UNITED NATIONS EDUCATIONAL, SCIENTIFIC AND CULTURAL ORGANIZATION
INTERNATIONAL ATOMIC ENERGY AGENCY
INTERNATIONAL CENTRE FOR THEORETICAL PHYSICS
I.C.T.P., P.O. BOX 586, 34100 TRIESTE, ITALY, CABLE: CENTRATOM TRIESTE

SMR.959 - 41

MINIWORKSHOP ON STRONG ELECTRON CORRELATIONS
"Disorder and Interaction in Quantum Systems and Their Classical Analogs"

(1 - 19 July 1996)

"Non-Fermi-liquid behaviour in correlated electron systems"

Hilbert v. Löhneysen
Universität Karlsruhe
Physikalisches Institut
76128 Karlsruhe
Germany

These are preliminary lecture notes, intended only for distribution to participants.

MAIN BUILDING STRADA COSTIERA, 11 TEL. 2240111 TELEFAX 224163 TELEX 460392 ADRIATICO GUEST HOUSE VIA GRIGNANO, 9 TEL. 224241 TELEFAX 224531 TELEX 460449
MICROPROCESSOR LAB VIA BEIRUT, 31 TEL. 2249911 TELEFAX 224600 TELEX 460392 GALILEO GUEST HOUSE VIA BEIRUT, 7 TEL. 2240311 TELEFAX 2240310 TELEX 460392

Non-Fermi-liquid behavior in correlated electron systems

H. v. Löhneysen

Introduction:

- heavy fermions and Kondo effect

Non-Fermi liquid at a magnetic instability:

- $CeCu_{6-x}Au_x$: $T_N(x) \geq 0$ for $x \geq x_c$
- pressure tuning
- effect of magnetic field

Non-Fermi liquid arising from single-ion effects

- two-channel Kondo effect
- distribution of T_K at metal-insul. transition

Summary and outlook

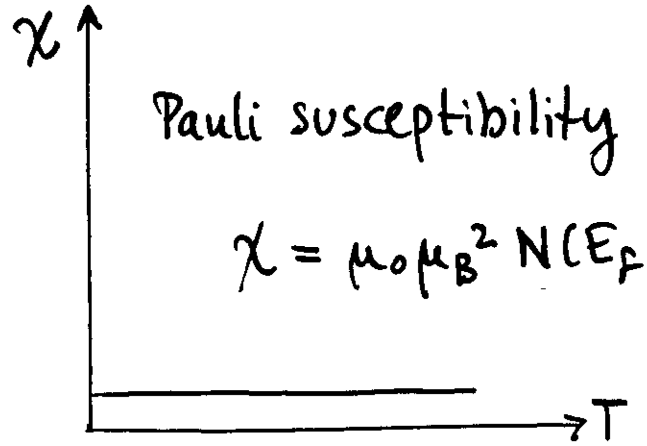
Benedict Bogenberger
Steffen Mock
Thomas Pietrus
Günther Portisch
Hans-Georg Schlager
Almut Schröder
Michael Sieck
Oliver Stockert
Thomas Trappmann
Matthias Waffenschmidt

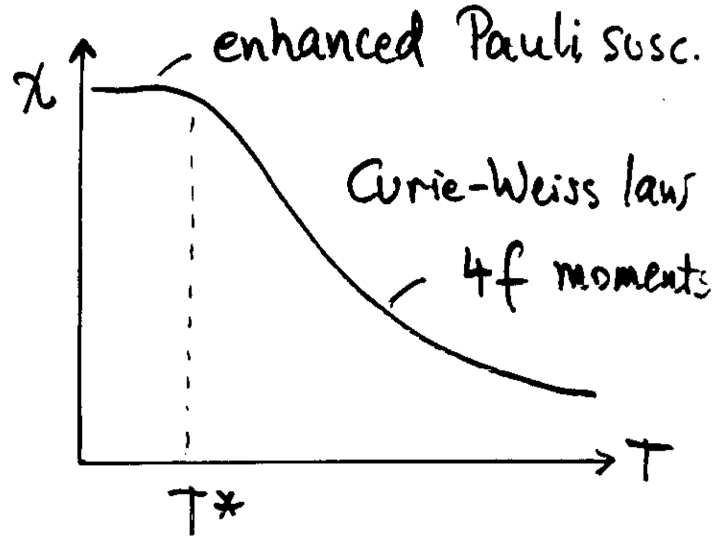
Frank Huster
Anja Neubert

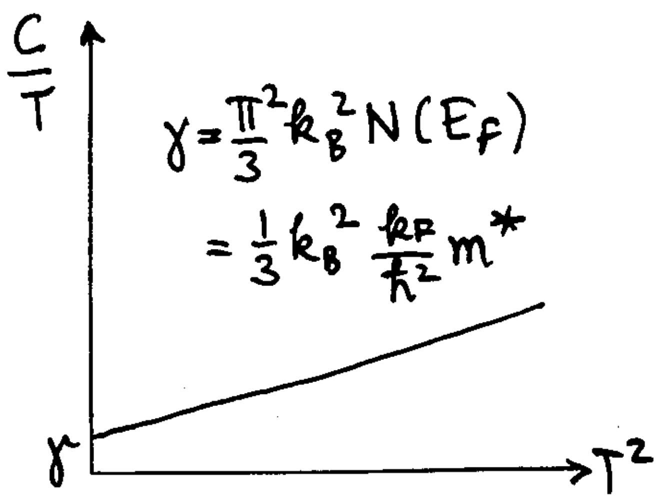
M. Loewenhaupt, J. Lynn, N. Pyka
B. Lüthi, F. Bruls, ...

