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"Disorder and Interaction in Quantum Systems and Their Classical Analogs"

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"Fermi liquid and non-Fermi liquid behaviour in layered perovskite oxide superconductors: Sr_2RuO_4 vs $Tl_2Ba_2CuO_{6+\delta}$"

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Fermi liquid and non-Fermi liquid behaviour in layered perovskite oxide superconductors: Sr_2RuO_4 vs $Tl_2Ba_2CuO_{6+\delta}$

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1. Introduction

2. non-Fermi liquid behaviour in the cuprates
    - high vs. low temperature transport in $Tl_2Ba_2CuO_{6+\delta}$

3. Fermi liquid behaviour in Sr_2RuO_4
    - transport properties: low temperature cross-over to Fermi liquid power laws
    - quantum oscillation measurements
    - comparison with photoemission measurements

4. discussion/conclusion

Introduction

- ***non-Fermi liquid behaviour is well established at high temperatures in the cuprate superconductors***

  a generic property of low dimensional metals? (e.g. of 2-d Hubbard model); due to proximity to antiferromagnetism?; due to disorder?; ...?

- ***One approach to understanding this is to try to find the conditions under which a cuprate <u>is</u> a Fermi liquid:***

  find a clean system and examine the T –> 0 limit

  (cf NCCO)

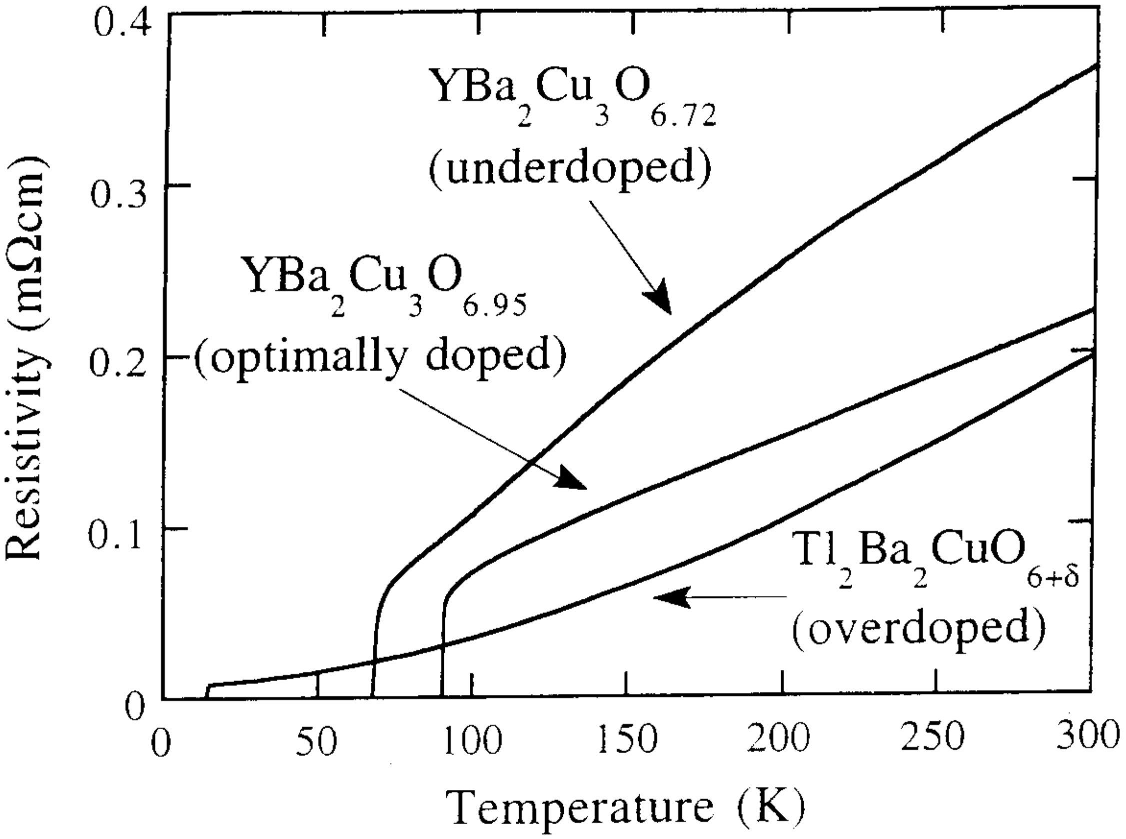
$Tl_2Ba_2CuO_{6+\delta}$ (Tl 2201)

- clean system because doping takes place away from the copper-oxide plane
- can supress superconductivity by extreme overdoping

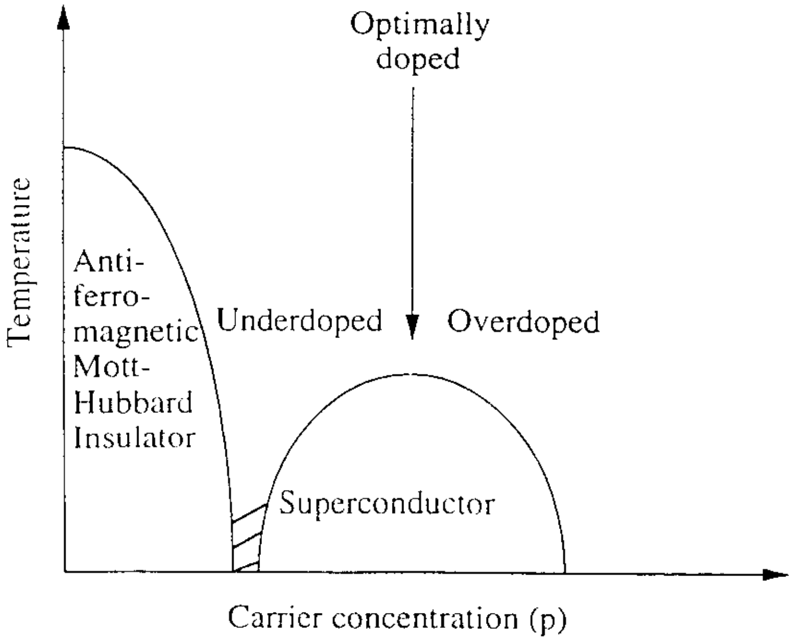
Sr_2RuO_4

- stoichiometric, superconducting (T_c=1K) layered perovskite oxide
- not a cuprate, same crystal structure as $La_{2-x}Sr_xCuO_4$

