Hund's-Kondo pairing mechanism for triplet superconductivity – applications to UTe_2 & beyond

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RUTGERS

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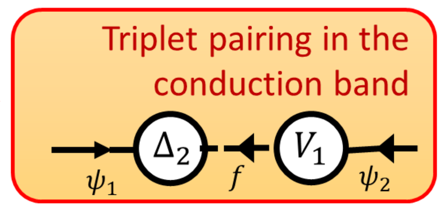
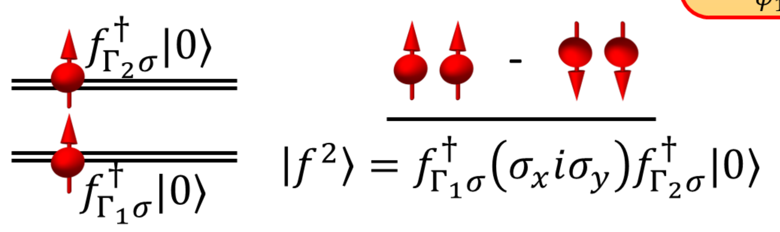
How does Hund's coupling affect superconductivity?

Hund's coupling ⇒ Preformed triplet pairs ⇒ Triplet Kondo coupling ⇒ Triplet pairing in the conduction band



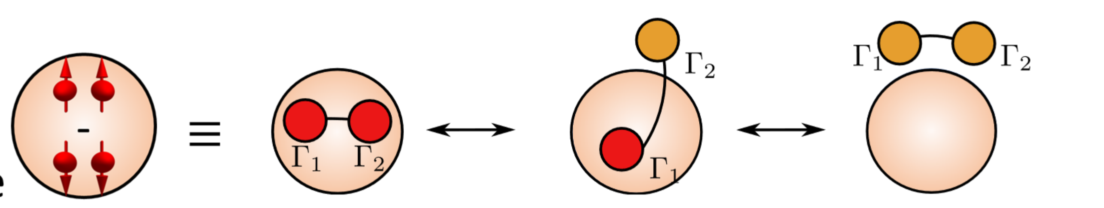
Consider an atom with two low-lying orbitals occupied



$|f^2\rangle = f^\dagger_{\Gamma_1\sigma}(\sigma_x i\sigma_y) f^\dagger_{\Gamma_2\sigma}|0\rangle$

Hund's coupling favors spins to align

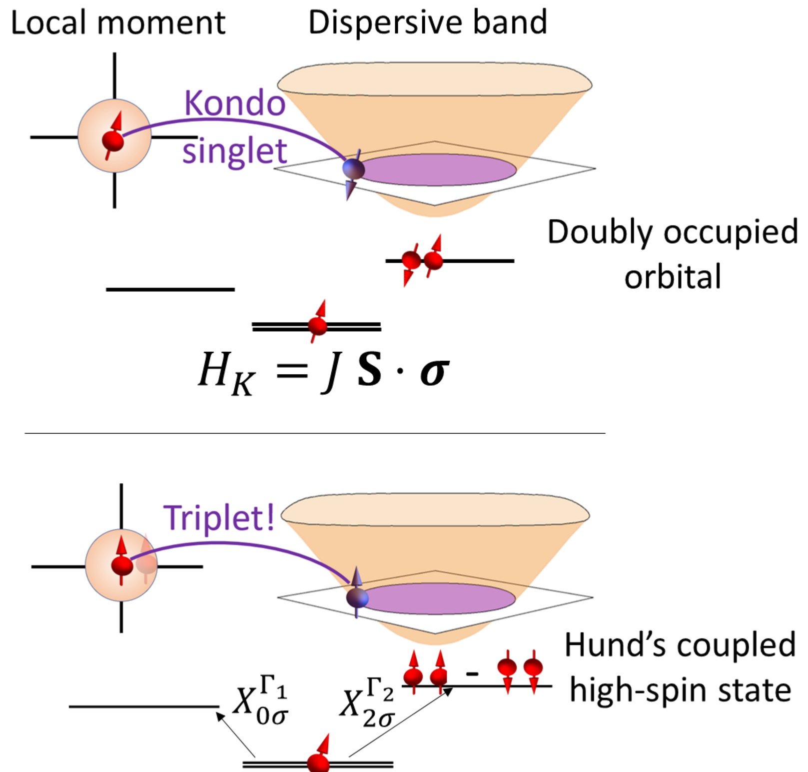
Localized triplet pairs : Triplet valence bonds



