UNCONVENTIONAL SPIN DENSITY WAVE IN THE PSEUDOGAP PHASE IN HIGH T_c CUPRATES?*

Balázs Dóra[a], Attila Virosztek[a,b] and Kazumi Maki[c,d]

[a]Department of Physics, Budapest University of Technology and Economics
1521 Budapest, Hungary

[b]Research Institute for Solid State Physics and Optics
P.O. Box 49, 1525 Budapest, Hungary

[c]Max Planck Institute for the Physics of Complex Systems
Nöthnitzer Str. 38, 01187, Dresden, Germany

[d]Department of Physics and Astronomy, University of Southern California
Los Angeles, CA 90089-0484, USA

(Received July 10, 2002)

We propose that the pseudogap phase in high T_c cuprates may well be d-wave spin density wave. We show that both the micro-magnetism observed by neutron scattering in the pseudogap regime of Bi2212 and the optical dichroism seen by ARPES follow naturally from USDW. Also we predict that the magneto-resistance in the pseudogap regime should exhibit a peculiar angular dependence, which should be accessible experimentally.

PACS numbers: 75.30.Fv, 74.25.Gz, 74.72.–h

Recently it was proposed that T^* in the phase diagram in high T_c cuprates is not a crossover but a transition temperature to d-wave charge density wave [1,2] or d-wave spin density wave [3]. The d-wave nature of the hidden order parameter below T^* is known from ARPES, which indicates $\Delta(\boldsymbol{k}) \sim \cos(k_x a) - \cos(k_y a)$ [4,5]. Also a mysterious relation $\Delta(0)/T^* = 2.14$ found in the pseudogap region where $\Delta(0)$ is the maximum of the quasiparticle energy gap [6,7] is simply interpreted in terms of d-density wave when the chemical potential μ is not too large ($|\mu| \ll \Delta(0)$) [8,9].

Also the appearance of the weak antiferromagnetic order just below T^* [10] and that of the optical dichroism [11] indicate T^* is the transition temperature associated with a second order phase transition.

* Presented at the International Conference on Strongly Correlated Electron Systems, (SCES 02), Cracow, Poland, July 10–13, 2002.

In the following we shall first indicate how the micro-magnetism and the optical dichroism follow from d-wave spin density wave. Then we shall discuss the magneto-resistance in d-wave density waves. Indeed we have succeeded in identifying UCDW in the low temperature phase of $\alpha-$(BEDT-TTF)$_2$KHg(SCN)$_4$ through the angular dependence of the magneto-resistance [12].

As to the micro-magnetism, localized impurities or defects, which couple to the conduction electron with the exchange interaction (*i.e.* the Kondo model) can generate the coherent AF order [3] in d-wave spin density wave. Indeed this model describes the micro-magnetism seen by neutron scattering in the AF state of URu_2Si_2 [13].

On the other hand, this simple model cannot describe the temperature dependence of the micro-magnetism seen in underdoped Bi2212 [10]. But there are other contributions to the AF order we have neglected. So perhaps the elaboration of the present model can clarify the issue.

Very recently a surprising optical dichroism which appears immediately below the pseudogap transition temperature T^* has been reported [11]. This requires first of all that the condensate has to break the time reversal symmetry. To fulfill this requirement, Varma has been proposing the order parameter with orbital angular momentum with nonzero chirality [14]. However, as we shall show the optical dichroism follows naturally from d-wave SDW. As the neutron scattering shows the spin in SDW lies in the a–b plane [10], then the spin can take one of two configurations $S_x \pm iS_y$, which are related with the time reversal symmetry to each other. Then it follows that the intensity of the outcoming electron is

$$I_\pm \sim 1 \pm \frac{\Delta(\boldsymbol{k})}{E(\boldsymbol{k})}\,, \tag{1}$$

or

$$\frac{I_+ - I_-}{I_+ + I_-} = \frac{\Delta(\boldsymbol{k})}{E(\boldsymbol{k})}\,. \tag{2}$$

Indeed Eq. (2) shows (a) the optical dishroism appears at $T = T^*$, (b) it is absent when $\boldsymbol{k}$ is parallel to the nodal direction (*i.e.* $\boldsymbol{k} \parallel (1,1)$,*etc.*), (c) it takes the maximum value in the antinodal direction and (d) the spin of the outcoming electron is polarized in the same direction as the one for impinging photon. Indeed (a), (b) and (c) are consistent with the observation. Therefore, the detection of the spin direction of the outcoming electron will be of great interest.

