Coexistence of triplet superconductivity and itinerant ferromagnetism

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Outline

- Interplay of singlet superconductivity and ferromagnetism
- P,T phase diagrams in heavy fermionic superconducting ferromagnets UGe2, URhGe, UCoGe
- Phase transitions F→FSC and SC→FSC - physical picture
- Symmetry of Normal, Ferromagnet and Superconducting Ferromagnet states
- Phase transitions F→FSC and SC→FSC - GL description
- Ferromagnet superconducting domains
- Interdomain Josephson coupling
- Conclusion.

Coexistence of ferromagnetism and superconductivity in ternary compounds

$T_{sc} >> T_{curie}$ $\xi_0 >> \lambda$

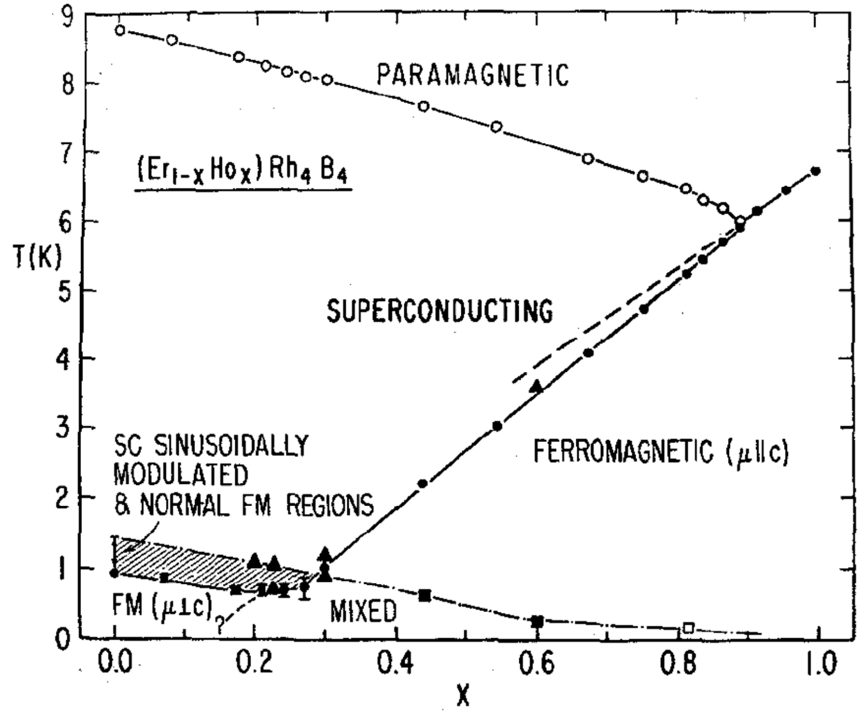
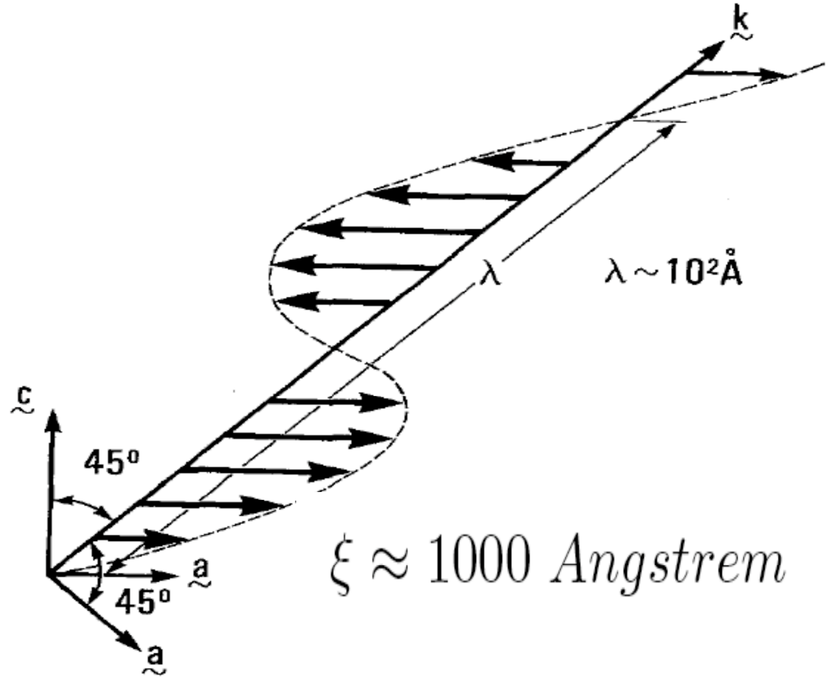


Fig. 6. Low temperature phase diagram for the $(Er_{1-x}Ho_x)Rh_4B_4$ pseudoternary system. After Refs. [46–48].

