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Kondo effect from a Lorentz-violating domain wall description of superconductivity

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A B S T R A C T

We extend recent results on domain wall description of superconductivity in an Abelian Higgs model by introducing a particular Lorentz-violating term. The temperature of the system is interpreted through the fact that the soliton following accelerating orbits is a Rindler observer experiencing a thermal bath. We show that this term can be associated with the *Kondo effect*, that is, the Lorentz-violating parameter is closely related to the concentration of magnetic impurities living on a superconducting domain wall. We also found that the critical temperature decreasing with the impurity concentration as a non-single-valued function, for the case $T_K < T_{c0}$, develops a negative curvature and presents deviations from the Abrikosov and Gor'kov theory, a phenomenon already supported by experimental evidence.

1. Introduction

In a recent study was put forward an alternative theory of superconductivity in field theory through domain wall description of superconductivity [1]. Now we extend this investigation by considering a theory that allows Lorentz and CPT violation. The possibility of breaking Lorentz and CPT symmetries has been considered in many works in the literature [2–4]. On the other hand, there are many studies on superconducting solitons as, for example, superconducting strings [5,6] and related solutions such as domain walls with internal structures [7,8]. Since such soliton solutions can follow non-trivial orbits in the field space [8], they are mostly forced to move along accelerated trajectories. In the limit of small velocities these solutions can be identified as Rindler observers [1] in a thermal bath which allows to introduce temperature in the system via Unruh effect, supporting an investigation of thermodynamic quantities in the domain wall description of superconductivity. The quantum field theory can explain several important effects of superconductivity through an appropriate classical regime of a quantum field theory inspired by the Ginzburg–Landau (GL) theory [9,10]. In the present model, this description uses a dynamical complex scalar field coupled to Abelian gauge field (the Abelian Higgs sector) which is responsible for superconductivity of the system and an extra real scalar field responsible for the domain walls plus other terms that breaks the Lorentz and CPT symmetries.

Lorentz and CPT symmetries are important properties in particle physics models and the possibility of breaking these symmetries has been considered in several different contexts [3,4]. The models considering Lorentz and CPT symmetries violations as extensions of the standard model can modify the scalar Higgs sector and this gives room for defect structures of more general profiles [2].

The main feature presented in our model is that it can describe a domain wall superconductivity whose Lorentz-violating term can play the role of magnetic impurities in the superconductor. Magnetic impurities have a number of striking effects on superconductivity and one of their effects is the Kondo effect [11,12]. As we shall show, our model can describe the well-known competition between Kondo effect and superconductivity [13,14] at the domain wall.

The Letter is organized as follows. In Sec. 2 we present the model enriched with the term that allows the Lorentz and CPT symmetries breaking, which enjoys a new parameter — the *Lorentz-violating parameter*. In Sec. 3 we consider the soliton solutions as background fields to solve a Schroedinger-like equation for the electromagnetic field. In Sec. 4 we calculate the condensate at finite temperature as a function of the new parameter. In Sec. 5 we find the optical conductivity of the system and discuss the influence of the new parameter. In Sec. 6, we establish a clear relationship between the Lorentz-violating parameter and the concentration of impurities of a superconducting material with

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magnetic impurities which develops the *Kondo effect*. Finally, in the Sec. 7 we make our conclusions.

2. The model with $\kappa^{\mu\nu}$

In this section we follow the Lagrangian that describes the superconducting domain wall given by [1]

$$\mathcal{L}=\frac{1}{2}\partial_\mu\phi\partial^\mu\phi+(\partial^\mu\chi+iqA^\mu\chi)(\partial_\mu\chi^*-iqA_\mu\chi^*)$$
$$-V(\phi,\chi,\chi^*)-\frac{1}{4}F_{\mu\nu}F^{\mu\nu}, \tag{1}$$

where $\mu,\nu=0,1,2,...,d$ are bulk indices for arbitrary $(d-2)$-dimensional domain walls. In the present case, we shall focus on 2-dimensional domain walls such that $\mu,\nu=t,x,y,r$.

Let us now extend this Lagrangian to study a model with the possibility of Lorentz-symmetry violation. Firstly, we consider the class of models with real scalar fields [2]

$$\mathcal{L}=\frac{1}{2}\partial_\mu\phi\partial^\mu\phi+\frac{1}{2}\kappa^{\mu\nu}\partial_\mu\phi\partial_\nu\phi+\frac{1}{2}\partial_\mu\chi\partial^\mu\chi$$
$$+\frac{1}{2}\kappa^{\mu\nu}\partial_\mu\chi\partial_\nu\chi-V(\phi,\chi), \tag{2}$$

where $\kappa^{\mu\nu}$ is a constant tensor whose components in general read

$$\kappa^{\mu\nu}=\begin{pmatrix}\zeta & \varepsilon & \varepsilon & \varepsilon\\ \varepsilon & \zeta & \varepsilon & \varepsilon\\ \varepsilon & \varepsilon & \zeta & \varepsilon\\ \varepsilon & \varepsilon & \varepsilon & \zeta\end{pmatrix}, \tag{3}$$

with ζ and ε being real parameters and the scalar potential is given in terms of a 'superpotential' W as follows

$$V(\phi,\chi)=\frac{1}{2}W_\phi^2+\frac{1}{2}W_\chi^2, \tag{4}$$

where W_{ϕ_i} stands for partial derivatives of W with respect to fields ϕ_i. The equations of motion are given by

$$\Box\phi+\kappa^{\mu\nu}\partial_\mu\partial_\nu\phi=-\frac{\partial V(\phi,\chi)}{\partial\phi}, \tag{5}$$

$$\Box\chi+\kappa^{\mu\nu}\partial_\mu\partial_\nu\chi=-\frac{\partial V(\phi,\chi)}{\partial\chi}. \tag{6}$$

