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XII WORKSHOP ON
STRONGLY CORRELATED ELECTRON SYSTEMS

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UNCONVENTIONAL METALS AND SUPERCONDUCTORS IN THE LAYERED RUTHENATES

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

Unconventional Metals and Superconductors in the Layered Ruthenates

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Shin-ichi Ikeda.

Christian Pfleiderer.

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1. Introduction – electronic structure of Sr_2RuO_4 and suggestion of triplet superconductivity.
2. Evidence that the superconducting state is not isotropically gapped.
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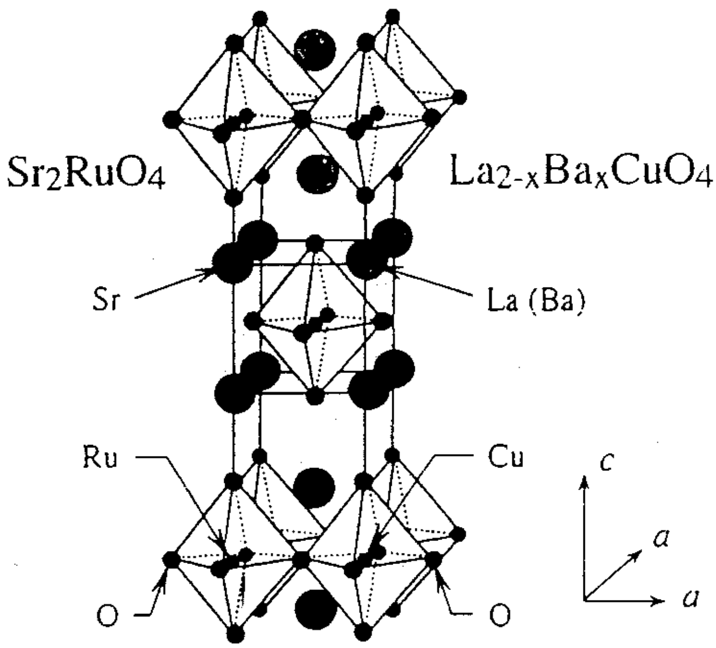
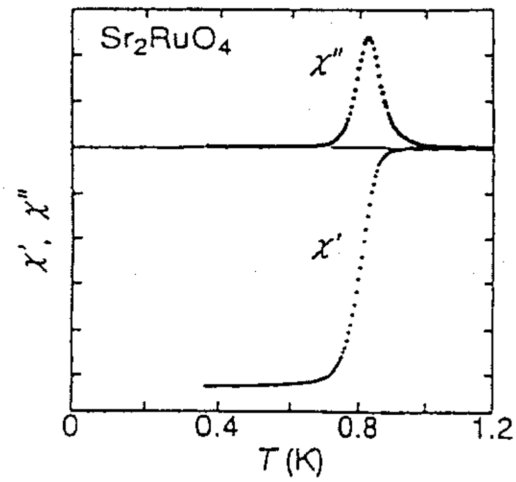
4. Comparison with $Sr_3Ru_2O_7$.
5. Summary and conclusions.

The oxide superconductor Sr_2RuO_4

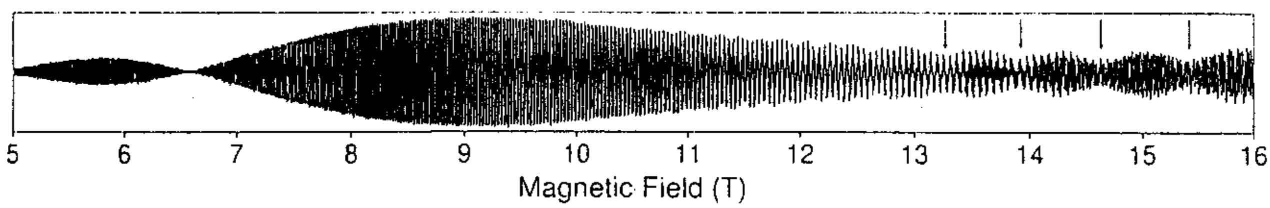




Y. Maeno et al., Nature 372, 594 (1994)

Isostructural to La_2CuO_4 but a metal in the absence of chemical doping. It is possible to prepare samples of very high purity.