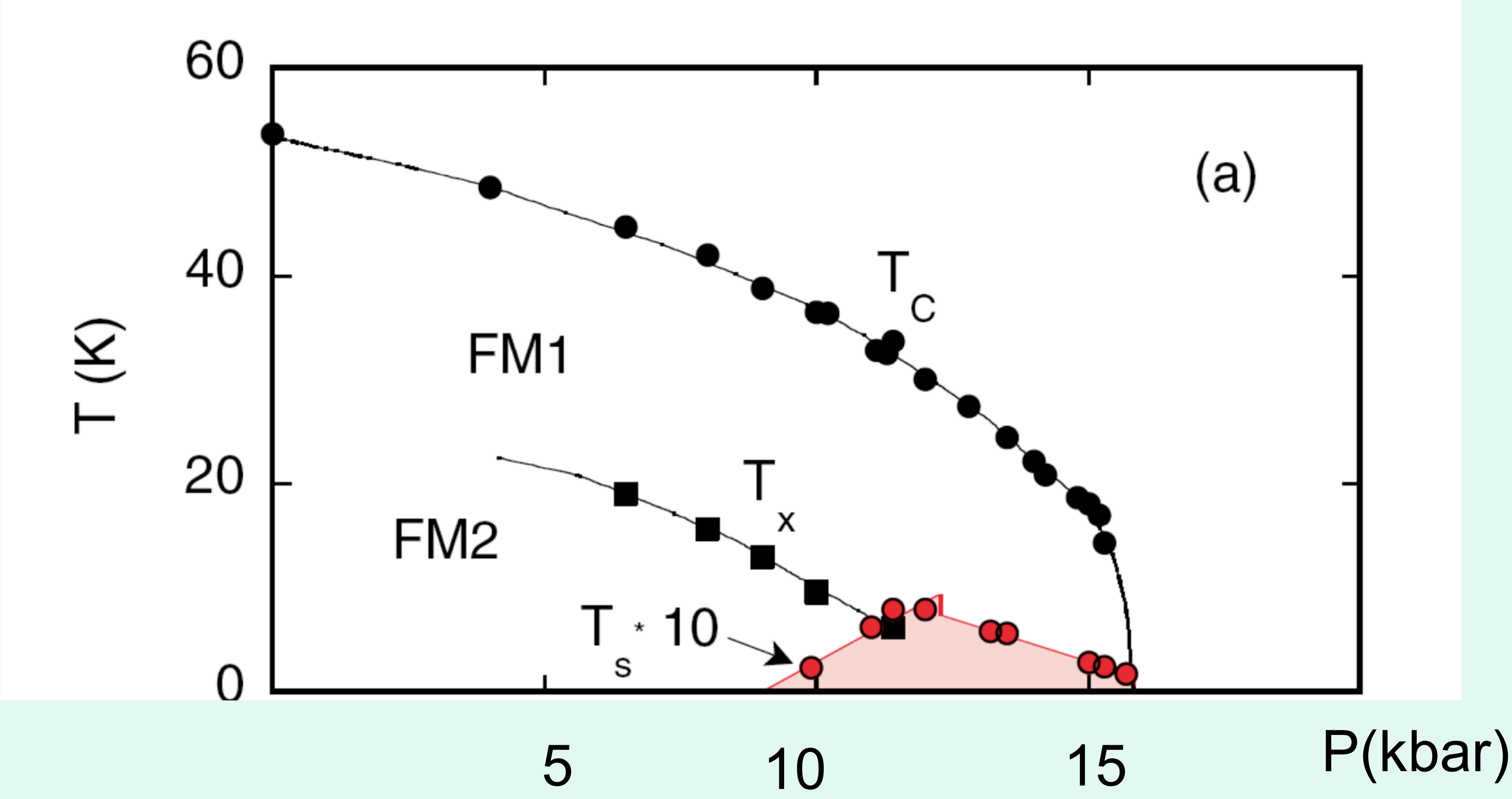


$\xi \approx 1000$ *Angstrem*

Fig. 5. Schematic representation of the linearly polarized sinusoidally modulated magnetic state that coexists with superconductivity in $ErRh_4B_4$.

