NMR Evidence for Scaling in the Kondo Lattice

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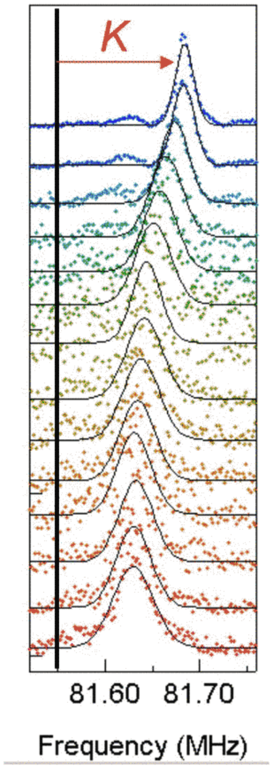
Knight Shift

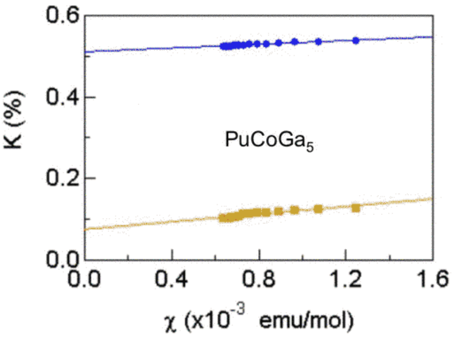


$$\mathcal{H} = \gamma\hbar\hat{\mathbf{I}}\cdot\mathbf{H}_0 + \hbar\hat{\mathbf{I}}\cdot\mathbf{A}\cdot\hat{\mathbf{S}} + g\mu_B\hat{\mathbf{S}}\cdot\mathbf{H}_0$$

Nuclear spin Hyperfine coupling Electron spin

$$\hat{\mathbf{S}} \rightarrow \langle\hat{\mathbf{S}}\rangle = \chi\mathbf{H}_0/g\mu_B$$

$$\mathcal{H} \rightarrow \mathcal{H}_{\text{eff}} = \gamma\hbar\hat{\mathbf{I}}\cdot(\mathbf{1}+\mathbf{K})\cdot\mathbf{H}_0$$



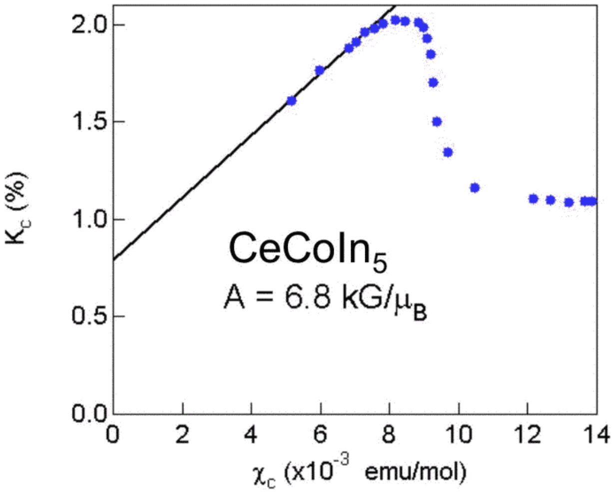
$$\boxed{K_\alpha(T) = (A_\alpha/\gamma g\mu_B)\,\chi_\alpha(T)}$$

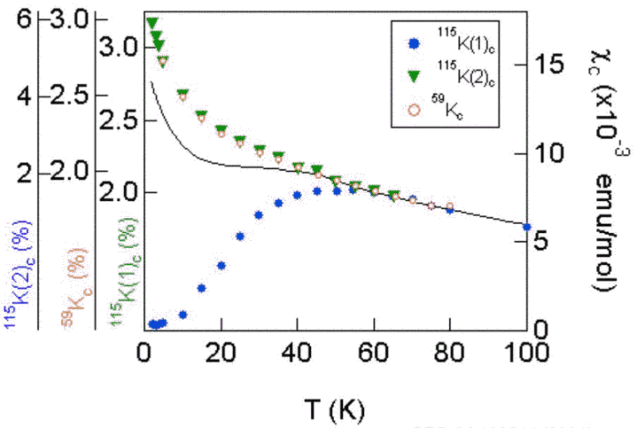
Single spin component:

