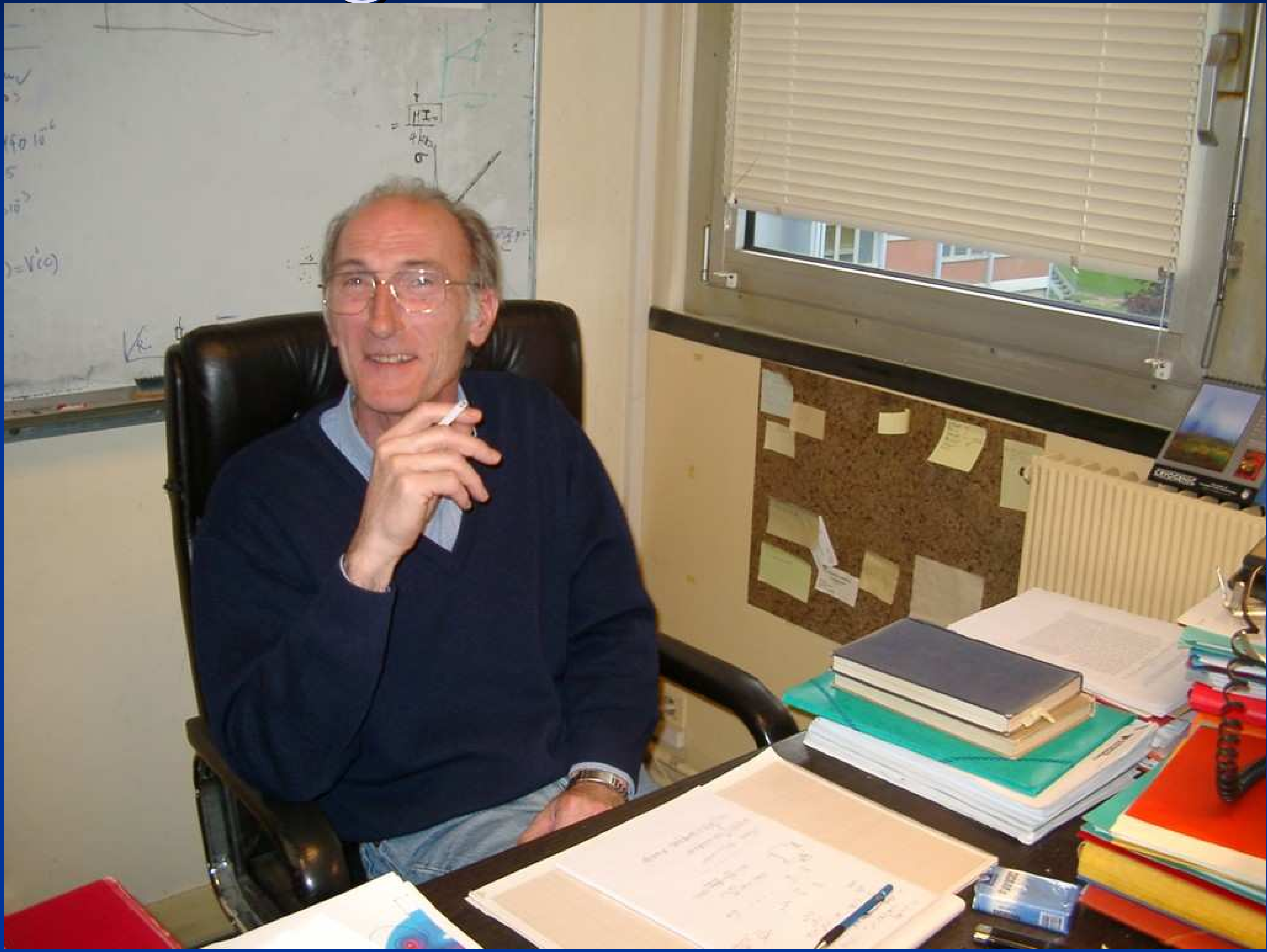
My memories of Miguel Ocio

(A side trip to Heavy Fermion)

2005. 10. 3.

Y. Miyako

Miguel in his office



Miguel's footsteps to Japan

- ***1985 ICM conference in San Francisco.*** Ocio: Noise measurement (Invited talk)

  1987 The conference on High Tc in Sendai
- 1988 The 2nd Yukawa Seminar in Kyoto

  Discussion of our collaboration
- 1989 Guest Professor of Osaka University

  Stayed in ***Hokkaido University*** for 3 months and Ocio gave a lecture on SQUID
- 1990 MPT conference in Osaka (Invited talk)

Sapporo

- 1991 Invited to Osaka University together with P.Pari for 1 month to install Dilution fridge .

  Since 1994, Miguel visited ***Osaka University*** every year
- Start of collaboration on heavy fermion $Ce(Ru_{1-x}Rh_x)_2Si_2$
- PhD thesis of ***Tabata*** (Researcher of Osaka university)
- ***2002 LT conference in Hiroshima.*** Ocio: Advanced experiment on fluctuation dissipation relation in non-ergodic systems.

Osaka


YAMADA
MAGNETIC PHASE TRANSITION

Heavy Fermions

- $CeRu_2Si_2$ (Flouquet, Grenoble)

- URu_2Si_2 (Superconductivity appears in the antiferromagnetic phase.)

"Is it true? "was my question !!

The Research on $CeRu_2Si_2$

- In our collaboration, Miguel paid attention to the magnetic phase transitions in $Ce(Ru_{1-x}Rh_x)_2Si_2$.
- Interesting point of heavy fermions is a lot of varieties in the low temperature properties.

Characteristic feature of heavy fermion$CeRu_2Si_2$

- $CeRu_2Si_2$ is a paramagnetic heavy fermion compound.
- The characteristic feature of magnetism in $CeRu_2Si_2$ is coexistence of many short range orders with incommennsurate magnetic wave vector q below T_K. By inelastic neutron scattering study scanned in the c*- and a*-planes in the first Brillouin zone, 3 peaks were found at the scattering vectors q_1(0.3 0 0), q_2(0.3 0.3 0) and q_3(0 0 0.35).
- By replacing parts of constituent atoms, one of short range orders is stabilized to make a long range order (spin density wave : SDW).

Phase transition in $Ce(Ru_{1-x}Rh_x)_2Si_2$ compound

- $CeRh_2Si_2$ shows antiferromagnetic order.
- $Ce(Ru_{0.5}Rh_{0.5})_2Si_2$ is close to QCP.

  QCP is the quantum critical point where non-magnetic to magnetic transition occurs at T = 0 .
- Miguel focused his attention to the study near the QCP in $Ce(Ru_{0.5}Rh_{0.5})_2Si_2$ and worked as the supervisor for Tabata.