Quantum oscillations in the magnetisation: the 'dHvA' effect.



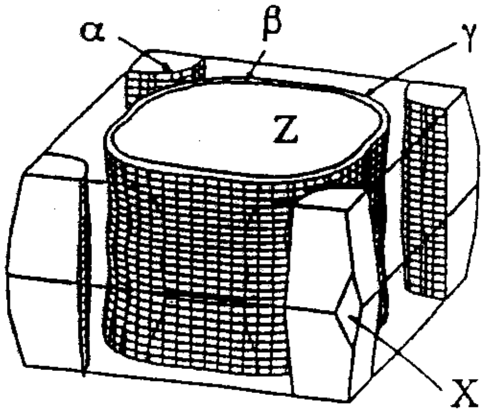
Careful analysis of the temperature, field and angular dependence of the oscillations can be used to obtain a detailed understanding of the Fermi surface topography and low energy excitations.

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).

Resolution in **k** of 1 part in 10^5 of the Brillouin zone just demonstrated.

C. Bergemann, S.R. Julian, A.P. Mackenzie, S. NishiZaki and Y. Maeno, Phys. Rev. Lett. 84, 2662 (2000).

The low temperature metallic state of Sr_2RuO_4



Very simple electronic structure - nearly two-dimensional, with three Fermi surface sheets.

Fermi liquid, m* up to 15 m_e. $\langle m^*/m_{band} \rangle \sim 4$, accounting fully for electronic specific heat.

Quantitative link with ^3He, a known 'p-wave' superfluid.

Could Sr_2RuO_4 be a p-wave superconductor?

T.M. Rice and M. Sigrist, J. Phys.: Cond. Matt. 7, L643 (1995)
G. Baskaran, Physica B 223 & 224, 490 (1996)

Nomenclature of superconducting states

Pair orbital angular momentum, L	*Name*	*Parity of spatial part*	*Spin state*
0	s-wave	even	singlet
1	p-wave	odd	triplet
2	d-wave	even	singlet
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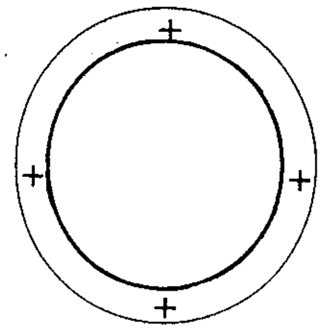
.			

For an elementary discussion see J.F. Annett, Contemp. Phys. 36, 423 (1995).

Singlet superconductors

s-wave

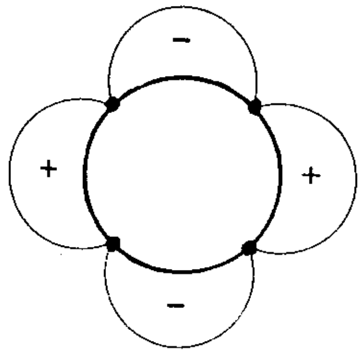


L=0
S=0

$$\frac{1}{\sqrt{2}}\left(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle\right)$$

Cannot suppress T_c to zero by elastic scattering

d-wave e.g. $d_{x^2-y^2}$



L=2
S=0

$$\frac{1}{\sqrt{2}}\left(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle\right)$$

$T_c \rightarrow 0$ with strong scattering. Other signatures in thermodynamics, Josephson effects etc.