$K(T) = K_0 + A\chi(T)$

Anomalies

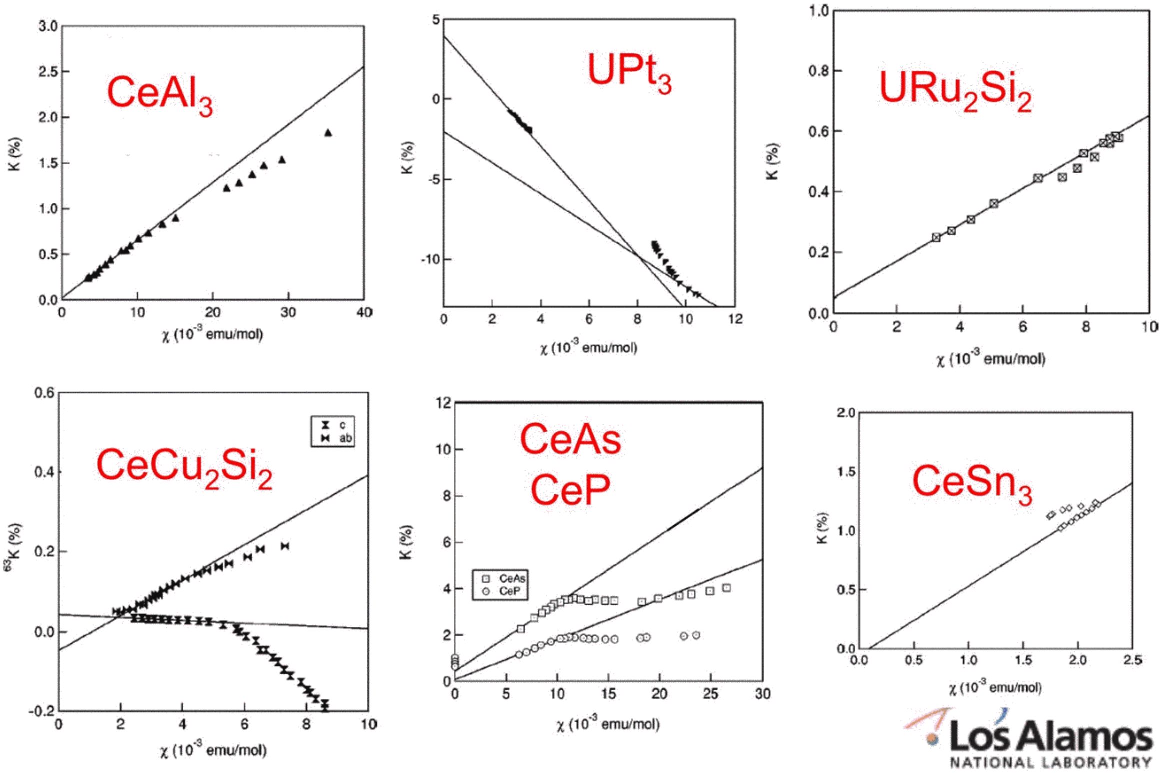
For many Kondo lattice systems, this relationship breaks down!





PRB **64** 180514 (2001)

Other Examples



Possible Explanations

Historically there have been two distinct explanations:

A. *Cox*: Anomaly related to Kondo screening cloud [PRL **75** 2015 (95)]

Local susceptibility position dependent

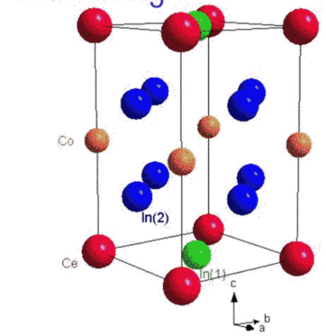
B. *Kitaoka/Fisk*: Anomaly related to CEF excitation [JPSJ **64** 2628 (95)]

