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The geometric field (gravity) as an electro-chemical potential in a Ginzburg-Landau theory of superconductivity

Victor Atanasov

Department of Condensed Matter Physics, Sofia University, 5 boul. J. Bourchier, 1164, Sofia, Bulgaria

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ABSTRACT

We extend the superconductor's free energy to include an interaction of the order parameter with the curvature of space-time. This interaction leads to geometry dependent coherence length and Ginzburg-Landau parameter which suggests that the curvature of space-time can change the superconductor's type. The curvature of space-time doesn't affect the ideal diamagnetism of the superconductor but acts as chemical potential. In a particular circumstance, the geometric field becomes order-parameter dependent, therefore the superconductor's order parameter dynamics affects the curvature of space-time and electrical or internal quantum mechanical energy can be channelled into the curvature of space-time. Experimental consequences are discussed.

1. Introduction

The predictions of the General Theory of Relativity (GTR), which offered an understanding of gravitation in terms of geometric field, were confirmed in a series of spectacular experiments [1]. However, the interaction of the geometric field with material media, the way in which the curvature of space-time affects the electronic properties of condensed matters systems on a micro- and macro-scopic scale is to a large extent unknown and due to its ability to be experimentally verified of interest and importance since this venue can provide an exit from the predicament that gravitation remains an observational phenomenon and not an interaction we can control and artificially create and explore. The exit from the predicament lies in condensed matter systems that can affect the properties of space-time, that is they are coupled to the geometric field in a reversible way and obey laws of conservation of energy. Therefore, by changing their state, energy can be channelled into the geometric field. In this paper we extend the Ginzburg-Landau theory of superconductivity to include an interaction of the order parameter with the geometric field and explore its consequences.

The interplay of geometry and topology in condensed matter systems has been well explored in low-dimensional magnetic systems. In support of the statement in the present paper, we remind an interesting result, namely a magnetic system (multiple interacting solitons) on a cylinder with constant radius cannot reach an absolute minimum of its magnetic energy due to the interaction between individual excitations. However, provided the underlying elastic support (the cylinder) is allowed to change radius, an interaction between the magnetic system's degrees of freedom and the geometry of the underlying support is established. Its form is very similar to the term discussed here. As a result of this extension the combined magnetic and geometric (elastic support) system reaches absolute minimum by relaxing the extra magnetic energy into deformation of the underlying support. Therefore, it is not an unique statement that we make in this paper, namely the underlying geometry can change as a result of the interaction with a condensed matter system [2].

Before we proceed, we would like to make an important distinction between two things: i.) the effects of the background geometry on the quantum condensate and ii.) the effects of the wave-function ($\psi -$ field) on the gravitational field. The background geometry enters the dynamics of the quantum condensate in two places, one is the coupling term which action we are going to discuss and the second is the covariant derivative which contains the Christoffel symbols. Throughout the paper we are going to assume that ∇ represents covariant differentiation and contains a remnant of the curved background geometry. However, due to the particular limiting cases we are going to consider, the presence of the Christoffel symbols in the covariant derivatives of the wave-function is not affecting the conclusions we are going to make. Indeed, one is tempted to assume that the background geometry is set on a macroscopic level by the distribution of matter as governed by GTR. The coupling of the matter content to the geometric field on a macro scale, that is the Einstein's gravitational constant $\approx 1.9 \times 10^{-26}\ \mathrm{m\,kg^{-1}}$ is hopelessly small to expect any interaction of the $\psi -$ field with the gravitational one. However, as discussed in the Appendix A, in the quantum condensate acting like a material medium an energy conservation relation emerges. This relation is

E-mail address: vatanaso@phys.uni-sofia.bg.

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analogous in meaning to the GTR equation (a form of conservation of energy on a macro scale) and involves a term containing an expression for the energy of the geometric field on a micro scale. Therefore, one can exploit this energy conservation relation to channel energy/change the curvature of the background field at least on microscopic scale. Moreover, as discussed in the Appendix A, the non-vanishing effects the wave-function of a quantum condensate can have on the gravitational field are associated with the similar action the Bohmian quantum potential and the geometric field have in the hydrodynamic form of the Schrödinger equation – they enter on an equal footing. As a result, we are led to believe that they have similar nature and therefore interact on a microscopic scale outside of what GTR governs. Ideas and experimental attempts on gravity-superconductor interactions are discussed in [3]. A strong point in favour of the ideas discussed here is the existence of experimental attempts at gravitational field generation via electric discharge through a superconducting medium [4]. However, the utilised structures are not characterised and the presence of intrinsic Josephson junctions is neither proven, nor deliberately sought. Therefore, we believe the paper would act as a stimulus, explanatory framework and experimental guidance for a future systematic attempt at verification.

The paper is organised as follows. Section 2 is devoted to the extension of the Ginzburg-Landau theory of superconductivity in order to include the interaction with the geometric field. The extra term is justified in this section but motivated in the Appendix A. Section 3 discusses the consequences of the extra term and leads to Section 4 where the experimentally relevant conditions to verify the quantum condensate – geometric field interaction are discussed. Section 5 concludes the paper which ends with an Appendix A.