$$\Delta = \Delta_o(\mathbf{k})e^{i\phi(\mathbf{k})}$$

Triplet superconductors

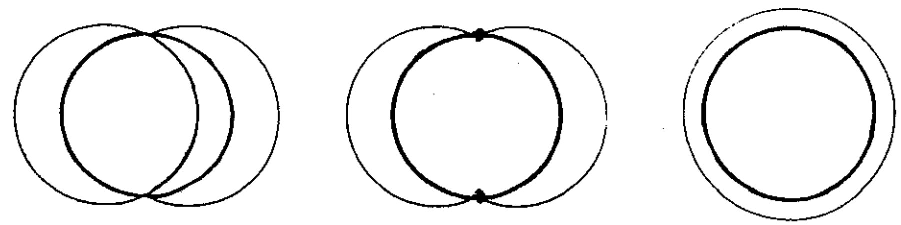
p-wave L=1
S=1

$$|\uparrow\uparrow\rangle$$
$$\frac{1}{\sqrt{2}}\left(|\uparrow\downarrow\rangle + |\downarrow\uparrow\rangle\right)$$
$$|\downarrow\downarrow\rangle$$

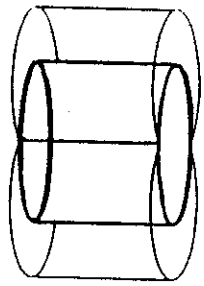
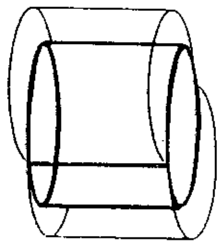
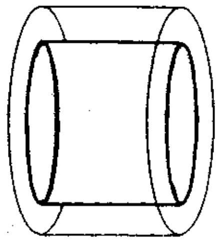
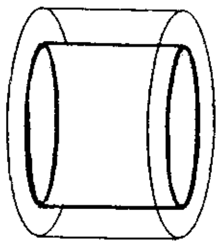
Order parameter is a three dimensional complex vector $\mathbf{d}(\mathbf{k})$, usually 'pinned' in a crystal.

R. Balian & N.R. Werthamer, Phys. Rev. ***131****, 1553 (1963)*
A.J. Leggett, Rev. Mod. Phys. ***47****, 331 (1975)*

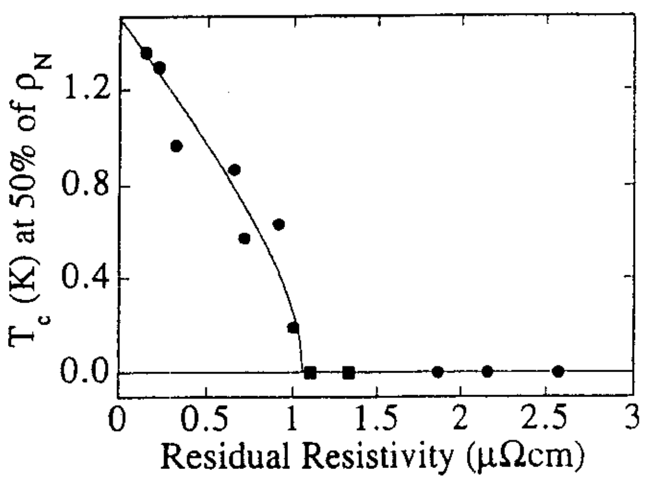
Wide variety of allowed states:



Some allowed triplet states for Sr_2RuO_4:

d(k)	Gap structure	Time reversal symmetry?
$\begin{bmatrix} 0 \\ 0 \\ k_x \end{bmatrix}$		*YES*
$\begin{bmatrix} 0 \\ 0 \\ k_x + k_y \end{bmatrix}$		*YES*
$\begin{bmatrix} 0 \\ 0 \\ k_x + ik_y \end{bmatrix}$		*NO*
$\begin{bmatrix} k_x \\ k_y \\ 0 \end{bmatrix}$		*YES*

Extremely strong impurity effect in Sr_2RuO_4



ℓ > 900Å for the observation of superconductivity.