Two or more components of χ with different T dependence:

$K(T) = K_0 + A_1\chi_1(T) + A_2\chi_2(T)$

Two Fluid Description

$CeCoIn_5$:

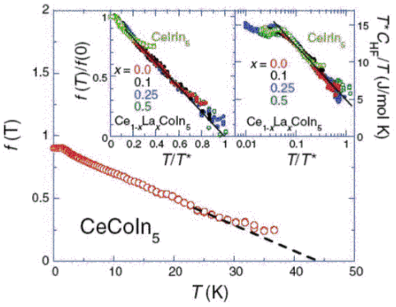


- $CeCoIn_5$ has strong Knight shift anomalies at ~60K, but this coincides with neither a CEF excitation nor T_{Kondo} ~ 3K
- Only one Ce site per unit cell – only one component of χ?

Nakatsuji, Pines & Fisk [PRL **92** 16401 (2004)] -Analysis of dilute $CeCoIn_5$ via two fluids

$$\chi(T) = [1 - f(T)]\chi_{\mathrm{KI}}(T) + f(T)\chi_{\mathrm{HF}}(T)$$

$$C_{\mathrm{MAG}}/T = [1 - f(T)](C_{\mathrm{KI}}/T) + f(T)(C_{\mathrm{HF}}/T),$$

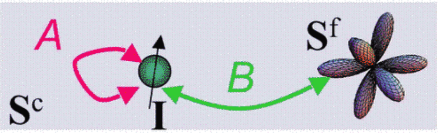


Second “heavy fermion” component emerges below *T**

Two Spin Components

Assume hyperfine coupling to conduction electrons, f-spins is different:

$$\mathcal{H}_{\text{hyp}} = \gamma\hbar\sum_{l} \mathbf{I}(\mathbf{r}_l)\cdot\mathbf{A}\cdot\mathbf{S}^{\text{c}}(\mathbf{r}_l) + \gamma\hbar\sum_{i,l} \mathbf{I}(\mathbf{r}_l)\cdot\mathbf{B}_i\cdot\mathbf{S}^{\text{f}}(\mathbf{r}_i)$$



$$\chi = \chi_{\text{ff}} + 2\chi_{\text{cf}} + \cancel{\chi_{\text{cc}}}$$

negligible

$$\chi_{\text{ff}} = (1/N)\Sigma_{i,i'}\langle\mathbf{S}^{\text{f}}(\mathbf{r}_i)\mathbf{S}^{\text{f}}(\mathbf{r}_{i'})\rangle$$

$$\chi_{\text{cf}} = (1/N)\Sigma_{i,l}\langle\mathbf{S}^{\text{f}}(\mathbf{r}_i)\mathbf{S}^{\text{c}}(\mathbf{r}_l)\rangle$$

Two different susceptibilities!

Two Component Knight Shift

Knight shift and χ measurements allow one to decompose two components:

$$K_\alpha(T) = K_{0,\alpha} + (A_\alpha + B_\alpha)\chi_{\text{cf}}(T) + B_\alpha\chi_{\text{ff}}(T)$$

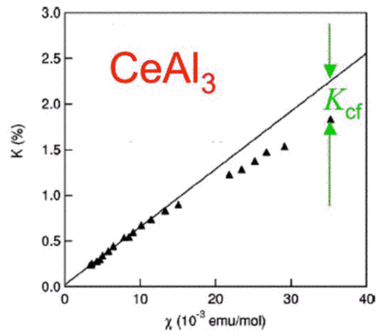
$$\chi = \chi_{\text{ff}} + 2\chi_{\text{cf}}$$

Two assumptions:

