CONF-931247--11

BNL-61337

Properties of an Orbital Kondo Array

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ABSTRACT- We consider a solvable model of a one dimensional electron gas interacting with an array of dynamical scattering centers, whose state is specified by a pseudospin variable. In the dilute limit, for frequencies ω and temperatures T below the single-center Kondo scale but above a coherence scale Δ, the physics is governed by the fixed point of the single-impurity two-channel Kondo problem. In that region, the physical properties are governed by composite (or odd-frequency) pairing fluctuations and they are reminiscent of the normal state of high temperature superconductors. As ω and $T \rightarrow 0$, three susceptibilities are equally divergent: 1) conventional, spin-singlet even-parity pairing 2) composite spin-singlet odd-parity η-pairing and 3) odd parity pseudospin.

The consequences of frustrated phase separation in high temperature superconductors [1] may be explored by studying the behavior of an electron gas interacting with an array of dynamical scattering centers.[2] The model is an orbital analog of the Kondo problem, in which the scattering center is specified by a pseudospin variable which couples to the orbital states of the electron-gas, rather than to their true spin. It has been solved exactly in one dimension for a particular value of one of the coupling constants [2] and, among other things, it has been found that the behavior of the dilute array is remarkably reminiscent of the observed normal state of high temperature superconductors. [3] In this regard, the most striking feature is a T-linear (for $T > \omega$) or ω-linear (for $\omega > T$) contribution to the resistivity, which we identify as a *paraconductivity* associated with composite (or odd-frequency) pairing fluctuations extending to temperatures of the order of the Kondo scale Γ. This contribution is insensitive to all other details, including scattering from ordinary impurities and phonons, as one might expect of a paraconductivity. We know of no other explanation for fact that the T-linear resistivity of optimally-doped high temperature superconductors is undisturbed by phonons up to 1000K.[4] On the other hand, as we shall see, the (coherent) superconducting state of an array of such scattering centers in higher dimensions may have conventional even-frequency pairing and may be granular.

The Hamiltonian for the field-theory version of the model [2] is given by:

$$H = H_0 + H_1 \tag{1}$$

where H_0 is the kinetic energy:

$$H_0 = iv_F \sum_\sigma \int dr \left[\psi^\dagger_{1,\sigma}\partial_r\psi_{1,\sigma} - \psi^\dagger_{2,\sigma}\partial_r\psi_{2,\sigma}\right]. \tag{2}$$

Here $\psi^\dagger_{1,\sigma}(r)$ and $\psi^\dagger_{2,\sigma}(r)$ create respectively a right and left moving electron at position r and with z component of spin $\sigma = \pm 1/2$. H_1 is the coupling between the electron gas and the dynamical scattering centers:

$$\begin{aligned} H_1 = \quad & J_{\|}a \sum_{R,\sigma} \tau^z_R \left[\psi^\dagger_{1,\sigma}(R)\psi_{1,\sigma}(R) - \psi^\dagger_{2,\sigma}(R)\psi_{2,\sigma}(R)\right] \\ & + J_\perp a \sum_{R,\sigma} \left[\tau^-_R e^{2ik_F R}\psi^\dagger_{2,\sigma}(R)\psi_{1,\sigma}(R) + \text{H.c.}\right] \end{aligned} \tag{3}$$

where τ^λ_R are pseudospin-half operators repesenting the degrees of freedom of the scattering center at position R, a is a lattice constant, and k_F is the Fermi wave vector. Since τ^z_R couples to the local electronic current, it must be odd under time reversal and parity. This coupling is an important feature of our model, and it is responsible for some of the unusual consequences.

There are two important energy scales in the problem; the single-center Kondo scale Γ and a coherence scale Δ, which characterizes the induced interactions between neighboring pseudospins. Δ is a calculable function of $J_\perp/v_F$ and the concentration of pseudospins, c. We shall focus on the dilute limit $c \ll c_1$ in which $\Gamma \gg \Delta$. Such a limit must exist since $\Delta \to 0$ as $c \to 0$. There are three distinct regimes of temperature: 1) $T > \Gamma$, where the

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scattering from the pseudospins is weak; 2) $\Delta \ll T \ll \Gamma$, where *universal* single-impurity Kondo physics is observed; 3) $T \ll \Delta$ where the pseudospins form a state with long-range coherence, in which the critical fluctuations associated with a single impurity are cut off and, as we shall see, long-range pairing fluctuations are enhanced.