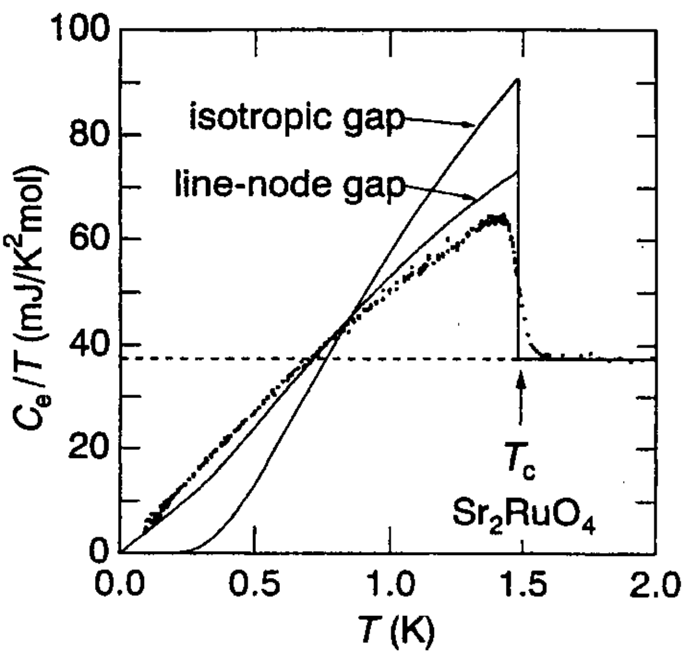
Consistent with known value of ξ.

Maximum $T_c \sim 1.5$K in high purity limit.

Strong evidence for non-s-wave superconductivity.

A.P. Mackenzie et al., Phys. Rev. Lett **80**, *161 (1998)*

Linear temperature dependence of specific heat below T_c.



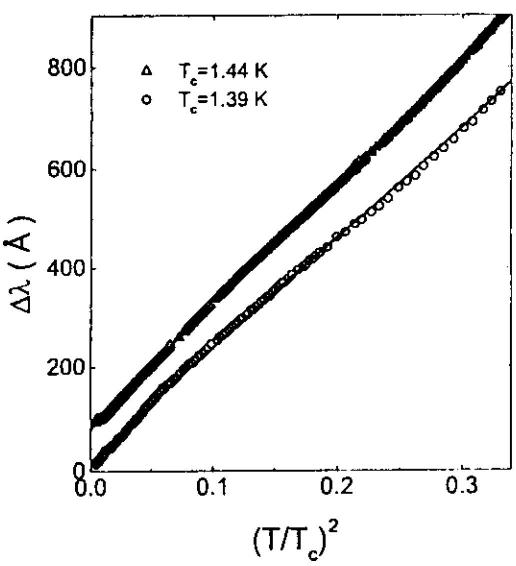
S. NishiZaki, Y. Maeno and Z.Q. Mao, J. Low Temp. Phys. ***117****, 1581 (1999); J. Phys. Soc. Jpn.* ***69****, 572 (2000).*

Consistent with T^3 variation of $1/T_1$ in Ru NQR study.

H. Mukuda, K. Ishida, K. Kitaoka et al., preprint

POWER LAWS ALSO IN ULTRASOUND, THERMAL COND.

High frequency measurements of penetration depth show power law behaviour



T^2 in pure samples, T^3 in disordered samples at 28 MHz

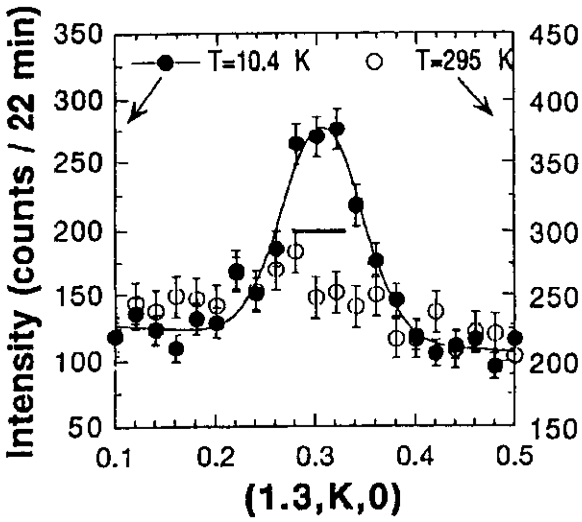
I. Bonalde, B.D. Yanoff, M.B. Salomon, D.J. van Harlingen, E.M.E. Chia, Z.Q. Mao and Y. Maeno, preprint.

