Thermal transport in quantum materials

Lecture no. 2

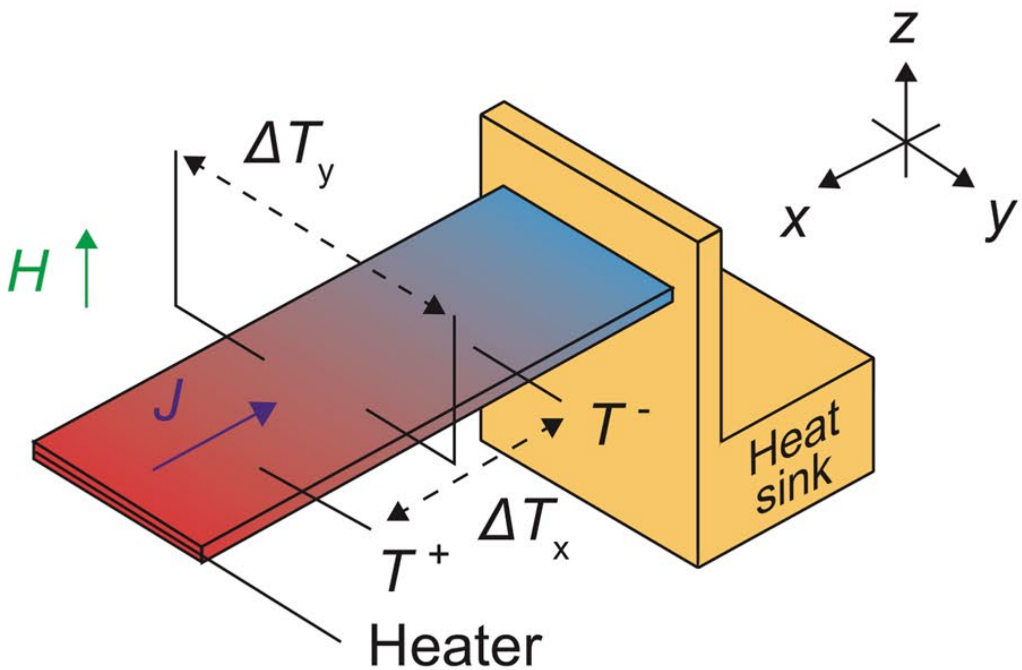
Louis Taillefer

Université de Sherbrooke

CIFAR

Exosup2022 Summer School, Cargèse, June 2022

Measurement of thermal transport



$$\kappa_{xx} = \frac{\dot{Q}}{\Delta T_x \, \alpha}$$

$$\kappa_{xy} = -\kappa_{xx} \frac{\Delta T_y}{\Delta T_x} \frac{L}{w}$$

Thermal transport in quantum materials

PART I — Kxx

METALS

1) Electrons & phonons

2) Wiedemann-Franz law in cuprates

SUPERCONDUCTORS

1) Cuprates — *d*-wave + Hc2

2) Iron pnictides — *s*+- or *d*-wave

3) Ruthenate — *d*-wave ?

INSULATORS

1) Nd2CuO4 — phonons

2) Nd2CuO4 — magnons

3) dmit — spinons ?

