Magnetic Field Induced Confinement in Strongly Correlated Anisotropic Materials

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We have previously argued that strong correlation effects in highly anisotropic materials can lead to "confinement" in the sense that single particle motion in some directions is intrinsically incoherent. The presence of a magnetic field transverse to the direction of the hopping would enhance this effect and could potentially change the nature of hopping itself if the material were close to the coherence-incoherence transition. We believe that such an effect has already been observed in the unusual commensurability effects observed in the magnetoresistance of the highly anisotropic organic conductor $(TMTSF)_2PF_6$.

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The organic conductors of the $(TMTSF)_2X$ family are highly anisotropic, with bandwidths associated with motion in the different directions approximately given by $t_a \sim 0.25$ eV, $t_b \sim 0.025$ eV, and $t_c \sim 0.001$ eV. The estimated values are based on conductivity anisotropy and magnetic field effects [1]. In magnetic fields of order a few Tesla and at pressures of order several kilobar these materials exhibit a "metallic" state in which large dips are observed in the magnetoresistance whenever the applied field is parallel to one of the bc plane real-space lattice vectors [2] (see Fig 1). We offer here a natural interpretation of these features in the magnetoresistivity in terms of a new fixed point recently proposed by us [3] for strongly correlated systems with large anisotropy.

In a recent Letter [3], we have argued that the single particle hopping between spin-charge separated Luttinger liquids [4] is rendered completely incoherent for sufficiently weak interliquid hopping. This effect will be present at arbitrarily low temperatures in arbitrarily pure systems and has dramatic consequences for the physical properties of such a system. For example, if infinitely many Hubbard chains are coupled into a plane by a sufficiently weak interchain hopping, then there is no dispersion in the direction perpendicular to the original chains and no two dimensional Fermi surface forms. Transport in this direction will be highly anomalous and intrachain correlation functions are expected to retain their one dimensional character. We find that a magnetic field transverse to the chain axis and the direction of hopping enhances incoherence within that model. A generalization to higher dimensions offers the most natural explanation for the unusual commensurability effects observed in the quasi-one dimensional organic conductor $(TMTSF)_2X$. For clarity we shall discuss only the case of $(TMTSF)_2PF_6$, for which the best experimental data are available.

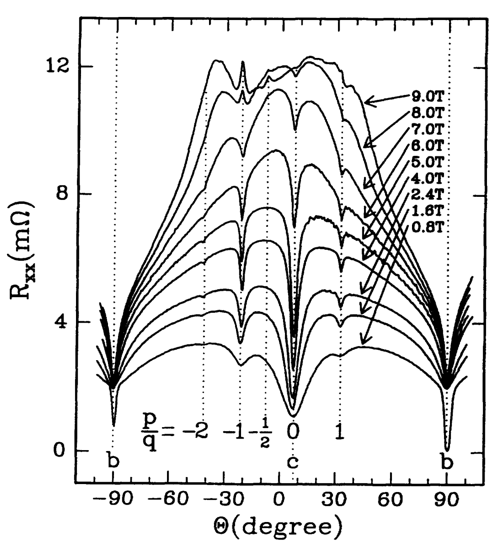

FIG. 1. Resistance of $(TMTSF)_2PF_6$ at 0.5 K under 10 kbar of pressure [2]. At the lowest field superconducting effects are observed near the b axis.