T^2 in pure samples with interesting $\omega\tau \sim 1$ behaviour at $\sim$ 10 GHz

R.J. Ormeno, M. Hein, A. Sibley, C.E. Gough and Y. Maeno, preprint.

See also theory for chiral superconductor by T. Morinari and M. Sigrist, preprint

$\chi(q)$ is not as simple as intuitive expectation:



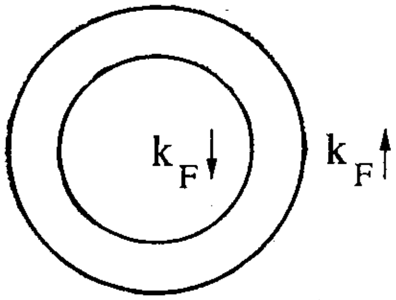
Y. Sidis, M. Braden, P. Bourges, B. Hennion, S. NishiZaki, Y. Maeno and Y. Mori, Phys. Rev. Lett. 83, 3320 (1999).

I.I. Mazin and D.J. Singh, Phys. Rev. Lett. 82, 4324 (1999).

Tempting to postulate d-wave superconductivity.

However ……

Spin susceptibility as a probe for triplet pairing.



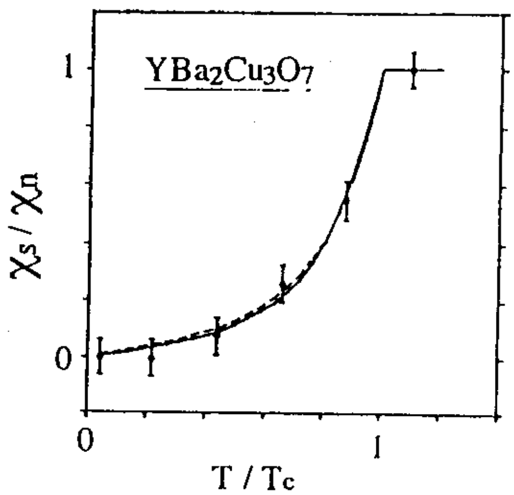
Energy gain for polarisation opposes condensation energy for singlet superconductivity on an unpolarised Fermi surface.

For low applied field, the singlet pairing wins:
$\chi_s / \chi_n \rightarrow 0$ as $T \rightarrow 0$.

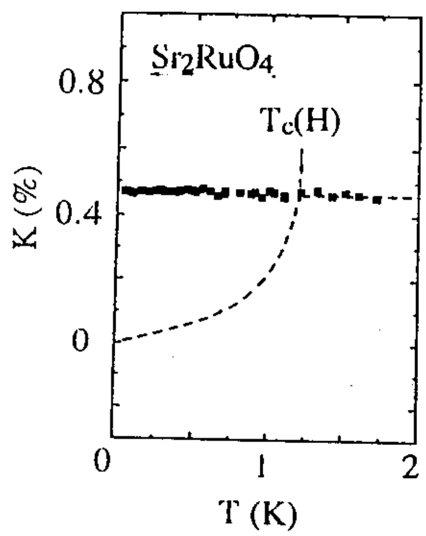
For triplet pairing this is not the case.

Problem: measuring the spin susceptibility in the presence of Meissner diamagnetism.