Resistivity vs. temperature in the cuprates

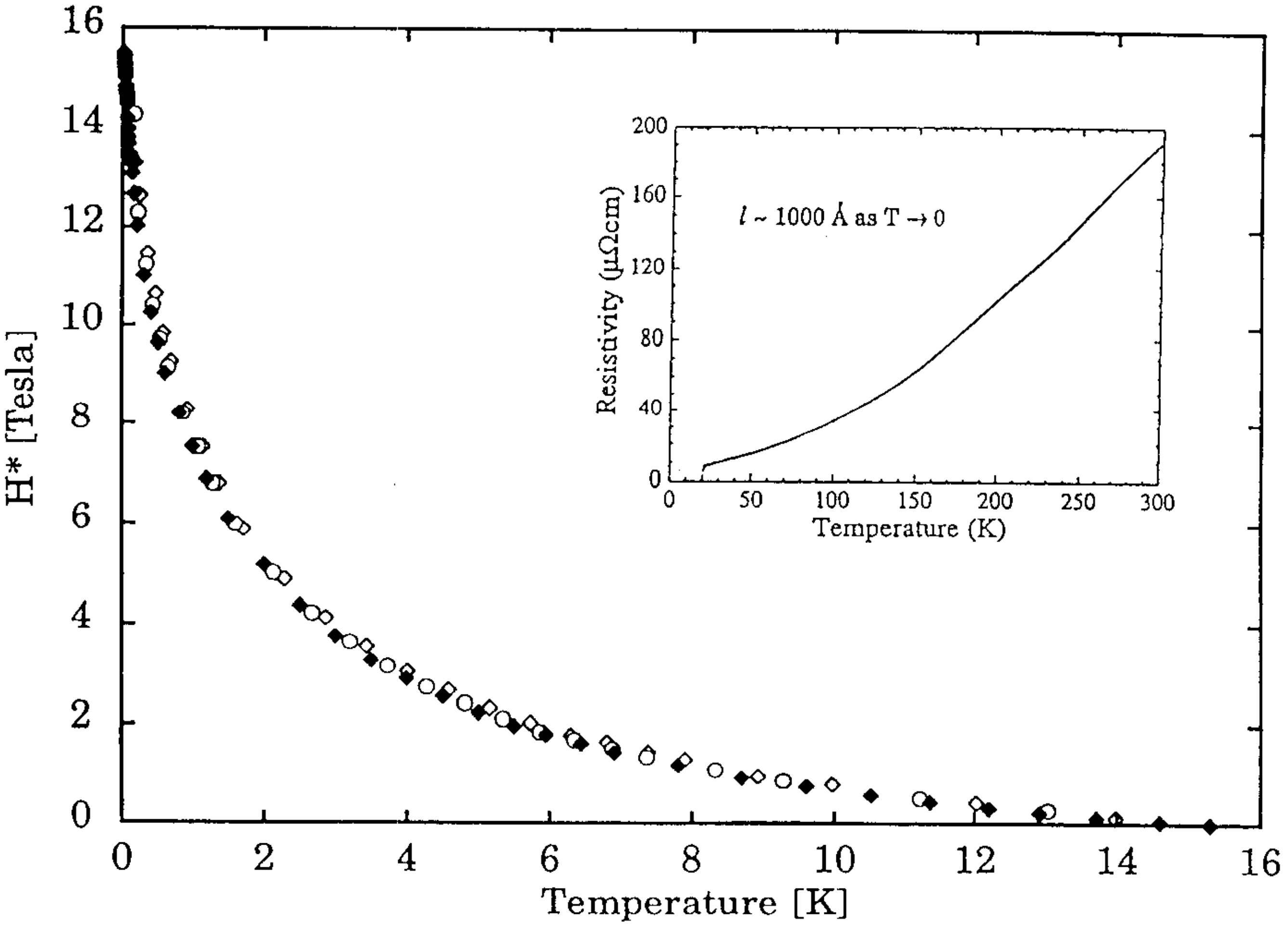


- *the overdoped 2201 system looks the most "Fermi liquid like", but at least at the high temperatures shown, the resistivity does not fit a* T^2 *law*



- *it proves to be very difficult to dope single crystals of* $Tl_2Ba_2CuO_{6+\delta}$ *to the point where superconductivity is completely supressed; we use magnetic field to supress* T_c *the rest of the way*

$Tl_2Ba_2CuO_6$: Temperature Dependence of the Upper Critical Field

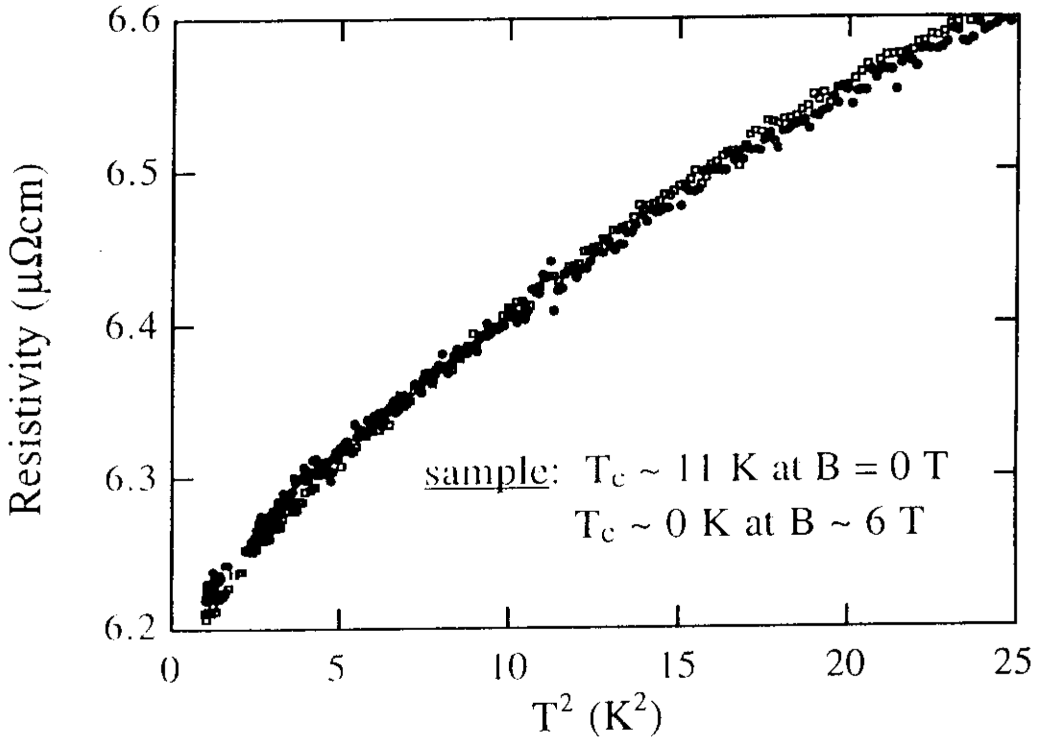


<u>sample</u>: $T_c \sim 15$ K at $B = 0$ T
$T_c \sim 0$ K at $B \sim 16$ T

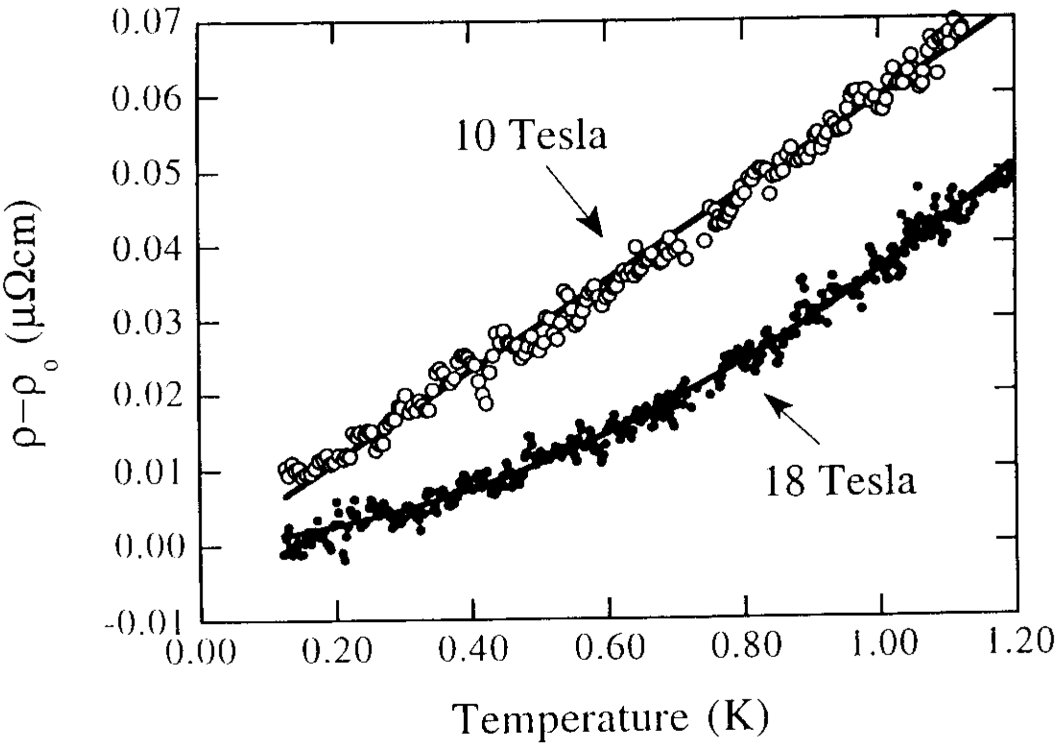
A. P. Mackenzie et al., Phys Rev Lett **71** (1993) 1238.