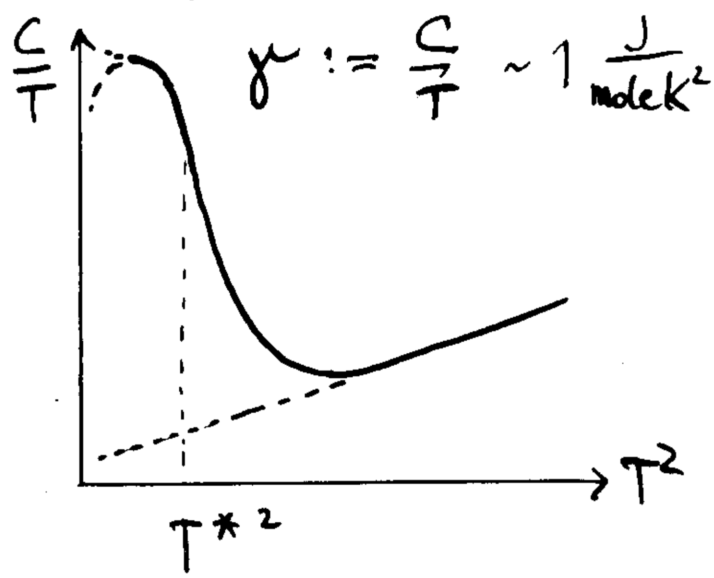
Introduction to heavy-fermion metals

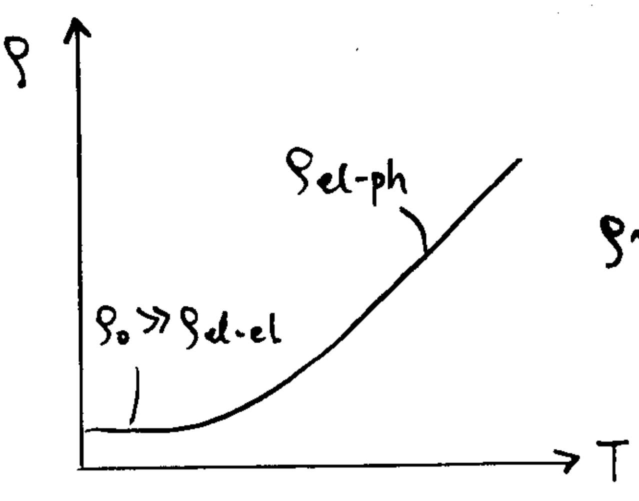
Normal metal | **heavy-fermion metal**

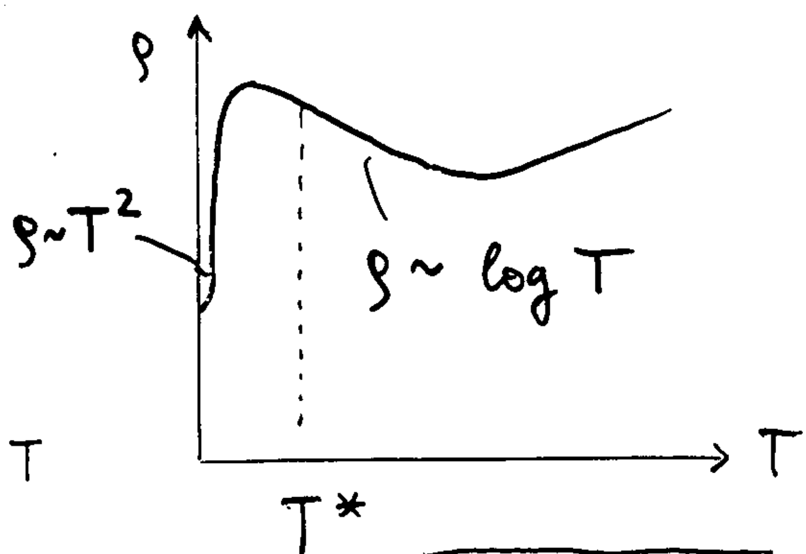








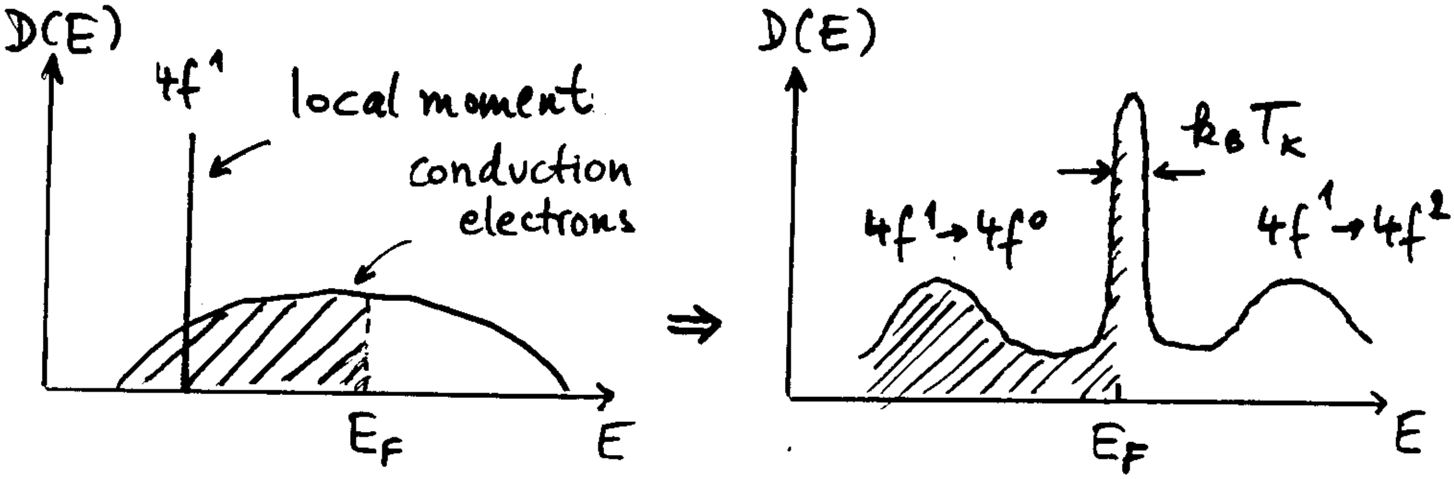




$m^* \approx m_0$

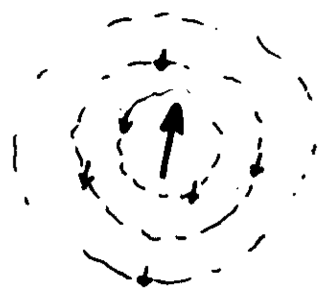
$m^* \approx 100\, m_0$

Kondo effect

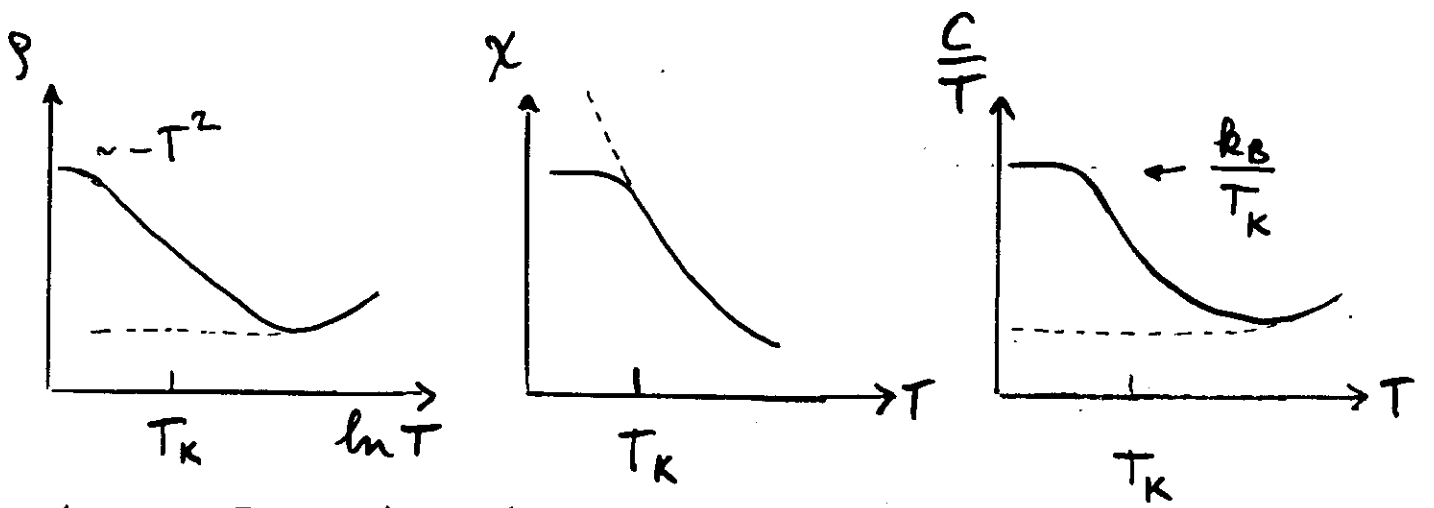


Hybridization between 4f and conduction electrons
+ 4f on-site correlations
⇓
"Resonance" near E_F builds up at low T

Screening of 4f moment
by conduction electrons



Kondo anomalies at low T:



local Fermi liquid   Nozieres $T_K = 10K$: $\frac{C}{T} \sim 0.8 \frac{J}{mol\,K^2}$

Fermi liquid description of heavy-fermion metals

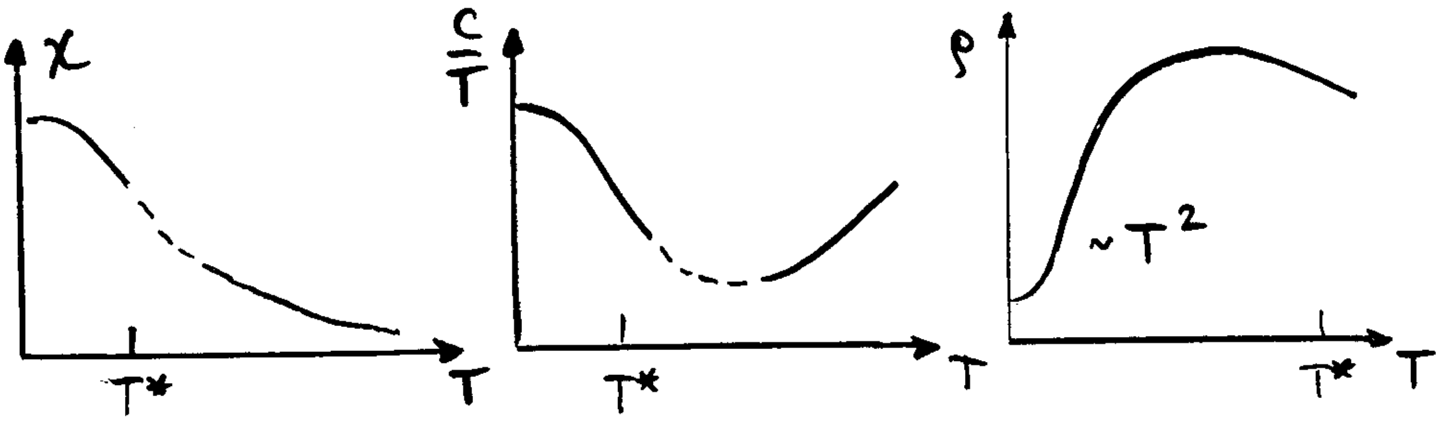
Fermi liquid (FL) for interacting fermions

- one-to-one correspondence between excitations of FL and noninteracting Fermi gas
- transport equation for QP

Heavy-fermion metals:

$T \gg T^* \approx T_K$: conduction electrons, local moments

$T \ll T^*$: strongly interacting quasiparticles



Fermi liquid (Landau)

$$\gamma = \frac{C}{T} \sim m^* \sim \frac{1}{T^*}$$

$$\chi \sim \frac{m^*}{1 + F_0^a}$$

$$\Delta\rho = AT^2 \sim \left(\frac{T}{T^*}\right)^2 \sim \gamma^2 T^2$$

Non-Fermi liquid at a magnetic instability

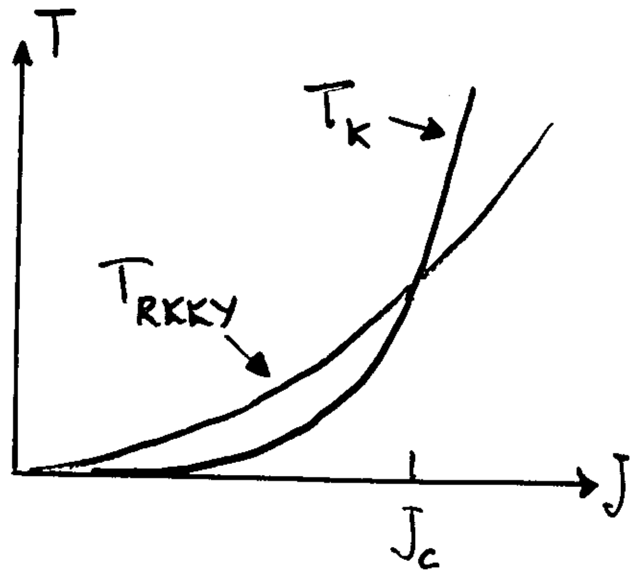
heavy-fermion systems

competition between nonmagnetic and magnetic groundstates

local singlet formation $T_K \sim \exp\left(-\frac{1}{N(E_F)J}\right)$

RKKY interaction $T_{RKKY} \sim J^2 N(E_F)$

Doniach



$0 \lesssim J \ll J_c$

local moments

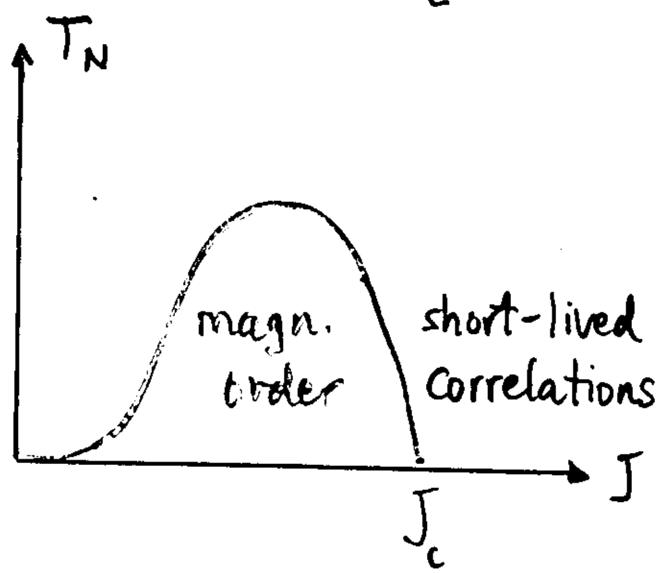
magnetic order

"small" Fermi volume

$J > J_c$

local singlets

"large" Fermi volume



what happens at J_c ?

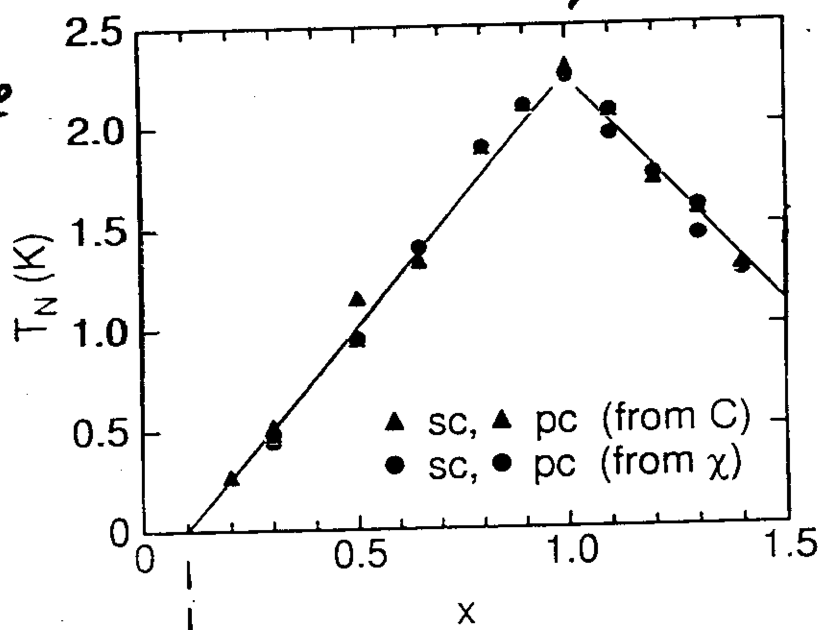
Magnetic instability in $CeCu_{6-x}Au_x$

$CeCu_6$: heavy fermions with $\gamma = 1.6\ J/mol\,K^2$
nonmagnetic groundstate Onuki, Amato,
short-lived short-range AF correlations
Aeppli, Rossat-Mignod

Alloying with Au: long-range AF order

$CeCu_{6-x}Au_x$
neg. lattice pressure explains $T_N(x)$ for $x < 1$

CeCu$_5$Au



Fermi liquid | magn. order | Fermi liquid + local moments
no magn. order

$T_K \approx 6K$ $x_c \approx 0.1$

magnetic instability $J = J_c$
phase transition at $T = 0$?

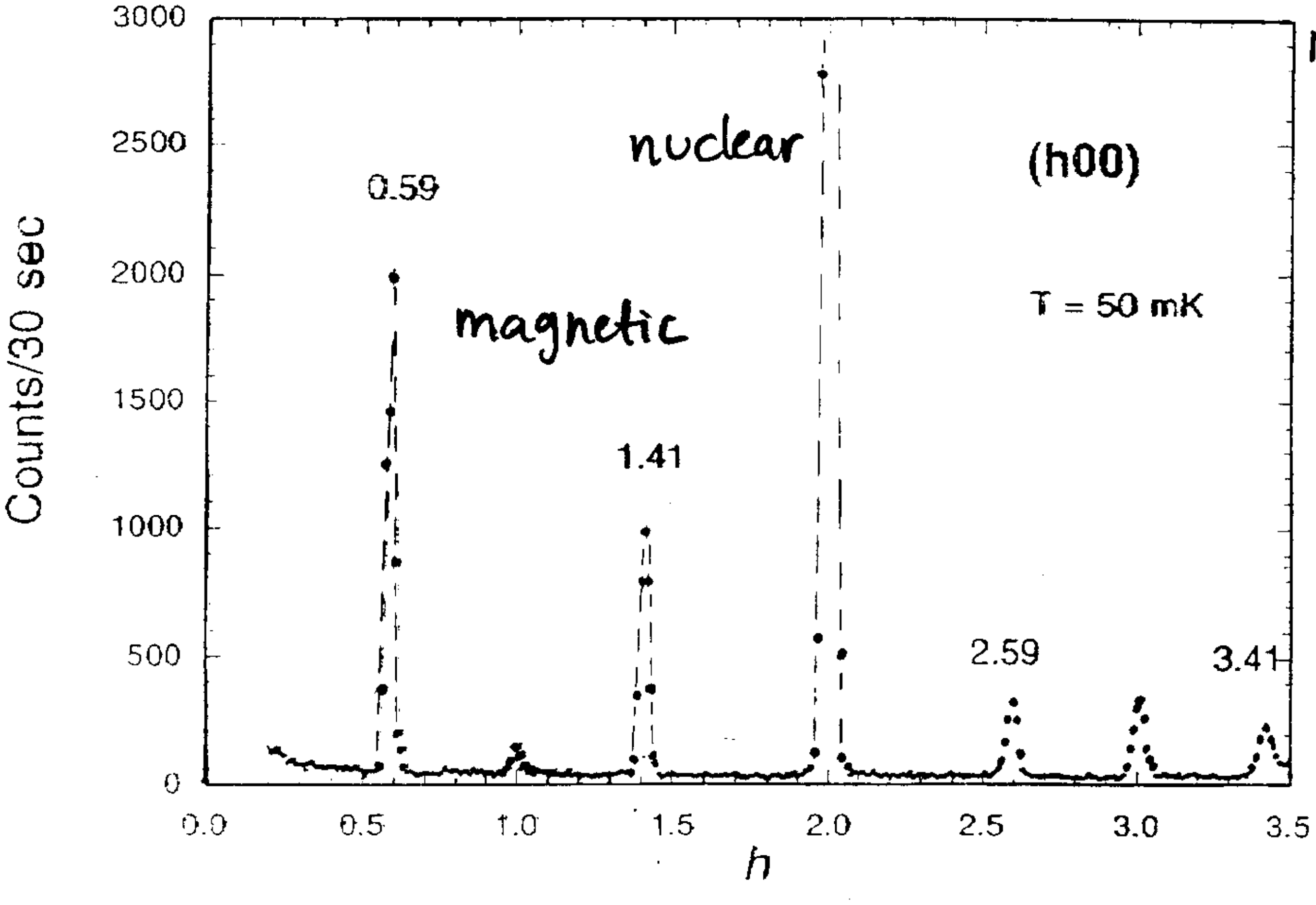
Elastic neutron scattering on a $CeCu_{5.5}Au_{0.5}$ single crystal