The central feature of our picture for these materials is a *field dependent renormalization of the coherent part of the c axis hopping*, $t_c^{\rm coh}$ (this is the property measured, for example, by the warping of the Fermi surface). On the basis of the calculation described later in this Letter, we believe that this type of renormalization should be a general feature of sufficiently anisotropic strongly correlated systems. In particular, it should apply to the TMTSF materials in fields with components perpendicular to the ac plane of order a few Tesla. In an appropriate gauge it can be seen that these fields introduce into the c axis hopping nonconservation of the a momentum by an amount $q = eBl_c$ where l_c is the separation of the planes in the c direction, B is the field strength, and e is the electron charge. Therefore, effective inelasticities, $qv_F = 0.2B$ meV/T, comparable in size to $t_c^{\rm coh}$ arise and the field dependence of $t_c^{\rm coh}$ should be important for these materials. While previous theoretical attempts to explain the commensurate features in the magnetoresistance of the TMTSF compounds [5,6] have assumed that the electron dispersion and $t_c^{\rm coh}$ could be taken to be field independent,

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our explanation focuses on the renormalization of the coherent c-axis hopping, $t_c^{\rm coh}$, to *zero*.

The picture we propose for these materials is as follows. Turning on a magnetic field in the b direction introduces inelasticity into the c direction hopping, with $evBl_c \sim 0.2B$ meV/T. This reduces the value of $t_c^{\rm coh}$ until, for a field of order 2 T, $t_c^{\rm coh} = 0$. For other field orientations, it is the projection of $\vec{B}$ onto the vector perpendicular to the ac plane which matters. When the field is sufficiently large and away from the $\hat{c}$ direction (and from certain other magic angles as described later in this Letter), the material is rendered two dimensional by the vanishing of $t_c^{\rm coh}$. If the field is very nearly in the $\hat{c}$ direction then the three dimensional character of the material survives. It is known [5,7] that the scattering due to the electron-electron interaction is very sensitive to the shape of the Fermi surface and in general we expect the scattering to be significantly stronger in the two dimensional state, causing a large dip in the a and b resistivities for fields nearly parallel to the $\hat{c}$ direction. A large dip in the c resistivity should also occur trivially when the c axis motion becomes coherent.

If $t_c^{\rm coh}$ renormalizes strongly due to the magnetic field then we need to consider the higher order effects of this renormalization. In particular, higher order hops directed along the magnetic field will not suffer from field-induced inelasticity and when generated will remain coherent. These hops will be generated if the renormalization of $t_b^{\rm coh}$ is at least weakly field dependent. Coherent three dimensional hopping can therefore survive even for $t_c^{\rm coh} = 0$, provided that the field points along a real space lattice vector, $m\hat{c} + n\hat{b}$ with integer m and n, leaving a finite induced $t_{m\hat{c}+n\hat{b}}^{\rm coh}$. This will result in sharp dips in the resistivity for fields away from the c direction if the magnetic field is parallel to a real space lattice vector and the temperature is lower than the induced hopping, $t_{m\hat{c}+n\hat{b}}^{\rm coh}$, as observed experimentally. Note that these long distance hops are generated by renormalization due to the field: they do not represent features of the zero field band structure.

Our picture has a number of experimental consequences, all of which are in agreement with observations. It explains the presence of the dips at exactly the locations observed without invoking any peculiarities of band structure or any need to adjust parameters. It also predicts that the dips should appear hierarchically with the presence of the central dip being essential for the presence of the first noncentral dip and so on. Since each successive dip is generated at a higher order in perturbation theory, the magnitude of the coherent hopping out of the ab plane should decrease very rapidly with the dip number. Higher dips will therefore be smaller and will require lower temperatures for their observation. This explains naturally why the number of dips seen is not a function of magnetic field in the way that one would expect if they arose from commensurability effects of the quasiclassical k space trajectories.

Since the most important parameter in our theory is the incoherence inducing field, $\vec{B} \cdot \hat{n}_{ac}$, where $\hat{n}_{ac}$ is the unit vector normal to the ac plane, we would predict that the width of the central dip should scale very nearly as B^{-1}. Experimentally [2], the full width at half maximum drops by a factor of about 5 between 0.8 and 5 T in good agreement with the $1/B$ scaling. The widths of higher dips will not necessarily obey this scaling since their effective hopping is also field dependent.