- *H* shows unexpected and dramatic upward curvature that extends into the millikelvin regime*

Resistivity vs. T in $Tl_2Ba_2CuO_{6+\delta}$ in the $T \rightarrow 0$ limit

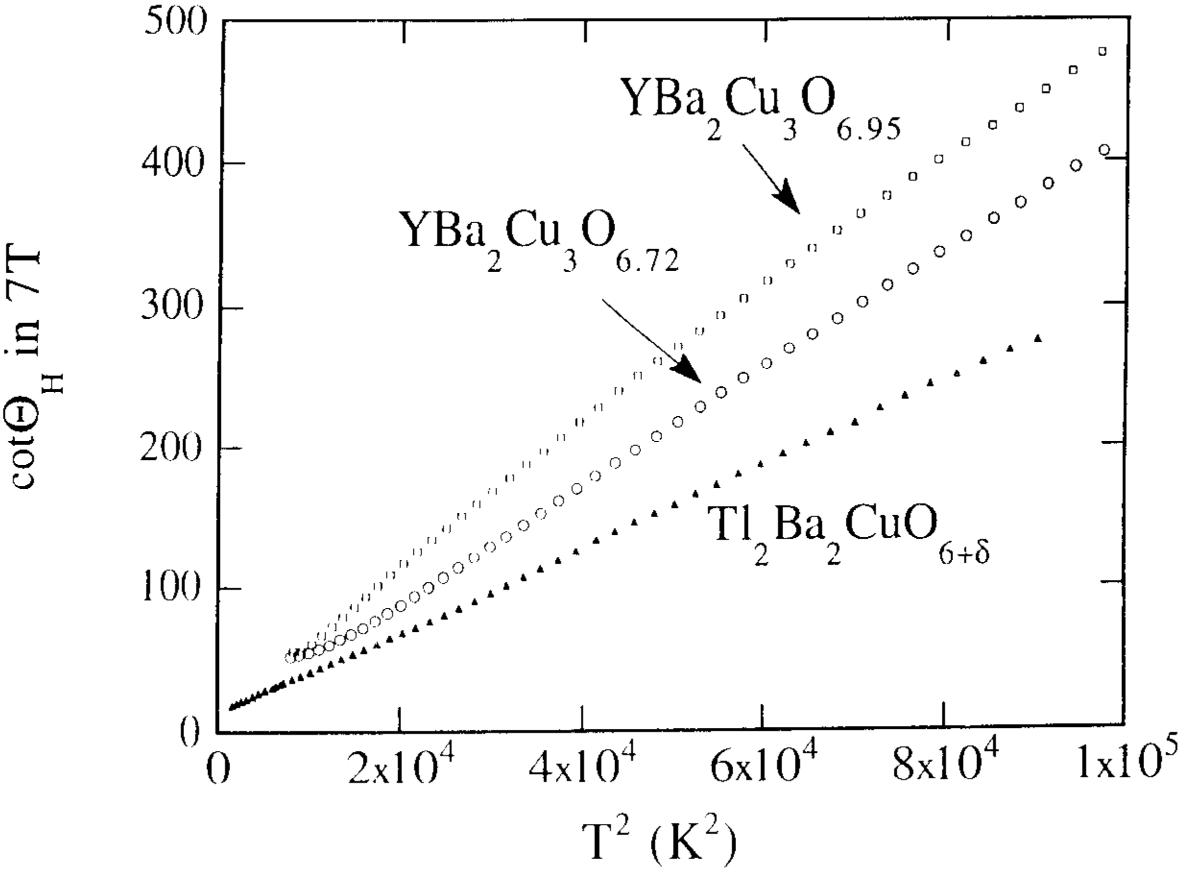


- "expected" cross-over to T^2 behaviour is not seen, to below 1K



- increasing the field to 18 T produces upward curvature; may signal cross-over towards FL.

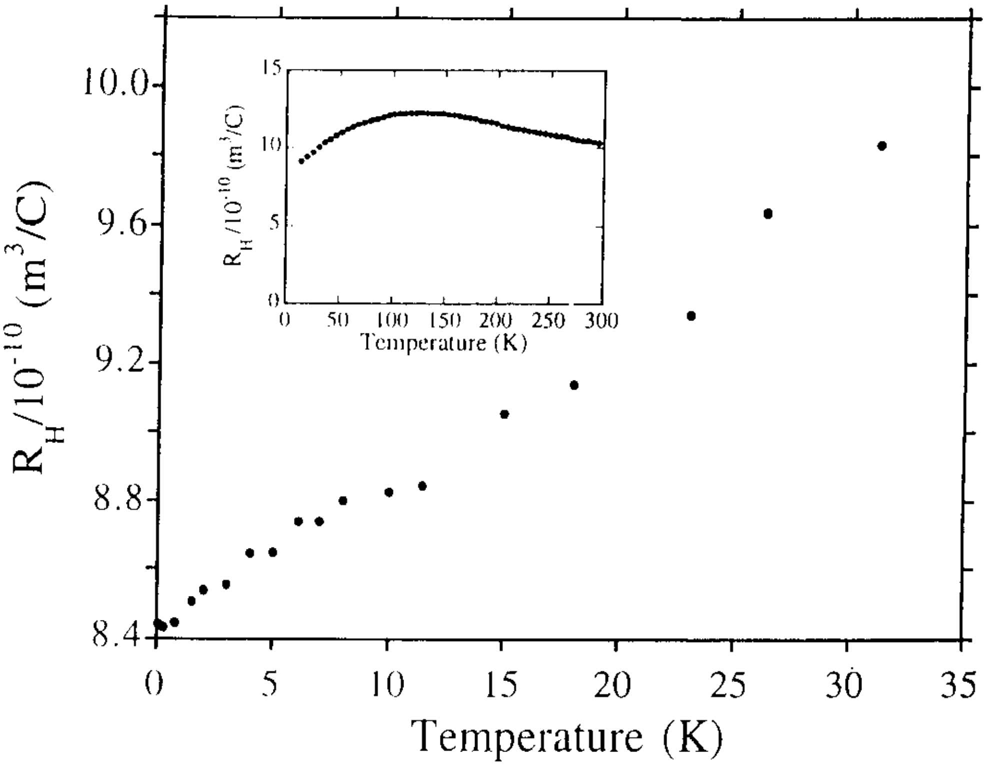
"two lifetime" phenomenology of transport in the cuprates



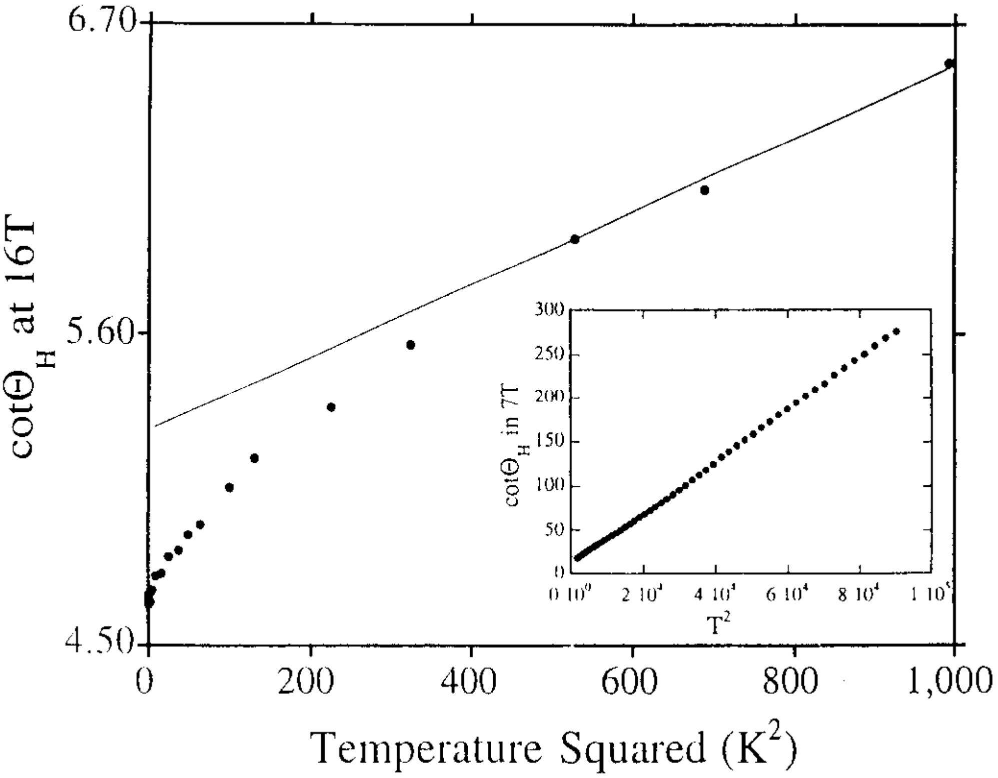
- $\rho(T)$, $R_H(T)$ have 'strange' temperature dependences, however the Hall angle, $\cot\Theta_H = \rho/R_H B$, varies as $a + bT^2$

P.W. Anderson,
PRL 67 (1991) 2092.

