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

H4.SMR/1001-11

*IX TRIESTE WORKSHOP ON
OPEN PROBLEMS IN
STRONGLY CORRELATED SYSTEMS*

14 - 25 July 1997

RECENT RESULTS ON THE LAYERED PEROVSKITE Sr_2RuO_4

A. MACKENZIE
University of Cambridge
Interdisciplinary Research Centre
in Superconductivity
Cambridge
U.K.

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
ENRICO FERMI BUILDING VIA BEIRUT, 6 (TELEPHONE, FAX AND TELEX THROUGH MAIN BUILDING)

Recent results on the layered perovskite Sr_2RuO_4

Talk by Andy Mackenzie

Interdisciplinary Research Centre in Superconductivity,
University of Cambridge, UK

e-mail am134@cam.ac.uk

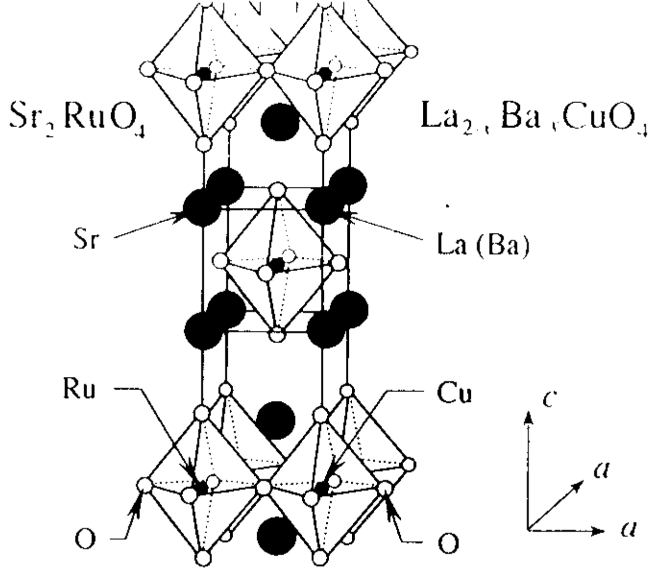
Collaborators

S.R. Julian, N.E. Hussey, A.J. Diver, G.J. McMullan,
A.W. Tyler and G.G. Lonzarich
University of Cambridge

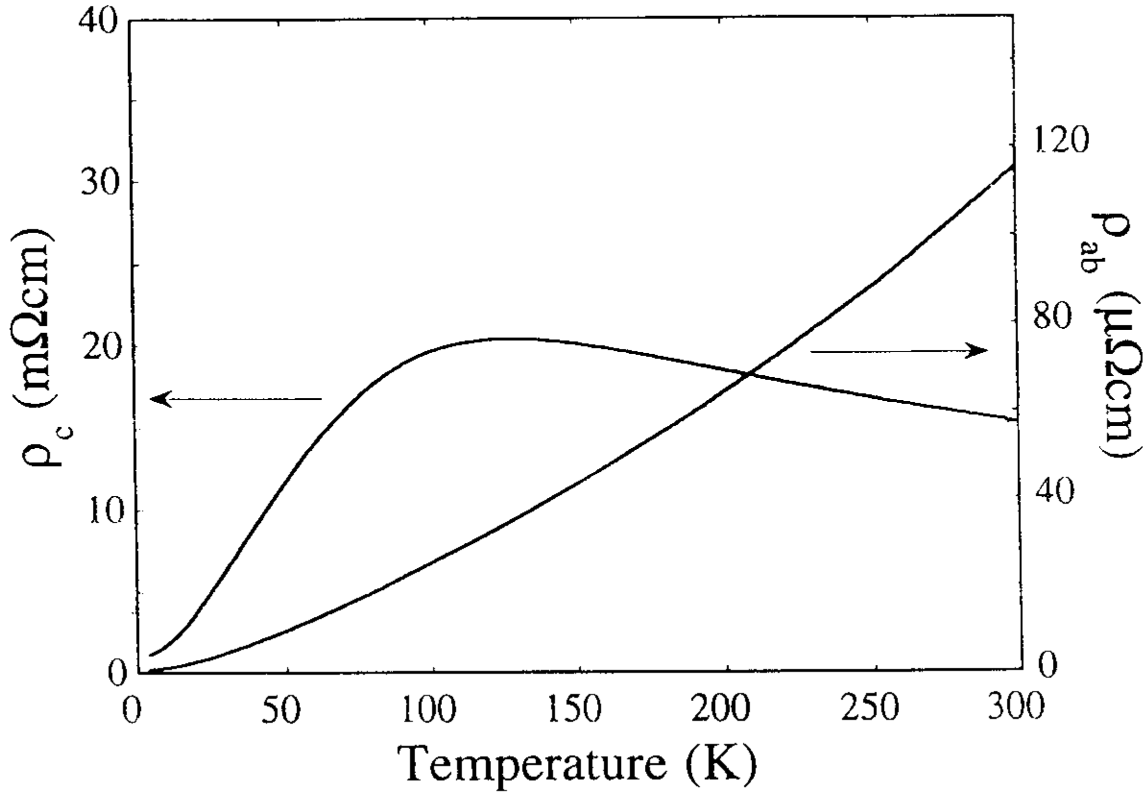
Y. Maeno, S. Nishizaki, S.Ikeda
University of Kyoto, Japan

K. Yoshida, T. Fujita
University of Hiroshima, Japan

Contents



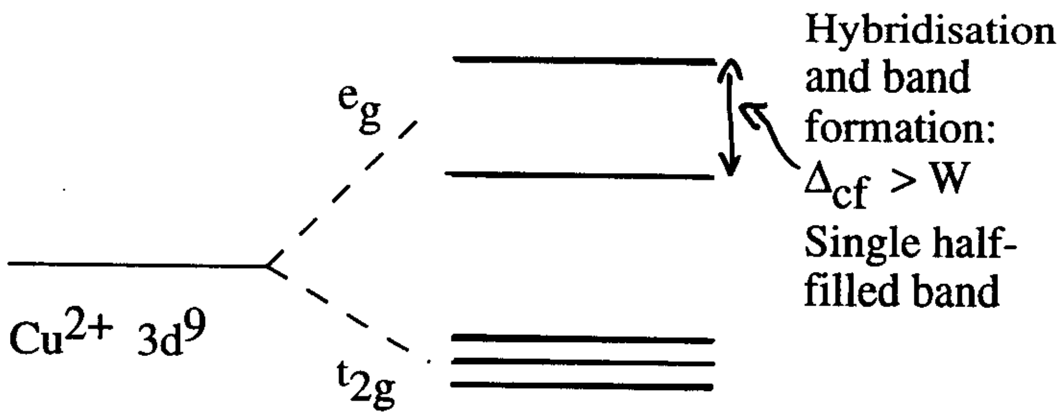
F. Lichtenberg et al., Appl. Phys. Letts. ***60****, 1138 (1992)*



