Heavy–fermion physics: frontier of condensed matter research

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Why is condensed matter physics intriguing?

- Reductionism vs. emergence
  (P. Anderson, More is Different, *Science* **177**, 393 (1972))
- CM physics offers possibility to study many effective field theories with large experimental feedback

Condensed-matter physicists are often motivated to deal with phenomena because the phenomena themselves are intrinsically so interesting. Who would not be fascinated by weird things, such as superconductivity, superfluidity, or the quantum Hall effect? On the other hand, I don't think that elementary-particle physicists are generally very excited by the phenomena they study. The particles themselves are practically featureless, every electron looking tediously just like every other electron.

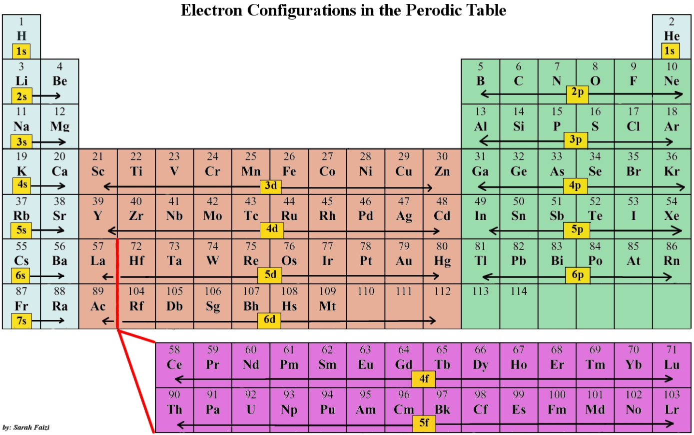
S. Weinberg, 2007

Why are heavy-fermion systems interesting?

- They exhibit many different magnetic and electronic phases: 'electrons at the edge of magnetism'
- Possible applications in spintronics: coupling of electronic and magnetic degrees of freedom
- They may shed new light on the theory of unconvential high temperature superconductivity

Heavy-fermion compounds

- Intermetallic compounds of rare-earth or actinides ions with unfilled *f* shells, e.g. $\mathrm{CeAl_3, CeCu_6, UBe_{13}}$



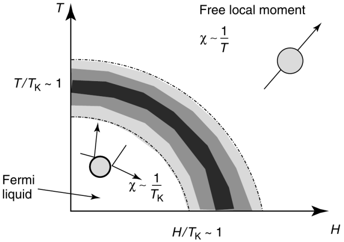
Electron Configurations in the Perodic Table

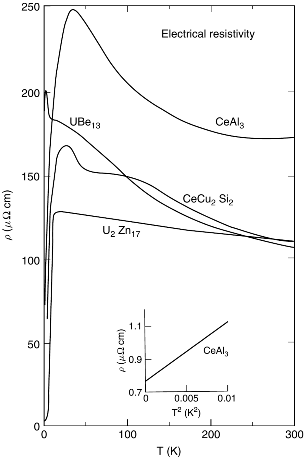
1 H 1s																	2 He 1s
3 Li 2s	4 Be											5 B	6 C	7 N	8 O 2p	9 F	10 Ne
11 Na 3s	12 Mg											13 Al	14 Si	15 P 3p	16 S	17 Cl	18 Ar
19 K 4s	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe 3d	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As 4p	34 Se	35 Br	36 Kr
37 Rb 5s	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru 4d	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te 5p	53 I	54 Xe
55 Cs 6s	56 Ba	57 La	72 Hf	73 Ta	74 W	75 Re	76 Os 5d	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po 6p	85 At	86 Rn
87 Fr 7s	88 Ra	89 Ac	104 Rf	105 Db	106 Sg	107 Bh 6d	108 Hs	109 Mt	110	111	112	113	114				
				58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb 4f	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu
				90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk 5f	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr

by: Sarah Faizi

General properties of heavy-fermion compounds

- Low T: Fermi liquid, electronic density of states at Fermi energy up to 1000 times larger than in Cu
  $\rightsquigarrow$ large effective mass, specific heat, susceptibility etc.
- High T: Curie susceptibility $\chi \sim \frac{1}{T}$
  $\rightsquigarrow$ magnetic moments