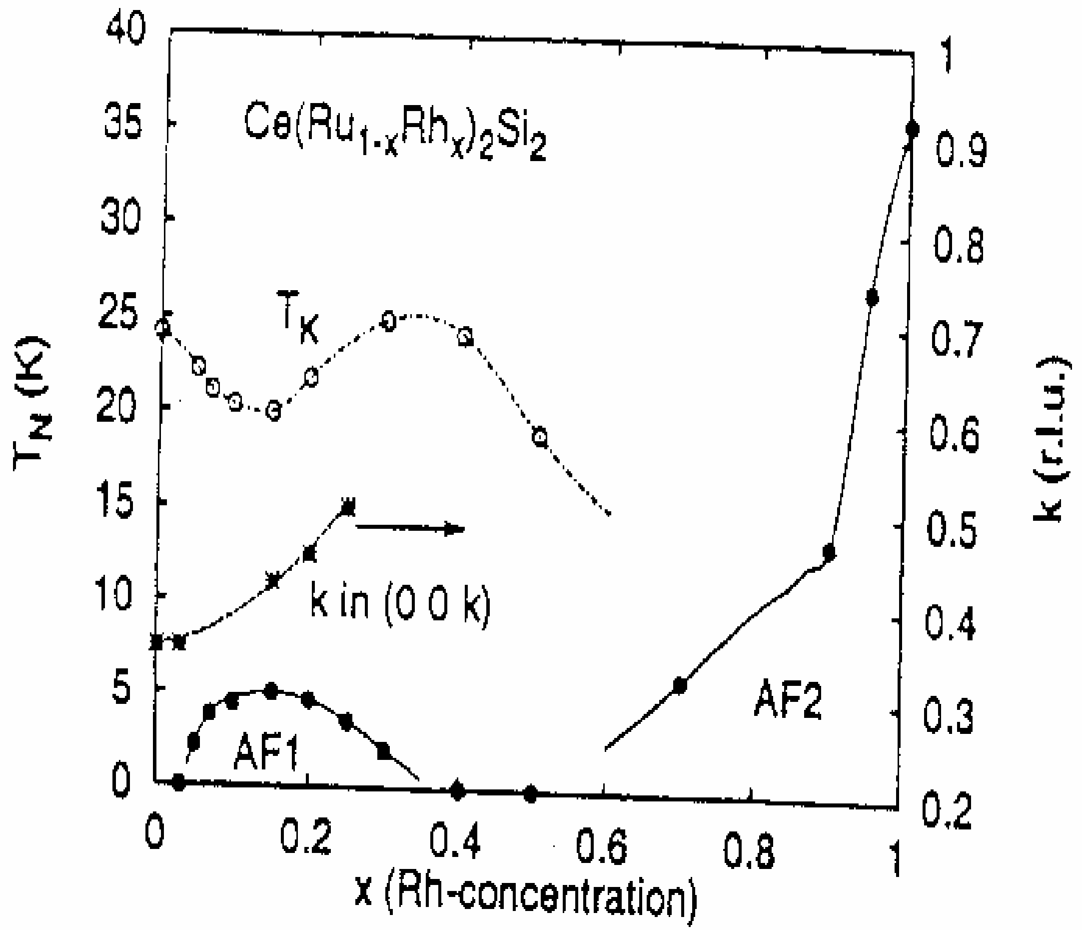
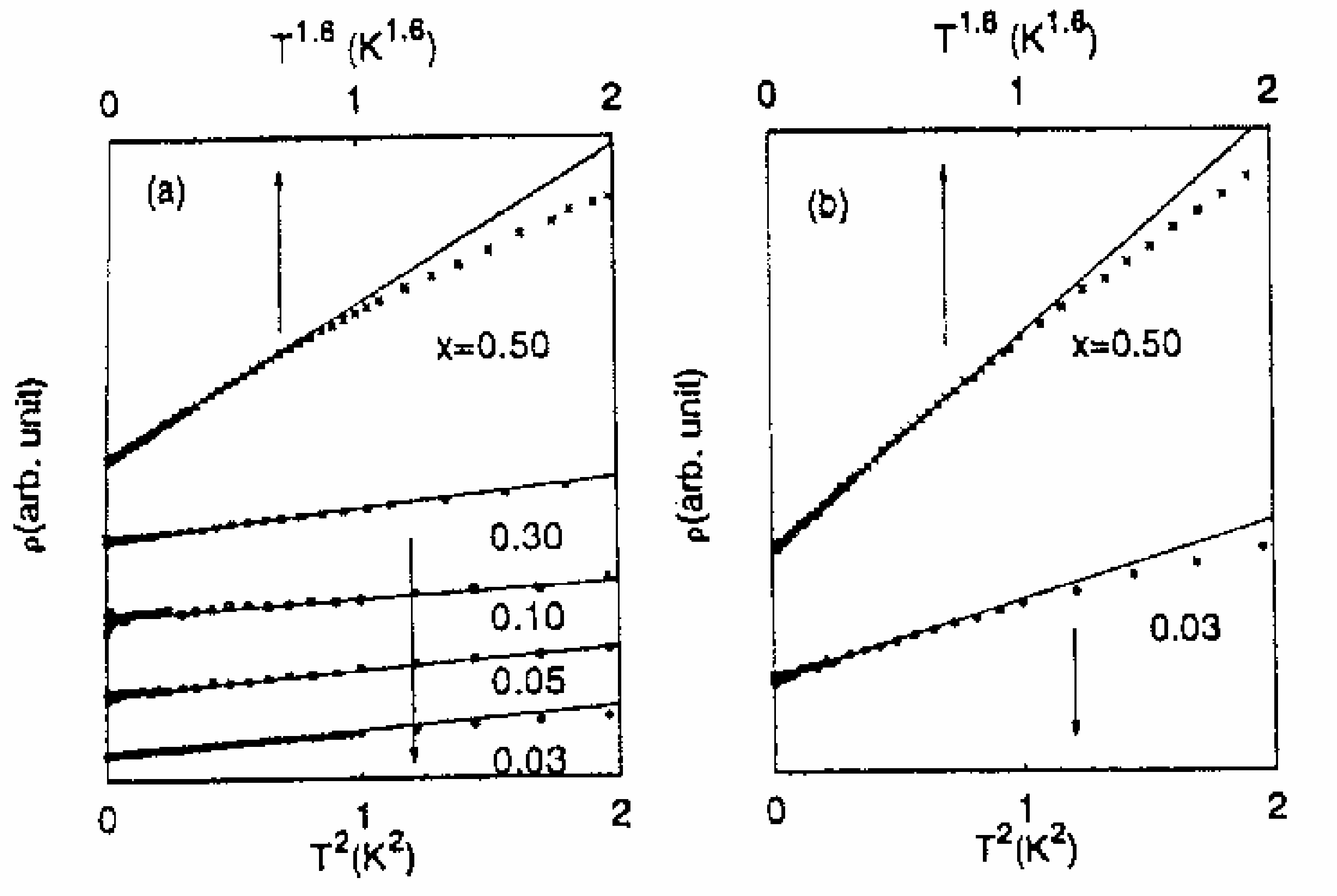


Fig. 1. Magnetic phase diagram for $Ce(Ru_{1-x}Rh_x)_2Si_2$. The wave number k of the magnetic wave vector $q_3(0\ 0\ k)$ varies as a function of x.



T^1.6 (K^1.6)
0
1
2
(a)
x=0.50
0.30
0.10
0.05
0.03
ρ(arb. unit)
T^2(K^2)
(b)
x=0.50
0.03

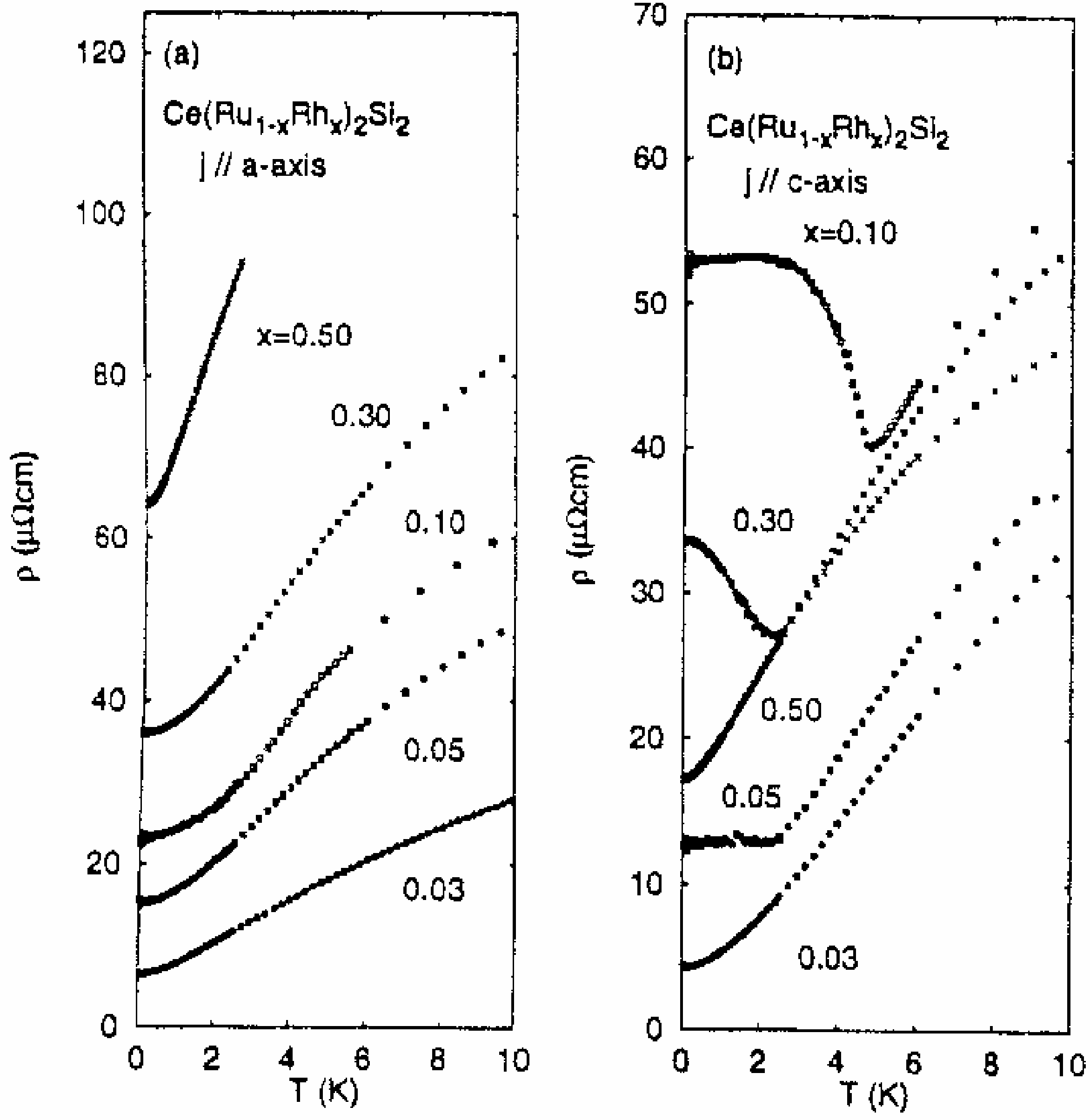
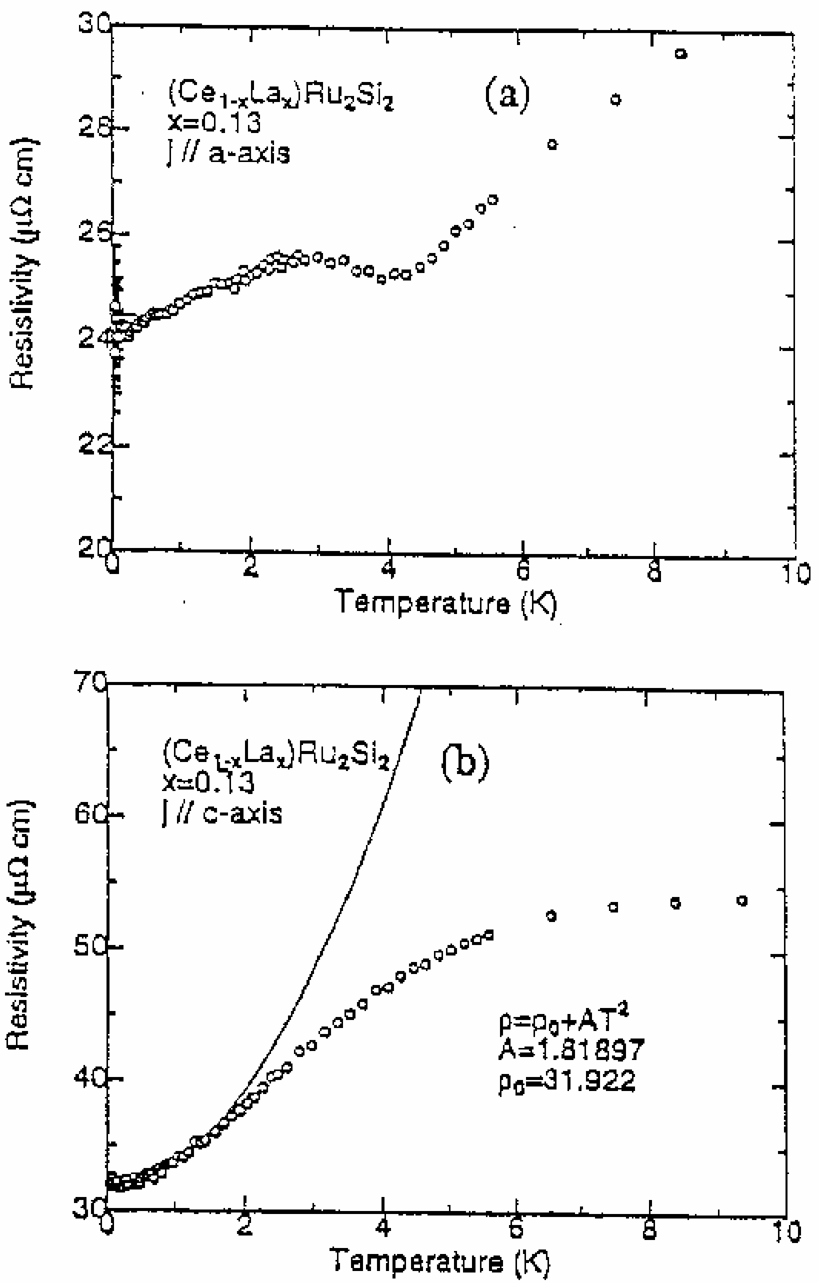


