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Ginzburg-Landau functional
for nearly AFM
perfect and disordered Kondo lattices

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Outline

- Criticality in HF compounds
- Kondo Lattice Model
- AFM and Spin Liquid instabilities
- Spin Glass transition
- Doniach’s Diagram revisited
- Correlations between Kondo clouds
- Conclusions

References:

Competition between Kondo and AFM order in heavy fermion compounds

A. Rosch et al. PRL 79, 159 (1997)

Non-Fermi Liquid behavior in the vicinity of QCP
Disordered Kondo systems

FIG. 1. Concentration dependence of the cell volume (full circles) and the Kondo temperature estimated from different techniques: magnetic susceptibility ($\theta_p/10$, full squares), quasielastic neutron scattering (QENS, open squares) for the CeNi$_{1-x}$Cu$_x$ series. The broken lines separate the FeB-CrB crystallographic structures and AFM-FM magnetic states. Full lines are guides for the eyes.

FIG. 4. Magnetic phase diagram for the CeNi$_{1-x}$Cu$_x$ series as a function of Cu concentration, where open squares represent the long-range magnetic ordering temperature $T_{C,N}$ and full squares represent the spin-glass freezing temperature $T_f$. Inset: Van Hemmen classical phase diagram proposed in Ref. 19. The arrow shows the direction of the displacement for increasing Ni content to help the comparison with the experimental diagram.

J.Garsia Soldevilla et al. PRB 61, 6821 (2000)
Interplay between Kondo effect and Spin Glass correlations

Non-Fermi-Liquid behavior

Fig. 1. Low temperature - U concentration phase diagram of $Y_{1-x}U_xPd_3$. From Ref. 2.

M.B. Maple et al, JLTP 1995
C.L. Seaman et al, PRL 1991

Fig. 2. (a) Temperature dependence of the electronic specific heat per U, $\Delta C(T)/T$ vs $T$, for $Y_{1-x}U_xPd_3$. 0.2 $\leq x \leq$ 0.5. $T_{SG}$ is the peak position of $\Delta C(T)/T$ associated with apparent spin-glass freezing; $\chi(T)$ shows an onset to irreversibility at the same temperature. Note (i) the lack of a peak for $x=0.2$, and (ii) the upturn near 20 K due to an apparent excited-state Schottky anomaly. (b) $\Delta C(T)/T$ vs ln$T$ for $Y_{0.8}U_{0.2}Pd_3$. The solid line represents a least-squares fit of the data by the form $-0.25/T_x\ln(T/0.41T_x) + b$ [9]. From the slope we obtain $T_x=42$ K, and the background coefficient $b$ is 61 mJ/mol K$^2$, which likely arises from an excited-state Schottky anomaly.
Competition between AFM and Spin Glass

$Ce_2Au_{1-x}Co_xSi_3$

Non-ergodic Spin Glass
Shender, Korenblit 1986

de Almeida – Thouless Line
Doniach's diagram evolution (1977-2004)

FIG. 1. Doniach diagram: Plot of the Néel and Kondo temperatures as a function of $|J_{K}\rho|$, as explained in text.

Y. Onuki et al., Physica B 2001

MNK et al PRB 2002

Z. Housain et al, PRB 2004
Magnetic and Kondo correlations in Kondo Lattices
Single impurity Kondo effect

Kondo screening

Short range order
Kondo Cloud

Kondo-Screening
Model

\[ H = \sum_k \varepsilon(k)c^+_k\sigma c_{k,\sigma} + J \sum_i \vec{S}_i \cdot \vec{s}_i + \sum_{ij} I_{ij} \vec{S}_i \cdot \vec{S}_j \]

d-electrons  \hspace{1cm} \text{Kondo}  \hspace{1cm} \text{RKKY}

\[ I_{ij} = I^{RKKY} = -\left( \frac{J^2}{\varepsilon_F} \right) \cos \left[ \frac{2k_F R_{ij} - \pi (d + 1)/2 + \delta(R_{ij})}{(2k_F R_{ij})^d} \right] \]

