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LETTER TO THE EDITOR

Confined field induced density waves in unconventional superconductors

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Abstract
We demonstrate that a magnetic field may induce a first order transition from a d-wave superconducting (SC) state to a state in which SC coexists and competes with confined field induced spin (or charge) density waves (CFIDW) that develop over a portion of the Fermi surface (FS) centred in the node regions. The extension of the CFIDW states over the FS is fixed by their competition with SC and shows a *non-integer quantization*. Novel macroscopic quantum phenomena like the *non-integer quantization of the superfluid density* are therefore generated. We argue that CFIDW states may be the origin of the numerous puzzling field induced phenomena reported in high-T_c cuprates and as an example we analyse the field induced plateaus observed in thermal transport data in connection with the field induced reduction of the superfluid density.

After 15 years of very intense investigations, a consensus emerged on numerous aspects of the superconducting (SC) phenomenology of high-T_c cuprates. These materials are now seen as classical examples of unconventional superconductors. The gap symmetry has been identified to have the $d_{x^2-y^2}$ structure having nodes in the (π, π) direction and in this respect high-T_c cuprates are perhaps the best understood unconventional SC. However, despite all that progress, in the presence of a magnetic field applied *perpendicular* to the Cu–O planes, a number of absolutely puzzling phenomena have been reported. In a remarkable thermal transport experiment, Krishana *et al* [1] have reported that when such a magnetic field is applied, the thermal conductivity shows sharp transitions from a field dependent regime as the one we expect when gap nodes are present [2] to a field independent regime which indicates the elimination of normal quasiparticles in the node region. According to their data, above a critical field and below a critical temperature there is a distinct first order phase transition to a novel quasiparticle ground state without nodes.

These surprising findings have been interpreted by Laughlin as signatures of a transition from $d_{x^2-y^2}$ superconductivity (SC) to the nodeless $d_{x^2-y^2} + id_{xy}$ SC state [3]. This suggestion has been analysed in [4–6]. On the other hand, experimental controversy developed and although other measurements of thermal conductivity have confirmed the findings of [1] at least on some samples, they have also reported strong hysteretic behaviour [7] and sample dependence [8] which have cast doubt on the intrinsic microscopic character of the phenomenon. Possible explanations in the framework of macroscopic theory of vortex dynamics have also been put forward [9]. However, more recent measurements from the same groups that have initially been critical about the reality of the plateaus phenomenon in thermal transport appear to definitely establish its intrinsic character [10].

A series of additional unexplained field induced phenomena have been reported in the cuprates after the pioneering work of Krishana *et al*. Sonier *et al* [11] have measured the penetration depth in the presence of a strong magnetic field confirming the elimination of the nodes and showing that it is accompanied by *a substantial reduction of the superfluid density*. Such a reduction, although contested by some theoreticians [12], is incompatible with a transition to a new $d_{x^2-y^2} + id_{xy}$ SC state. Scanning tunnelling spectroscopy results in the presence of a perpendicular magnetic field report a checkerboard charge distribution around the vortices [13] that have found no explanation so far. Neutron diffraction [14] and NMR [15] experiments show that below a given temperature and above a given field (which depends on temperature), there appear *antiferromagnetic moments in the SC state*. Moreover there is a bulk of anomalous vortex states reported in the cuprates like the unexplained cascade of vortex glass transitions [16]. These vortex structure puzzles are generally believed to be related to the macroscopic vortex physics and therefore unrelated to the previous microscopic phenomena. However, recent thermal expansivity measurements [17] show that these vortex states involve *microscopic* charge degrees of freedom indicating a relationship between the microscopic field induced puzzles and the vortex structure puzzles.