Hall coefficient in overdoped $Tl_2Ba_2CuO_{6+\delta}$ in the T → 0 limit

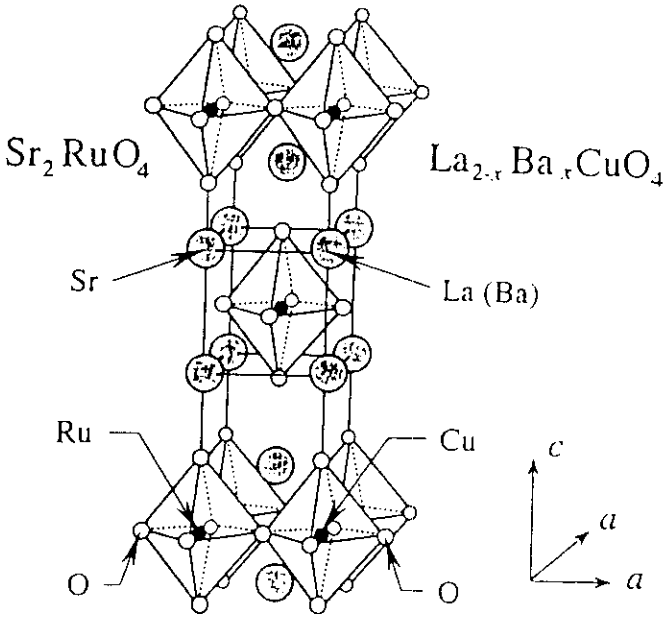


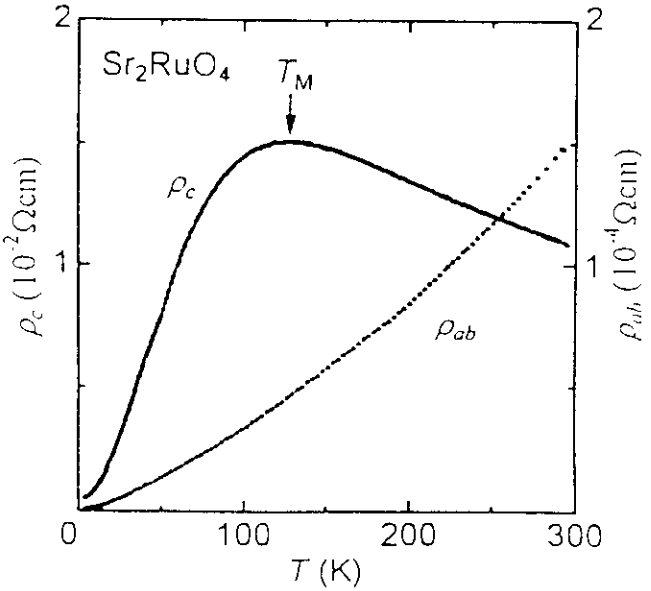
- R_H continues to show a T dependence as T → 0

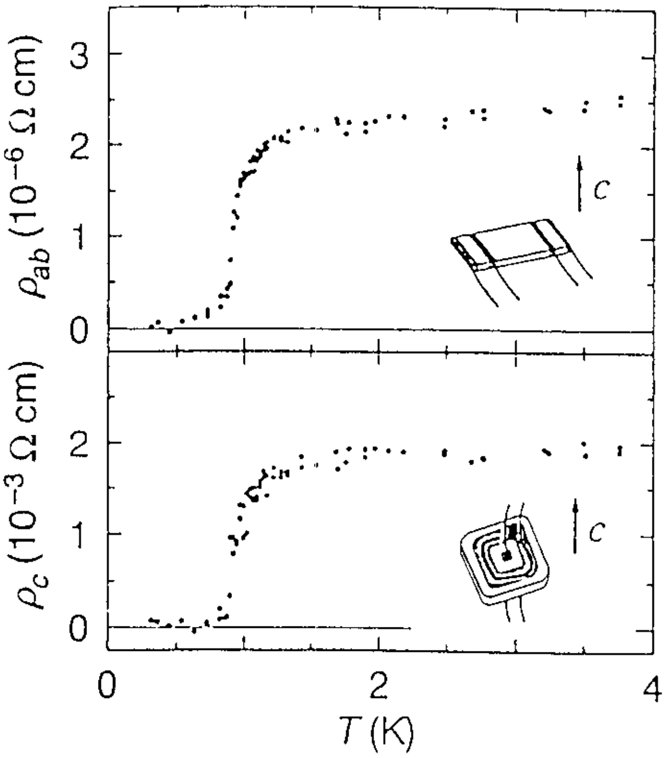


- $\cot\Theta_H$ loses its T^2 dependence at low temperature, crossing over to a lower power of T