Spin susceptibility in superconductors by NMR

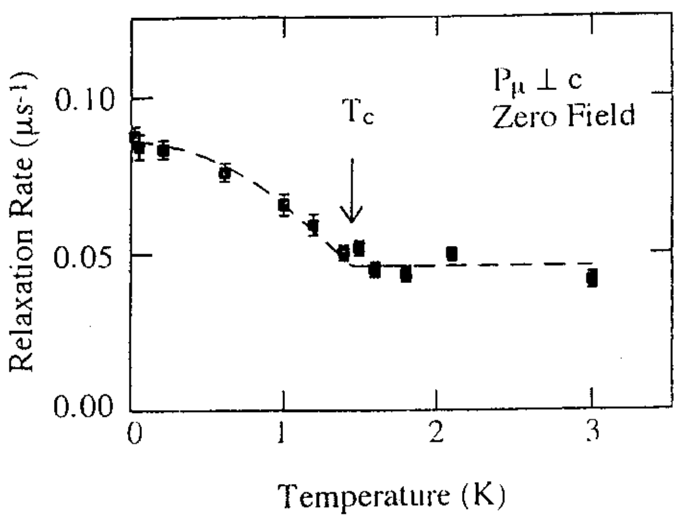


S.E. Barrett, D.J. Durand, C.H. Pennington, C.P. Slichter, T.A. Friedmann, J.P. Rice and D.M. Ginsberg, *Phys. Rev. B* **41**, 6283 (1990)



K. Ishida, H. Mukuda, Y. Kitaoka, K. Asayama, Z.Q. Mao, Y. Mori and Y. Maeno, *Nature* **396**, 658 (1998)

Evidence for breaking of time reversal symmetry at T_c.



Muon spin rotation gives evidence for a spontaneous magnetic moment at T_c.

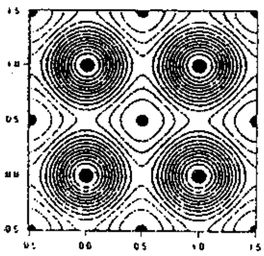
Superconducting state breaks time reversal symmetry.

Implication: $d + id$ or $\hat{z}(k_x + ik_y)$, BUT two d states not expected to be degenerate in a tetragonal system.

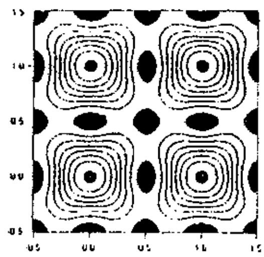
G.M. Luke, Y. Fudamoto, K.M. Kojima, M.I. Larkin, J. Merrin, B. Nachumi, Y.J. Uemura, Y. Maeno, Z.Q. Mao, Y. Mori, H. Nakamura and M. Sigrist, Nature **394**, *558 (1998)*

Support for time reversal symmetry breaking from small angle neutron scattering (SANS).

