Highly correlated materials have intermediate electron densities and are frequently doped Mott insulators, so that neither the kinetic energy nor the potential energy is totally dominant, and both must be treated on equal footing. The question arises, are there actual “intermediate” low temperature phases of matter which interpolate between the high density “gas” phase (usually called a Fermi liquid) and the low density strongly insulating Wigner crystal phase? We have shown that, at least in the case of lightly-doped antiferromagnets, the tendency of the antiferromagnet to expel holes always leads to phase separation which, when frustrated by the long-range piece of the Coulomb interaction, leads to the formation of states which are inhomogeneous on intermediate length scales and (possibly) time scales. The most common self-organized structures which result from these competing interactions are “stripes”, by which, we generally mean d – 1 dimensional antiphase domain walls across which the antiferromagnetic order changes sign, and along which the doped holes are concentrated. The term “stripe” is, of course, a reference to the important two-dimensional case relevant to the high temperature superconductors.

Even if the discussion is confined to ordered phases of doped antiferromagnets we are left with an exceedingly complex problem. Many varieties of order have been observed in doped antiferromagnets, including spin and charge order and, of course, superconductivity. The spin and charge order can be commensurate or incommensurate, and both can be ideal or glassy. There are also various structural phases, such as the tetragonal and orthorhombic phases of La1.86Sr0.14CuO4, which may reflect important changes in the electronic state, as the structural order can couple to various forms of “electronic liquid crystalline” order. Of course all of these types of order can compete or coexist in various ways.

I. LANDAU THEORY OF COUPLED CDW AND SDW ORDER

We begin by discussing density-wave order, and in particular the interplay between spin-density wave (SDW) and charge-density wave (CDW) order. This can be analyzed most simply by studying the Landau theory of coupled order parameters. While it is possible to have various sorts of “spiral” spin phases, the only spin order in much of parameter space is collinear, so the discussion will be confined to this region. The resulting phase diagram is shown schematically in Fig. 1. Three features of the analysis, which is discussed in detail in Ref. 11, bear repeating: 1) In order for the SDW order parameter $S_\parallel$ and the CDW order parameter $\rho - \rho_c$ to couple in the lowest possible order (third), it is necessary that the ordering vectors satisfy the relation $Q = 2\bar{q}$, or in other words, the wavelength of the SDW is twice that of the CDW; this gives precise meaning of the concept of “topological doping” and implies that the charge is effectively concentrated along antiphase domain walls in the magnetic order. 2) It is possible to have a phase with CDW order, but no SDW order, whereas SDW order always implies CDW order. This is important to bear in mind when thinking about the experimentally determined phase diagram of the high temperature superconductors or any other doped antiferromagnet, since there are many good probes (such as NMR, $\mu$SR, and neutron scattering) that are sensitive to spin order or fluctuations, but fewer that are sensitive to charge order. Where incommensurate spin order is detected, we can directly infer the existence of charge order, but where no magnetic order is observed, there may or may not exist as yet undetected charge order. 3) Although Landau theory by its very character is relatively insensitive to the microscopic considerations conventionally referred to as the “mechanism” of ordering, an important classification of mechanisms follows directly from these considerations. If, upon lowering temperature, CDW order is encountered first and SDW order is either entirely absent or only appears at lower temperatures when the CDW order is already well developed, the density wave transition is “charge-driven”, and we can infer that the SDW order is in some sense parasitic, i.e. driven by the interaction with the CDW. On the other hand, if both CDW and SDW order develop simultaneously, but with the CDW order turning on more slowly at the transition accord-
The charge ordering described above, which we think of as ordered arrangements of charged “stripes”, differs from more usual CDW order in metals in that it is a consequence of frustrated phase separation, not a Fermi-surface instability. There are three important consequences: 1) Whereas conventional CDW order, as observed in many charge-transfer salts and bronzes, tends to oscillate in all directions, the stripe order that we have in mind here involves a one dimensional modulation of the charge density, hence the name “stripes”. 2) There can be additional low energy electronic degrees of freedom within a stripe, i.e. the stripe can be metallic and have its own spin dynamics. 3) The density of states at the Fermi level is increased, not decreased by the opening of a gap in the electron energy spectrum, as for a CDW driven by a Fermi-surface instability.

