Kondo problem to heavy fermions and local quantum criticality (Experiment I)

F. Steglich
MPI for Chemical Physics of Solids, 01187 Dresden, Germany

outline:

Kondo effect

Superconductivity vs. magnetism

Heavy fermions

Heavy-fermion superconductors

1930: T- dependence of the electrical resistivity in pure metals?

ANNALEN DER PHYSIK

5. FOLGE, 1930, BAND 7, HEFT 7

Messungen mit Hilfe von flüssigem Helium XI

Widerstand der reinen Metalle in tiefen Temperaturen

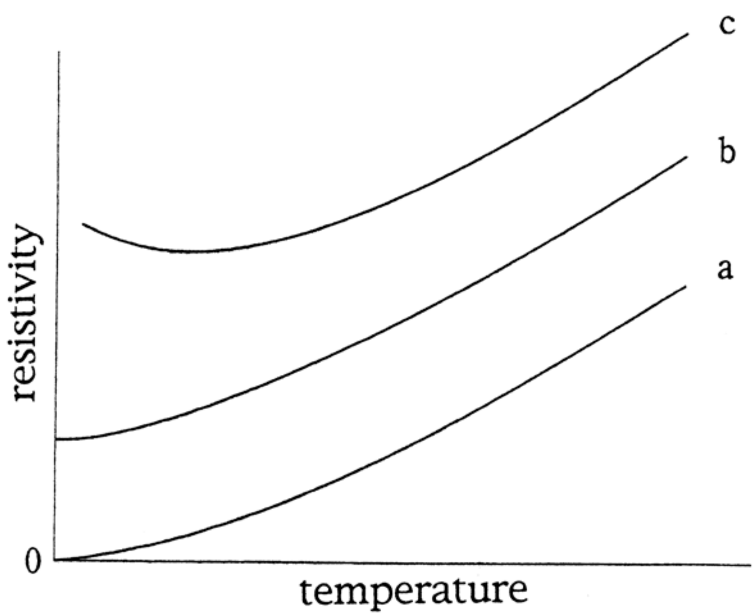
Von W. Meissner und B. Voigt

(Mit 13 Figuren)

(Mitteilung aus der Physikalisch-Technischen Reichsanstalt)

Tabelle 6. Kupfer

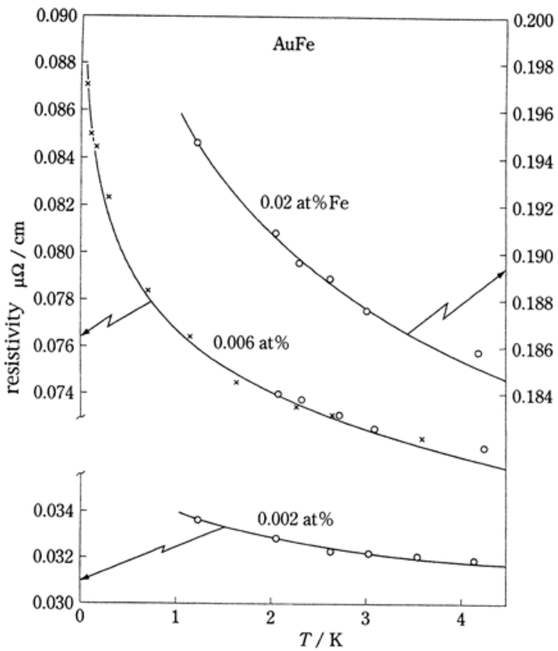
Atom-Nr. Kristallsyst. / Metall		29 K. fz. Cu 1		Cu 2			$\theta = 355$, berechnet nach Formel (2)
Herkunft, Verunreinigung		Schott Cu 1 Gr.-Goe. ?		Johnsen Cu 2 Gr.-Goe. ?			
Bemerkungen		Kristall getemp.		Kristall getemp.			
Länge / Dicke		— / 2 mm ϕ		— / 1,5 mm ϕ			
Abstand d. Stromdr / „ d. Spanngsdr.		— / 16 mm		— / 19 mm			
He-Dpfdr. mm Hg	Grad abs.	$r_{beob.}$	$r_{red.}$	$r_{beob.}$	$r_{red.}$	$r_{red.}$ Mittel	$r_{ber.}$
—	273,16	1	1	1	1	1	1
—	82,19	0,148	$0{,}147_7$	—	—	$0{,}147_7$	0,1469
—	81,62	—	—	0,144	$0{,}143_8$	$0{,}143_8$	0,1446
—	20,42	0,00086	0,00052	0,00078	0,00050	0,00051	0,00117
764	4,20	—	—	0,00029	0,00001	$0{,}0000_1$	$0{,}0000_0$
756	4,18	0,00034	0,00000	—	—	$0{,}0000_0$	$0{,}0000_0$
46	2,42	0,00038	0,00000	—	—	$0{,}0000_0$	$0{,}0000_0$
17	1,97	—	—	0,00028	0,00000	$0{,}0000_0$	$0{,}0000_0$
1,9	1,32	0,00035	0,00000	0,00029	0,00001	$0{,}0000_0$	$0{,}0000_0$
—	0,00	(0,00034)	—	(0,00028)	—	—	—
R_0 in Ω bei 273,16		$7{,}35 \cdot 10^{-5}$		$1{,}60 \cdot 10^{-4}$		—	—



≤ 1970: Noble metals with transition-metal impurities

D.K.C. MacDonald et al.,
Proc. Roy. Soc. **A266**, 161 (1962)

resistivity



Kondo effect:

(J. Kondo 1964)

susceptibility

Curie Weiss law

$\chi(T) \sim (T + \theta)^{-1}, \theta = f\,(T_K) > 0$

effective moment $\mu_{eff}(T)$:

$\chi(T) \sim \mu^2_{eff}(T)/T$

$T \rightarrow 0$ ↷ $\mu_{eff}(T) \rightarrow 0$

VOLUME 27, NUMBER 15 PHYSICAL REVIEW LETTERS 11 OCTOBER 1971

Calorimetric Evidence for a Singlet Ground State in *Cu*Cr and *Cu*Fe†

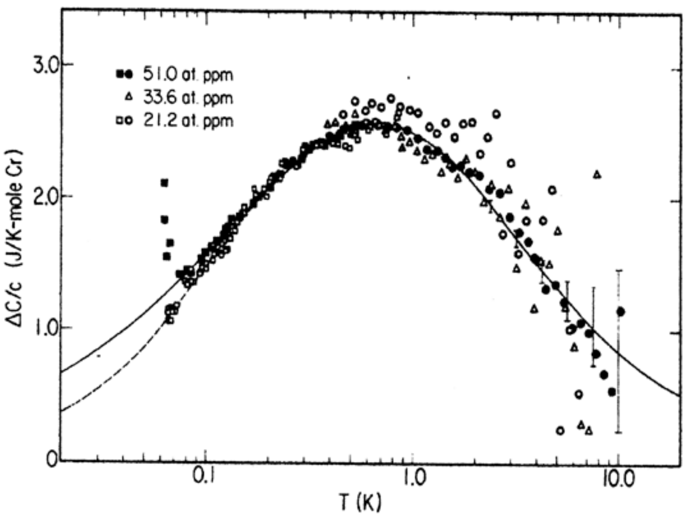
B. B. Triplett and Norman E. Phillips*
Inorganic Materials Research Division of the Lawrence Berkeley Laboratory, and Department of Chemistry, University of California, Berkeley, California 94720
(Received 16 August 1971)

Incremental specific heat of $Cu_{1-x}M_x$ (M: Cr, Fe):

$$\Delta C(T) = C(T) - C_{Cu}(T)$$

per mole M: $\Delta C(T)/x = \gamma T$

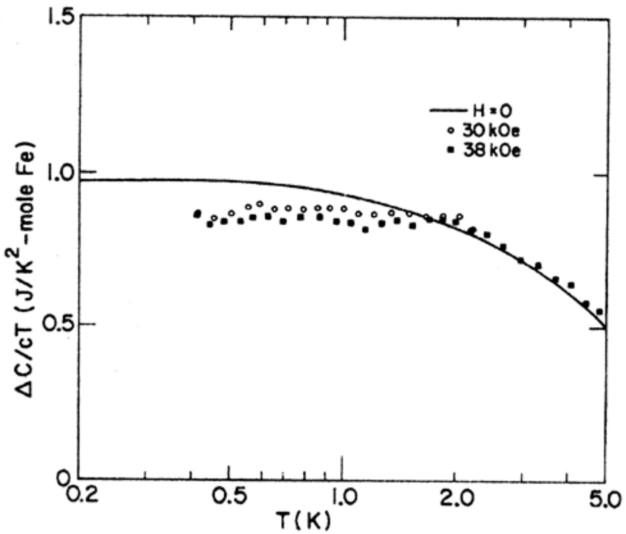
CuCr



γ $[J/K^2\text{-mole}^{Cr}_{Fe}]$

16 **1.0**

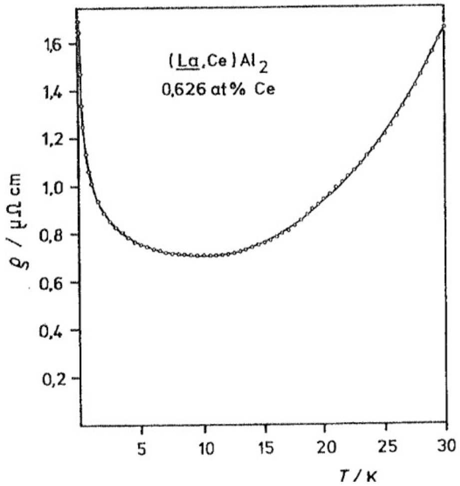
CuFe



$T = T_K$: local Fermi liquid (P. Nozières 1974)