Sr_2RuO_4: a layered perovskite without copper

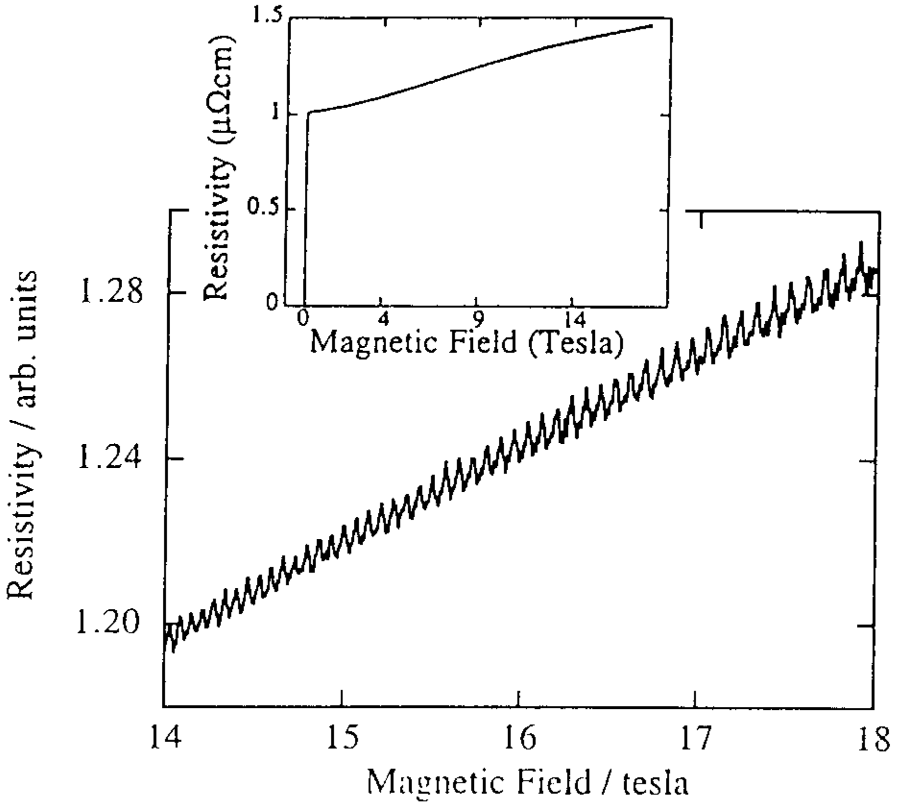


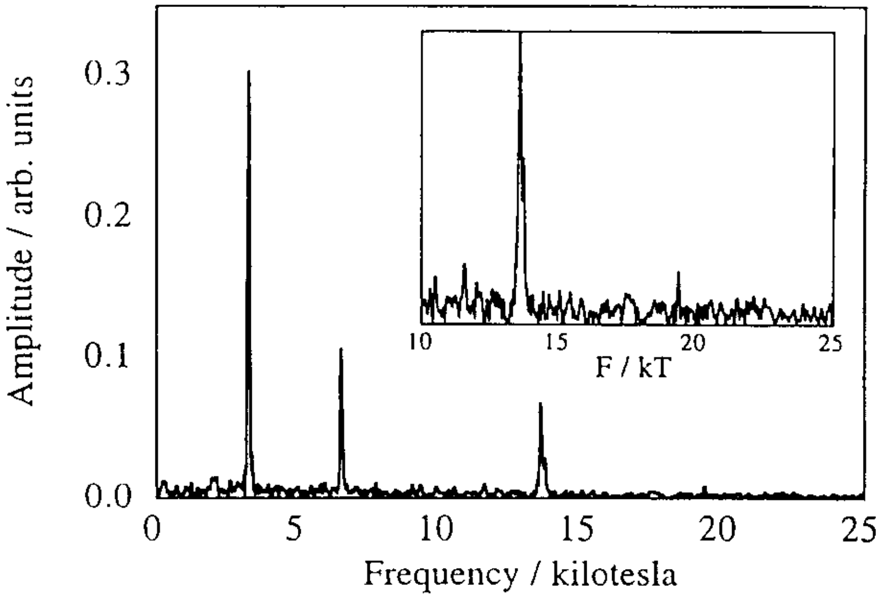




Y. Maeno et al.
Nature **372** (1994) 532.

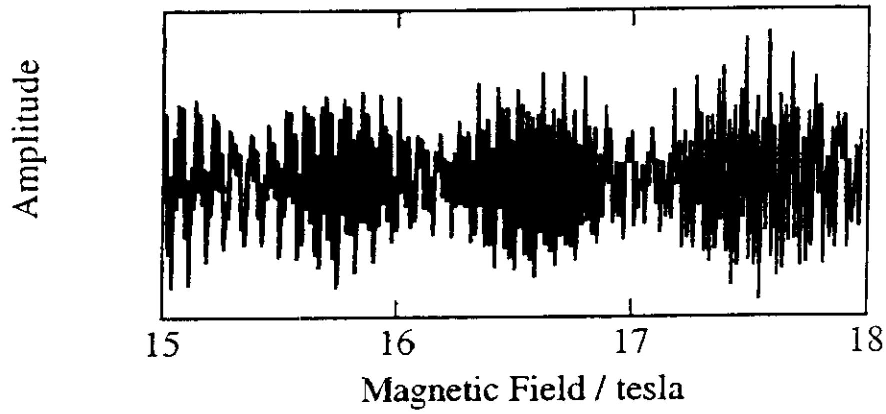
Quantum oscillatory magnetoresistance in Sr_2RuO_4

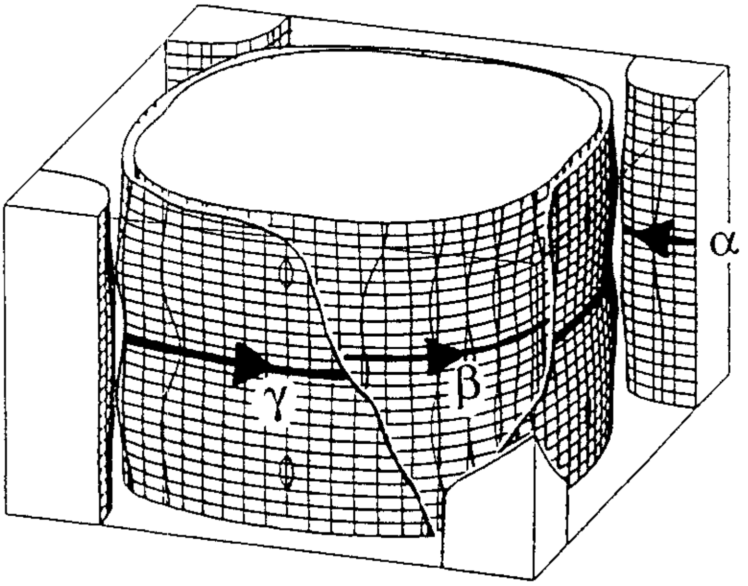




The quantum oscillatio freqency F is related to the extremal Fermi surface cross-section A by $A = 2\pi eF/\hbar$

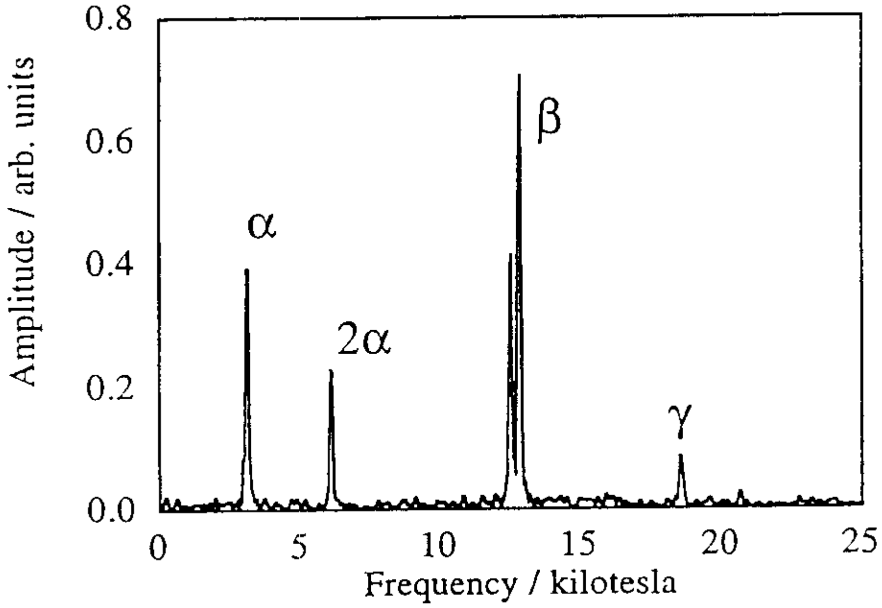
Quantum oscillatory magnetisation in Sr_2RuO_4



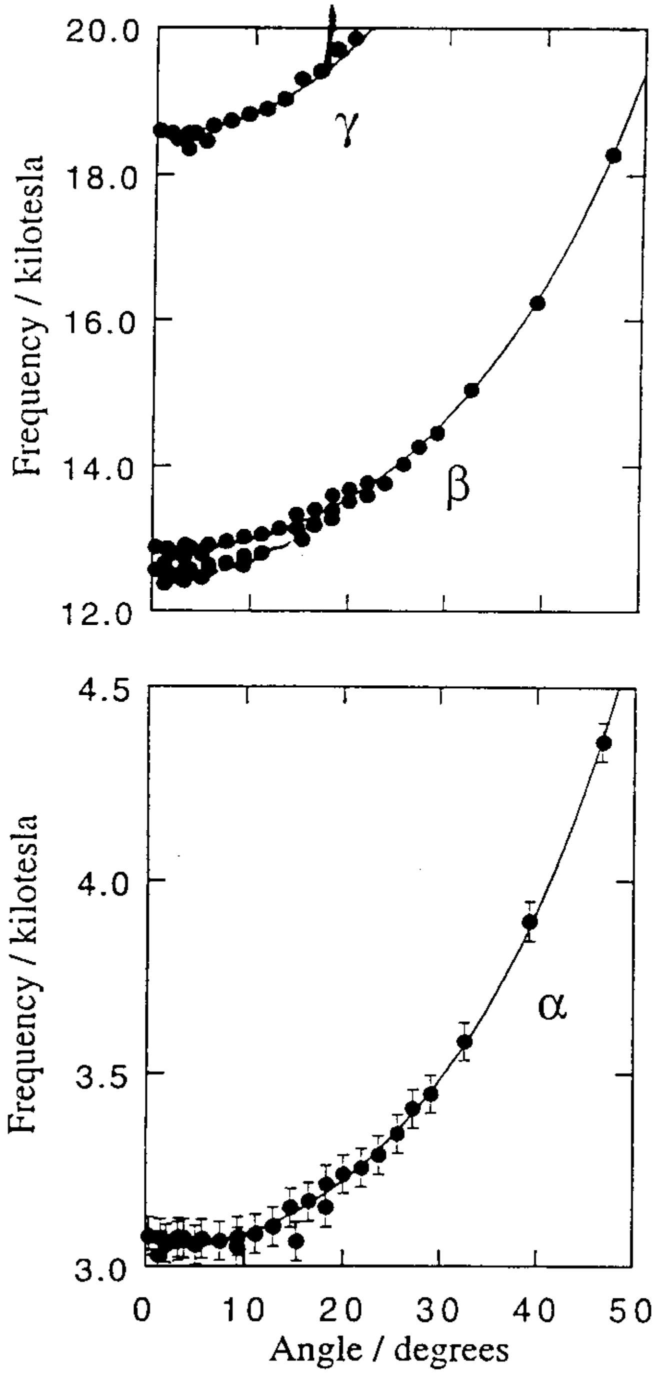


G.J. McMullan, M.P. Ray

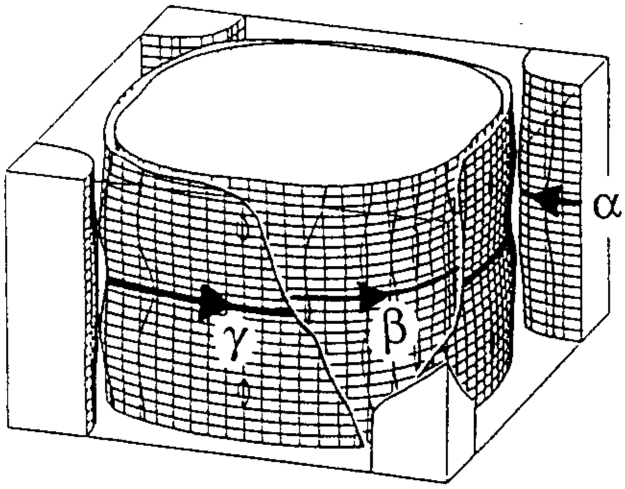
T. Oguchi
Phys. Rev. B
51 (1995) 1385.