Kondo-AFM-SL  \hspace{1cm} \text{Kondo-Spin Glass}
Methods

Semi-fermionic representation

\[ \vec{S} = f_{\alpha}^+ \tau_{\alpha\beta} f_{\beta} \]

\[
\begin{align*}
\omega &= 2\pi T \left(n + \frac{1}{4}\right) \\
\omega &= 2\pi T \left(n + \frac{1}{3}\right) \\
\mu &= -i \frac{\pi T}{2S + 1}
\end{align*}
\]

\[ Z_S = Tr\left[ \exp(-\beta H_S) \right] = ATr\left[ \exp(-\beta H_F + \beta \mu N_F) \right] \]
Ginzburg-Landau functional for KL model

Program:

• Represent spins in terms of semi-fermions
• Integrate out the highest energies
• Introduce effective bosonic fields responsible for magnetic (spin glass, spin liquid) correlations
• Introduce effective „semi-bosonic“ fields describing Kondo correlations
• Calculate a free energy taking into account Kondo corrections, construct Ginzburg-Landau functional
• Derive new saddle point equations for magnetic (SL) transitions
• Include fluctuations

Advantages of semi-fermionic techniques

Proper accounts for spin statistics (no local constraint)

Correctly describes Kondo effect (no “Kondo condensate”)
GL functional near AFM transition point

\[ I_{ij} = I^{RKKY} = -\left( \frac{J^2}{\varepsilon_F} \right) \cos \left[ \frac{2k_F R_{ij} - \pi (d + 1)/2}{(2k_F R_{ij})^d} \right] \]

\[ \beta F_{N,\Delta} = \frac{\beta |I| zN^2}{4} \tau_N + c_N N^4 + \frac{\beta |I| z\Delta^2}{2} + c_{sl} \Delta^4 \]

Notations:  \( N \)-Neel,  \( \Delta \) - Spin Liquid,  \( q \) – Spin Glass,  \( \phi \) - Kondo,  \( \tau_\alpha = 1 - \frac{T_\alpha}{T} \)
Spin Liquid

Resonating Valence Bonds

$$\Delta = - \sum_q \nu(q) \tanh \left( \frac{I_q \Delta}{T} \right)$$
Antiferromagnetic transition

\[ A_N = \sum_{q,n} \left[ \frac{1}{J} - \Pi(N, q) \right] |\phi(q)|^2 - Tr \frac{1}{J_Q} N_Q N_{-Q} \]

\[ N = \tanh \left( \frac{I_Q N}{2T} \right) \left[ 1 - \frac{a_N}{\ln(T/T_K)} \cosh^2 \left( \frac{I_Q N / 2T}{\ln(T/T_K)} \right) \cosh^2 \left( \frac{I_Q N / T}{\ln(T/T_K)} \right) \right] \]

Local-field corrections reduce the Neel temperature

Kondo screening suppresses AFM transition
RVB spin liquid crossover

\[ A_\Delta = \sum_{q,n} \left[ \frac{1}{J} - \Pi(\Delta, q) \right] |\phi(q)|^2 - Tr \left[ \frac{1}{J_{p-k}} \Delta_p \Delta_k \right] \]

\[ \Delta = \sum_q \nu(q) \left[ \tanh \left( \frac{I_q \Delta}{T} \right) + a_{sl} \frac{I_q \Delta}{T \ln(T / T_K)} \right] \]

Kondo „antiscreening“ effectively decreases SL free energy

Kondo scattering favors crossover to SL state
Doniach's diagram revisited
GL functional near Spin Glass transition point

\[ I_{ij} = I^{RKKY} = -\left( \frac{J^2}{\varepsilon_F} \right) \cos \left[ \frac{2k_F R_{ij} - \pi (d + 1)/2 + \delta(R_{ij})}{(2k_F R_{ij})^d} \right] \]

\[ \beta F_{SG} = \frac{z(\beta I)^2}{4} q^2 \tau_{SG} - c_{SG} q^3 + d_{SG} q^4 \]