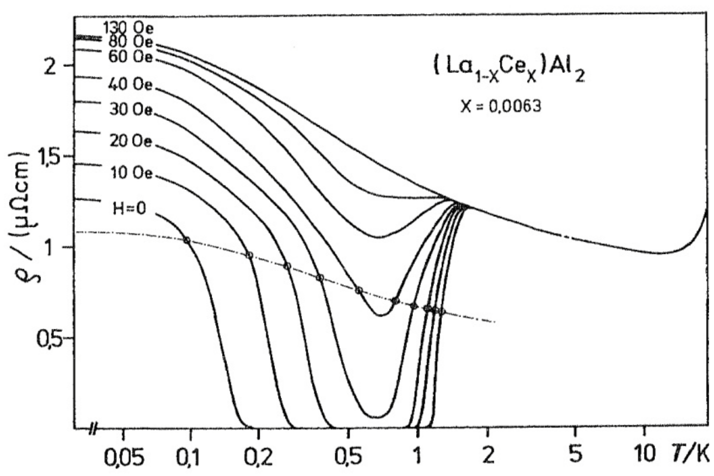
> 1970: Rare earth impurities

K. Winzer, Z. Phys. **265**, 139 (1973)
resistivity

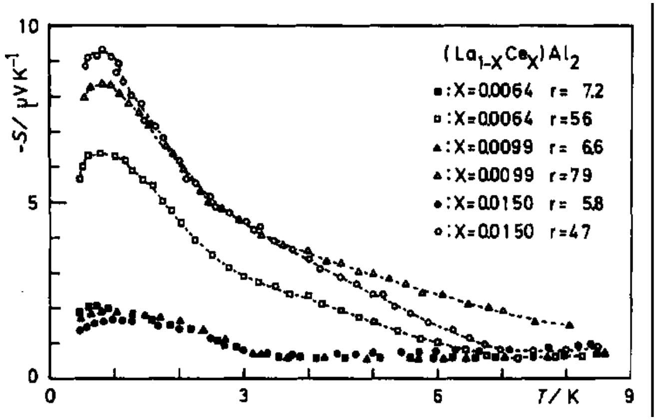


$(La_{1-x}Ce_x)Al_2$

x = 0.00626
re-entrant superconductivity

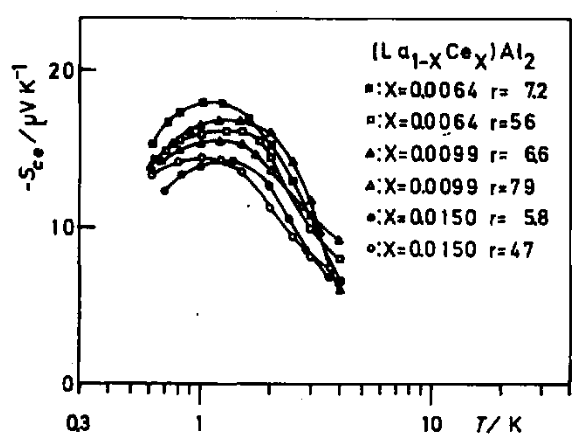


J. Moeser, F. Steglich, G.v. Minnigerode
J. Low Temp. Phys. **15**, 9 (1974)
giant thermoelectric power



Gorter-Nordheim:

$$S_{ce} = \frac{\rho(T)S - [\rho(T) - \rho_{ce}(T)]S_{La}}{\rho_{ce}(T)}$$



outline:

Kondo effect

Superconductivity vs. magnetism

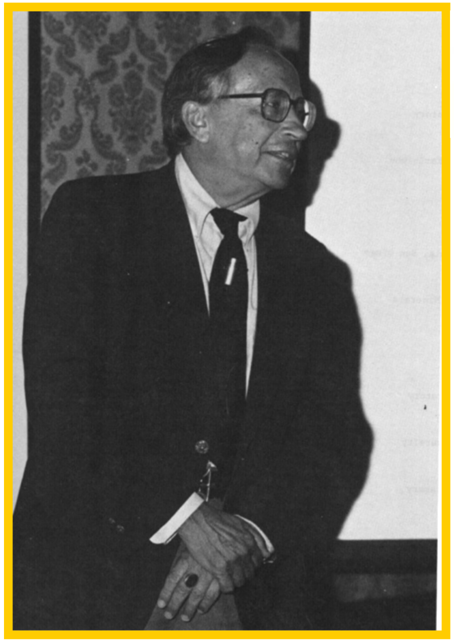
Heavy fermions

Heavy-fermion superconductors

Superconductivity vs. magnetism

IA	IIA	IIIB	IVB	VB	VIB	VIIB	VIIIB	VIIIB	VIIIB	IB	IIB	IIIA	IVA	VA	VIA	VIIA	VIIIA
1 H 1.008																	2 He 4.003
3 Li 6.941	4 Be 9.012											5 B 10.81	6 C 12.01	7 N 14.01	8 O 16.00	9 F 19.00	10 Ne 20.18
11 Na 22.99	12 Mg 24.31											13 Al 26.98	14 Si 28.09	15 P 30.97	16 S 32.07	17 Cl 35.45	18 Ar 39.95
19 K 39.10	20 Ca 40.08	21 Sc 44.96	22 Ti 47.87	23 V 50.94	24 Cr 52.00	25 Mn 54.94	26 Fe 55.85	27 Co 58.93	28 Ni 58.69	29 Cu 63.55	30 Zn 65.39	31 Ga 69.72	32 Ge 72.61	33 As 74.92	34 Se 78.96	35 Br 79.90	36 Kr 83.80
37 Rb 85.47	38 Sr 87.62	39 Y 88.91	40 Zr 91.22	41 Nb 92.91	42 Mo 95.94	43 Tc (98)	44 Ru 101.1	45 Rh 102.9	46 Pd 106.4	47 Ag 107.9	48 Cd 112.4	49 In 114.8	50 Sn 118.7	51 Sb 121.8	52 Te 127.6	53 I 126.9	54 Xe 131.3
55 Cs 132.9	56 Ba 137.3	57 La 138.9	72 Hf 178.5	73 Ta 180.9	74 W 183.8	75 Re 186.2	76 Os 190.2	77 Ir 192.2	78 Pt 195.1	79 Au 197.0	80 Hg 200.6	81 Tl 204.4	82 Pb 207.2	83 Bi 209.0	84 Po (209)	85 At (210)	86 Rn (222)
87 Fr (223)	88 Ra (226)	89 Ac (227)	104 Rf (261)	105 Db (262)	106 Sg (266)	107 Bh (264)	108 Hs (269)	109 Mt (268)									
			58 Ce 140.1	59 Pr 140.9	60 Nd 144.2	61 Pm (145)	62 Sm 150.4	63 Eu 152.0	64 Gd 157.3	65 Tb 158.9	66 Dy 162.5	67 Ho 164.9	68 Er 167.3	69 Tm 168.9	70 Yb 173.0	71 Lu 175.0	
			90 Th 232.0	91 Pa (231)	92 U 238.0	93 Np (237)	94 Pu (244)	95 Am (243)	96 Cm (247)	97 Bk (247)	98 Cf (251)	99 Es (252)	100 Fm (257)	101 Md (258)	102 No (259)	103 Lr (262)	

T_c of $La_{0.99}RE_{0.01}$



VOLUME 1, NUMBER 3 PHYSICAL REVIEW LETTERS AUGUST 1, 1958

SPIN EXCHANGE IN SUPERCONDUCTORS

B. T. Matthias, H. Suhl, and E. Corenzwit
Bell Telephone Laboratories,
Murray Hill, New Jersey
(Received July 15, 1958)

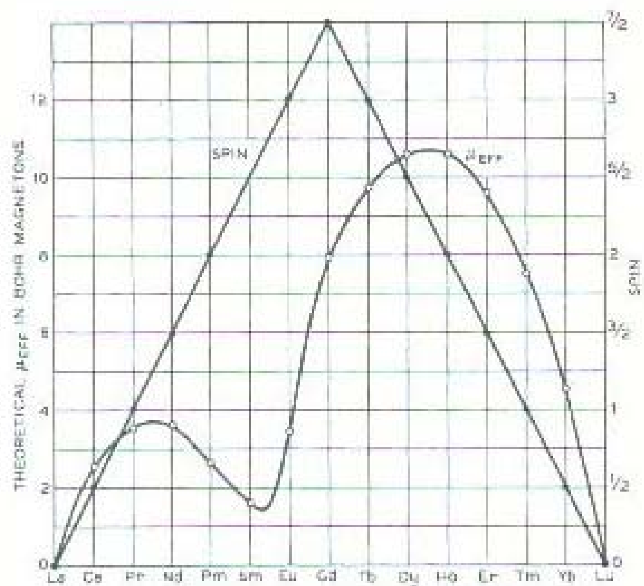


FIG. 1. Effective magnetic moments and spins of the rare earth elements (see reference 2).

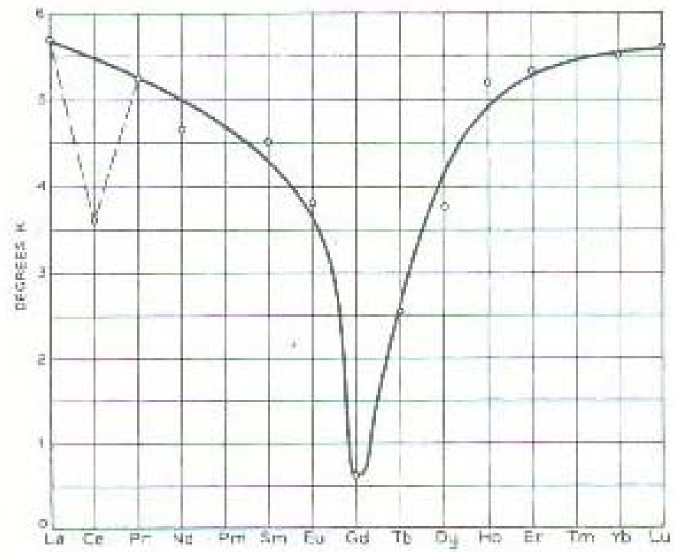


FIG. 2. Superconducting transition temperatures of 1 at % rare earth solid solutions in lanthanum.

Pairbreaking by magnetic impurities (theory)

SOVIET PHYSICS JETP VOLUME 12, NUMBER 6 JUNE, 1961

CONTRIBUTION TO THE THEORY OF SUPERCONDUCTING ALLOYS WITH PARAMAGNETIC IMPURITIES

A. A. ABRIKOSOV and L. P. GOR'KOV

Institute for Physics Problems, Academy of Sciences, U.S.S.R.

Submitted to JETP editor July 25, 1960

J. Exptl. Theoret. Phys. (U.S.S.R.) 39, 1781-1796 (December, 1960)

$H_{int} = 2J\ \mathbf{S} \cdot \mathbf{s}$

$\alpha \sim x\, S(S+1)$

37

Progress of Theoretical Physics, Vol. 32, No. 1, July 1964

Resistance Minimum in Dilute Magnetic Alloys

Jun KONDO

Electro-technical Laboratory
Nagatacho, Chiyodaku, Tokyo

(Received March 19, 1964)

$J > 0$

$T_K \sim T_F \exp(-1/N_F J)$

VOLUME 26, NUMBER 8 PHYSICAL REVIEW LETTERS 22 FEBRUARY 1971

Kondo Effect in Superconductors*

E. Müller-Hartmann† and J. Zittartz‡

Department of Physics, University of California, San Diego, La Jolla, California 92037

(Received 23 November 1970)

$$\alpha \sim x \frac{\pi^2 S(S+1)}{\ln^2(T/T_K) + \pi^2 (S(S+1))}$$

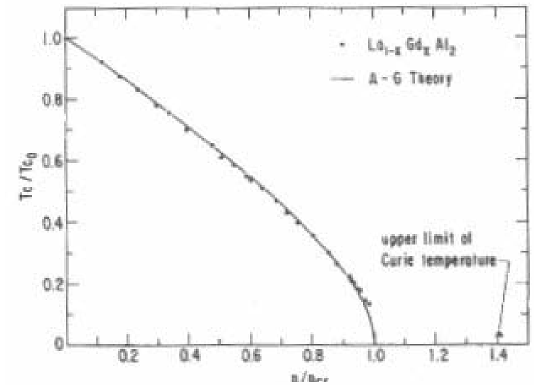
Pairbreaking by magnetic impurities (experiment)

Volume 26A, number 10 PHYSICS LETTERS 8 April 1968

THE SUPERCONDUCTING TRANSITION TEMPERATURE OF $La_{1-x}Gd_xAl_2$ *

M. B. MAPLE
Department of Physics and Tinstitute for Pure and Applied Physical Sciences, University of California, San Diego, La Jolla, California 92037, *USA*

