mentary constituent of matter allow the low values of the mass that are preferred by the fit, and certain of these models even require it. The most ambitious models of this type, "supersymmetric grand unified theories," require that the Higgs boson is light (*17*). These models contain a huge number of new particles—a heavy partner for every particle in the standard theory. Surprisingly, though, the particular species predicted by these models give very small additional contributions to the vacuum polarization (*18*).

The new measurements, then, put the structure of the weak interactions into focus in a way that brings the story of elementary particle physics to a state of high tension. The possibilities for what we might find around the next corner are increasingly limited. The alternatives include the simple possibility of one light Higgs boson. But they also include models whose new symmetries lead to a parade of exotic particles and even to promised new visions of space and time. In the next decade, at the next step in accelerator energy, we will learn which of these alternatives nature chooses.

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PERSPECTIVES: CONDENSED MATTER PHYSICS

# Electronic Confinement in Organic Metals

**Claude Bourbonnais and Denis Jérome**

In the last two decades, the synthesis of new low-dimensional materials such as the organic and high–transition-temperature superconductors has shattered our traditional views about the properties of electrons in metals. This has been especially true since the 1980s with the coming of the Bechgaard salts, the so-called $(TMTSF)_2X$ organic superconductors and their sulfur analogs $(TMTTF)_2X$. These systems consist of a vast series of isostructural organic metals for which the donor constituents TMTSF (tetramethyltetraselenafulvalene) or TMTTF (tetramethyltetrathiafulvalene) are planar molecules and the acceptor X is an inorganic radical. On page 1181 of this issue, Vescoli *et al.* report new evidence for the unusual electronic properties of these materials (*1*).

Because TMTSF and TMTTF interact only weakly in the solid state, the cation retains its planar conformation. The result is a plane-to-plane stacking and an electronic delocalization along a particular direction, which turns these materials into a close realization of a one-dimensional metal. The Coulomb interaction between electrons is found to have special consequences in low-dimensional systems. The concept of "quasi-particles"—so successful in the Fermi liquid description of ordinary metals as a collection of effectively noninteracting electrons—turns out to be inapplicable in one spatial dimension, where the spin and charge degrees of freedom separately merge into collective low-energy excitations (*2*). These collective modes completely replace the quasi-particles, giving rise to a quite different electronic state called a Luttinger liquid.

Although real organic metals like the Bechgaard salts exhibit a small but finite coupling between chains, making them not purely one dimensional but rather quasi–one dimensional, these materials are among the best candidates for detecting signs of a Luttinger liquid state (*3*, *4*) as well as its possible instabilities, namely the recovery by the interchain coupling of a Fermi liquid state and the stabilization of various ordered phases (*5*). Working on this wide-ranging series of isostructural quasi–one-dimensional materials offers great advantages, including the possibility of following almost continuously the evolution of physical properties of the normal state as a function of anion (X = $PF_6$, $AsF_6$, Br, $ClO_4$, and so forth) and cation (TMTTF or TMTSF) substitutions, the application of hydrostatic pressure (*3*, *4*), or even working in nonzero magnetic field (*6*, *7*).

In a effort to seek concrete evidence of a Luttinger liquid in these systems, Vescoli *et al.* (*1*) have performed a nice set of optical reflectivity measurements that display the evolution of the optical transport in the presence of a correlation gap $\Delta_\rho$. The results allow analysis of an important reduction of the amplitude of the gap when the optical probe goes from members of the insulating sulfur series to the metallic selenides (from left to the right in the figure). Moreover, they corroborate and complete previous optical studies by the groups of Timusk (*8*) and Elridge (*9*), who pointed out from the start the existence of a gap in the normal state of the selenide compounds $(TMTSF)_2AsF_6$ and $(TMTSF)_2ClO_4$.

For typical sulfur compounds like $(TMTTF)_2PF_6$ and $(TMTTF)_2Br$, located on the left side of the figure, the experiments show that the correlation gap is associated with an insulating behavior below the temperature $T_\rho = \Delta_\rho/3$. The temperature variation of magnetic spin susceptibility is well known to remain unaffected by the gap (*3*), indicating that the spins are apparently decoupled from the charge degrees of freedom. A spin-charge decoupling of this sort is predicted to occur when electrons in a half-filled or quarter-filled one-dimensional energy band interact to form a Luttinger liquid state that is severed of its charge component ($LL_\sigma$), also known as a one-dimensional Mott-Hubbard insulator. Electronic correlations then become so strong that charge carriers remain confined along the organic stacks. In the experiments of Vescoli *et al.* (*1*),

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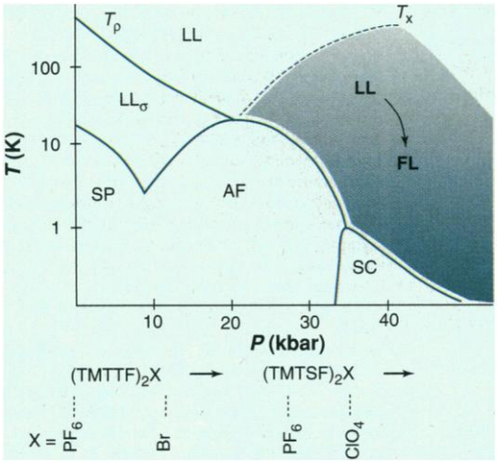


