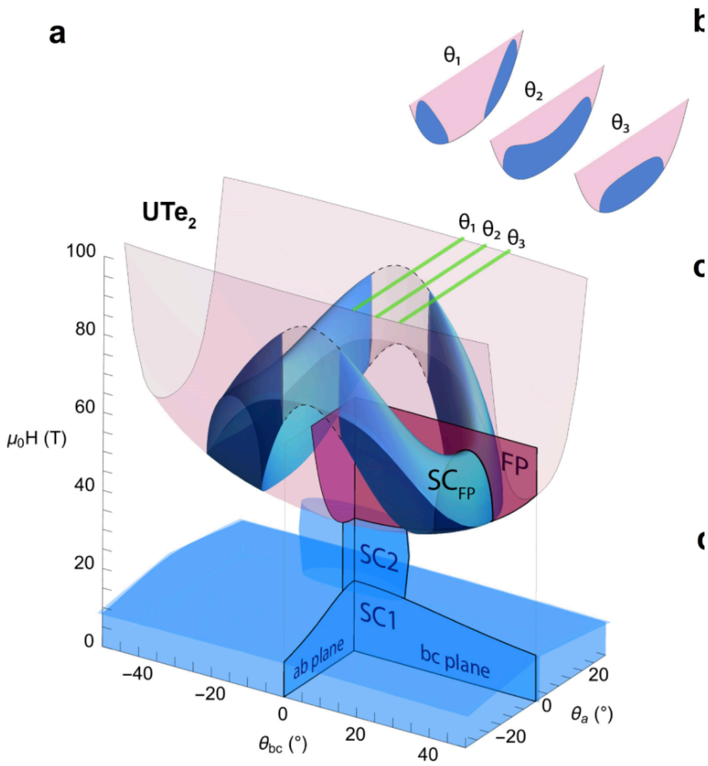
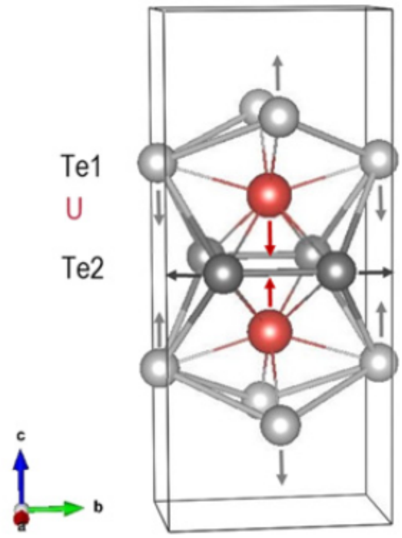
L22: UTe_2 and Beyond BCS order parameters.

UTe_2 is a 2K heavy fermion superconductor which eats magnetic fields for breakfast. In certain directions its superconductivity survives beyond 70 Tesla. These upper-critical fields are akin to those of a high T_c superconductor.

Certain properties of this superconductor, most notably the observation of chiral surface currents, suggest that the ground-state spontaneously breaks time reversal symmetry, via a single transition. This last feature is controversial, because BCS theory does not allow a single time-reversal symmetry breaking transition in an orthorhombic crystal. This motivates a search for pairing beyond the BCS paradigm.



Lewin et al arXiv 2402.185 64



Hard Axis

D. Aoki J. Cond Matt 2022

Kondo-Kitaev Lattice. ("CPT" model)

Can we have pairing outside the BCS model?

$$\boxed{\begin{aligned}\mathcal{H} = & -t\sum\left(c^\dagger_{i\sigma}c_{j\sigma} + h.c\right) - \mu\sum c^\dagger_{i\sigma}c_{i\sigma} \\ & + \left(\frac{K}{2}\right)\sum\left(\sigma_i\cdot\sigma_j\right)\lambda_i^{\alpha_{ij}}\lambda_j^{\alpha_{ij}} \\ & + J\sum S_j\left(c^\dagger_j\vec{\sigma}c_j\right)\end{aligned}}$$

$$\left(\vec{S}_j \rightarrow -i\frac{\vec{\chi}_j}{2}\times\vec{\chi}_j\right)$$

$$J\left(c^\dagger_j\sigma c_j\right)\cdot\left(\frac{-i}{2}\vec{\chi}_j\times\vec{\chi}_j\right)$$

$$= \frac{J}{2}\, c^\dagger_{j\alpha}c_{j\beta}\;\underbrace{-i\,\epsilon_{abc}\,\sigma^c_{\alpha\beta}}_{-\frac{1}{2}[\sigma^a,\sigma^b]_{\alpha\beta}}\,\chi^a\chi^b$$

$$= -\frac{J}{4}\, c^\dagger_{j\alpha}c_{j\beta}\,\left(\sigma^a\sigma^b\right)_{\alpha\beta}\underbrace{\left(\chi^a\chi^b - \chi^b\chi^a\right)}$$

$$\sigma^a\sigma^b\left(2\chi^a\chi^b - \delta^{ab}\right)$$

$$= -\frac{J}{2}\, c^\dagger_j\left[(\sigma\cdot\chi)^2 - \frac{3}{2}\right]c_j$$

$$H = -\frac{J}{2}\sum_j \hat{V}_j^{\dagger} V_j$$

"Fractionalized Order"

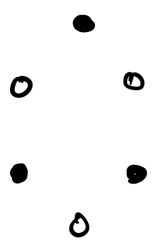
Bound state between a Majorana $S=1$ spinon + $S=1/2$ $q=e$ electron.