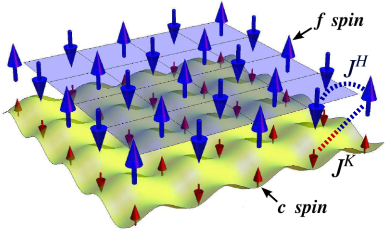




(Smith, Riseborough, 1985)

Kondo effect

- (Kondo, 1964) anomalous resistivity at small T due to the scattering off the single magnetic impurity
- At $T < T_K$ electrons screen the impurity such that magnetic moment vanish
- At $T > T_K$ magnetic impurity becomes asymptotically free
- (Doniach, 1977) Heavy-fermion compound = lattice of local magnetic moments (Kondo lattice)



(by O. Howczak)

History

- (Andres, Graebner and Ott, 1975)
  first heavy-fermion system discovered - $\mathrm{CeAl_3}$
- (Steglich *et al.*, 1976)
  first heavy-fermion superconductor discovered - $\mathrm{CeCu_2Si_2}$
- (Doniach, 1977)
  heavy-fermion system as a dense Kondo lattice
- (von Löhneysen *et al.*, 1994)
  quantum phase transition in $\mathrm{CeCu}_{6-x}\mathrm{Au}_x$ by varying x

Periodic Anderson Hamiltonian

- Microscopic model: mixing of conduction electrons (c) with the lattice of localized f electrons

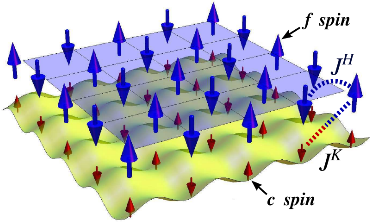
$$H_{\mathrm{A}} = \sum_{ij\sigma} t_{ij} c^{\dagger}_{i\sigma} c_{j\sigma} + \epsilon_f \sum_{i\sigma} \hat{n}^{f}_{i\sigma} + \frac{U}{2} \sum_{i\sigma\sigma'} \hat{n}^{f}_{i\sigma} \hat{n}^{f}_{i\sigma'} + \sum_{i\sigma} \left(V c^{\dagger}_{i\sigma} f_{i\sigma} + V^{*} f^{\dagger}_{i\sigma} c_{i\sigma} \right)$$

- $\sigma = -\mathcal{J}, \dots, \mathcal{J}$
  $\rightsquigarrow \mathcal{N}_f = 2\mathcal{J} + 1$ degenerate states per unit cell
- Localized f electrons strongly repel each other
- Bloch waves c hybridize with f states

Kondo lattice Hamiltonian

- $\left\langle \hat{n}_i^f \right\rangle = \sum_\sigma \left\langle \hat{n}_{i\sigma}^f \right\rangle = 1 \rightsquigarrow$ one *f* electron per unit cell
- $U \to \infty \rightsquigarrow$ *f* electrons freeze $\rightsquigarrow \hat{n}_i^f = 1$
- local moments form, $J \approx \frac{2|V|^2}{U+\epsilon_f}$, $\hat{\mathbf{S}}_i^c = c_{i\sigma}^\dagger \mathbf{S}_{\sigma\sigma'}^j c_{i\sigma'}$
- effective model for $T \sim T_K \approx De^{-\frac{1}{2J\rho(0)}}$, $\rho(0)$ - density of *c* states at Fermi level, D - bandwidth

$$H_{\mathrm{K}} = -\sum_{ij\sigma} t c_{i\sigma}^\dagger c_{j\sigma} + J \sum_i \hat{\mathbf{S}}_i^f \hat{\mathbf{S}}_i^c + \sum_{i\sigma} \lambda_i \left(\hat{n}_{i\sigma}^f - \frac{1}{\mathcal{N}_f} \right)$$