incommensurate magnetic reflections

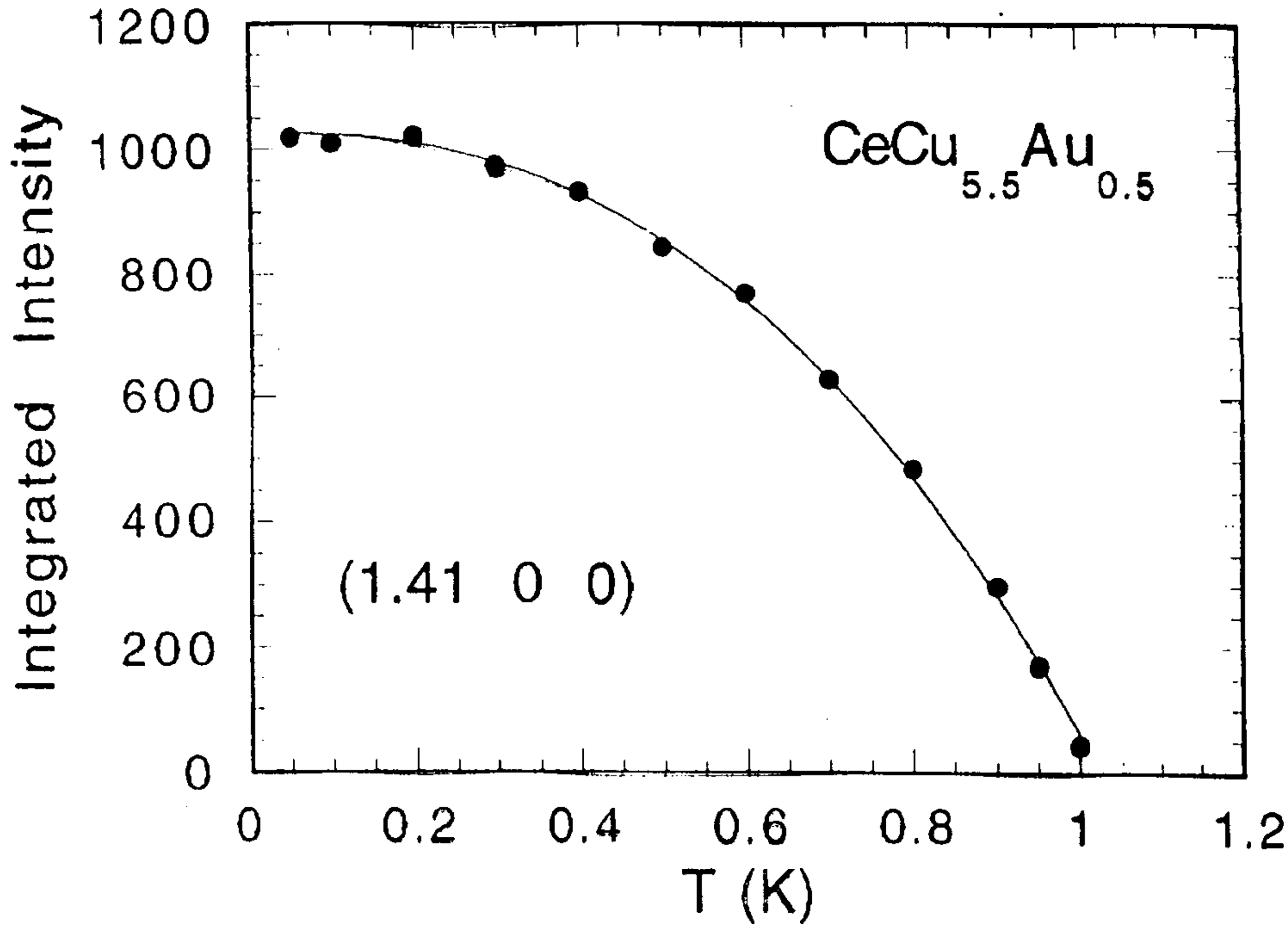
(±0.59 0 0)