Received 28 February 1968

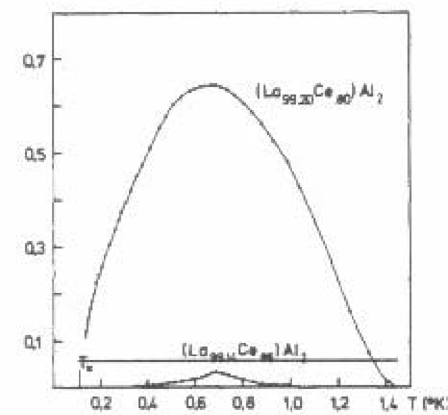


Solid State Communications, Vol. 9, 1663–1665, 1971. Pergamon Press Printed in Great Britain

VANISHING OF SUPERCONDUCTIVITY BELOW A SECOND TRANSITION TEMPERATURE IN $(La_{1-x}Ce_x)\,Al_2$ ALLOYS DUE TO THE KONDO EFFECT

G. Riblet and K. Winzer
II. Physikalisches Institut der Universität zu Köln

(*Received* 24 *July* 1971 *by B. Mühlschlegel*)

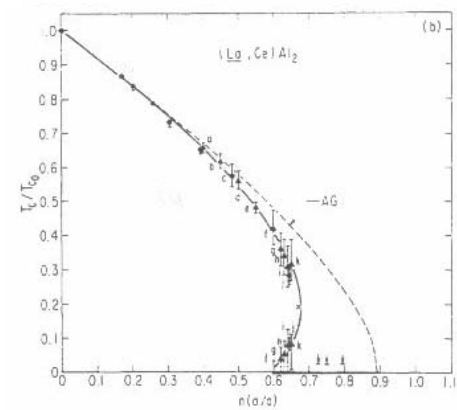


Solid State Communications, Vol. 11, pp. 829–834, 1972. Pergamon Press. Printed in Great Britain

THE RE-ENTRANT SUPERCONDUCTING–NORMAL PHASE BOUNDARY OF THE KONDO SYSTEM $(La,Ce)Al_2$*

M.B. Maple, W.A. Fertig, A.C. Mota, L.E. DeLong, D. Wohlleben and R. Fitzgerald
Institute for Pure and Applied Physical Sciences, University of California, San Diego, La Jolla, California 92037

(*Received* 5 *July* 1972 *by A.A. Maradudin*)



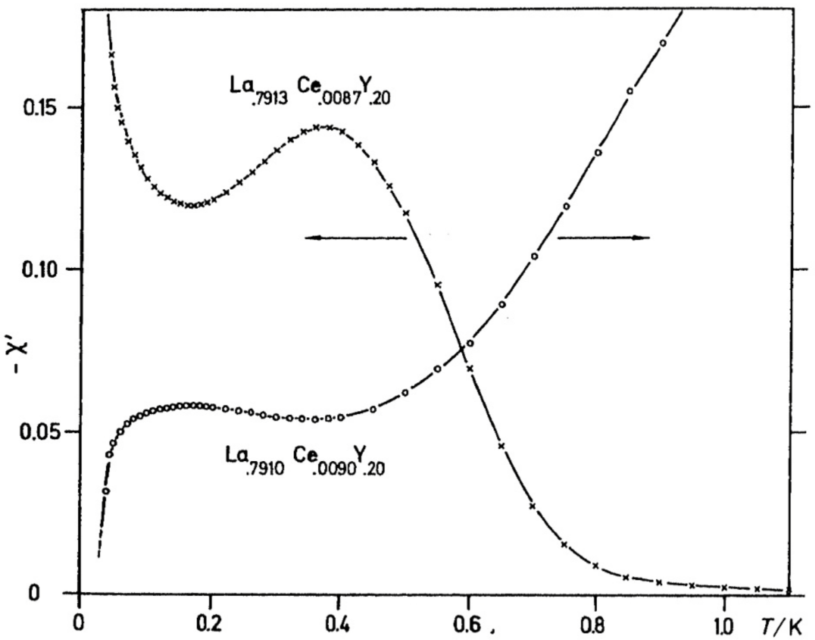
Solid State Communications, Vol. 24, pp. 551–556, 1977. Pergamon Press. Printed in Great Britain

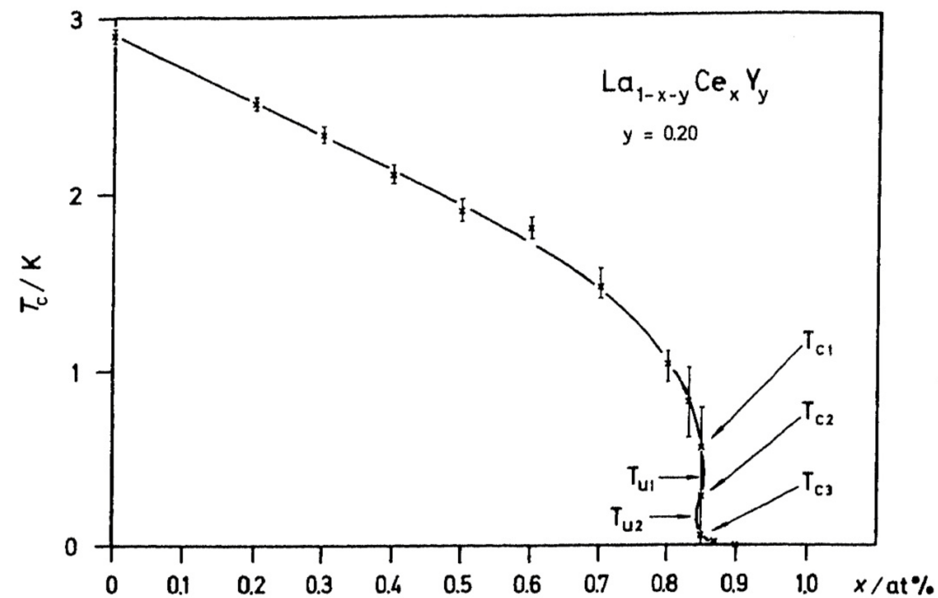
EVIDENCE FOR A THREE T_c BEHAVIOR OF THE KONDO SUPERCONDUCTOR (La, Y)Ce

K. Winzer

I. Physikalisches Institut der Universität Göttingen, Germany

(*Received* 30 *June* 1977 *by B. Mühlschlegel*)





outline:

Kondo effect

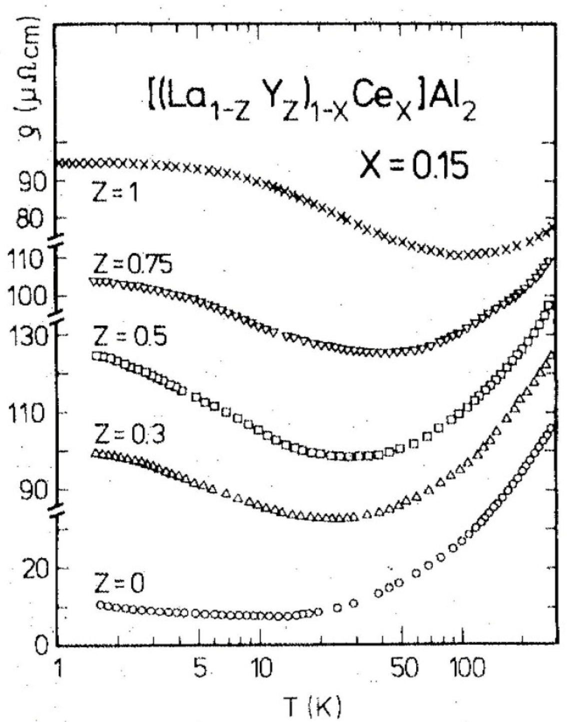
Superconductivity vs. magnetism

Heavy fermions

Heavy-fermion superconductors

Volume dependence of Kondo effect, cf.$[(La_{1-z}Y_z)_{1-x}Ce_x]Al_2$

F.S. et al., Physica **86-88B**, 503 (1977).

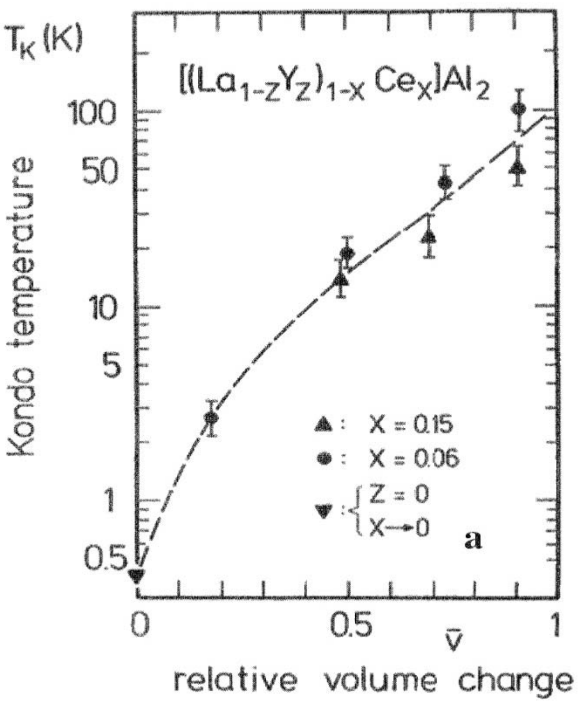


$T << T_K$: $\Delta\rho = \rho_0\,(1-AT^2)$

$A = \pi^2/(4\,T_K^2)$

(M. Larsen '75)

F.S., Adv. Solid State Phys. (1977), Vol. XVII, p.319.



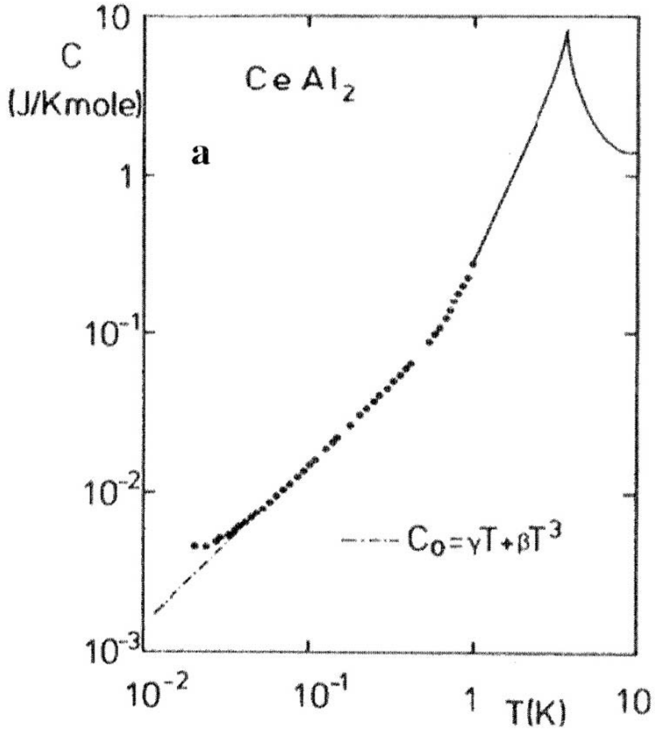
$\bar{v} = (\bar{V} - V_{LaAl_2})/(V_{YAl_2} - V_{LaAl_2})$