Now for simplicity, but keeping the scenario still rich enough for our present discussion, we take $\varepsilon=0$, then the equations of motion for the fields $\phi\equiv\phi(t,r)$ and $\chi\equiv\chi(t,r)$ are

$$\ddot\phi-\phi''+\zeta(\ddot\phi+\phi'')=-\frac{\partial V(\phi,\chi)}{\partial\phi}, \tag{7}$$

$$\ddot\chi-\chi''+\zeta(\ddot\chi+\chi'')=-\frac{\partial V(\phi,\chi)}{\partial\chi}. \tag{8}$$

Thus, for static solutions we get

$$\phi''(1-\zeta)=\frac{\partial V(\phi,\chi)}{\partial\phi}, \tag{9}$$

$$\chi''(1-\zeta)=\frac{\partial V(\phi,\chi)}{\partial\chi}. \tag{10}$$

By making the following transformation on the transversal coordinate r

$$\widetilde{r}=\frac{r}{\sqrt{1-\zeta}}, \tag{11}$$

the equations of motion for the scalar fields can be rewritten as

$$\phi''(\widetilde{r})=\frac{\partial V}{\partial\phi}, \tag{12}$$

and

$$\chi''(\widetilde{r})=\frac{\partial V}{\partial\chi}. \tag{13}$$

The dynamics of the model (2) governed by the equations of motion (12) and (13) can be reduced to the first order equations [7,8]

$$\frac{d\phi}{d\widetilde{r}}=W_\phi, \qquad \frac{d\chi}{d\widetilde{r}}=W_\chi. \tag{14}$$

For a specific superpotential

$$W(\phi,\chi)=\lambda\left(\frac{1}{3}\phi^3-\phi a^2\right)+\mu\phi\chi^2 \tag{15}$$

the model produces domain wall solutions whose kink profiles are the following well-known BPS static solutions, known as type I solution

$$\phi=-a\tanh(\lambda a\widetilde{r})$$
$$\chi=0 \tag{16}$$

and type II solution

$$\phi=-a\tanh(2\mu a\widetilde{r})$$
$$\chi=\pm a\sqrt{\frac{\lambda}{\mu}-2}\,\mathrm{sech}(2\mu a\widetilde{r}). \tag{17}$$

For latter convenience, the type II solution in terms of the original coordinate r is

$$\widetilde{\phi}=-a\tanh\left(\frac{2\mu a}{\sqrt{1-\zeta}}r\right)$$
$$\widetilde{\chi}=\pm a\sqrt{\frac{\lambda}{\mu}-2}\,\mathrm{sech}\left(\frac{2\mu a}{\sqrt{1-\zeta}}r\right). \tag{18}$$

3. Superconducting type II domain wall solution

The superconducting domain wall developing a condensate can be obtained from the following Lagrangian with Lorentz-violating symmetry but preserves the $Z_2\times U(1)$ symmetry:

$$\mathcal{L}=\frac{1}{2}\partial_\mu\phi\partial^\mu\phi+\frac{1}{2}\kappa^{\mu\nu}\partial_\mu\phi\partial_\nu\phi+D_\mu\chi(D^\mu\chi)^*$$
$$+\kappa^{\mu\nu}D_\mu\chi(D_\nu\chi)^*-V(\phi,\chi,\chi^*)-\frac{1}{4}F_{\mu\nu}F^{\mu\nu}, \tag{19}$$

where $D_\mu=\partial_\mu-iqA_\mu$ and $F^{\mu\nu}=\partial^\mu A^\nu-\partial^\nu A^\mu$. The potential is appropriately chosen as

$$V(\phi,\chi,\chi^*)=\frac{1}{2}\lambda^2(\phi^2-a^2)^2+\lambda\mu(\phi^2-a^2)|\chi|^2$$
$$+\frac{1}{2}\mu^2|\chi|^4+\mu^2\phi^2|\chi|^2. \tag{20}$$

The equations of motion for the coupled complex scalar and electromagnetic fields are given by

$$\Box\chi+\kappa^{\mu\nu}[\partial_\mu\partial_\nu\chi-iqA^\nu\partial_\nu\chi-iqA_\mu\partial_\mu\chi-q^2A_\mu A_\nu\chi]$$
$$+\frac{\partial V}{\partial\chi^*}-q^2A_\mu A^\nu\chi-2iqA^\gamma\partial_\gamma\chi=0, \tag{21}$$

$$\Box A^\theta+\kappa^{\mu\nu}[iq\chi^*\partial^\theta\chi-iq\chi\partial^\theta\chi^*+q^2\delta^\theta_\mu A_\nu|\chi|^2$$
$$+q^2\delta^\theta_\nu A_\mu|\chi|^2]+iq[\chi^*\partial^\theta\chi-\chi\partial^\theta\chi^*]-2q^2A^\theta|\chi|^2=0. \tag{22}$$