A. Schröder, J. Lynn, ...

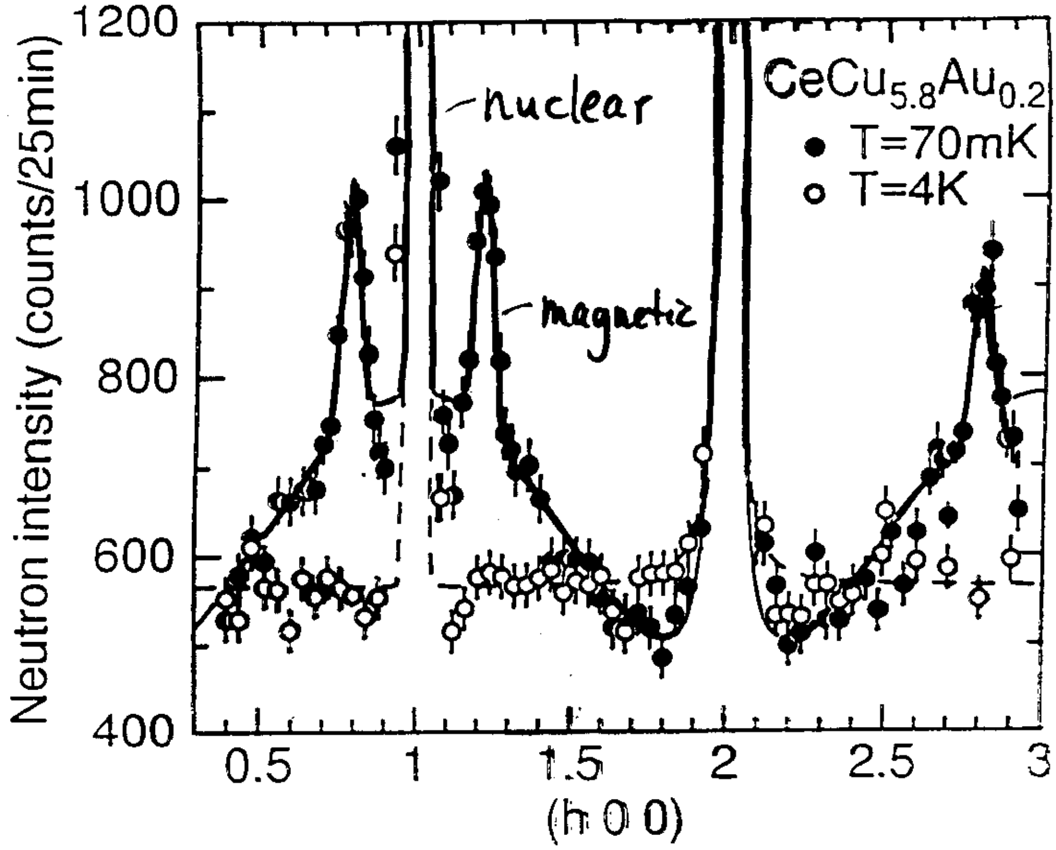
NIST

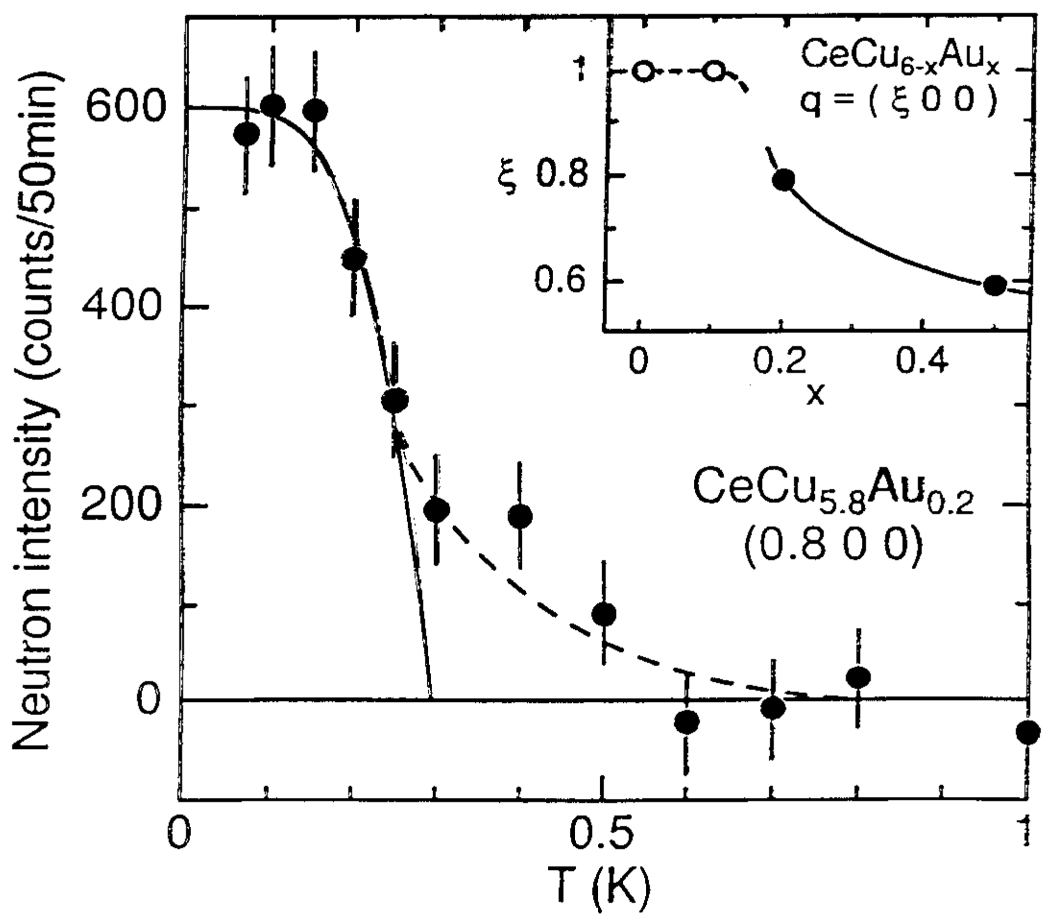


different from (100) and (0 1±0.15 0)
inelastic correlations in $CeCu_6$

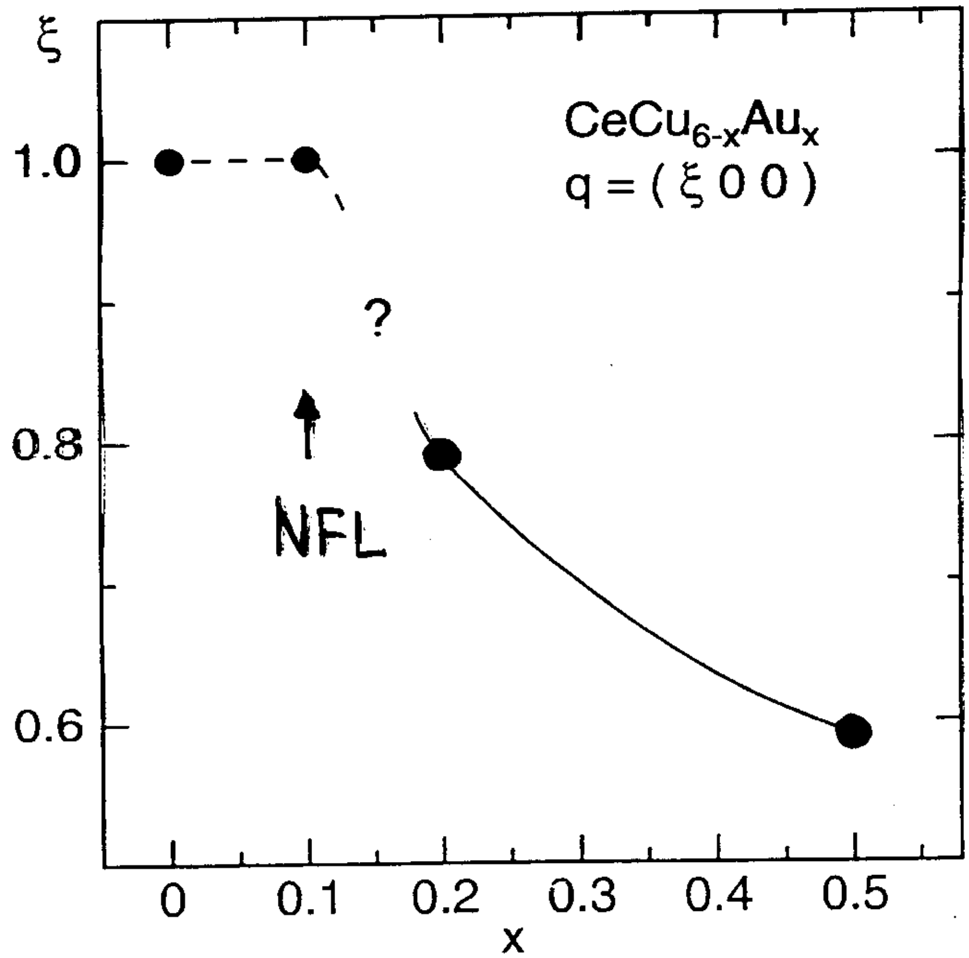


Integrated Intensity
1200
1000
800
600
400
200
0
0
0.2
0.4
0.6
0.8
1
1.2
T (K)
CeCu5.5Au0.5
(1.41 0 0)


CeCu5.8Au0.2
T=70mK
T=4K
nuclear
magnetic
Neutron intensity (counts/25min)
(h 0 0)
1200
1000
800
600
400
0.5
1
1.5
2
2.5
3


CeCu6-xAux
q = (ξ 0 0)
ξ
x
CeCu5.8Au0.2
(0.8 0 0)
Neutron intensity (counts/50min)
T (K)
600
400
200
0
0
0.5
1

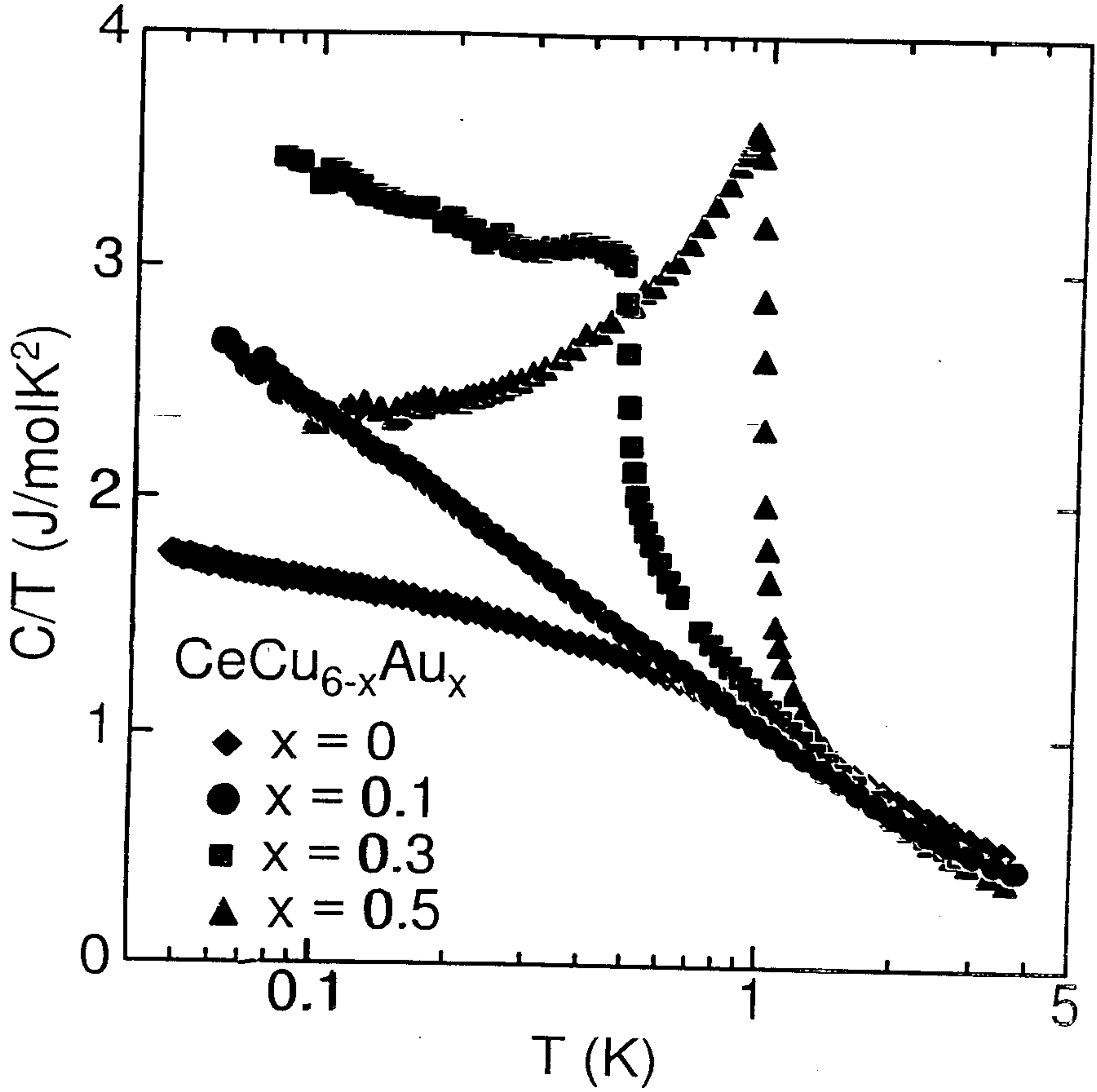
Evolution of magnetic order out of short-range correlations