P,T phase diagram of UGe$_2$

$T_{curie} >> T_{sc}$ $\xi_0 << a$ $\mu_{ord} < \mu_{curie\text{-}weiss}$



P-T phase diagram URhGe

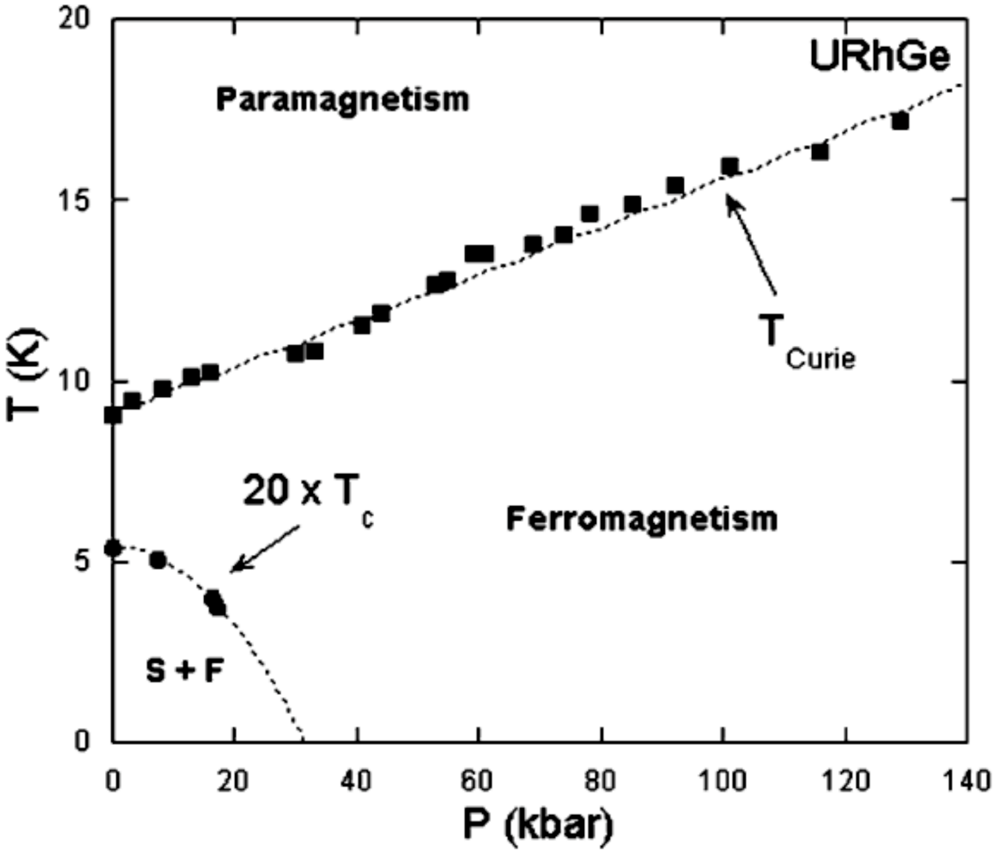
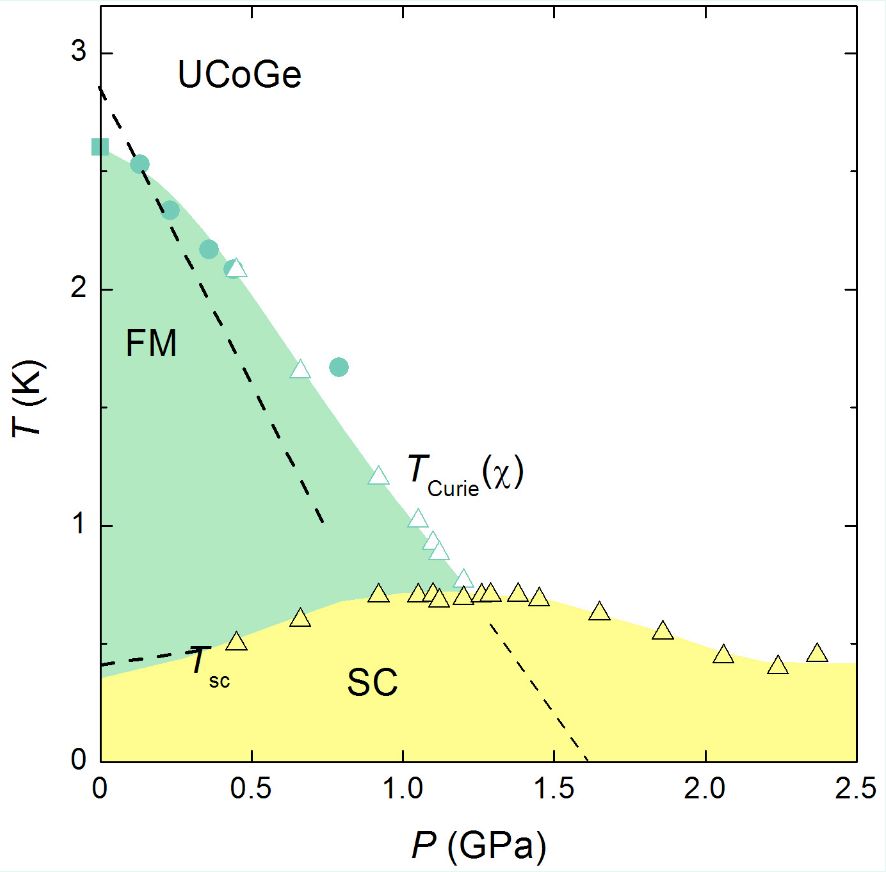


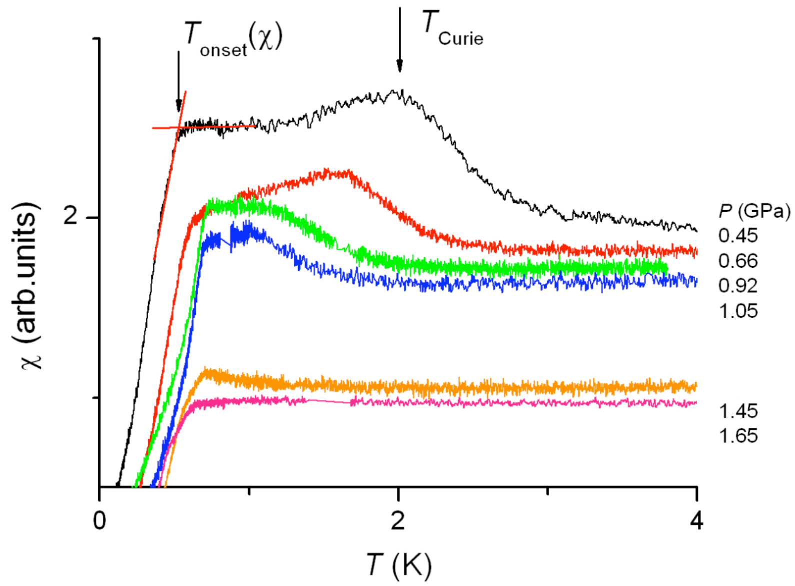
Fig. 3. Pressure–temperature phase diagram of URhGe from AC calorimetry (■) and resistivity measurements (●). Lines are guides for the eyes.