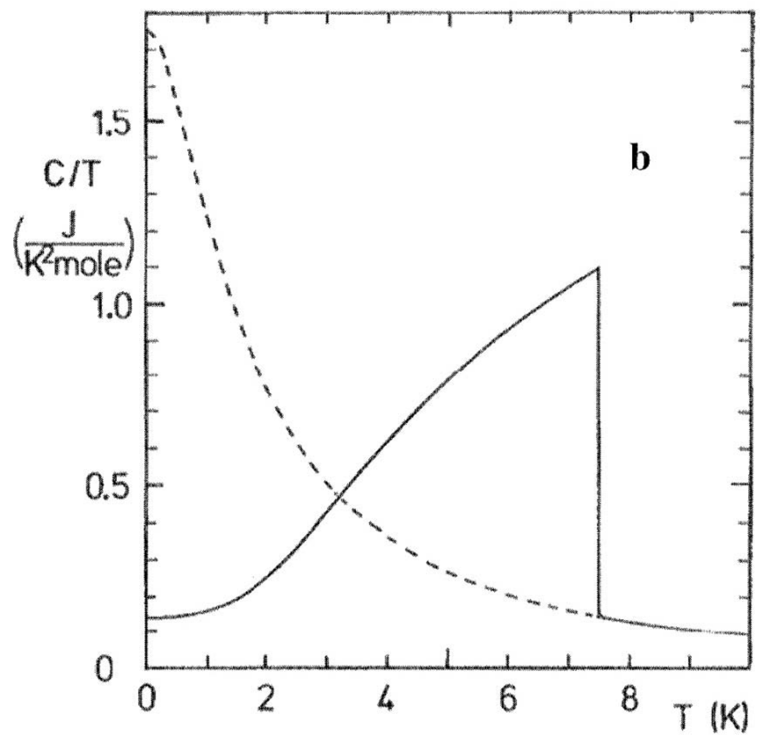
T_K increases by a factor of 250

$CeAl_2$ (x = 1): $\bar{v} \approx 0.3$

$\Rightarrow$ $T_K \approx 5$ K

Specific heat of $CeAl_2$





$\gamma = 0.135$ J/K^{2}mole

F. S. et al.,
J. Phys. (Paris) **40**, C5-301 (1979).

C.D. Bredl et al.,
Z. Phys. B **29**, 327 (1978).

4f-Virtual-Bound-State Formation in $CeAl_3$ at Low Temperatures

K. Andres and J. E. Graebner
Bell Laboratories, Murray Hill, New Jersey 07974

and

H. R. Ott
Laboratorium für Festkörperphysik, Eidgenössische Technische Hochschule, Hönggerberg, Zürich, Switzerland
(Received 25 August 1975)

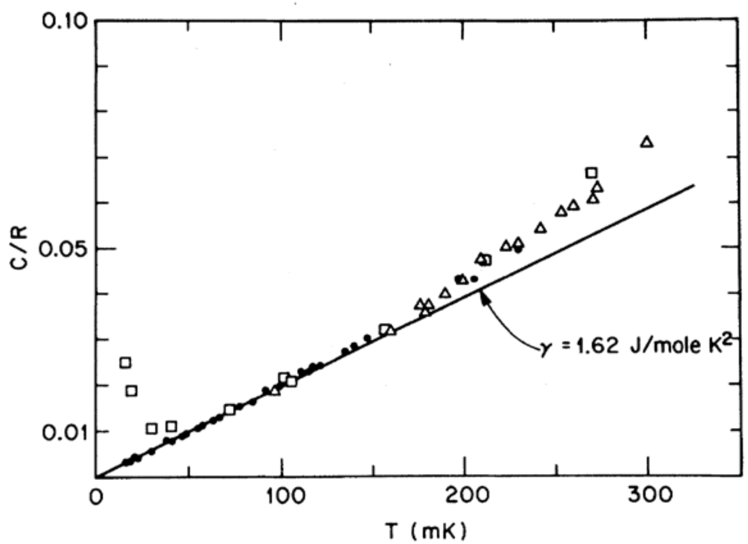


FIG. 1. Specific heat of $CeAl_3$ at very low temperatures in zero field (●, Δ) and in 10 kOe (□).

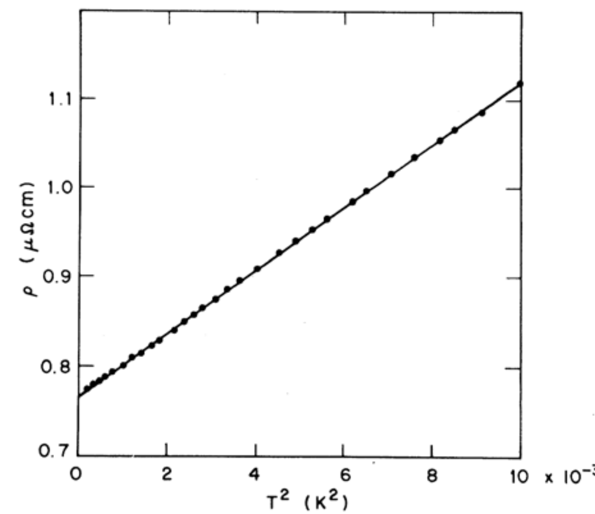


FIG. 3. Electrical resistivity of $CeAl_3$ below 100 mK, plotted against T^2.

$\gamma = 1.62$ J/K^{2}mole

$A = 35\ \mu\Omega\text{cm/K}^2$

Superconductivity in $CeCu_2Si_2$

VOLUME 43, NUMBER 25 PHYSICAL REVIEW LETTERS 17 DECEMBER 1979

Superconductivity in the Presence of Strong Pauli Paramagnetism: $CeCu_2Si_2$

F. Steglich
Institut für Festkörperphysik, Technische Hochschule Darmstadt, D-6100 Darmstadt, West Germany

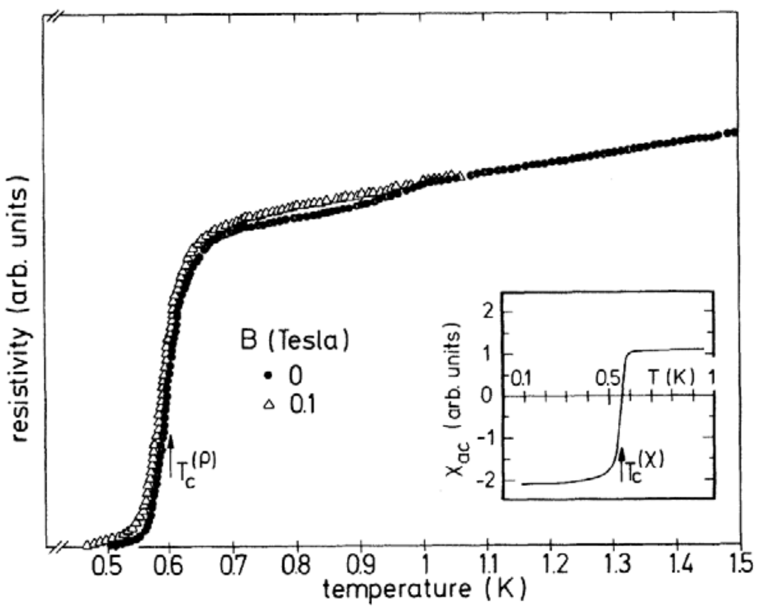
and

J. Aarts, C. D. Bredl, W. Lieke, D. Meschede, and W. Franz
II. Physikalisches Institut, Universität zu Köln, D-5000 Köln 41, West Germany

and

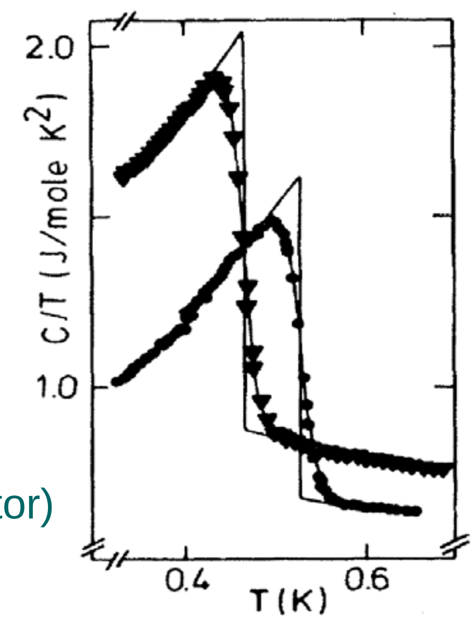
H. Schäfer
Eduard-Zintl-Institut, Technische Hochschule Darmstadt, D-6100 Darmstadt, West Germany

(Received 10 August 1979; revised manuscript received 7 November 1979)



100 at% Ce^{3+} ions **necessary** for superconductivity

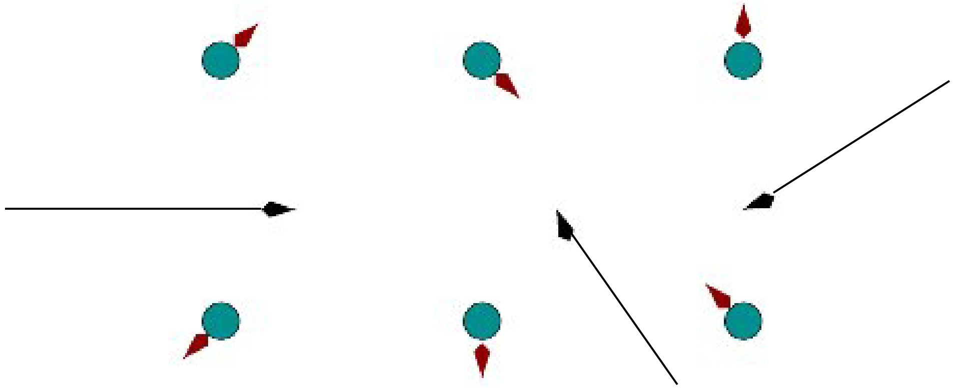
($LaCu_2Si_2$ is not a superconductor)



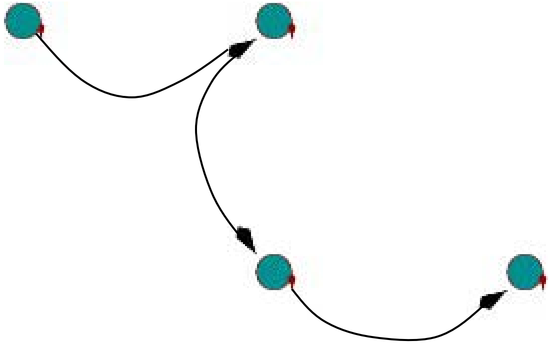
Heavy-Fermion metals

$T >> T_K$ (10 ... 100 K)

$v_F \approx 10^6 \frac{m}{s}$



$T << T_K$: Heavy electrons ("composite fermions")



$v_F^* \approx 10^3 \frac{m}{s}$

→ $m^* \approx 1000\, m_{el}$: "strongly correlated electron system"

Groundstate properties

- Heavy Landau Fermi liquid (LFL) : $CeCu_6$
- Non-Fermi liquid (NFL) : $YbRh_2Si_2$
- Magnetic order : $NpBe_{13}$
- Superconductivity : UPd_2Al_3

outline:

Kondo effect

Superconductivity vs. magnetism

Heavy fermions

Heavy-fermion superconductors

Superconductivity in $CeCu_2Si_2$

VOLUME 43, NUMBER 25 PHYSICAL REVIEW LETTERS 17 DECEMBER 1979

Superconductivity in the Presence of Strong Pauli Paramagnetism: $CeCu_2Si_2$

F. Steglich
Institut für Festkörperphysik, Technische Hochschule Darmstadt, D-6100 Darmstadt, West Germany

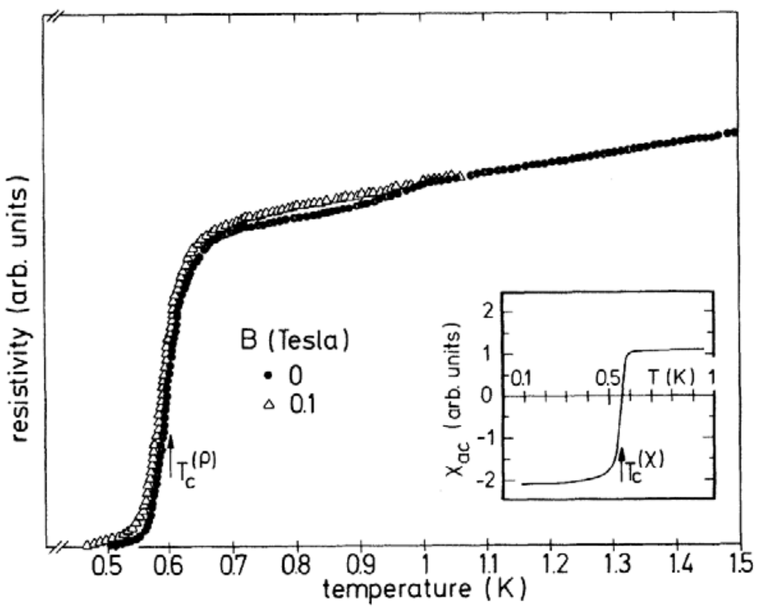
and

J. Aarts, C. D. Bredl, W. Lieke, D. Meschede, and W. Franz
II. Physikalisches Institut, Universität zu Köln, D-5000 Köln 41, West Germany

and

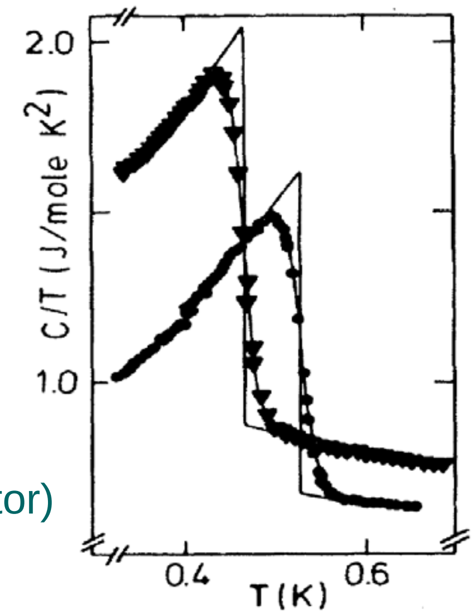
H. Schäfer
Eduard-Zintl-Institut, Technische Hochschule Darmstadt, D-6100 Darmstadt, West Germany

(Received 10 August 1979; revised manuscript received 7 November 1979)



100 at% Ce^{3+} ions **necessary** for superconductivity

($LaCu_2Si_2$ is not a superconductor)



Heavy-fermion superconductivity in $CeCu_2Si_2$

VOLUME 52, NUMBER 6 PHYSICAL REVIEW LETTERS 6 FEBRUARY 1984

Superconductivity in $CeCu_2Si_2$ Single Crystals

W. Assmus and M. Herrmann
Physikalisches Institut, Universität Frankfurt, D-6000 Frankfurt am Main, West Germany

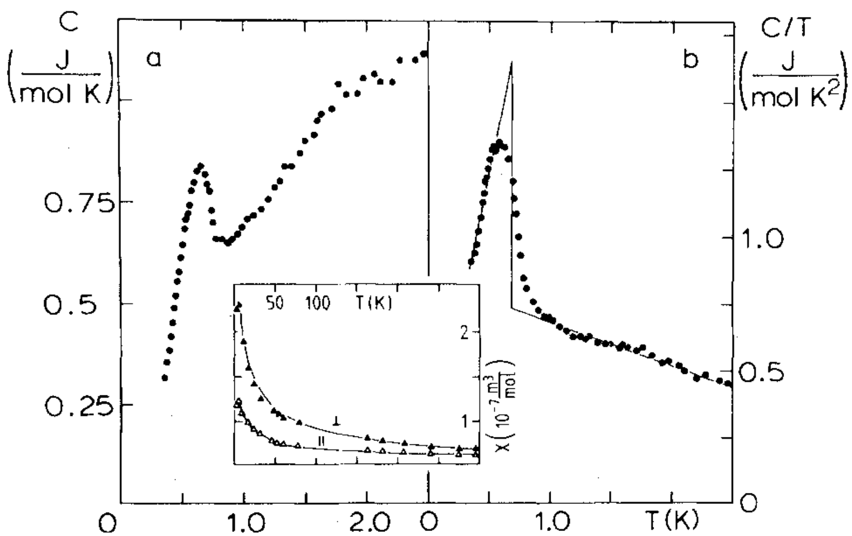
and

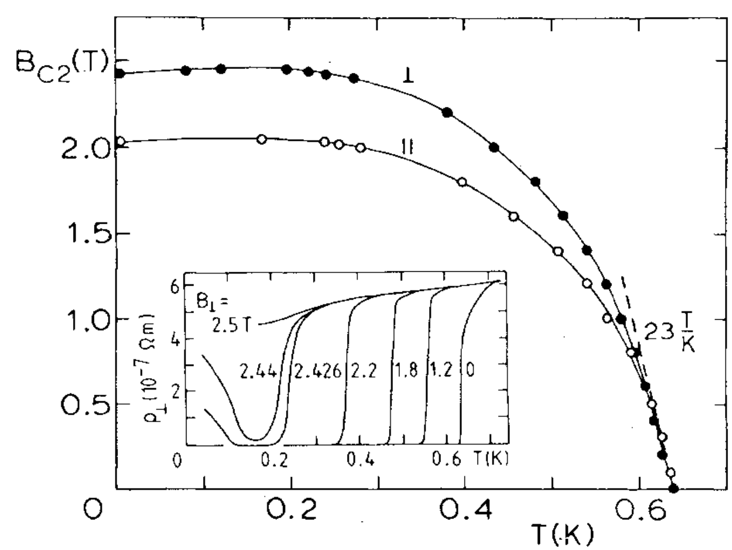
U. Rauchschwalbe, S. Riegel, W. Lieke, H. Spille, S. Horn, G. Weber, and F. Steglich
Institut für Festkörperphysik, Technische Hochschule Darmstadt, D-6100 Darmstadt, West Germany

and

G. Cordier
E. Zintl Institut, Technische Hochschule Darmstadt, D-6100 Darmstadt, West Germany

(Received 19 August 1983)





Heavy-fermion superconductivity in UBe_{13}

VOLUME 50, NUMBER 20 PHYSICAL REVIEW LETTERS 16 MAY 1983

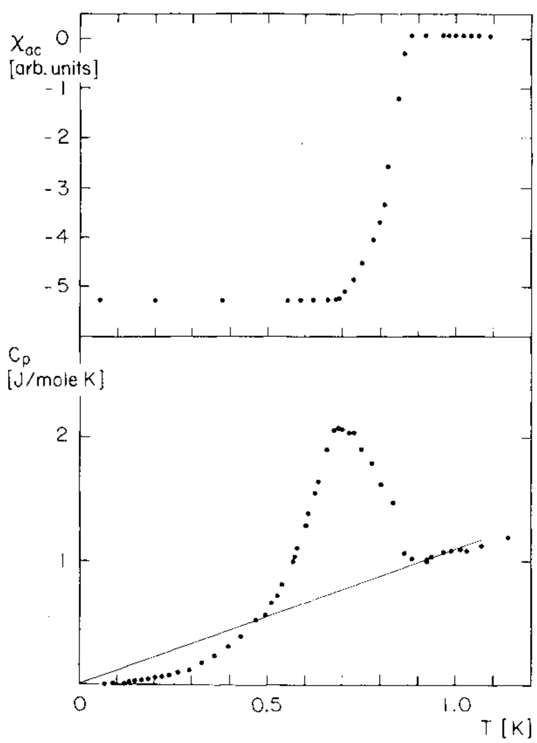
UBe_{13}: An Unconventional Actinide Superconductor

H. R. Ott and H. Rudigier
Laboratorium für Festkörperphysik, Eidgenössische Technische Hochschule–Hönggerberg, CH-8093 Zürich, Switzerland

and

Z. Fisk and J. L. Smith
Los Alamos National Laboratory, Los Alamos, New Mexico 87545

(Received 14 March 1983)



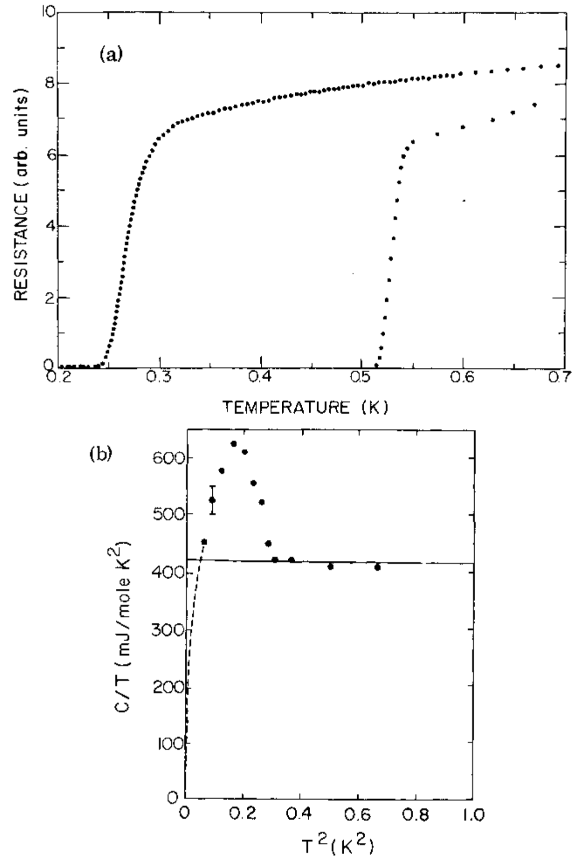
Heavy-fermion superconductivity in UPt_3

VOLUME 52, NUMBER 8 PHYSICAL REVIEW LETTERS 20 FEBRUARY 1984

Possibility of Coexistence of Bulk Superconductivity and Spin Fluctuations in UPt_3

G. R. Stewart, Z. Fisk, J. O. Willis, and J. L. Smith
Los Alamos National Laboratory, Los Alamos, New Mexico 87545

(Received 24 October 1983)



Heavy-fermion superconductivity in URu_2Si_2

[W. Schlabitz et al., Poster ICVF, Cologne 1984 (unpublished)]

Z. Phys. B – Condensed Matter 62, 171–177 (1986)

Condensed Matter
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Superconductivity and Magnetic Order in a Strongly Interacting Fermi-System: URu_2Si_2