cf. $CeRu_2Si_2 \rightarrow La_xCe_{1-x}Ru_2Si_2$

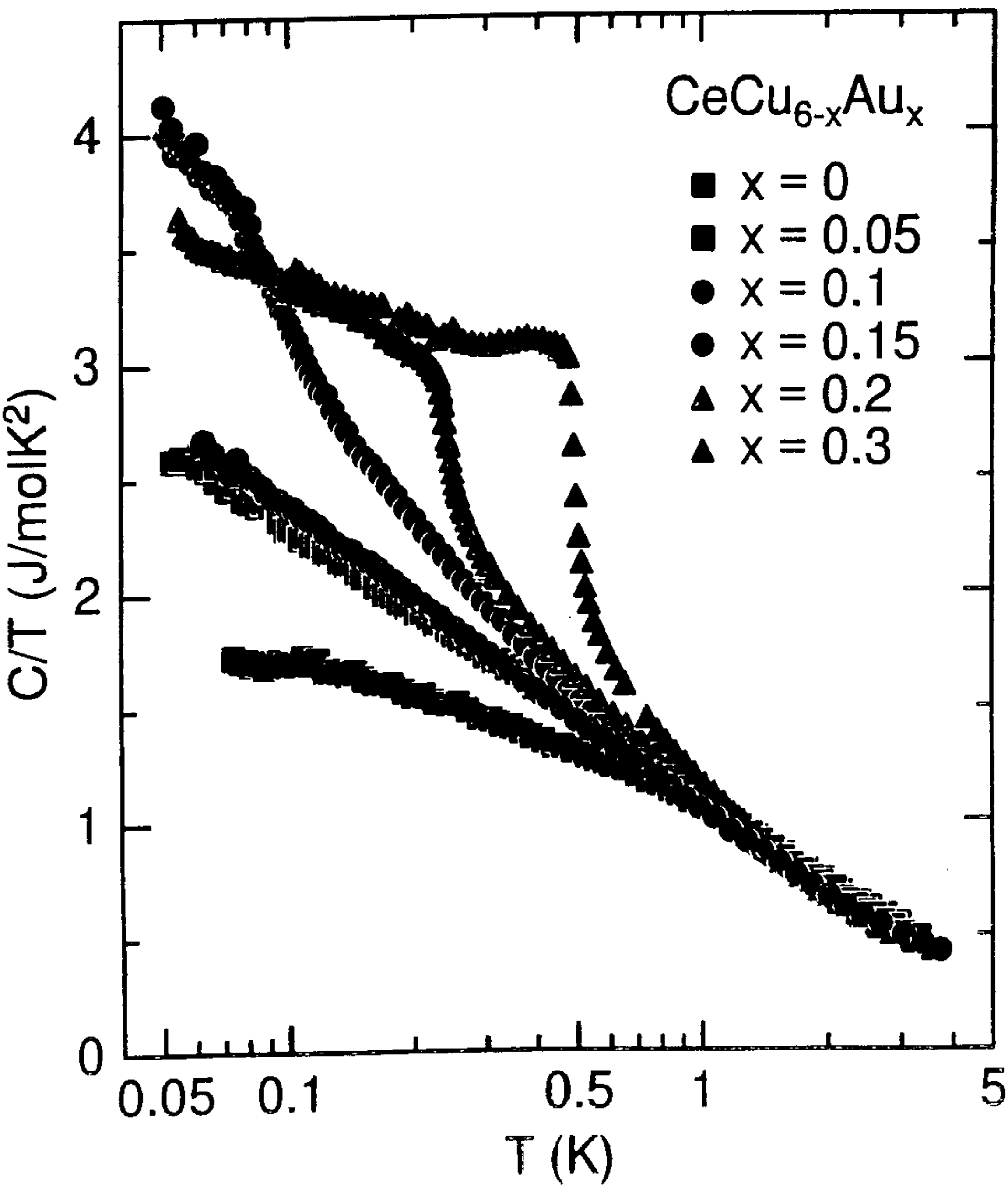
$Q = (0.3\ 0\ 0)$

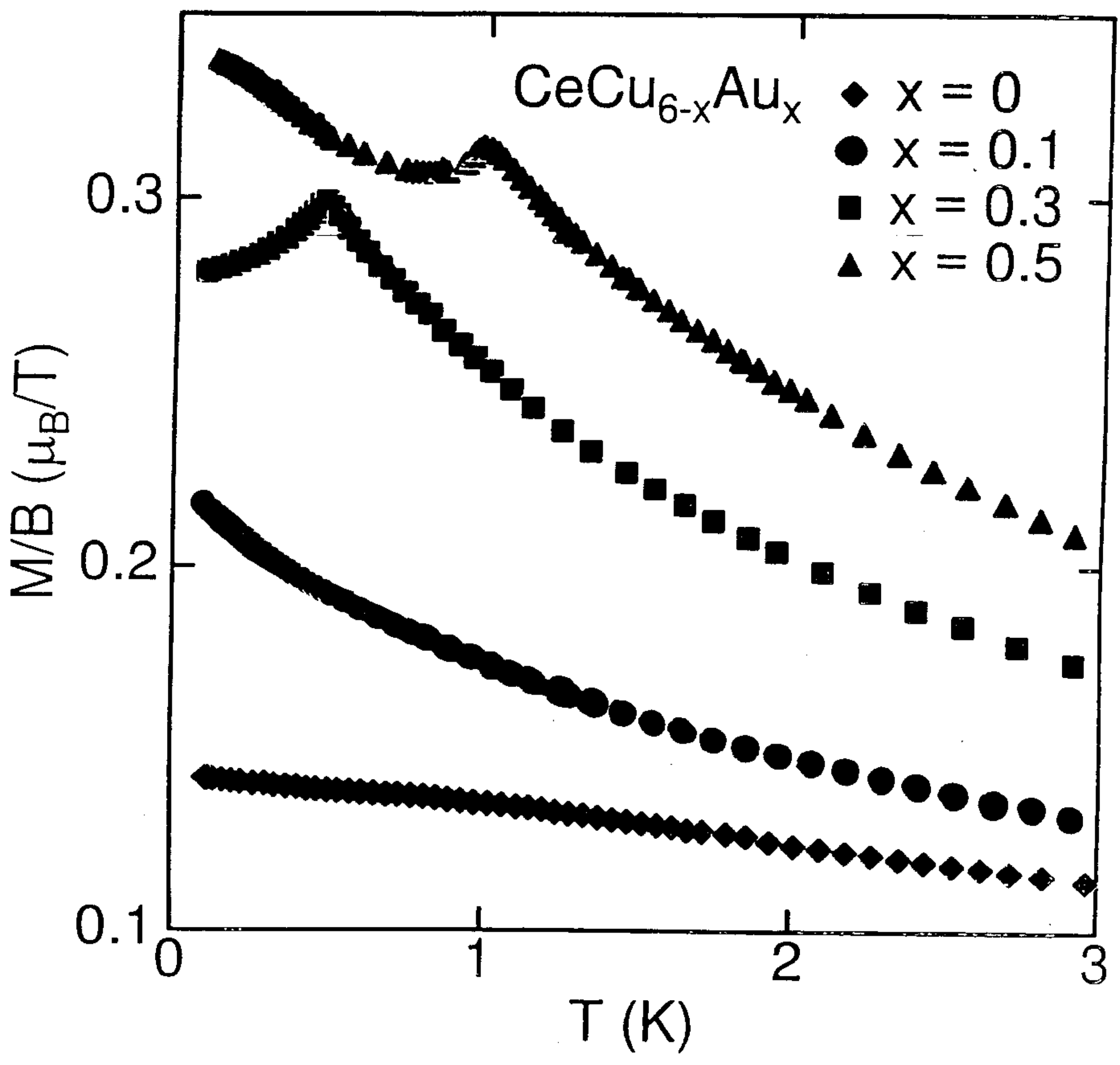
Specific heat of $CeCu_{6-x}Au_x$ single crystals



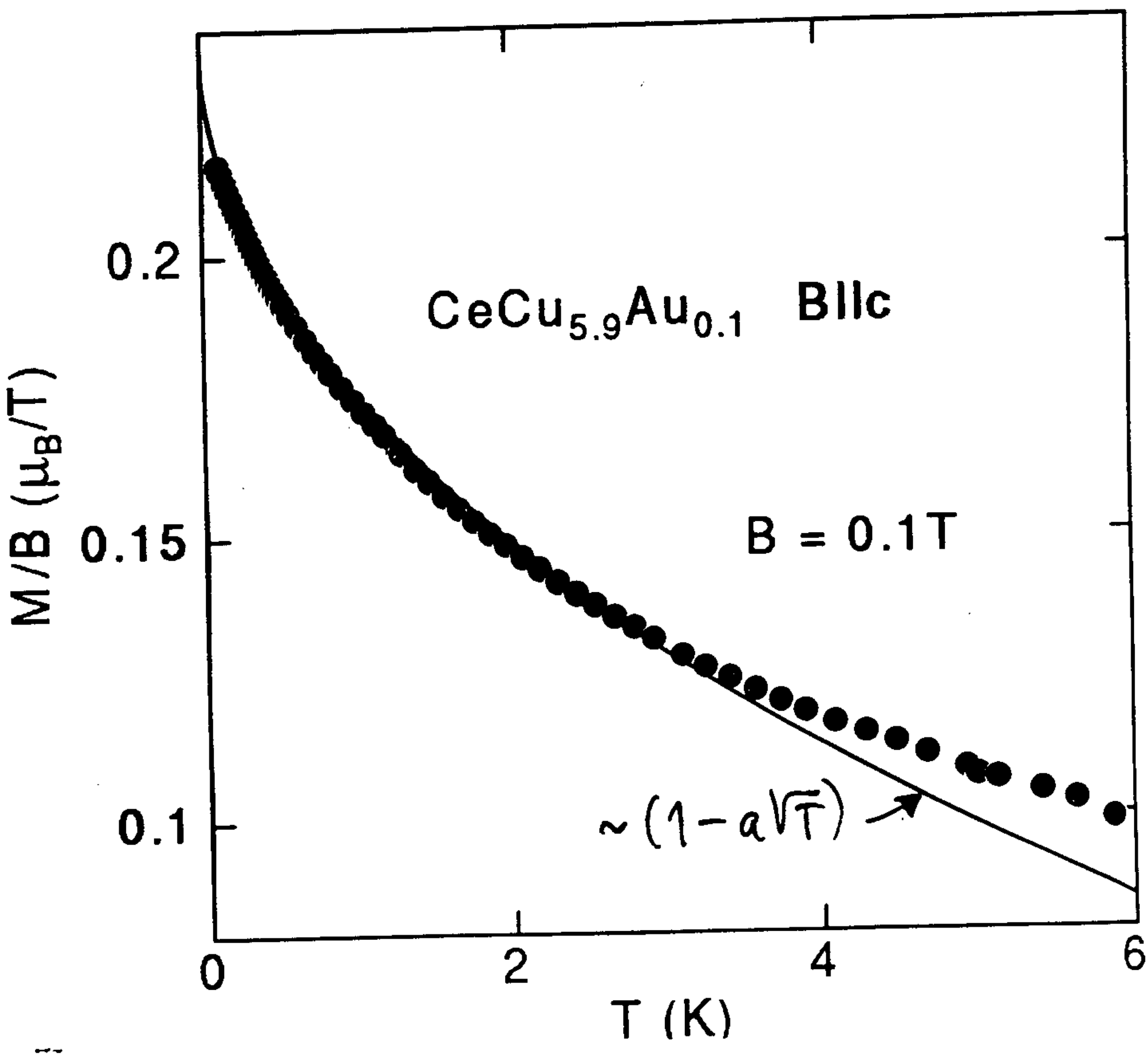
μSR for $x = 0.1$: $\mu < 0.003\,\mu_B$
(same as for $CeCu_6$)

A. Amato et al.

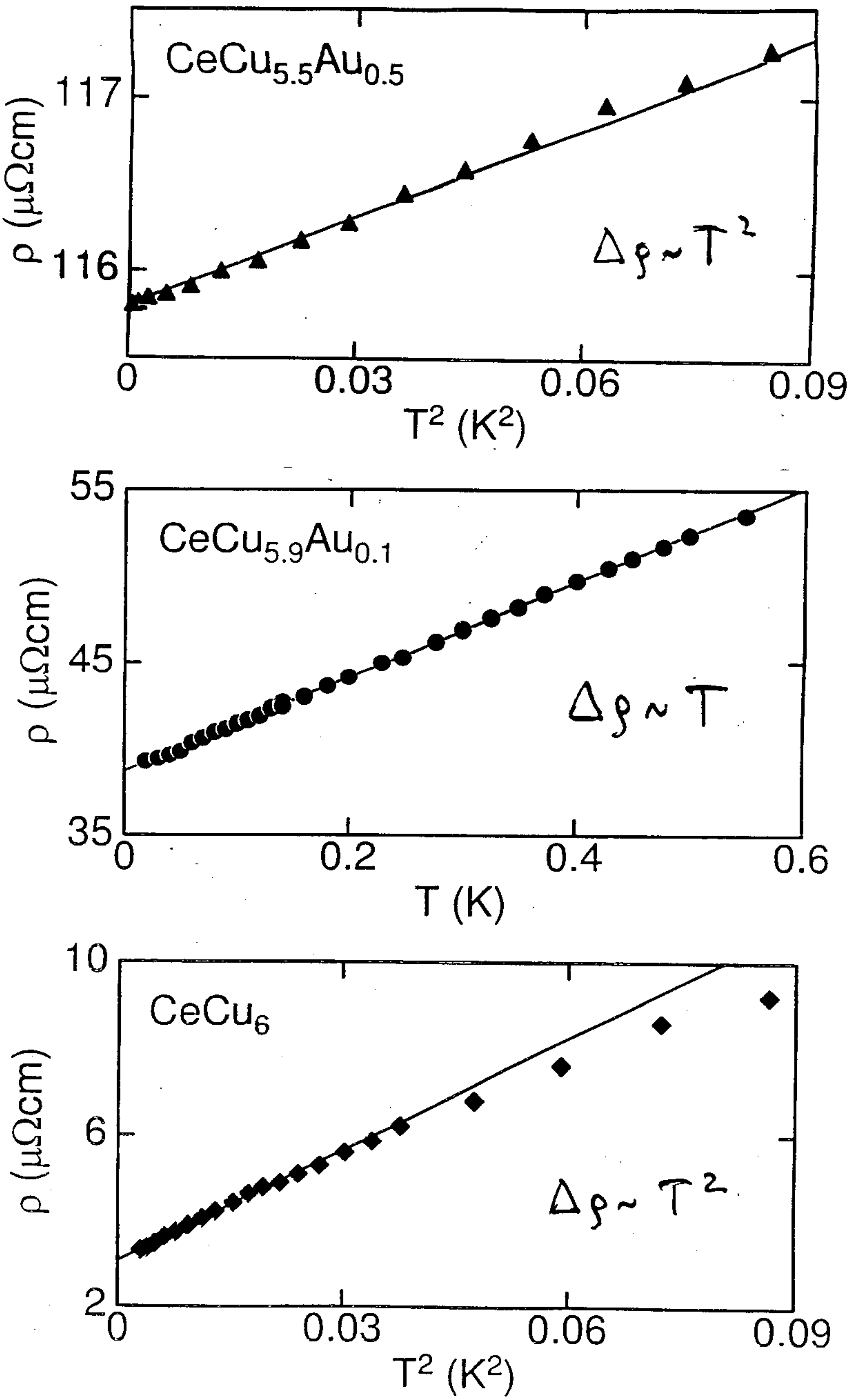

CeCu$_{6-x}$Au$_x$
x = 0
x = 0.05
x = 0.1
x = 0.15
x = 0.2
x = 0.3
C/T (J/molK^2)
T (K)
0
1
2
3
4
0.05
0.1
0.5
1
5



CeCu6-xAux
x = 0
x = 0.1
x = 0.3
x = 0.5
0.3
0.2
0.1
M/B (μB/T)
0
1
2
3
T (K)



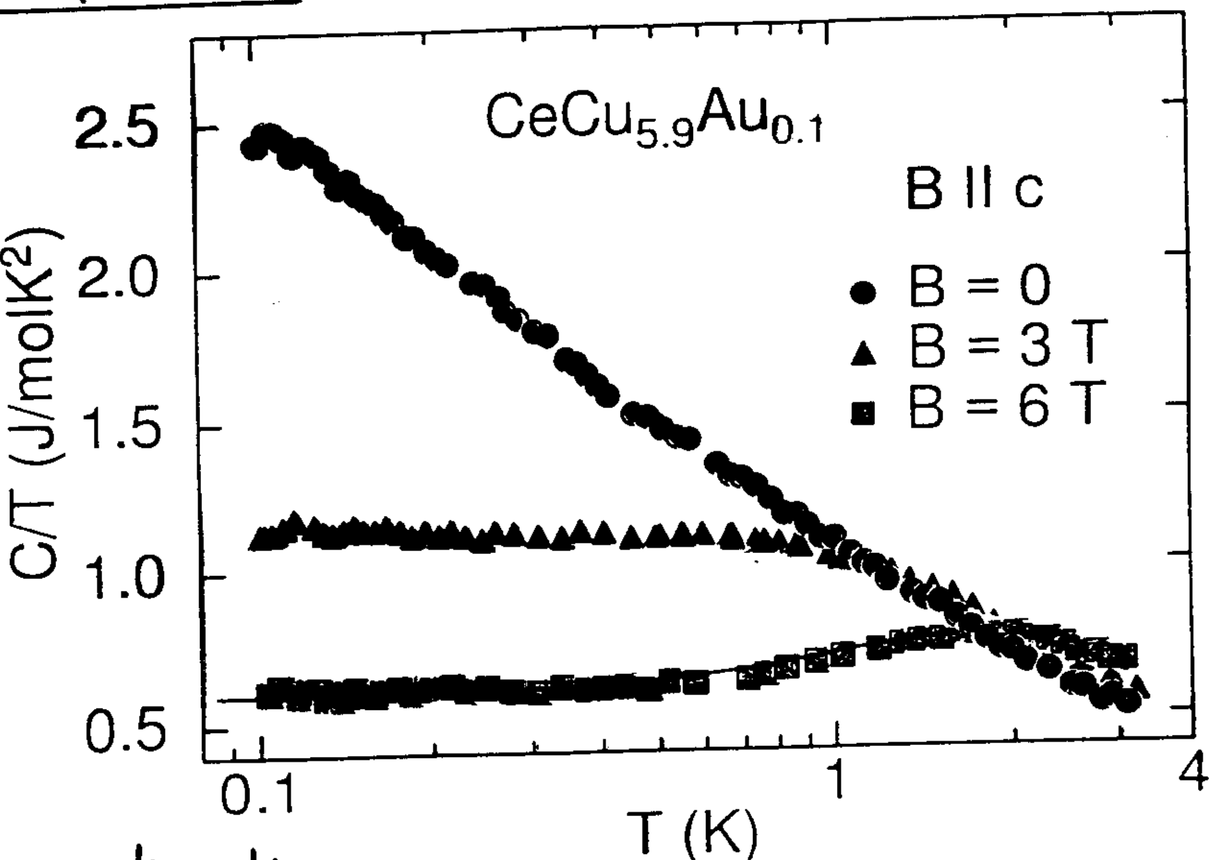
CeCu$_{5.9}$Au$_{0.1}$ B||c
B = 0.1T
~(1−a√T)
M/B (μ_B/T)
0.2
0.15
0.1
0
2
4
6
T (K)


