Disorder-induced resistive anomaly near ferromagnetic phase transitions

with: Carsten Timm (FU Berlin) and M.E. Raikh (Utah)

PRL **94**, 036602 (2005)

Felix von Oppen

Freie Universität Berlin

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Nr. 24 15. Dezember 1932 33. Jahrgang
Redaktionsschluß für Nr. 2 am 1. Januar 1933.

VORTRÄGE UND DISKUSSIONEN DES VIII. DEUTSCHEN PHYSIKERTAGES IN BAD NAUHEIM, VOM 20.—24. SEPTEMBER 1932.

Walther Gerlach (München), Die Änderung des elektrischen Widerstandes bei der Magnetisierung.

$\rho(T)$

Fig. 1 zeigt die Abhängigkeit des Widerstandes von Nickel von der Temperatur. Man erkennt den anomalen Verlauf im ferromagnetischen

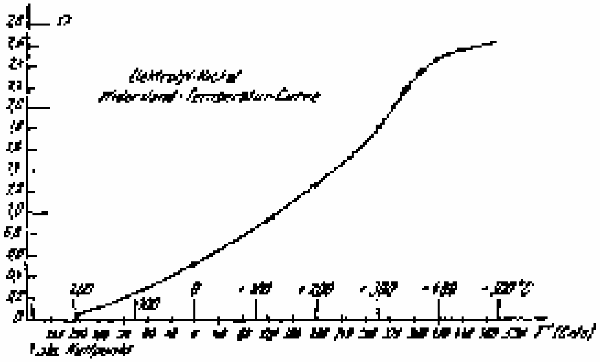


Fig. 1.

$d\rho/dT$

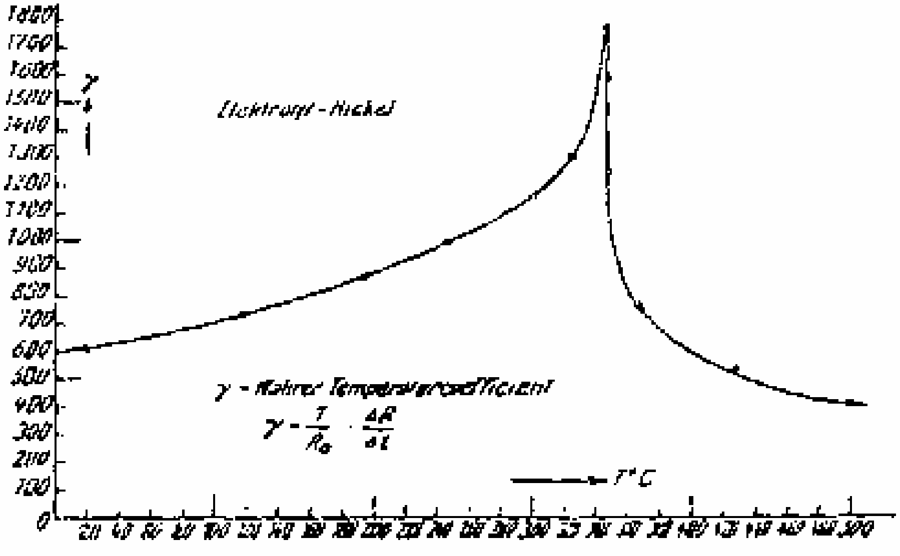


Fig. 2.