W. Schlabitz, J. Baumann, and B. Pollit
II. Physikalisches Institut, Universität zu Köln, Federal Republic of Germany

U. Rauchschwalbe, H.M. Mayer, U. Ahlheim, and C.D. Bredl
Institut für Festkörperphysik, Technische Hochschule Darmsta
Federal Republic of Germany

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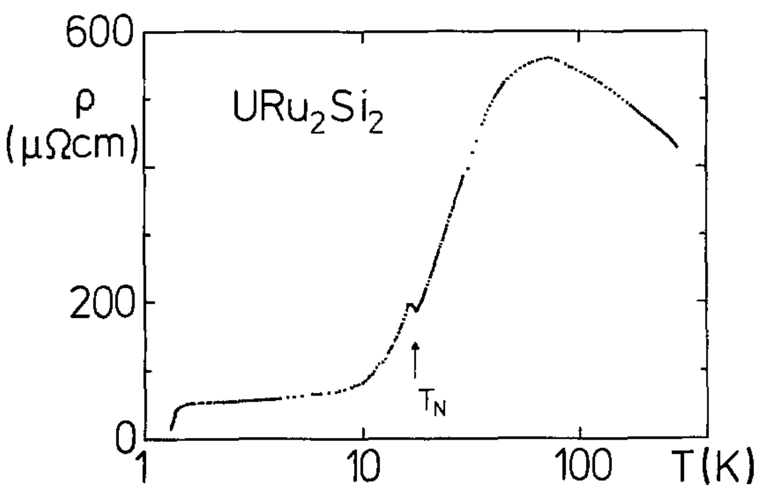
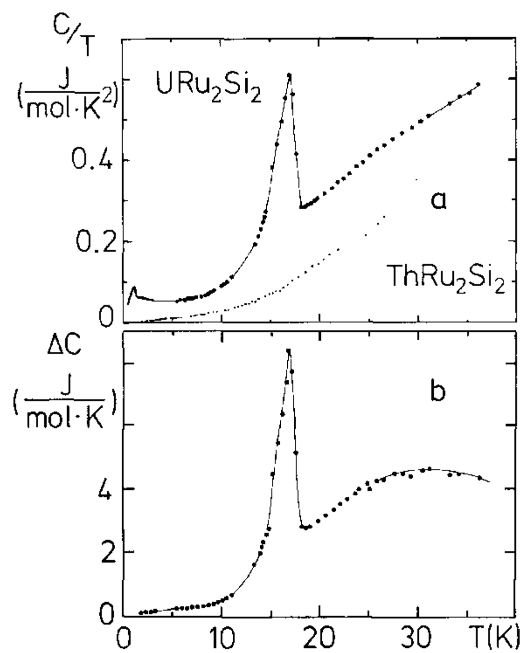
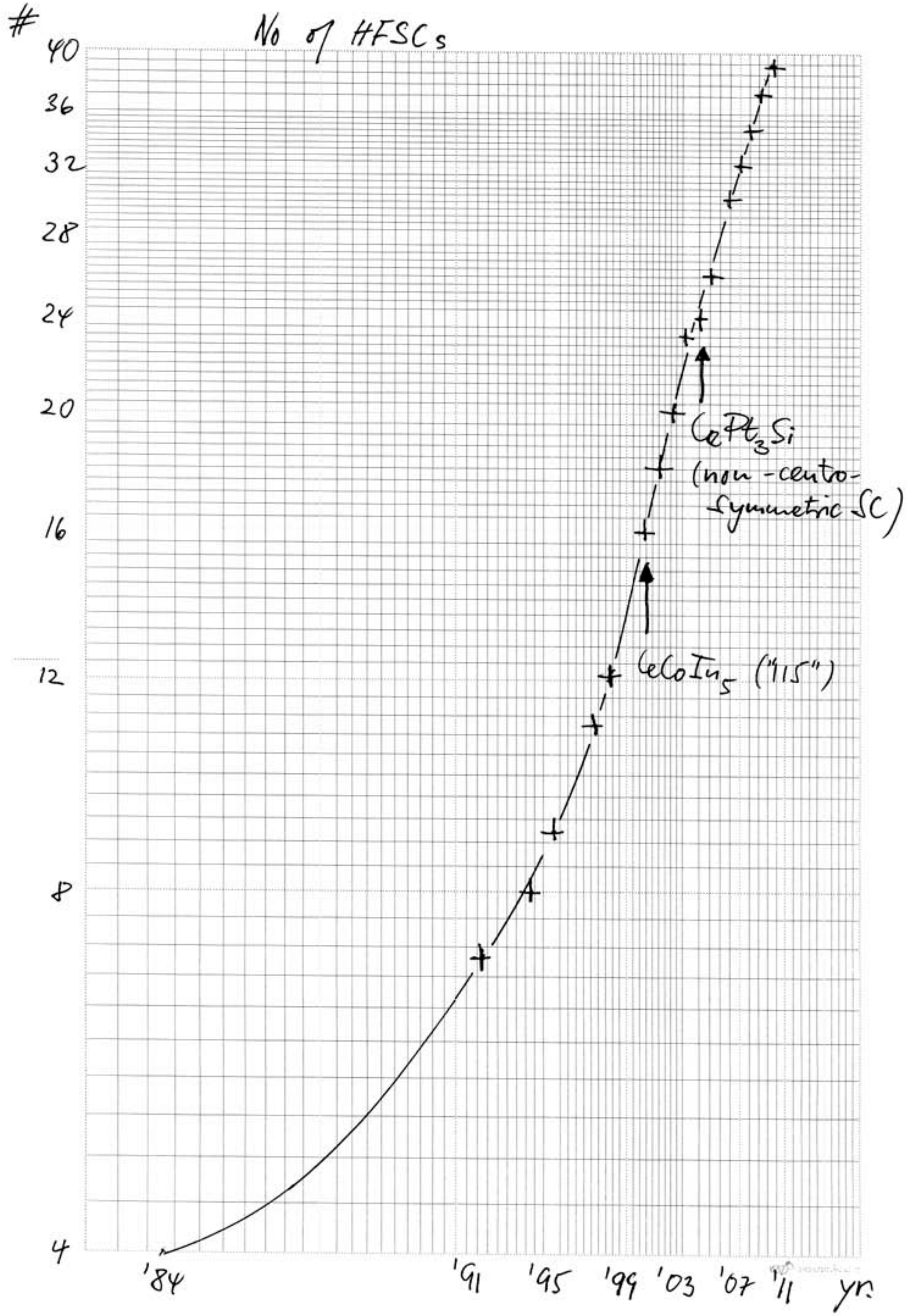




cf. also, T.T.M. Palstra et al., PRL **55**, 2727 (1985)
M.B. Maple et al., PRL **56**, 185 (1986).



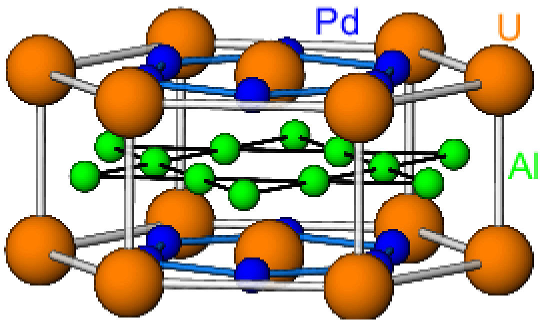
#
No of HFSCs
40
36
32
28
24
20
16
12
8
4
CePt3Si
(non-centro-
symmetric SC)
CeCoIn5 ("115")
'84
'91
'95
'99
'03
'07
'11
yr.

Heavy-fermion superconductors

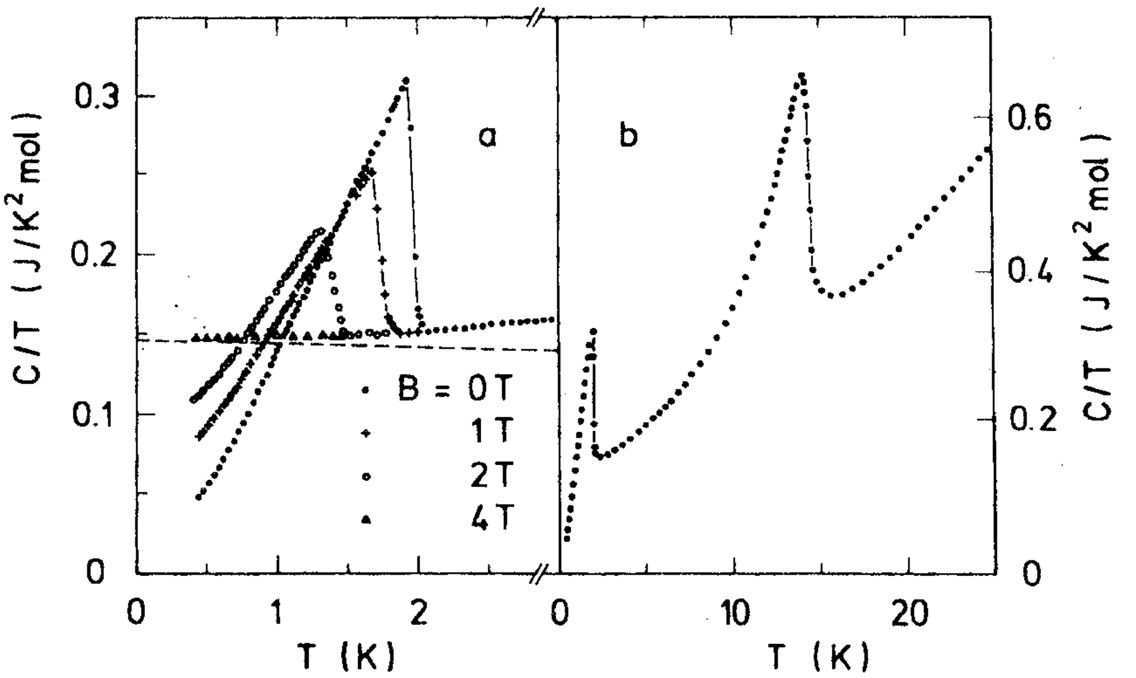
	T_c(K)	
$CeCu_2Si_2$	0.6	('79 DA/K)
[p = 2.9 GPa:	2.3	('84 GE/GR)]
$CeNi_2Ge_2$	0.2	('97 DA, '98 CA/GR)
$CeIrIn_5$	0.4	('00 LANL)
$CeCoIn_5$	2.3	('00 LANL)
Ce_2CoIn_8	0.4	('02 NA)
Ce_2PdIn_8	0.7	('09 WR)
$CePt_3Si$	0.7	('03 VI)
p > 0		
$CeCu_2Ge_2$	0.6	('92 GE)
$CePd_2Si_2$	0.4	('94 CA)
$CeRh_2Si_2$	0.4	('95 LANL)
$CeCu_2$	0.15	('97 GE/KA)
$CeIn_3$	0.2	('98 CA)
$CeRhIn_5$	2.1	('00 LANL)
Ce_2RhIn_8	1.1	('03 LANL)
$CeRhSi_3$	0.8	('05 SE)
$CeIrSi_3$	1.6	('06 OS)
$CeCoGe_3$	0.7	('06 OS)
$Ce_2Ni_3Ge_5$	0.26	('06 OS)
$CeNiGe_3$	0.4	('06 OS)
$CePd_5Al_2$	0,57	('08 OS)
$CeRhGe_2$	0.45	('09 OS)
$CePt_2In_7$	2.1	('10 LANL)
$CeIrGe_3$	1.5	('10 OS)