The most striking prediction *unique to our model* is that of a transition between three and two dimensional behavior (confinement) as a function of $\vec{B} \cdot \hat{n}_{ac}$. The presence of the dips demonstrates that these materials are three dimensional; however, our theory requires and predicts that in moving away from the dips the system makes a transition to two dimensional physics with incoherent interplane coupling. This prediction has dramatic and easily testable experimental consequences. If confinement occurs, and essentially only if confinement occurs, can the magnetoresistance depend solely on $\vec{B} \cdot \hat{n}_{ab}$, the projection of the magnetic field onto the vector perpendicular to the ab plane. This should happen for all fields which have a larger than critical value for $\vec{B} \cdot \hat{n}_{ac}$ [8]. The data from various field strengths satisfying this criterion should collapse onto a single scaling function when plotted as magnetoresistance versus the projection of the magnetic field onto n_{ab}. We show such a plot of R_{xx} for fields with $\vec{B} \cdot \hat{n}_{ac} \gtrsim 0.5$ T in Fig. 2. Scaling should hold strictly for the points associated with fields having $\vec{B} \cdot \hat{n}_{ac} \gtrsim 2$ T. This is evident from the plot which shows the data collapsing onto a single function for the larger values of B; in fact, $R_{xx}(\vec{B}) - R_{xx}^0 \sim (\vec{B} \cdot \hat{n}_{ab})^{1/2}$, where R_{xx}^0 is the resistivity measured for a sufficiently strong field directly in the b direction, a well defined constant. Surprisingly, approximate scaling holds for the smaller fields as well; however, this does not continue to still smaller values of $\vec{B} \cdot \hat{n}_{ac}$. To show this we have plotted for comparison $R_{xx}(\vec{B}) - R_{xx}^0$ [2], for fields parallel to $\hat{c}$ where $\vec{B} \cdot \hat{n}_{ac} = 0$ and the system should retain three dimensional coherence. In that case the scaling relationship should not hold, as is clear in the plot.

The crossover to two-dimensional behavior predicted [9] for $v_F q = \omega_c > 4t_c$ cannot explain the effect seen. The smallest ω_c points in the scaling plot correspond to values of about 0.1 meV or about *one-fortieth* of $4t_c$. A renormalization in field of t_c offers the only credible explanation for this rapid transition to two dimensional behavior in field and we believe that proximity to the coherence-incoherence transition is the most reasonable explanation for such a strong renormalization.

The data for R_{zz} provide even more compelling evidence for the two dimensionalization [10]. The data for different field strengths again lie on a single curve describing a simple power law, $R_{zz}(\vec{B}) - R_{zz}^0 \sim (\vec{B} \cdot \hat{n}_{ab})^{3/2}$. This result is even more striking because in any picture where the c transport is coherent the *maximal* effect should result for $\vec{B} \parallel \hat{b}$, since for this geometry the Lorenz force is maximized for the quasiparticles with wave numbers having the highest group velocity in the c direction,

