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Theoretical Analysis of a Reported Weak Gravitational Shielding Effect.

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Abstract

Under special conditions (Meissner-effect levitation in a high frequency magnetic field and rapid rotation) a disk of high-T_c superconducting material has recently been found to produce a weak shielding of the gravitational field. We show that this phenomenon has no explanation in the standard gravity theories, except possibly in the non-perturbative Euclidean quantum theory.

04.20.-q Classical general relativity.
04.60.-m Quantum gravity.
74.72.-h High-T_c cuprates.

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In two recent experiments [1, 2], Podkletnov and co-workers have found indications for a possible weak shielding of the gravitational force through a disk of high-T_c superconducting material. In the first experiment a sample made of silicon dioxide of the weight of ca. 5 g, was found to lose about 0.05% of its weight when placed 15 mm above the disk. The diameter of the disk was 145 mm and its thickness 6 mm. The disk was refrigerated using liquid helium and was levitating over a solenoid due to the Meissner effect. When the disk was set in rotation by means of lateral alternating magnetic fields, the shielding effect increased up to 0.3%. When the disk was not levitating, but was placed over a fixed support, no shielding was observed.

In the second experiment the disk had the form of a toroid with the outer diameter of 275 mm and was enclosed in a stainless steel cryostat. Samples of different composition and weight (10 to 50 g) were placed over the disk and the same percentual weight loss was observed for different samples, thus enforcing the interpretation of the effect as a slight diminution of the gravitational acceleration. While the toroid was rotating (at an angular speed of 5000 rpm) the weight loss was of 0.3-0.5%, like in the first experiment, but it reached a maximum of 1.9-2.1% when the speed was slowly reduced by varying the current in the solenoids.

In both experiments, the magnetic fields were produced by high frequency currents and the maximum effect was observed at frequencies of the order of ca. 1 MHz. Measurements were effected also in the vacuum, in order to rule out possible buoyancy effects. The dependence of the shielding value on the height above the disk was very weak. Within the considered range (from a few cm to 300 cm) no sensible variation of the shielding value was observed. This weak height dependence is a severe challenge for any candidate theoretical interpretation, as it violates an intuitive vectorial representation of the shielding. We have analyzed in detail this issue in [3].

Independent repetitions of the experiment have already been undertaken, stimulated by scientific and especially technological interest. We would like to stress here the importance of precise measurements. In particular, it is essential to obtain exact spatial field maps and information about the transient stages. It is also crucial to use a different kind of balance from that used by the authors of [1, 2] and possibly a gravity gradiometer [4]. If the effect turned out to be of non-gravitational nature, its fundamental interest would be strongly reduced. On the contrary, if the effect is really a gravitational shielding its theoretical explanation calls for new and non-trivial dynamical mechanisms, as we argue in the following.

For clarity we shall organize our analysis as follows. Considering two masses m_1 and m_2 (which represent the Earth and the sample) and a medium between them (the disk), we shall evaluate their potential energy in these alternatives:

(1) the *medium* can be regarded as a classical system, as a quantum system, or as a Bose condensate with macroscopic wave function;

(2) the *gravitational field* can be regarded as classical or quantized, and in both cases as weak (perturbations theory) or strong.

In which of these approximations could a shielding effect arise? We can immediately observe that the possibilities of Point (1) are severely restricted by a large body of experimental evidence. Namely a sensible gravitational shielding has never previously been observed. Several experiments, starting with the classical measurements of Q. Majorana, have shown that the gravitational force is not influenced by any medium, up to one part in 10^{10} or less (for a very complete list of references see [5]). For a "classical" medium the reason for this is essentially the absence of charges of opposite sign which, by shifting or migrating inside the medium, might generate a field which counteracts the applied field. On the other hand when the medium is regarded as a quantum system, it is easy to check that the probability of a (virtual) process in which a graviton excites an atom or a molecule of the medium and is absorbed is exceedingly small, essentially due to the smallness of the gravitational coupling at the atomic level (see for instance [6]). It is then clear that the reported shielding can only be due to the Bose condensate present in the high-T_c superconductor.