We point out in this letter that all these puzzles may have a common origin. We demonstrate that a magnetic field can induce a first order transition from a $d_{x^2-y^2}$ SC state to a state in which $d_{x^2-y^2}$ SC *coexists with a confined field induced spin (or charge) density wave (CFIDW) state*. Above a critical field and below a critical temperature, it is energetically favourable for the system to establish a CFIDW over a portion of the Fermi surface (FS) centred in the node positions. The momentum extension of the CFIDW is fixed by energetic competition with superconductivity with which it coexists. The possible momentum extensions of the CFIDW are *quantized* and correspond to *two* characteristic momentum extensions for each Landau level. Therefore distinct quantum configurations are created. This gives rise to novel experimentally accessible macroscopic quantum phenomena like the *non-integer* quantization of the superfluid density. To the best of our knowledge, the CFIDW states we report have never been discussed before.

Field induced density waves have been widely studied in the 1980s [18–22] in order to explain field induced metal–insulator transitions and related quantum Hall phenomena in $(TMTSF)_2X$ ($X = PF_6$, ClO_4) quasi-one-dimensional synthetic compounds [23, 24] under pressure. Our original CFIDW states show a qualitatively novel behaviour related to novel macroscopic quantum phenomena like the non-integer quantization of the superfluid density. For our analysis we adopt the following hybrid approach. We consider the FS of our HTSC system divided into two subsystems: subsystem I is the FS region covered by the SC gap and subsystem II is the normal quasiparticle region centred in the points of the FS where otherwise the nodes of the gap would appear. The CFIDW will eventually develop in region II. The relative momentum extension of regions I and II over the FS is a variational parameter and will be determined by energetic considerations below.

In the HTSC system that we consider, the gap is $d_{x^2-y^2}$ with nodes in the (π, π) direction where region II is centred. We define new wavevector coordinates $(\hat{k}_1, \hat{k}_2)$ corresponding to a $\pi/4$ rotation of the $\hat{k}_x$ and $\hat{k}_y$ axes respectively. In region II we necessarily have open FS sheets. The electronic dispersion in region II can be written as follows:

$$\xi_{\mathbf{k}}^{\mathrm{II}} = \upsilon_{\mathrm{F}}(|k_1| - k_{\mathrm{F}}) - 2t_2\cos(k_2/X) - 2t_2'\cos(2k_2/X) \tag{1}$$

where X is the momentum extension of region II and is an unknown variable. k_1 is along the (π, π) direction perpendicular to the open FS sheet of region II, and k_2 is perpendicular to k_1 and therefore along the open FS sheet where we retain only two harmonics. There is not perfect nesting and therefore no DW in region II in the absence of a magnetic field.

Writing the dispersion as in (1), we have effectively in region II a system analogous to $(\mathrm{TMTSF})_2\mathrm{X}$ compounds but with a variable length of its Brillouin zone. We apply in region II an analysis similar to that made for the full Fermi surface of the $(\mathrm{TMTSF})_2\mathrm{X}$ compounds [19]. The details of the calculation, as well as the study of the influence of various parameters, will be given elsewhere. We report here the simplest results in order to illustrate the surprising physics of our system. Constraining the nesting in the (π, π) direction one can show that a first order field induced density wave gap in region II can be given by

$$\Delta_{\mathrm{DW}} = W\exp\left\{-\frac{1}{gN(E_{\mathrm{F}})I_L^2(X)}\right\} \tag{2}$$

with

$$I_L(X) = \sum_n J_{L-2n}\left(\frac{4t_2X}{eH\upsilon_{\mathrm{F}}}\right)J_n\left(\frac{2t_2'X}{eH\upsilon_{\mathrm{F}}}\right) \tag{3}$$

where $J_n(x)$ are Bessel functions, L is the index of the Landau configuration, e is the charge of the electron, H the magnetic field, $N(E_{\mathrm{F}})$ the density of states at the Fermi level (in region II), g a scattering amplitude of Coulombic or phononic origin, W the bandwidth in the (π, π) direction and υ_{F} the Fermi velocity. Higher order gaps are not reported here for clarity.