P-T phase diagram UCoGe

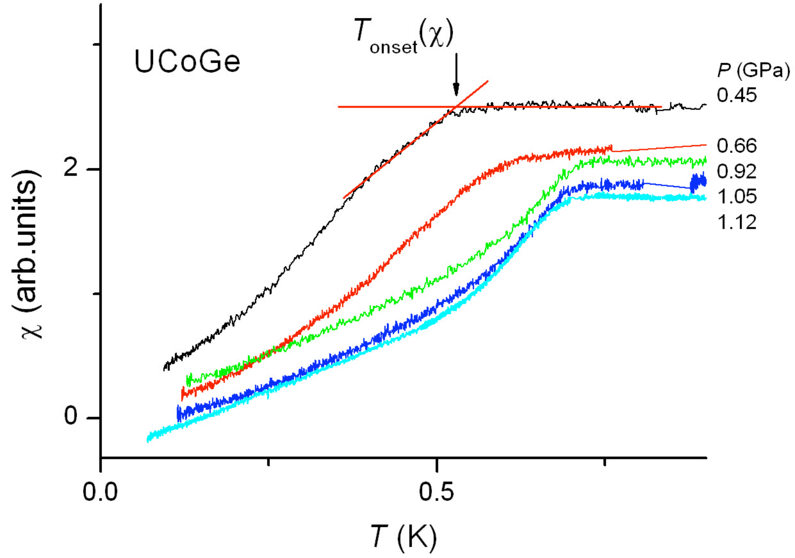


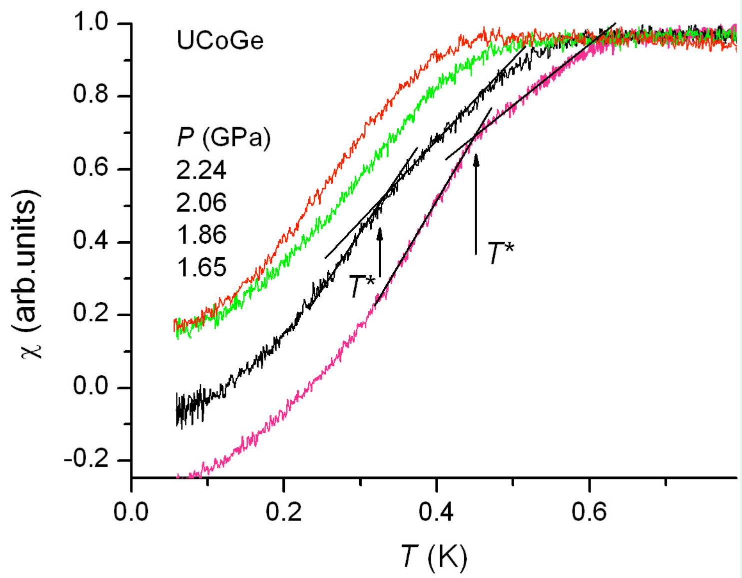
- Susceptibility confirms resistivity measurements on polycrystalline sample
- SC also in high pressure region
- Upturn in χ_{ac} indicating FM transition disappears at 1.65 Gpa (pressure of linear extrapolation)
- two clear steps for $P > P_c \sim 1.2$ GPa

Ac-susceptibility under pressure



- We can nicely follow T_{Curie}
- Upturn disappears only at 1.65 GPa
- Demagnetization factor decreases with P
- characteristic T^* appears