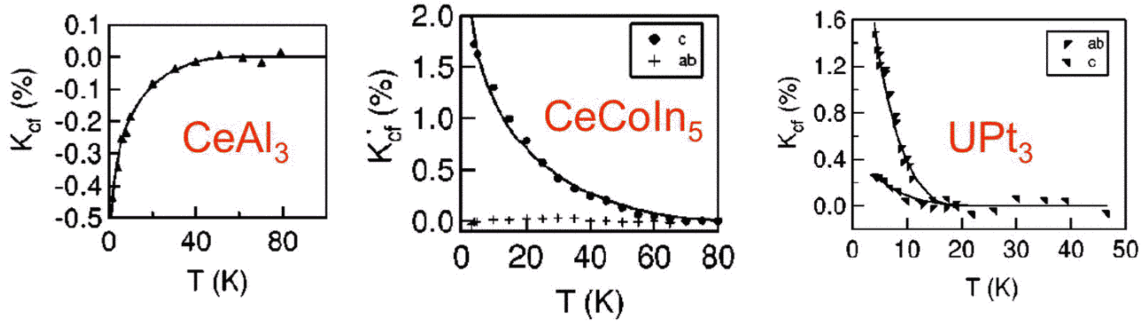
(a) $\chi_{\text{cf}}(T)$ and $\chi_{\text{ff}}(T)$ have different T dependences

(b) $\chi_{\text{cf}}(T) \sim 0$ for $T > T^*$

Temperature Dependence of χ_{cf}

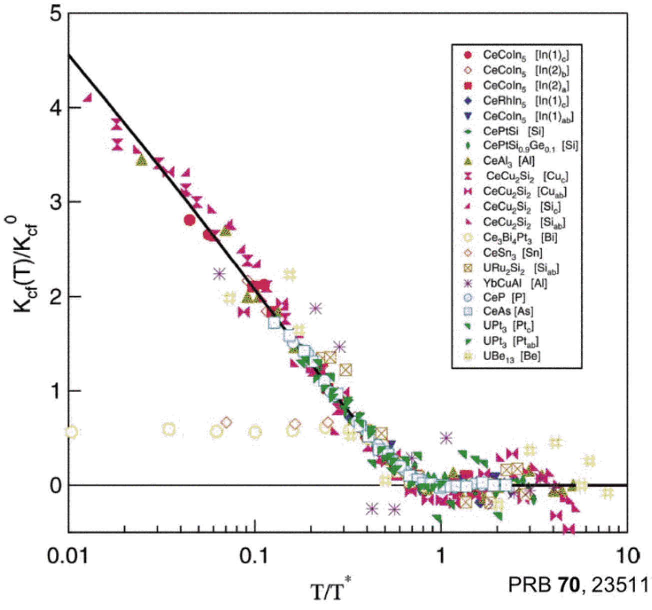


Plot K_{cf} versus temperature



➡ *Similar temperature dependences for all materials!*

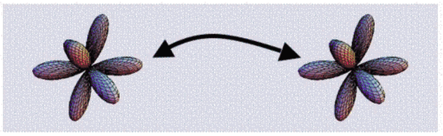
Scaling Behavior



PRB **70**, 235117 (2004)

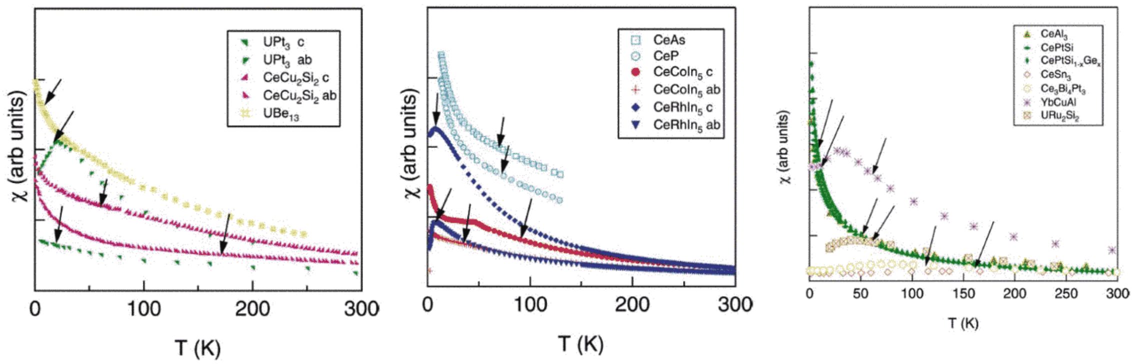
$$\chi_{cf} \sim \left(1 - \frac{T}{T^*}\right) \log \frac{T^*}{T}$$

*T** is a measure of intersite coupling



- •Model independent
- •Behavior common to all Kondo lattices?