To examine whether it is energetically favourable for the system to develop CFIDW states, we must compare the condensation free energy gain due to the opening of a CFIDW gap in region II to the condensation free energy lost by the elimination of SC from this region. If Z is the relative extension of region II, the condensation free energy lost from the $\mathrm{d}_{x^2-y^2}$ SC is to a first approximation given by

$$\Delta E_{\mathrm{sc}} = \tfrac{1}{2}\int_{-Z\pi/2}^{Z\pi/2}\Delta_{\mathrm{sc}}^2\sin^2(\phi)\,\mathrm{d}\phi = \tfrac{1}{4}\Delta_{\mathrm{sc}}^2[\pi Z - \sin(\pi Z)] \tag{4}$$

where Z is a dimensionless parameter varying from 0 to 1, representing the percentage of the FS occupied by the CFIDW, and is related to X by $X \approx k_{\mathrm{F}}\sin(Z\pi/2)$. Δ_{sc} is the maximum value of the SC gap. This is to be compared with the free energy gain due to the opening of the CFIDW gap in region II given by $\Delta E_{\mathrm{DW}} = (1/2)\pi Z\Delta_{\mathrm{DW}}^2$. Therefore, it is energetically favourable for the system to develop a CFIDW only if the following condition is fulfilled:

$$I_L^2(k_{\mathrm{F}}\sin(Z\pi/2)) > \frac{2}{gN(E_{\mathrm{F}})}\left[\ln\frac{2W^2\pi Z}{\Delta_{\mathrm{sc}}^2[\pi Z - \sin(\pi Z)]}\right]^{-1}. \tag{5}$$

On the other hand, the CFIDW state must be *confined in momentum space* with a DW gap smaller or equal to the SC gap in the borders of region II. We therefore have

$$I_L^2(k_{\mathrm{F}}\sin(Z\pi/2)) \leqslant \left[gN(E_{\mathrm{F}})\ln\frac{W}{\Delta_{\mathrm{sc}}\sin(Z\pi/2)}\right]^{-1}. \tag{6}$$

The equality in (6) fixes the relative extension Z of the CFIDW (for each L) and therefore $I_L^2(k_{\mathrm{F}}\sin(Z\pi/2))$ which then determines the CFIDW gap Δ_{DW} and the critical temperature T_{DW} at which the CFIDW forms. A graphic solution for Z is shown in figure 1. There is more

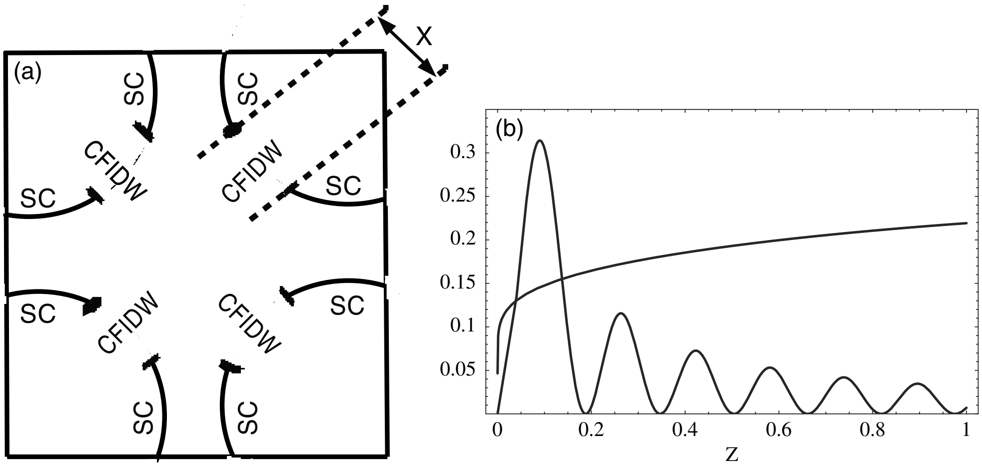

Figure 1. (a): Schematic illustration of the coexistence of CFIDW and SC on the first Brillouin zone of high-T_c cuprates. (b): A graphic solution of equation (6) in the $L = 1$ configuration and a field of 3 T. Two different relative extensions Z of the CFIDW are possible.

than one value of Z for a given Landau level. Therefore the Landau configuration numbers L are not sufficient to index our quantum states. A *novel quantum number* ζ, associated with the two possible momentum extensions Z for each Landau level, must therefore be introduced. Physically ζ will index *the quantization of the superfluid density*. In fact, each value of Z corresponds to a different relative extension of the SC region and therefore to a different density of carriers in the superfluid state. The ζ configuration with the higher Z, and therefore the bigger momentum extension of the CFIDW, requires smaller cyclotron orbits in real space and would be favoured by scattering with impurities. The higher Z solution provides the higher value for I_L and therefore the bigger $\Delta_{\rm DW}$ and $T_{\rm DW}$.