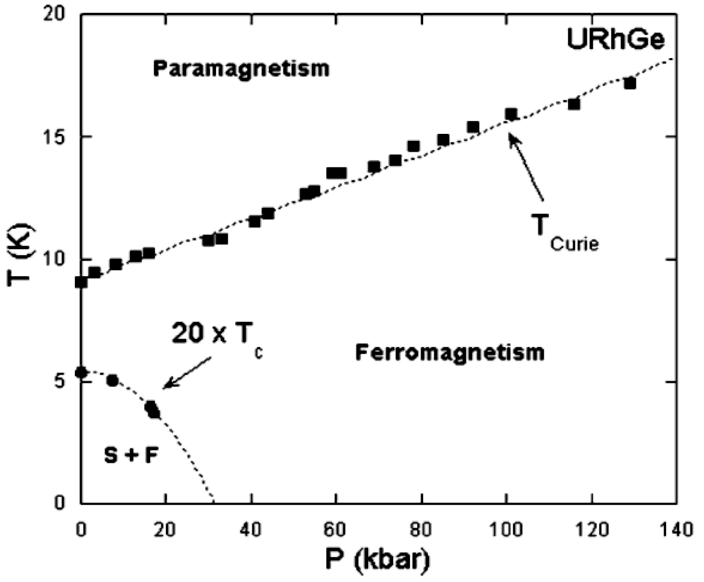
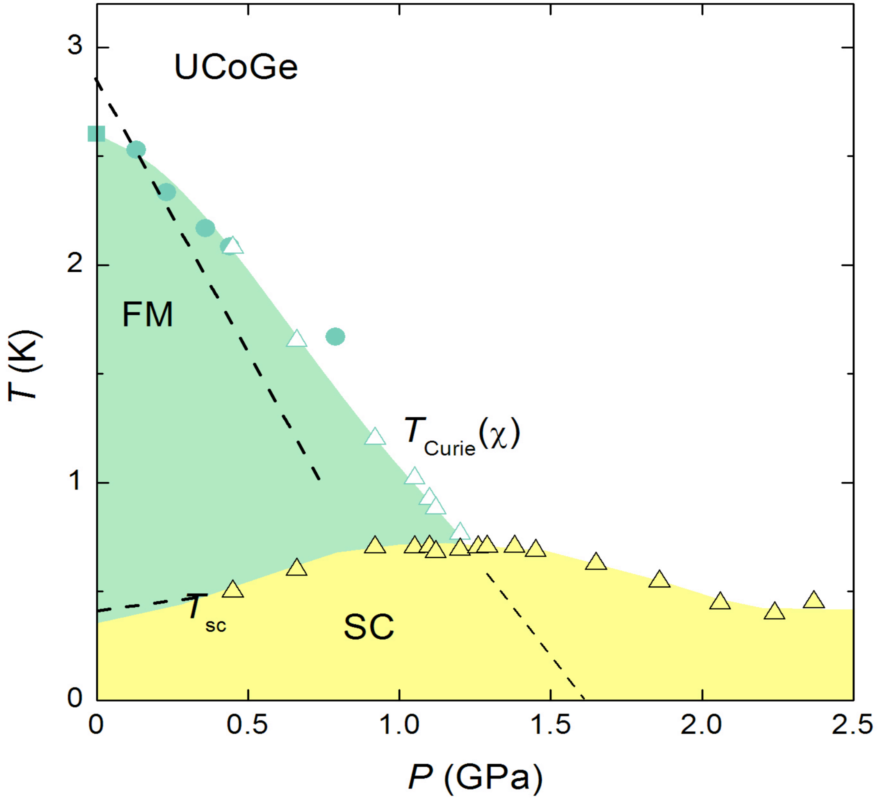
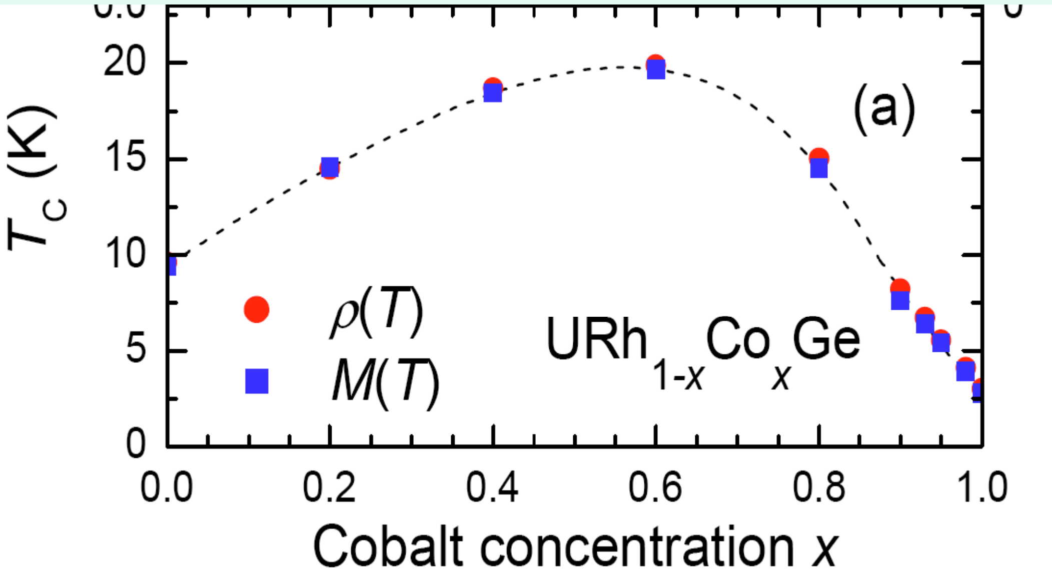
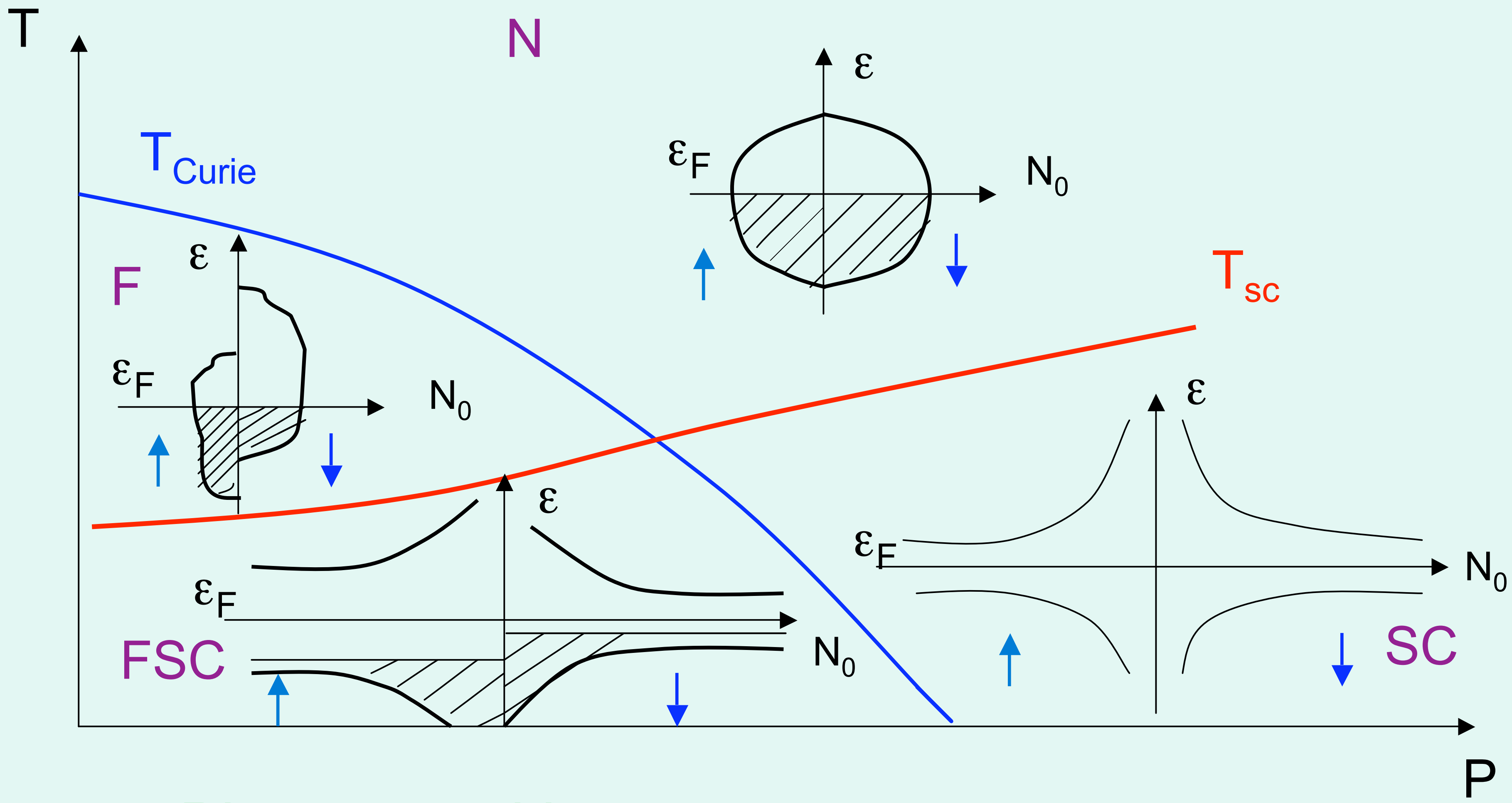