Iron-based superconductors

Iron-based superconductors

1) Antiferromagnetic superconductors

2) Inter-band pairing

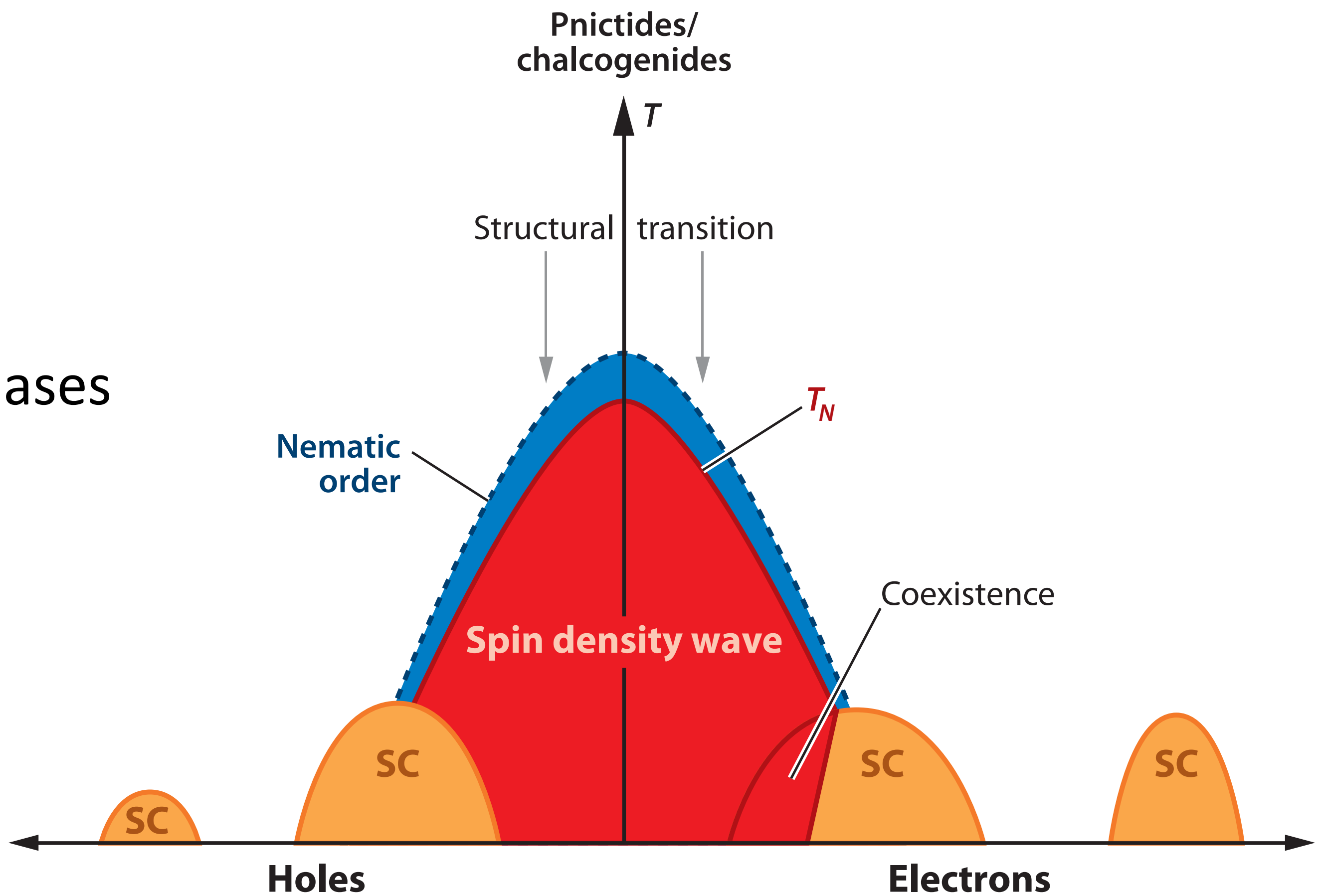
3) Quantum criticality

4) Nematicity

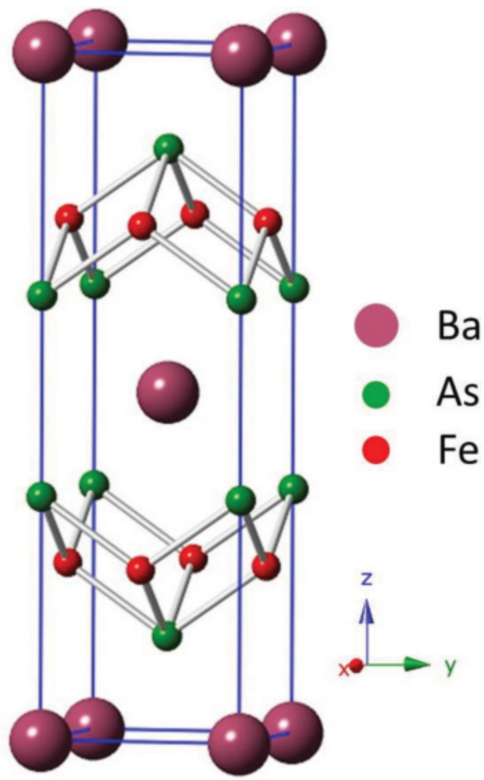
5) Multiple magnetic phases

6) Pairing symmetry

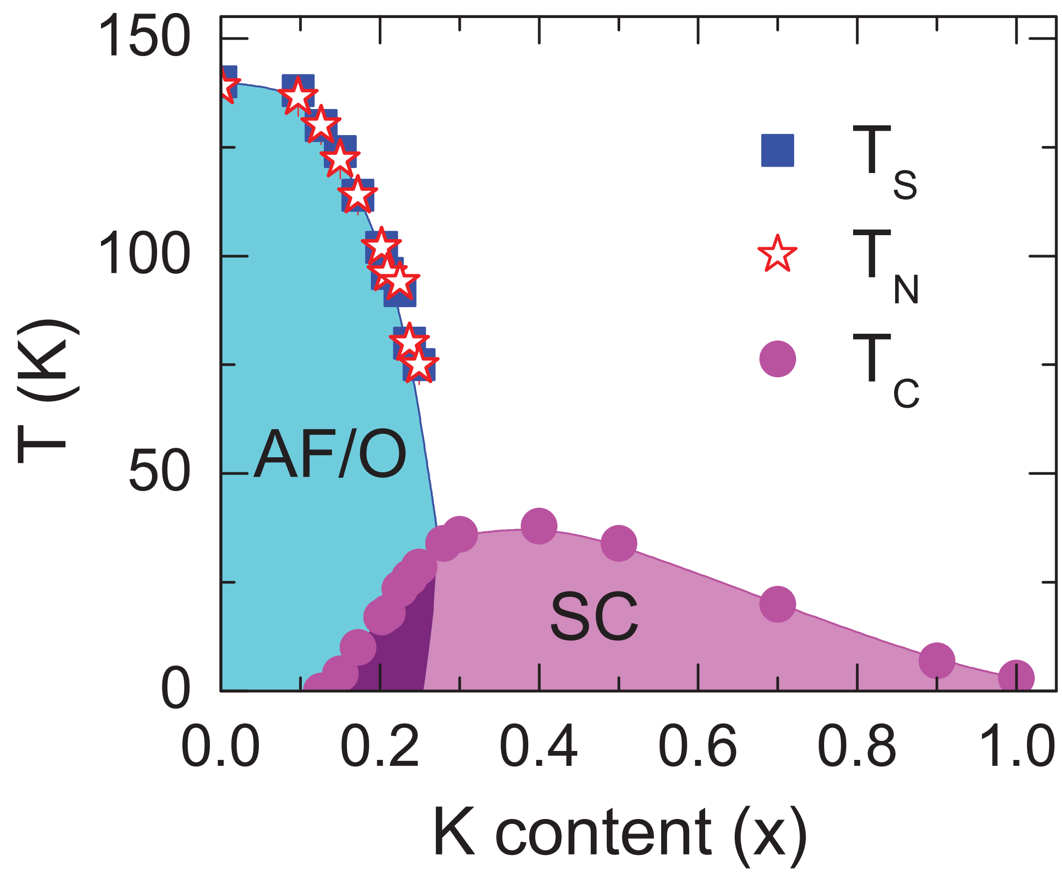
7) High T_c



BaFe2As2



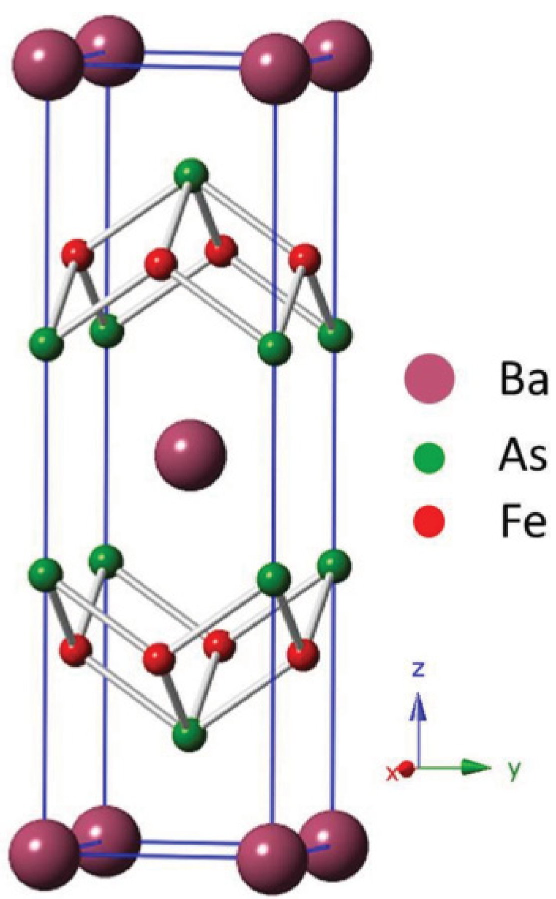
Ba
As
Fe
z
x
y

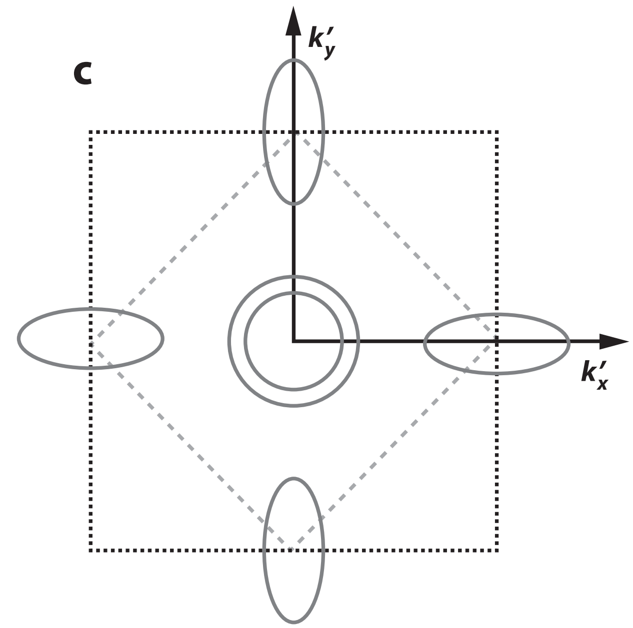


150
100
50
0
T (K)
0.0
0.2
0.4
0.6
0.8
1.0
K content (x)
AF/O
SC
T_S
T_N
T_C

Fermi surface

BaFe2As2

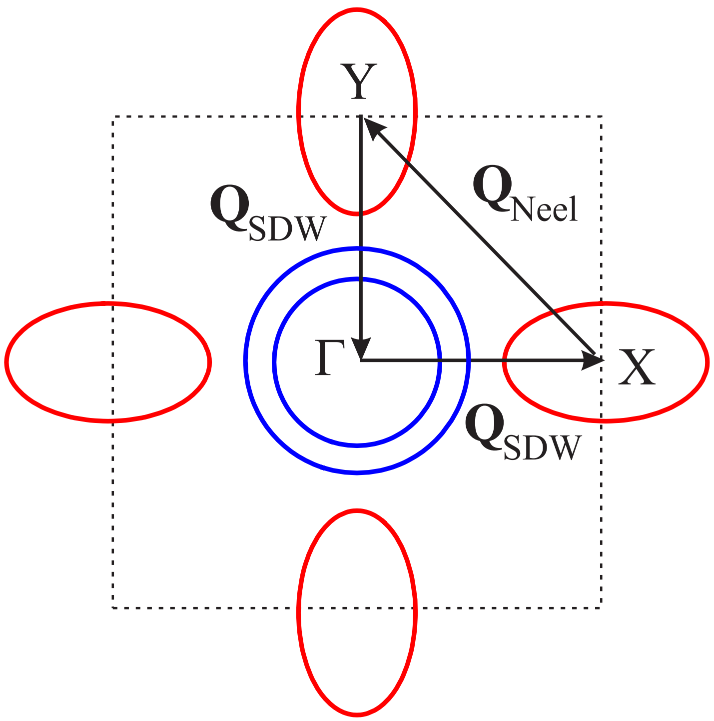


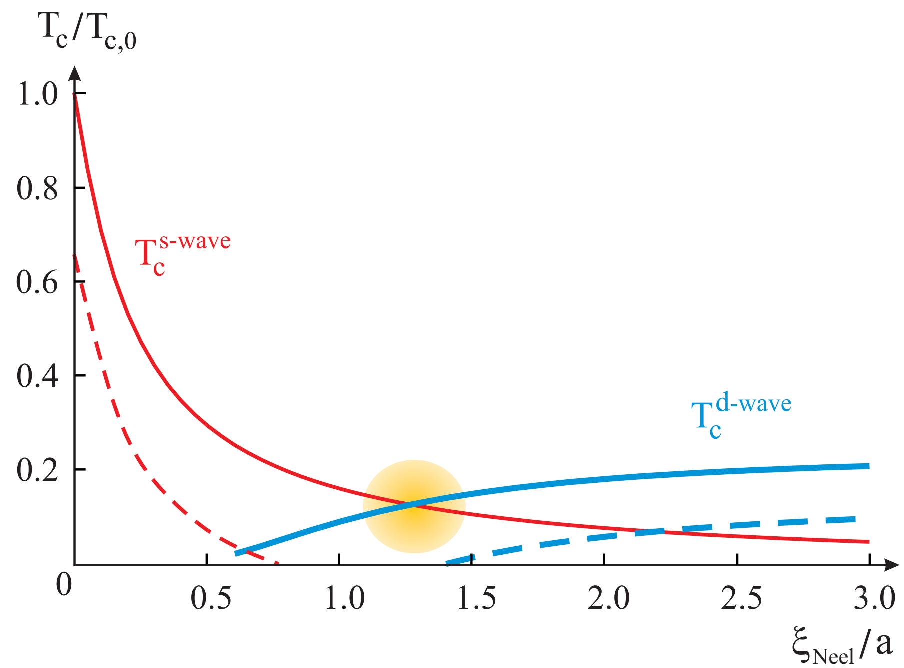


Multi-band
Quasi-2D
Nesting : SDW or SC

Pairing : inter-band !

Pairing symmetry & mechanism





1) S+- and d are close
2) Max Tc higher for s+-
3) No nodes in S+- ; nodes in d-wave
4) Both sensitive to impurities, in general

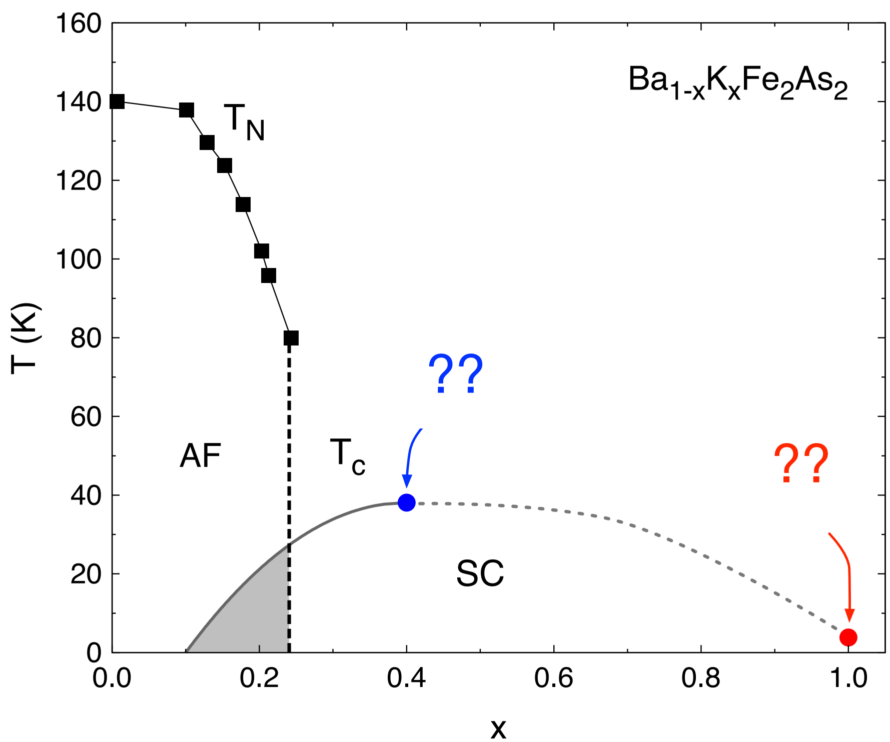
Fernandes & Millis, PRL **110**, 117004 (2013)

SUPERCONDUCTORS Iron pnictides (Ba,K)Fe2As2

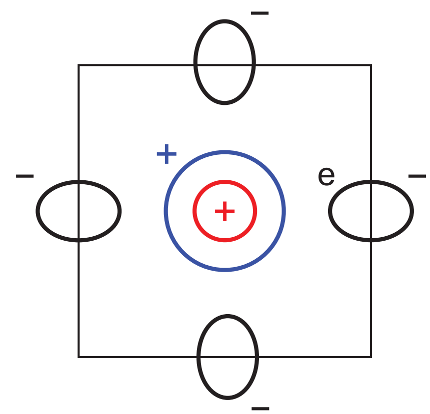
IOP Publishing Superconductor Science and Technology
Supercond. Sci. Technol. **25** (2012) 084013 (10pp) doi:10.1088/0953-2048/25/8/084013

From d-wave to s-wave pairing in the iron-pnictide superconductor (Ba, K)Fe_2As_2

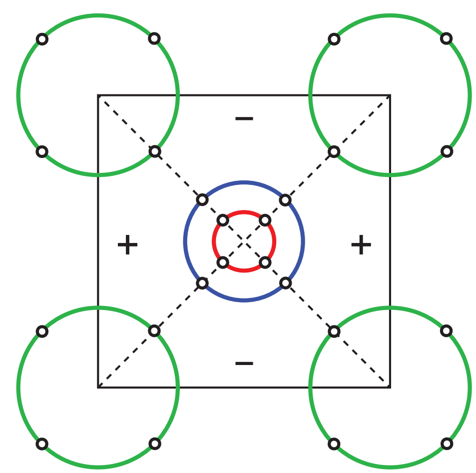
J-Ph Reid[1], A Juneau-Fecteau[1], R T Gordon[1], S René de Cotret[1], N Doiron-Leyraud[1], X G Luo[1], H Shakeripour[1], J Chang[1], M A Tanatar[2,3], H Kim[2,3], R Prozorov[2,3], T Saito[4], H Fukazawa[4], Y Kohori[4], K Kihou[5], C H Lee[5], A Iyo[5], H Eisaki[5], B Shen[6], H-H Wen[6,7] and Louis Taillefer[1,7]



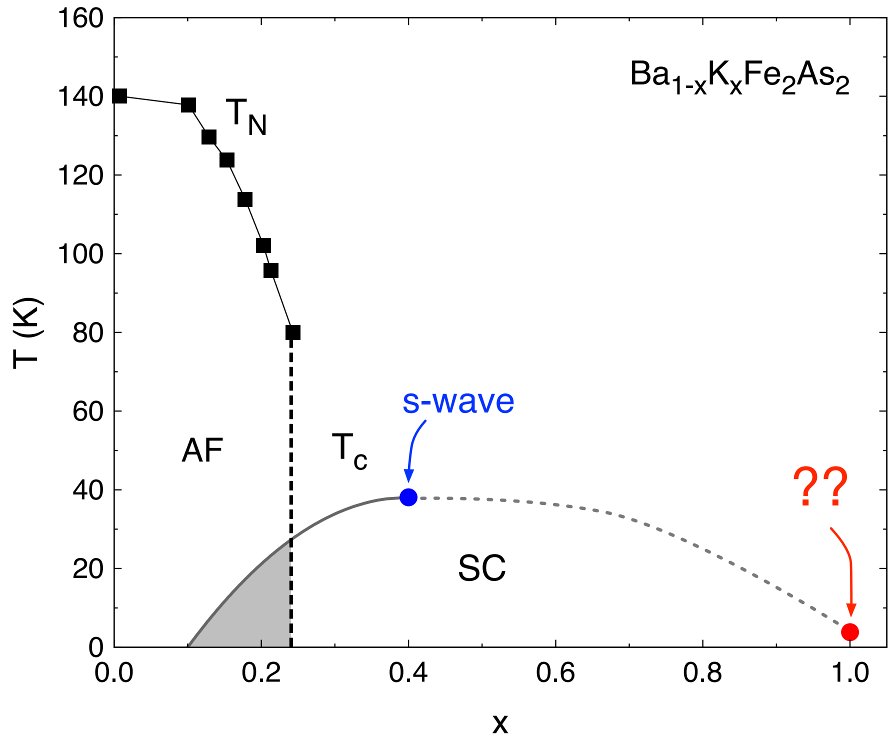
s+-

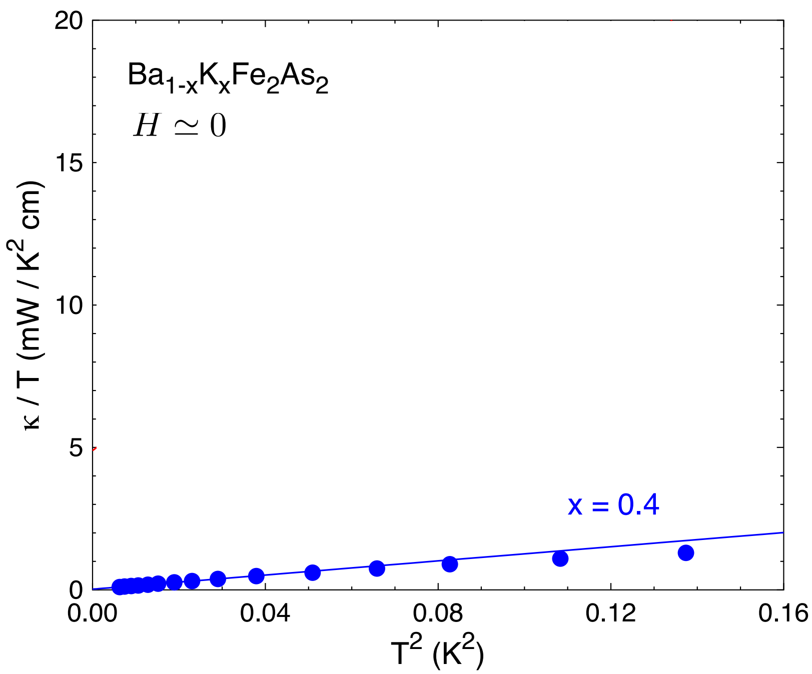


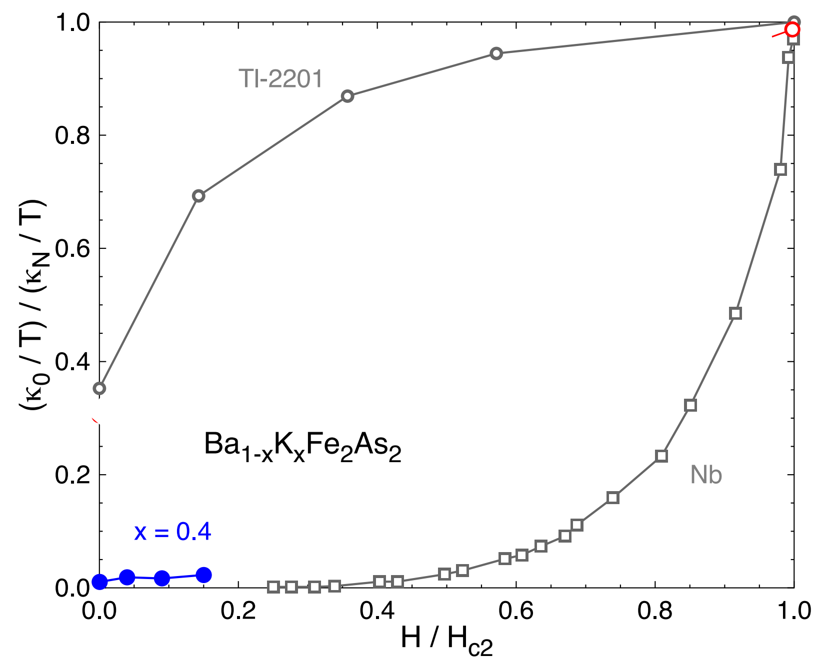
d-wave



SUPERCONDUCTORS *d*-wave (Ba,K)Fe2As2





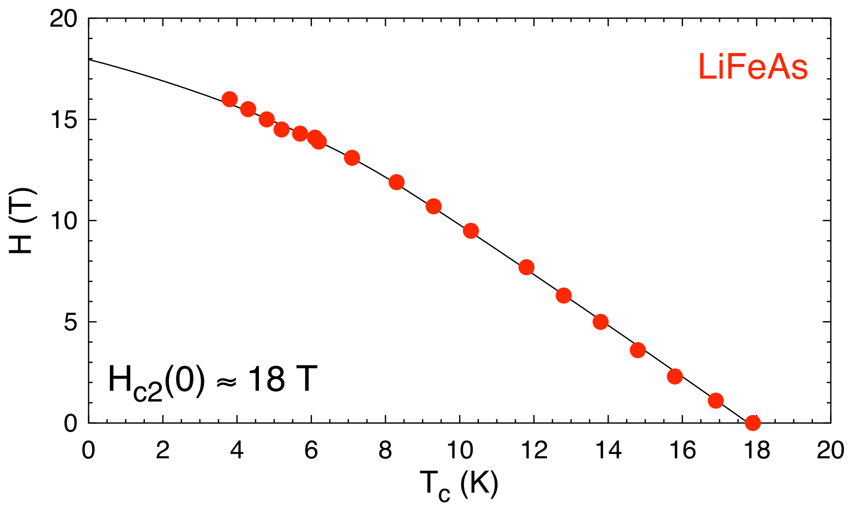


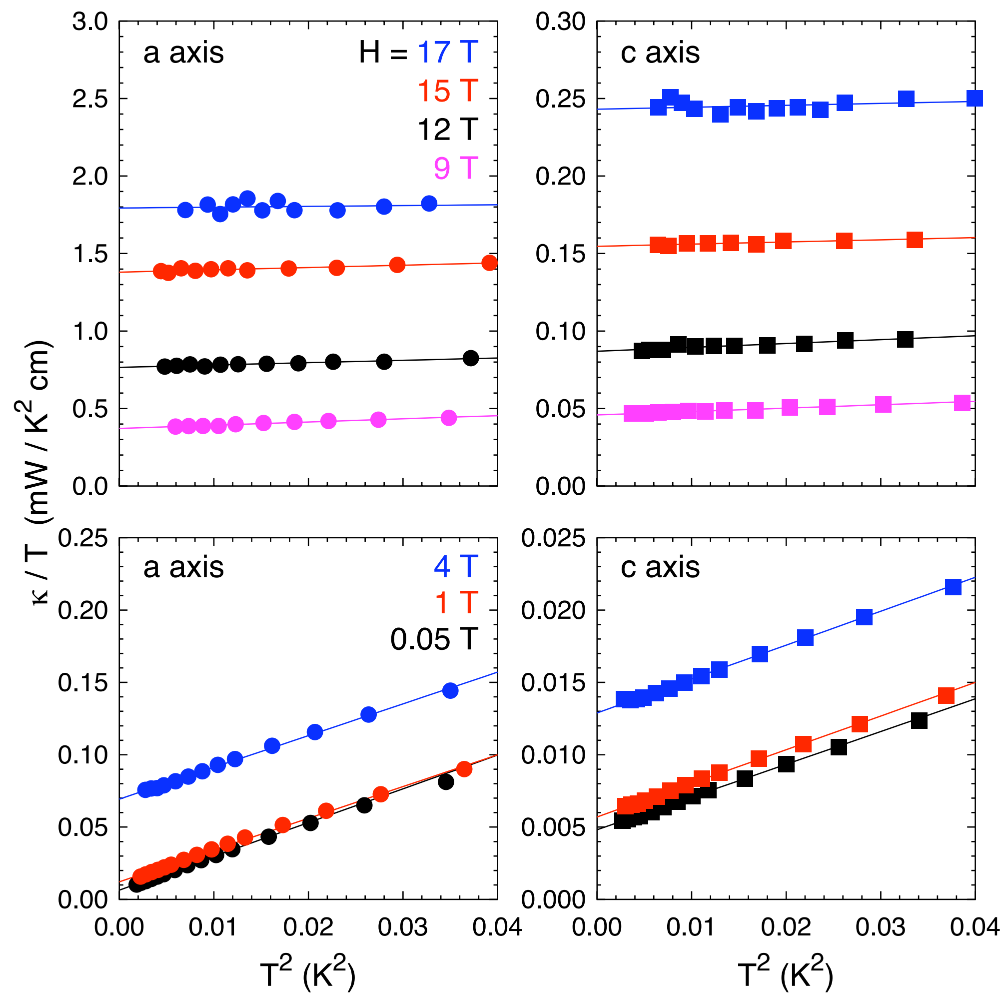
x = 0.4 : *s*-wave

PHYSICAL REVIEW B **84**, 054507 (2011)