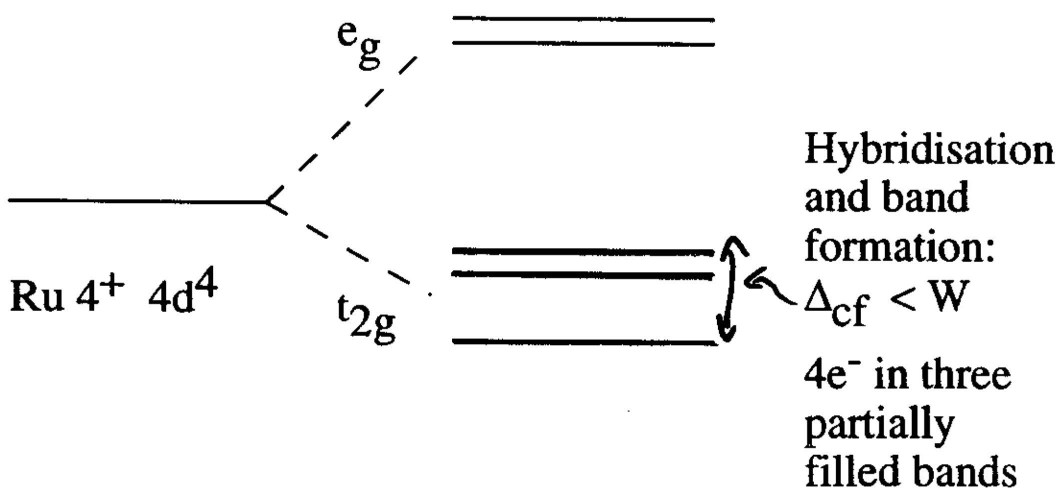
Most people only became interested after the discovery of superconductivity with T_c ~ 1K (*Maeno et al., Nature 372, 532 [1994]*).

Electronic structure is significantly different from that of the cuprates, since the relevant orbitals are 4d's rather than 3d's.

Cuprate in the presence of a crystal field:



Ruthenate in the presence of a crystal field:



Results of actual band structure calculations for Sr_2RuO_4:

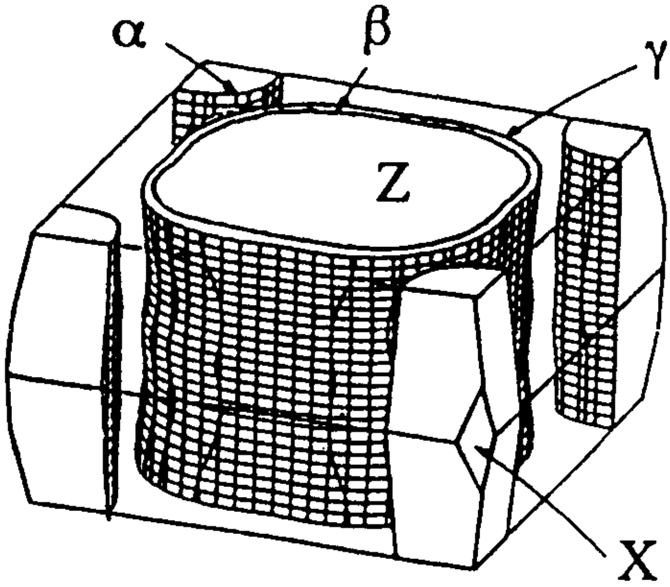
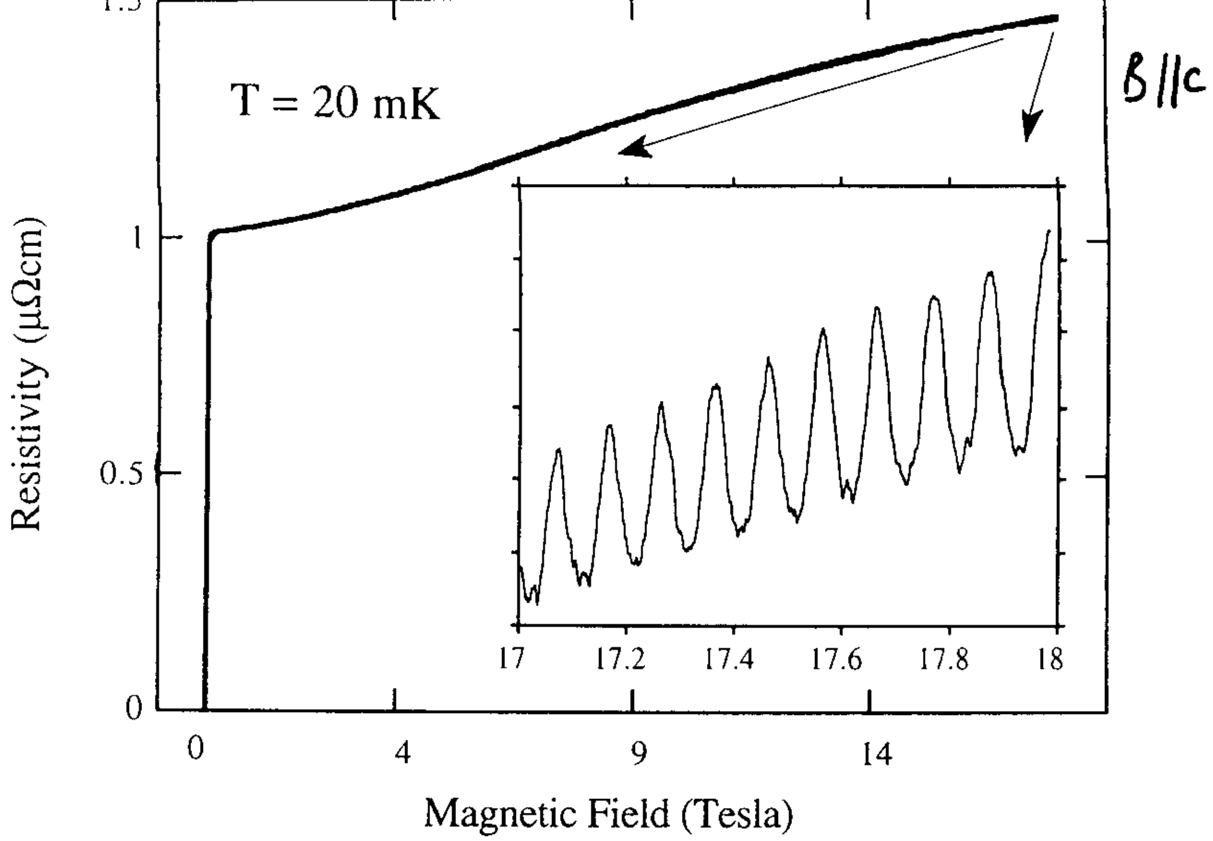