The second point is exceedingly important in distinguishing mechanisms of stripe formation, and is a unique feature of stripes produced by competing long and short-range interactions, stripes, if they form at all, have a preferred hole density which is usually commensurate and, in turn, determines the stripe concentration. Consequently, in general, even if there were a region of parameters in which a putative stripe phase were not unstable to phase separation, it always would be insulating with a substantial charge gap. By contrast, whenever the stripes arise as a consequence of a competition between a long-range Coulomb interaction, and a short-range tendency to phase separation, the stripe concentration is a compromise between these two forces, so gaps in the intra-stripe excitation spectrum are no longer the rule.

Finally, self-organized stripe structures are an intrinsic property of a doped antiferromagnet. While they certainly couple in interesting material-specific ways to external inclusions, such as the lattice modulation in Bi$_2$Sr$_2$CaCu$_2$O$_{8+δ}$ or the chains in YBa$_2$Cu$_3$O$_{7−δ}$, these extrinsic effects should be viewed as reflecting the intrinsic stripe physics, rather than causing it.

### III. ELECTRONIC LIQUID CRYSTAL PHASES

Following the work in Ref. 10 we analyze the case in which intra-stripe metallic degrees of freedom interact with the fluctuating “geometry” of the stripe arrangement, resulting in a set of new states of matter, which in analogy with classical liquid crystals, we have named “electronic liquid crystals.”

By analogy with classical liquid crystals, we can readily deduce the schematic phase diagram, as shown in Fig. 2. Here, the x axis is a quantum parameter, $\hbar \omega$, related to the transverse zero-point energy of the stripes, i.e. it measures the extent of quantum fluctuations of the stripe order. These phases, which can exist at either zero or finite temperature, can be classified as follows:

1) **Stripe crystal phases**: Here translational symmetry in the direction perpendicular to the stripes is broken because the stripes are ordered, and translational symmetry along the stripe is broken because the electrons along the stripe form a CDW which is phase locked between stripes. This phase is conceptually similar to the CDW phases that occur in charge transfer salts and, in common with them, it is insulating. In the important, but special cases in which the stripes have no low energy internal degrees of freedom, (e.g. stripes that are full of holes or electrons), the insulating state is achieved without breaking translational symmetry along the stripe direction. At zero temperature in two spatial dimensions, the stripe order is always pinned at a period commensurate with the host crystalline lattice, while at non-zero temperature it can be commensurate or incommensurate, but where it is incommensurate, the positional order is only quasi-long range.

2) **Electronic smectic phases**: If the stripe order is maintained, but the intra-stripe excitations remain unpinned, one obtains an electronic smectic phase. This
phase possesses the same broken symmetries transverse to the stripe direction as the stripe crystal phases (with all the same dimension specific considerations mentioned above), but simultaneously exhibits liquid-like behavior associated with the motion of electrons within a stripe, and the tunnelling of electrons between stripes. Depending on additional interactions in the problem, this phase can either remain an electron liquid down to zero temperature, or can become superconducting below a critical temperature, \( T_c \).

A major portion of the work in Ref. 10 addressed the issue of how the transverse fluctuations of the stripes control both the transition between the stripe crystal and electronic smectic phases, and the magnitude of the superconducting \( T_c \) within the smectic phase. Basically, in the presence of a spin gap, the intra-stripe electron gas is prone to large superconducting and CDW fluctuations. In two spatial dimensions (where within a stripe the electrons form an effective one dimensional electron gas), it is known that both these susceptibilities typically will diverge as \( T \to 0 \), with the CDW being the more divergent. In higher dimensions, more complicated possibilities exist, but the physics is not qualitatively different. Now, because the CDW order involves short-wavelength density oscillations along the stripe, the CDW ordering on neighboring stripes is readily dephased by transverse stripe fluctuations; through this mechanism, increasing transverse stripe fluctuations (either quantum or thermal) can easily be shown to stabilize the smectic phase at the expense of the stripe crystal. Conversely, pair tunnelling between neighboring stripes, and hence the transverse component of the superfluid density, is enhanced by transverse stripe fluctuations. To see this, we note that the local pair-tunneling matrix element, \( J_{\text{pair}} \), depends exponentially on the local separation, \( w \), between stripes

\[
J_{\text{pair}} \approx J_0 \exp[-\alpha w].
\]

To get an idea for the physics, we average this quantity over transverse stripe fluctuations, keeping terms up to second order in a cumulant expansion, with the result

\[
\bar{J}_{\text{pair}} \approx J_0 \exp[-\alpha \bar{w}] \exp[\alpha^2 (\Delta w)^2 / 2]
\]

where \( \Delta w \) is the variance of \( w \). Clearly, for fixed mean spacing \( \bar{w} \) between stripes, the pair tunnelling is a strongly increasing function of \( \Delta w \).