Coming to Point (2), first we regard the gravitational field as classical. It is readily realized that in general neither the superconducting disk nor any other object of reasonable density, if placed close to the sample mass, can influence the local geometry so much as to modify its weight by the observed amount. To check this one just needs to write the Einstein equations (or even some generalizations of them) and impose suitable conditions on the source $T_{\mu\nu}$:

$$\begin{aligned} & R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = -8\pi G T_{\mu\nu}; \qquad (1) \\ & G \sim 10^{-66}\ cm^2 \quad \text{in natural units;} \\ & |T_{\mu\nu}| < ... \end{aligned}$$

Let us be more explicit: according to Einstein equations any apparatus with mass-energy comparable to that of Ref.s [1, 2], if placed far away from any other source of gravitation, is unable to produce a gravitational field of the intensity of ca. 0.01 g †. The shielding effect, if

† When examining this possibility one should hypothesize that the disk produces a repulsive force. But it is known that arguments in favour of "antigravity" are untenable [7] and that local negative energy densities

true, must then consist of some kind of "absorbtion" of the Earth's field in the superconducting disk.

Having thus excluded any possibility of shielding for a classical gravitational field, we need now an expression for the gravitational potential energy of two masses m_1 and m_2 which takes into account quantum field effects, possibly also at non-perturbative level. This is given in Euclidean quantum gravity by the functional integral [13]

$$E = \lim_{T\to\infty} -\frac{\hbar}{T}\log\frac{\int d[g]\,\exp\left\{-\hbar^{-1}\left[S_g+\sum_{i=1,2}m_i\int_{-\frac{T}{2}}^{\frac{T}{2}}dt\,\sqrt{g_{\mu\nu}[x_i(t)]\dot{x}_i^\mu(t)\dot{x}_i^\nu(t)}\right]\right\}}{\int d[g]\,\exp\left\{-\hbar^{-1}S_g\right\}} \tag{2}$$

$$\equiv \lim_{T\to\infty} -\frac{\hbar}{T}\log\left\langle \exp\left\{-\hbar^{-1}\sum_{i=1,2}m_i\int_{-\frac{T}{2}}^{\frac{T}{2}}ds_i\right\}\right\rangle_{S_g}. \tag{3}$$

where S_g is the gravitational action

$$S_g = \int d^4x\,\sqrt{g}\left(\frac{\Lambda}{8\pi G}-\frac{R}{8\pi G}+\frac{1}{4}aR_{\mu\nu\rho\sigma}R^{\mu\nu\rho\sigma}\right). \tag{4}$$

The R^2 term in S_g (important only at very small scale) is necessary to ensure the positivity of the action. The trajectories $x_i(t)$ of m_1 and m_2 are parallel with respect to the metric g; let L be the distance between them, corresponding to the spatial distance of the two masses. An evaluation of (3) in the non-perturbative lattice theory has ben carried out recently by Hamber and Williams [14].

In perturbation theory [15] the metric $g_{\mu\nu}(x)$ is expanded in the traditional way as the sum of a flat background $\delta_{\mu\nu}$ plus small fluctuations $\kappa h_{\mu\nu}(x)$ ($\kappa=\sqrt{8\pi G}$). The cosmological and the R^2 terms are dropped, leaving the pure Einstein action. Eq. (2) is rewritten as

$$E = \lim_{T\to\infty} -\frac{\hbar}{T}\log\frac{\int d[h]\,\exp\left\{-\hbar^{-1}\left[S_{\mathrm{Einst.}}+\sum_{i=1,2}m_i\int_{-\frac{T}{2}}^{\frac{T}{2}}dt\,\sqrt{1+h_{00}[x_i(t)]}\right]\right\}}{\int d[h]\,\exp\left\{-\hbar^{-1}S_{\mathrm{Einst.}}\right\}}, \tag{5}$$

where the trajectories $x_1(t)$ and $x_2(t)$ are two parallel lines in flat space. Expanding (5) in powers of κ one obtains to lowest order the Newton potential [13], and to higher orders its relativistic and quantum corrections [16].

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are strongly constrained in Quantum Field Theory (see for instance [8]). There remains only the possibility of gravitomagnetic and gravitoelectric effects, which are however usually very small [9]. In [10] it is argued using the Maxwell-like approximated form of Einstein equations that the gravitoelectric field produced by a superconductor could be abnormally strong. In our opinion this conclusion contrasts with the full equations (2). For a comparison, consider the strength of the "gravitational Meissner effect": in a neutron star with density of about 10^{17} kg/m^3 the gravitational London penetration depth is ca. 12 km [11]. An experimental check disproving the hypothesis of a repulsive force is the measurement of g *below* the disk. Preliminary measurements [12] do not show any variation of g.