Isotropic three-dimensional gap in the iron arsenide superconductor LiFeAs from directional heat transport measurements

M. A. Tanatar,[1,*] J.-Ph. Reid,[2] S. René de Cotret,[2] N. Doiron-Leyraud,[2] F. Laliberté,[2] E. Hassinger,[2] J. Chang,[2] H. Kim,[1,3] K. Cho,[1] Yoo Jang Song,[4] Yong Seung Kwon,[4] R. Prozorov,[1,3] and Louis Taillefer[2,5,†]





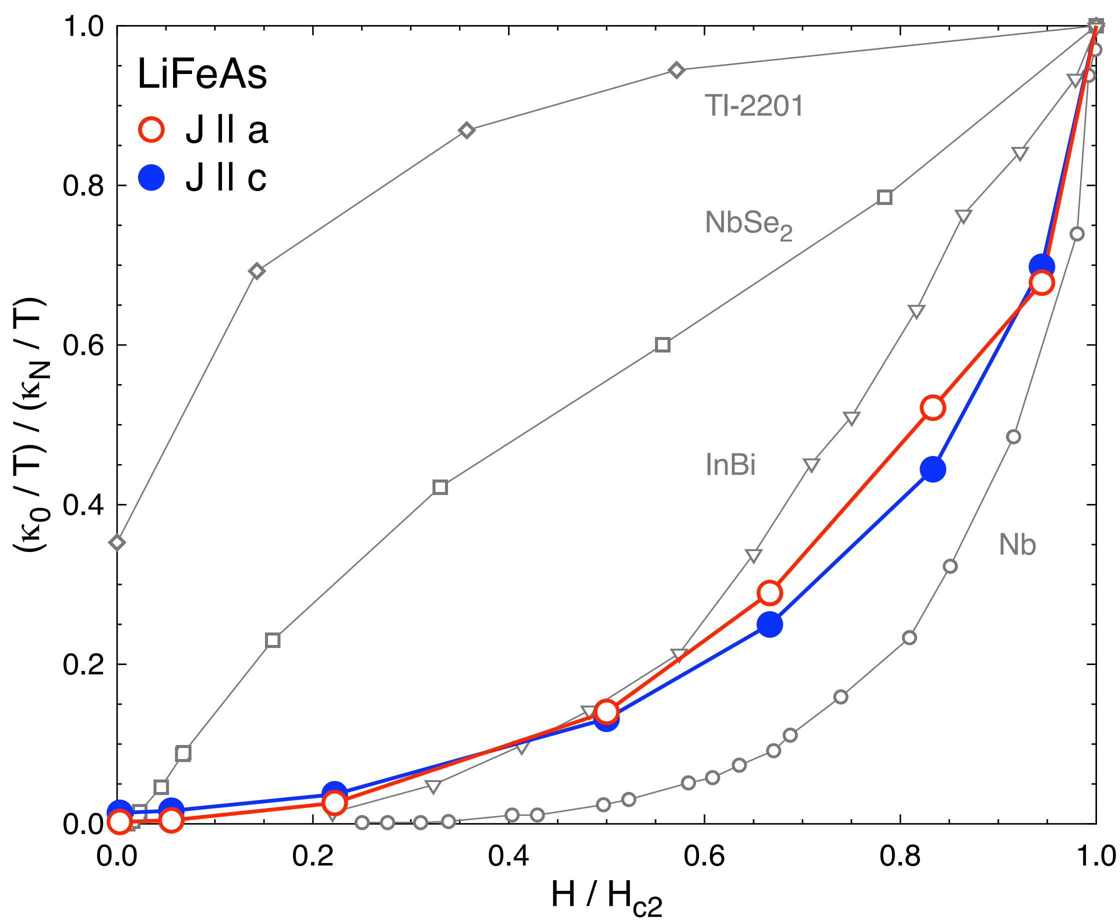
SUPERCONDUCTORS *s*-wave LiFeAs

PHYSICAL REVIEW B **84**, 054507 (2011)

Tc = 18 K

Isotropic three-dimensional gap in the iron arsenide superconductor LiFeAs from directional heat transport measurements

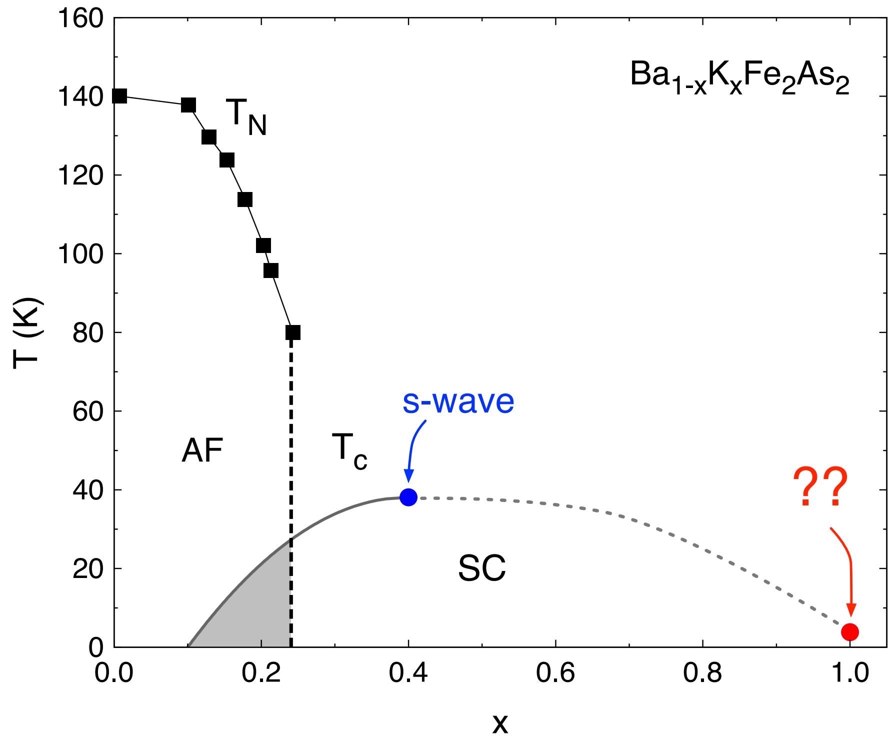
M. A. Tanatar,[1,*] J.-Ph. Reid,[2] S. René de Cotret,[2] N. Doiron-Leyraud,[2] F. Laliberté,[2] E. Hassinger,[2] J. Chang,[2] H. Kim,[1,3] K. Cho,[1] Yoo Jang Song,[4] Yong Seung Kwon,[4] R. Prozorov,[1,3] and Louis Taillefer[2,5,†]

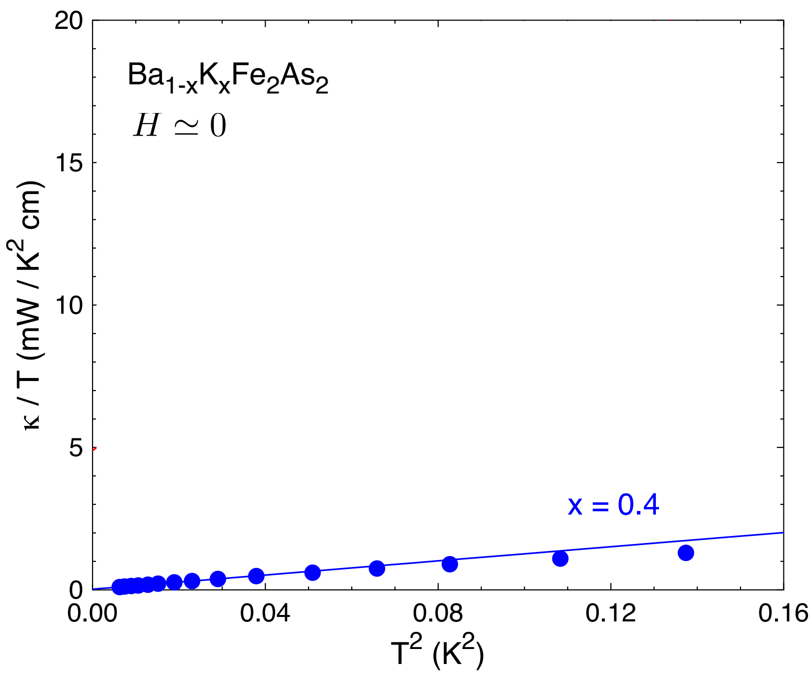


SUPERCONDUCTORS

d-wave

(Ba,K)Fe2As2





x = 0.4 : *s*-wave

x = 1.0 : ??

SUPERCONDUCTORS *d*-wave KFe2As2

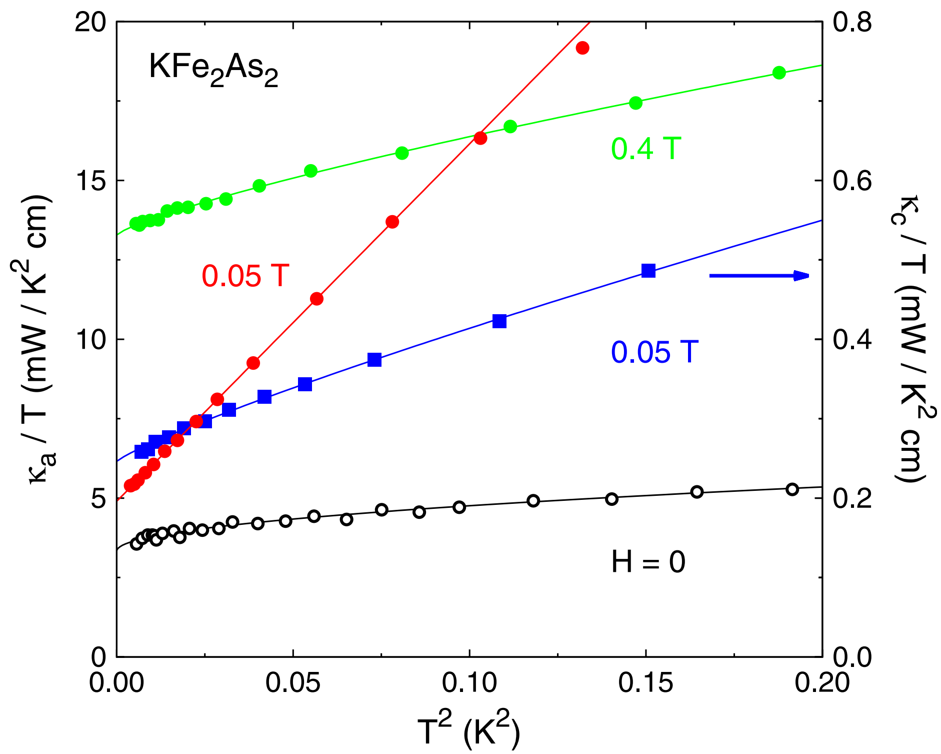
Tc = 4 K

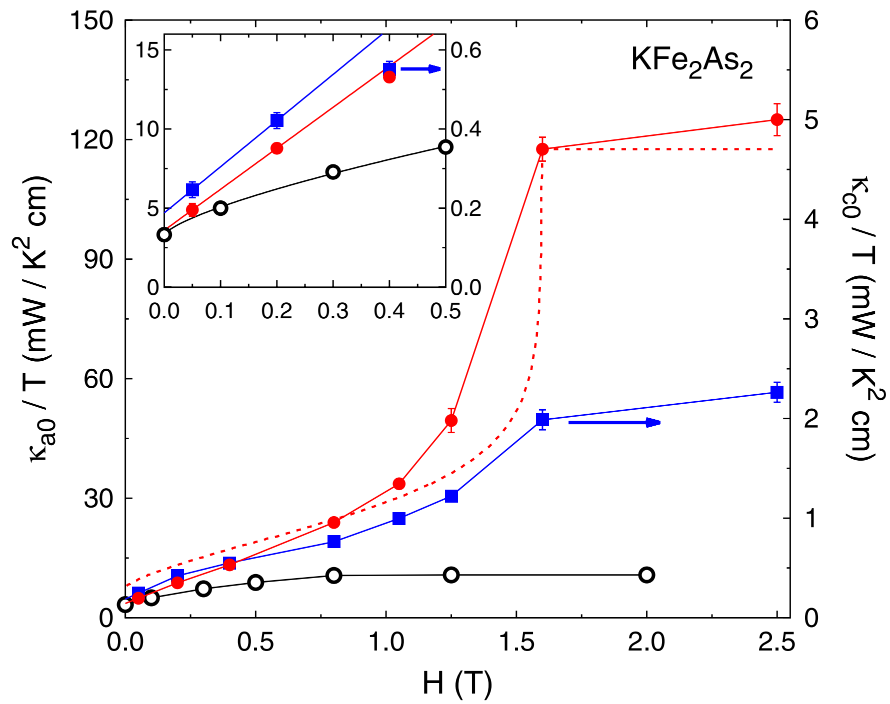
PRL **109,** 087001 (2012) PHYSICAL REVIEW LETTERS week ending 24 AUGUST 2012

Universal Heat Conduction in the Iron Arsenide Superconductor KFe_2As_2: Evidence of a *d*-Wave State

J.-Ph. Reid,[1] M. A. Tanatar,[2] A. Juneau-Fecteau,[1] R. T. Gordon,[1] S. René de Cotret,[1] N. Doiron-Leyraud,[1] T. Saito,[3] H. Fukazawa,[3] Y. Kohori,[3] K. Kihou,[4] C. H. Lee,[4] A. Iyo,[4] H. Eisaki,[4] R. Prozorov,[2,5] and Louis Taillefer[1,6,*]

$$\kappa_0/T = 3.6 \pm 0.5 \text{ mW/K}^2\text{ cm}$$





<u>Open circles</u>: Dong *et al.*, PRL **104**, 087004 (2010)