Fig. 2. Electrical resistivity of $Ce(Ru_{1-x}Rh_x)_2Si_2$ as a function of temperature.



(a) and (b) Electrical resistivity of $La_{0.13}Ce_{0.87}Ru_2Si_2$.

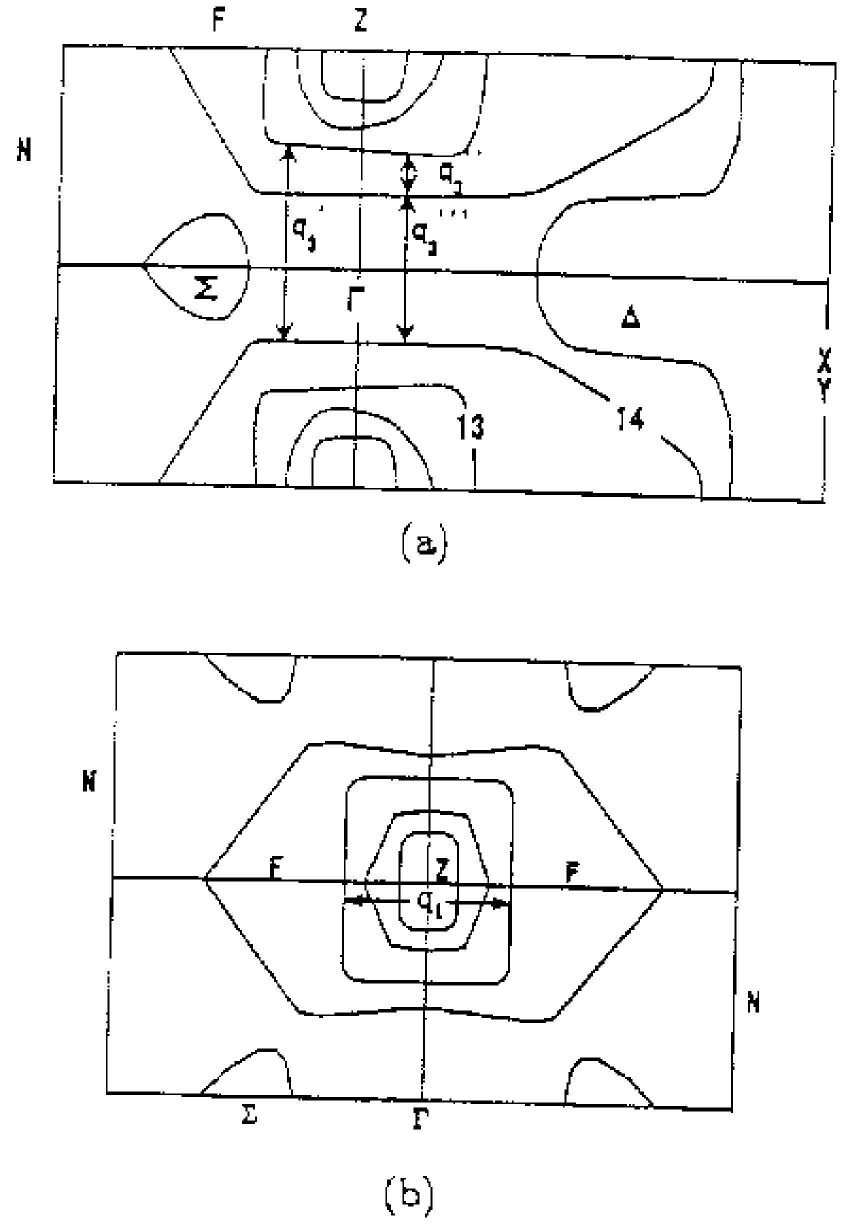


Fig. 6. (a) and (b) The intersection of the Fermi surface of hole bands after Ref. 45. The notation for bands, 13th and 14th bands, follow Ref. 46.

Characteristic feature of heavy fermion at SDW transition

- The Kondo coupling between s-band conduction electrons and localized f-electrons creates heavy fermion band at the Fermi level below the T_K.
- The band gap opening occurs at the Fermi surface by nesting.

$\Downarrow$

- As a ressult, the resistivity increases steeply below the SDW transition temperature.

$\Downarrow$

- This is the characteristic behavior of heavy fermion in Ru rich $Ce(Ru_{1-x}Rh_x)_2Si_2$ compound and in a normal metal like Cr, there is no such an anomalous behavior below the SDW transition.

Miguel's idea

- In heavy fermions, there is competition between on-site Kondo interaction (T_K) showing Kondo screening and the RKKY interaction (J) between localized moments. At $T_K \sim J$, magnetic to non-magnetic transition occurs at T = 0, which is quantum critical point (QCP).
- From a proliferation of magnetic excitations characteristic of QCP, non-Fermi liquid behavior appears.

  Miguel focused his attention to the non-Fermi liquid behavior (deviation from the Fermi liquid behavior) in $Ce(Ru_{0.5}Rh_{0.5})_2Si_2$. This compound is considered to be close to the QCP and also to have large effect of disorder. Then, in addition to the spin fluctuations characteristic of the QCP, there is quantum Griffiths like behavior.