The occurrence of a solution as in figure 1 is not guaranteed and depends on the parameters. For a given magnetic field, we can examine for each configuration L whether a CFIDW is possible and obtain $T_{\rm DW}$ at which the CFIDW state will eventually develop for each accessible ζ configuration. Using for our parameters values extracted from the experiments on HTSC and assuming a conventional scattering $gN \approx 1$ we can obtain results like those reported in figures 2 and 3 that fit surprisingly well the data of [1] and [11]. While such fits should be viewed as schematic in view of our approximations, they establish however that the orders of magnitude of the parameters involved are compatible with the experimental findings. A small magnetic field affects the large SC gap of HTSC because of momentum confinement which constrains the cyclotron orbits to be large in real space. If the system is sufficiently clean, then even a small magnetic field can induce CFIDW states over a small portion of the FS. The occurrence of this transition depends sensitively on sample quality explaining the findings in [8]. Our $\mathrm{d}_{x^2-y^2}$ to $\mathrm{d}_{x^2-y^2}$+CFIDW transition appears only above 1 T in [7] while it is already present at 0.6 T in [1] probably because samples in [1] are cleaner, admitting bigger cyclotron orbits.

In figure 2(a) is reported the dependence of the critical temperature $T_{\rm DW}$ on the critical magnetic field for the development of CFIDW in the various $|L, \zeta\rangle$ configurations. We also plot in figure 2(a) the corresponding experimental points of [1] and [11]. In figure 3(a) we plot the corresponding dependence of the accessible extensions Z in each $|L, \zeta\rangle$ configuration as a function of the magnetic field. Figures 2(b) and 3(b) are derived from figures 2(a) and 3(a),

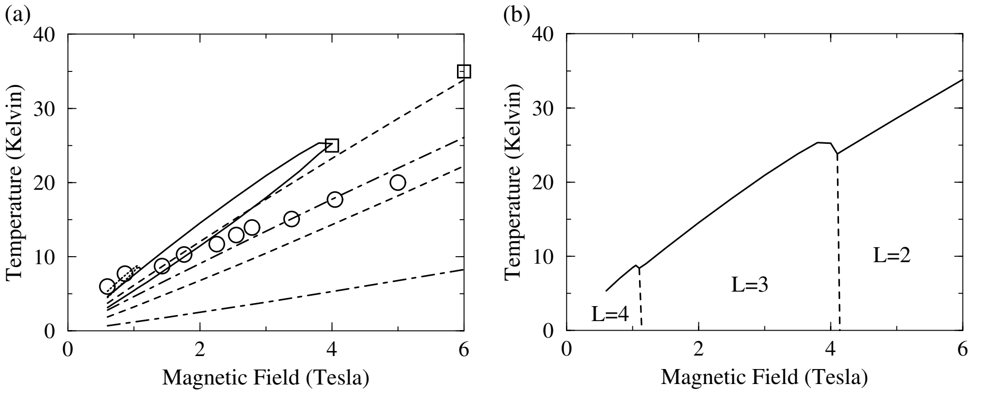

Figure 2. (a): Critical temperature T_{DW} versus critical field for the formation of a CFIDW state in the different quantum configurations $|L, \zeta\rangle$: $L = 4$ (dotted lines), $L = 3$ (full curves), $L = 2$ (dashed lines), and $L = 1$ (dot–dashed lines). In all cases, the upper and lower lines correspond to the two different ζ configurations (higher T_{DW} correspond to higher Z). The $L = 0$ lines are not shown for clarity. The open circles are the experimental points of [1] and the open squares the experimental points of [11]. (b) The configuration adopted by the system when cooled in the presence of the field as in [11].