SUPERCONDUCTORS *d*-wave KFe2As2

Tc = 4 K

PRL **109,** 087001 (2012) PHYSICAL REVIEW LETTERS week ending 24 AUGUST 2012

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EXPERIMENT

$$\kappa_0/T = 3.6 \pm 0.5 \ \mathrm{mW/K^2\,cm}$$

Finite residual linear term (RLT)

$$\frac{\kappa_0}{T} = \frac{{k_B}^2}{3\hbar}\frac{n}{c}\left(\frac{v_F}{v_\Delta} + \frac{v_\Delta}{v_F}\right)$$ *d*-wave

THEORY

$$\frac{\kappa_0}{T} \simeq \frac{\kappa_{00}}{T} \equiv \frac{\hbar}{2\pi}\frac{\gamma_N v_F^2}{\Delta_0}$$

$$v_F \simeq 4 \times 10^6 \ \mathrm{cm/s}$$

$$\gamma_N = 85 \pm 10 \ \mathrm{mJ/K^2\,mol}$$

$$\Delta_0 = 2.14 k_B T_{c0}$$

$$\kappa_{00}/T = 3.3 \pm 0.5 \ \mathrm{mW/K^2\,cm}$$

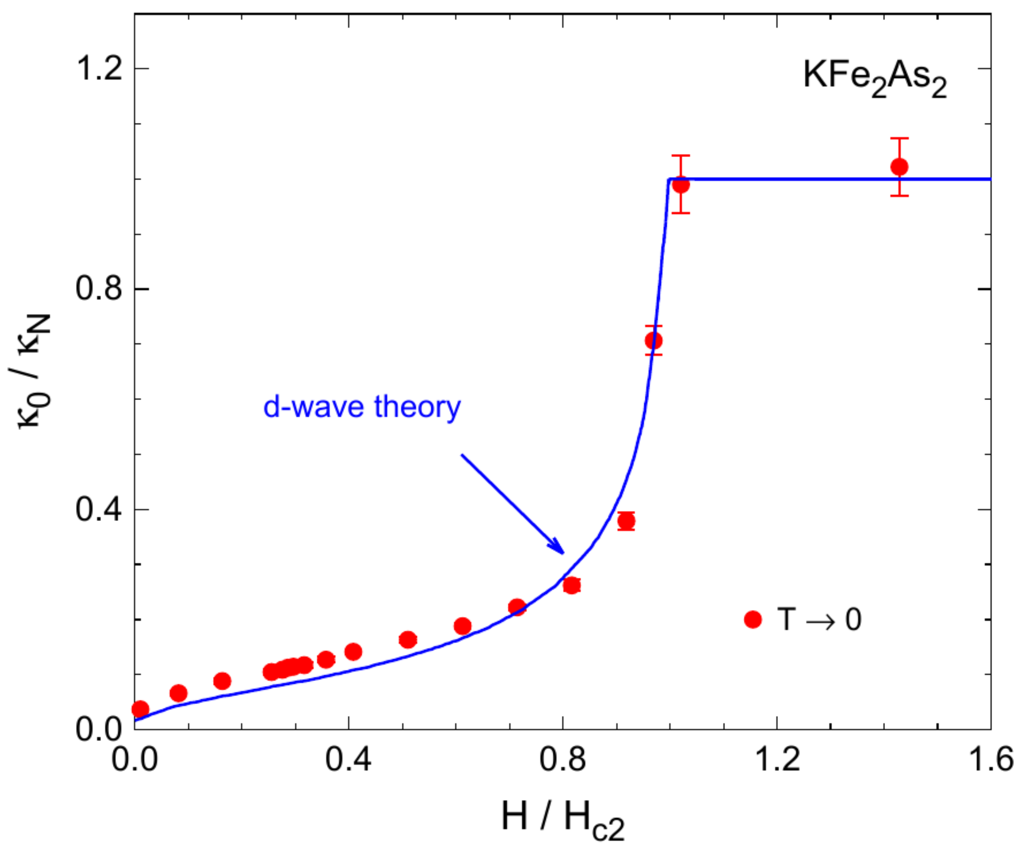
SUPERCONDUCTORS

d-wave

KFe2As2

Tc = 4 K

Pure limit



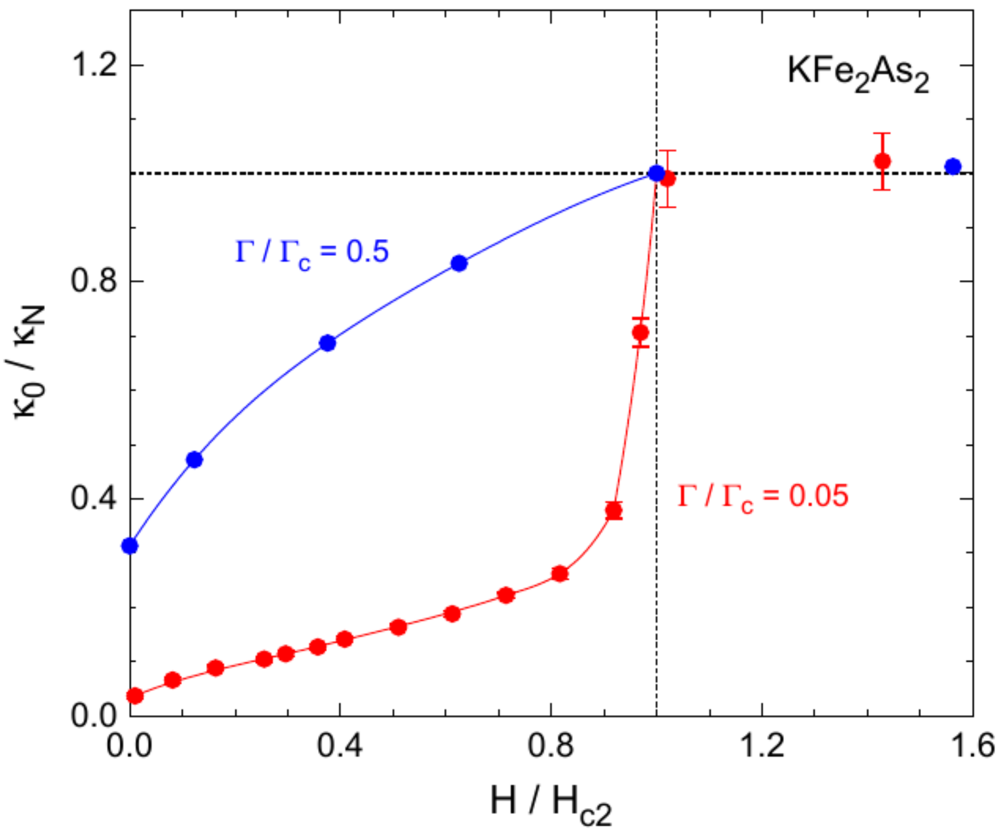
Vekhter & Houghton, PRL **83**, 4626 (1999)

Data: Reid *et al.*, PRL **109**, 087001 (2012)

SUPERCONDUCTORS *d*-wave KFe2As2

Tc = 4 K

Different impurity levels

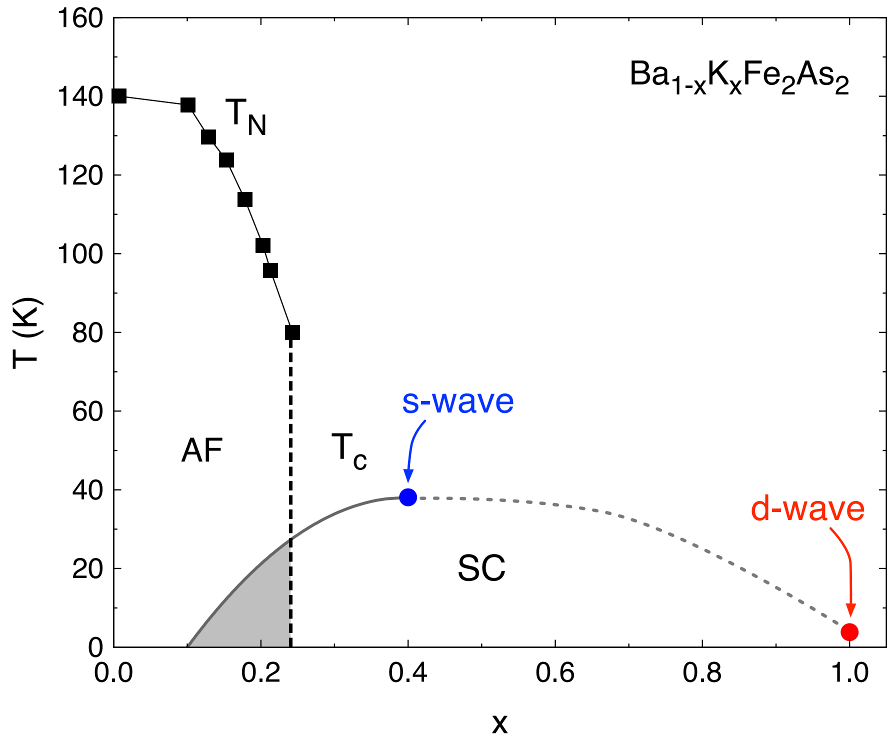


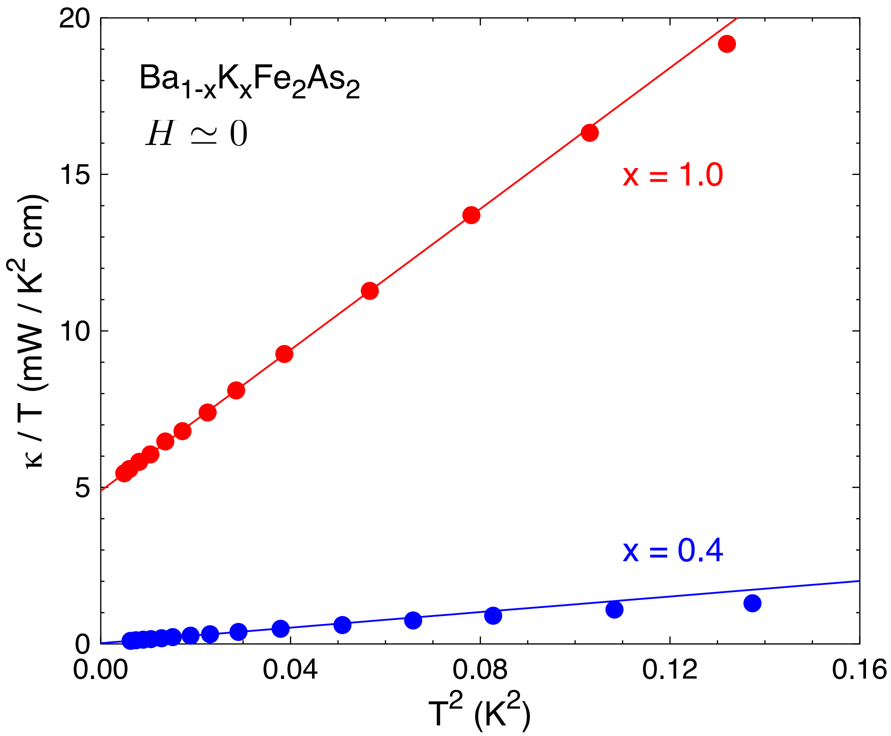
Data: Reid *et al.*, PRL **109**, 087001 (2012)

Data: Dong *et al.*, PRL **104**, 087004 (2010)

SUPERCONDUCTORS

(Ba,K)Fe2As2





x = 0.4 : *s*-wave

x = 1.0 : *d*-wave

SUPERCONDUCTORS

KFe2As2

nature physics

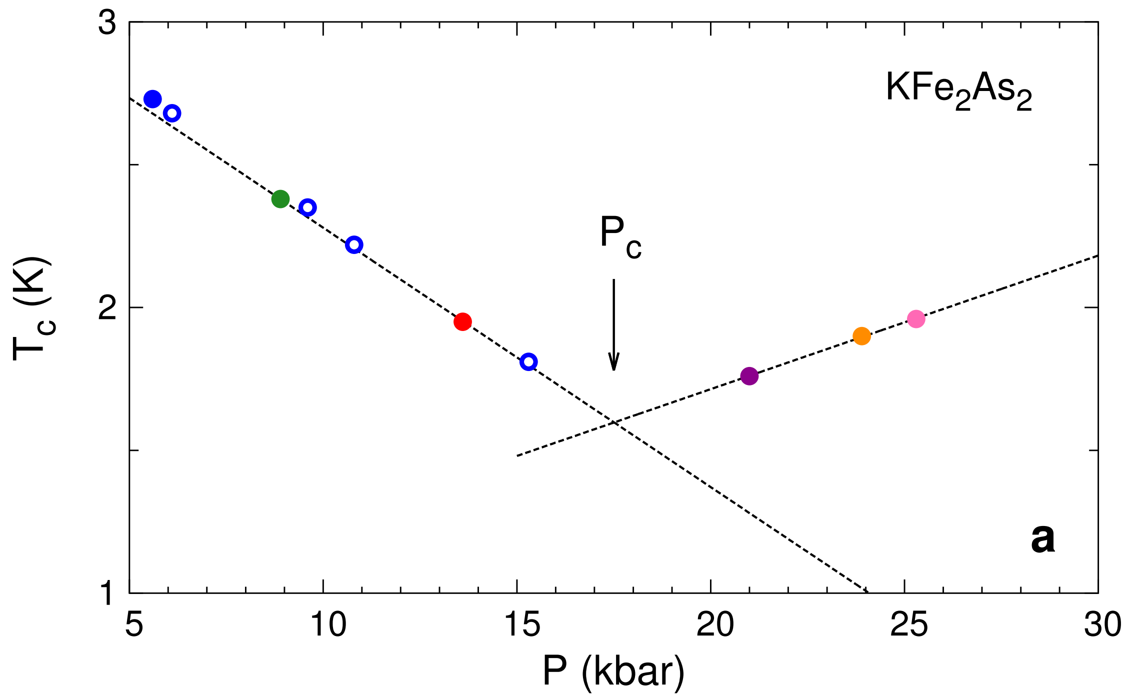
LETTERS

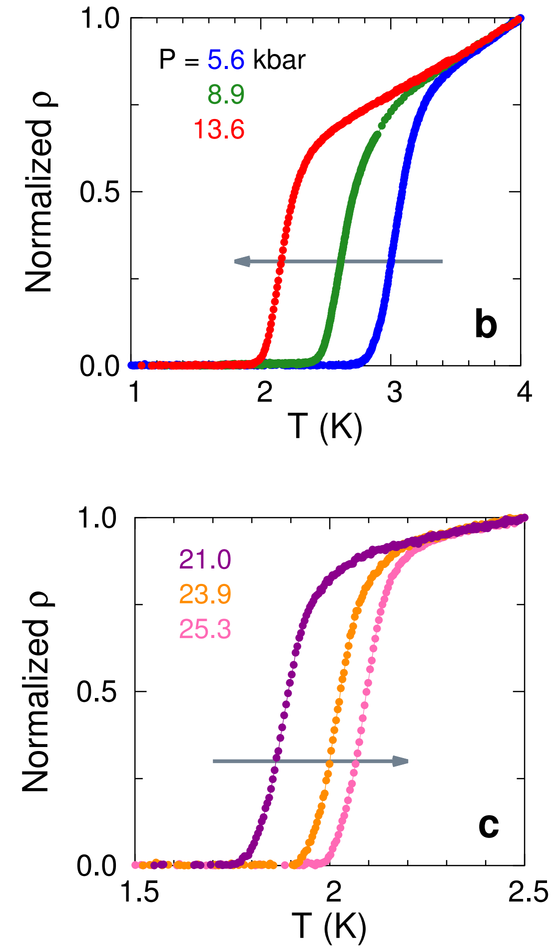
PUBLISHED ONLINE: 12 MAY 2013 | DOI: 10.1038/NPHYS2617