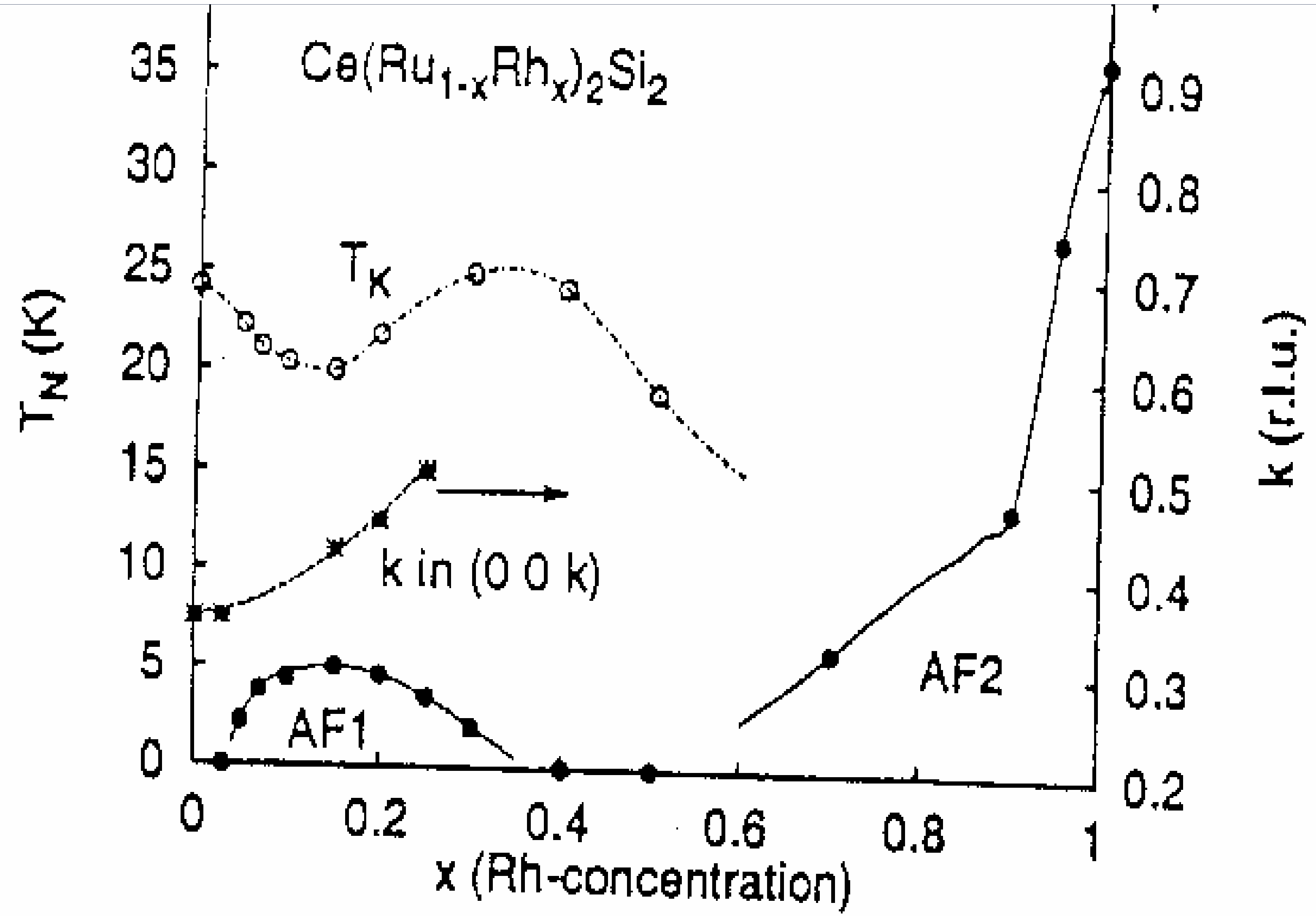


Fig. 1. Magnetic phase diagram for $Ce(Ru_{1-x}Rh_x)_2Si_2$. The wave number k of the magnetic wave vector $q_3(0\ 0\ k)$ varies as a function of x.

The Model by Grempel and Rozenberg(Phys.Rev.B60,1999-I)

- In a disordered Kondo alloy, random distributed spins interact with a band of conduction electrons through a local Kondo coupling. There is also a residual RKKY exchange interaction between the spins, which is random because of the disorder in their positions. Many of rare earth Kondo alloys exhibit uniaxial anisotoropy. To a first approximation, the Hamiltonian of the model is

$$H = - \sum_{i,j} t_{ij} c_i^{+} c_j + J_z^K \sum_i S_i^z s_i^z + J_{x,y}^K \sum_i (S_i{+} s_i{-} + H.c.) - ½ \sum_{i,j} J_{ij} S^z_i S^z_j.$$

TABATA *et al.*

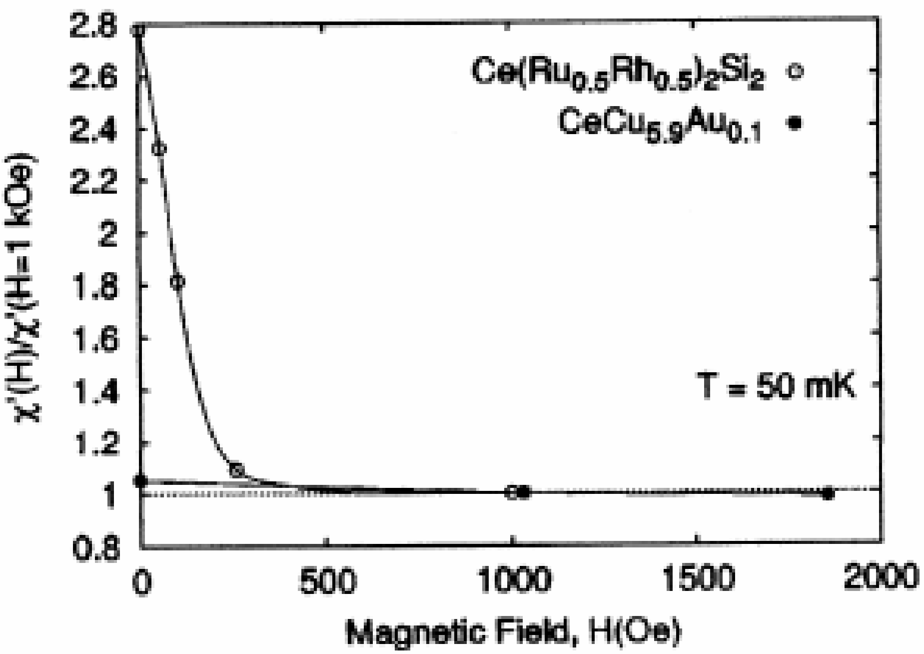


FIG. 4. The field dependences of the susceptibilities of $Ce(Ru_{0.5}Rh_{0.5})_2Si_2$ and $CeCu_{5.9}Au_{0.1}$ at 50 mK. The solid lines are guides to the eyes.

$\delta\chi(T,H)$ disorder-driven component.

$\chi_{MF}(T)$ the MF component.

Non-Fermi-Liquid Scaling in $Ce(Ru_{0.5}Rh_{0.5})_2Si_2$

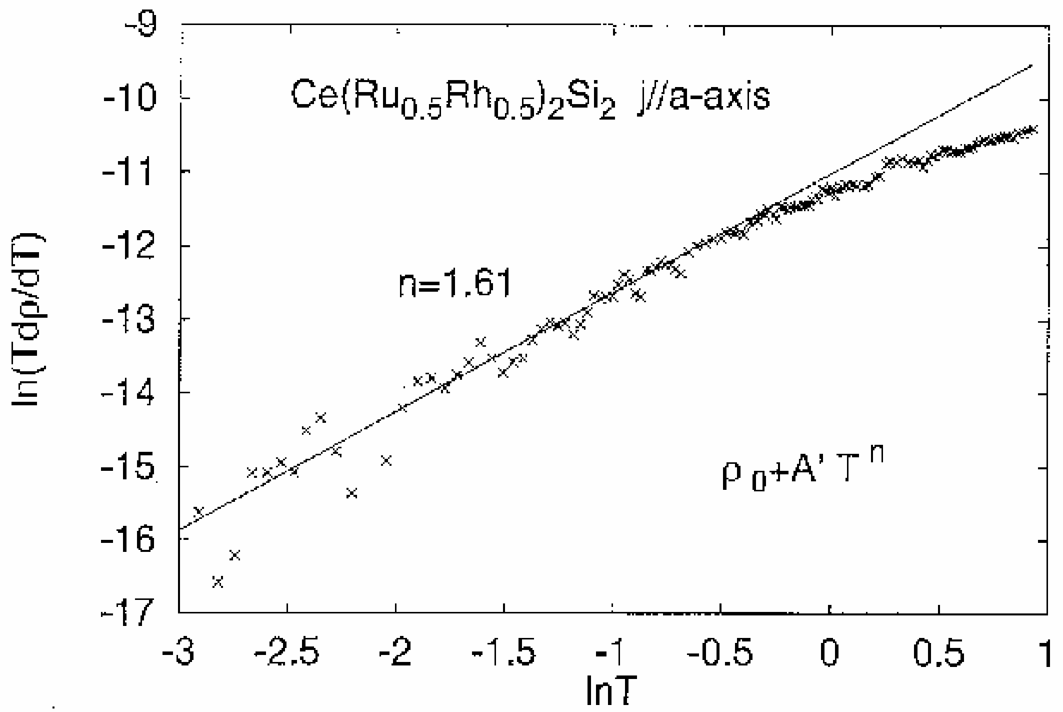


Figure 3.33: The differential resistivity of $x = 0.5$ along a axis at zero filed is shown in the form of $\log(T d\rho/dT)$ vs $\log T$.