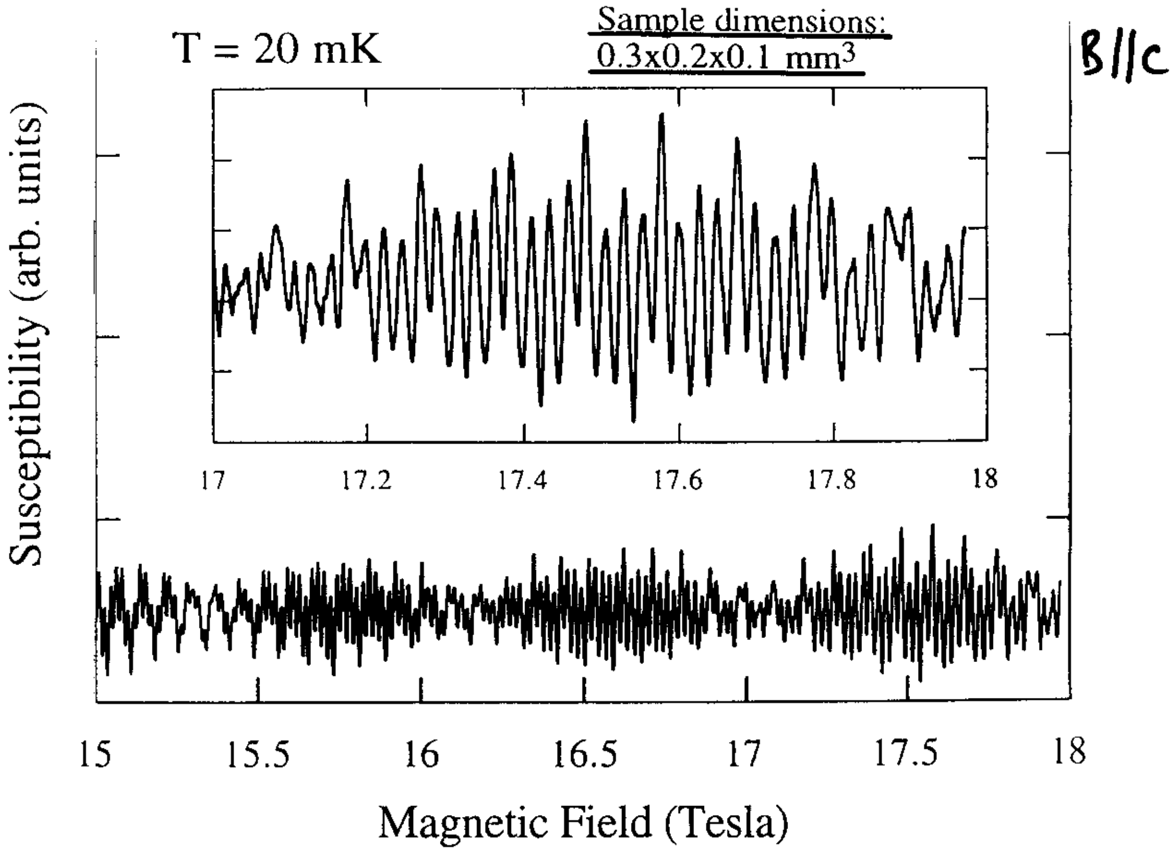
*Figure based on a calculation by G.J. McMullan, M.P. Ray and R.J. Needs. Previous published band calculations: T. Oguchi, Phys. Rev. B **51**, 1385 (1995); D.J. Singh, Phys. Rev. B **52**, 1358 (1995). All are in qualitative agreement.*



Oscillations come from quantisation of cyclotron motion of charge carriers in a magnetic field **B**.

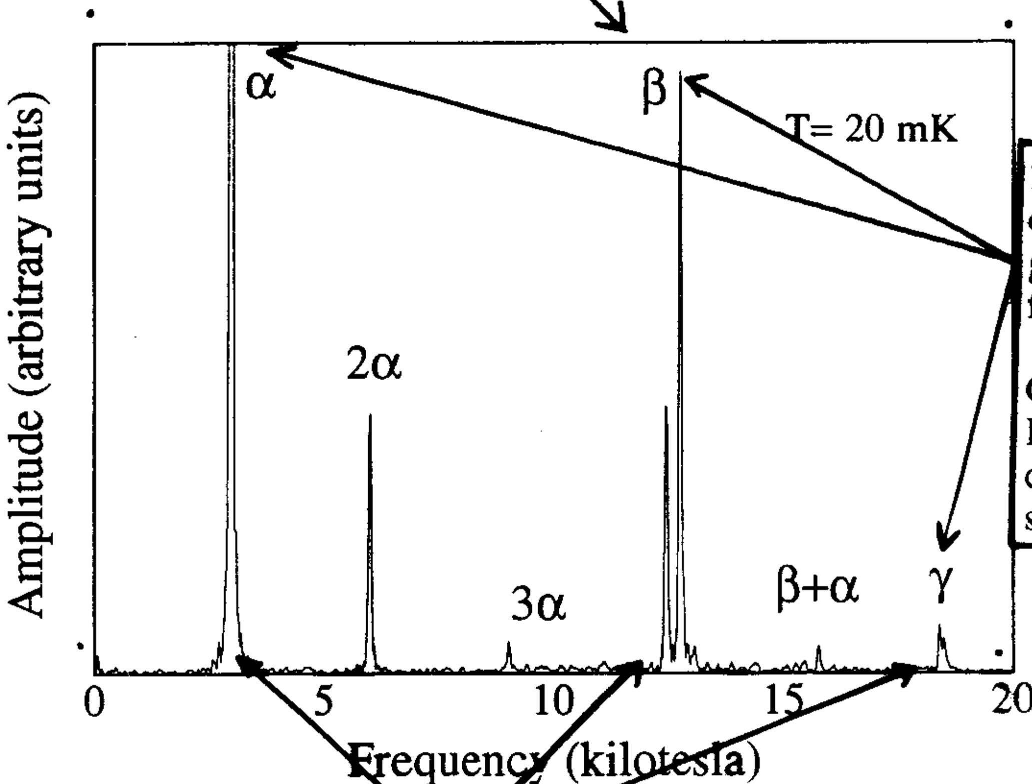
Fermi liquid theory makes specific predictions of the temperature and field dependence of the oscillations, which can be analysed to give the quasiparticle masses and mean free paths respectively.

Observation is difficult-requires low temperatures, high magnetic fields and clean samples.



T = 20 mK
Sample dimensions:
0.3x0.2x0.1 mm3
B//c
Susceptibility (arb. units)
17
17.2
17.4
17.6
17.8
18
15
15.5
16
16.5
17
17.5
18
Magnetic Field (Tesla)

Splitting of fundamental peaks, resolved by studying the oscillations over a wide field range, gives information about the small *3D dispersion*. We can measure the average transfer integral $t_\perp$ for each FS sheet.

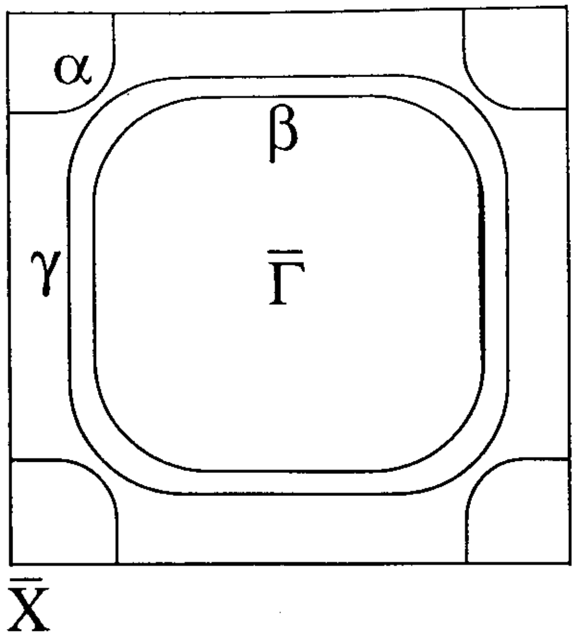


Temperature dependence of *amplitude* of each component gives cyclotron effective mass for each FS sheet.

Good agreement with Lifshitz-Kosevich formula (not shown) confirms Fermi Liquid ground state.

Frequencies of fundamental components give *topological* information via Onsager relation: $A_{ext}=2\pi eF/\hbar$

Angular dependence confirms essentially 2D nature of FS.