Notations:  \( \text{N-Neel} \),  \( \Delta \) - Spin Liquid,  \( q \) – Spin Glass,  \( \phi \) - Kondo,  \( \tau_\alpha = 1 - \frac{T_\alpha}{T} \)
Spin glass transition

\[ q = \int_{z}^{G} \tanh^2 \left( \frac{I_z \sqrt{q/T}}{1 + 2c_{sg} (I/T)^2 (\bar{q} - q)/\ln(T/T_K)} \right) \]

\[ q_{EA} = \langle S_i^a (0) S_i^b (t \to \infty) \rangle \]

\[ \bar{q} = 1 - \frac{c_{sg}}{\ln(T/T_K)} \]

Local correlations reduce the spin-glass transition temperature

Kondo scattering screens Edwards-Anderson order parameter
Interplay between Kondo effect and SG transition
Interplay between AFM and SG transitions

AFM-Spin Glass

- Kondo effect is absent
- Ising-like interaction between spins
- Large coordination number (long-range interaction)

\[ H = - \sum_{ij} I_{ij} S_i^z S_j^z \]

\[ P(I_{ij}) \propto \exp\left[ -\left( I_{ij} - \bar{I} \right)^2 N / (2I_0^2) \right] \]

\[ \mathcal{H} = - \sum_{i_1=1}^{N_S} \sum_{j_2=1}^{N_S} J(r_{i_1}, r_{j_2}) S(r_{i_1}) S(r_{j_2}) - \frac{J_K}{2N_1} \sum_{l=1}^{N_p} \sigma(R_l) \sum_{i_1, i_2=1}^{N_1} [S(R_l + r_{i_1}) + S(R_l + r_{i_2})] \]

\[ -H \sum_{l=1}^{N_p} \sum_{i_1, i_2=1}^{N_S} [\sigma(R_l) + S(R_l + r_{i_1}) + S(R_l + r_{i_2})] - \frac{1}{N_p} \sum_{l=1}^{N_p} \sum_{k=1}^{N_p} J_{l-k} \sigma(R_l) \sigma(R_{l+k}) - \sum_{l=1}^{N_p} \mu_l n(R_l), \]
Stability of Replica-symmetric solution

AT-surface

de Almeida – Thouless Line
Electron-mediated correlations between Kondo Clouds

- Dynamical effects far beyond mean-field description
- Magnetically ordered Kondo Clouds
- Universality vs. non-universality
Overlap between Kondo Clouds

\[ \Pi_4 \sim \frac{1}{T \varepsilon_F^2} \frac{\cos\left(2k_F R - (d-1)\pi / 2\right)}{(2k_F R)^{d-1}} \]

FIG. 1. Feynman diagrams describing the Kondo cloud (a) and interaction between clouds centered at different sites (b).

\[ K(q, \omega) = \left\langle \phi_{q,\omega} \phi_{q,\omega} \right\rangle \]

FIG. 2. Feynman diagrams for nonlocal excitations associated with the overlap of Kondo clouds.
Beyond the mean-field

\[ K_{loc}^{-1}(\omega) = \frac{-i\omega}{\gamma T} + \ln \left( \frac{\{T, \omega\}}{T_K} \right) \]

\[ K^{-1}(q, \omega) = K_{loc}^{-1}(\omega) + \alpha q^2 \]

\[ \chi^{-1}(T) = \Theta + T^\lambda \]

\[ \lambda = \lambda(\varepsilon_F, R) \quad \text{Critical exponents are non-universal} \]
Local and nonlocal corrections to magnetic susceptibility
Correlation between Kondo Clouds

A) $2k_F R = \pi$

B) $2k_F R = \frac{3\pi}{2}$

C) $2k_F R = 2\pi$

D) $2k_F R = \frac{5\pi}{2}$
Conclusions

- Kondo screening suppresses magnetic and spin-glass transitions
- Kondo correlations enhance temperature of crossover to spin-liquid state
- Correlations between Kondo clouds result in non-universal temperature dependence of static magnetic susceptibility