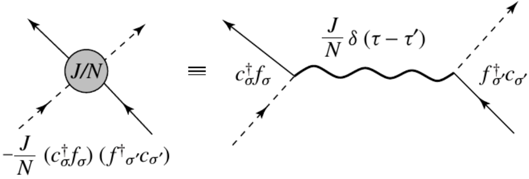
(by O. Howczak)

Path-integral formulation (Read, Newns, 1983)

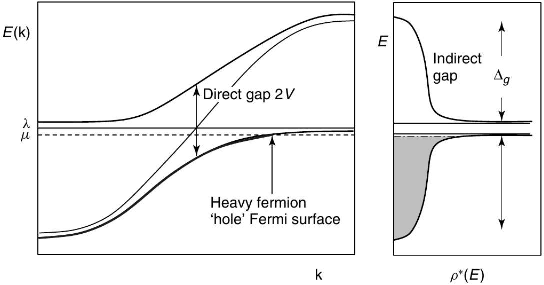
$$H_{\mathrm{K}} = \sum_{\mathbf{k}\sigma} \left(\epsilon_{\mathbf{k}} - \frac{J}{\mathcal{N}_f} \right) \hat{n}^{c}_{\mathbf{k}\sigma} - \frac{J}{\mathcal{N}_f} \sum_{i\sigma\sigma'} \left(f^{\dagger}_{i\sigma} c_{i\sigma} \right) \left(c^{\dagger}_{i\sigma'} f_{i\sigma'} \right)$$

$$+ \sum_{i\sigma} \lambda_i \left(\hat{n}^{f}_{i\sigma} - \frac{1}{\mathcal{N}_f} \right)$$

$$Z = \mathrm{Tr} \left[\mathcal{T} \exp \left(\int_0^{1/T} L d\tau \right) \right] = \int \mathcal{D}[V,\lambda] \mathrm{Tr} \left[\mathcal{T} \exp \left(\int_0^{1/T} L[V,\lambda] d\tau \right) \right]$$



Heavy fermion band structure



(after P. Coleman, 2007)

$$\lambda = \mathcal{N}_f \rho(0)|V|^2 = \frac{T_K}{e^2}$$

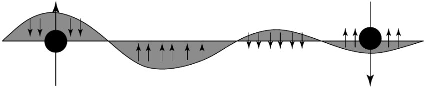
$$\rho(0)|V|^2 = \frac{T_K}{e^2 \mathcal{N}_f}$$

$$\rho^*(0) = \rho(0) + \frac{e^2}{\mathcal{N}_f T_K}$$

RKKY (Ruderman, Kittel, Kasuya, Yosida) interaction

- Presence of local moments f causes oscillations in the spin density of conduction electrons:

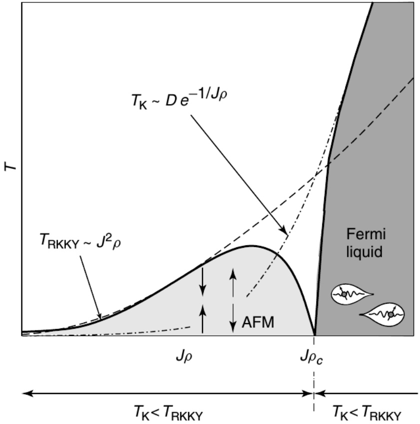
$$\left\langle (\hat{S}^z)^c(r) \right\rangle \approx -J\rho(0)\frac{\cos(2k_F r)}{|k_F r|^3}\left\langle (\hat{S}^z)^f(0) \right\rangle$$



$$H_{\mathrm{K}} = -\sum_{ij\sigma} t c^{\dagger}_{i\sigma} c_{j\sigma} + J\sum_{i} \hat{\mathbf{S}}^f_i \hat{\mathbf{S}}^c_i + \sum_{i\sigma}\lambda_i\left(\hat{n}^f_{i\sigma} - \frac{1}{\mathcal{N}_f}\right) - \sum_{ij} J^2\rho(0)\frac{\cos(2k_F|\mathbf{R}_i - \mathbf{R}_j|)}{k_F^3|\mathbf{R}_i - \mathbf{R}_j|^3}\hat{\mathbf{S}}^f_i \hat{\mathbf{S}}^f_j$$