	α	β	γ
Freq F (kT)	3.05	12.7	18.5
Band calc.	3.4	13.4	17.6
Avg. k_F ($Å^{-1}$)	0.302	0.621	0.750
Band calc.	0.319	0.638	0.732
Cyc. mass (m_e)	3.4	7.5	14.6
Band calc.	1.1	2.0	2.9
Mass enhancement	3.1	3.8	5.0

Experiment and explicit comparison with in-house band calculation: A.P. Mackenzie, S.R. Julian, A.J. Diver, G.J. McMullan, M.P. Ray, G.G. Lonzarich, Y. Maeno, S. Nishizaki and T. Fujita, Phys. Rev. Lett. **76**, *3786 (1996). Previous published band calculations: T. Oguchi, Phys. Rev. B* **51**, *1385 (1995); D.J. Singh, Phys. Rev. B* **52**, *1358 (1995).*

We have a detailed, sheet specific knowledge of the low energy excitations which determine the physical properties of the material, and can perform successful quantitative calculations of all independently measured low temperature properties.

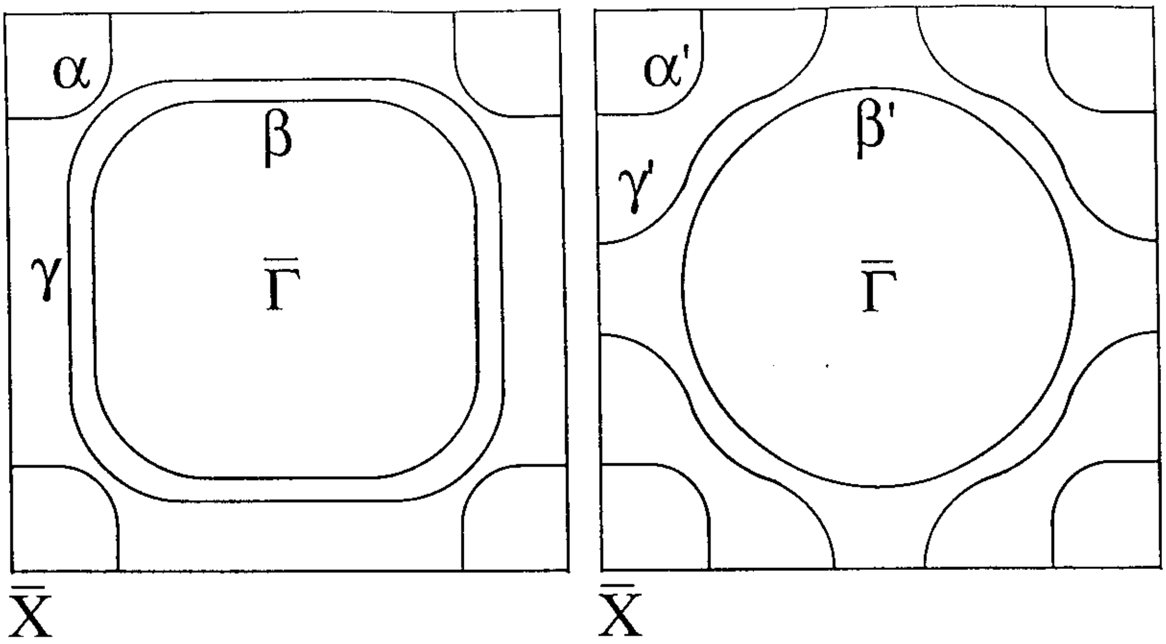
Electronic specific heat $\gamma = 39$ mJ/molK^2
*(Y. Maeno et al., Nature **372**, 532 [1994])*

Hall coefficient $R_H = -1.1 \times 10^{-9}$ m^3/C
*(A.P. Mackenzie et al., Phys. Rev. B **54**, 7425 [1996])*

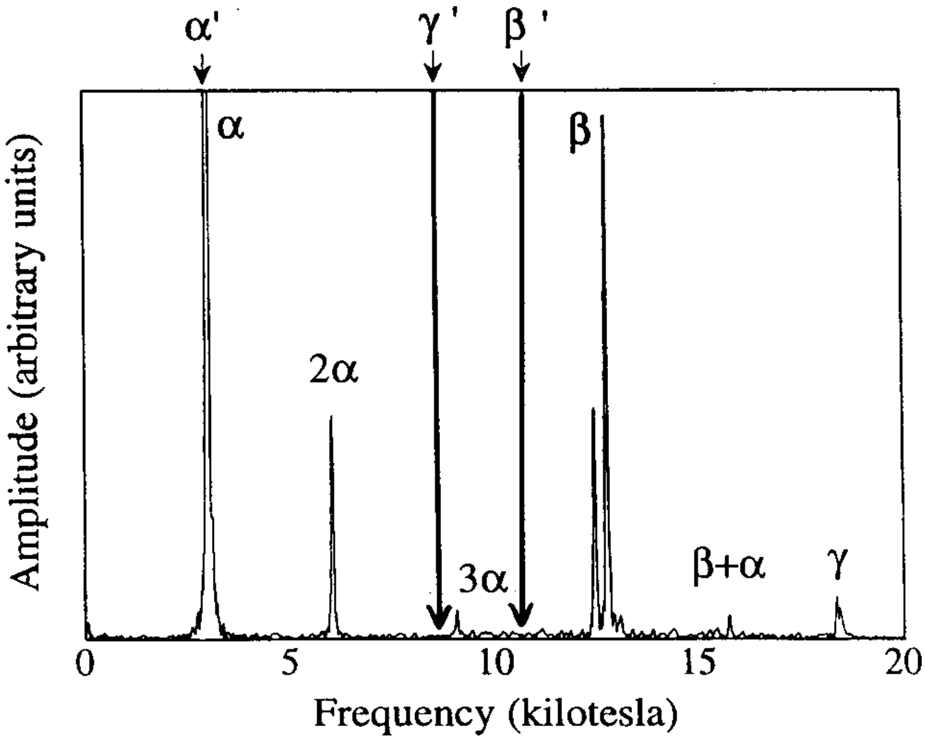
Superconducting upper critical field $H_{c2}(0) \approx 400$ Oe
*(K. Yoshida et al., Physica C **263**, 519 [1996]*
*A.P. Mackenzie et al., Physica C **263**, 510 [1996])*

Sr_2RuO_4 is a Pauli paramagnet with a temperature independent susceptibility of approximately 10^{-3} emu/mol up to 700K.
(Y. Maeno et al., to appear in J. Phys. Soc. Jpn. [1997]).

All in all, Sr_2RuO_4 is one of the best understood correlated metals in condensed matter physics. Ten years ago, it was impossible to imagine a ternary oxide in such a role.



dHvA / LDA Fermi surface   ARPES Fermi surface



dHvA: A.P. Mackenzie, S.R. Julian, A.J. Diver, G.J. McMullan, M.P. Ray, G.G. Lonzarich, Y. Maeno, S. Nishizaki and T. Fujita, Phys. Rev. Lett. ***76****, 3786 (1996); A.P. Mackenzie, S.R. Julian, G.G. Lonzarich, Y. Maeno and T. Fujita, Phys. Rev. Lett.* ***78****, 2271 (1997).*

ARPES: T. Yokoya et al., Phys. Rev. Lett. ***76****, 3009 (1996); Phys. Rev. Lett 78, 2272 (1997); D.H. Lu et al., Phys. Rev. Lett 76, 4585 (1996).*

Superconductivity of Sr_2RuO_4

Immediately after discovery - $T_c \sim 1K$ is unspectacular after the cuprates, and so probably conventional (phononic?) mechanism.