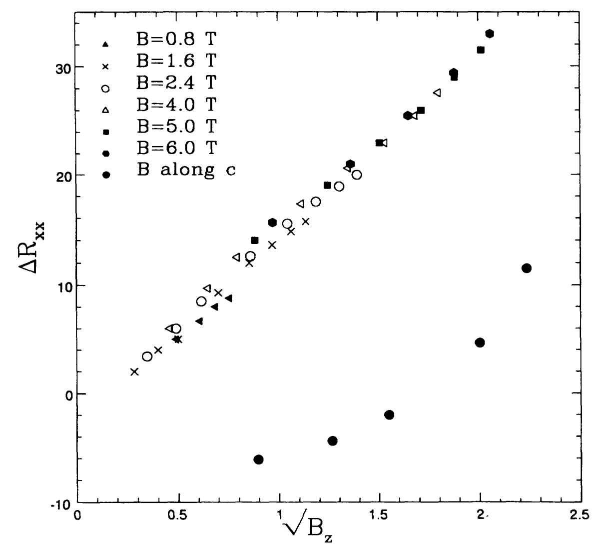

FIG. 2. Scaling plot of a-axis magnetoresistance (data from Fig. 1). As explained in the text, for sufficiently large $\vec{B} \cdot \hat{n}_{ac}$ the magnetoresistance scales: $R_{xx}(\vec{B}) = R_{xx}^0 + f(\vec{B} \cdot \hat{n}_{ab})$ where $f(x) \sim \sqrt{x}$. For the sake of comparison, we have plotted the data for $\vec{B}$ along $\hat{c}$, for which no such scaling occurs. In the figure, $B_z \equiv \vec{B} \cdot \hat{n}_{ab}$. (Note: the scale for ΔR_{xx} is related to that used in Fig. 1 by a simple multiplicative factor.)

and hence carrying the most current. Only in our picture, where the coherence of the c motion has been destroyed, is there no c component in the velocities associated with the various wave vectors, and hence such considerations do not apply.

We believe that the nontrivial power laws found in the dependences on B of the magnetoresistances requires that the two dimensional state resulting from the quenching of t_c^{coh} be non-Fermi-liquid-like [11]. For example, quasi-classical arguments using a k dependent, field independent scattering time predict that behavior independent of $\vec{B} \cdot \hat{b}$ can only be achieved if the scattering rate is independent of k_c, already requiring some two dimensionality. If this is assumed, the magnetoresistance in the a direction then grows like $\vec{B} \cdot \hat{n}_{ab}$ for weak field and saturates when the cyclotron frequency of the b motion is large compared to the largest scattering rate. The dependence of the scattering rate on field has been argued to be either proportional to B or B^2 for an anisotropic Fermi liquid [5]. Thus neither of the potential sources of field dependence in a Fermi-liquid picture can yield either a square-root behavior or a $\frac{3}{2}$ power.

We are as yet unable to carry out detailed, quantitative calculations of the square-root behavior, the dip shape, and other aspects of the magnetoresistance data because of the unknown nature of the non-Fermi-liquid state realized away from the dips and the undeveloped state of our understanding of the coherence-incoherence transition. We can, however, treat the effects of magnetic field on the calculation of [3] to demonstrate that the magnetic field enhances the effects of the correlations on the interliquid hopping. We consider a model with a pair of Luttinger liquid chains. The chains lie in the x direction and are stacked in the z direction. We couple the chains through a weak interliquid hopping, $t_\perp \sum_{k_x} c_2^\dagger(k_x) c_1(k_x) +$ H.c. The effect of a magnetic field, $\vec{B} = B\hat{y}$, can be taken into account by introducing a Peierls phase into the hopping perturbation. We neglect effects due to Zeeman splitting. In k space the field leads to the replacement of our original perturbation by $t_\perp \sum_{k_x} c_2^\dagger(k_x + q) c_1(k_x) +$ H.c., where $q = eBl_c$ and l_c is the separation of the chains in the $\hat{z}$ direction. The magnetic field therefore introduces an inelasticity into the hopping which will tend to suppress coherence [12].

As in [3], we take the time dependence of the rate of transitions out of the initial state when we switch on $t_\perp$ as our measure of coherence. The probability to have left the initial state by time t after the switching on of $t_\perp$ is given by

$$1 - P(t) \sim t_\perp^2 L \text{Re} \int_0^t dt' \int_0^t dt'' \int dx \times \left\{ e^{iqx} G_e^{(1)}(x, t' - t'') G_h^{(2)}(x, t' - t'') + e^{-iqx} G_e^{(2)}(x, t' - t'') G_h^{(1)}(x, t' - t'') \right\}, \quad (1)$$

where Δk is the shift of the Fermi momentum of one chain relative to the other. This may be separated into three terms:

$$1 - P(t) \sim t_\perp^2 L \Lambda^{-4\alpha} \text{Re} \left(\int_0^t dT \int_0^T d\tau [\alpha Z_1(\Delta k, \tau) + Z_2(\Delta k, \tau) + \alpha Z_3(\Delta k, \tau)] \right) \quad (2)$$