Doniach diagram

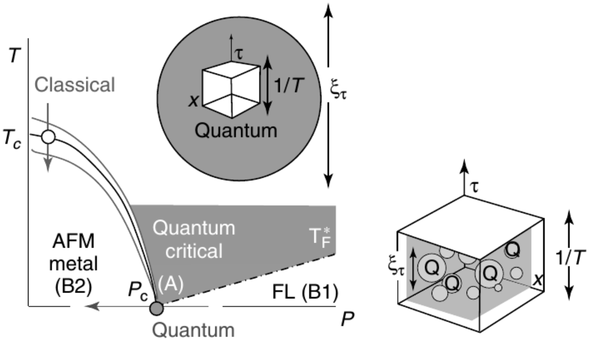
- Competition between antiferromagnetic RKKY and Kondo interaction drives the quantum phase transition at $T = 0\,\mathrm{K}$



(after P. Coleman, 2007)

Quantum criticality

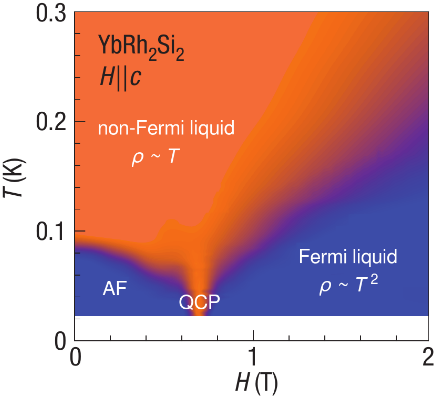
- Quantum phase transition occurs at $T = 0$ when some control parameter P is being changed
- Diverging correlation length ξ_x and correlation time $\xi_\tau \sim (\xi_x)^z$



(after P. Coleman, 2007)

Phase diagram

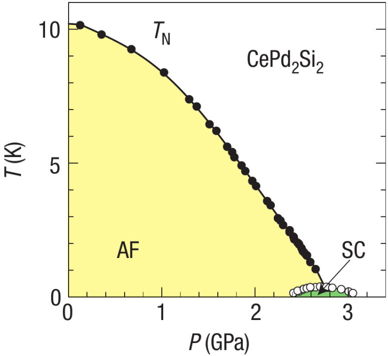
- Non-Fermi liquid behaviour in the quantum critical region - universality of quantum critical matter?



(after Custers, 2003)

Superconductivity

- Superconductivity ($T_C < 20\,\mathrm{K}$) often emerges in the vicinity of quantum critical point (QCP) in heavy-fermion systems
- What is the role of magnetism and the quantum criticality in the formation of SC state?



(Mathur, 1998)

Summary

- Heavy-fermion systems have many faces:
  - Fermi liquid with heavy quasiparticles
  - Kondo insulator
  - antiferromagnetism
  - non-Fermi liquid near the QCP - strange metal
  - unconvential superconductivity
  - ferromagnetism, semiconducting behaviour, metamagnetism

  (eg. Spałek, Doradziński, 1999; Spałek, Howczak, 2012)
- Their properties follow from the mixing between conduction and localized f electronic states
- Variety of exotic phases and new experimental results require better theoretical understanding and development of new methods - there is still much to do!

Literature

- P. Coleman, Heavy Fermions: electrons at the edge of magnetism in *Handbook of Magnetism and Advanced Magnetic Materials* (J. Wiley and Sons, 2007)
- P. Gegenwart, Q. Si, F. Steglich, Quantum Criticality in Heavy Fermion Metals, *Nature Physics* **4**, 186 (2008)