Bulk Susceptibilities



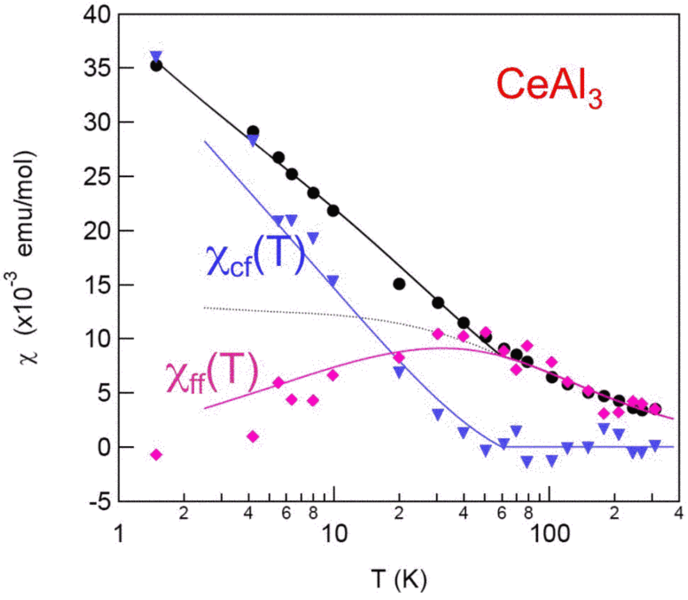
- *T* is not obvious from the bulk susceptibility*
- *Need Knight shift to determine T**

$\chi_{cf}(T)$ versus $\chi_{ff}(T)$

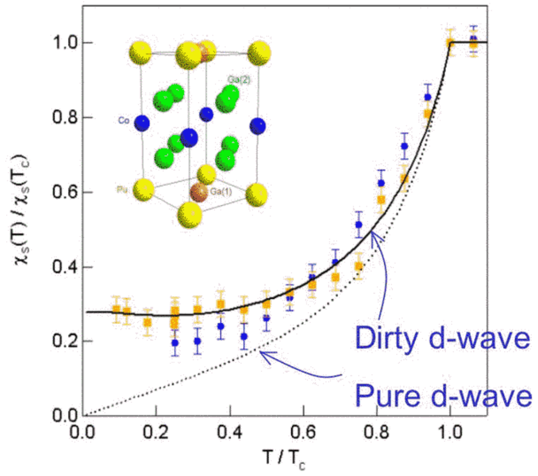
What about the χ_{ff}(T)?

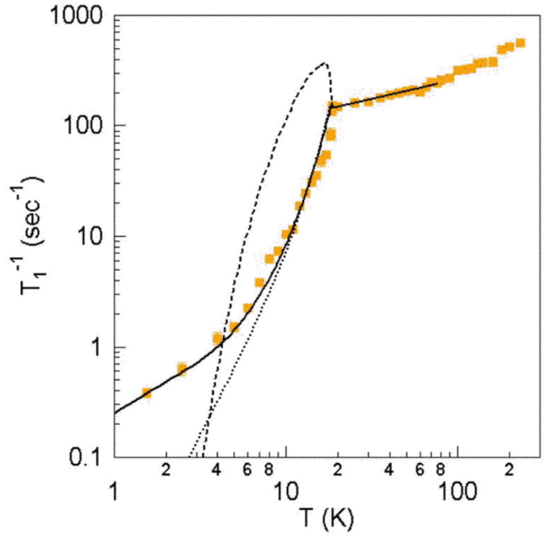
$$\chi_{ff}(T) = (1 - f(T))\,\frac{C\mu_B^2}{T + \alpha T^*}$$