	T_c(K)	
$PrOs_4Sb_{12}$	1.85	('01 UCSD)
β-$YbAlB_4$	0.08	('08 TO/IR)
p > 0		
Eu metal	1.8-2.8	('09 SL, OS)
UBe_{13}	0.9	('83 Z/LANL)
UPt_3	0.5	('84 LANL)
URu_2Si_2	1.4	('84 K/DA)
UNi_2Al_3	1.2	('91 DA)
UPd_2Al_3	2.0	('91 DA)
URhGe	0.3	('01 GR)
UCoGe	3.0	('07 AM/KA)
p > 0		
UGe_2	0.7	('00 CA/GR)
UIr	0.14	('04 OS)
$NpPd_5Al_2$	5.0	('07 OS)
$PuCoGa_5$	18.5	('02 LANL)
PuRhGa5	8.7	('03 KA)
p > 0		
Am metal	2.2	('05 KA)

Magnetic Cooper pairing in UPd_2Al_3



C. Geibel et. al., 1991



T_{magn}	$\approx$	14 K
μ_s	$\approx$	0.85 μ_B
γ	$\approx$	140 mJ/K^{2}mol
T_c	$\approx$	2 K
$2\Delta_0/k_BT_c$	$\approx$	6 (Kyougaku et al., 1993)

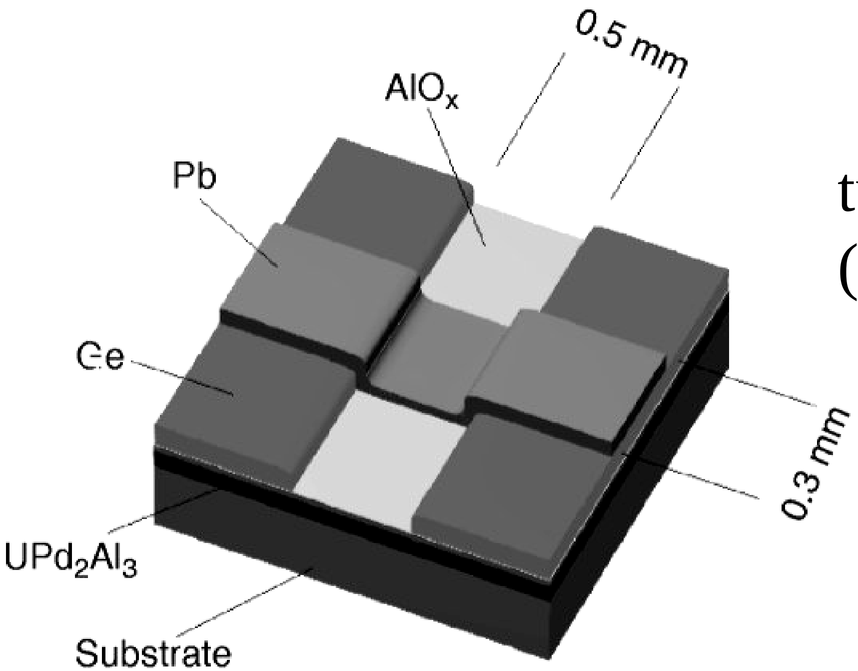
U^{3+} ($5f^3$)

- **Two more localized ("core") electrons:** magnetism
- **one less localized ("heavy" itinerant) electron:**
  - heavy LFL state ($T_c < T < T_N$)
  - heavy-fermion SC ($T < T_c$)

  coexisting with local AF

Quasiparticle tunneling

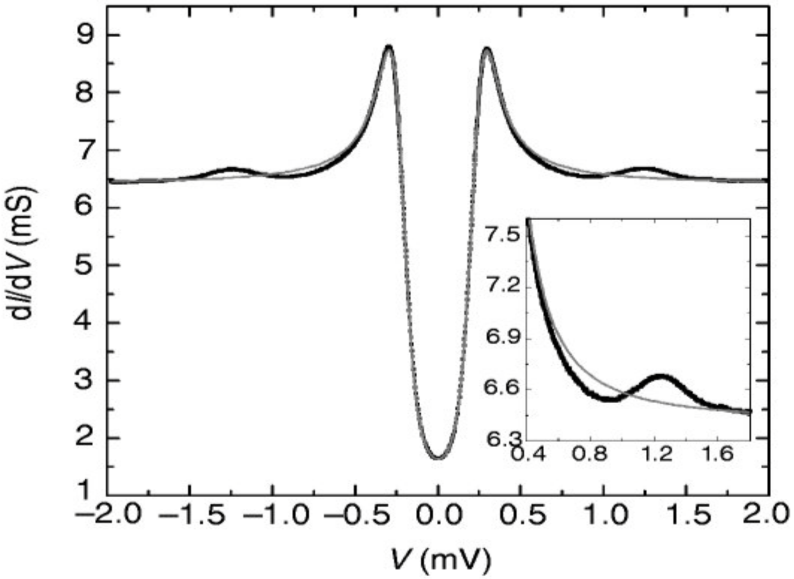
[M. Jourdan et. al., Nature **398,** 47 (1999)]



tunnel diode UPd$_2$Al$_3$ - AlO$_x$ - Pb
(Pb normal conducting : B = 0.3 T)

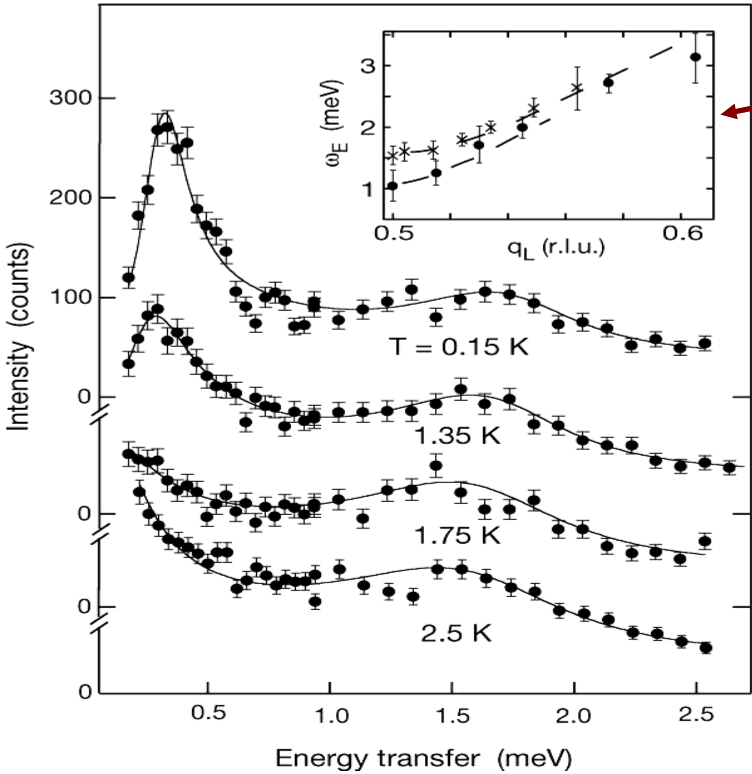
dI/dV

(T = 0.15 K)



Inelastic neutron scattering

[N.K. Sato et al., Nature **410**, 340 (2001)]



acoustic magnon

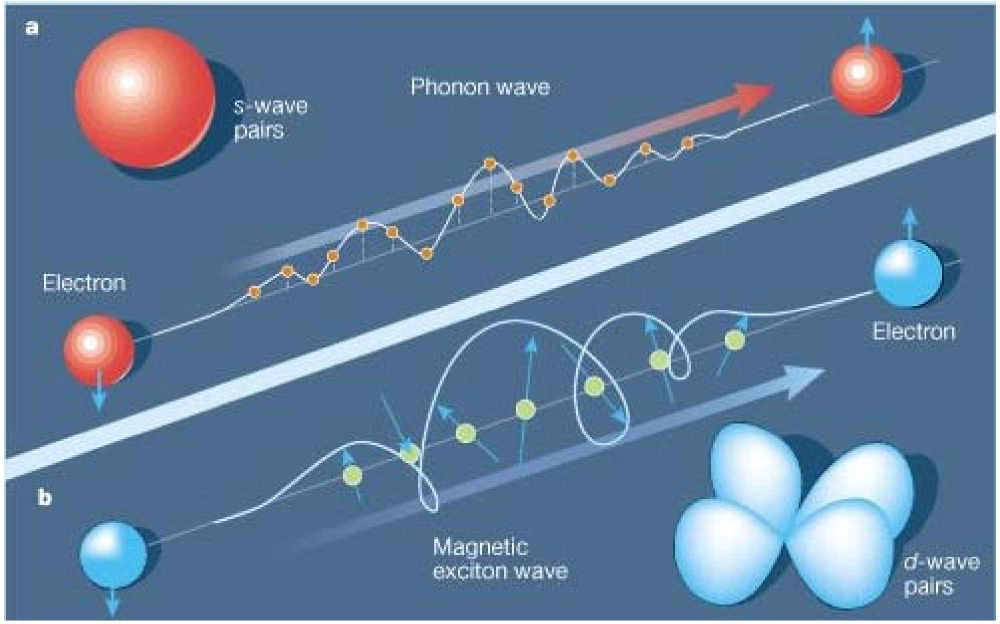
("magnetic exciton")

$$\vec{Q} = \vec{Q_0} = (0, 0, 1/2)$$

$T_c = 1.8$ K

Cooper pairs formed by heavy electrons ("itinerant" 5f electrons)

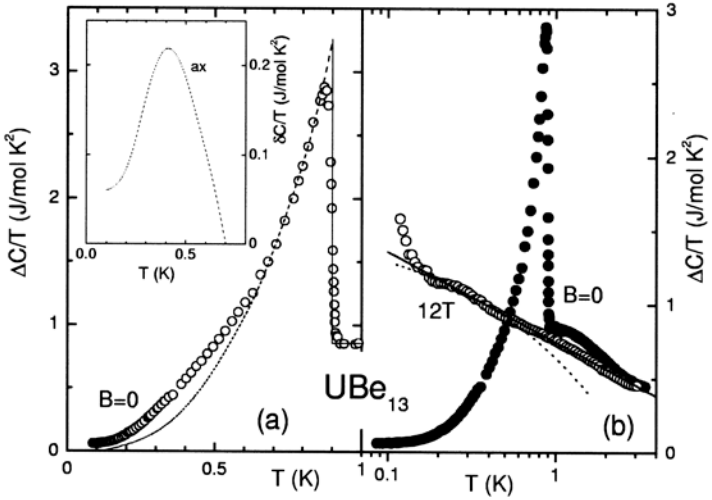
superconducting glue provided by magnetic excitons in the system of "localized" 5f electrons