NATURE PHYSICS | VOL 9 | JUNE 2013 | 349

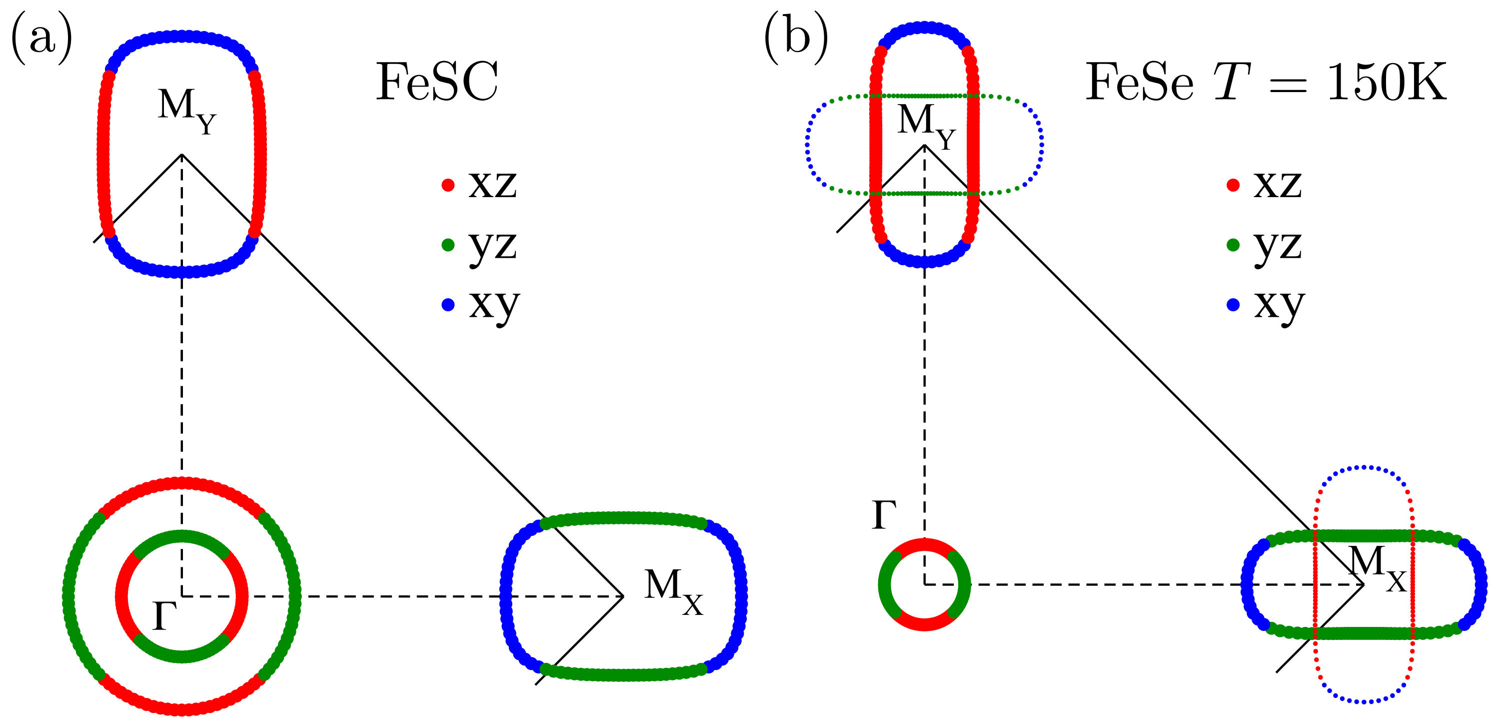
Sudden reversal in the pressure dependence of T_c in the iron-based superconductor KFe_2As_2

F. F. Tafti[1], A. Juneau-Fecteau[1], M-È. Delage[1], S. René de Cotret[1], J-Ph. Reid[1†], A. F. Wang[2], X-G. Luo[2], X. H. Chen[2], N. Doiron-Leyraud[1] and Louis Taillefer[1,3★]

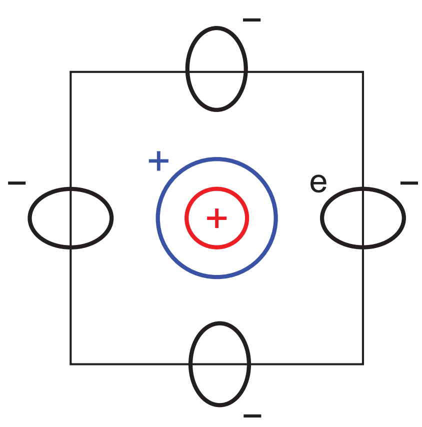




SUPERCONDUCTORS FeSe $T_c = 9$ K



s+-



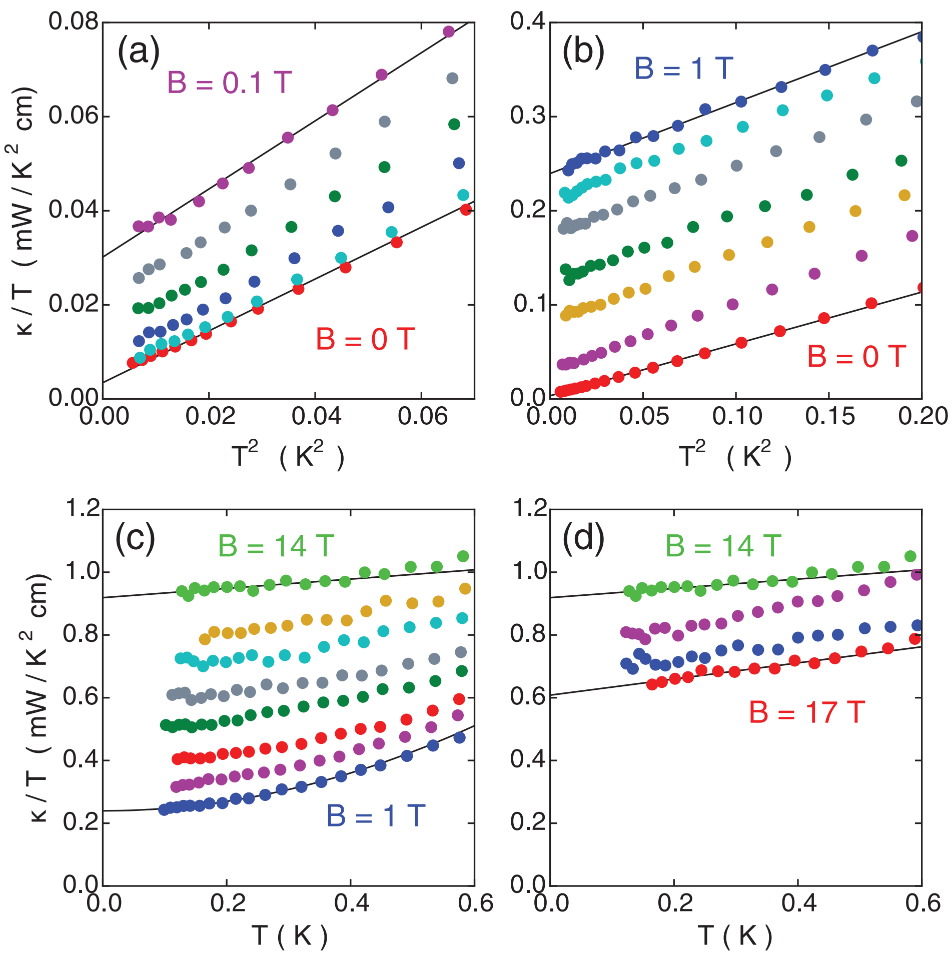
SUPERCONDUCTORS   *s*-wave   FeSe

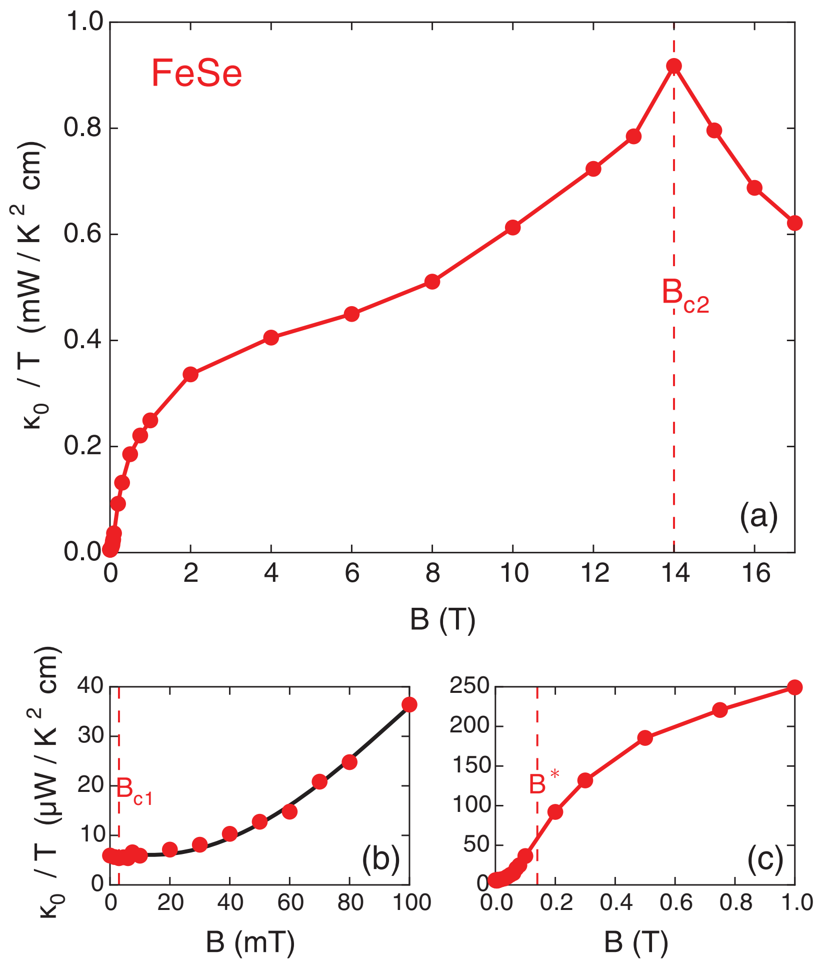
PRL **117,** 097003 (2016)   PHYSICAL REVIEW LETTERS   week ending 26 AUGUST 2016

Thermal Conductivity of the Iron-Based Superconductor FeSe: Nodeless Gap with a Strong Two-Band Character

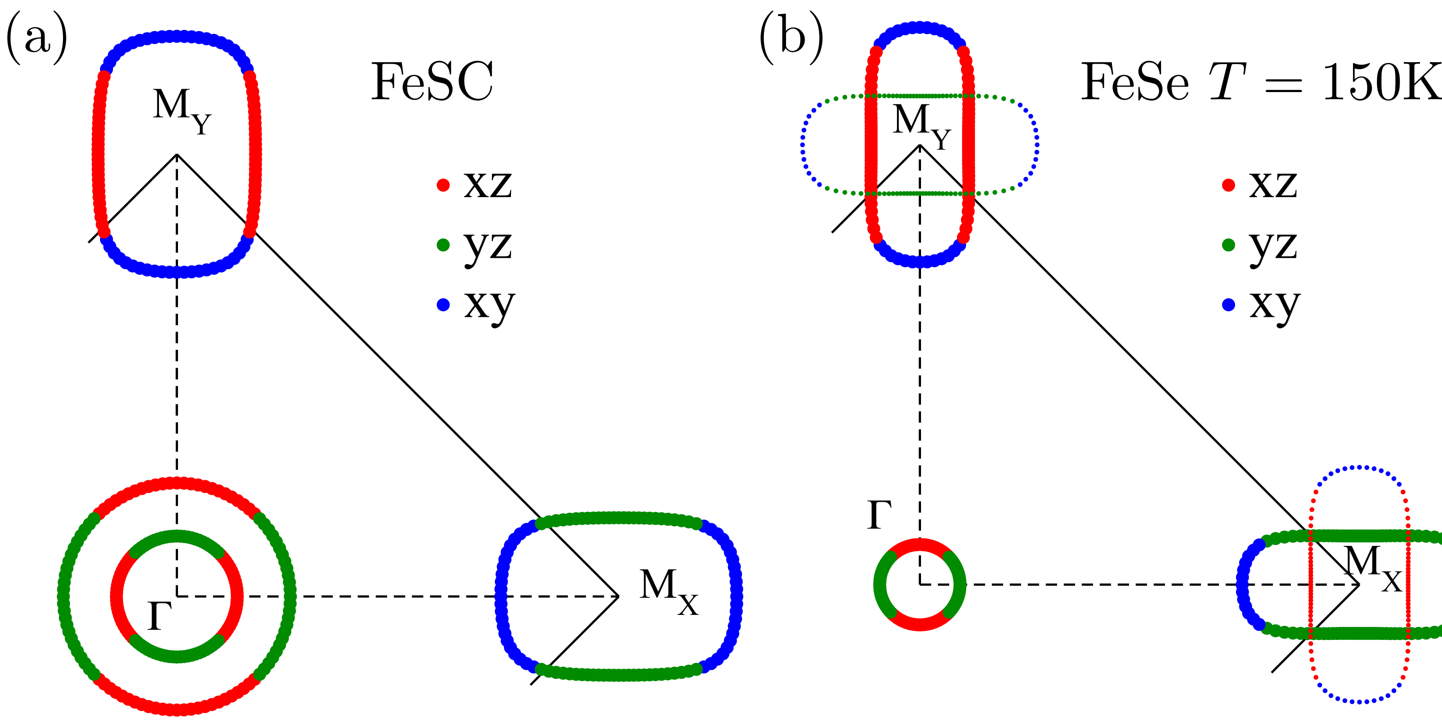
Tc = 9 K

P. Bourgeois-Hope,[1] S. Chi,[2] D. A. Bonn,[2,3] R. Liang,[2,3] W. N. Hardy,[2,3] T. Wolf,[4] C. Meingast,[4] N. Doiron-Leyraud,[1] and Louis Taillefer[1,3,*]

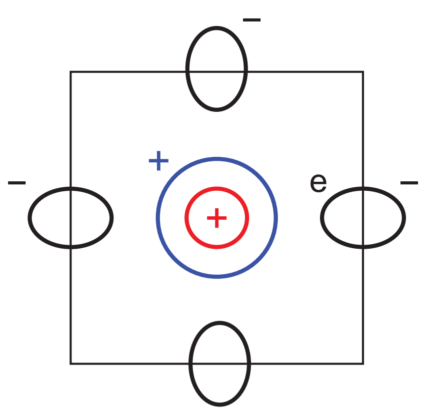




SUPERCONDUCTORS FeSe Tc = 9 K



s+-



Thermal transport in quantum materials

PART I — Kxx

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SUPERCONDUCTORS

1) Cuprates — *d*-wave + Hc2

2) Iron pnictides — *s*+- or *d*-wave

3) Ruthenate — *d*-wave ?