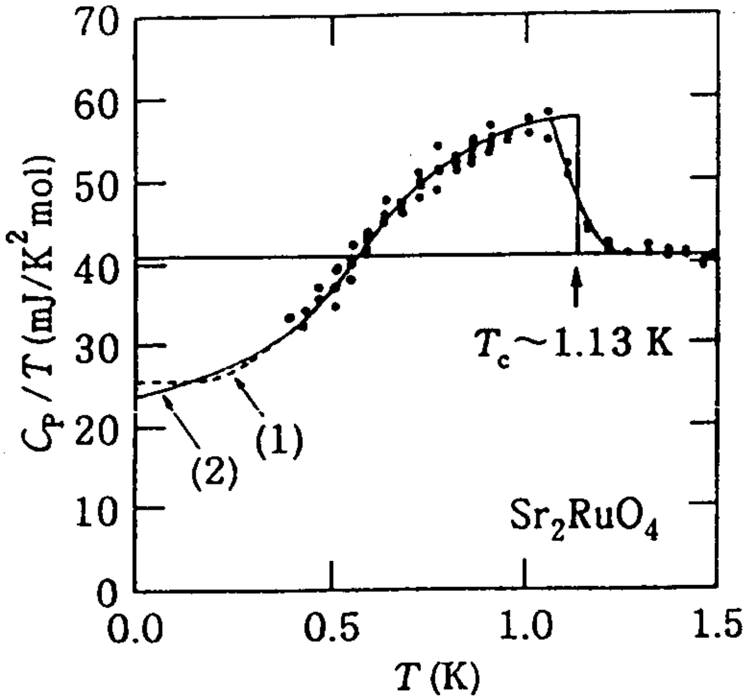
After quasiparticle parameters known from quantum oscillations, it was noticed that they are very similar to those of ^3He, a p-wave superfluid. (*T.M. Rice and M. Sigrist, J. Phys.: Cond. Matt. 7, L643 [1995]).*

Their suggestion - could Sr_2RuO_4 be a p-wave superconductor?

Other circumstantial evidence -
- related compounds such as the cubic perovskite $SrRuO_3$ are ferromagnetic
- if the Ru^{4+} ion is present in an insulating layered perovskite (e.g. at dilute concentrations in Sr_2IrO_4, or in the hypothetical insulating form of Sr_2RuO_4) it exists in the S=1 state due to Hund's rule coupling.

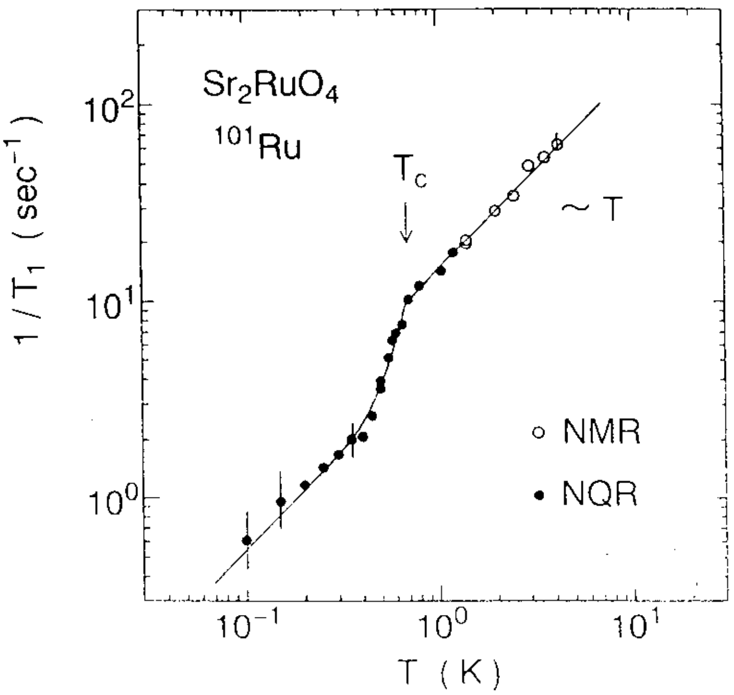
It is not so crazy to consider the possibility of triplet pairing in Sr_2RuO_4.

Evidence for something unusual



Specific heat

Y. Maeno et al.,
J. Low Temp. Phys. ***105,*** *1577 (1997).*



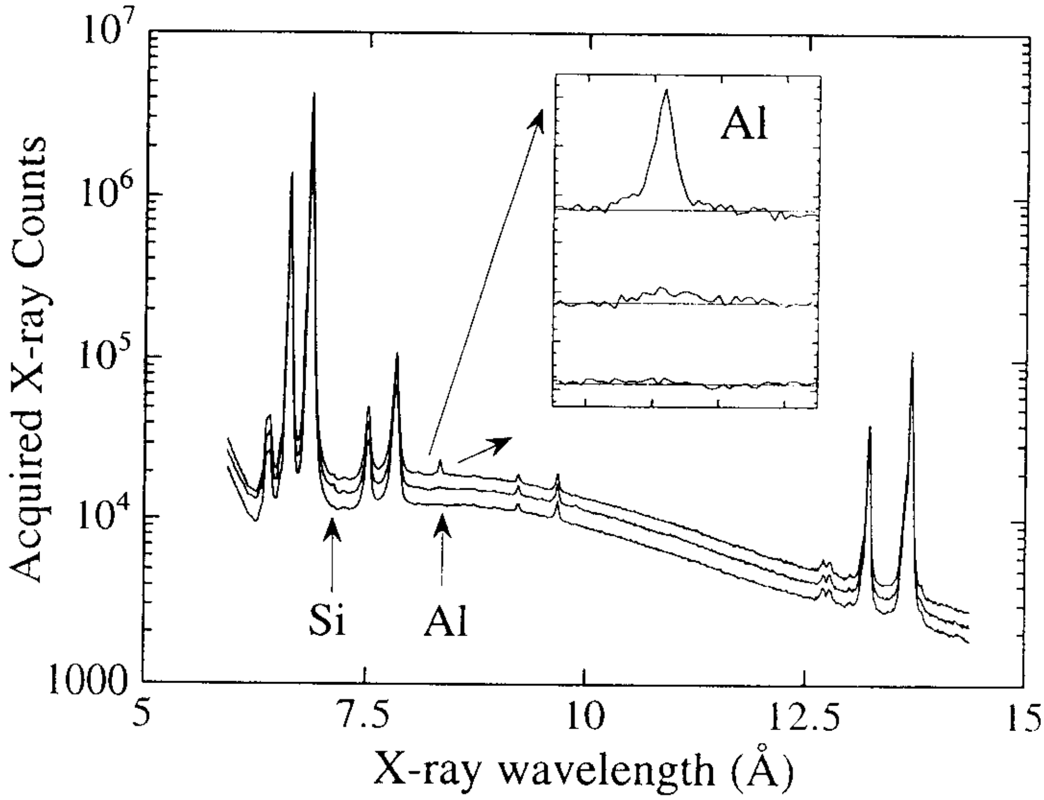
NMR / NQR into the superconducting state

K. Ishida, Y. Kitaoka et al., to appear in Phys. Rev. B.

Known to be a strong growth batch dependence of T_c.

