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Brave new world of unconventional density waves

K. Maki, B. Dora[1], B. Korin-Hamzic[2], M. Basletic[3],
A. Virosztek[4,5] and M.V. Kartsovnik[6]

*Department of Physics and Astronomy, University of Southern California,
Los Angeles, CA 90089-0484, U.S.A.*
[1] *The Abdus Salam ICTP, P.O. Box 586, 34014 Trieste, Italy*
[2] *Institute of Physics, P.O. Box 304, 10001 Zagreb, Croatia*
[3] *Department of Physics, Faculty of Science, P.O. Box 331, 10001 Zagreb, Croatia*
[4] *Department of Physics, Technical University of Budapest, 1521 Budapest, Hungary*
[5] *Research Institute for Solid Sfate Physics and Optics, P.O. Box 49, 1525 Budapest, Hungary*
[6] *Walther-Meissner Institute, 85748 Garching, Germany*

Abstract.

Recently many people discuss unconventional density wave (i.e. UCDW and USDW). Unlike in conventional density waves, the quasiparticle excitations in these systems are gapless. The appearence of these systems suggests paradigm shift from quasi 1D system to quasi 2D and 3D systems. Here we limit ourselves to the angular dependent magnetoresistance (ADMR) observed in the low temperature phase (LTP) of α-(BEDT-TTF)$_2$KHg(SCN)$_4$. Here we show that UCDW describes successfully many features of ADMR as manifestation of the Landau quantization of the quasiparticle spectrum in magnetic field. Indeed ADMR will provide a unique window to access UDW like the AF phase in URu_2Si_2, the pseudogap phase in high T_c cuprates and the glassy phase in organic superconductor κ-(ET)$_2$ salts.

1 Introduction

As is well known the quasi-one dimensional electron systems have 4 canonical ground states [1–4]: s-wave (spin singlet) superconductor, p-wave (spin triplet) superconductor, charge density wave (CDW) and spin density wave (SDW). All these states have quasiparticle (QP) energy gap A and their QP density decreases exponentially at low temperatures ($T \ll$ A). Also the thermodynamics of these states is practically described by the BCS theory of s-wave superconductors [5]. Indeed except for p-wave superconductor these ground states have been found and their properties are actively persued even today.

However, since 1979 a new class of superconductors have appeared on the scene: heavy fermion superconductors (1979), organic superconductors (1979), high T_c cuprate superconductors (1986), Sr_2RuO_4 and borocarbides (1994). Is is now well-known that most of these superconductors are unconventional and/or nodal [6,7]. Indeed superconductivity in high T_c cuprates, $CeCoIn_5$, κ-(ET)$_2$ salts are $d_{x^2-y^2}$, the one in UPt_3 and Sr_2RuO_4 are triplet f-wave [8]. Therefore unconventional superconductivity takes center stage in the physics of the 21st century.

Parallel to these developments it is very natural to consider unconventional or nodal density waves [9–12]. Indeed we believe that the low temperature phase (LTP) of α-(BEDT-TTF)$_2$KHg(SCN)$_4$ [13–15], the AF phase in URu_2Si_2 [16,17], the pseudogap phase in high T_c cuprates [10, 12,181 and the glassy phase in κ-(ET)$_2$ salts [19] belong to UDW.

2 What are UCDW and USDW?

Unlike conventional density wave the energy gap $\Delta(\mathbf{k})$ in UCDW and USDW depends on $\mathbf{k}$, the QP wavevector lying on the Fermi surface. In quasi 1D systems the $\mathbf{k}$ dependence of $\Delta(\mathbf{k})$ is mostly $\sim \cos(bk_y)$, where b is the direction perpendicular to the most conducting one. Then UDW has clear thermodynamic signal as in usual mean field theory. In particular most of UDW has the same thermodynamic property as the one in d-wave superconductor [11, 20]. Further the transition into UDW is metal to metal unlike the one into conventional DW. In the latter case it is metal to semiconductor. Also unlike in conventional DW there is no clear X-ray signal or spin signal indicating the transition, since $\langle\Delta(\mathbf{k})\rangle = 0$. Here $\langle\ldots\rangle$ means the average over the Fermi surface. For this reason UDW is an example state with "hidden order parameter".

We have a few more candidates for UDW than mentioned earlier. For example it is known that ADMR in SDW in $(TMTSF)_2PF_6$ behaves quite differently across $\mathbf{T} = T^*(\sim$ **4K** at ambient pressure) [21, 22]. For $T > T^*$ ADMR is described in terms of quasiparticles with imperfect nesting in a magnetic field [23]. On the otherhand ADMR for $T < T^*$ can be described if we assume USDW on top of the existing SDW [24]. One necessary condition for the existence of UDW is higher dimensionality and competing interactions. The existence requires delicate balance between different interactions [11] and their detection requires more subtle experimental technique.