Fig. 3. Pressure–temperature phase diagram of URhGe from AC calorimetry (■) and resistivity measurements (●). Lines are guides for the eyes.



$URh_{1-x}Co_xGe$





Phase transitions

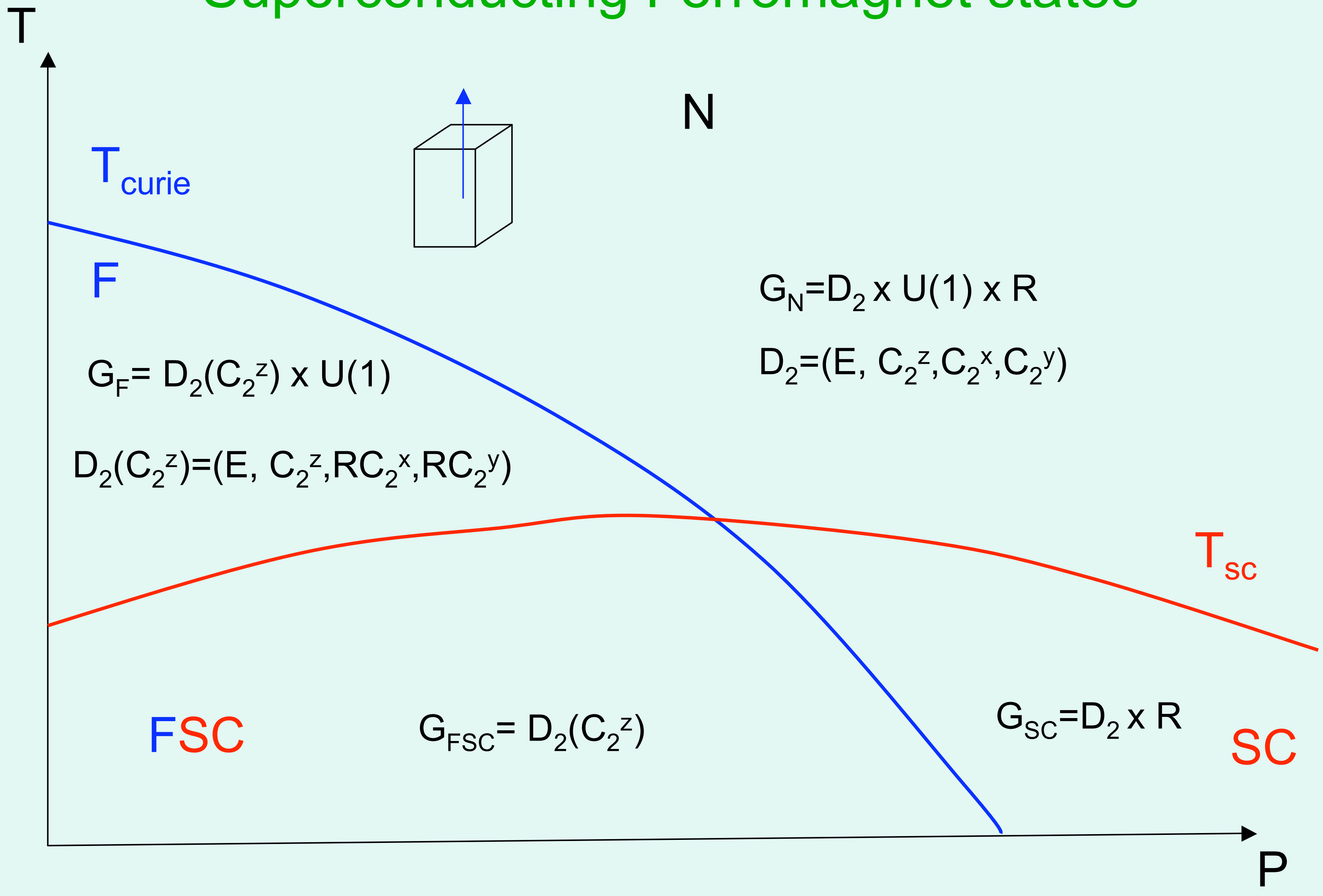
N→F One band metal→Two band metal

N→SC One band metal→One band superconductor

F →FSC Two band metal→Two band superconductor

SC→FSC One band superconductor→Two band superconductor

Symmetry of Normal, Ferromagnet and Superconducting Ferromagnet states



$G_N = D_2 \times U(1) \times R$

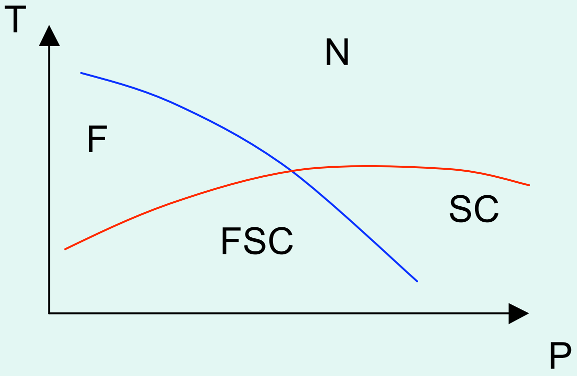
$D_2 = (E, C_2^z, C_2^x, C_2^y)$

$G_F = D_2(C_2^z) \times U(1)$

$D_2(C_2^z) = (E, C_2^z, RC_2^x, RC_2^y)$

$G_{FSC} = D_2(C_2^z)$

$G_{SC} = D_2 \times R$



F→FSC

$$\mathbf{d}_{|\uparrow\uparrow\rangle}(\mathbf{r},\mathbf{k}) = \eta_1(\mathbf{r})(k_x u_1 + i k_y u_2)(\hat{x} + i\hat{y}) \qquad \eta_1 = |\eta_1| e^{i\varphi_1}$$

$$\mathbf{d}_{|\downarrow\downarrow\rangle}(\mathbf{r},\mathbf{k}) = \eta_2(\mathbf{r})(k_x u_3 + i k_y u_4)(\hat{x} - i\hat{y}) \qquad \eta_2 = |\eta_2| e^{i\varphi_2}$$

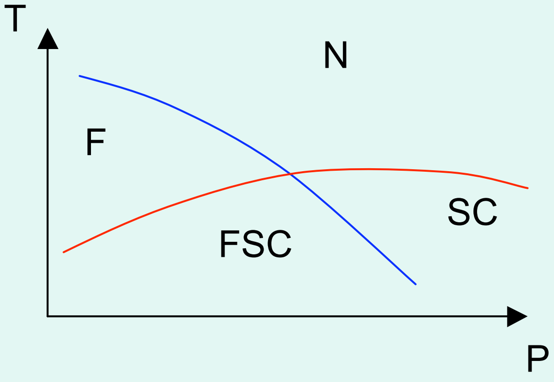