INSULATORS

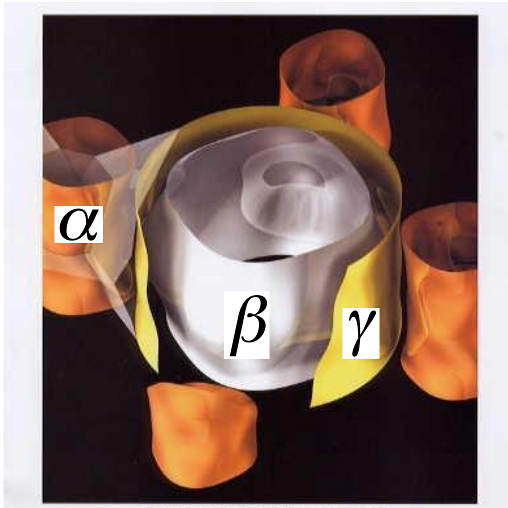
1) Nd2CuO4 — phonons

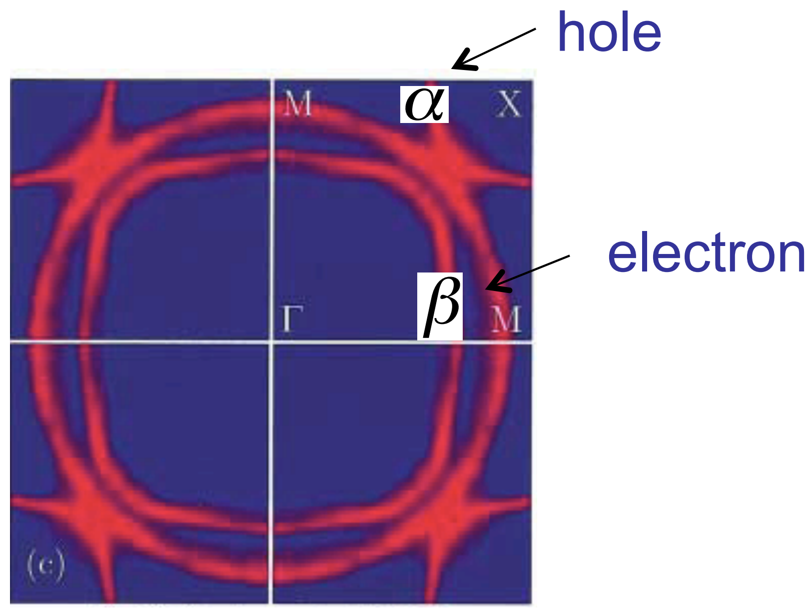
2) Nd2CuO4 — magnons

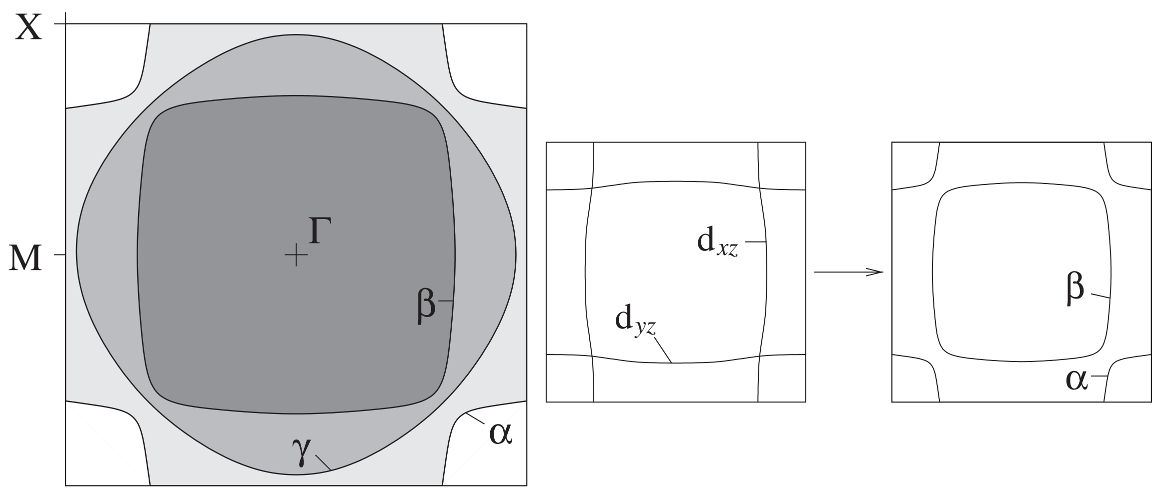
3) dmit — spinons ?