3 Angular dependent magnetoresistance in α-(BEDT-TTF)$_2$KHg(SCN)$_4$

The LTP in α-(ET)$_2$MHg(SCN)$_4$ with M=K, Tl, Rb is still not completely identified. The destruction of the LTP under magnetic field clearly favours the CDW scenario, although no spin or charge ordering has been detected. The presence of the nonlinear conductivity and the temperature dependence of the threshold electric field is interpreted successfully in terms of UCDW [13–15]. It is well known that the magnetoresistance of the LTP exhibits surprising angular dependence [25–27]. But the origin of this phenomenon remains elusive. In the following we show that UCDW provides simple description of ADMR [28]. As is well known, the Fermi surface of α-(ET)$_2$ salts consists of quasi 1D and quasi 2D portions We assume that UCDW is formed on the quasi 1D Fermi surface with QP spectrum

$$E(\mathbf{k}) = \sqrt{(v_F(k_x - k_F))^2 + \Delta^2(\cos(ck_z))^2} - \varepsilon_0 \cos(2\mathbf{b}'\mathbf{k}), \quad (1)$$

where v_F, A and ε_0 are the Fermi velocity paralle to the a axis, the UCDW order parameter and the imperfect nesting parameter, respectively. Nesting of the quasi 1D Fermi surface was detected recently by X-ray scattering [29].

In the presence of magnetic field B tilted by θ from the b axis by ϕ from the a axis in the a – c plane, the QP spectrum changes into

$$E, = \sqrt{2v_a\Delta ce|B\cos\theta|n} - \varepsilon_0 \exp\left[-\frac{2\Delta cb'}{v_F}e|B\cos(\theta)|(\tan(\theta)\cos(\phi-\phi_0) - \tan(\theta_0))^2\right], \quad (2)$$

where n $= 0,\ 1, 2,\ \ldots$. The above spectrum follows from Landau quantization of the QP orbit [9]. Then for $\beta E_1 \gg 1\,(1/\beta = k_BT)$, the magnetoresistance is given by

$$R(\mathbf{B},0) = (1+\alpha)\frac{1+e^x}{2+\alpha(1+e^x)}, \quad (3)$$

where $x = \beta E_1$ and a is the relative weight of the 2nd channel (i.e. 2D Fermi surface).

In Fig. 1, we compare the measured ADMR with the theoretical expression for current parallel and perpendicular to the a – c plane for a magnetic field lying in the diagonal a – c direction (i.e. $\phi = 45$**")**. As is seen, the fits are excellent. However in order to describe the multidip structure, the imperfect nesting term (i.e. the second term in Eq. **(1)**) has to be generalized as

$$\varepsilon_0 \cos(2\mathbf{b}'\mathbf{k}) \longrightarrow \sum_n \varepsilon_n \cos(2\mathbf{b}'_n\mathbf{k}) \quad (4)$$

with $\mathbf{b}'_n = b'(sin\theta_n\cos\phi_0, \sin\theta_n sin\phi_0, \cos\theta_n)$, where $\tan\theta_n = \tan\theta_0 + nd_0$, $\tan\theta_0 \simeq 0.5$, $d_0 \simeq 1.25$, $\phi_0 \simeq 27°$, $\varepsilon_n \sim 1/2^n$.

This suggests nonlocal imperfect nesting whose implication is currently under study. We believe that this excellent fit provides definitive proof that the LTP in α-(ET)$_2$KHg(SCN)$_4$ is unconventional CDW. Very similar ADMR has been observed in the related salts with M=Tl and Rb.

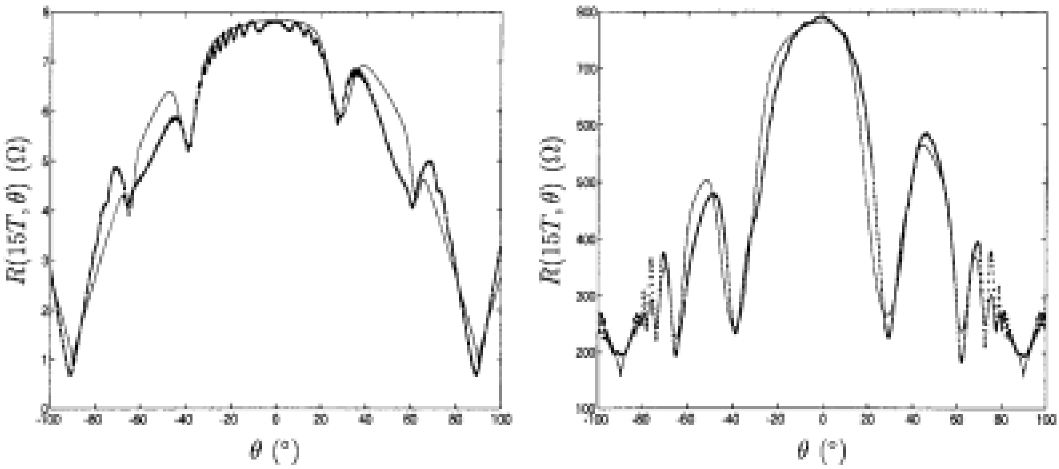

Figure 1: The angular dependent magnetoresistance is shown for current parallel (left panel) and perpendicular (right panel) to the a-c plane at $T = 1.4$K, $B = 15$T. The thick dots belong to the experimental data, the thin solid line is our fit described in **Eq.** (2).

4 Concluding remarks

First of all we would like to point out that there are many candidates for UCDW and USDW. Second we have shown that ADMR in α-$(ET)_2KHg(SCN)_4$ is consistently described in terms of UCDW with Landau quantization of QP. Indeed we believe that ADMR will provide unique way to access USDW or UCDW in the pseudogap phase of high T_c cuprates and the glassy phase of κ-$(ET)_2$ salts.

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