CeCu5.5Au0.5
117
116
ρ (μΩcm)
Δρ ~ T²
0
0.03
0.06
0.09
T² (K²)
55
45
35
CeCu5.9Au0.1
ρ (μΩcm)
Δρ ~ T
0
0.2
0.4
0.6
T (K)
10
6
2
CeCu6
ρ (μΩcm)
Δρ ~ T²
0
0.03
0.06
0.09
T² (K²)

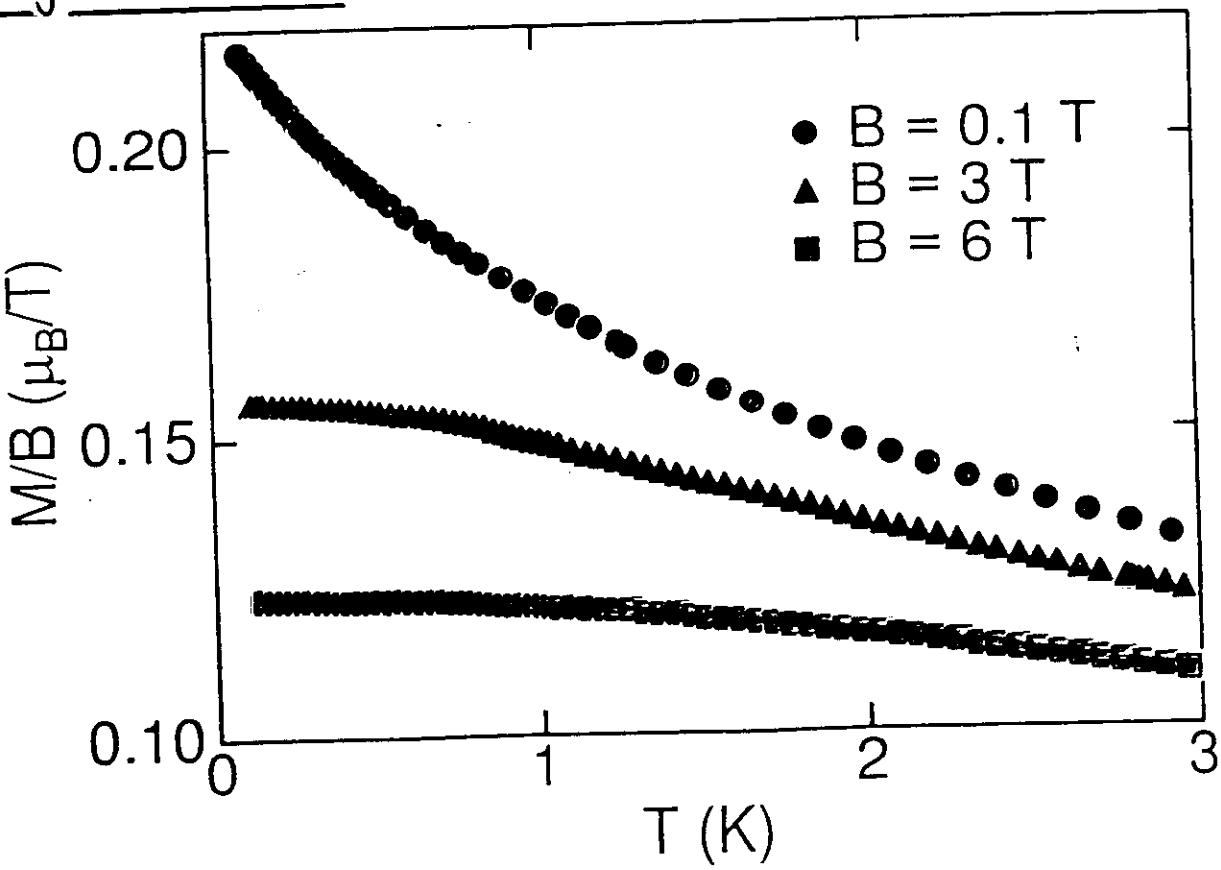
Recovery of Fermi-liquid in high magnetic fields

Specific heat

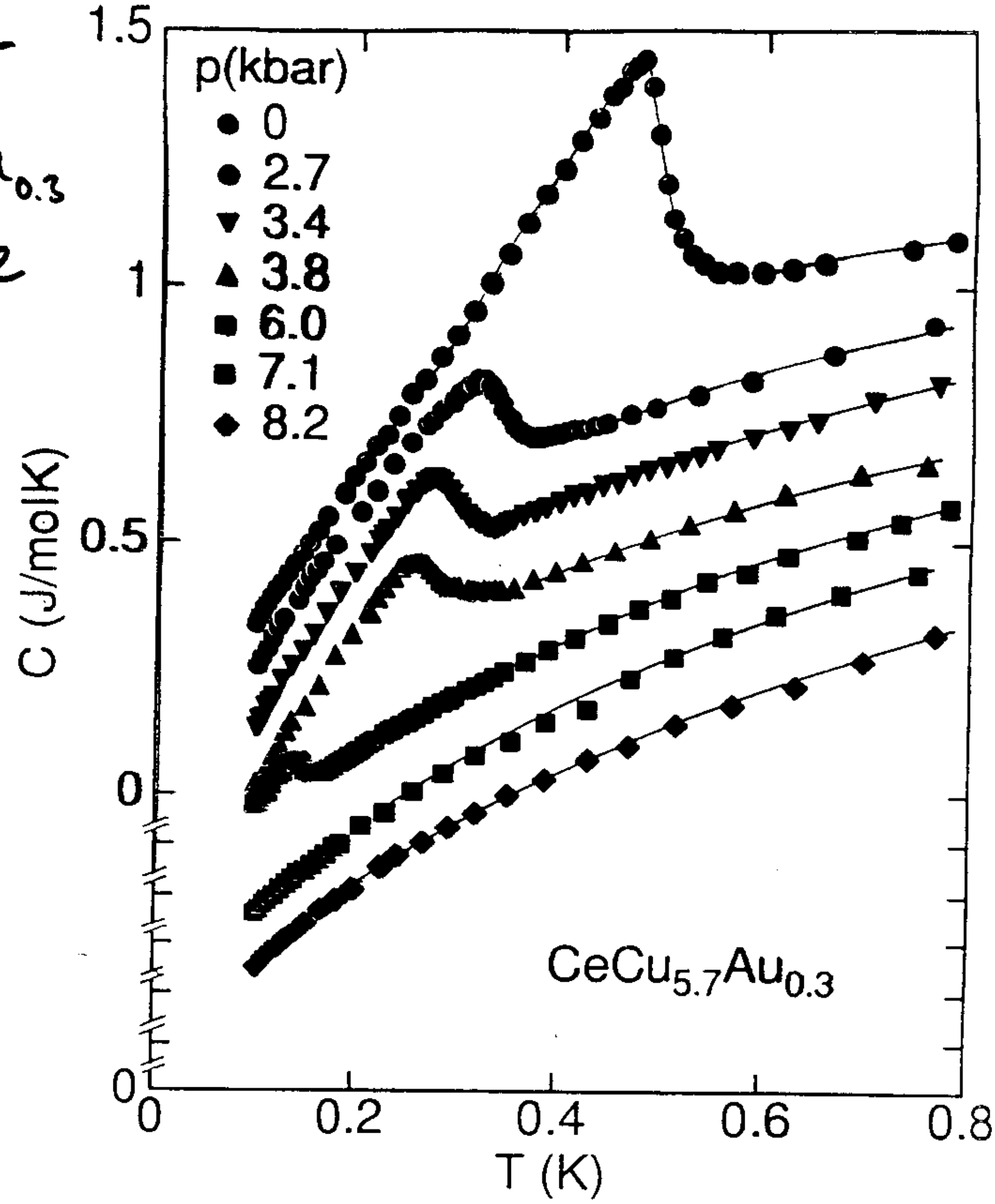
(hf contribution subtracted)