The Resistivity as a Function of a Magnetic Field H

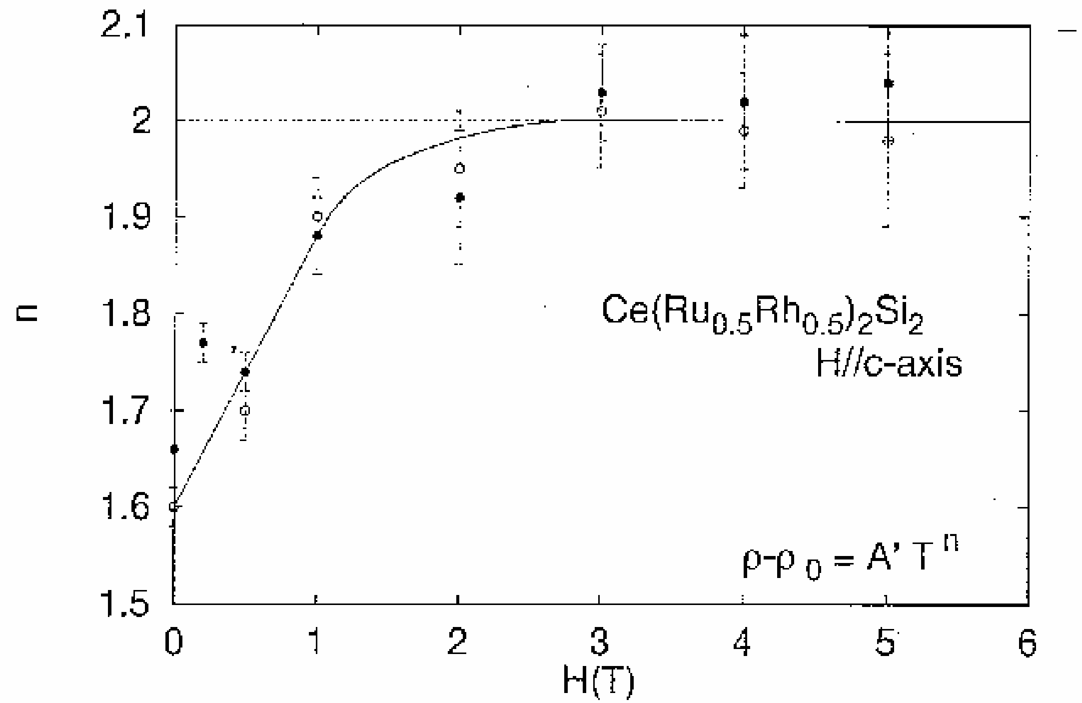


Figure 3.34: The power of the resistivity n is shown as a function of a magnetic field H. In this figure the open circles represent that along c-axis and the closed circles represent that along a-axis.

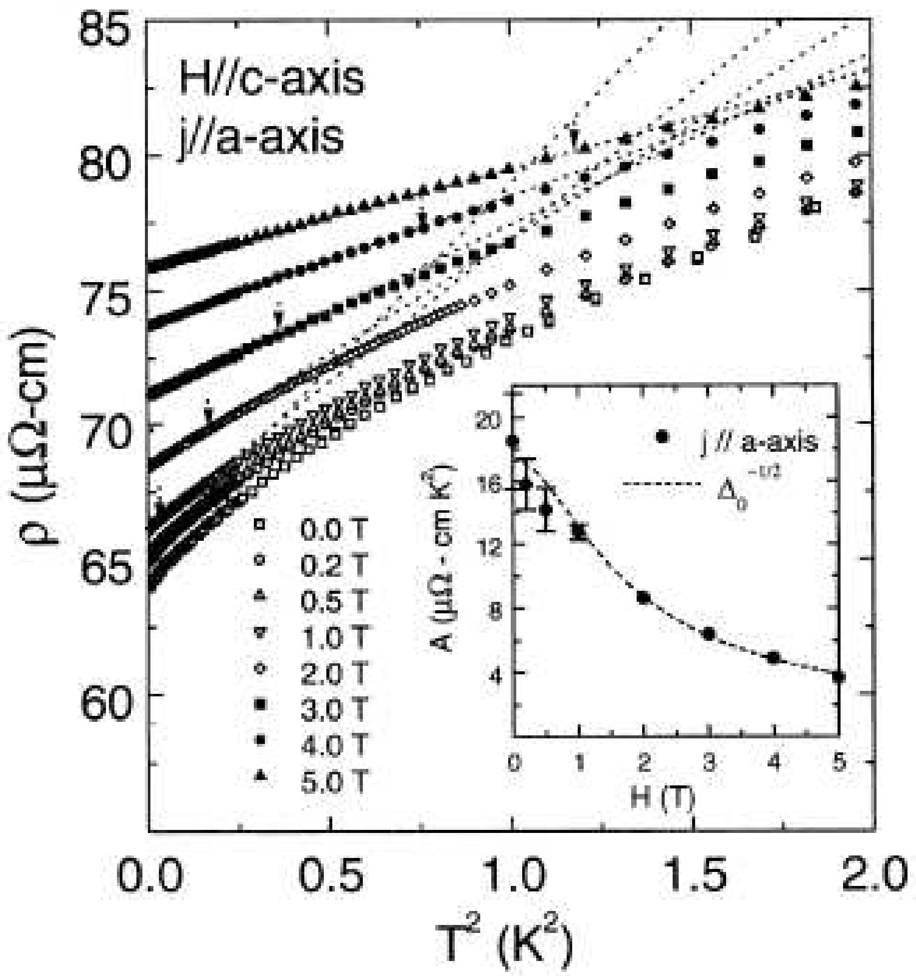


FIG. 1. Resistivity of $Ce(Ru_{0.5}Rh_{0.5})_2Si_2$ in a magnetic field as a function of T^2. The magnetic field is along the c axis and the current flows along the a axis. The arrows indicate the range of temperature where the resistivity varies as T^2. Inset: field dependence of $A = d\rho/dT^2$ determined from the data below 100 mK.

Origin of non-Fermi liquid behaviors

(1) Ploliferation of spin fluctuations near QCP.

(2) Distribution of T_K in mixed compound.

- magnetic to non-magnetic transition occurs at T = 0, which is quantum critical point (QCP). In $Ce(Ru_{0.5}Rh_{0.5})_2Si_2$, Ru rich side is non-magnetic and Rh rich side is magnetic. In addition to the spin fluctuations characteristic of the QCP, there is quantum Griffiths like behavior.
- **$Ce(Ru_{0.5}Rh_{0.5})_2Si_2$ is expected to be another example of non-Fermi liquid behavior.**
-

The experimental results were interpreted by Grempel's theory for spin glass QCP model and the quantum Griffths – phase scenario.

Theoretical predictions

- $\rho\,(T,H) - \rho\,(0,H) \sim T^{3/2}\,\Psi\,(T/\Delta T_0)$, where $\Delta\,(T,H)$ is the effective distance to the QCP and $\delta\rho = T^{3/2}$ at QCP.
- $\delta\chi = \chi(0) - \chi(T) \sim T^{3/4}$ at QCP.
- $\gamma_{MF} = C/T \sim 1 - b\,T^{1/2}$