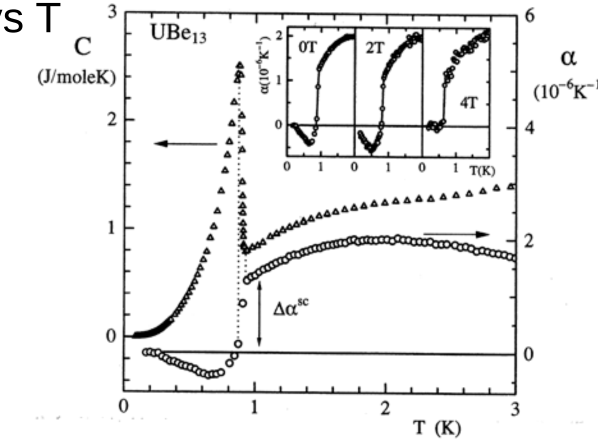
Non-Fermi-liquid superconductor UBe_{13}

[F. Kromer et al., PRL **81**, 4476 (1998); N. Oeschler et al., Acta Phys. Pol. **34**, 255 (2003)]

$\frac{\Delta C}{T}$ vs T

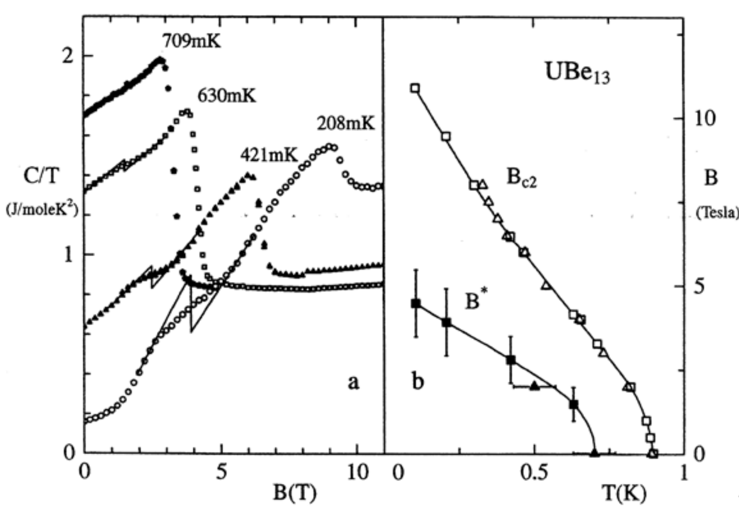


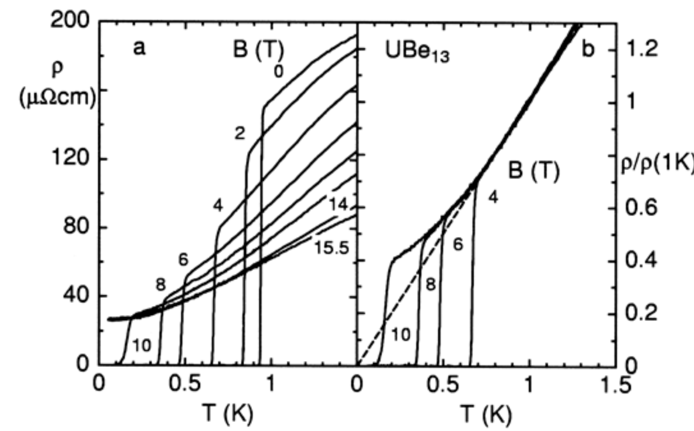
C vs T



α vs T

(α = l^{-1} δl/δT)





P. Gegenwart et al. (2004)

$T_L \rightarrow 0$ at B* ≈ 4.2 T: QCP (3D-SDW)

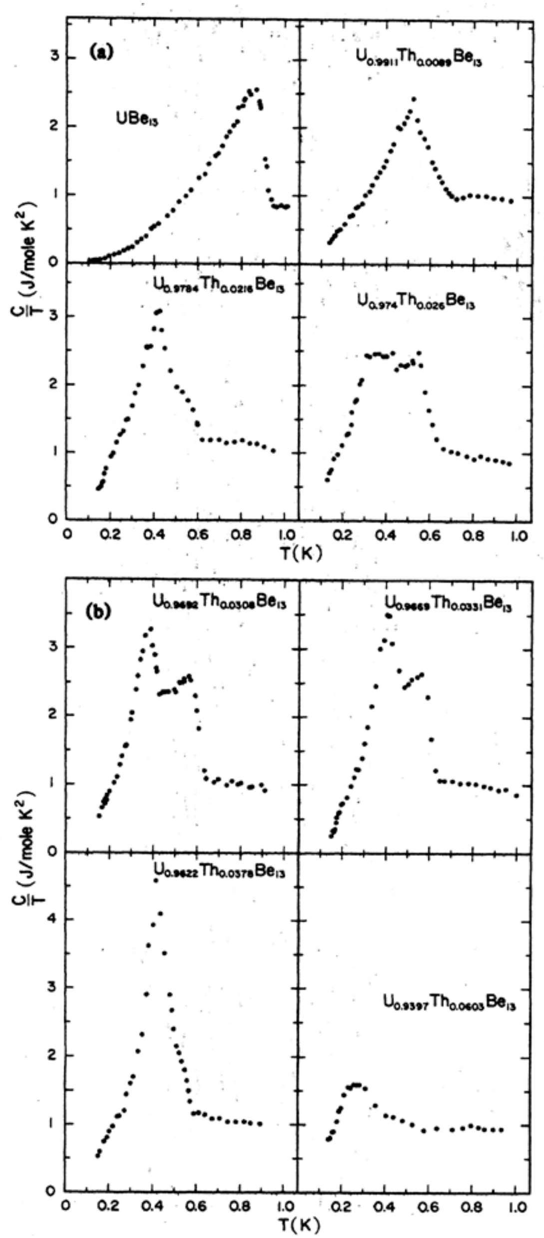
4T ≤ B ≤ 10 T : ρ/ρ(1K) vs T universal

T → 0 : $\Delta\rho \sim T^{1.5}$

$\Delta C/T = \gamma_0 - \beta T^{0.5}$ (B = 12 T)

Double transition in $(U_{1-x}Th_x)Be_{13}$ 0.019 < x < 0.046

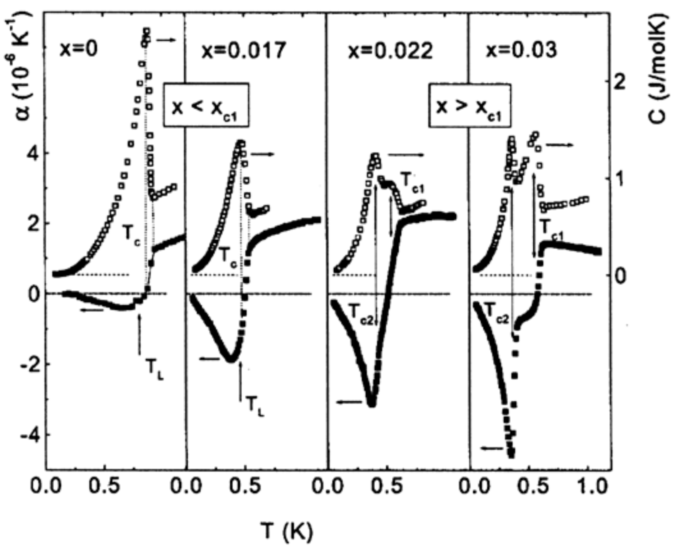
[H.R. Ott et al., Phys. Rev. B **31**, 1651 (1985)]

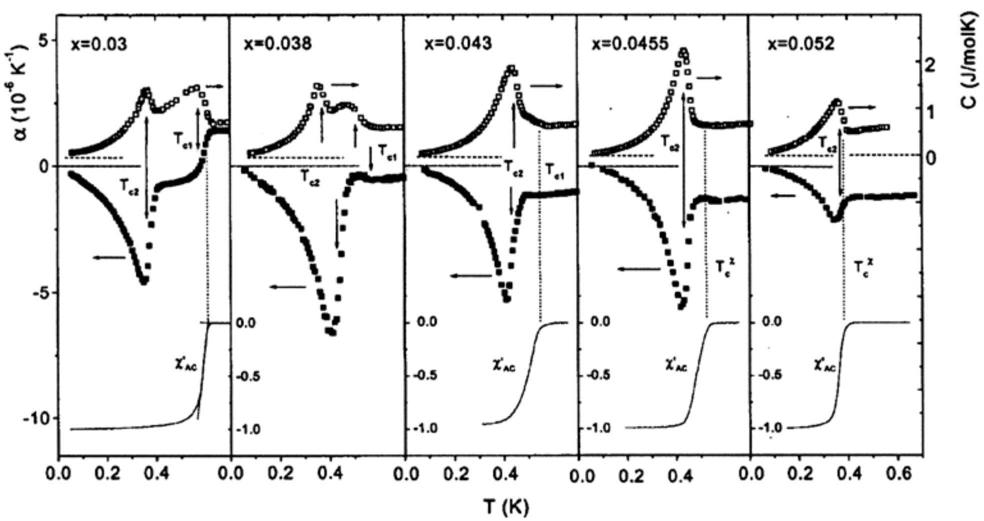


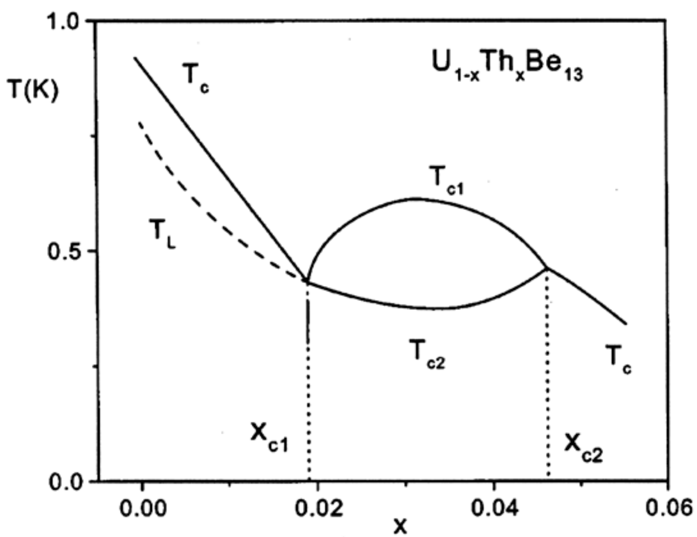
Phase diagram of $U_{1-x}Th_xBe_{13}$

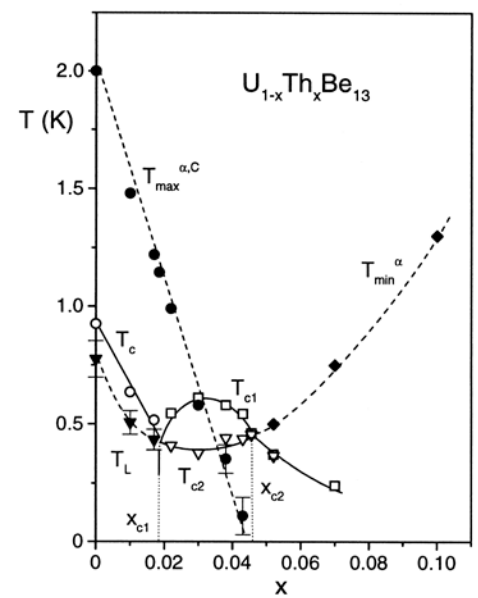
[F. Kromer et al., PRB **62**, 12477 (2000); JLTP **126**, 815 (2002)]

α vs T









Kondo problem to heavy fermions and local quantum criticality (Experiment II):

Interplay of incipient magnetism and superconductivity in heavy-fermion metals