The Bose condensate composed by the Cooper pairs inside the superconductor is described by a bosonic field ϕ with non-vanishing vacuum expectation value $\phi_0 = \langle 0|\phi|0\rangle$. Using the notation $\phi = \phi_0 + \tilde{\phi}$, the action of such a field coupled to the gravitational field has the form

$$S_\phi = \int d^4x \sqrt{g(x)} \quad \Big\{\partial_\mu \left[\phi_0(x) + \tilde{\phi}(x)\right]^* \partial_\nu \left[\phi_0(x) + \tilde{\phi}(x)\right] g^{\mu\nu}(x) \\ + \frac{1}{2}m^2|\phi_0(x)|^2 + \frac{1}{2}m^2 \left[\phi_0^*(x)\tilde{\phi}(x) + \phi_0(x)\tilde{\phi}^*(x)\right] + \frac{1}{2}m^2|\tilde{\phi}(x)|^2\Big\}, \quad (6)$$

where m is the mass of a Cooper pair. In order to describe the interaction we insert S_ϕ into (2) and include $\tilde{\phi}$ into the integration variables, while ϕ_0 is considered as an external source, being determined essentially by the structure of the superconductor and by the external e.m. fields. In the following we shall disregard in S_ϕ the terms containing $\tilde{\phi}$, as they give rise to emission-absorption processes of gravitons which we know to be irrelevant.

Perturbatively, the interaction of $h_{\mu\nu}(x)$ with the condensate $\phi_0(x)$ is principally mediated by the vertex

$$\mathcal{L}_{h\phi_0} = \kappa\partial_\mu\phi_0^*(x)\partial_\nu\phi_0(x)h^{\mu\nu}(x). \quad (7)$$

This produces corrections to the gravitational propagator, which are however practically irrelevant, because they are proportional to powers of $\kappa \sim 10^{-33}$ cm. It is straightforward to compute the corresponding corrections to eq. (5). We do not need to investigate in detail the signs of these corrections or their dependence from ϕ_0: they are in any case too small (by several magnitude orders) to account for the reported shielding effect.

Looking at the total action $S = S_g + S_\phi$ we recognize besides the familiar vertex (7) a further coupling between $g_{\mu\nu}(x)$ and $\phi_0(x)$. Namely, the Bose condensate contributes to the cosmological term. We can rewrite the total action (without the R^2 term for gravity) as

$$S = S_g + S_\phi = \int d^4x \sqrt{g(x)} \left\{ \left[\frac{\Lambda}{8\pi G} + \frac{1}{2}\mu^2(x)\right] - \frac{R}{8\pi G}\right\} + S_{h\phi_0} + S_{\tilde{\phi}}, \quad (8)$$

where

$$\frac{1}{2}\mu^2(x) = \frac{1}{2}\left[\partial_\mu\phi_0(x)\right]^* \left[\partial^\mu\phi_0(x)\right] + \frac{1}{2}m^2|\phi_0(x)|^2, \quad (9)$$

$$S_{h\phi_0} = \int d^4x \sqrt{g(x)}\mathcal{L}_{h\phi_0} \quad (10)$$

and $S_{\tilde{\phi}}$ comprises the terms which contain at least one field $\tilde{\phi}$ and are thus irrelevant, as we mentioned above.

We see from (8) that the condensate $\phi_0(x)$ and its four-dimensional gradient give a positive contribution to the intrinsic cosmological term $\Lambda/8\pi G$. It is known that a positive cosmological constant turns Eintein gravity into an unstable theory, as it corresponds in the action to a mass term with negative sign [15]. In the case we are considering here, the cosmological term is spacetime dependent. The situation is thus quite complicated and we shall just sketch it briefly in the following; a more complete account can be found in [17].