3) Electronic (Ising) Nematic: When the transverse stripe fluctuations get sufficiently violent, they will certainly lead to a liquid state, with full translational symmetry. However, it is possible that the general orientation of the stripes can persist beyond the melting transition. In this case the electronic phase is liquid-like and translationally invariant, but it breaks the discrete rotational symmetry of the host crystal. The nematic phase in fact breaks this discrete symmetry. For instance, in a tetragonal crystal with a four-fold rotational symmetry, the nematic phase would be electronically orthorhombic, with only a two-fold rotational symmetry surviving. Of course, there is bound to be some back coupling between electronic and lattice structure, so such a phase would also be accompanied by a locally orthorhombic distortion of the crystalline lattice. Like the smectic, the nematic phase can either remain a normal liquid down to zero temperature, or become superconducting.

We have sketched a representative superconducting phase boundary as a dashed line in Fig. 2. The logic governing its shape is as follows: Superconductivity requires both pairing, which occurs below a temperature \( T_{\text{pair}} \sim \Delta(0)/2 \), where \( \Delta(0) \) is the zero temperature magnitude of the superconducting (spin) gap or pseudogap, and phase ordering, which sets in below a temperature \( T_\theta \) which is proportional to the zero temperature superfluid density. It is clear that the general trend found in the smectic, in which an increase in the transverse fluctuations increases the transverse phase stiffness, should apply in the nematic phase close to the smectic phase boundary. Thus, as long as \( T_\theta \) determines \( T_c \), it will be an increasing function of \( \hbar \omega \). Of course, ultimately the transverse fluctuations become so violent that even the local concept of a stripe ceases to be well defined; if we take the view that stripes are an essential ingredient in the pairing mechanism (equivalently, in the spin-gap formation) then \( T_c \) must first rise and then decrease with increasing fluctuations.

We have shown the peak in \( T_c \) near the nematic to isotropic phase boundary, because we imagine that this is where the stripes start to fall apart at a local level. The points marked \( C_j \) are quantum critical points. As drawn, the superconducting phase boundary crosses the nematic phase boundary at a tetracritical point, \( T_1 \), but it is equally possible that the superconducting phase boundary could end at a bicritical point (say, roughly where \( T_1 \) appears in the figure), and that beyond this there is a (possibly weak) first order phase boundary marking the simultaneous onset of superconducting and nematic order. Alternatively, the superconducting phase might, in some circumstances, lie entirely inside the nematic phase, if the quantum critical points \( C_2 \) and \( C_3 \) were exchanged, in which case there would be no multicritical point analogous to \( T_1 \).

4) Isotropic stripe liquid: With sufficiently large transverse fluctuations, all symmetry is restored, so an isotropic liquid phase results. However, if sufficient stripe order persists on a local level, the resulting isotropic stripe liquid may be quite different from a non-interacting electron gas. Since there is no symmetry distinction, it is possible that the evolution from a stripe liquid to a Fermi gas involves a crossover, but often, as in a liquid gas transition, a first order transition separates two qualitative different but asymptotically similar phases; for that reason, we have included such a first order line, ending in a critical point, in Fig. 2.
FIG. 2. Schematic phase diagram of the electronic liquid crystal phases of a doped Mott insulator, as discussed in the text. The quantum parameter, $\hbar \omega$, depends in a complicated way on material parameters, as well as the doped hole concentration. The dotted lines can be thought of as representing the temperature evolution of different materials: Along I, the insulating stripe crystal ground state melts in two steps, a sequence of transitions similar to that seen in La$_{4/3}$Sr$_{1/3}$NiO$_4$. Along II, the simultaneous stripe (smectic) and superconducting order of the ground state evolve through a sequence of transitions in which first the superconducting, then the stripe, and finally the orientational (nematic) order are lost; this is reminiscent of the transitions observed in La$_{1-x}$Nd$_x$CuO$_4$. Along III, the ground state exhibits only superconducting and orientational order, but the proximity of the quantum critical point, $C_3$, implies that significant stripe correlations, with dynamics and thermal evolution governed by this critical point, should be observable at low temperatures; this is highly reminiscent of the behavior of La$_{1.86}$Sr$_{0.14}$CuO$_4$.