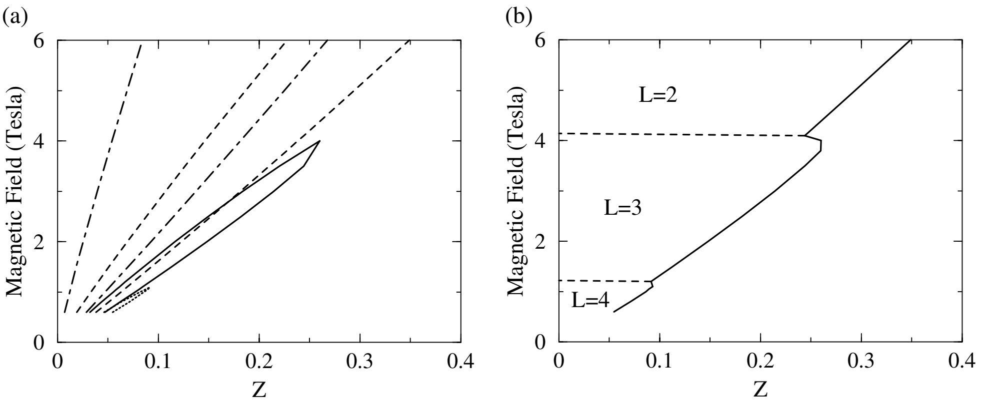

Figure 3. (a): Relative extensions Z versus magnetic field for various quantum configurations $|L, \zeta\rangle$. The different line-styles correspond to the same $|L, \zeta\rangle$ as in figure 2(a). (b) The maximum momentum extension versus the critical field for CFIDW generation when the sample is cooled in the presence of the field.

and show the case of the highest accessible T_{DW} and Z for a given magnetic field that will be the configuration of the system when cooled in the presence of the magnetic field as in [11]. Fields of 4–6 T not only induce the CFIDW transition at temperatures compatible with the experiment [11], but they can also eliminate SC from about a quarter of the FS which can easily account for the ≈15% reduction of the superfluid density reported in [11]. We argue that a similar reduction of the superfluid density is also reported in the quasi-two-dimensional synthetic compound κ-(BEDT–TTF)$_2$Cu(NCS)$_2$ [25] where there are also indications of d-wave SC [26]. We can attribute the absence of the effect in another experiment on the same synthetic compound [27] to a lower sample quality. The CFIDW states may be at the origin of part of the controversy on the symmetry of the order parameter in κ-(BEDT–TTF)$_2$Cu(NCS)$_2$ from these penetration depth measurements [26].

There is a qualitative aspect of the results in [1] which strongly supports our analysis. As one can see in figure 2(a), the T_{DW} versus critical magnetic field profile of the data in [1] show a *reptation* shape. The first two points have a bigger field slope than the next two points and so on. Within our analysis this is due to the *quantization* of the CFIDW states. Each slope corresponds to a different $|L, \zeta\rangle$ quantum configuration of the system. In addition, because all accessible $|L, \zeta\rangle$ configurations are nearly degenerate energetically for the total system, the presence of hysteresis on a dynamic probe like thermal conductivity will depend on the exact conditions of the magnetic cycle and on sample quality. This may explain the presence of hysteresis in [7] while in [1] magnetic hysteresis is negligible.

Furthermore, the orientation of the checkerboard charge textures observed by STM in [13] is compatible with our CFIDW states. In addition, our CFIDW states may also be at the origin of the puzzles in the vortex structure of the cuprates. This would be the first microscopic picture for the vortex structure anomalies compatible with the recent experimental findings that suggest the involvement of the microscopic charge physics in the vortex structure transitions in the cuprates [17]. In fact, the vortex solid to vortex glass transition can be associated with the transition from SC to SC + CFIDW. In that case one can understand the unexplained cascade vortex glass transition of [16] as a transition between two different $|L, \zeta\rangle$ configurations of our SC + CFIDW state. Indeed, since the higher field state corresponds to a larger CFIDW extension over the FS, the vortex structure should be less rigid as in the experiment.