Single component Ginzburg-Landau

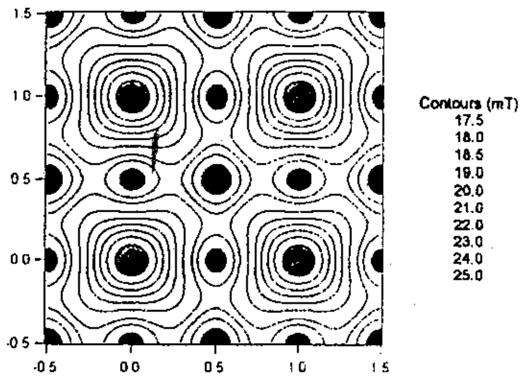


Two component Ginzburg-Landau

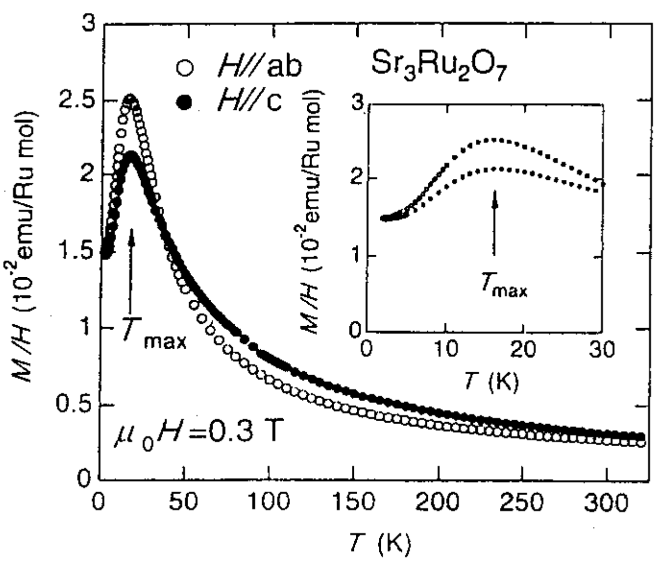


P.G. Kealey, T.M. Riseman, E.M. Forgan, L.M. Galvin, A.P. Mackenzie, S.L. Lee, D. McK. Paul, R. Cubitt, D.F. Agterberg, R. Heeb, Z.Q. Mao and Y. Maeno, Phys. Rev. Lett. ***84****, 6094 (2000)*

Experimental



Magnetic susceptibility of $Sr_3Ru_2O_7$

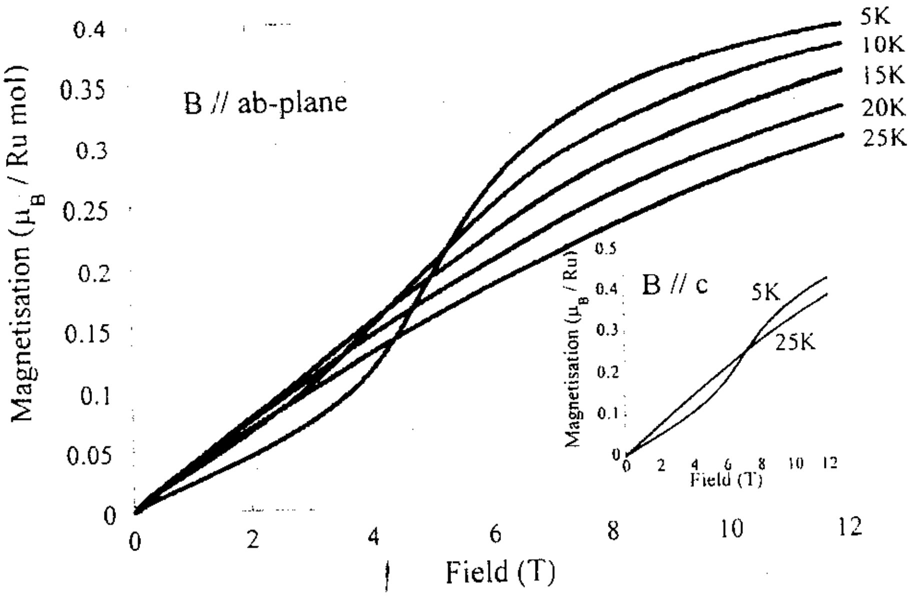


Large susceptibility enhancement in $Sr_3Ru_2O_7$. χ is over an order of magnitude bigger than Sr_2RuO_4. Cleanest crystals are *paramagnetic*.

Specific heat shows broad feature near maximum in χ, and a large γ of up to 100 mJ/mol-RuK^2.