$|f^2\rangle \equiv c^\dagger_{\Gamma_2}(\sigma_y i\sigma_y) f^\dagger_{\Gamma_1}|0\rangle \leftrightarrow c^\dagger_{\Gamma_2}(\sigma_y i\sigma_y) c^\dagger_{\Gamma_1}|0\rangle$

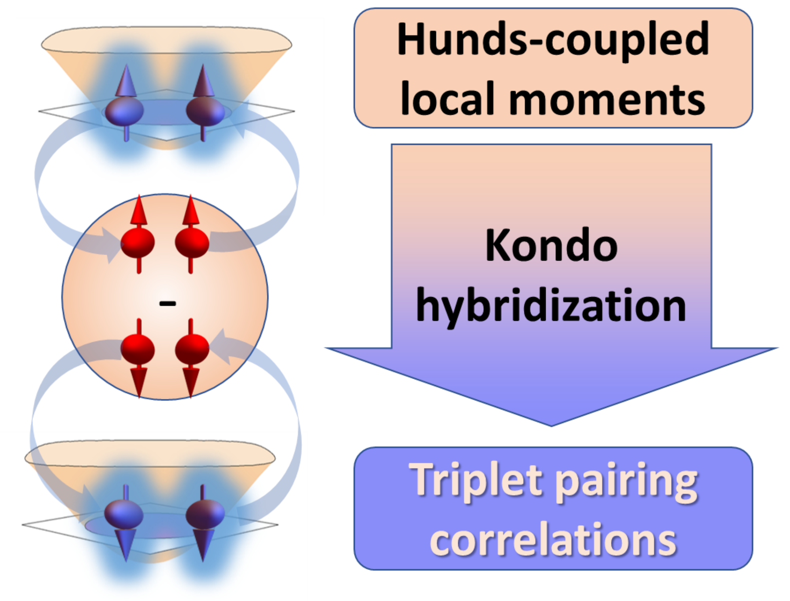
Resonate via Kondo hybridization

Kondo hybridization allows these triplet pairs to delocalize ⇒ Resonating valence bond [4]



$H_K = J\,\mathbf{S}\cdot\boldsymbol{\sigma}$

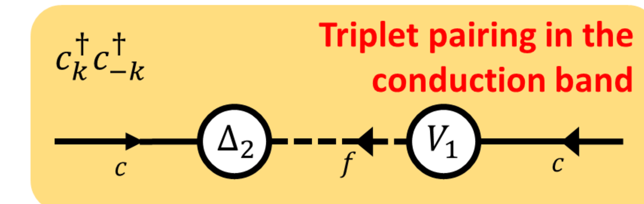
$H_K = J_1 \mathbf{S}\cdot\boldsymbol{\sigma}^{\Gamma_1} + J_2\mathbf{S}\cdot(\sigma_x \boldsymbol{\sigma}^{\Gamma_2}\sigma_x)$



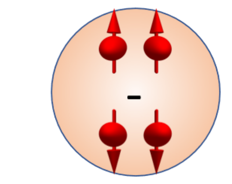
Kondo hybridization allows the triplet correlations to bleed onto the electron cloud that screens the local moment.