$$F = \alpha_{10}(T - T_{c1})|\eta_1|^2 + \alpha_{20}(T - T_{c2})|\eta_2|^2 + \gamma(\eta_1^*\eta_2 + \eta_1\eta_2^*) + i\delta(\eta_1^*\eta_2 - \eta_1\eta_2^*)$$

$$\frac{\partial F}{\partial(\varphi_1 - \varphi_2)} = 0 \qquad \Longrightarrow \qquad \tan(\varphi_1 - \varphi_2) = \frac{\delta}{\gamma}$$

$$F = \alpha_{10}(T - T_{c1})|\eta_1|^2 + \alpha_{20}(T - T_{c2})|\eta_2|^2 + \sqrt{\gamma^2 + \delta^2}(\eta_1^*\eta_2 + \eta_1\eta_2^*)$$

$$\eta_1 = |\eta_1| e^{i\varphi} \qquad \eta_2 = |\eta_2| e^{i\varphi}, \qquad \varphi = \frac{\varphi_1 + \varphi_2}{2}$$

$$T_{sc} = \frac{T_{c1} + T_{c2}}{2} + \sqrt{\left(\frac{T_{c1} - T_{c2}}{2}\right)^2 + \frac{\gamma^2 + \delta^2}{\alpha_{10}\alpha_{20}}}$$



SC→FSC

Unitary one band state

$$\mathbf{d}(\mathbf{k}) = 2\eta(k_x w_1 \hat{x} + k_y w_2 \hat{y}) =$$

$$\eta(k_x w_1 - i k_y w_2)(\hat{x} + i\hat{y}) + \eta(k_x w_1 + i k_y w_2)(\hat{x} - i\hat{y})$$

→ Nonunitary two band state

$$\tilde{\mathbf{d}}(\mathbf{k}) =$$

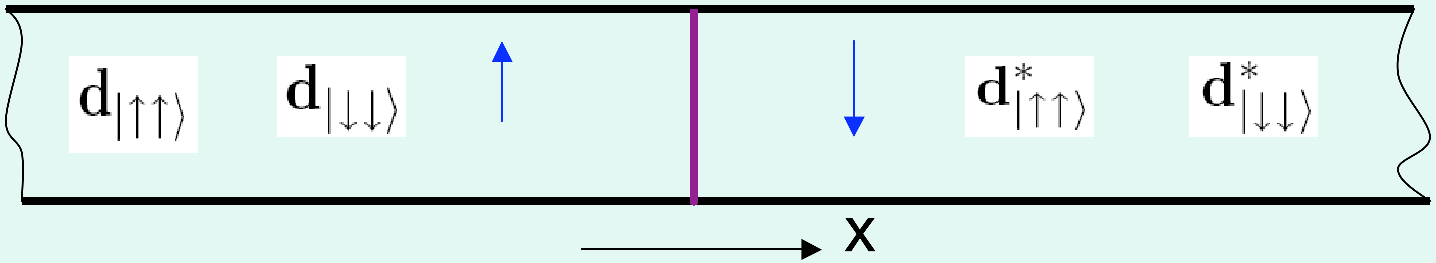
$$(\eta + \delta\eta)(k_x w_1 - i k_y w_2)(\hat{x} + i\hat{y}) + (\eta - \delta\eta)(k_x w_1 + i k_y w_2)(\hat{x} - i\hat{y})$$