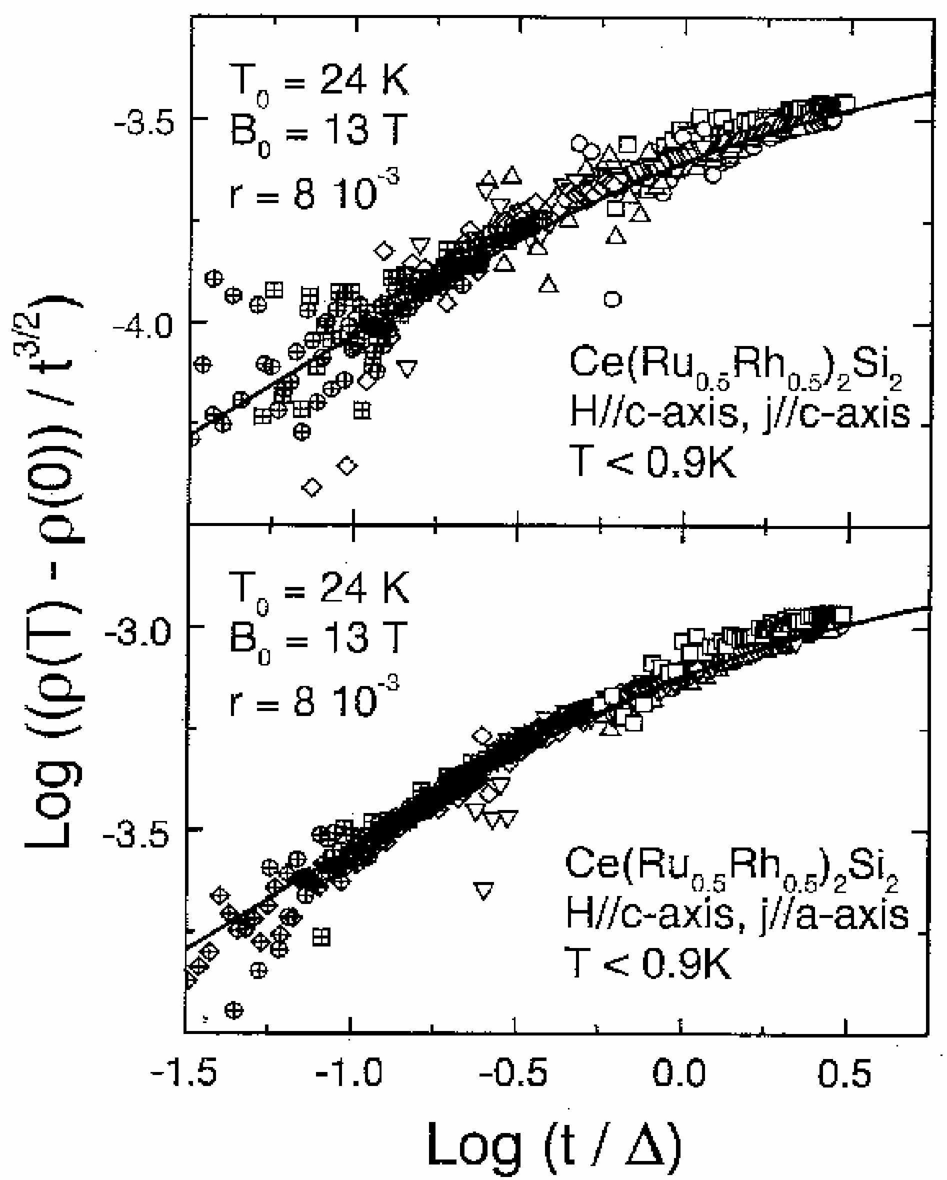


Figure 3.40: Scaling plots of the resistivity along a- and c-axis. The solid line is the theoretical scaling curve.

The Susceptibility

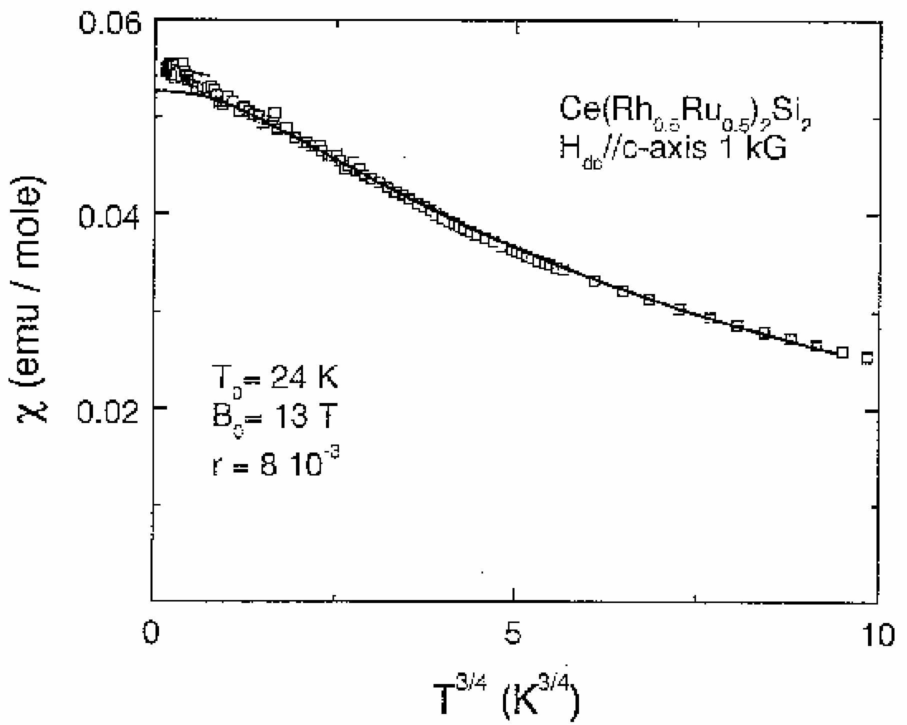
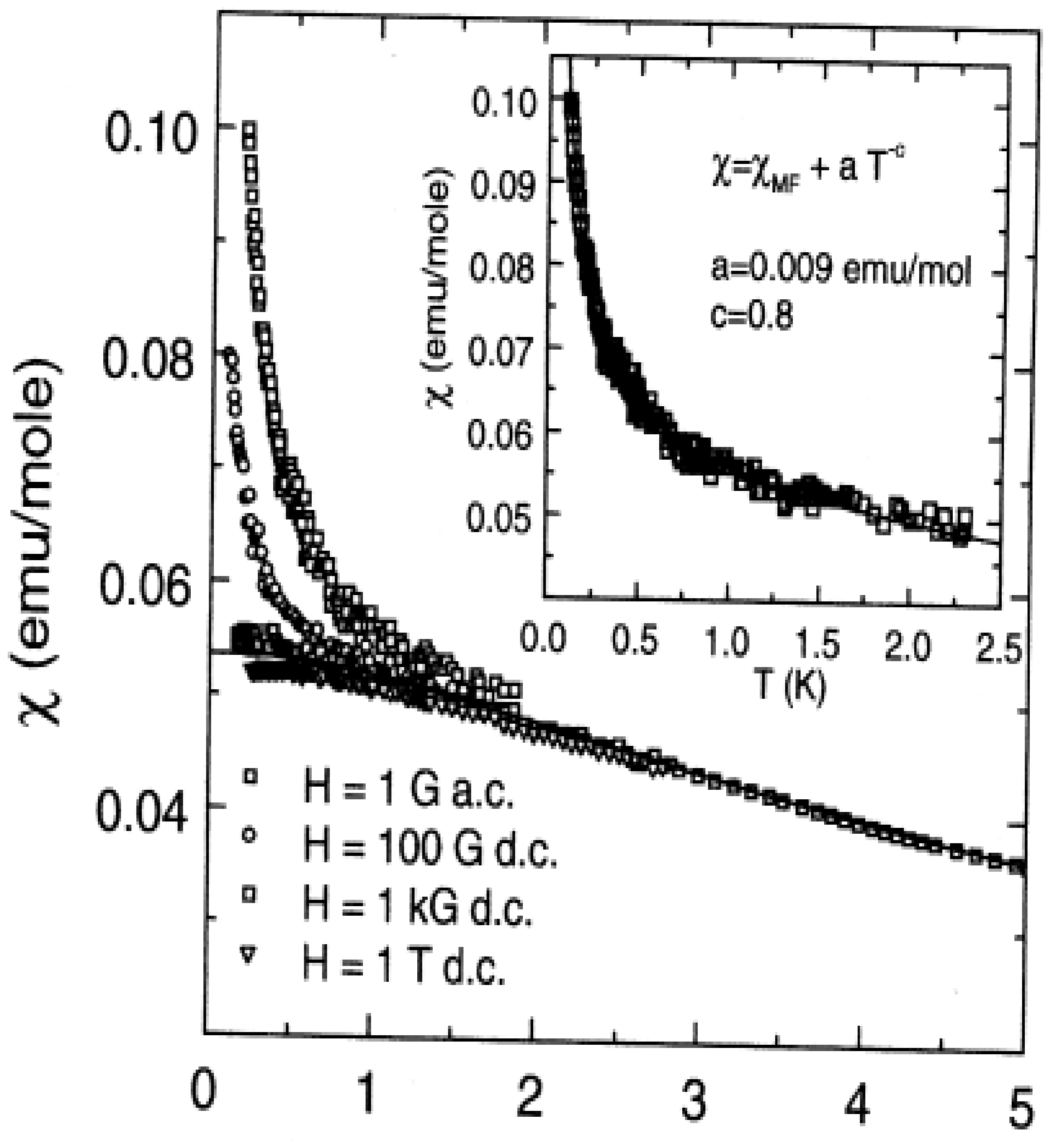


Figure 3.39: The DC susceptibility at 1kG down to 100 mK along c-axis is shown. The solid line represents the theoretical result computed as described in the text.

- The value of the parameters are $r = 8 \times 10^{-3}$, $T_0 = 24$ K and $H_0 = 13$ T.

$r = \delta J / J_C$ measures the distance to the true QCP, giving $\delta J \sim 0.2$ K.

For the measurement of small magnetic field less than 1kG, the susceptibility shows divergent behavior toward T = 0. This divergent behavior is due to Rh rich domains in the mixed compound of $Ce(Ru_{0.5}Rh_{0.5})_2Si_2$. The magnetic moment remains in the Rh rich region.



χ (emu/mole)
0.10
0.08
0.06
0.04
0
1
2
3
4
5
H = 1 G a.c.
H = 100 G d.c.
H = 1 kG d.c.
H = 1 T d.c.
χ=χ_MF + a T^-c
a=0.009 emu/mol
c=0.8
0.10
0.09
0.08
0.07
0.06
0.05
0.0
0.5
1.0
1.5
2.0
2.5
T (K)

- Antiferromagnetic clusterings develop rapidly near 2 K and the cluster size seems to stay finite below 0.7 K with 1 μ sec correlation time inside the clusters.