IV. QUENCHED DISORDER AND STRIPE GLASS PHASES

It was shown by Larkin that quenched disorder is relevant in CDW systems in dimension $d < 4$, i.e., in any physical dimension, true long range CDW order simply does not occur in the presence of disorder! However, in high enough dimension and for weak enough disorder, there exists a “Bragg glass” phase, which in the present context we refer to as a “stripe-glass”, which has power-law density-wave order. This is a distinct state of matter, and hence must be separated from the high temperature melted phase by a sharp phase transition. This phase is now more or less established in $d = 3$, and it has been argued that in $d = 2$, even if an exponentially dilute concentration of free dislocations spoils the power-law decay of correlations at very long distances, this has very little practical consequence. For the materials of interest to us here, which are either three dimensional or quasi-two dimensional, it is safe to conclude that a true stripe glass phase exists, with a sharply defined glass transition temperature, $T_g$.

Where, as a function of varying material parameters, $T_g \to 0$, we expect a quantum critical point. However, this quantum critical point will have quite different character than those invoked in various theories of high temperature superconductivity in that the glass transition is disorder driven. Rather, the quantum critical properties will be more or less similar to the melting of a “Wigner glass”, which has been invoked to explain the apparent metal-insulator transition observed in Si MOSFETs.

Since the charged stripes in doped antiferromagnets are typically, anti-phase domain walls in the magnetic order, the freezing of the stripe motion at $T_g$ opens up the possibility of subsequent (i.e., at still lower temperature) ordering of the spins. As we discussed some time ago, spin ordering in a stripe glass will lead to a “cluster spin-glass” phase. Since spin-glass ordering involves a broken symmetry (time reversal), it is easier to detect experimentally than stripe-glass ordering, and so more is known about the occurrence of this sort of ordering in doped antiferromagnets. We infer that, in doped antiferromagnets in which cluster spin-glass ordering is observed below a spin-glass transition temperature $T_{sg}$, there also should be a stripe-glass ordering transition with $T_g \geq T_{sg}$.

Finally, it is worth making a couple of general observations concerning the effects of quenched disorder. 1) One of the most dramatic features of all glasses is the dramatic slowing down of dynamics over a broad range of temperatures as the glass transition is approached. One consequence is that $T_g$ is always very difficult to determine experimentally (or even to determine whether there really is a finite $T_g$ at all); rather, there is an apparent $T_g$ which depends on the frequency at which the system is probed. Thus, it is to be expected when dealing with a glass transition, that the phase diagram, as determined by different experimental probes, will look rather different, with $T_g^{\text{fast}} > T_g^{\text{slow}}$. For instance, a glass phase boundary, as determined by neutrons, will be a function of the energy resolution, and will extrapolate to the $\mu$-SR phase boundary as the energy resolution tends to zero. 2) It can be proven that disorder eliminates any first order transitions in two dimensions. Weak disorder can either convert a first order line into a more or less sharp crossover or turn it into a continuous transition if there remains a fundamental distinction between the two phases. For instance, in the phase diagram in Fig. 2, if the tetracritical point $T_1$ were replaced by a bicritical point, $B_1$, followed by a first order transition to a superconducting nematic phase, the first-order line would be replaced by a line of continuous phase transitions in the presence of disorder.
V. SOME COMMENTS ON PARTICULAR PHASES OBSERVED IN THE HIGH TEMPERATURE SUPERCONDUCTORS

We conclude by making some remarks about a few recent experimental discoveries in the most studied of doped antiferromagnets, the high temperature superconductors, and their relationship to the theoretical considerations discussed above. Here, the “undoped” system is a highly-insulating spin-1/2 antiferromagnet, which is made conducting and superconducting by the addition of a small concentration $x$ of “doped” holes. While much of what we discuss is known or presumed to be common to all of the high temperature superconductors, we will explicitly refer to experiments in the LSCO and YBCO families of materials.