S. Ikeda et al., cond-mat '99 & to appear in Phys. Rev. B

Metamagnetism of $Sr_3Ru_2O_7$

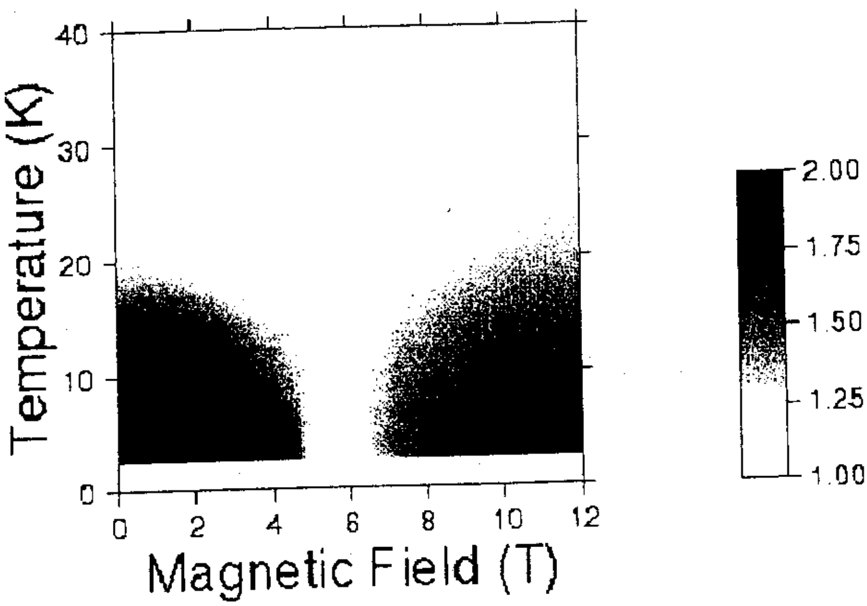


Metamagnetism seen below 10K.

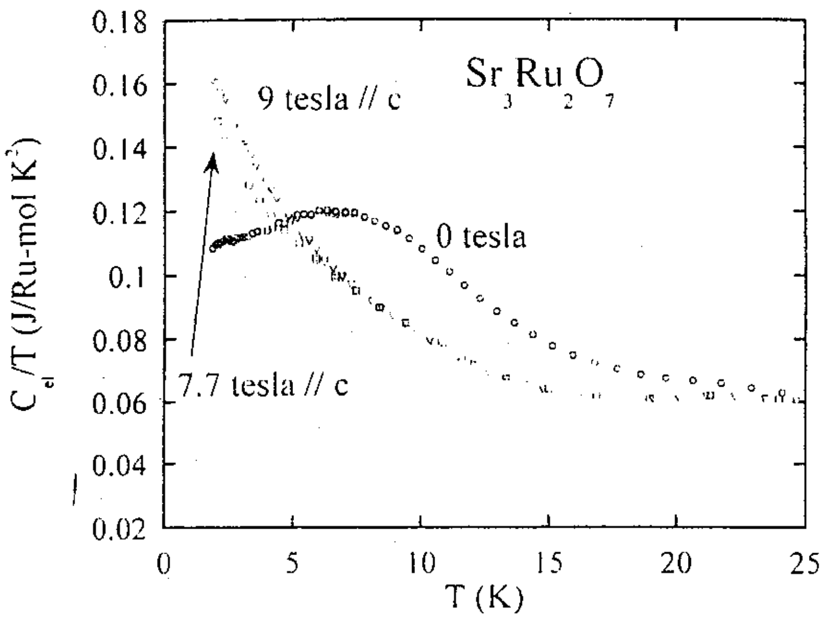
Isotropic for in-plane fields, and only a mild anisotropy for B // c.

These vibrating sample magnetometer measurements have low T limit of 5K.

Empirical phase diagram for $Sr_3Ru_2O_7$ based on measurement of resistivity with B // ab



Diverging specific heat γ at the metamagnetic field in $Sr_3Ru_2O_7$



R.S. Perry, L.M. Galvin, S. Grigera, L. Capogna, A.J. Schofield, A.P. Mackenzie, M. Chiao, S.R. Julian, S. Ikeda, S. Nakatsuji, Y. Maeno and C. Pfleiderer, cond-mat '00

Summary and conclusions

Measurements sensitive to the density of states below T_c give good evidence that it is not isotropically gapped.

However, there is also good evidence that the superconducting state is spin triplet, and breaks time reversal symmetry *at* T_c.

Possibilities for understanding these results are

a) P-wave superconductivity with $\boldsymbol{d} = \hat{z}(k_x + ik_y)$ and a pairing interaction that has a strong dependence on Fermi surface sheet and **k**.

b) More exotic triplet states.