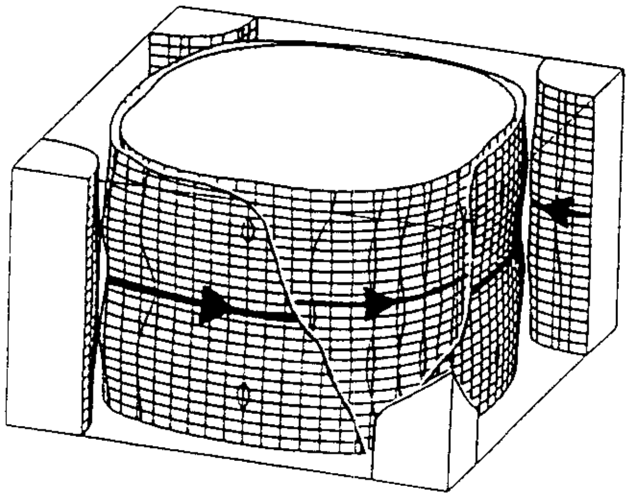
Angle dependence of frequencies

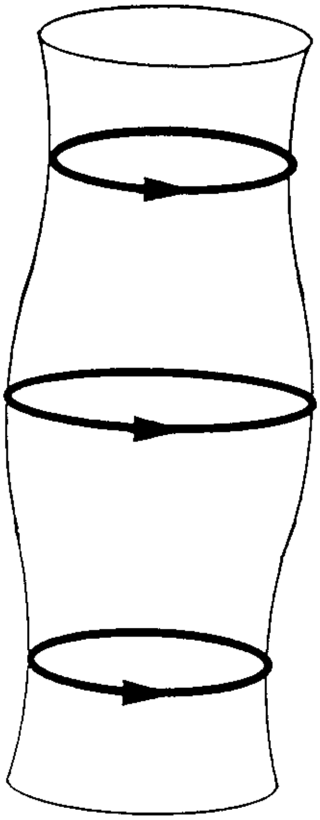


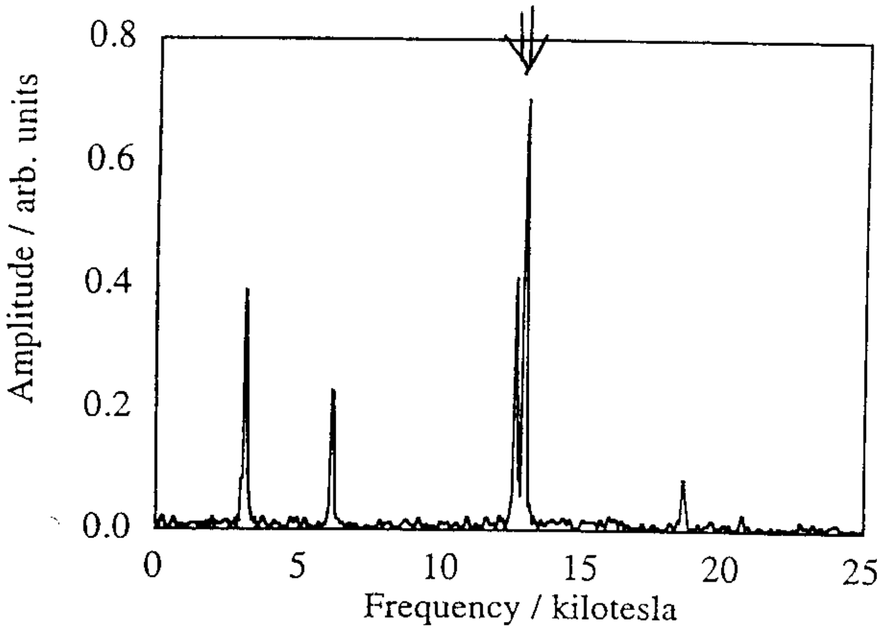
$\frac{1}{\cos \Theta}$ = cylinders.



Departure from two-dimensionality







Temperature Dependence of the Amplitude of Magneto-oscillations

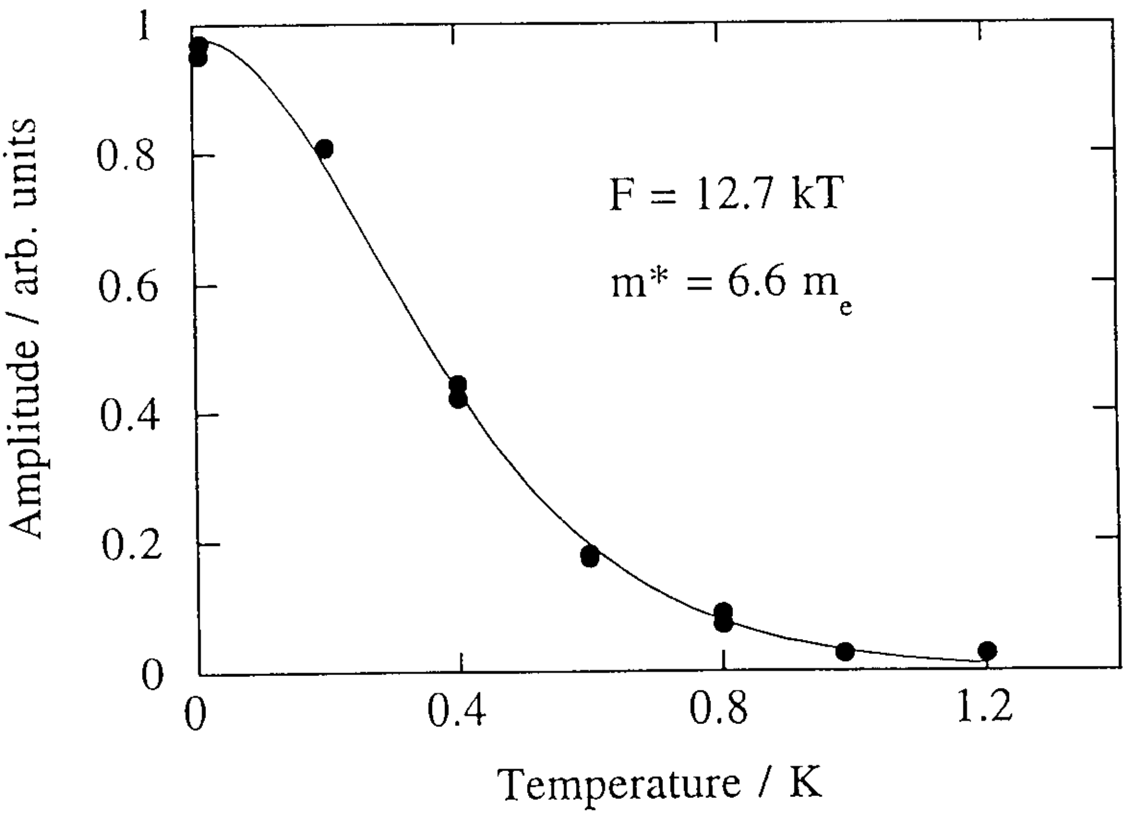
Amplitude = Average of $e^{i2\pi\varepsilon/\hbar\omega_c}$ over thermal broadening function $P(\varepsilon)$ of width ~ kT

—— for $P(\varepsilon) = -\frac{\partial}{\partial\varepsilon}$ (Fermi Function)