Strontium ruthenate

Fermi surface

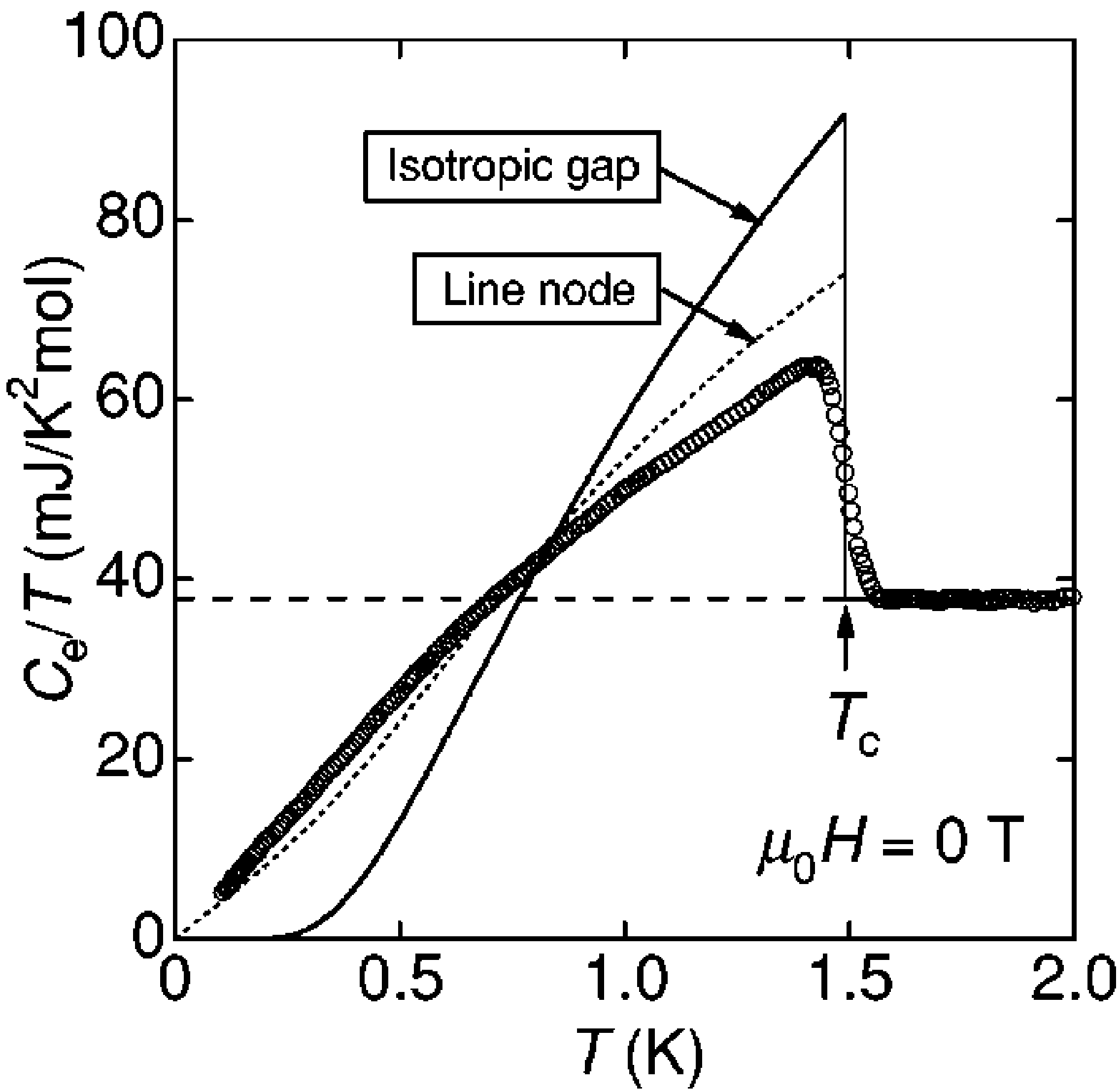






Sr_2RuO_4

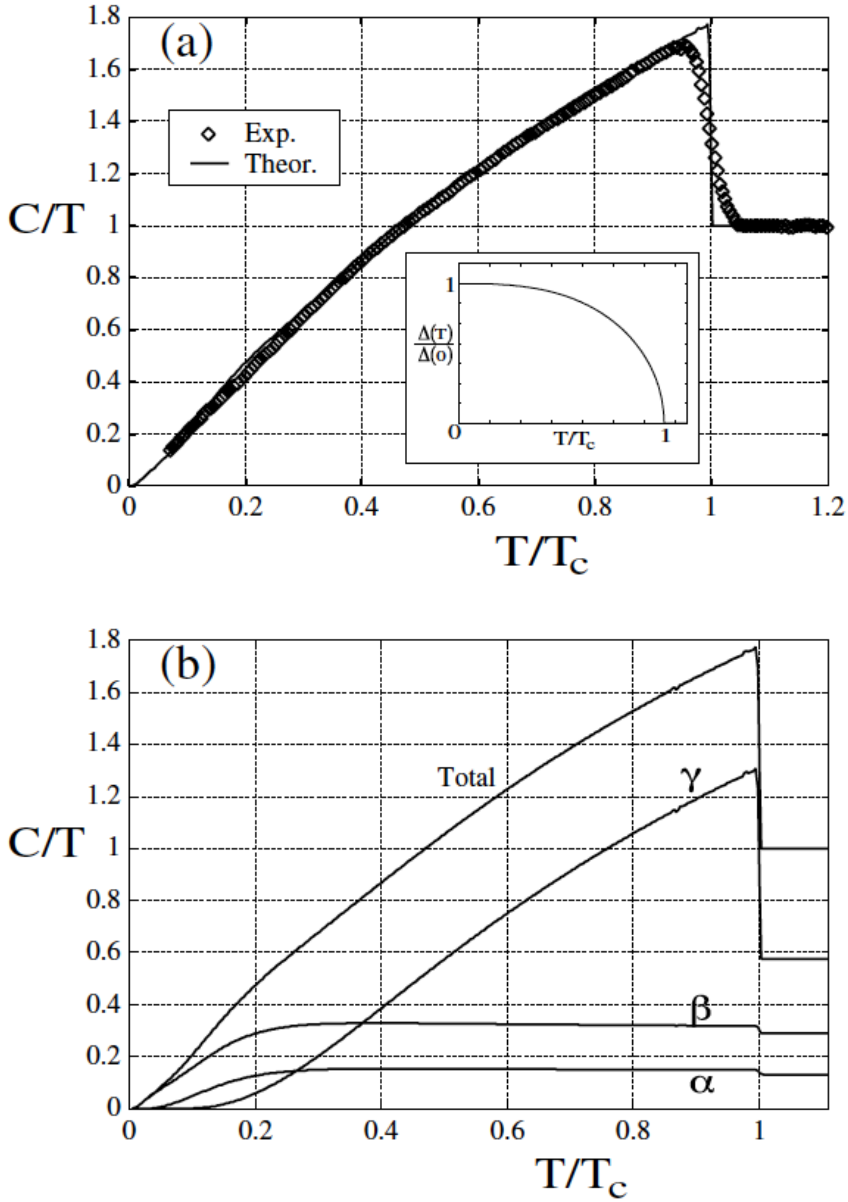
Specific heat

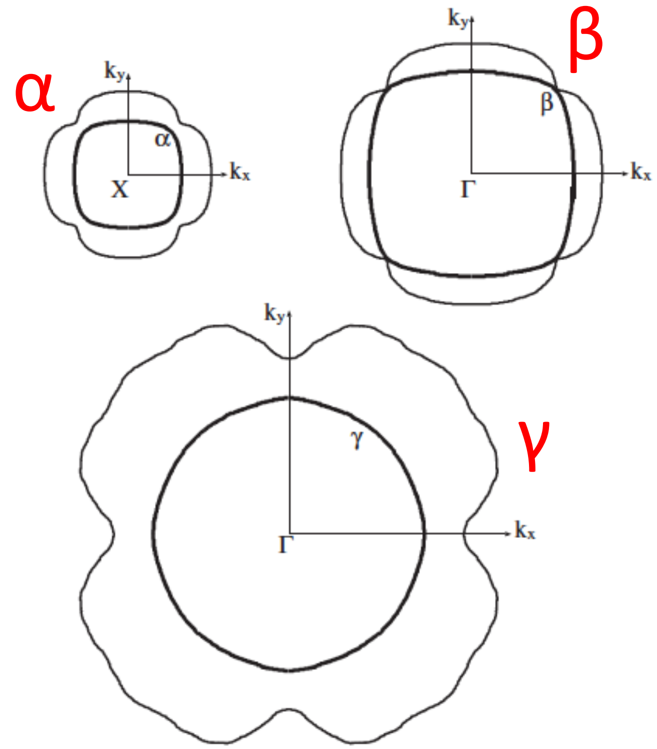


Nishizaki et al. JLT 2000

Sr_2RuO_4

P-wave with deep minima





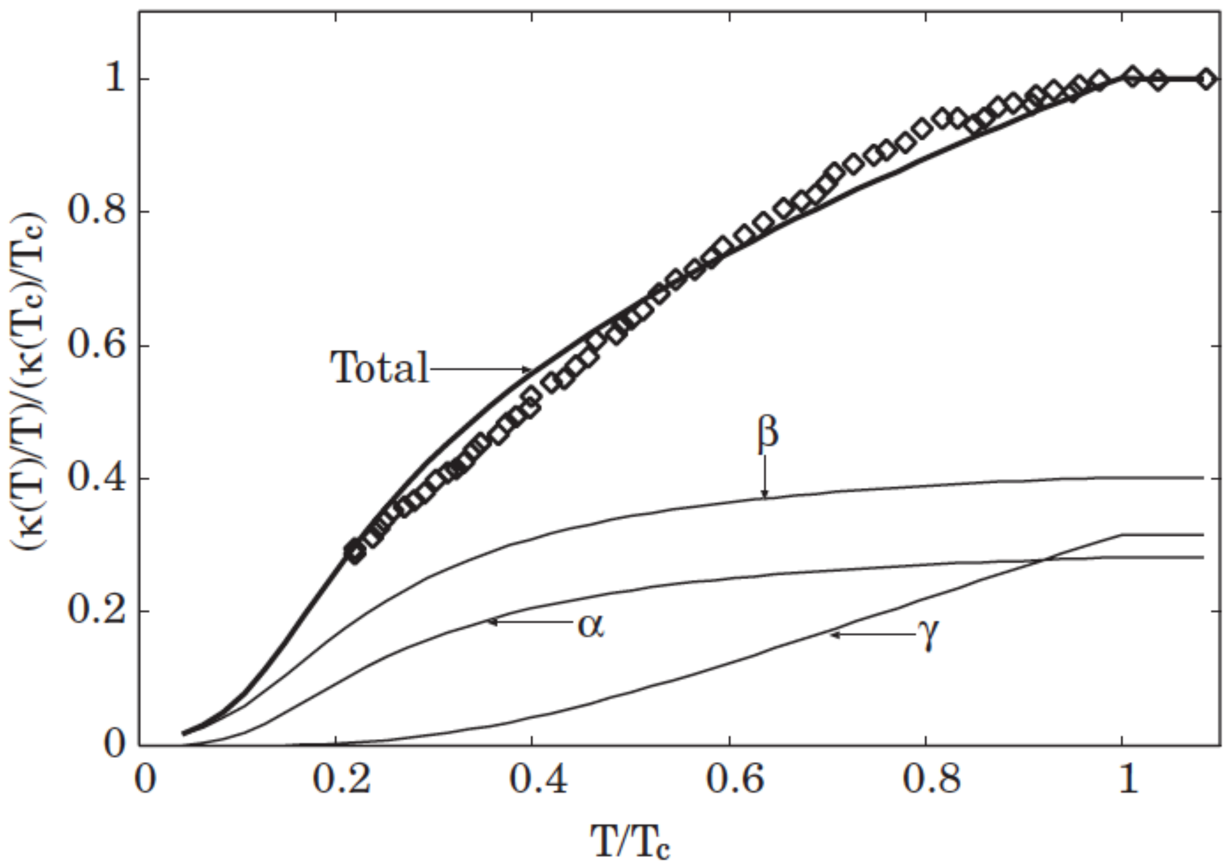
Specific heat

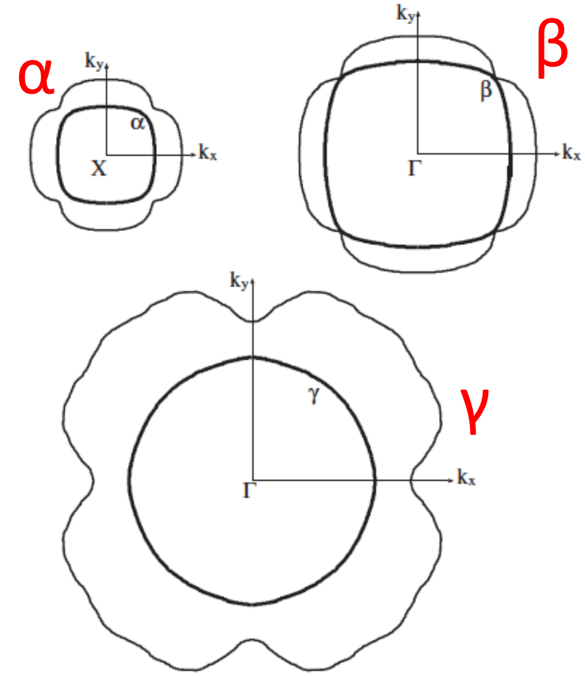
Nomura JPSJ 2005

Sr_2RuO_4

P-wave with deep minima

Thermal conductivity



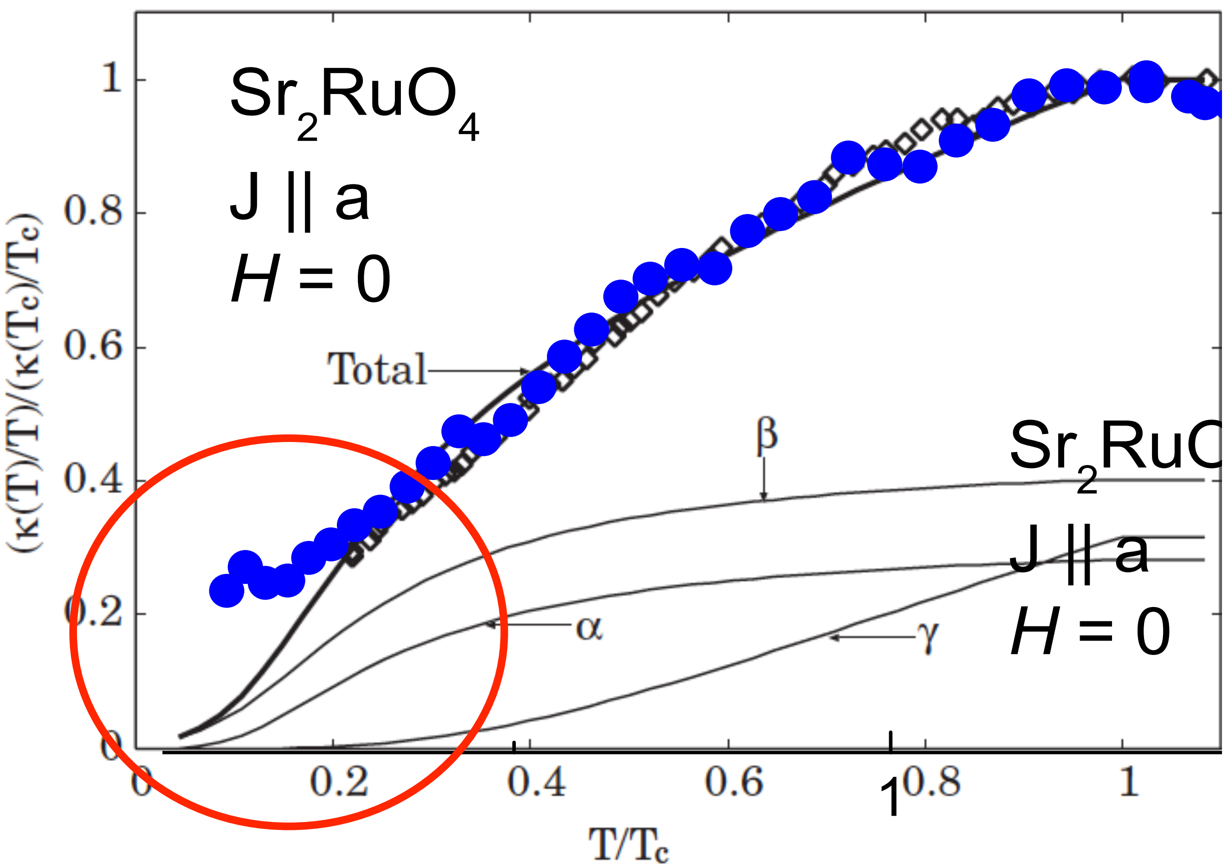


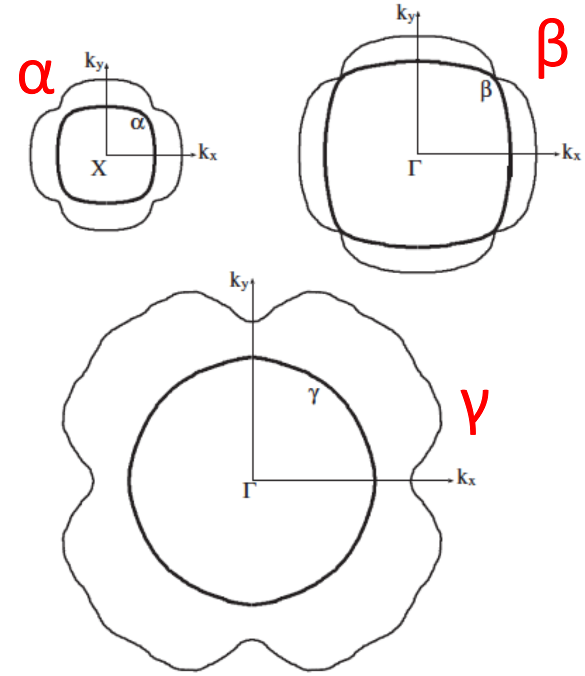
Nomura JPSJ 2005

Sr_2RuO_4

P-wave with deep minima

Thermal conductivity





Nomura JPSJ 2005

Hassinger et al., PRX 2017

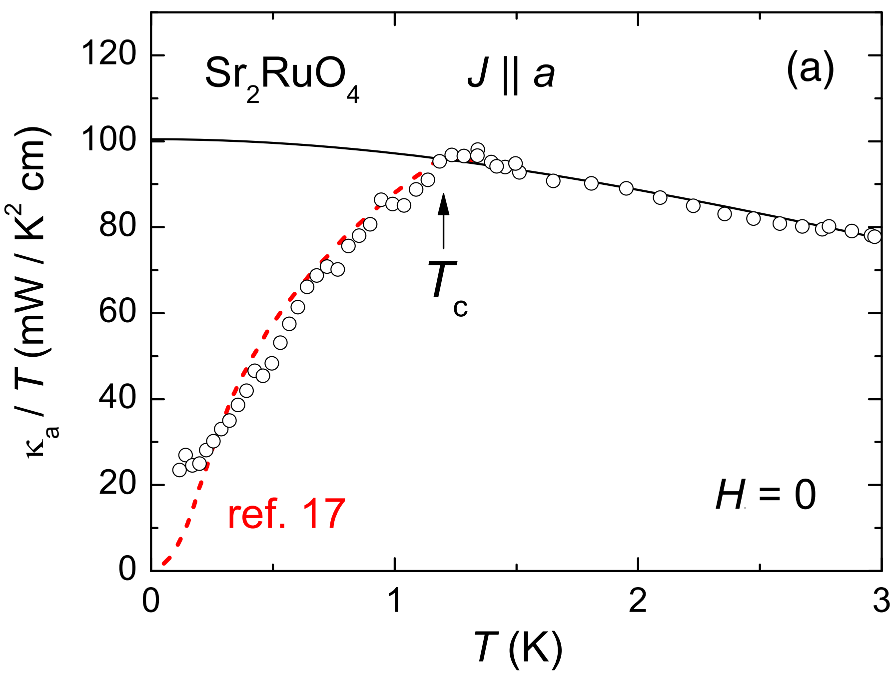
Sr_2RuO_4

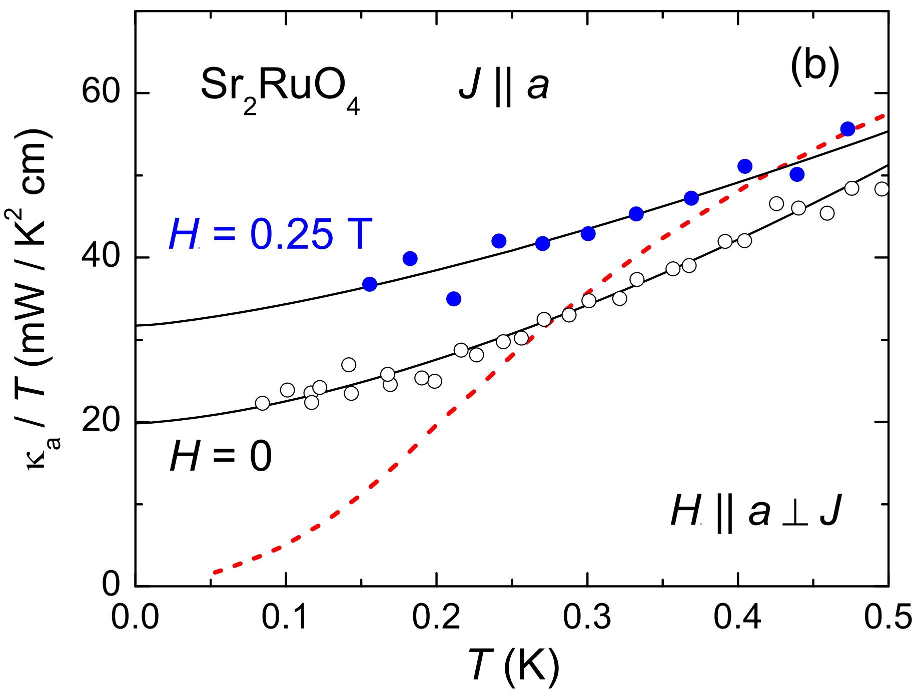
Thermal conductivity

PHYSICAL REVIEW X **7,** 011032 (2017)

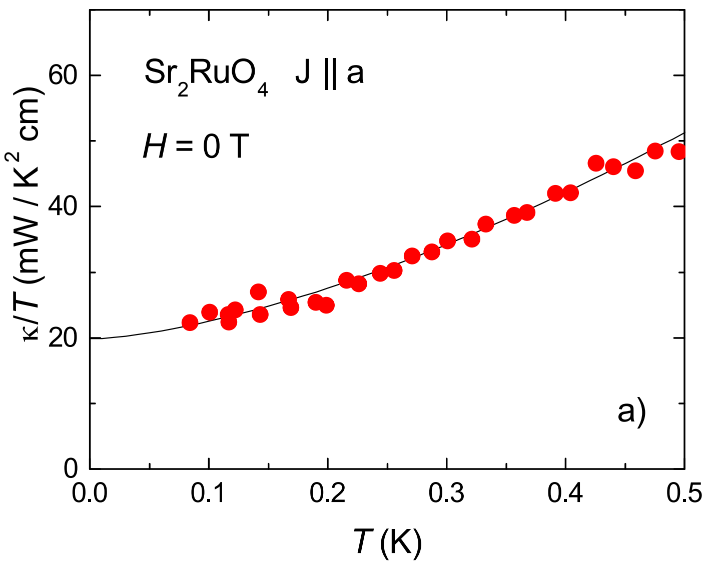
Vertical Line Nodes in the Superconducting Gap Structure of Sr_2RuO_4

E. Hassinger,[1,2,3,*] P. Bourgeois-Hope,[1] H. Taniguchi,[4,‡] S. René de Cotret,[1] G. Grissonnanche,[1]
M. S. Anwar,[4] Y. Maeno,[3,4] N. Doiron-Leyraud,[1] and Louis Taillefer[1,3,†]





Heat conduction in the plane



H = 0 T

κ_0 / T = 20 mW / K^2 cm

Fit: $\frac{\kappa}{T} = \frac{\kappa_0}{T} + cT^{\alpha}$ for $T < 0.35\,\mathrm{K}$.

Nodes!

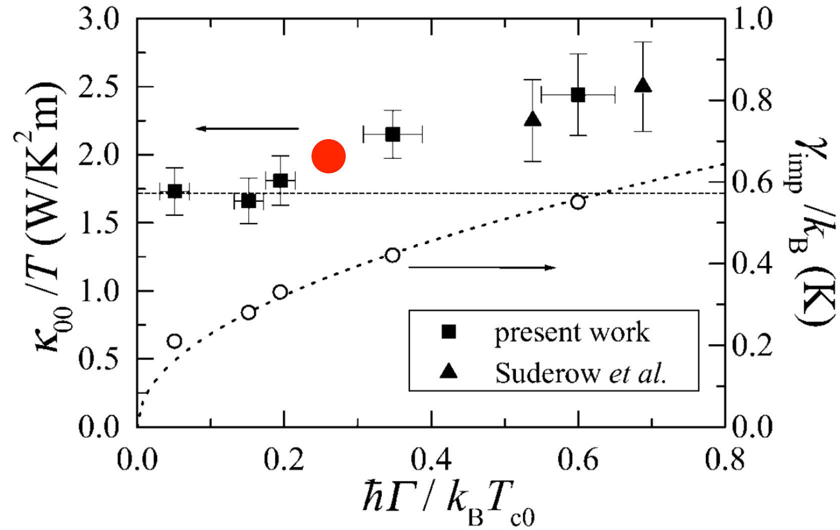


TABLE I. The properties of five single crystals of Sr_2RuO_4. T_c and δT_c were determined from the ac susceptibility measurements. The impurity scattering rate normalized by the maximum T_c, $\hbar\Gamma/k_B T_{c0}$ is deduced from Eq. (1).