Finally, in agreement with the experiments on HTSC, the CFIDWs appear only for fields perpendicular to the planes because for fields parallel to the planes cyclotron effects are irrelevant.

In summary, we demonstrated the generation by a magnetic field of novel macroscopic quantum states in a superconductor with nodes. Our CFIDW states have a number of qualitative signatures and a series of experiments can be designed in order to observe them in unconventional superconductors. We argue that our CFIDW states have already been observed in the cuprates directly by STM and indirectly in a series of experiments including thermal transport, neutron spectroscopy, NMR and penetration depth measurements. We argue that anomalous structures of the vortex matter may have a microscopic origin on our CFIDW states as well. Some indications of CFIDW states are also present in penetration depth measurements on quasi-two-dimensional synthetic SC.

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References

[1] Krishana K *et al* 1997 *Science* **277** 83
[2] Simon S and Lee P A 1997 *Phys. Rev. Lett.* **78** 1548
[3] Laughlin R B 1998 *Phys. Rev. Lett.* **80** 5188
[4] Franz M and Tesanovic Z 1998 *Phys. Rev. Lett.* **80** 4763
[5] Ramakrishnan T V 1998 *J. Phys. Chem. Solids* **59** 1750
[6] Balatsky A V 2000 *Phys. Rev.* B **61** 6940
[7] Aubin H *et al* 1999 *Phys. Rev. Lett.* **82** 624
[8] Ando Y *et al* 2000 *Phys. Rev.* B **62** 626
[9] Franz M 1999 *Phys. Rev. Lett.* **82** 1760
[10] Ando Y *et al* 2002 *Phys. Rev. Lett.* **88** 147004
[11] Sonier J E *et al* 1999 *Phys. Rev. Lett.* **83** 4156
[12] Amin M H S, Franz M and Affleck I 2000 *Phys. Rev. Lett.* **84** 5864
[13] Hoffmann J E *et al* 2002 *Science* **295** 466

[14] Lake B *et al* 2001 *Science* **291** 175
[15] Mitrovic V F *et al* 2001 *Nature* **413** 501
[16] Bouquet F *et al* 2001 *Nature* **411** 448
[17] Lortz R *et al* 2003 *Phys. Rev. Lett.* **90** 237002
[18] Gorkov L P and Lebed A G 1984 *J. Physique Lett.* **45** L433
[19] Héritier M, Montambaux G and Lederer P 1984 *J. Physique Lett.* **45** L943
Montambaux G, Héritier M and Lederer P 1985 *Phys. Rev. Lett.* **55** 2078
Poilblanc D *et al* 1986 *J. Phys. C: Solid State Phys.* **19** L321
[20] Maki K 1986 *Phys. Rev.* B **33** 4826
Virosztel A, Chen L and Maki K 1986 *Phys. Rev.* B **34** 3371
Chen L and Maki K 1987 *Phys. Rev.* B **35** 8462
[21] Yamaji K 1985 *J. Phys. Soc. Japan* **54** 1034
Yamaji K 1986 *Synth. Met.* **13** 29
[22] Montambaux G and Littlewood P B 1989 *Phys. Rev. Lett.* **62** 953
Montambaux G and Littlewood P B 1989 *Phys. Rev. Lett.* **63** 818
[23] Kwak J *et al* 1981 *Phys. Rev. Lett.* **46** 1296
Azevedo L *et al* 1981 *Physica* B **108** 1183
Takahashi T, Jerome D and Bechgaard K 1982 *J. Physique Lett.* **44** L565
[24] Ishiguro T, Yamaji K and Saito G 1997 *Organic Superconductors* (*Springer Series in Solid State Sciences*) (Heidelberg: Springer)
[25] Harshman D R *et al* 1990 *Phys. Rev. Lett.* **64** 1293
[26] Lang M 1990 *Supercond. Rev.* **2** a.1–116
Annett J F 1999 *Physica* C **317/318** 1
Wosnitza J 1999 *Physica* C **317/318** 98
[27] Le L P *et al* 1992 *Phys. Rev. Lett.* **68** 1923