linear scattering process. The role of the “Millikan oil drops” is
that they can greatly enhance the coupling between EM and GR waves due to their extreme rigidity and large masses. The electrons on their surfaces tightly tie the local B field lines to these drops, so that these lines are firmly anchored to the drops. At very low temperatures when the system remains adiabatically in the ground state, the B field lines and the drops co-move rigidly together according to a distant observer, when the system is disturbed by the passage of a GR or an EM wave. A given drop, however, remains at rest with respect to a local inertial observer at the center of the drop, and the local B field lines also do not appear to move with respect to this local inertial observer. By contrast, to the distant inertial observer in an asymptotically flat region of spacetime far away from the drops, where radiation fields become asymptotically well defined, a pair of massive, charged drops appear to be in relative motion, and the system emits energy in both GR and EM radiations. Thus a graviton (spin 2) can in principle be produced from a photon (spin 1) in the presence of a DC magnetic field (spin 1), in a scattering process from the drops.

[21] R. Y. Chiao in the proceedings of the NASA conference “Quantum to Cosmos” [quant-ph/0606118], to be published in Int. J. Mod. Phys. D.