$$\delta\eta \quad - \quad order \quad parameter$$

$\eta_1 = |\eta_1| e^{i\varphi}$ $\eta_2 = |\eta_2| e^{i\varphi}$

Domains

$\zeta_1 = |\zeta_1| e^{i\phi}$ $\zeta_2 = |\zeta_2| e^{i\phi}$



$$F_s = \left[\alpha_1(|\eta_1|^2 + |\zeta_1|^2) + \gamma_1(\eta_1^*\zeta_1 + \eta_1\zeta_1^*) + i\delta_1(\eta_1^\star\zeta_1 - \eta_1\zeta_1^\star) + \right.$$

$$\alpha_2(|\eta_2|^2 + |\zeta_2|^2) + \gamma_2(\eta_2^*\zeta_2 + \eta_2\zeta_2^*) + i\delta_2(\eta_2^*\zeta_2 - \eta_2\zeta_2^*) +$$

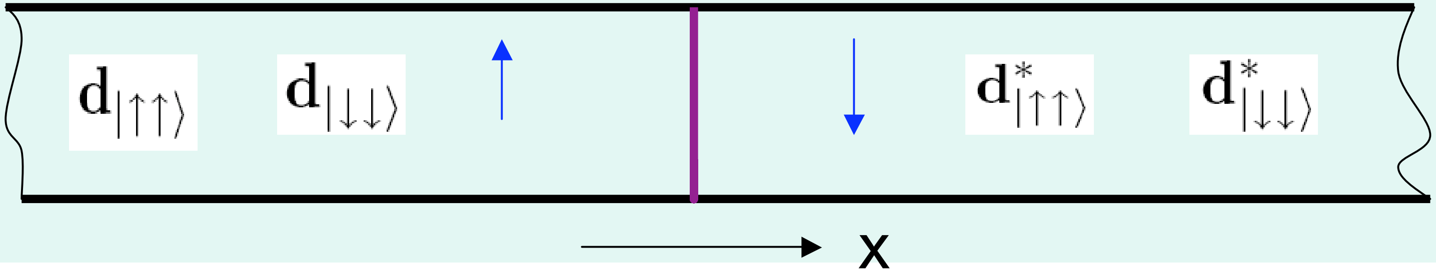
$$\left.\gamma_3(\eta_1^*\zeta_2 + \eta_1\zeta_2^* + \eta_2^*\zeta_1 + \eta_2\zeta_1^*) + i\delta_3(\eta_1^*\zeta_2 - \eta_1\zeta_2^* + \eta_2^*\zeta_1 - \eta_2\zeta_1^*)\right] \delta(x)$$

$$F_{grad}(x < 0) = K_1 \left|\frac{\partial \eta_1}{\partial x}\right|^2 + K_2 \left|\frac{\partial \eta_2}{\partial x}\right|^2$$

$$F_{grad}(x > 0) = K_1 \left|\frac{\partial \zeta_1}{\partial x}\right|^2 + K_2 \left|\frac{\partial \zeta_2}{\partial x}\right|^2$$

Interdomain Josephson couling

$$-K_1\frac{\partial\eta_1}{\partial x}=\alpha_1\eta_1+(\gamma_1+i\delta_1)\zeta_1+(\gamma_3+i\delta_3)\zeta_2$$



$$\mathbf{j}=\frac{2\pi ic}{\Phi_0}\left\{K_1\left(\eta_1^*\frac{\partial\eta_1}{\partial x}-\eta_1\frac{\partial\eta_1^*}{\partial x}\right)+(\eta_1\rightarrow\zeta_1)+\right.$$

$$\left.K_2\left(\eta_2^*\frac{\partial\eta_2}{\partial x}-\eta_2\frac{\partial\eta_2^*}{\partial x}\right)+(\eta_2\rightarrow\zeta_2)\right\}=$$

$$=\frac{8\pi c}{\Phi_0}\{[\gamma_1|\eta_1|^2+\gamma_2|\eta_2|^2+\gamma_3|\eta_1||\eta_2|]\sin(\phi-\varphi)+$$

$$+[\delta_1|\eta_1|^2+\delta_2|\eta_2|^2+\delta_3|\eta_1||\eta_2|]\cos(\phi-\varphi)\}$$

Conclusion

- The coexistence of superconductivity and ferromagnetism in several uranium compounds is found to arise as a co-operative phenomenon rather than as the overlap of two mutually competing orders.
- In all these compounds the substantial reduction of the ordered moment as compared with the Curie-Weiss moment provides clear evidence of 5f itineracy.
- The large exchange field in comparison with superconducting gap points out that here we deal with Cooper pairing in the triplet state.

- In UCoGe the pressure dependent critical lines of ferromagnet and superconducting phase transitions intersect each other. The two band multidomain superconducting ferromagnet state arises at temperatures below both of these lines.
- The symmetry and the order parameters of normal, ferromagnet, superconducting and ferromagnet superconducting states are discussed.
- The specific intradomain Josepson coupling as well the Josepson coupling between two adjacent ferromagnet superconducting domains is established.