Hund's + Kondo coupling ⇒ Triplet Kondo coupling

Singlet + Triplet Kondo coupling ⇒ Triplet Superconductor



$\Delta_{cc} = \frac{V_1\Delta_2}{\lambda} p^z_k \sigma_y \sim B_{3u}$



$f^\dagger_{\Gamma_1}(\sigma_x i\sigma_y) f^\dagger_{\Gamma_2}|0\rangle$

Preformed pairs in local moments

Symmetry equivalent

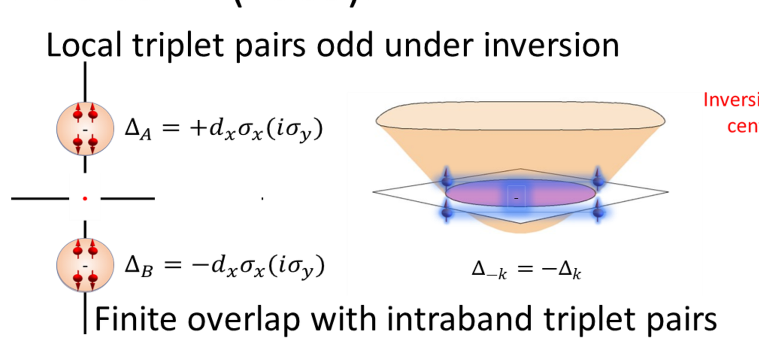
Symmetry of atomic states ↔ Pairing symmetry

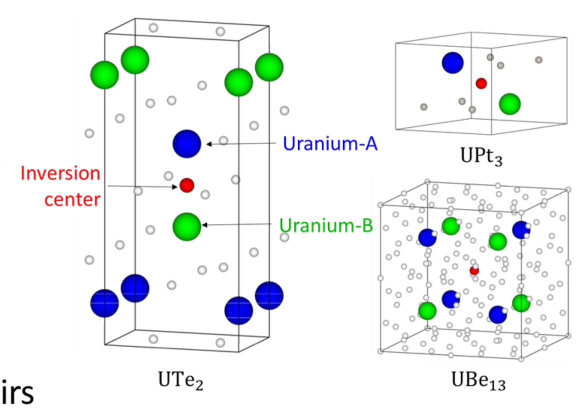
Experimentally constrained

One might expect that when there is a lattice of such moments, triplet pairs would delocalize, acquire stiffness and condense.

Problem : triplet pairing on the Fermi surface is odd parity, and if the f^2 moment sits at an inversion center, local pair wavefunction has even parity.

Anderson[1] (1985):



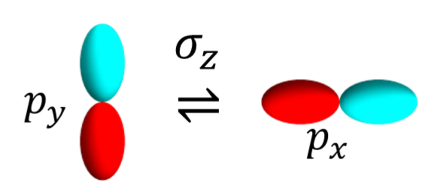


This structural motif is common to all candidate-triplet superconductors

UTe_2, UGe_2, UCoGe, URhGe, UBe_{13}, UPt_3, $CeRh_2As_2$, $CeSb_2$ except UAu_2 and $YbRh_2Si_2$

Spin-orbit ⇒ spin-dependent form-factor

$f_{\Gamma\sigma} \rightleftharpoons \Phi^\Gamma_{\sigma\sigma'} c_{\sigma'}$



Suppose channel 1 has higher Kondo temperature $T_{K1} \equiv T_K$. Then the singlet channel screens the moment, deconfined spinons hybridize with conduction electrons in channel 1 and on the heavy Fermi surfaces, the triplet Kondo coupling acts as a residual pairing interaction.

Sublattice ⇒ odd-in-k form-factor

$$H = H_c + J_1\mathbf{S}\cdot\boldsymbol{\sigma}^{\Gamma_1} + J_2\mathbf{S}\cdot(\sigma_x\boldsymbol{\sigma}^{\Gamma_1}\sigma_x)$$

singlet: $\Phi^{\Gamma_1} = 1$, $\boldsymbol{\sigma}^{\Gamma_1} = c^\dagger\boldsymbol{\sigma}\,c$

triplet: $\Phi^{\Gamma_1} = i\sigma_z(\alpha_z p^z_{\mathbf{k}})$, $\boldsymbol{\sigma}^{\Gamma_2} = c^\dagger p^z_{\mathbf{k}}\sigma_z\boldsymbol{\sigma}\sigma_z p^z_{\mathbf{k}} c$