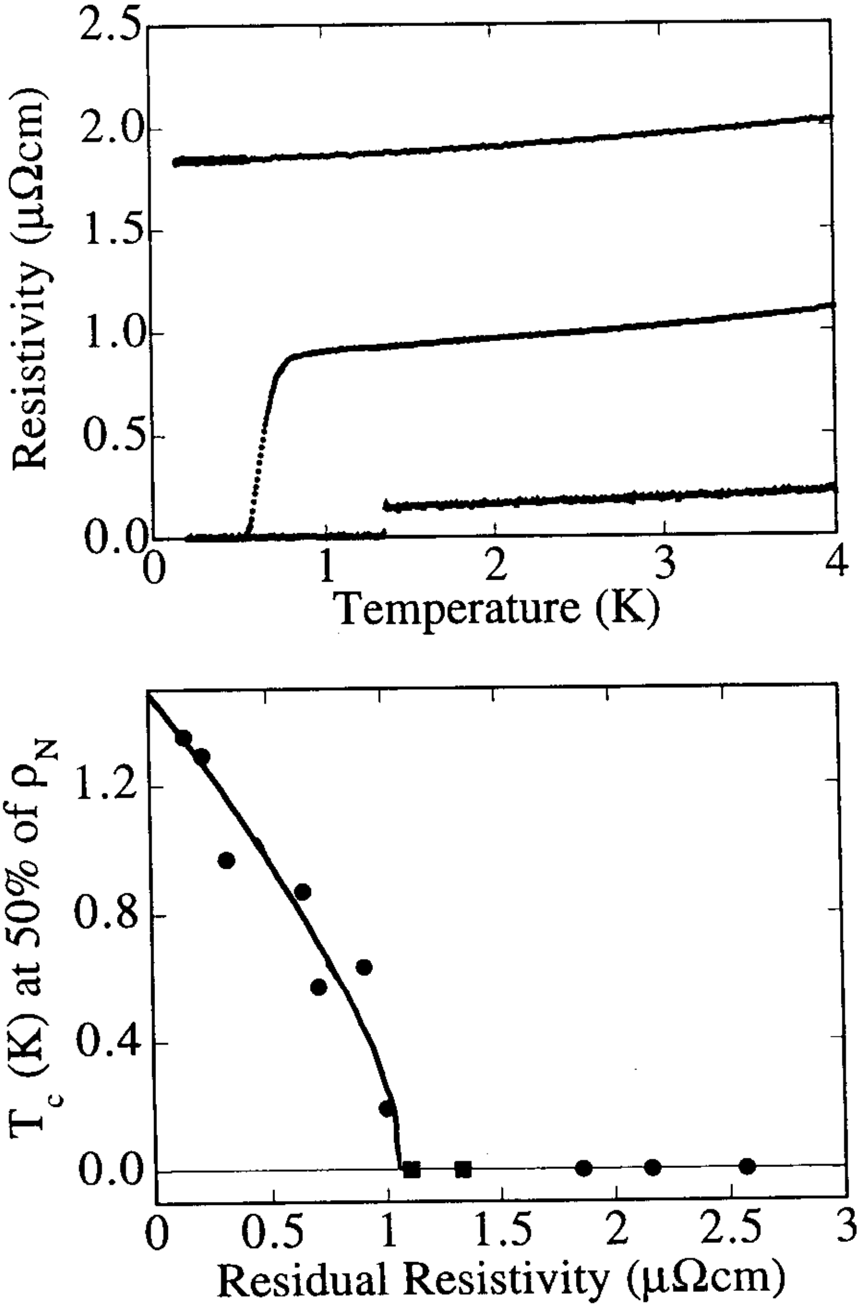
Could this be due to impurities? We have performed a stoichiometric analysis for every element between Na and Bi. Sensitivity is good - detection limits are between 25ppm and 50ppm depending on the element.

A typical scan over part of the x-ray wavelength range for samples with different T_c:



Only impurities detected are Al, Si, Ca and Ba. All of these are thought to be non-magnetic.

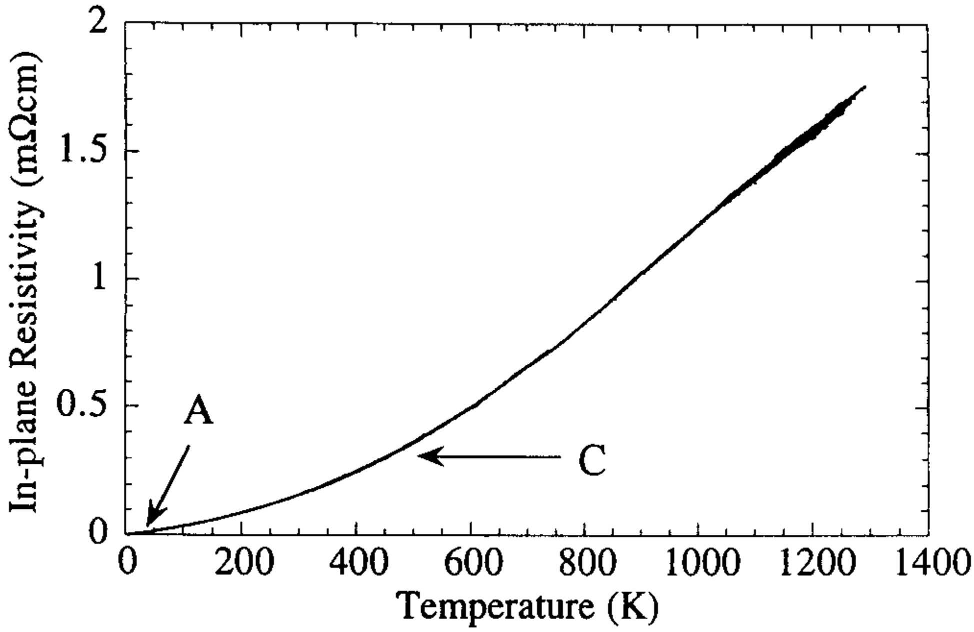
The effect of residual resistivity on superconductivity is spectacular:

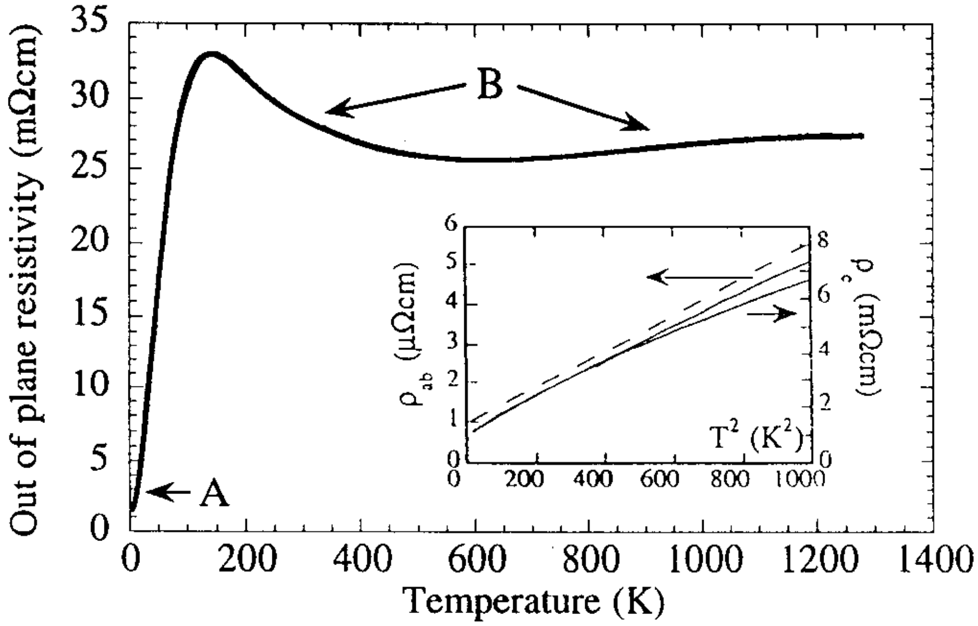


A.P. Mackenzie, R.K.W. Haselwimmer, A.W. Tyler, G.G. Lonzarich, Y. Mori, S. Nishizaki and Y. Maeno, preprint

Open question: Is Sr_2RuO_4 p- or d-wave? New measurements of specific heat on the best samples should help to resolve issue.