magnetization



Specific heat of $CeCu_{5.7}Au_{0.3}$ under pressure



Néel temperature

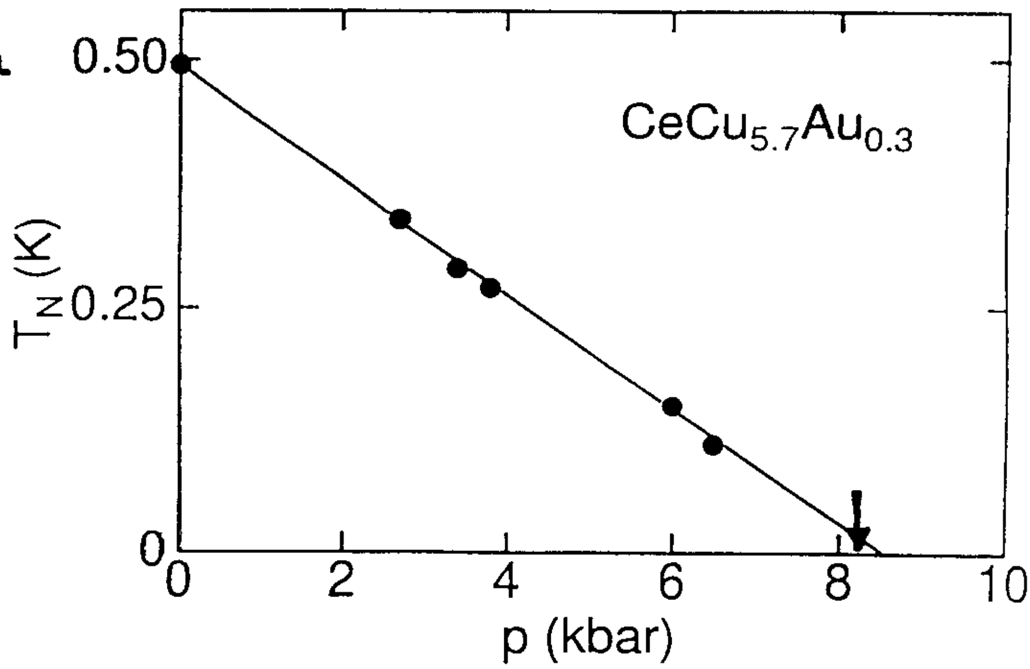
$T_N \sim |p - p_c|^{\mu}$

$\mu = 1$

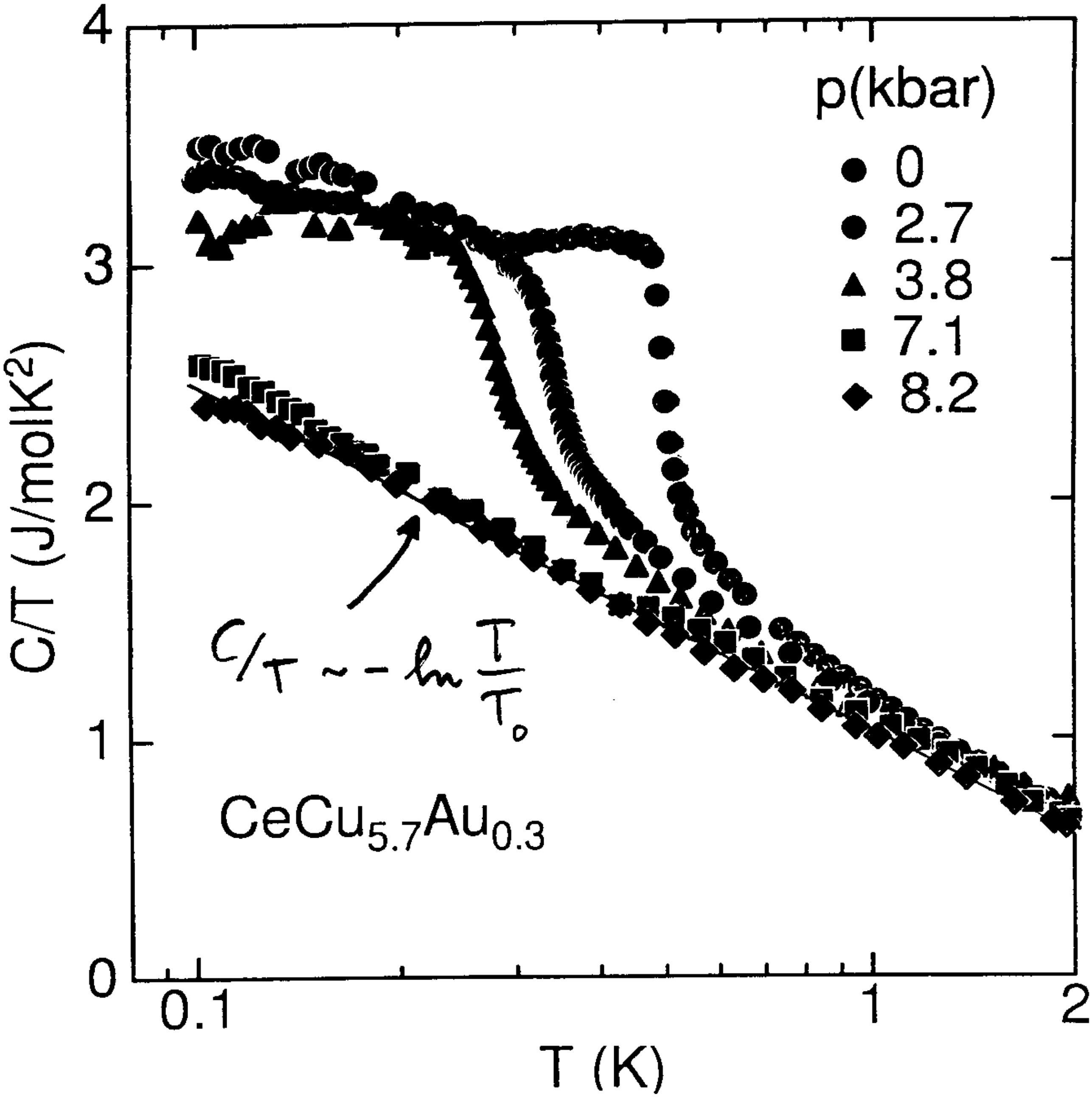
cf.

$T_N \sim |x - x_c|^{\mu}$

$\mu = 1$



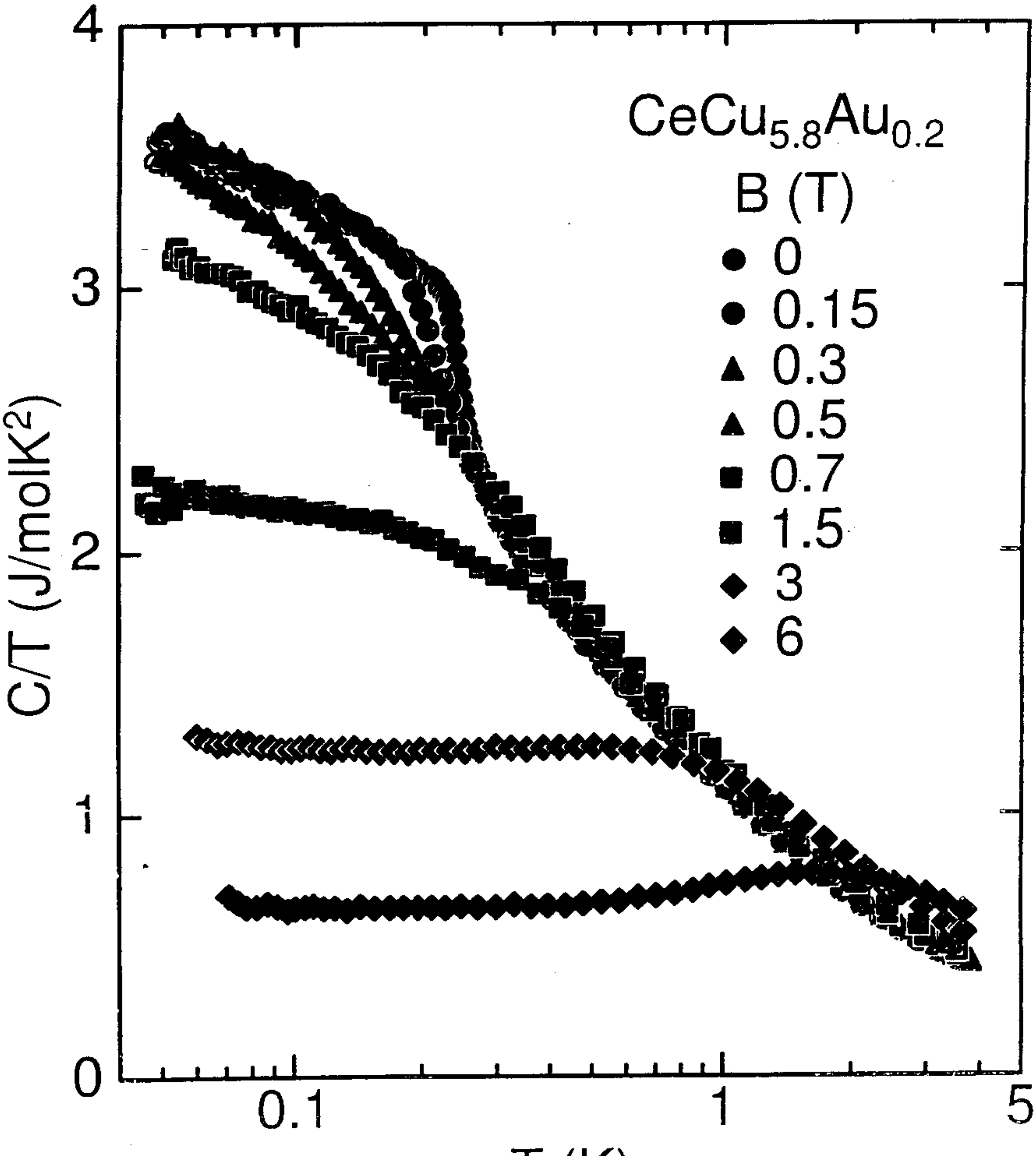
Tuning of non-Fermi-liquid behavior with hydrostatic pressure