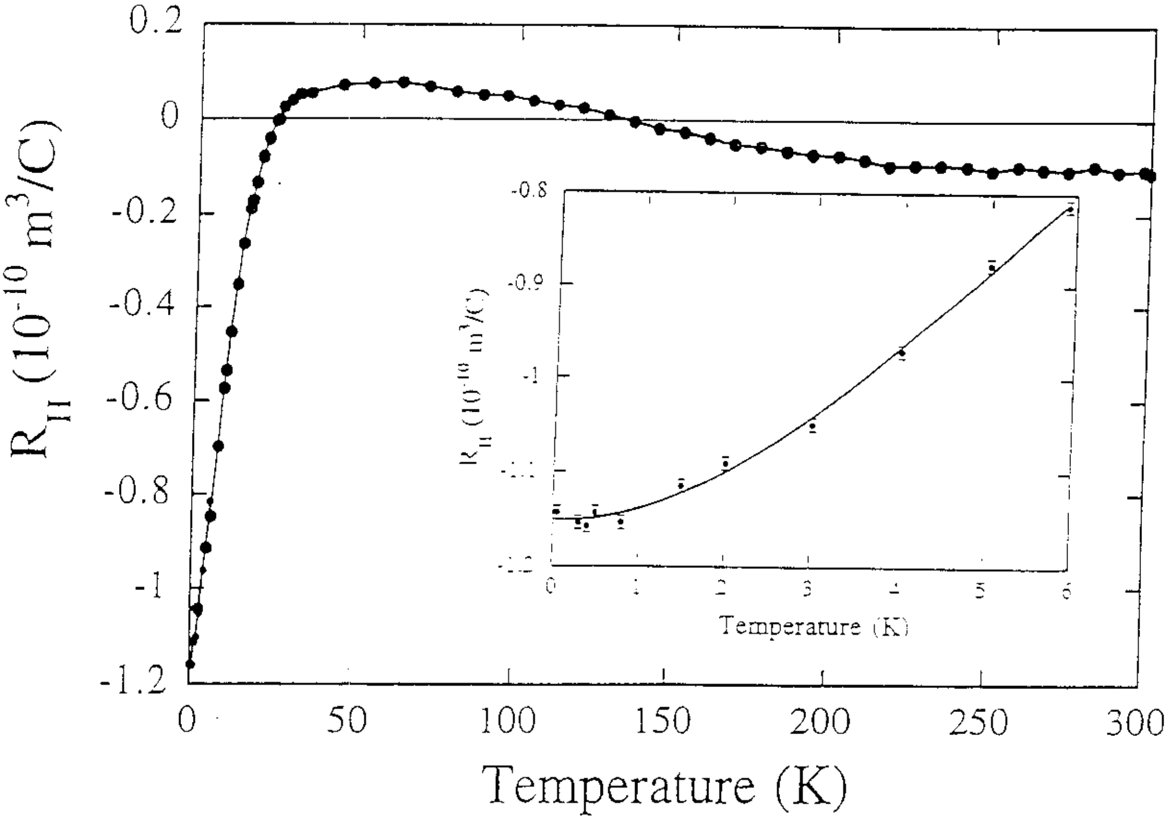
	α	β	γ
m^*/m_e:	3.2	6.6	12
m^*/m_{band}:	~3	~3	~4

Predicted linear coefficient of specific heat from measured quasiparticle masses is ~ 32 mJ/mole K^2

Measured: 29 (S. A. Carter et al., Phys Rev B 51 (1995) 17184)
39 (Y. Maeno et al., Nature 372 (1994) 532.)



Hall coefficient in Sr_2RuO_4



- *R_H is strongly temperature dependent, which is not remarkable in a **multiband** system, but it saturates below 1K*

- *using our measured Fermi surface areas, and assuming isotropic mean free path at low temperature, we can estimate $R_H \sim -0.9 \times 10^{-10}$ m^3/C, in fair agreement with the measured value of -1.1×10^{-10} m^3/C*

Calculation of the electron number and Hall coefficient from dHvA data

Pocket areas (A) are related to observed frequencies:

$$A = 2\pi eF/\hbar$$

Zone area (containing 2 electrons) = $(2\pi/a)^2$
$a = 0.387$ nm

Relationship between number of carriers (N_c) enclosed in a pocket and the observed frequency:

$$N_c = 0.0724F, \text{ where F is in kT}$$

So in the 2-D approximation, we have three pockets, containing 0.22, 0.92 and 1.34 carriers respectively.

Quantum oscillation measurements do not give the sign of the carriers in each pocket.

Only help that we need from band structure calculations: there are three bands crossing the Fermi level.

If our small pocket is a hole pocket, and the larger two are electron pockets, we sum to 4 electrons in the B.Z. to an accuracy of 1%.

- *this is the only assignment which is consistent with the negative low T Hall coefficient*

Further assumption - circular pockets.

Notation - pockets a,b,c

$$\sigma_{xx} = \frac{\ell e^2}{h d}(k_F^a + k_F^b + k_F^c)$$

Result - $\ell \sim 10^3$ Å

Consistent with estimates made from the field dependence of the oscillations.

$$R_H = \frac{-2\pi d}{e}(k_F^a + k_F^b + k_F^c)^{-2}$$

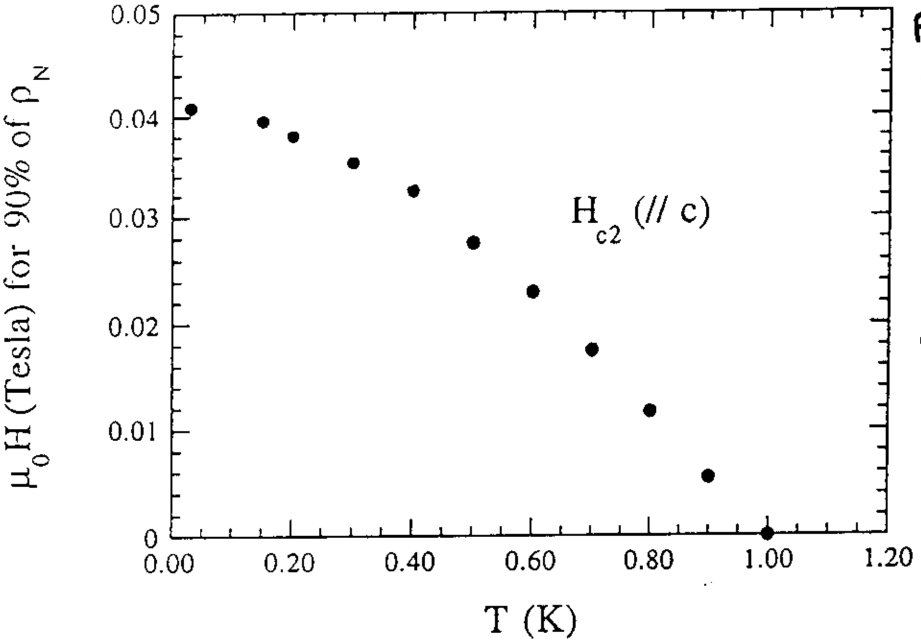
using $BR_H = \sigma_{xy}/\sigma_{xx}^2$ and summing conductivities.

Result - $R_H = -0.9 \times 10^{-10}$ m^3/C, in fair agreement with experimental value of -1.15×10^{-10} m^3/C

Conclusion - isotropic ℓ approximation is not a bad one in spite of the rather different value of k_F for the hole pocket.

c) The upper critical field.

H_{c2} has a conventional temperature dependence whether measured by a.c. susceptibility (Hiroshima) or resistivity (Cambridge):



FOR DATA FROM A.C. SUSCEPTIBILITY WITH H || ab AND H || c, SEE K. YOSHIDA, Y. MAENO AND T. FUJITA (UNPUBLISHED)

Now using $\xi_o = \dfrac{\hbar^2 k_F}{1.76 m^* \pi k_B T_c}$

and $H_{c2}(0) \sim \dfrac{\Phi_o}{2\pi\xi^2}$

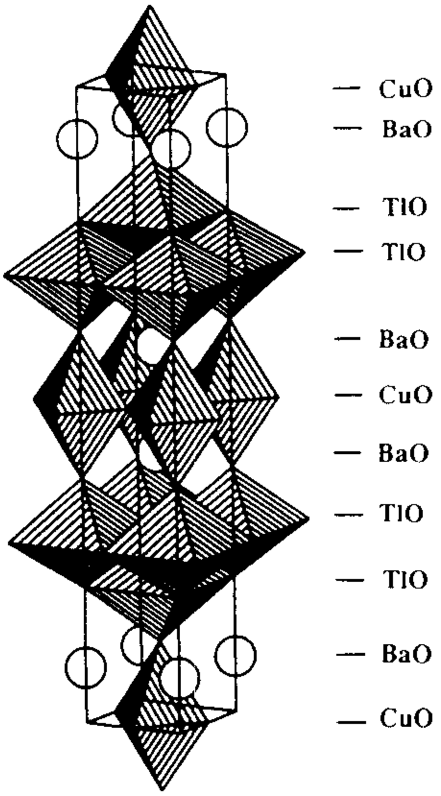
gives an estimate of $H_{c2}(0)$ of 0.034 T, in pleasing agreement with experiment.