2. Extension to the Ginzburg-Landau theory

The macroscopic phenomenological theory of superconductivity supposes that the superconductor is simply a charged quantum condensate superfluid. Its free energy was postulated by Ginzburg and Landau [5]. There are two degrees of freedom: i.) the complex valued superconductor's order parameter field

$$\psi(\vec{r}) = |\psi(\vec{r})| e^{i\theta(\vec{r})} = \sqrt{n_s(\vec{r})}\, e^{i\theta(\vec{r})}, \tag{1}$$

where $n_s = |\psi(\vec{r})|^2$ is the superfluid (charge) density and $|\psi(\vec{r})| = 0$ denotes the destruction of the superconducting state; ii.) the vector potential field $\vec{A}(\vec{r})$ for the electromagnetic degrees of freedom.

The Ginzburg-Landau free energy has the form

$$F_{net}(\psi, \vec{A}) = \int d^3x \mathcal{F}_{GL}, \tag{2}$$

where

$$\mathcal{F}_{GL} = \mathcal{F}_L + \mathcal{F}_{grad} + w_{mag}. \tag{3}$$

Here the first term

$$\mathcal{F}_L = \alpha |\psi(\vec{r})|^2 + \frac{\beta}{2} |\psi(\vec{r})|^4 \tag{4}$$

is the Landau term of mean field theory type and codes the free energy in a spatially homogenious state. The second term $\mathcal{F}_{grad} = \frac{\hbar^2}{2m^*} |\nabla\psi(\vec{r})|^2$ is of gradient type and codes the kinetic energy of the condensate correctly only near the critical temperature (T_c) where $|\psi| \ll 1$ is small. In the case of a charged fluid (superconductor) the theory needs slight modification, that is the addition of magnetic field energy density $w_{mag} = \frac{|\vec{B}|^2}{2\mu_0}$ and the gradient is replaced by its gauge invariant version

$$\mathcal{F}_{grad} = \frac{\hbar^2}{2m^*} |\nabla_A \psi(\vec{r})|^2 = \frac{\hbar^2}{2m^*} \left| \left(\nabla - \frac{ie^*}{\hbar m^*} \vec{A}(\vec{r}) \right) \psi(\vec{r}) \right|^2 \tag{5}$$

Provided the interaction between the electrons in the material is short-ranged as compared to the scale on which $\psi(\vec{r})$ varies, the different terms have the following origin: i.) gradient term is the kinetic energy; ii.) $|\psi(\vec{r})|^4$ term represents interaction and iii.) $|\psi(\vec{r})|^2$ term represents a combination of electrical and temperature-dependent chemical potential. In the superconductor the chemical potential controls the pairing ability of the fermions and as Lagrange multiplier reveals the number of (density of) bosons, that is Cooper pairs.

In the present paper we are going to extend the Ginzburg-Landau theory with an extra term in order to encode the properties of the quantum condensate in curved space-time and the interaction of its wavefunction with the geometric field (and vice-versa). The extra free energy density that needs to be included in the expression (3) is

$$\mathcal{F}_{geom} = \gamma R^{(3d)} |\psi(\vec{r})|^2, \tag{6}$$

where $R^{(3d)}$ is the induced three-dimensional Ricci scalar curvature and $\gamma = -\hbar^2/24\, m^*$. This extra term preserves the symmetries of Ginzburg-Landau theory as they are, therefore the theory

$$F_{net}(\psi, \vec{A}) = \int d^3x (\mathcal{F}_{GL} + \mathcal{F}_{geom}) \tag{7}$$

is invariant under the same gauge transformations.

The justification of the geometric term can be traced from the time-dependent extension of the Ginzburg-Landau theory

$$i\hbar \frac{\partial\psi}{\partial t} = \frac{\delta F_{net}}{\delta\overline{\psi}}, \tag{8}$$

where $\overline{\psi}$ denotes complex conjugation. This can be split into real and imaginary parts with the help of the trigonometric substitution (1):

$$\hbar \frac{\partial\theta}{\partial t} = -\frac{\delta F_{net}}{\delta n_s}, \tag{9}$$

$$\hbar \frac{\partial n_s}{\partial t} = \frac{\delta F_{net}}{\delta\theta}. \tag{10}$$

These last two equations resemble Hamilton's equations of motion. Therefore, n_s and θ are canonically conjugate.

Dirac proposed a phase observable operator $\hat{\theta}$, presumably canonically conjugate to the number of particles operator [7], that is $\hat{n}_s$ (using a harmonic oscillator as a toy model the commutator is given by $[\hat{n}_s, \hat{\theta}] = i\hat{1}$). Unfortunately, defining these operators in the general case has long been an unresolved problem in quantum mechanics [8].

However, in the case of a quantum condensate, particles share a macroscopic quantum state, and the condensate exhibits manifestly classical properties. In the case of a Josephson junction between superconductors the phase difference between the two condensates is measurable as well as its particle number expressed as charge density. Anderson used the uncertainty relation

$$\delta n_s \delta\theta \geq \frac{1}{2} \tag{11}$$

between phase and charge density in the semi-classical context of superconductors [9]. Thus as operators in the case of charged quantum condensates, $\hat{n}_s$ and $\hat{\theta}$ are quantum mechanically conjugate [10,11]. As a result, the Heisenberg uncertainty principle stated above applies and can be read in the following manner: as the quantum condensate is destroyed n_s=0 ($\delta n_s = 0$) (specified exactly), its phase is indefinite $\delta\theta = \infty$ (cannot be specified). In the present paper we will show a relation between the phase of the quantum condensate and the curvature of the geometric field (that is gravity). Since there exists a state in which the phase cannot be specified, then in this state the geometry of space-time cannot be specified to being exactly flat. In this state one can channel energy into the geometric field and create curved space-time configuration.

Now, let us return to the justification of the geometric term (6) to the free energy density (7). We put (7) into (12) to obtain

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