Open questions posed by transport properties:





A.W. Tyler, A.P. Mackenzie, K. Yoshida, S. Ikeda, S. Nishizaki, Y. Maeno and T. Fujita (unpublished).

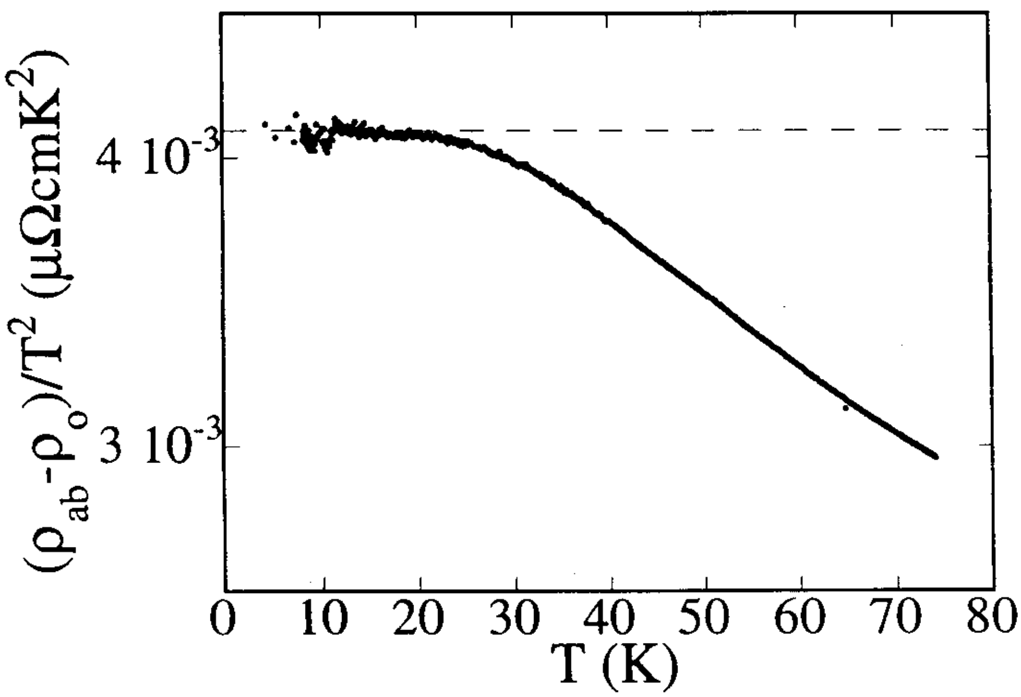
A: What is the origin of the loss of T^2 resistivity in all directions at T≈ 20K?

Most "conventional" viewpoint - some scale principally relevant to in-plane physics causes a change in ρ_{ab}, and ρ_c also changes because Sr_2RuO_4 is a three dimensional Fermi liquid at low temperatures.

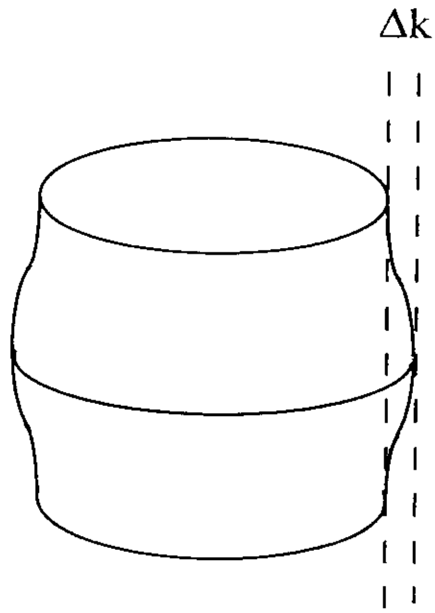
Note: a) T_F ~ 1700K.

b) It cannot be an additive scattering mechanism.

c) The change is not simply due to higher powers of temperature, but is a fairly well-defined crossover:



There is one scale which makes a crossover in this region of temperature, which is coherent band formation in the c-direction.



dHvA can also give an estimate of $t_\perp$

$(\Delta A/A) = 2(\Delta k_F/k_F)$

$\Delta k_F \propto t_\perp, \langle v_\perp \rangle$

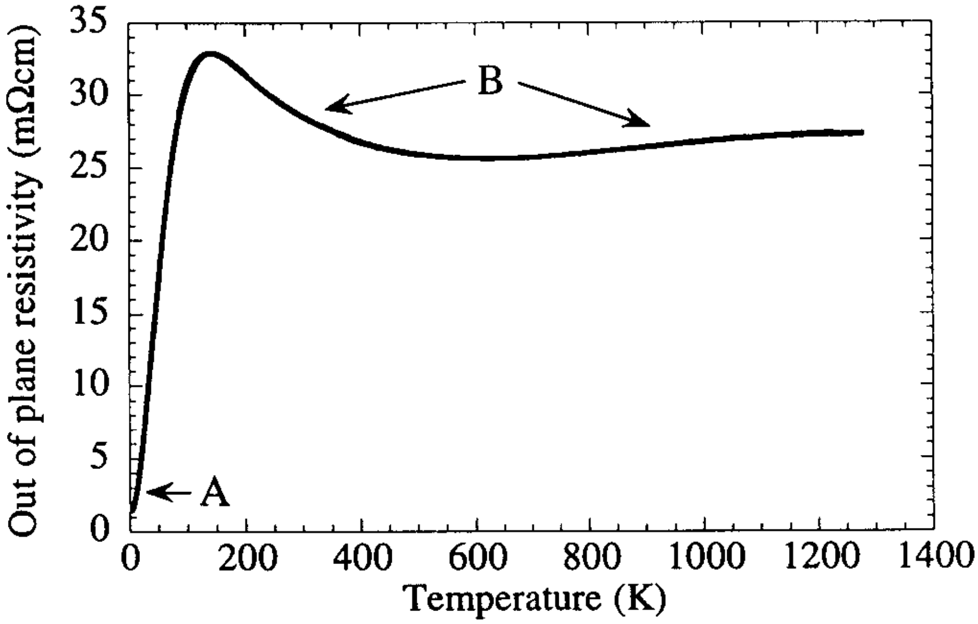
	α	β	γ
$t_\perp$ (meV)	0.1	1.3	0.2

Condition for coherence: $\tau_{mf} > \tau_{hop}$

We can estimate τ_{mf} from ρ_{ab}, since in-plane motion and scattering dominate in a very anisotropic material. τ_{hop} perpendicular to the planes can be estimated from $\hbar/t_\perp$.