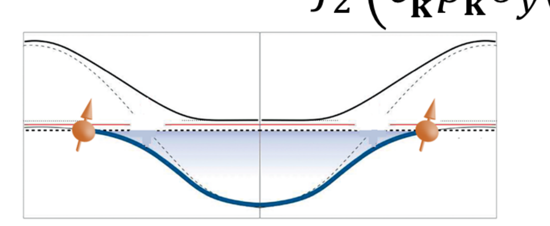
α_z: sublattice-space Pauli matrix; $p^z_{\mathbf{k}}$: z-like xtal harmonic

$$H = \epsilon^{\mathrm{HF}}_{\mathbf{k}} a^\dagger_{\mathbf{k}} a_{\mathbf{k}} + J_2\mathbf{S}\cdot c^\dagger_{\mathbf{k}}(p^z_{\mathbf{k}}\sigma_y\boldsymbol{\sigma}\sigma_y p^z_{\mathbf{k}})c_{\mathbf{k}}$$

if $J_1 > J_2$

$a_{\mathbf{k}} = u_{\mathbf{k}} f_{\mathbf{k}} + v_{\mathbf{k}} c_{\mathbf{k}}$ $\qquad$ $\mathbf{S} = f^\dagger\boldsymbol{\sigma}f$

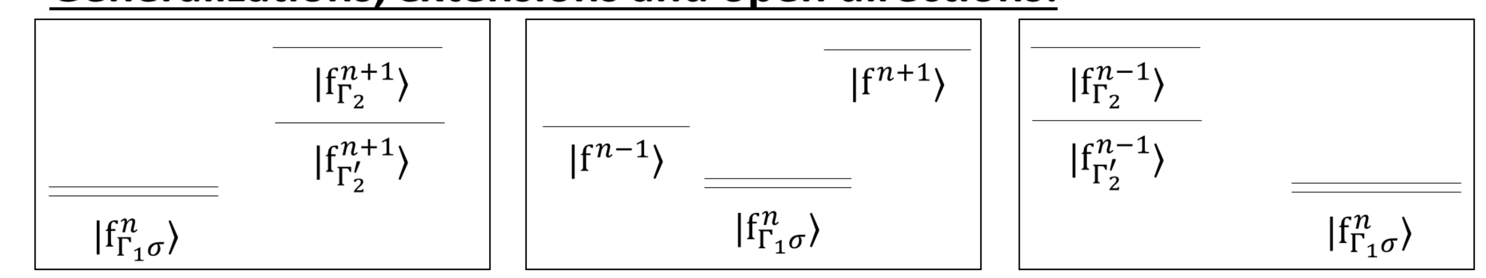
$$-J_2\left(c^\dagger_{\mathbf{k}} p^z_{\mathbf{k}}\sigma_y(i\sigma_y)^\dagger f^\dagger_{-\mathbf{k}}\right)\cdot\left(f_{-\mathbf{k}}(i\sigma_y)\sigma_y p^z_{\mathbf{k}} c_{\mathbf{k}}\right)$$



Residual interaction = triplet pair scattering ($S_y = 0$)

Pseudospin triplet pairs on Fermi surface

Generalizations, extensions and open directions:



Any two distinct valence fluctuation channels from a Kramer's doublet ⇒ two-channel Kondo model leading to possible triplet superconductivity

Superconducting transition ↔ involvement of second Kondo channel

⇒ change in f valence at T_c

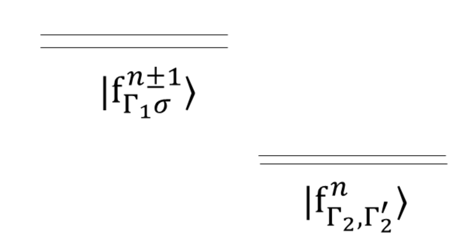
(core level spectroscopy, inverse photoemission, x-ray scattering)

OR

⇒ change in local electric fields

(nuclear quadrupole resonance)

f^n with n even: Non-Kramer's doublet ground state [16] :



- Role of spin and channel interchanged
- Rotations within the non-Kramer's doublet – coupled between the local moment and the dispersive electrons.