	#1	#2	#3	#4	#5
T_c (K)	1.44	1.32	1.27	1.09	0.71
δT_c (K)	0.02	0.03	0.03	0.05	0.15
$\hbar\Gamma/k_B T_{c0}$	0.051	0.15	0.20	0.35	0.60

Suzuki et al. PRL 2002

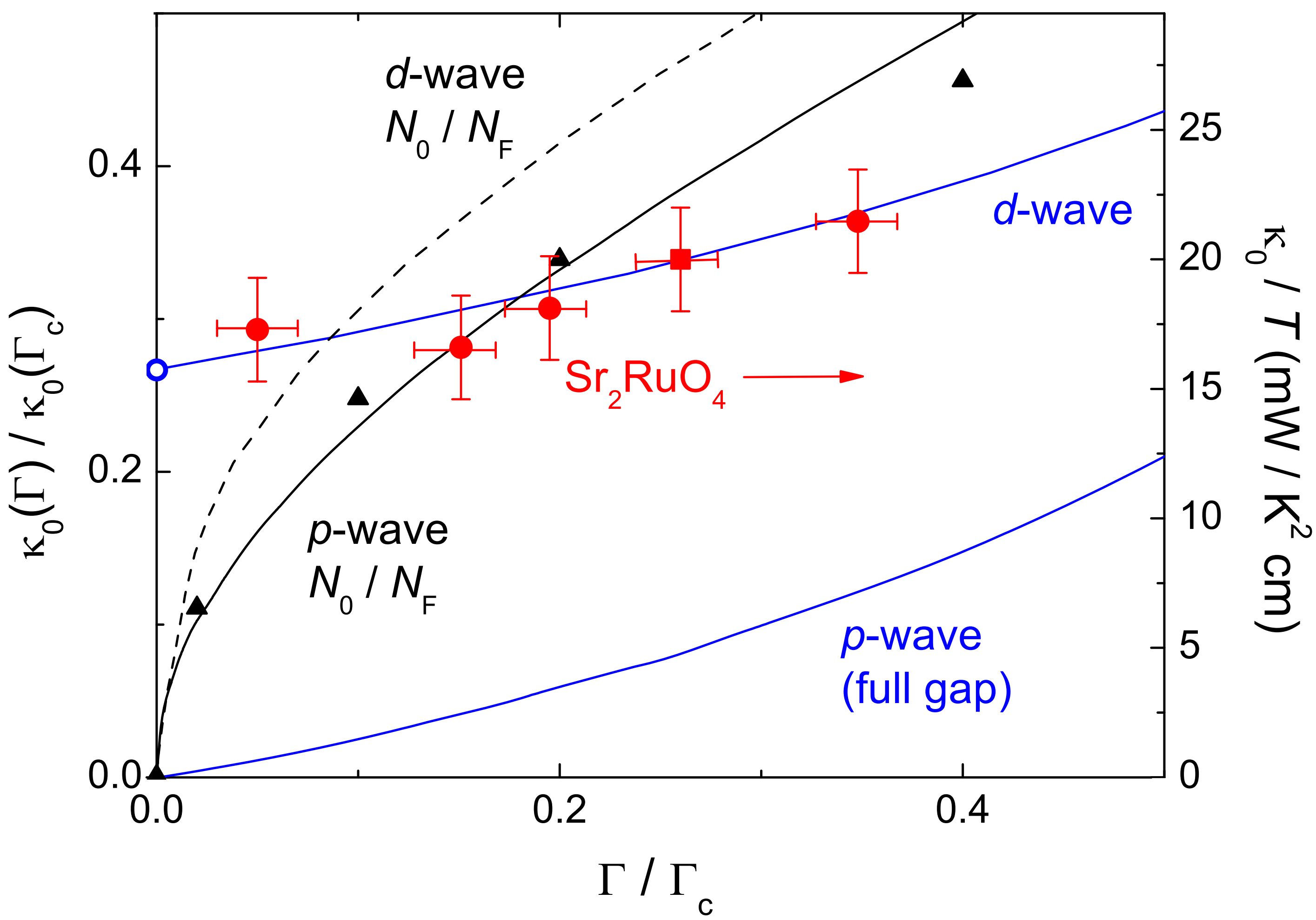
Hassinger et al., PRX 2017

Sr_2RuO_4 Universal heat conduction

PHYSICAL REVIEW X **7,** 011032 (2017)

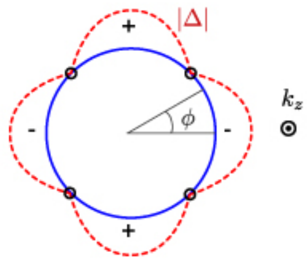
Vertical Line Nodes in the Superconducting Gap Structure of Sr_2RuO_4

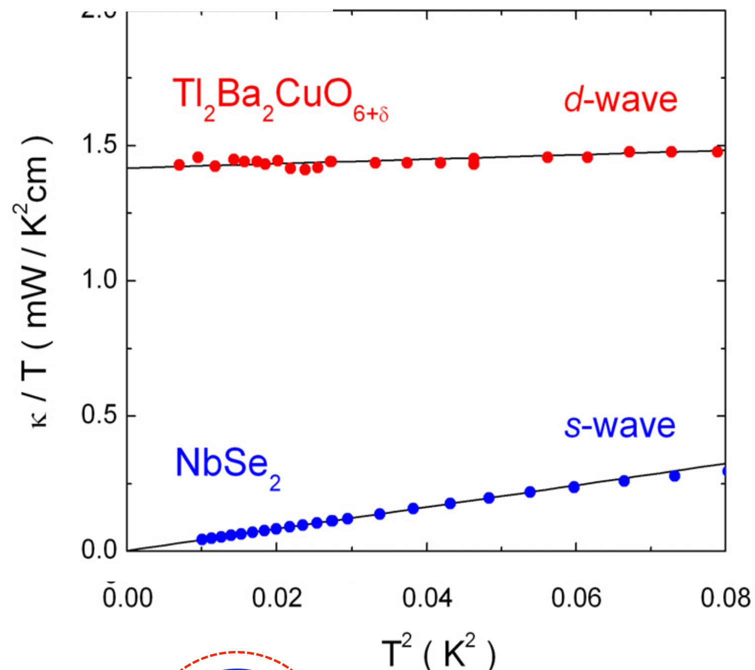
E. Hassinger,[1,2,3,*] P. Bourgeois-Hope,[1] H. Taniguchi,[4,‡] S. René de Cotret,[1] G. Grissonnanche,[1]
M. S. Anwar,[4] Y. Maeno,[3,4] N. Doiron-Leyraud,[1] and Louis Taillefer[1,3,†]

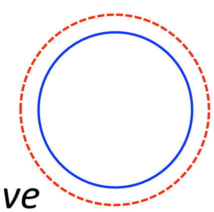


Thermal conductivity

d-wave







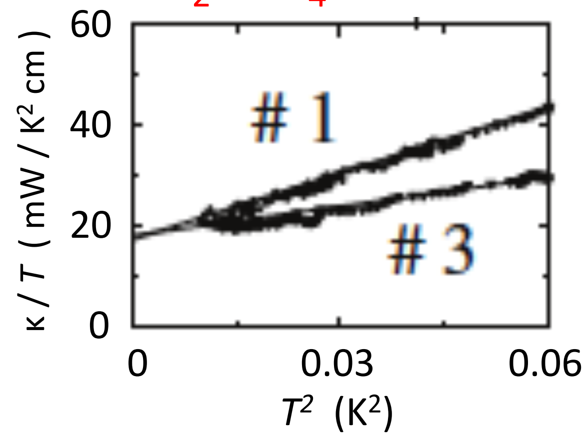
s-wave

Graf et al. PRB 1996
Durst and Lee PRB 2000
Shakeripour NJP 2009

Large finite residual linear term

$$\frac{\kappa_0}{T} = \frac{k_B{}^2}{3\hbar}\frac{n}{c}\left(\frac{v_F}{v_\Delta} + \frac{v_\Delta}{v_F}\right)$$ *d*-wave

Sr_2RuO_4



=> Line nodes in Sr_2RuO_4

Suzuki et al. PRL 2002

Heat conduction in the plane residual linear term

$$\frac{\kappa_0}{T} = \frac{{k_B}^2}{3\hbar}\frac{n}{c}\left(\frac{v_F}{v_\Delta} + \frac{v_\Delta}{v_F}\right)$$

$$\Delta_\theta = \Delta_0 \cos 2\theta$$

$$v_\Delta = \frac{2\Delta_0}{\hbar k_F}$$

$$\Delta_0 = 2.14 k_B T_c$$

Experiment (clean limit)
κ_0 / T = 17 mW / K^2 cm

Theory (line node on all three FS sheets):
d-wave symmetry (4 vertical line nodes):
κ_0 / T = 15.5 mW / K^2 cm

Polar gap (horizontal line node):
κ_0 / T = 12 mW / K^2 cm

Consistent with line nodes on all three FS sheets

Graf et al. PRB 1996
Durst and Lee PRB 2000

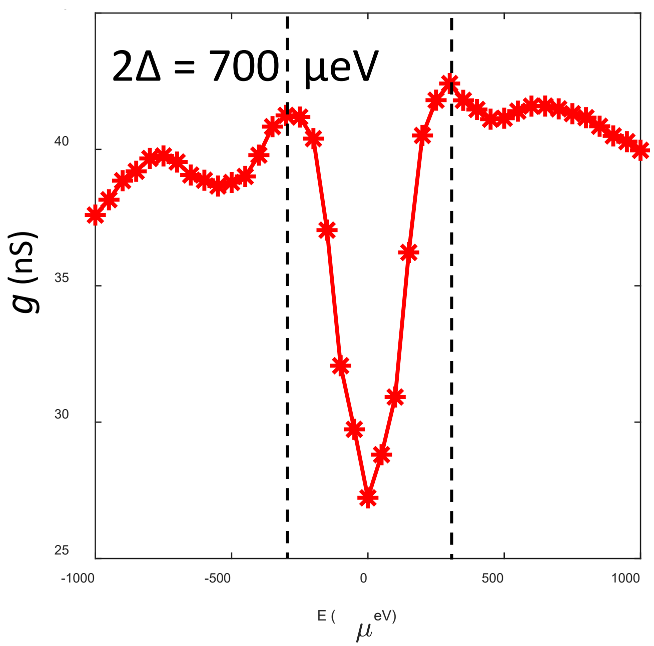
Hassinger et al., PRX 2017

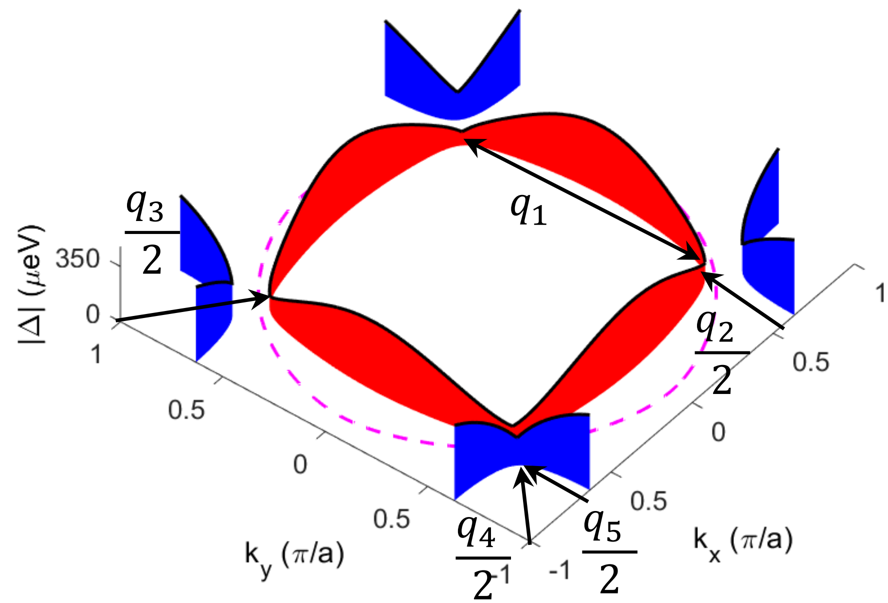
Sr_2RuO_4 **STM**

Momentum-resolved superconducting energy gaps of Sr_2RuO_4 from quasiparticle interference imaging

Rahul Sharma[a,b], Stephen D. Edkins[c], Zhenyu Wang[d], Andrey Kostin[a,b], Chanchal Sow[e,f], Yoshiteru Maeno[e], Andrew P. Mackenzie[g,h], J. C. Séamus Davis[a,g,i,j,1], and Vidya Madhavan[d,1]

5222–5227 | PNAS | **March 10, 2020** | vol. 117 | no. 10





$\Delta_{max} \approx 350\mu eV$ $\Delta_{max}/\mathrm{kT}_c \approx 2$

Sr_2RuO_4

Vertical line nodes

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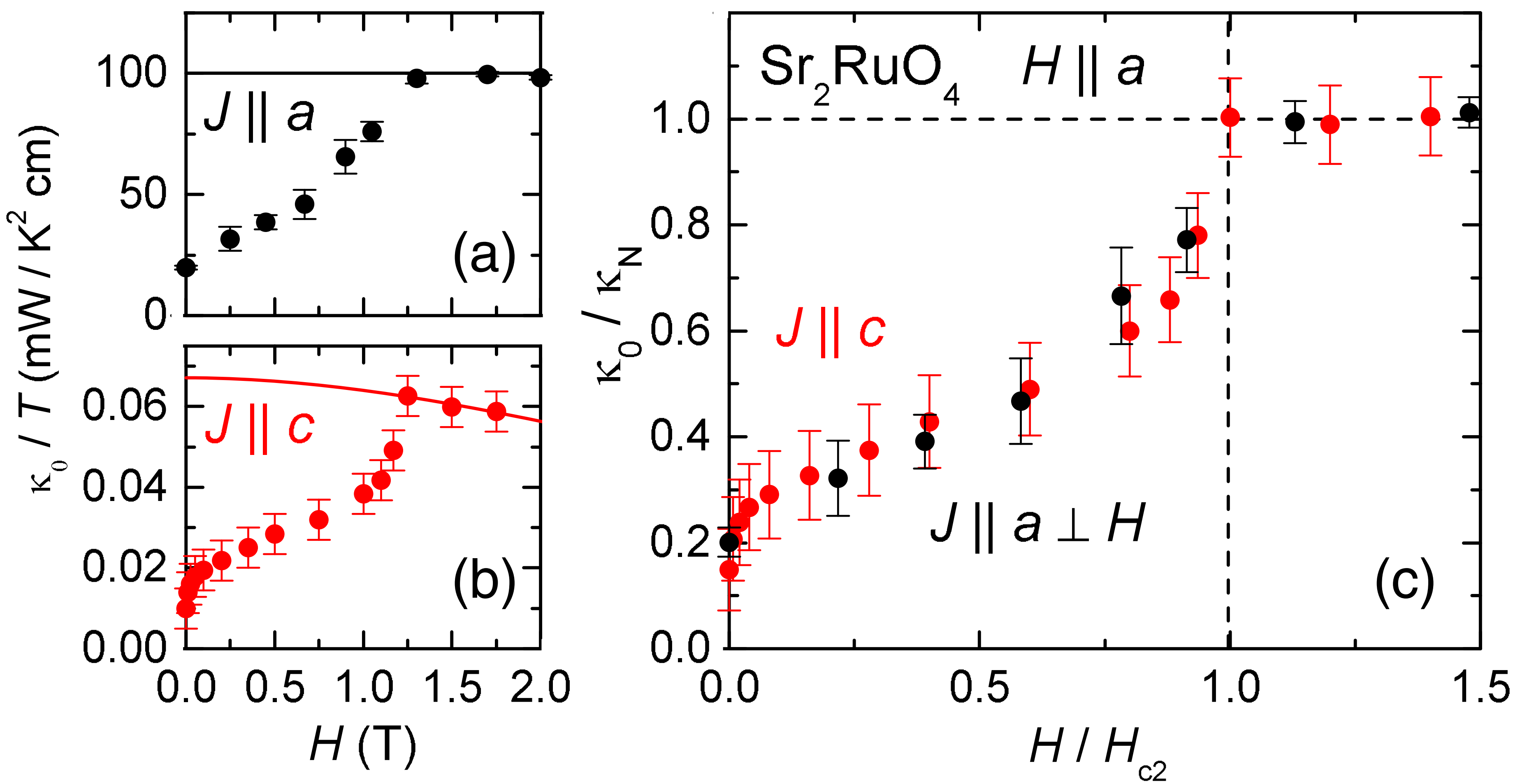

Field dependence

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