Annalen der Physik. 5. Folge. Band 33. 1938

Ferromagnetismus und elektrische Eigenschaften

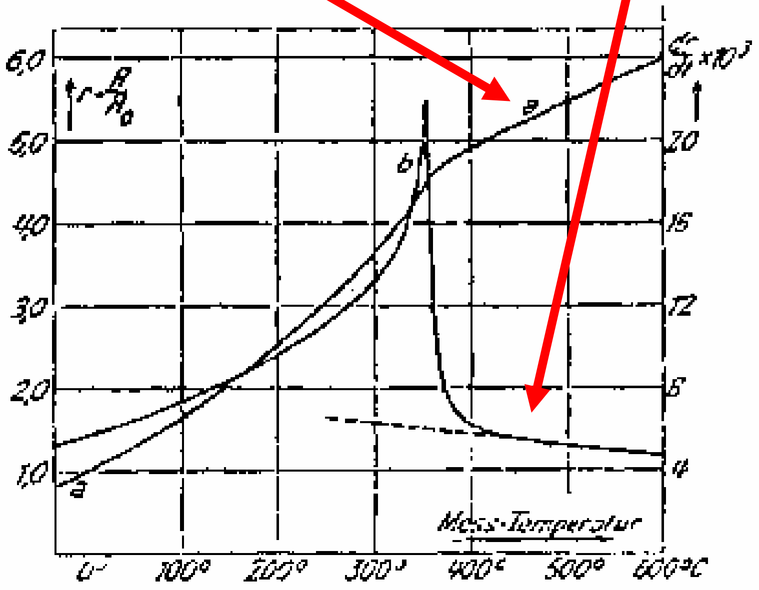
IX. Mitteilung:

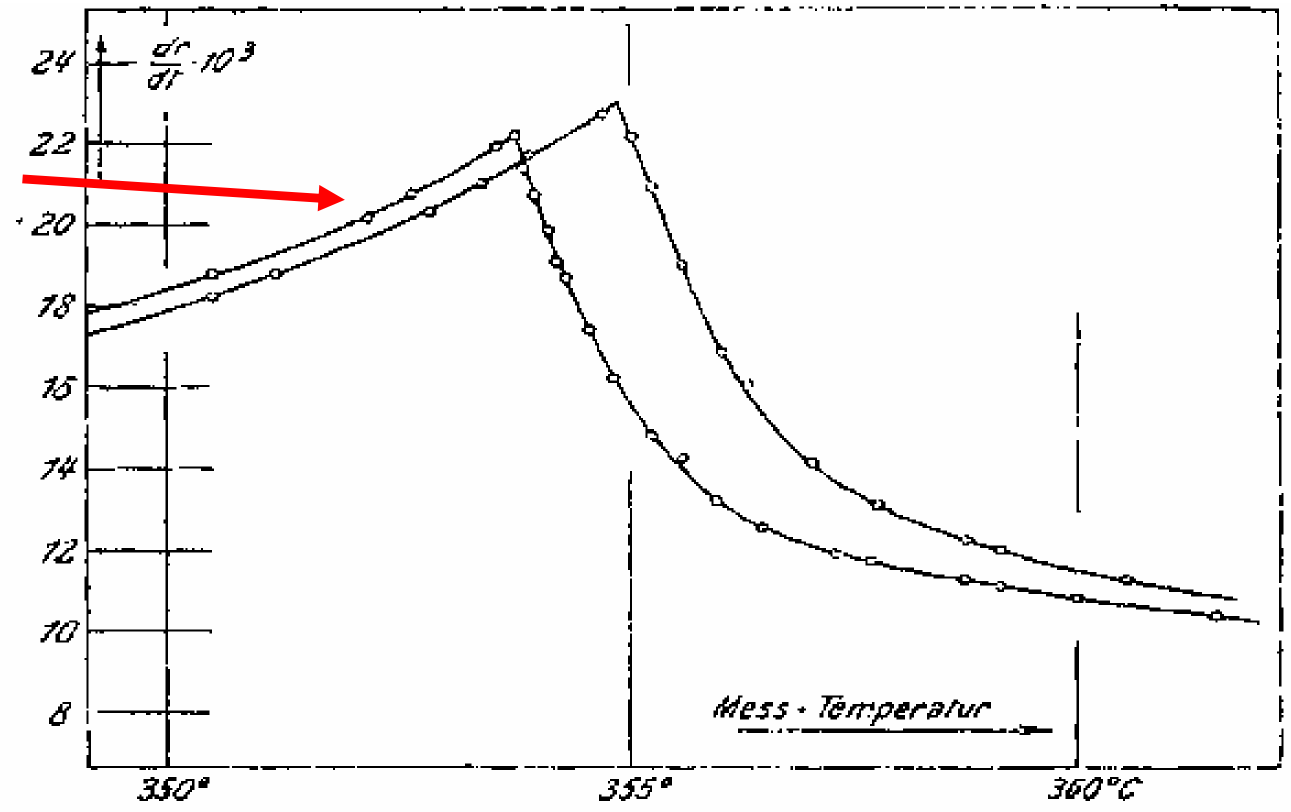
Curiepunkt und elektrischer Widerstand

Von H. Bittel und W. Gerlach

$d\rho/dT$

$\rho(T)$





J. Phys. Chem. Solids Pergamon Press 1958. Vol. 4. pp. 71–77.

ANOMALIES DE RÉSISTIVITÉ DANS CERTAINS MÉTAUX MAGNÉTIQUES

P. G. DE GENNES* et J. FRIEDEL†

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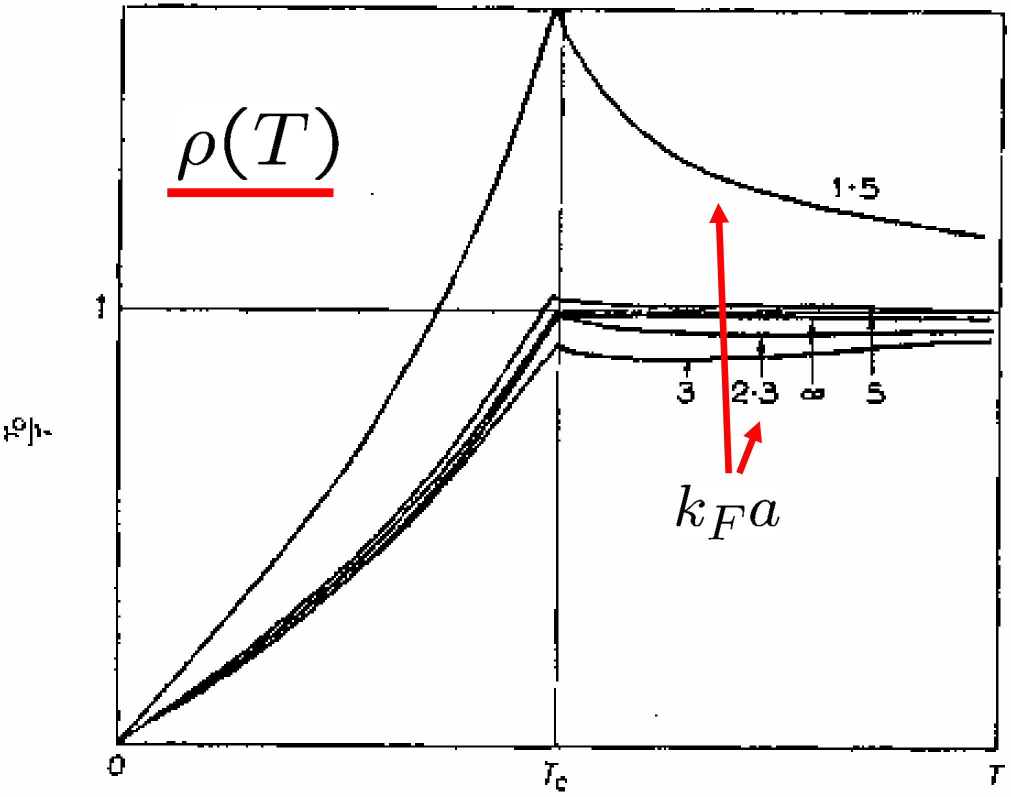
Abstract—The anomalous resistivity of some rare earth metals, and of alloys like AuMn, Au_3Mn, is studied by assuming a coupling between conduction electrons and atomic spins. The magnitude of the corresponding cross section is treated as a phenomenological quantity. At high temperatures, the atomic spins are at random, and the conduction electrons have a finite mean free path. At low temperatures, the atomic spins are all alined and no scattering can occur. Short-range order effects in the spin lattice are analysed in the Born approximation, and shown to be small in most physical situations.