**Materials of many phases.** The generic phase diagram of the Bechgaard salts $(TMTSF)_2X$ and their sulfur analog $(TMTTF)_2X$ as a function of pressure ($P$) or anion X substitution. On the left, the normal phase of sulfur compounds is a Luttinger liquid (LL) that becomes gapped in the charge sector ($LL_\sigma$) below $T_\rho$ and can develop either a spin-Peierls (SP) or localized antiferromagnetic (AF) ordered state. Under pressure, the properties of the sulfur series evolve toward those of the selenides for which the normal state shows a progressive restoration of a Fermi liquid (FL) precursor to itinerant antiferromagnetism and superconductivity (SC).

neat signs of charge confinement are given by the absence of a transverse plasma mode when the oscillating electric field is oriented perpendicular to the chains. Spin degrees of freedom remain gapless, however, and will produce a characteristic enhancement of the magnetic response of the system, as can be shown in nuclear magnetic resonance experiments. A quantity like the nuclear relaxation rate, which probes fluctuations of the electronic spin system, is predicted to vary as a power of the temperature in a Luttinger liquid (*10*). Systematic nuclear magnetic resonance measurements carried out by the Orsay group on several members of the sulfur series at low temperature have established a power law enhancement of the relaxation rate that corresponds to the one predicted for a one-dimensional Mott-Hubbard insulator (*11*).

Spins ultimately deconfine at lower temperature through an effective spin exchange coupling that is always finite between chains (*4*, *12*). The system then evolves toward a true three-dimensional ordered state that can be either antiferromagnetic or structural with a spin gap—the so-called spin-Peierls state—whenever the coupling of spins to phonons becomes sufficiently strong. Occurring below 25 K, these ordered phases then fix the rather large domain of stability of the Luttinger state in the sulfur series at low pressure (see figure).

The optical data reported in this issue by Vescoli *et al.* (*1*) also suggest that as one moves to the right-hand side of the phase diagram, the onset of electronic deconfinement leading to a transverse plasma mode would occur when the single electron hopping, which increases in amplitude according to band calculations, becomes on the order of the correlation gap ($t_\perp \sim \Delta_\rho/2$ ). According to previous renormalization group calculations performed on a lattice of coupled Luttinger liquids (*4*, *12*), this condition corresponds to the pressure range where the temperature scale $T_\rho$ meets the critical domain associated with the antiferromagnetic transition in the figure, defining the insulating-metallic boundary of these systems in the normal state. It is worthwhile to note that many properties of these organic metals show a noticeable change in behavior in this pressure domain (*13*). In particular, the power law exponent for the enhancement of the nuclear magnetic resonance relaxation rate goes through a sizable reduction, indicating a weakening in the charge confinement (*14*).

Another experimental feature that further supports the onset of charge deconfinement in this pressure domain and above is provided by direct current transport measurements along the transverse $c$ direction, which has the weakest interchain kinetic coupling (*15*). Transverse resistivity can give valuable information about charge motion in the perpendicular directions corresponding here to the *ab* plane. Moser *et al.* (*15*) report the existence of a maximum in transverse resistivity as a function of temperature emerging from the metallic-insulating boundary for the chains and moving to higher temperatures under pressure ($T_x$ in the figure). The temperature dependence of the transverse resistivity, albeit metallic and proportional to $T^{1.5}$ below $T_x$ [which is on the order of 80 K in a compound like $(TMTSF)_2PF_6$ at ambient pressure], differs substantially from what is observed for the parallel resistivity to the chains, which is known to evolve to a $T^2$ dependence below 50 K, corresponding to what would be expected for a Fermi liquid (*15*).

This difference between the longitudinal and transverse electrical transport suggests, however, that the charge deconfinement and the restoration of a Fermi liquid picture are likely not to be fully achieved. This is further supported by the fact that for selenide (sulfur) compounds at low (high) pressure, the enhancement of the nuclear relaxation induced by spin correlations is still anomalously large in the normal state. For a system like $(TMTSF)_2ClO_4$ at ambient pressure, the enhancement only shows signs of saturation around 10 K (*16*). The shaded area of the figure is then indicative of a rather large crossover region where non–Fermi liquid features apparently maintain some robustness. As shown by the data of Vescoli *et al.* (*1*) and Dressell *et al.* (*17*), for compounds like $(TMTSF)_2PF_6$ and $(TMTSF)_2ClO_4$, remnants of the correlation gap still continue to capture most of the spectral weight of optical conductivity, whereas the zero-energy response that gives rise to conductivity shows strong deviations with respect to the Drude model for ordinary metals.

Because the itinerant antiferromagnetic or spin-density-wave ground state results from the so-called nesting properties of the electron spectrum, its suppression under pressure (which causes superconductivity) indicates that a coherent Fermi liquid component is present in at least two directions. This is so in order to frustrate the symmetry properties of the electron spectrum, which are a prerequisite to long-range magnetic ordering at high pressure.

The results of Vescoli *et al.* bring additional support for the relevance of non–Fermi liquid concepts in the description of the normal state of these organic metals. This allows us to hope that it will prompt interest in gaining more information about the continuous change from a well-defined Luttinger liquid to a Fermi liquid state from which organic superconductivity emerges in these materials.

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