with $\alpha \sim 0.1$



NMR in PuCoGa$_5$

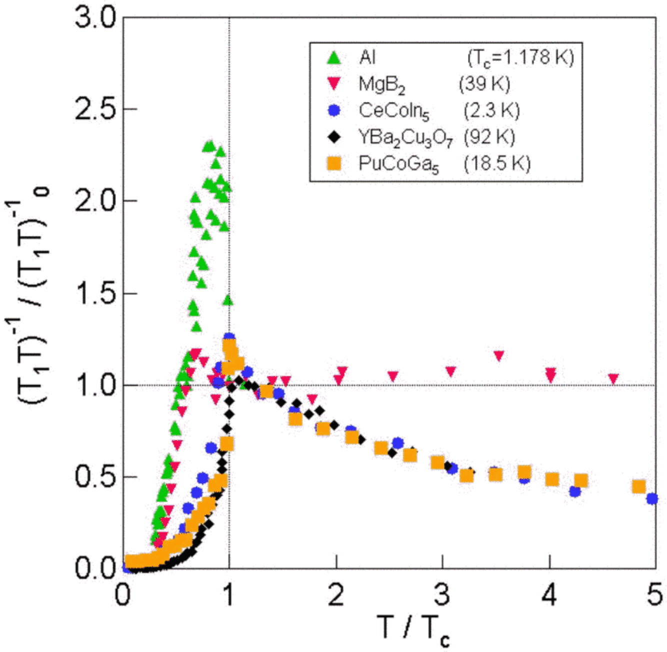




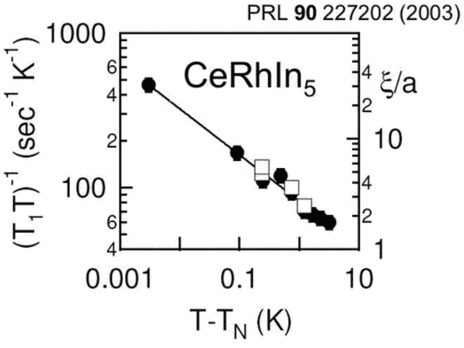
Spin singlet, with lines of nodes in gap

Most likely d-wave

Scaling of Relaxation data



Normal state scaling of *$1/T_1T$* data in all d-wave superconductors



Evidence for similar divergence of AF fluctuations?

Conclusions

Static NMR probes of Kondo Lattices:

- Reasonable assumptions lead to universal scaling
- What is T*, and why logarithmic?

Dynamics of d-wave superconductors:

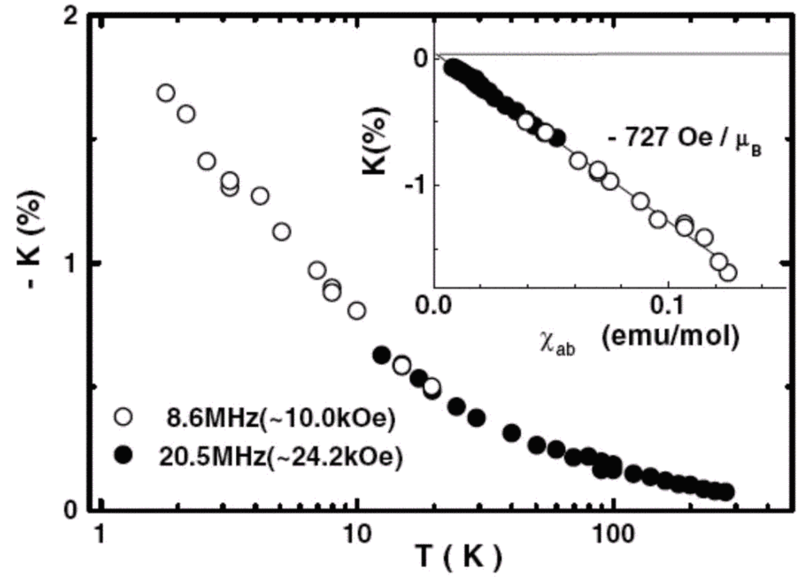
- d-wave superconductivity may arise when long range AF order cannot?

