Committee Meeting

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RAPID COMMUNICATIONS

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Enhancement of electronic spin susceptibility in Pauli-limited unconventional superconductors

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We calculate the wave-vector-dependent electronic spin susceptibility $\chi_{\alpha\beta}(\mathbf{q},\mathbf{H}_0)$ of a d-wave superconductor in uniform magnetic field $\mathbf{H}_0$ with Pauli pair-breaking. We find that the transverse component of the susceptibility tensor can be greater than its normal state value; the longitudinal component also slightly increases but in a very limited range of q's. We identify several wave vectors $\{\mathbf{q}_\perp,\mathbf{q}_\parallel\}$ that correspond to the maxima of either $\chi_\perp$ or $\chi_\parallel$. We compare our results with available data on the high-field phase in heavy-fermion $CeCoIn_5$.

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The interplay of superconductivity (SC) and magnetism has been an active field of research for many years. Ferromagnetic order produces strong uniform internal fields that tend to destroy spin-singlet Cooper pairs. Such competition usually results in suppression of one of the orders [1]. The antiferromagnetic (AFM) order, on the other hand, interferes much less with superconductivity, as it gives rise to field oscillations on a short atomic scale, much smaller than the Cooper pair size ξ_0 [2]. Furthermore, in unconventional superconductors under certain conditions the superconducting and aniferromagnetic spin-density wave (SDW) orders are attractive [3].

Recent years have seen another cycle of interest in understanding the details of the SC-SDW interactions due to the discovery of iron-based superconductors [4] and the Ce family of heavy fermion materials [5,6]. In pnictides the

The details of this "attraction" between SDW order and Pauli-suppressed SC are still not fully uncovered. All theories so far assumed only a single direction of the SDW ordering vector $\mathbf{q}$, connecting nodes, independent of temperature and the field. The size of the SDW phase has not been explicitly connected with the microscopic parameters such as size of the SC gap, bandwidth or Fermi energy, and strength of the magnetic interactions.

In this Rapid Communication we present a microscopic picture of the SDW instability in unconventional d superconductors, and find several key features consistent with the experiments on $CeCoIn_5$. We calculate the spin susceptibility as a function of magnetization ordering vector $\mathbf{q}$, temperature, and field, and determine onset of the magnetic instability in the phase diagram. Susceptibility gives detailed information

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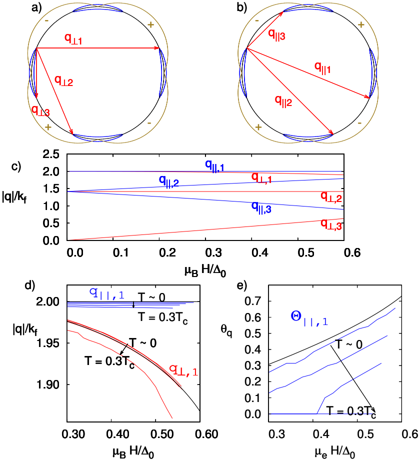
Nodal gap has negative quasi-particle energy states when in external field

$$E_{\mathbf{k}\sigma} = \sqrt{\xi_{\mathbf{k}}^2 + \Delta_{\mathbf{k}}^2} + \sigma H \qquad \Delta_{\mathbf{k}} = \Delta sin(2\theta_{\mathbf{k}}) \qquad \sigma = \pm 1 \tag{1}$$

AFM correlations which connect ("Nest") these negative/zero energy states in a particular way are enhanced

$$\chi_{\perp}(\mathbf{q}) = \sum_{\mathbf{k}\sigma} \frac{A_{\sigma}(\mathbf{k},\mathbf{q})}{E_{\mathbf{k}+\mathbf{q}/2\sigma} + E_{\mathbf{k}-\mathbf{q}/2\sigma}} \tag{2}$$

$$+ \frac{B_{\sigma}(\mathbf{k},\mathbf{q})}{E_{\mathbf{k}+\mathbf{q}/2\sigma} - E_{\mathbf{k}-\mathbf{q}/2\bar{\sigma}}} \tag{3}$$