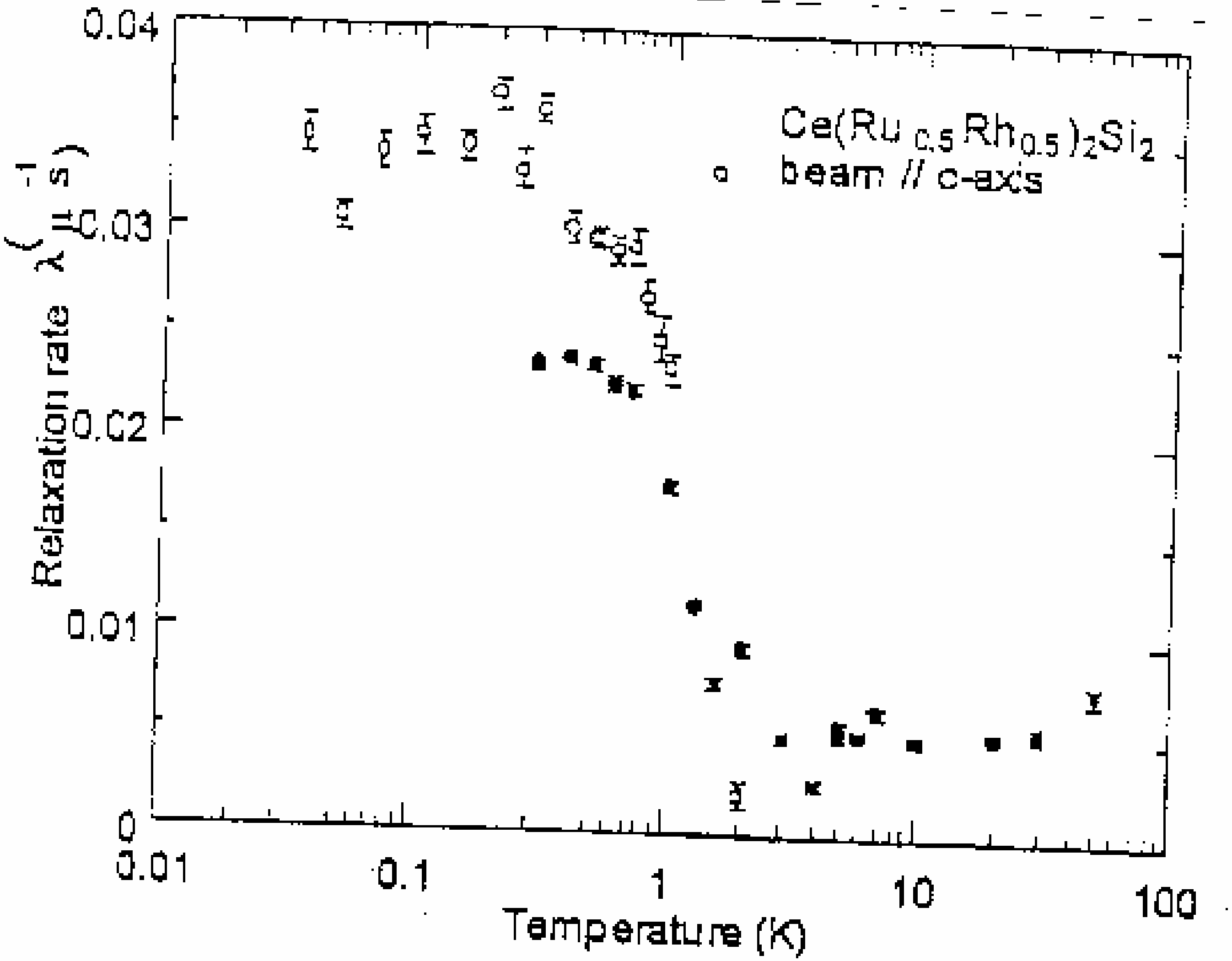
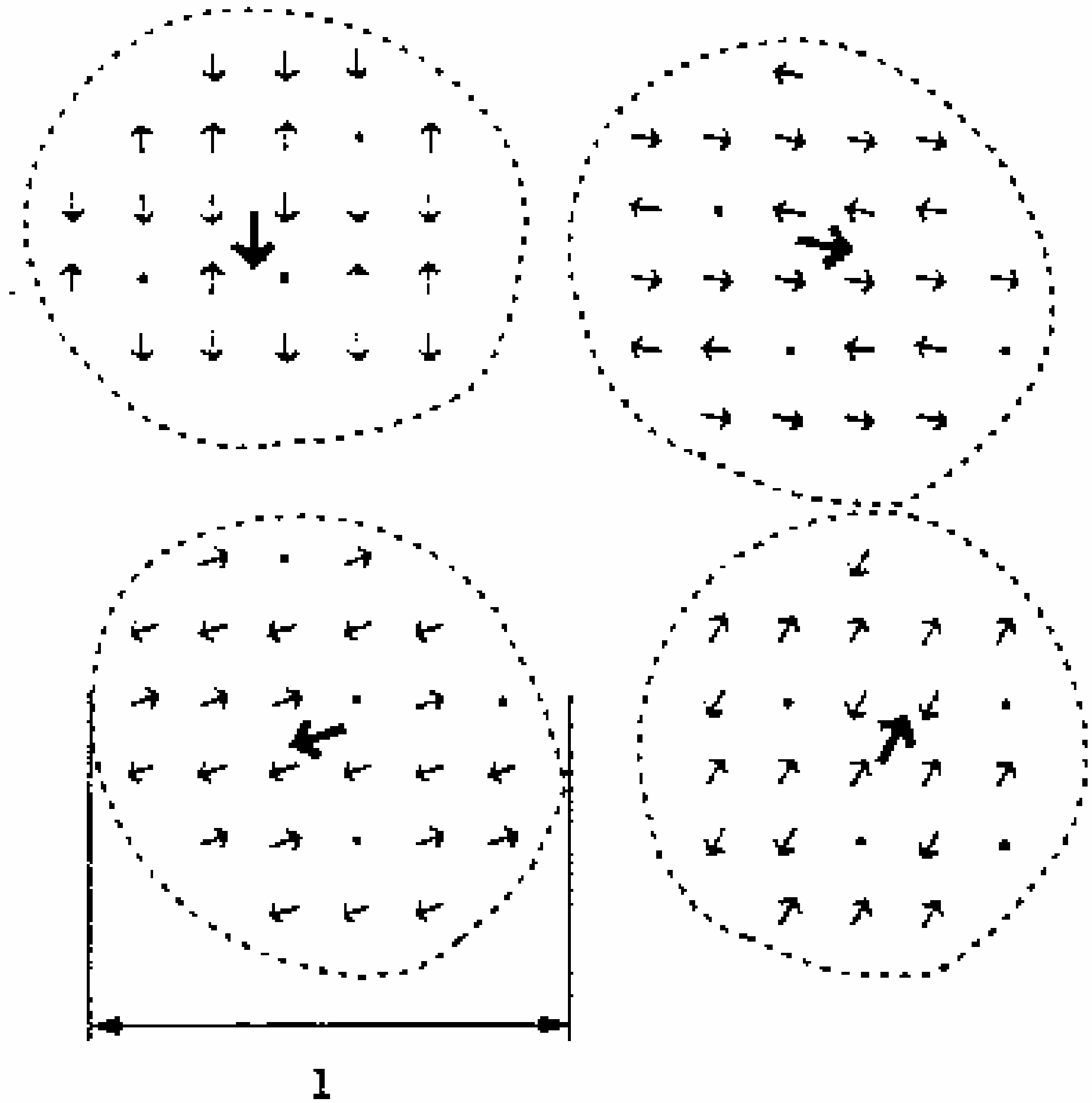


Fig. 12. Temperature dependence of the relaxation rate $\lambda(= 1/T_1)$ for $x = 0.5$. Open and closed circles are the data for the single crystal measured at KEK and Ratherford-Appleton Laboratory, respectively. The incident muon spin is parallel to the c-axis of the single crystal.



Schematic drawing of a Griffiths's like phase.

