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The Conditions Necessary for Superconductivity in Charge Density Wave Materials

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Abstract: *We investigate the criteria necessary for the occurrence of superconductivity in one-dimensional charge density wave (CDW) materials. If CDWs are unpinned, it is well-known that superconductivity can happen by the work of Fröhlich. One-dimensional CDW materials are comprised of periodic superconducting regions in the form of unpinned ones bridged by quantum wire equivalent to pinned one that connects them under the scheme of intrinsic Josephson arrays. Using the one-dimensional Kronig-Penney model, we obtain the conditions necessary for superconductivity in CDW materials.*

Keywords: *Charge Density Wave, Superconductivity, Josephson Array, Quantum wire, coherence length.*

1. INTRODUCTION

After the initial publication of Bardeen et al. (BCS) [1], Josephson [2] predicted a new phenomenon in low-T_c superconductors including a previously undiscovered supercurrent with completely new current-voltage characteristics. It was described the superconducting condensates are transferred into two weakly coupled superconductors by a quantum mechanical complex wave function and its respective phase. It was depicted that if the two phases differed by ψ, then a supercurrent given by $I = I_c \sin\psi$ flows spontaneously across the junction in the absence of an applied voltage, while this novel quantum mechanical phenomenon was confirmed one year later [3]. In the decades that followed, both theoretical and experimental research into the Josephson effect has been of great interest in low temperature physics. For theoretical and experimental focus [4-6] in one-dimensional realization, it is dominated by charge density waves (CDWs) in Si-nanowires, as originally conceived by Fröhlich in 1954, in order to explain BCS-type superconductivity at ultra low transition temperatures [7]. It was reported previously that metal-insulator transition will occur if there are electron-phonon interactions in a one-dimensional sense [8]. While Fröhlich considered the implied energy gap to be a superconducting gap consistent with the occurrence of CDWs, Peierls believed that CDWs occur concurrently with superlattices to induce an insulating gap. Sliding CDWs are pinned either by the impurity (impurity pinning) or by lattice ions (commensurate pinning). If CDWs are unpinned, it is well-known that superconductivity can happen by the work of Fröhlich [7]. Koo et al. [9](in our group) insisted that one-dimensional CDW materials are comprised of periodic superconducting regions that are unpinned and bridged by quantum wire of pinned one connecting them under the scheme of intrinsic Josephson junctions.

In this paper, we investigate the criteria necessary for the occurrence of superconductivity in one-dimensional charge density wave (CDW) materials.

2. THE CONDITIONS NECESSARY FOR SUPERCONDUCTIVITY IN CDW MATERIALS

One-dimensional Josephson arrays can be approximated by periodic Kronig-Penney models [10] as

$$\cos(ka) = \cos(\beta b)\cos[\alpha(a-b)] - \frac{\alpha^2+\beta^2}{2\alpha\beta}\sin(\beta b)\sin[\alpha(a-b)]$$
$$\alpha^2 = \frac{2mE}{\hbar^2}, \beta^2 = \frac{2m(E+V_0)}{\hbar^2}, \tag{1}$$

where E is the kinetic energy, m is the mass of an electron, V_0 is the potential height in the interval b with one net periodic interval a, $\hbar$ is Planck's constant divided by 2π, and k is a wave number corresponding to energy loss. To conserve superconductivity as shown in Fig 1., the following must be satisfied:

$$1 = \cos(\beta b)\cos[\alpha(a-b)] - \frac{\alpha^2+\beta^2}{2\alpha\beta}\sin(\beta b)\sin[\alpha(a-b)]$$
$$E = \varepsilon_F, V_0 = U_{BCS} + U_c, \tag{2}$$

where ε_F is the Fermi energy, U_{BCS} (U_c) is the phonon-mediated BCS (Coulomb) interaction between electrons, and

$$1 = \cos(\beta b)\cos[\alpha(a-b)]$$
$$\beta b = \pi, \alpha(a-b) = \pi. \tag{3}$$

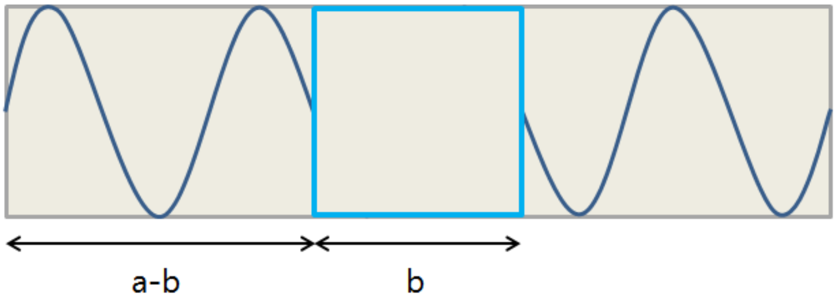

Fig1. *Pinned CDWs are confined [9] and superconductivity occurs inside this unpinned zone. The ripples show CDWs and the blue box denotes a normal insulating or metallic pinned zone, such that the superconductor-insulator-superconductor equivalent to unpinned-pinned-unpinned zone is a Josephson junction. This junction is periodically repeated through the bulk CDW material in order to be thought of in terms of intrinsic Josephson arrays*

The solution then becomes

$$b = \frac{\pi}{\beta}, a = \frac{\pi}{\alpha} + \frac{\pi}{\beta}$$
$$E = \varepsilon_F, V_0 = U_{BCS} + U_c \tag{4}$$
$$\alpha^2 = \frac{2m\varepsilon_F}{\hbar^2}, \beta^2 = \frac{2m(\varepsilon_F + U_{BCS} + U_c)}{\hbar^2}.$$

From the solution of Eq. (4), we set the correlation length as

$$\xi \equiv b \tag{5}$$

and the wavelength of CDW is given as

$$\lambda_{CDW} \equiv a. \tag{6}$$

The ideal CDW superconductivity occurs only if $\xi \geq b$.