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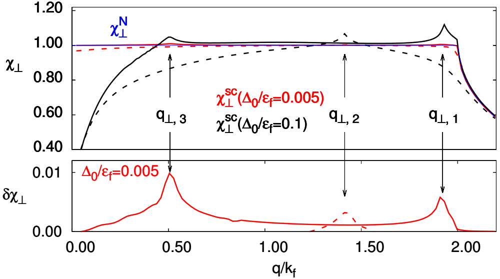
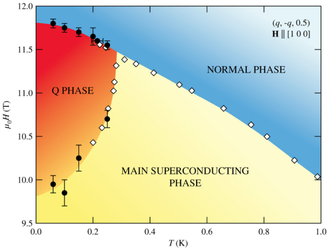
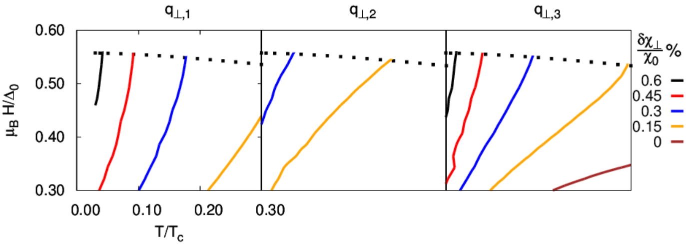
Qualitative agreement with $CeCoIn_5$ phase diagram!







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WHATS NEXT?

INHOMOGENEOUS SUPERCONDUCTIVITY
- Fulde Ferrell (phase modulations)
- Larkin Ovchinnikov (amplitude modulations) ********
- Layered Materials
- Josephson Junctions

-Creates quasi-particle states BELOW the gap (bound states)
-Increase DOS near Fermi level (whiteboard drawing)

WHATS NEXT?

SUB-GAP STATES:
-momentum is no longer a good quantum number
$\rightarrow$ but it's still pretty good for states far from Fermi level
-Need to solve Bogoliubov-de Gennes equations more carefully (whiteboard)

$$(-\delta_x^2 - \mu)u_n(\mathbf{x}) + \int d\mathbf{x}'\Delta(\mathbf{x},\mathbf{x}')v_n(\mathbf{x}') = E_n u_n(\mathbf{x}) \tag{4}$$

$$-(-\delta_x^2 - \mu)v_n(\mathbf{x}) + \int d\mathbf{x}'\Delta^*(\mathbf{x},\mathbf{x}')u_n(\mathbf{x}') = E_n v_n(\mathbf{x}) \tag{5}$$

Homogeneous: $u_n(\mathbf{x}) = u_{\mathbf{k}_n} e^{i\mathbf{k}_n\cdot\mathbf{x}}$ $\rightarrow$ Get E_n from $\mathbf{k}_n$
Inhomogeneous: $u_n(\mathbf{x}) = \sum_{\mathbf{k}} u_{n\mathbf{k}} e^{i\mathbf{k}\cdot\mathbf{x}}$

$\rightarrow$ solve eigenvalue eq for $u_{n\mathbf{k}}$ and E_n

WHATS NEXT?

$$E_n \left(\begin{array}{c} . \\ u_{n\mathbf{k}} \\ . \\ \hline . \\ v_{n\mathbf{k}} \\ . \end{array} \right) = \left(\begin{array}{ccc|ccc} . & 0 & 0 & & & \\ 0 & \xi_{\mathbf{k}} & 0 & & \Delta_{\mathbf{k}\mathbf{k}'} & \\ 0 & 0 & . & & & \\ \hline & & & . & 0 & 0 \\ & \Delta^*_{\mathbf{k}\mathbf{k}'} & & 0 & -\xi_{\mathbf{k}} & 0 \\ & & & 0 & 0 & \end{array} \right) \left(\begin{array}{c} . \\ u_{n\mathbf{k}'} \\ . \\ \hline . \\ v_{n\mathbf{k}'} \\ . \end{array} \right) \tag{6}$$

$$\Delta_{\mathbf{k}\mathbf{k}'} = \quad G[(\mathbf{k}+\mathbf{k}')/2] \quad F[\mathbf{k}-\mathbf{k}'] \tag{7}$$

$$\textit{relative FT} \qquad \textit{c.o.m. FT} \tag{8}$$

-Use these states to calculate magnetic susceptibility $\chi(\mathbf{q}, \mathbf{R})$
We started writting another paper on this but...
-MUST UNDERSTAND NEW QUASI-PARTICLE STATES TO SEE HOW/WHY SUSCEPTIBILITY IS ENHANCED
-SEE HOW NMR RELAXATION RATES ARE EFFECTED (recent paper on organic sc)