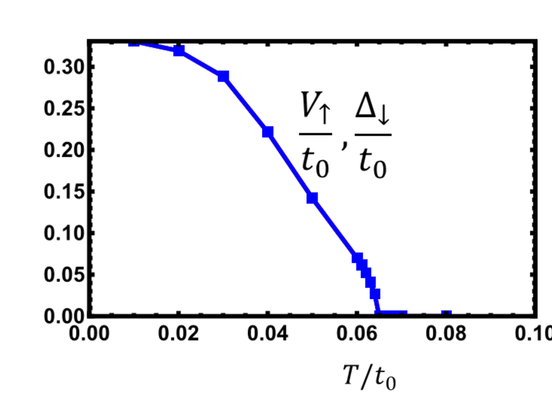
Two-spin channel-Kondo model

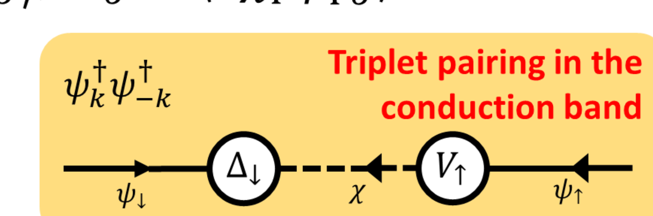
$$H_K = J_{CK}\sum_\sigma \mathbf{M}\cdot\psi^\dagger_{\Gamma\sigma}\mathbf{m}_{\Gamma\Gamma'}\psi_{\Gamma'\sigma}$$

Rotations of the local moment can be represented by fermionic partons which carry the channel quantum numbers.

$$\mathbf{M} = \chi^\dagger_\Gamma \mathbf{m}_{\Gamma\Gamma'}\chi_{\Gamma'}$$

Kondo hybridization then leads to spinor hybridization and pairing mean-fields [17] $\quad V_\sigma = \langle\chi^\dagger_\Gamma\psi_{\Gamma\sigma}\rangle$, $\Delta_\sigma = \langle\Gamma\chi_\Gamma\psi_{\bar\Gamma\bar\sigma}\rangle$





From two-spin channel-Kondo coupling

Tamaghna Hazra (in prep)

Scaling of Kondo coupling

$$\frac{1}{J_2} = \frac{1}{J_2^0} - \rho\ln\frac{D}{T_K} - \rho d^2\ln\frac{T_K}{T} \quad \text{diverges at} \quad T_c = T_{K2}^{\frac{1}{d^2}} T_{K1}^{1-\frac{1}{d^2}}$$

Kondo log $\qquad$ Cooper log

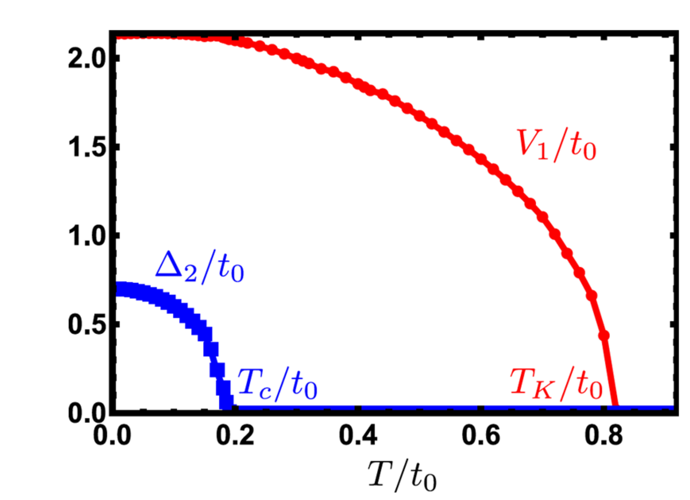
$d^2 = \langle(p^z_{\mathbf{k}})^2\rangle_{FS}$, ρ: conduction band DOS

SU(2) invariant parton mean-field theory

$$H = H_c + J_1\mathbf{S}\cdot\boldsymbol{\sigma} + J_2\mathbf{S}\cdot(p^z_k\sigma_y\,\boldsymbol{\sigma}\,\sigma_y p^z_k)$$