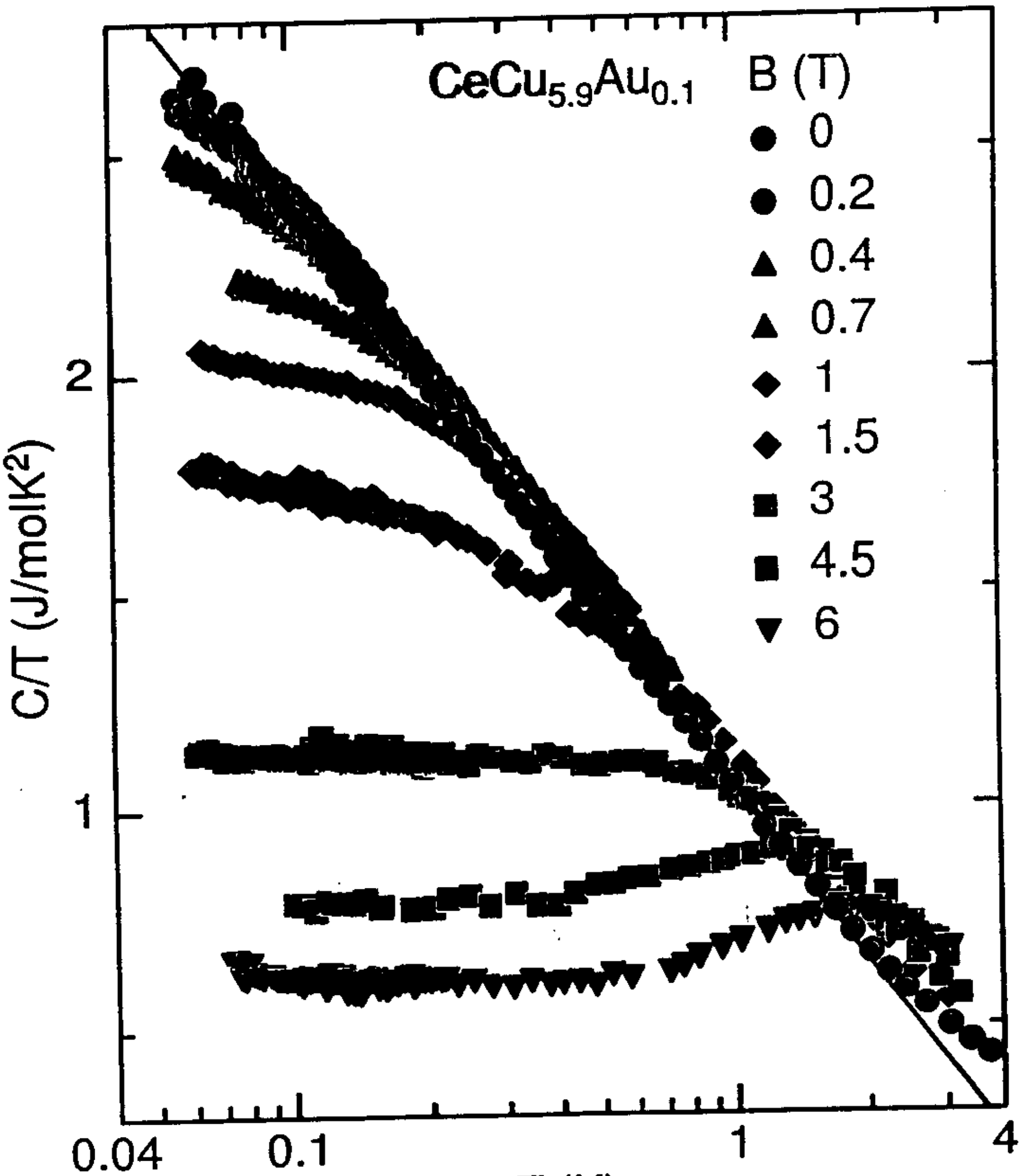
Specific heat of $CeCu_{5.8}Au_{0.2}$

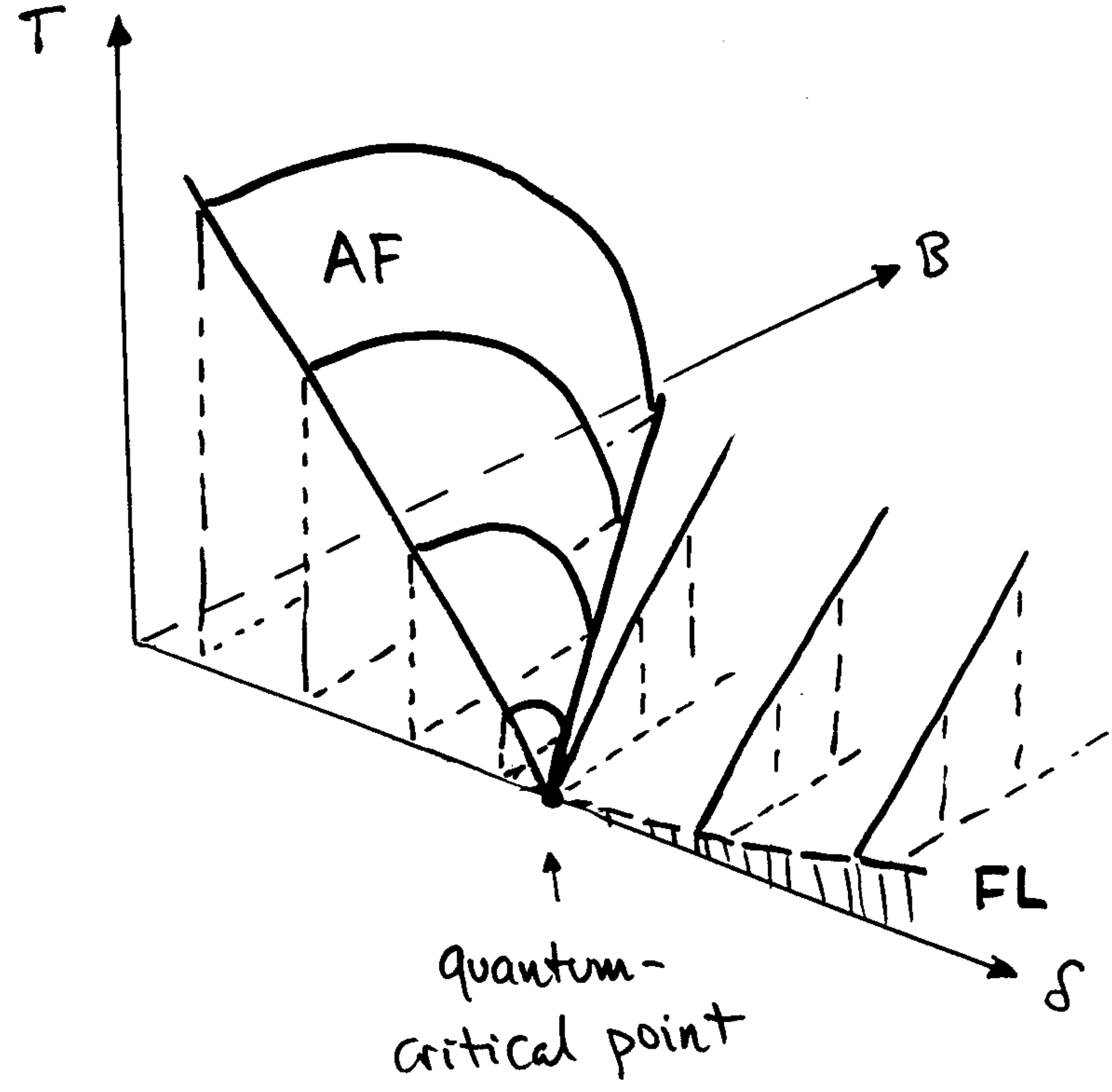
with $T_N = 0.25K$

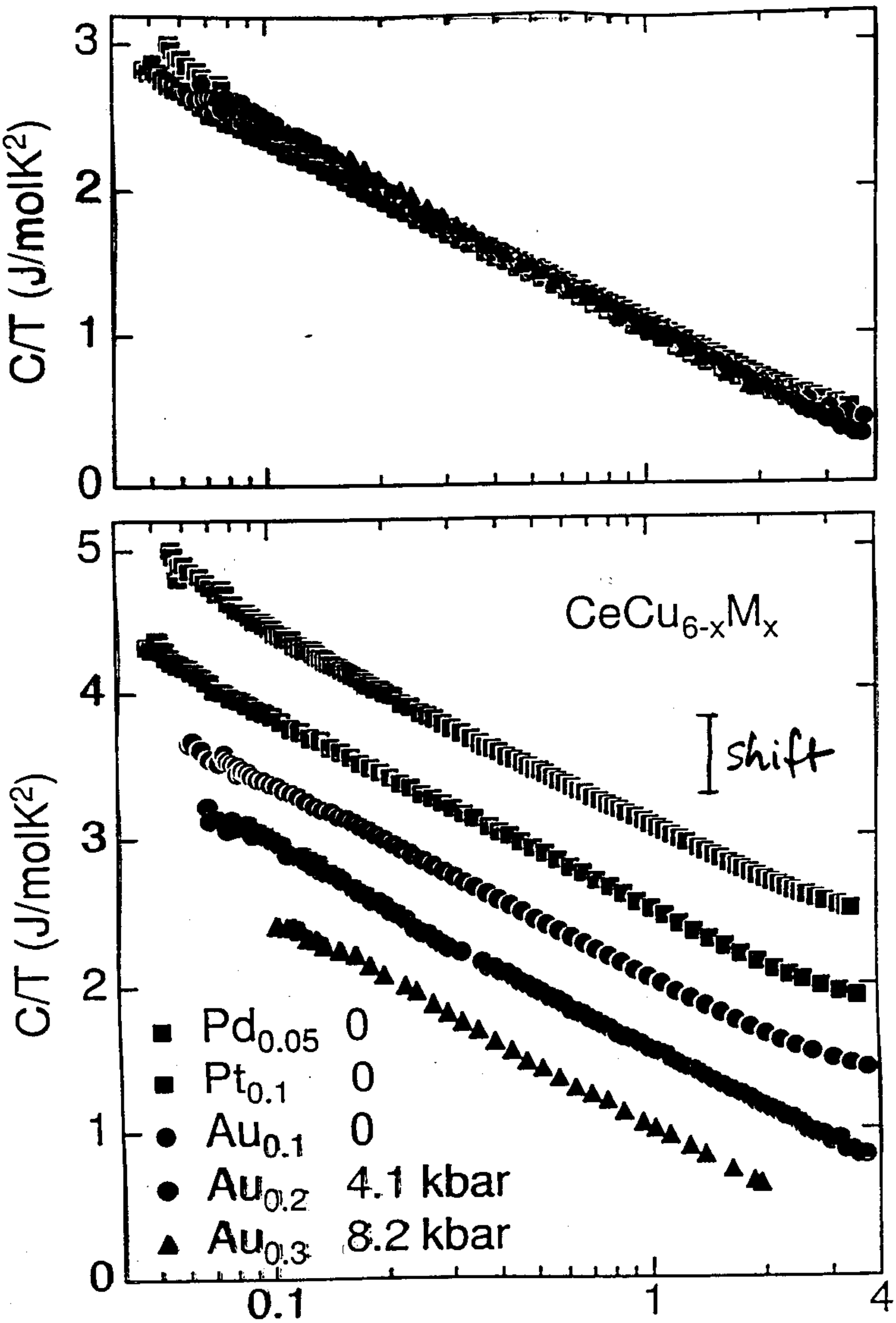
(hf contribution subtracted)



Crossover to Fermi-liquid behavior in magnetic fields




T
AF
B
FL
δ
quantum-
critical point



Universality in $CeCu_{6-x}M_x$: $C/T = a \ln(T/T_0)$

↑ (1)

Other systems showing NFL behavior

Magnetic instability

$CeCu_{6-x}Au_x$, $-Pd_x$, $-Pt_x$

$CePt(Si_{1-x}Ge_x)$ Steglich

$Ce_{0.1}La_{0.9}Cu_{2.2}Si_2$? Andraka

$UCu_{5-x}Pd_x$? Andraka, Stewart

$UCu_{4+x}Al_{8-x}$ Steglich

$U(Pt_{1-x}Pd_x)_3$ Kim, Stewart

$U_xY_{1-x}Pd_3$? Andraka, Tsevik 1991

$MnSi$, $ZrZn_2$ Lonzarich

Ce_7Ni_3 Takabatake

$CeRh_2Si_2$

$CePd_2Si_2$

Lonzarich, Thompson

Multichannel Kondo effect

$U_xY_{1-x}Pd_3$, ... ? Maple 1991

$U_xTh_{1-x}Ru_2Si_2$ Amatsuka

$U_xTh_{1-x}Be_{13}$ Aliev

$Ce_{0.1}La_{0.9}Cu_{2.2}Si_2$? Andraka

disordered metals (two-level tunneling states)

Distribution of Kondo temperatures

$UCu_{5-x}Pd_x$? Mc Laughlin

Si : P (above metal-insulator transition)

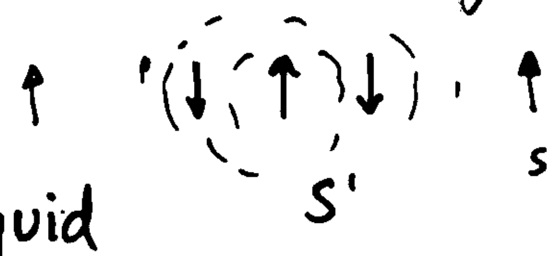
Other mechanisms leading to NFL behavior: single-ion effects

- Multichannel Kondo effect $\mathcal{H} = -\sum_\alpha J S s_\alpha$

  conduction-electron channels $\alpha = 1, \dots N$

  if $N > 2S$ "overscreening"

  $N=2, \; S=\frac{1}{2}$:



  local non-Fermi liquid

  $$\frac{C}{T} \sim \chi \sim -\ln T/T_K$$

  generalization: internal degree of freedom of impurity → "pseudospin"

  e.g. orbital coupling between conduction electrons and f electrons with quadrupole moment:

  pseudospin : electric quadrupole moment,

  ⇒ two conduction-electron channels

  quadrupolar Kondo effect D. Cox

- Distribution of T_K in disordered metals

  more precisely: incoherent superposition of local Fermi liquids

Distribution of Kondo temperatures

single impurity: $T_K \sim \exp\left(-\frac{1}{N(E_F)J}\right)$

usual metal hosts: $N(E_F)$, J well-defined

Metal-insulator transition with disorder

e.g. heavily doped semiconductors:

Si:P : $N_c \approx 3.5 \cdot 10^{18}\,\mathrm{cm}^{-3}$

formation of intrinsic magnetic moments already on the metallic side due to disorder

distribution of J and $N(E_F) \Rightarrow P(T_K)$

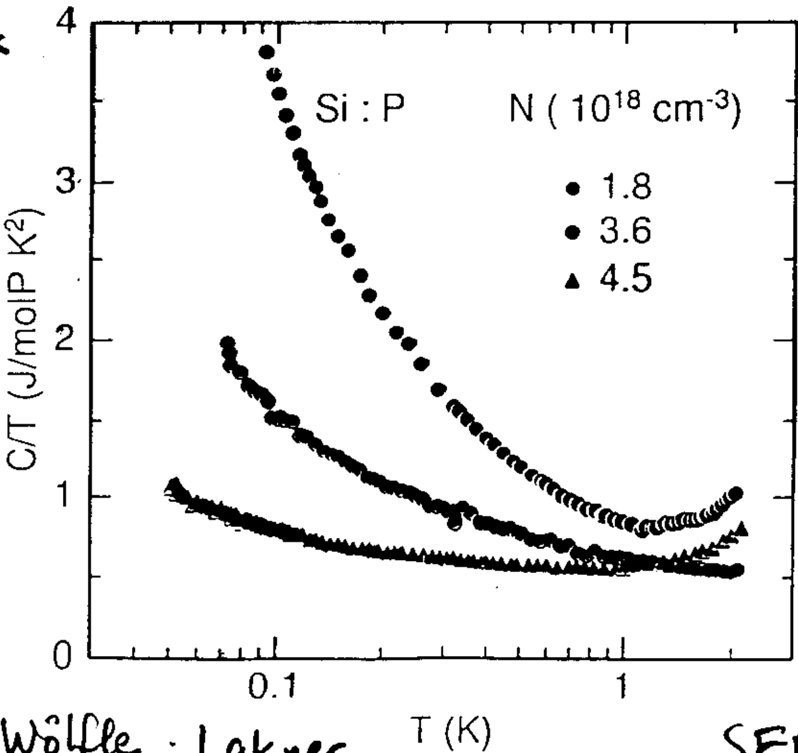
$P(T_K) \sim T_K^{-\alpha_K}$

$\Downarrow$

$\frac{C}{T} \sim T^{-\alpha_K}$

exptl. $\alpha_K \approx 0.8$

theor. $\alpha_K \approx 0.9$



Langenfeld, Wölfle ; Lakner

SFB 195

Conclusions

- NFL behavior can have different microscopic origin: single-ion vs. $T=0$ phase transition
- $CeCu_{6-x}Au_x$: concentration and pressure tuning of magnetic instability

Open problems:

- $\Delta\chi \sim \sqrt{T}$, $C/T \sim -\ln(T/T_0)$, $\Delta\rho \sim T$
  more generally: scaling properties ?
- role of disorder ?
- what type(s) of magnetic instability lead(s) to NFL behavior ?
- microscopic model ? Spin fluctuations as $T_N \to 0$ (FM vs AF)
- NFL: crossover or critical behavior for $T \to 0$
- one or two components: 3d vs. 4f heavy fermions