In $Tl_2Ba_2CuO_6$ the temperature dependence of H_{c2} is very unusual *and* the size of $H_{c2}(0)$ is much larger than that estimated by the above procedure.

Contrasting behaviour in Sr_2RuO_4 and $Tl_2Ba_2CuO_{6+\delta}$

- in the low temperature limit, Sr_2RuO_4 is a highly anisotropic Fermi liquid, whereas $Tl_2Ba_2CuO_{6+\delta}$ continues to show non-Fermi liquid behaviour to the lowest temperatures at which power laws can be reliably extracted (<1K). Why the difference?

- Sr_2RuO_4 differs from $Tl_2Ba_2CuO_{6+\delta}$ in a number of ways:
    - its c-axis conductivity is coherent below 25 K



doping + Cu → Tl sites.

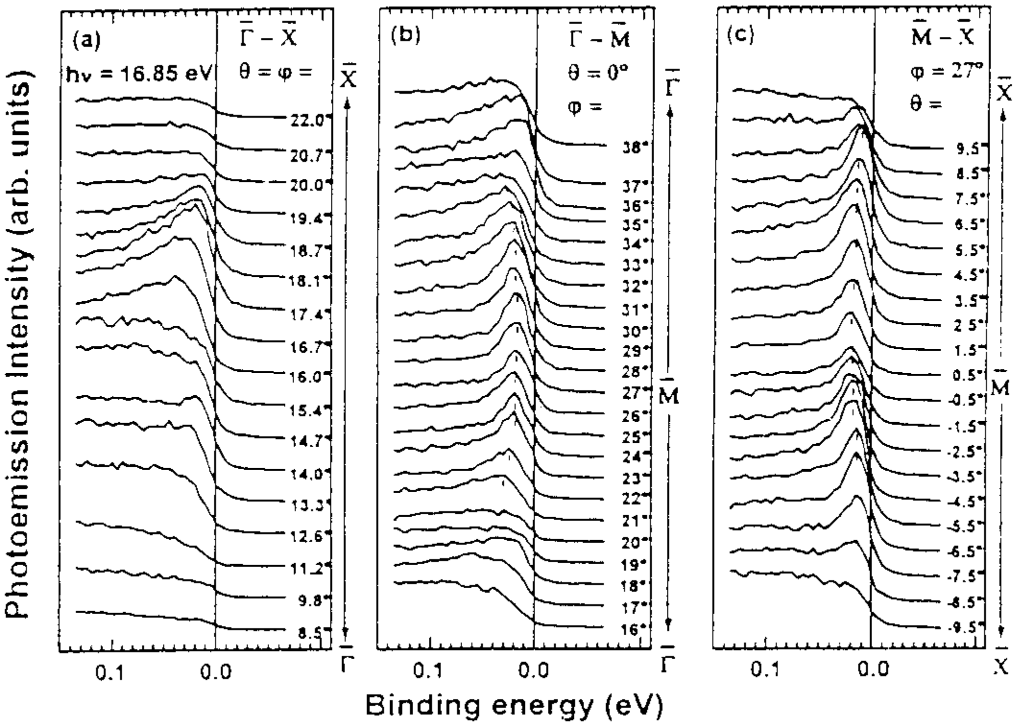
- **disorder between CuO_2 planes in 2201 means c-axis conductivity is even lower than expected from the in-plane mean free path; c-axis conductivity does *not* become coherent at low temperature**

- Sr_2RuO_4 is not believed to be close to antiferromagnetic order
- the Hubbard U is presumably smaller

(see also G. Baskaran, Proc. SCES '95, Goa, India)

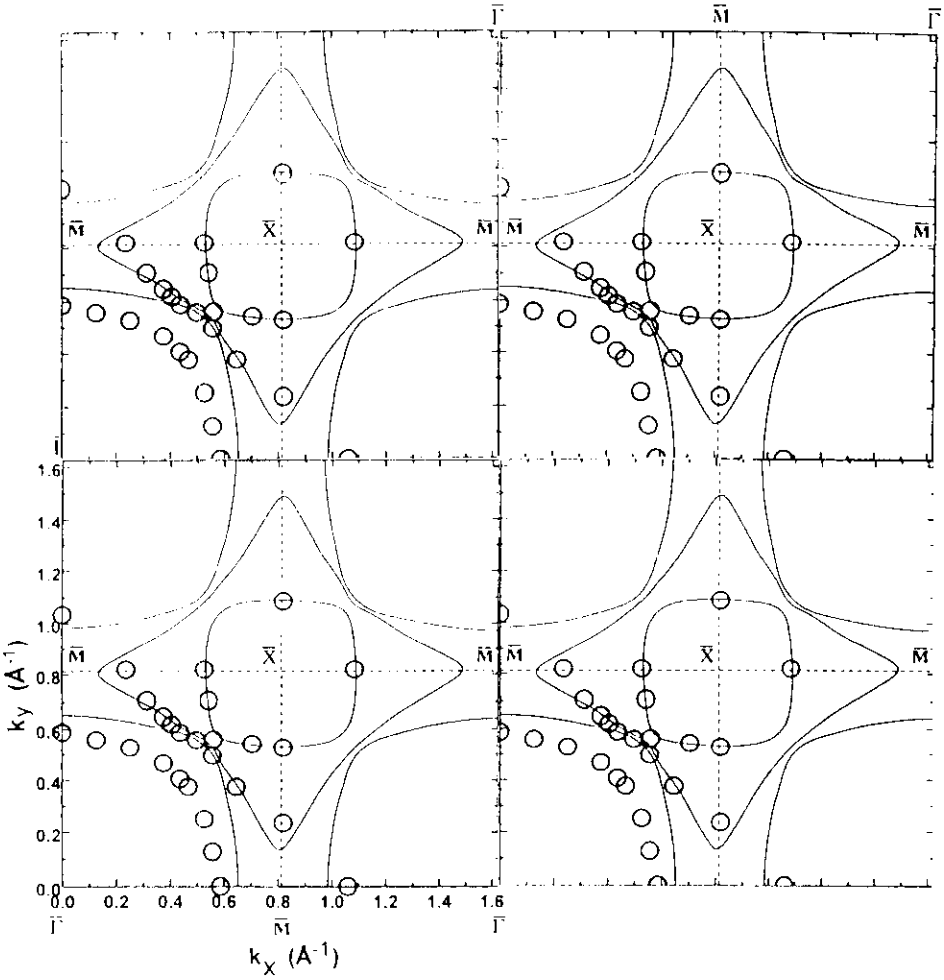
ARPES results in Sr_2RuO_4

- samples were cleaved at low temperature in vacuum
- stable material (samples can be left in air for long times without change in bulk properties)
- observation of an extended van Hove singularity is claimed



1. R. Lu et al., Phys Rev Lett **76** (1996) 4845.
2. T. Yokoya et al., Phys Rev Lett **76** (1996) 3786.

Comparison of ARPES and dHvA results in Sr_2RuO_4



Fermi surface areas (in kT), calculated from photoemission data, vs. direct measurement via the de Haas van Alphen effect

	orbit	ARPES[1]	dHvA value[2]	
	α	3.5 ± 0.7	3.05 ± 0.02	
*	γ	8.90 ± 0.16	18.84 ± 0.2	*
	β	11.0 ± 1.0	12.91 ± 0.01	

1. R. Lu et al., Phys Rev Lett **76** (1996) 4845.
2. A. P. Mackenzie et al., Phys Rev Lett **76** (1996) 3009.
3. see also ARPES measrurement of T. Yokoya et al., Phys Rev Lett **76** **(1996)** 3786, which agrees with Lu et al. for α and γ, but doesn't show β.

Conclusions

1. Fermi liquid behaviour in a hole doped cuprate has not yet been established, even in a favourable case of extreme overdoping and low residual (in-plane) resistivity. There is some indication that Fermi liquid behaviour emerges at high magnetic fields.

2. Quantum oscillations, combined with transport and thermodynamic measurements, give a complete, self-consistent picture of Sr_2RuO_4 as a strongly renormalised, multiband, highly anisotropic Fermi liquid.

3. ARPES measurements on Sr_2RuO_4 cannot be reconciled with these quantum oscillation results.