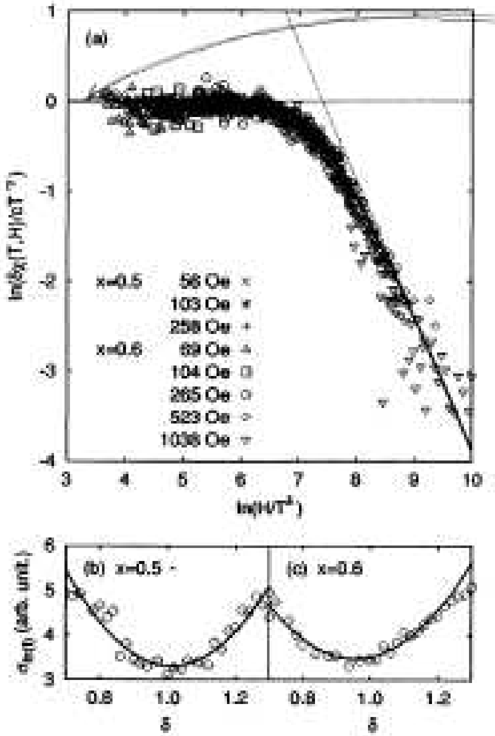


FIG. 5. (a) Scaling plots of $\delta\chi(T,H)$ for $x=0.5$ and 0.6. The values of γ and the c-coefficients are assigned the values obtained from the analysis at zero field, where $\gamma=0.71$ and 0.6 and $c=0.013$ and 0.0038 emu/mol for $x=0.5$ and 0.6, respectively. The values of δ are fixed to be 1 for both concentrations. The solid line represents the scaling function $f(h)$ described in the text. The dashed lines represent the asymptotic behaviors of $f(h)$ as $h\to 0$ and as $h\to\infty$, respectively. (b) and (c) show the mean square (log) deviation $\sigma_{\ln(f)}$ (see text) for $x=0.5$ and 0.6, respectively. The solid lines are fits to a quadratic function.

$f(h) = \dfrac{1}{(1+h^2)^{\varepsilon/2}}$

$\varepsilon = 1.5$

(no theoretical foundation.)

As $H \to 0$, $\delta\chi$ asymptotes to the divergent behavior $cT^{-\gamma}$

$\delta\chi(T,H) \to cH^{-1.5}T^{1.5-\gamma}$ as $T \to 0$.

$\Downarrow$

$\delta\chi(T,H) \to 0$ at 0K

$$\delta\chi(T,H) = cT^{-\gamma} f\left(\frac{H}{T^{\delta}}\right)$$

$$\ln\left(\delta\chi(T,H)/cT^{-\gamma}\right) \text{ vs } \ln\left(H/T^{\delta}\right)$$

Non-Fermi-Liquid Scaling in $Ce(Ru_{0.5}Rh_{0.5})_2Si_2$

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We study the temperature and field dependence of the magnetic and transport properties of the non-Fermi-liquid (NFL) compound $Ce(Ru_{0.5}Rh_{0.5})_2Si_2$. For fields $H \lesssim 0.1$ T the results suggest that the observed NFL behavior is disorder driven. For higher fields, however, magnetic and transport properties are dominated by the coupling of the conduction electrons to critical spin fluctuations. The temperature dependence of the susceptibility as well as the scaling properties of the magnetoresistance are in very good agreement with the predictions of recent dynamical mean-field theories of Kondo alloys close to a spin-glass quantum critical point.

DOI: 10.1103/PhysRevLett.86.524 PACS numbers: 75.30.Mb, 74.70.Tx, 75.40.Cx


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Ocio's most impressive research

- The study of 1/f magnetic fluctuations in spin glasses.

  Invited paper at ICM conf. in San Fransisco(1985)

- Experimental study on a generalization of the fluctuation dissipation relation in non-ergodicity system.

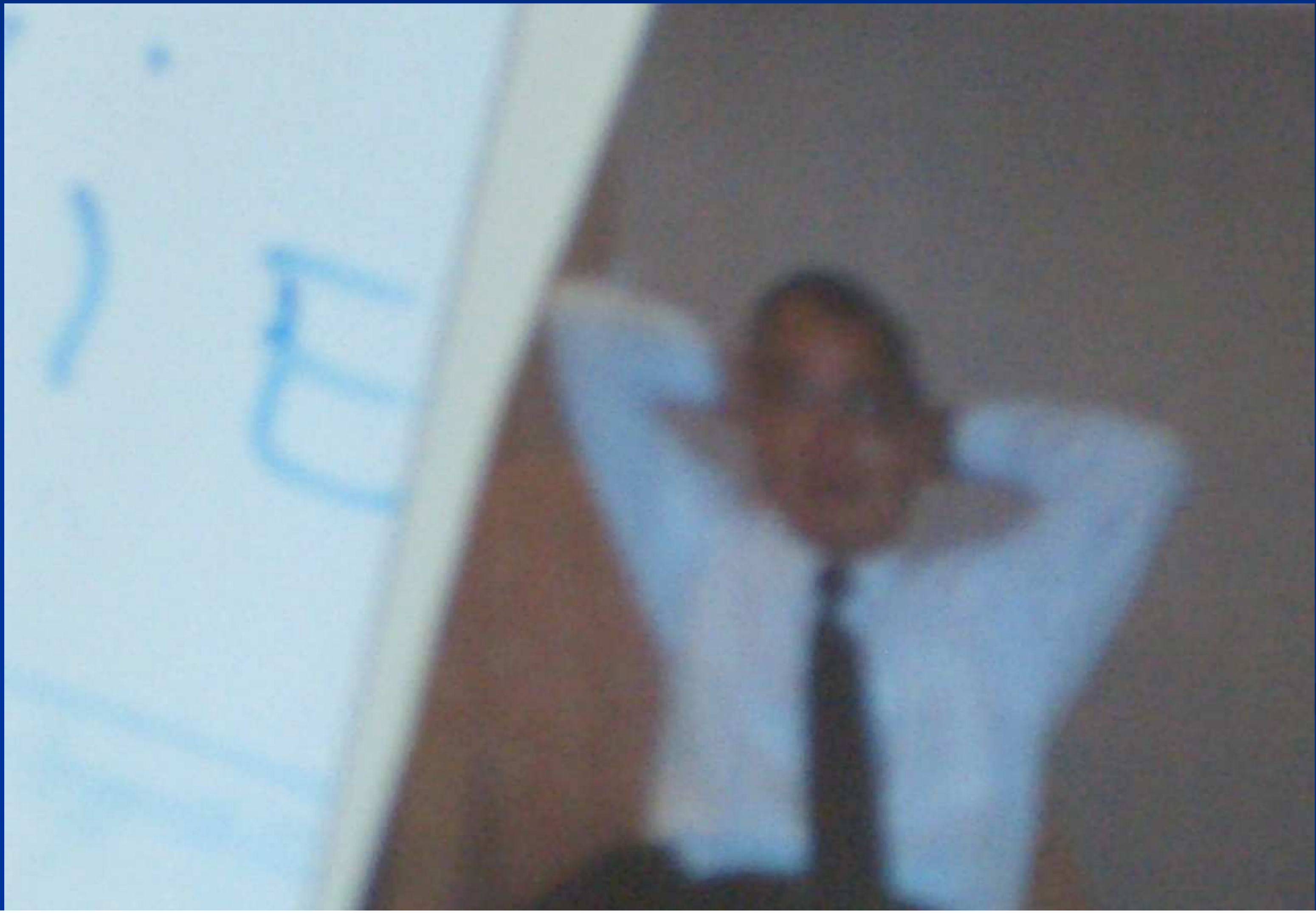
  Invited paper at LT conf. in Hiroshima (2002)


阿波おどり
徳島　夏
阿波おどり
DVD好評発売中。
▶SKI

Miguel's note and scientific articles

Miguel absent office

The photo stuck on the board in Miguel's office in April, 2004.



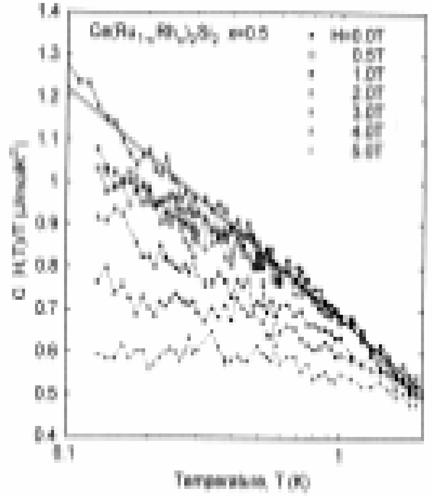


Fig. 1. The specific heat of $Ce(Ru_{0.5}Rh_{0.5})_2Si_2$ as C/T vs. T at varying magnetic field applied along c-axis. The solid line represents the logarithmic divergent behavior at zero field.

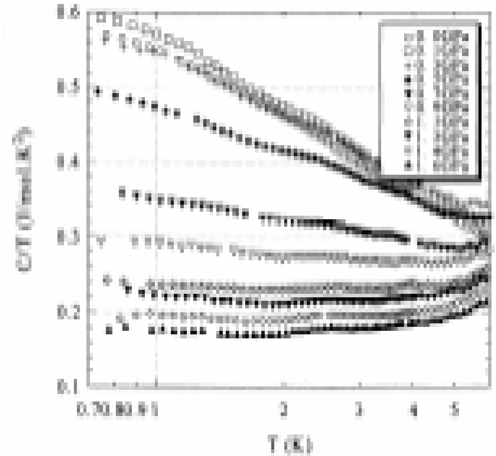


Fig. 1. Specific heat C divided by temperature T as a function of temperature on a logarithmic scale for the $Ce(Ru_{0.6}Rh_{0.4})_2Si_2$ compound at various pressures.