$S=1/2$ $Q=e$ SPINOR OP

$$\boxed{\hat{V}_j = (\sigma\cdot\chi)_{\alpha\beta}\, c_\beta = \begin{pmatrix} V_{j\uparrow} \\ V_{j\downarrow} \end{pmatrix}}$$

$$H_K = -\frac{J}{2}\sum c^{\dagger}(\sigma\cdot\chi)^2 c_j \rightarrow \sum V_j^{\dagger}\left[(\sigma\cdot\chi)c_j + h.c.\right] + \frac{2V_j^{\dagger}V_j}{J_K}$$

$$V_j = \begin{pmatrix} V_{j\uparrow} \\ V_{j\downarrow} \end{pmatrix} = -\frac{J}{2} V_j$$ at the s.p.



$$(c_{A\sigma}, c_{B\sigma}) \rightarrow (-i c_{A\sigma}, c_{B\sigma})$$

$$(V_{A\sigma}, V_{B\sigma}) \rightarrow (-i V_{A\sigma}, V_{B\sigma})$$

$$H_c = -i\sum (c_i^{\dagger} c_j - h.c.) - \mu \sum c_j^{\dagger} c_j$$

$$\psi_{k\Lambda} = \begin{pmatrix} c_{k\Lambda\uparrow} \\ c_{k\Lambda\downarrow} \\ -c^{\dagger}_{-k\Lambda\downarrow} \\ c^{\dagger}_{-k\Lambda\uparrow} \end{pmatrix}$$

$\Lambda = A, B$

$$\psi_k = \begin{pmatrix} \psi_{kA} \\ \psi_{kB} \end{pmatrix}$$

$$\vec{\alpha}_8 = \alpha_{(2)} \otimes 1 \otimes 1$$
$$\vec{\tau}_8 = 1 \times \tau_{(2)} \times 1$$
$$\sigma_8 = 1 \times 1 \times \sigma_{(2)}$$

$$\boxed{H_c = \sum_{k \in \Delta} \psi_k^+ \left(-t \vec{\gamma}_k \cdot \alpha - \mu \tau_3 \right) \psi_k}$$

$$V = \begin{pmatrix} V_{\Lambda\uparrow} \\ V_{\Lambda\downarrow} \\ -V_{\Lambda\downarrow}^* \\ V_{\Lambda\uparrow}^* \end{pmatrix} = V_\Lambda Z_\Lambda$$

$$H = H_c + H_{YL} + H_K$$

$$\boxed{\begin{aligned} H_c &= -it \sum \left(c_{i\sigma}^+ c_{j\sigma} + h.c \right) - \mu \sum c_{i\sigma}^+ c_{i\sigma} \\ H_{YL} &= -iK \sum \vec{\chi}_i^+ \cdot \vec{\chi}_j \\ H_K &= \sum \left(\bar{V}_j (\sigma \cdot \vec{\chi}_j) c_j + h.c \right) + \sum_j \frac{2 V_j^+ V_j}{J_K} \end{aligned}}$$

$$H_K = \sum_{\Lambda = A,B} \left\{ \sum_{k \in \Delta} \left[\left(\psi_{k\Lambda}^+ \vec{\sigma} V_\Lambda \right) \cdot \chi_{k\Lambda} + h.c \right] + \frac{2N V_\Lambda^2}{J} \right.$$

$$\Psi_{\vec{k}} = \begin{pmatrix} \psi_{\vec{k}} \\ \chi_{\vec{k}} \end{pmatrix} \qquad \psi_k = \begin{pmatrix} \psi_{kA} \\ \psi_{kA} \end{pmatrix} \qquad \chi_k = \begin{pmatrix} \chi_{kA} \\ \chi_{kB} \end{pmatrix}$$

$$\mathcal{H} = \sum_{k\in\Delta} \psi_k^\dagger \begin{pmatrix} -t(\gamma_k\cdot\vec{\alpha}) - \mu\tau_3 & \vec{\sigma}\,\mathcal{V} \\ \mathcal{V}^\dagger\vec{\sigma} & K(\gamma_k\cdot\vec{\alpha}) \end{pmatrix} \psi_k + \frac{4NV^2}{J}$$

$$\mathcal{V}_\Lambda = V_\Lambda z_\Lambda \qquad\qquad \frac{V_\Lambda}{\sqrt{2}} = V$$

$$z_\Lambda = \frac{1}{\sqrt{2}}\begin{pmatrix} z_{\Lambda\uparrow} \\ \vdots \\ z_{\Lambda\downarrow} \end{pmatrix}$$

$$\mu = 0 \qquad\qquad \psi^0_{kA} = z^\dagger\cdot\psi_k$$

$$\mathcal{H} = \sum \psi_{0k}^\dagger\left(-t\gamma_k\cdot\alpha\right)\psi_k + \frac{NV^2}{J}$$

$$+ \sum \left(\vec{\psi}_k^\dagger, \vec{\chi}_k^\dagger\right) \begin{pmatrix} -t\gamma_k\cdot\alpha & V \\ V & K\gamma_k\cdot\alpha \end{pmatrix}$$

$$E_k^\pm = \sqrt{V^2 + \left(\frac{\epsilon_c+\epsilon_s}{2}\right)^2} \pm \frac{(\epsilon_c-\epsilon_s)}{2} \qquad \epsilon_c = t|\gamma_k| \qquad \epsilon_s = K|\gamma_k|$$