Now we turn to the investigation of the Angle Dependent Magneto-Resistance (ADMR). Let us consider a magnetic field $\boldsymbol{H}$ applied as shown in Fig. 1. Then due to the Landau quantization [15] the quasiparticle spectrum in d-wave density wave is

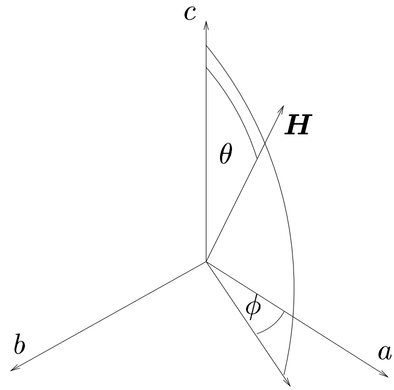

Fig. 1. The geometrical configuration of the magnetic field with respect to the conducting plane.

$$E_{\pm} = \sqrt{2\sqrt{2}e|H|\Delta\left(v_{\mathrm{F}}a|\cos(\theta)| + v_{\mathrm{c}}\,c\sin(\theta)|\sin\left(\phi \pm \tfrac{\pi}{4}\right)|\right)}\,, \tag{3}$$

where v_{F} and v_{c} are the Fermi (in-plane) and perpendicular velocity, respectively. Therefore, the electric resistance in the pseudogap phase may be written as

$$\frac{\rho(H,\theta,\phi) - \rho(0,\theta,\phi)}{\rho(0)} = \frac{e^{\beta(E_{+}+E_{-})} - 1}{e^{\beta E_{+}} + e^{\beta E_{-}} + 2}\,, \tag{4}$$

and $\beta = 1/k_{\mathrm{B}}T$. The angular dependent resistance for a few θ's is shown as a function of ϕ in Fig. 2. Here we took

$$v_{\mathrm{c}}\,c/v_{\mathrm{F}}a = 0.1\,, \quad \beta\sqrt{2\sqrt{2}e\Delta|H|v_{\mathrm{F}}a} = 10\,,$$

as an example. The angular dependent magnetoresistance will provide a definitive test for d-wave density wave in the pseudogap phase in HTS. However, this cannot differentiate USDW from UCDW.

A similar magnetoresistance should be observable in the AF phase of $\mathrm{URu_2Si_2}$, since this material has tetragonal symmetry as well. On the other hand for transition metal dichalcagonate like $\mathrm{NbSe_2}$ [16], which has hexagonal symmetry, the angular dependent magnetoresistance should be different.

We have proposed that the pseudogap phase may be d-wave spin density wave, which can describe both the micromagnetism observed by neutron scattering and the optical dichroism found by ARPES very consistently. The experimental observation of the spin lying in the a–b plane seems to be inconsistent with d-wave charge density wave, but supports our model.

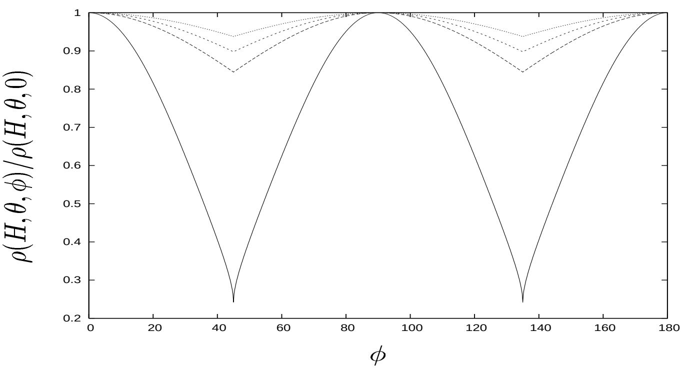

Fig. 2. The magnetoresistance is shown as a function of ϕ for $\theta = 90°$, $60°$, $45°$ and $30°$ from bottom to top.

Also we point out the Landau quantization in UDW discussed by Nersesyan *et al.*, found a new application in the angular dependent magnetoresistance. Very recently this effect was used successfully to identify UCDW in $\alpha-$(BEDT-TTF)$_2$KHg(SCN)$_4$ [13] and in USDW below $T \simeq 4$K in (TMTSF)$_2$PF$_6$ [17].

REFERENCES

[1] L. Benfatto *et al.*, *Eur. Phys. J.* **B17**, 95 (2000).

[2] S. Chakravarty *et al.*, *Phys. Rev.* **B63**, 094503 (2001).

[3] A. Virosztek *et al.*, submitted to *Int. J. Mod. Phys.* **B**.

[4] H. Ding *et al.*, *Nature* **382**, 51 (1996).

[5] T. Timusk, B. Statt, *Rep. Prog. Phys.* **62**, 61 (1999).

[6] M. Oda *et al.*, *Physica C* **281**, 135 (1997).

[7] M. Kugler *et al.*, *Phys. Rev. Lett.* **86**, 4911 (2001).

[8] H. Won, K. Maki, *Phys. Rev.* **B49**, 1397 (1994).

[9] B. Dóra, A. Virosztek, *Eur. Phys. J.* **B22**, 167 (2001).

[10] Y. Sidis *et al.*, *Phys. Rev. Lett.* **86**, 4100 (2001).

[11] A. Kaminski *et al.*, *Nature* **416**, 610 (2002).

[12] B. Dóra *et al.*, `cond-mat/0204321`.

[13] H. Amitsuka *et al.*, *Phys. Rev. Lett.* **83**, 5114 (1999).

[14] C.M. Varma, *Phys. Rev.* **B61**, R3804 (2000).

[15] A.A. Nersesyan, G.E. Vachnadze, *J. Low. Temp. Phys.* **77**, 293 (1989).

[16] A.H. Castro-Neto, *Phys. Rev. Lett.* **86**, 4382 (2001).

[17] M. Basletić *et al. Phys. Rev.* **B**, (in press).