A. The insulating “spin glass”

For $x$ in the range between about 2% and 5%, no long-range order of any sort has been observed, and the material is insulating at low temperatures. There is, however, a well defined spin-glass transition. While the spin-glass phase is generally viewed as a curiosity, of no central significance, we have long taken the view that, since this is the only ordered phase proximate to the high temperature superconducting phase, it should in fact play a central role in our thinking about these materials. We proposed that it is in fact a “cluster spin glass” phase, in which a frozen random array of stripes produces the frustration, so that the spin glass consists of patches of locally antiferromagnetically ordered spins with an axis of magnetization that varies from patch to patch. In particular, we showed that this proposal naturally accounts for the remarkable fact derived from early neutron scattering measurements of the spin structure factor, that the inverse correlation length, $\kappa(x,T)$, obeys the simple composition rule,

$$\kappa(x,T) = \kappa(0,T) + \kappa(x,0).$$

It is clear that there must be a transition at which the stripes freeze into a stripe glass. The spin-glass transition is more readily detected experimentally, since it involves symmetry breaking whereas the stripe-glass transition involves only replica-symmetry breaking. However, we believe that the stripe glass is the fundamental phenomenon and that the spin-glass transition is more or less parasitic. Indeed, it is likely that the stripe-glass transition temperature is greater than $T_g$, we await experimental input on this last issue.

B. The Superconducting stripe glass

The importance of the spin glass is further substantiated by the old observation, which has recently been dramatically confirmed by Budnick and collaborators, that spin-glass and superconducting order in fact coexist in underdoped high temperature superconductors! That static spin order and superconducting order can coexist in a single-component electronic system is very surprising in terms of conventional paradigms of superconductivity. Of course, the realization that the spin glass is actually a stripe glass, which can be viewed as a slightly disordered version of the electronic smectic phase discussed above, renders this observation a key experimental confirmation of the relevance of stripe physics to high temperature superconductivity. In a sense, self-organization into stripes, generates a two-component electronic system—a localized spin component which lives between the stripes, and a metallic component which flows along the stripes.

In the past few years, neutron scattering studies of La$_{1.6-x}$Nd$_{0.4}$Sr$_x$CuO$_4$ have revealed a still more dramatic and detailed aspect of the coexistence of superconducting and magnetic order. Specifically, Tranquada and collaborators found a sequence of transitions that depends somewhat on Sr concentration. As the temperature decreases there is: 1) A structural transition to a low temperature tetragonal (LTT) phase, 2) A charge-ordering transition at which the appearance of well-defined incommensurate elastic peaks in the lattice structure factor are driven by charge stripe ordering. 3) A spin-ordering transition, with ordering vector twice that of the charge ordering vector. 4) A superconducting transition, with, however, $T_c$ reduced relative to that in La$_{1.6}$Sr$_{0.4}$CuO$_4$ at the same Sr concentration. The coexistence of superconducting and stripe order was considered surprising, and indeed it has sometimes been attributed to sample inhomogeneity. However the evidence in favor of coexistence continues to increase. That charge order sets in before spin order confirms that the density-wave ordering is “charge driven”, in the sense defined above. The addition of Nd to the material stabilizes the LTT structure which allows the oxygen tilting phonon to couple more strongly to any charge order - in terms of the schematic phase diagram in Fig. 2, this reduces the magnitude of the quantum fluctuations of the stripes, so the material should be viewed as living farther to the left than La$_{1.6}$Sr$_{0.4}$CuO$_4$. Indeed, it is tempting to relate the sequence of observed charge transitions to those on a trajectory on our phase diagram which passes from the normal state at high temperature, through a nematic phase, to a smectic phase, and finally to a superconducting smectic phase at low temperatures. This identification is made slightly less than airtight by two subtleties: 1) It is not clear to what extent the structural phase transition to the LTT phase can be viewed as electronically driven. 2) The elastic peaks, observed in neutron scattering, have a finite width, corresponding to a long but finite correlation length for the density-wave order. As discussed above, this is to be expected in a quasi-two-dimensional system with disorder, where any ordered state must be glassy, but it makes the unambiguous identification of the various phases less secure.
Still more recently, neutron scattering experiments on the underdoped La_{1-x}Sr_xCuO_4 and even optimally oxygen-doped La_2CuO_4+δ (with θ, as high as 42K) have shown that static, fairly long-range stripe order and superconductivity coexist. In these materials, the transition temperatures for spin ordering (which is all that has been detected to date) and superconducting ordering appear to be close to each other, or possibly exactly the same. This demonstrates an intimate relation between stripe ordering and superconductivity, and is an important new piece of “theory independent” evidence for the critical role played by stripe order in the mechanism of high temperature superconductivity.

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