with the first term, Z_1, displaying incoherent behavior and the remaining two displaying coherent behaviors for short times. We need to consider the interaction of the various terms to determine the coherence or the incoherence of the effect of $t_\perp$. The prescription is given in [3]. The incoherent term, which is given by

$$Z_1(\Delta k, \tau) \sim \frac{1}{4\pi^2} \int_0^\infty dz \left\{ e^{iqv_c\tau} e^{i\Delta k(v - v_c)\tau} + e^{-(\Delta k - q)z} e^{iqv_c\tau} e^{-i\Delta k(v + v_c)\tau} \right\} \times z^{-2\alpha} [z + i(v_c + v_s)\tau + 1/\Lambda]^{-1} (z + 2iv_c\tau + 1/\Lambda)^{-1} (z + 2iv_c\tau + 2/\Lambda)^{-2\alpha}, \quad (3)$$

is essentially unaltered by the magnetic field since the effect of the field is to introduce an alternating phase factor into an already convergent integral. The first coherent term, Z_2, is given, for $\Delta k > q$, by:

$$\frac{1}{\pi} e^{iqv\tau}[(v_c - v_s)\tau]^{-1-2\alpha}[(v_c + v_s)\tau]^{-2\alpha} \sin\left(\frac{(\Delta k - q)(v_c - v_s)\tau}{2}\right). \tag{4}$$

Depending on the sign of q relative to Δk the coefficient of this term at short times obtained from expanding the sine may be either reduced or increased. For coherent motion between the chains to occur it must occur in both directions so that the reduction of the coefficient for $\mathrm{sgn}(\Delta k) \neq \mathrm{sgn}(q)$ could significantly reduce the coherence. Further, the coherent time dependence of Z_2 obtained from expanding the sine is reduced by an amount of order unity for $\tau \gtrsim (vq)^{-1}$ and its magnitude will be steadily reduced as the magnetic field is increased from zero. The effect on the second potentially coherent term, Z_3, is similar. The effect of the magnetic field is therefore to reduce the coherence of the interchain single particle hopping and, due to competition effects between the incoherent and coherent terms [3], a field of strength $\sim t_\perp^R/ecv$ should totally destroy the coherence of the interchain hopping. As a result of the competition of the incoherent and coherent terms, the field required may be a significantly smaller field than that given by $\sim t_\perp^R/ecv$ and this expression should give an upper bound on the field required. If the field does render the hopping incoherent then no band dispersing in the z direction can form and the Fermi surface shape and dispersion relation of the electrons are changed in an essential way. This will naturally affect all transport properties of the system. The electron-electron scattering rate should increase sharply and the resistivity in all directions, not just the c direction, should increase as a result.

In summary, the experimental data show that $(TMTSF)_2PF_6$ exhibits a transition to two dimensional behavior in an applied magnetic field. The small value of the field required indicates that this transition must be due to a significant field dependent renormalization of the coherent c axis hopping amplitude. The unusual scaling of the magnetoresistance with the square root of the field component perpendicular to the ab plane suggests that the resulting two dimensional state is a non-Fermi liquid. We propose that the strong renormalization of the effective t_c in field is due to the proximity of the material to a coherent-incoherent transition for c axis hopping [3] caused by the strong anisotropy of the material and the highly correlated nature of the $t_c^{\mathrm{coh}} = 0$ state. We have demonstrated that the effect of an applied field should be to reduce the coherence of hopping under such conditions. This reduction would be absent for a field parallel to the c axis leading to a sharp dip in the magnetoresistance as observed. Higher order hops generated by the renormalization of t_b and t_c would produce dips when the field is oriented along a real space lattice vector. This effect is also observed experimentally. The observed features of the dips are also in good agreement with the predictions of our theory.

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