Since in any four-dimensional region Ω in which $\mu^2 > |\Lambda|/8\pi G$ the mass term of the gravitational field is non-zero and negative, in this region the field can grow without limit, at least classically (suppose to minimize the action (4) by trial functions which are vacuum solutions ($R = 0$), disregarding the R^2 term). In fact there will be some physical cut-off; thus within Ω the gravitational field will be forced to some fixed value, independent of the external conditions. This is similar to what happens in electrostatics in the presence of perfect conductors: the electric field is constrained to be zero within the conductors. In that case the physical origin of the constraint is different (a redistribution of opposite charges); but in both cases the effect on the field propagator turns out to be that of a shielding.

At this point we would need an estimate for both $|\Lambda|/8\pi G$ and μ^2. It is known that the cosmological constant observed at astronomical scales is very small; a typical upper limit is $|\Lambda|G < 10^{-120}$, which means $|\Lambda|/8\pi G < 10^{12}\ cm^{-4}$. To estimate μ^2 we can assume an average density of Cooper pairs in the superconductor of $\sim 10^{20}\ cm^{-3}$. Remembering that the mass of a pair is $\sim 10^{10}\ cm^{-1}$ in natural units, we find that $\phi_0 \sim 10^5\ cm^{-1}$ and thus $m^2|\phi_0|^2 \sim 10^{30}\ cm^{-4}$. If ϕ_0 varies over distances of the order of $10^{-8} \div 10^{-7}\ cm$, as usual in high-T_c superconductors, the gradient $(\partial\phi_0/\partial x)$ can be of the order of $10^{12}\ cm^{-2}$.

These values support our hypothesis that the total cosmological term is positive in the superconductor. Actually the positive contribution of the condensate is such that one could expect the formation of gravitational singularities in any superconductor, subjected to external fields or not – a fact which contrasts with the observations. This can be avoided if we take the point of view, supported by lattice quantum gravity with a fundamental length [14, 17, 18], that the effective intrinsic cosmological constant depends on the momentum scale p like

$$|\Lambda|G \sim (\ell_0 p)^\gamma, \tag{11}$$

where $\ell_0 \sim \kappa$ is the fundamental lattice length (Planck length) and γ is a critical exponent which up to now has been computed only for small lattices. The sign of Λ is negative. This provides a well defined flat space limit for the non-perturbative Euclidean theory based on the action (4), and ensures that the signs in our discussion of the minimization of the total action are correct.

We hypothesize that at the length scale of $10^{-8} \div 10^{-6}$ cm Λ could be of the same order of the average of μ^2, so that the competition between the two terms would lead to singularities only in those regions of the superconductor where the condensate density is larger than elsewhere. From this hypothesis we deduce that $|\Lambda| \sim 10^{-36}$ cm^{-2}, a value well compatible with the conventional experimental data at that scale ‡.

In conclusion, a shielding effect of the reported magnitude cannot be explained by classical General Relativity, nor by the usual perturbation theory of quantum gravity coupled to the Cooper-pair density $\phi_0(x)$ through the vertex (7). We have then considered a further possible coupling mechanism: the term $\mu^2(x) = [\partial^\mu \phi_0^*(x)][\partial_\nu \phi_0(x)] + m^2\phi_0^2(x)$ in the condensate's action may act as a positive contribution to the effective gravitational cosmological constant. This may produce localized gravitational instabilities and thus an observable effect, in spite of the smallness of G, which makes the coupling (7) very weak. In the regions where the gravitational field becomes unstable it tends to take "fixed values" independent of the neighboring values. This reminds of the situation of electrostatics in the presence of perfect conductors. The effect on the field propagator and on the static potential is that of a partial shielding.

According to this picture, the magnetic fields which keep the disk levitating and rotating and produce currents inside it play the role (together with the microscopic structure of the HTC material) of determining the condensate density $\phi_0(x)$. The energy necessary for the partial "absorbtion" of the gravitational field is supplied by the high-frequency components of the magnetic field.

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‡ It corresponds to a graviton mass of $\sim 10^{-18}$ cm^{-1} and thus to a (unobservable) range of gravity of $\sim 10^{18}$ cm. Note that a similar argument allows to restrict the exponent γ in eq. (11) to $\gamma > 2$. In fact, for $\gamma = 2$ we would have $|\Lambda| \sim p^2$, in contradiction with the fact that in order to be unobservable the range of gravity must be much larger than the length scale p^{-1} which we are considering.

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