Let us consider time and temperature dependence similar to original methods.

It becomes

$$2\cos(ka) = \cos[\frac{2E+V_0}{\hbar}t + \beta b + \alpha(a-b)] + \cos[\frac{-V_0}{\hbar}t - \beta b + \alpha(a-b)]$$
$$-\frac{\alpha^2+\beta^2}{2\alpha\beta}\{\cos[\frac{-V_0}{\hbar}t - \beta b + \alpha(a-b)] - \cos[\frac{2E+V_0}{\hbar}t + \beta b + \alpha(a-b)]\} \tag{7}$$
$$\alpha^2 = \frac{2mE}{\hbar^2}, \beta^2 = \frac{2m(E+V_0)}{\hbar^2}$$

and

$$2 = \cosh[\frac{2E+V_0}{\hbar\hat{\beta}k_BT}] + \cosh[\frac{-V_0}{\hbar\hat{\beta}k_BT}] - \frac{\alpha^2+\beta^2}{2\alpha\beta}\{\cosh[\frac{-V_0}{\hbar\hat{\beta}k_BT}] - \cosh[\frac{2E+V_0}{\hbar\hat{\beta}k_BT}]\}$$
$$\beta b = \pi, \alpha(a-b) = \pi \tag{8}$$
$$\alpha^2 = \frac{2mE}{\hbar^2}, \beta^2 = \frac{2m(E+V_0)}{\hbar^2},$$

where $0 = k = K - K, t = i\frac{1}{\hat{\beta}k_BT}$ is given via Matusbara relation [11], $\hat{\beta}$ is a constant, and K is a momentum of an electron in a Cooper pair.

We now consider coherence lengths ξ in CDW materials.

We obtain

$$\xi_0 = \xi(T=0),$$
$$2 = \cosh[\frac{2E+V_0}{\hbar\hat{\beta}k_BT}] + \cosh[\frac{-V_0}{\hbar\hat{\beta}k_BT}] - \frac{\alpha^2+\tilde{\beta}^2}{2\alpha\tilde{\beta}}\{\cosh[\frac{-V_0}{\hbar\hat{\beta}k_BT}] - \cosh[\frac{2E+V_0}{\hbar\hat{\beta}k_BT}]\}$$
$$\xi(T=0) = \frac{\pi}{\tilde{\beta}(T=0)}$$
$$\xi(T=0) = \frac{\pi}{\tilde{\beta}(T)}$$
$$\tilde{\beta}^2 \equiv \frac{2m\{\varepsilon_F + N_{CDW}(U_{BCS}+U_c)\}}{\hbar^2} \tag{9}$$
$$b = \frac{\pi}{\beta}, a = \frac{\pi}{\alpha} + \frac{\pi}{\beta}$$
$$E = \varepsilon_F, V_0 = U_{BCS} + U_c$$
$$\alpha^2 = \frac{2m\varepsilon_F}{\hbar^2}, \beta^2 = \frac{2m(\varepsilon_F + U_{BCS} + U_c)}{\hbar^2},$$

where $\varepsilon\, and\, \Delta$ respectively represent the kinetic energy and superconducting gap, N_{CDW} is the mean number of electrons in each pinned CDW [9], and $U_{BCS} + U_c$ varies according to position. For phase fluctuations denoted as $\nabla\theta$ and for a phase angle θ, physical quantities are contributed by phase fluctuations as

$$\int_{r_i}^{r_f}\sum_i f_i((\nabla\theta)^i)\,\mathrm{dr} \equiv \sum_l a_l\cos(l\pi r)\sum_m b_m\sin(m\pi r)|_{r_i}^{r_f} \equiv 0 \tag{10}$$
$$\because \cos(l\pi r_i)\sin(m\pi r_i) = 0, \cos(l\pi r_f)\sin(m\pi r_f) = 0,$$

where a_l and b_m are coefficients, r_i (r_f) are boundary positions in a quantum well, and f_i are functions.

3. Conclusion

In conclusion, nanowires are known to be governed by charge density waves (CDW). One dimensional CDW materials are comprised of periodic superconducting regions that are pinned and bridged by quantum wire connecting them under the scheme of intrinsic Josephson arrays. We have investigated the criteria of occurrence of superconductivity in one-dimensional charge density wave (CDW) materials. One-dimensional Josephson arrays can be approximated by periodic Kronig-Penney models. The superconducting pinned CDW region is $\lambda_{CDW} - \xi \equiv a - b$ and the insulating or metallic region corresponds to $\xi \equiv b$. Cuprates may be ideal CDW superconductors [12,13] provided that the mean interval between the nearest pinned CDW regions is less than critical. The authors of this note contend that all superconductors, including heavy-fermion superconductors and organic superconductors, but not BCS-type low temperature ones, can be CDW superconductors.

In the case of heavy-fermion superconductors, the mean length between the nearest pinned CDW regions must be less than the superconducting correlation length at ultra-low temperatures in order for them to be considered in terms of superconducting Josephson arrays. The coexistence of spin density waves (SDWs) and superconductivity has been a long controversial problem and has not clarified so far [13].

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