The β sheet dominates, and is coherent at T=0. Increasing T decreases τ_{mf}, and violates the coherence condition at $T \approx 20K$.

Question B: How do we view the high temperature c-axis resistivity?



The very high temperature part is clearly completely incoherent. The rise in ρ_c above 600K cannot be easily interpreted until data for compressibility, thermal expansion and the pressure dependence of ρ_c are available.

The maximum at 130K may just be the result of a competition between incoherence at high T and the completely coherent behaviour at low T.

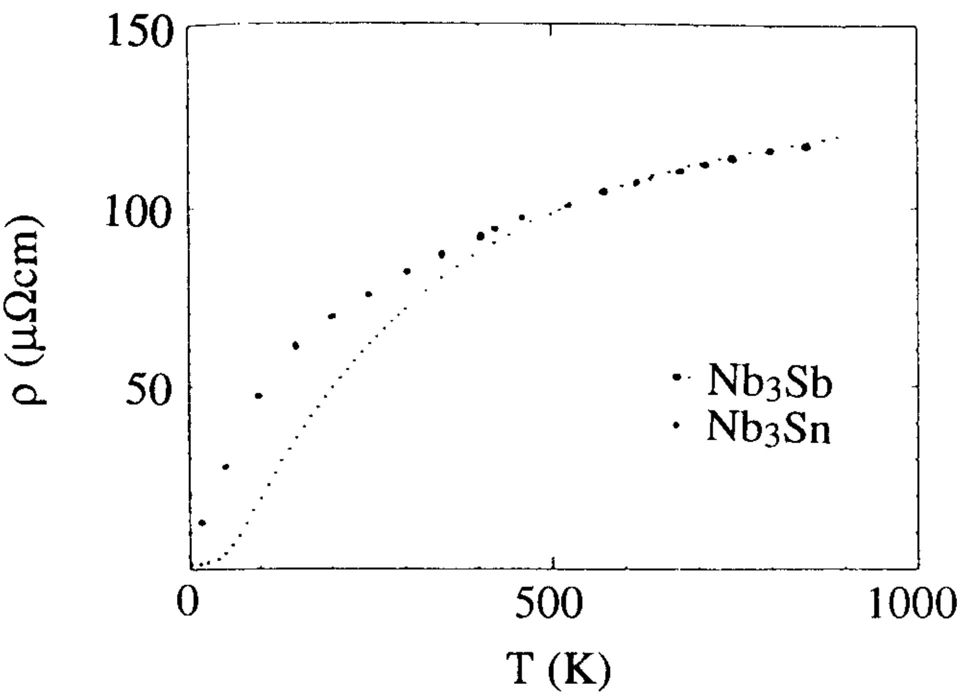
MR data *(Hussey et al., unpublished)* give evidence for competing positive and negative terms above 60K.

Optical conductivity *(Katsufuji, Kasai and Tokura, Phys. Rev. Letts. 76, 126 [1996])* is also consistent with a coherence - incoherence crossover between 15K and 130K.

Question C: What is the significance of the Mott-Ioffe-Regel limit to high temperature transport?

The Mott-Ioffe-Regel limit is a statement formulated for T=0 about a limiting value to metallic resistivity. It is expressed in terms of the mean free path ℓ, and has various forms, e.g. $k_F\ell = 1$, $k_F\ell = 2\pi$, $\ell = a$.

Some kind of high temperature resistivity saturation appears to be observed in many metals, e.g. the A15 compounds, at values which are consistent with the range given above:

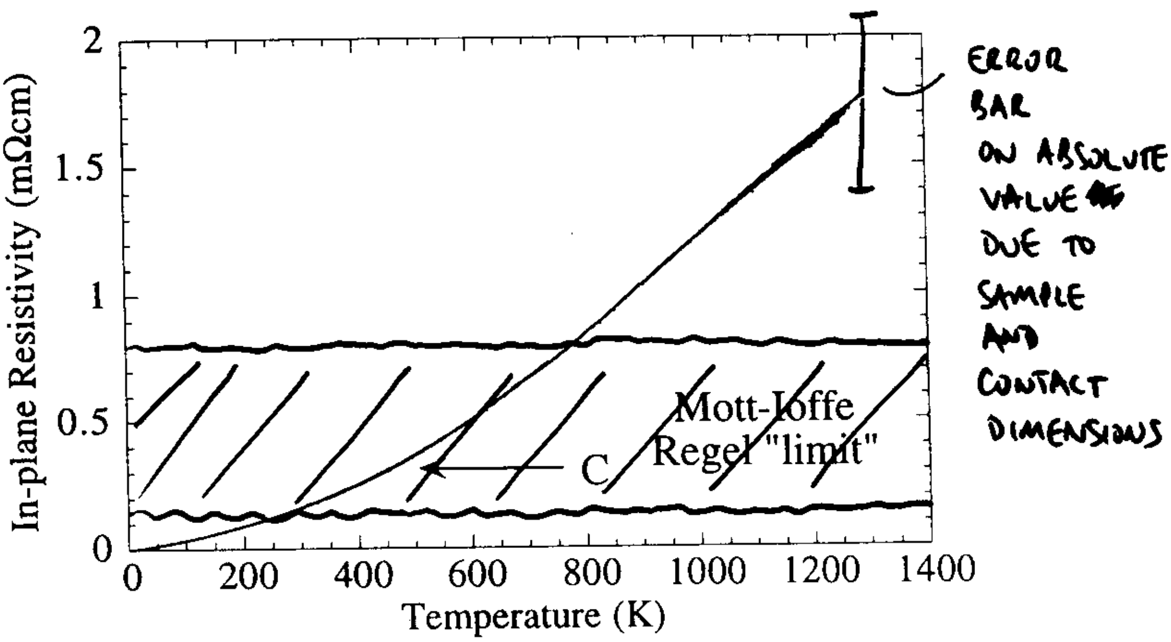


Fisk and Webb, Phys. Rev. Lett. ***36****, 1084 (1976).*

These observations have led to the high temperature MIRL being quite widely accepted.

However, resistivity saturation is not observed in a number of interesting cases, e.g. high T_c cuprates, some organic metals, $SrRuO_3$ and doped C_{60}. It has been suggested that in these "bad metals", an anomalous high temperature conduction mechanism exists which may even extend to low temperatures below the MIRL *(Emery and Kivelson, Phys. Rev. Letts. 74, 3253 [1995])*.

No sign of resistivity saturation is observed in Sr_2RuO_4, which by the above reasoning is a "bad metal" at high temperatures, although it is clearly a very good metal at low temperatures.



Does this indicate a crossover to a different conduction mechanism at high temperatures, or is the MIRL not, in fact, applicable in this regime?

Summary

Sr_2RuO_4 is a mass enhanced Fermi liquid at low temperatures, and its quasiparticle spectrum is understood in some detail.

The superconductivity is not s-wave; T_c has an extremely strong dependence on residual resistivity. Whether it is p-wave or d-wave is still an open question.

Although the normal state is understood at low temperatures, there are plenty of interesting questions about the observed behaviour at high temperatures ($T > 1K$!). Understanding some of these is likely to aid understanding of the cuprates.