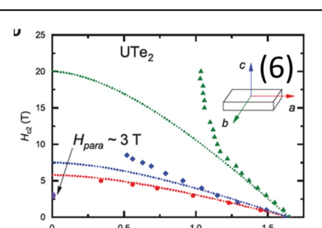
$$H = V_1 c^\dagger_k f_k + V_2 c^\dagger_k p^z_k\sigma_y f_k + \Delta_2 c^\dagger_k p^z_k\sigma_y(i\sigma_y)^\dagger f^\dagger_k$$

hybridization $\qquad$ Triplet pairing

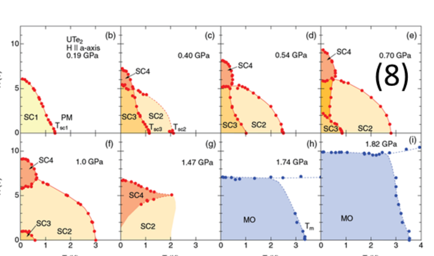


UTe_2

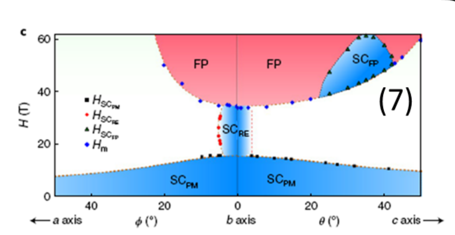
Many open puzzles



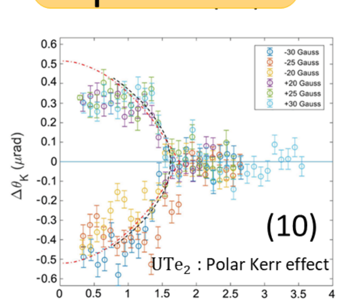
Strong violation of Pauli limit (6)



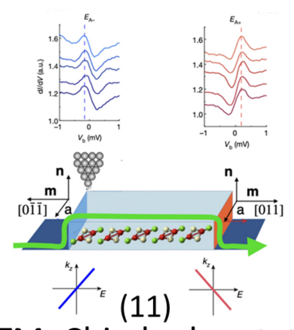
Multiple superconducting phases (8)



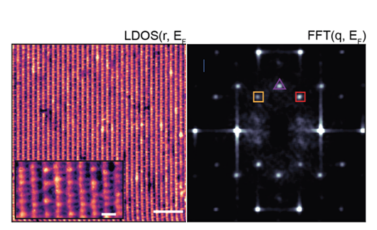
Re-entrant superconductivity at high fields (7)



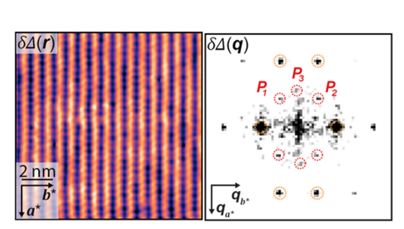
Time-reversal breaking superconductivity (10)



STM: Chiral edge states (11)



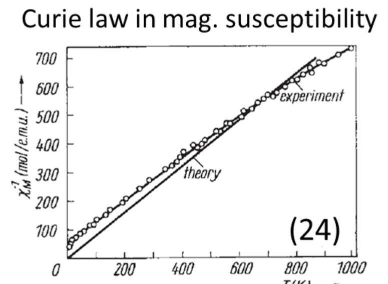
Charge density wave (9)



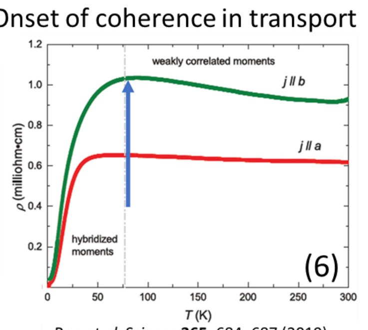
Pair density wave (16)

Evidence for local moments

Curie law in mag. susceptibility

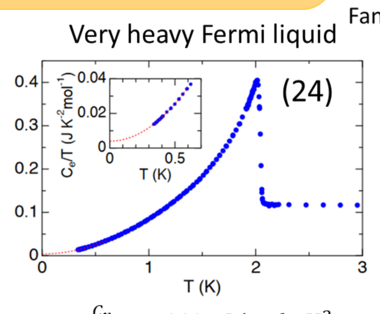


Onset of coherence in transport



Ran et al. Science 365, 684–687 (2019).

Very heavy Fermi liquid



$\frac{C_V}{T}$: $\gamma \sim 110$mJ/mol · K^2

Fano lineshapes characteristic of co-tunneling into Kondo-coupled local moments