In the dilute incoherent limit ($\Delta \ll T, \omega \ll W$), the different pseudospins are essentially independent and the behavior is governed by the same fixed-point as the isotropic ($J_{\parallel} = J_{\perp}$) two-channel Kondo problem.[2,5] The low-frequency, low-temperature properties depend on a single, nonuniversal energy scale, Γ (the Kondo scale) and there is a strong enhancement of the correlation function of a *composite* pairing operator $\tau^z_{R_r}(t)[\psi^{\dagger}_{2,\downarrow}(r,t)\psi^{\dagger}_{1,\uparrow}(r,t) - \psi^{\dagger}_{2,\uparrow}(r,t)\psi^{\dagger}_{1,\downarrow}(r,t)]$, where R_r signifies the pseudospin site closest to position r. (At long times, the correlation function is proportional to t^{-1}, whereas it varies as t^{-2} for noninteracting fermions.) In the same limit, there is an anomalous contribution to the conductivity:

$$\sigma_a(\omega, T) = (\frac{2a\Delta J_{\parallel}}{\pi})^2 c\delta_{a,b} \tanh(\beta\omega/2) \tag{4}$$

Evidently, as mentioned above, $\sigma_a(\omega, T) \sim 1/T$ if $\omega \ll T \ll \Gamma$ and $\sim 1/\omega$ if $T \ll \omega \ll \Gamma$. It is important to note that $\sigma_a(\omega, T)$ is *directly* proportional to the impurity concentration c: it is a *paraconductivity* reflecting enhanced composite (or equivalently odd-frequency) pairing correlations over a wide range of temperature and frequency.[2,5] We also have shown that $\sigma_a(\omega, T)$ is insensitive electron-phonon scattering and to various other perturbations which may be added to the model.

The low-temperature ($T < \Delta$) (coherent) behavior of the system may be characterized by the correlation functions of three order parameter fields: 1) conventional singlet, even parity superconducting pairing, $O_{SS} = [\psi^{\dagger}_{1,\uparrow}\psi^{\dagger}_{2,\downarrow} + \psi^{\dagger}_{2,\uparrow}\psi^{\dagger}_{1,\downarrow}]$, 2) composite, spin singlet, odd parity superconducting pairing, $O_{comp}(r,t) = \psi^{\dagger}_{2,\downarrow}(r,t)\psi^{\dagger}_{2,\uparrow}(r,t)\tau^{+}_{R_r}(t)$, 3) the orientation of the pseudospins, $\vec{O}_{\tau} = \vec{\tau}_R$. It has been shown [2] that, as $T \to 0$, the dominant long-time, long-distance contributions to all three correlation functions are proportional to $1/|r|$ and their Fourier transforms diverge like $1/T$ as $T \to 0$.

Since two distinct pairing operators are substantially enhanced at low temperatures, the physics of the orbital Kondo lattice may lead to different kinds of superconducting order parameter in higher dimensions, where the crossover becomes a true phase transition. The nature of the order will depend on the parameters of the model and possibly on additional interactions, not included in the Hamiltonian studied here. For example, in a three-dimensional system composed of orbital Kondo chains coupled by weak hopping, phase coherence would be most easily attained for conventional singlet pairing: composite, or odd-frequency pairing then would be no more than a fluctuation effect.

Finally, we note that the behavior of annealed scattering centers will depend on the interaction between the impurities. Possible low-energy states are dimers or clusters, (which would lead to "granular" behavior) or a lattice with a period that maximizes the interaction with the conduction electrons, via commensurability. At the same time the coherent low-temperature physics is the same in the dilute and dense limits, and is insensitive to the precise distribution of the scattering centers. A more extended discussion of the method of solution and the consequences is given in references 2 and 5.

VJE was supported by the Division of Materials Science, U.S.Department of Energy under Contract No. DE-AC02-76CH00016. SK was supported in part by the NSF under Grant No. DMR-90-11803.

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