Material Parameters

TABLE I. The Knight shift parameters in several Kondo lattice systems.

Material(site)	Ref.	$T^*(K)$	$K_0(\%)$	$B_\alpha(\mathrm{kOe}/\mu_B)$	$A_\alpha(\mathrm{kOe}/\mu_B)$	$K^0_{cf}(\%)$	$\gamma(\mathrm{mJ/mol\ K^2})$
$\mathrm{CeCoIn_5(In(1)_c)}$	17	89	0.79	8.9	13.7	3.3	290 (Ref. 20)
$\mathrm{CeCoIn_5(In(1)_{ab})}$	17	⋯	0.13	12.1	12.1	⋯	290 (Ref. 20)
$\mathrm{CeCoIn_5(In(1)_a)}$	17	42	1.14	−0.4	−5.9	−2.0	290 (Ref. 20)
$\mathrm{CeCoIn_5(In(2)_b)}$	17	42	0.77	10.3	−4.1	−1.3	290 (Ref. 20)
$\mathrm{CeCoIn_5(In(2)_c)}$	17	95	−2.43	28.1	12.1	3.1	290 (Ref. 20)
$\mathrm{CeCu_2Si_2(Cu_c)}$	13	171	0.04	−0.2	⋯	−0.3	700 (Ref. 21)
$\mathrm{CeCu_2Si_2(Cu_{ab})}$	13	58	−0.05	2.5	⋯	−0.1	700 (Ref. 21)
$\mathrm{CeCu_2Si_2(Si_c)}$	13	171	0.12	2.7	⋯	−0.3	700 (Ref. 21)
$\mathrm{CeCu_2Si_2(Si_{ab})}$	13	58	−0.11	8.2	⋯	−0.2	700 (Ref. 21)
$\mathrm{CeRhIn_5(In(1)_c)}$		12	−2.51	26.0	⋯	1.3	200 (Ref. 22)
$\mathrm{CeRhIn_5(In(1)_{ab})}$		10	−0.54	19.6	⋯	2.2	200 (Ref. 22)
$\mathrm{CeAl_3(Al)}$	23	60	0.02	3.5	⋯	−0.7	1620 (Ref. 24)
$\mathrm{CePtSi(Si)}$	25	20	−0.11	7.1	⋯	−1.7	800 (Ref. 26)
$\mathrm{CePtSi_{0.9}Ge_{0.1}(Si)}$	25	15	0.07	4.2	⋯	−1.4	1350 (Ref. 27)
$\mathrm{CeSn_3(Sn)}$	28	167	−0.05	32	⋯	0.2	70 (Ref. 29)
$\mathrm{Ce_3Bi_4Pt_3(Bi)}$	30	123	0.37	46	⋯	−1.0	3.3 (Ref. 31)
$\mathrm{YbCuAl(Cu)}$	32	73	0.07	−1.0	⋯	0.03	260 (Ref. 33)
$\mathrm{URu_2Si_2(Si_c)}$	34	84	0.05	3.37	⋯	−0.03	65 (Refs. 35 and 36)
$\mathrm{CeP(P)}$	11	76	0.03	9.98	⋯	−1.49	17 (Ref. 37)
$\mathrm{CeAs(As)}$	11	73	0.43	16.3	⋯	−2.41	unknown
$\mathrm{UPt_3(Pt_c)}$	38	23	3.95	−95.7	⋯	0.19	420 (Ref. 39)
$\mathrm{UPt_3(Pt_{ab})}$	38	19	−2.0	−54.4	⋯	1.30	420 (Ref. 39)
$\mathrm{UBe_{13}(Be)}$	40	10	−0.02	0.86	⋯	−0.008	900 (Ref. 41)

$YbRh_2Si_2$



K. Ishida, PRL **89** 107202 (2002)