Scattering on small-q spin fluctuations:

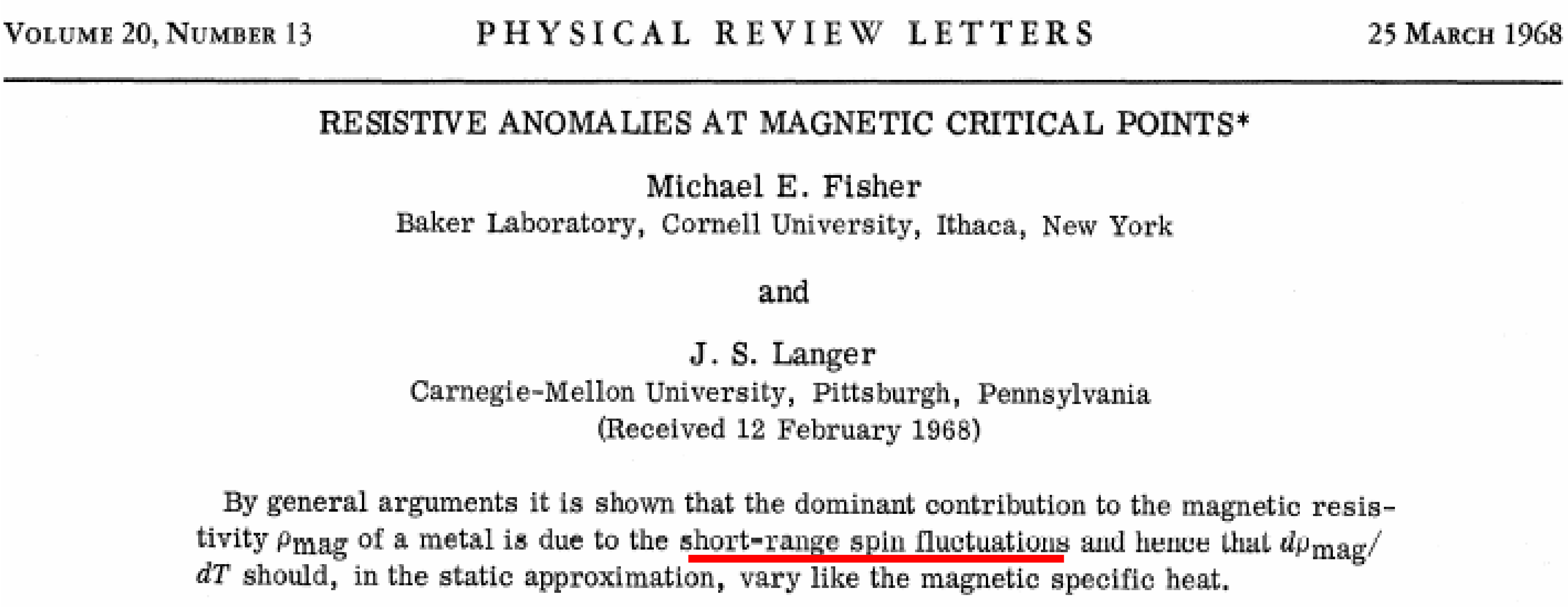
transport time

$$\frac{\tau_0}{\tau} = \frac{1}{4}\int_0^2 \frac{x^3\,dx}{t+(k_F a x)^2}$$

Ornstein-Zernike

$$\rho(t)-\rho(0) = -bt\ln\left(1/t\right)$$

$$\frac{\partial\rho}{\partial t} \propto \ln(t)$$



VOLUME 20, NUMBER 13 PHYSICAL REVIEW LETTERS 25 MARCH 1968

RESISTIVE ANOMALIES AT MAGNETIC CRITICAL POINTS*

Michael E. Fisher
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and

J. S. Langer
Carnegie-Mellon University, Pittsburgh, Pennsylvania

(Received 12 February 1968)

By general arguments it is shown that the dominant contribution to the magnetic resistivity ρ_{mag} of a metal is due to the short-range spin fluctuations and hence that $d\rho_{\text{mag}}/dT$ should, in the static approximation, vary like the magnetic specific heat.

Argument against de Gennes/Friedel:

electrons sensitive to spin coherence only within mean free path

➔ cuts off singularity when $\xi(T) \sim \ell$

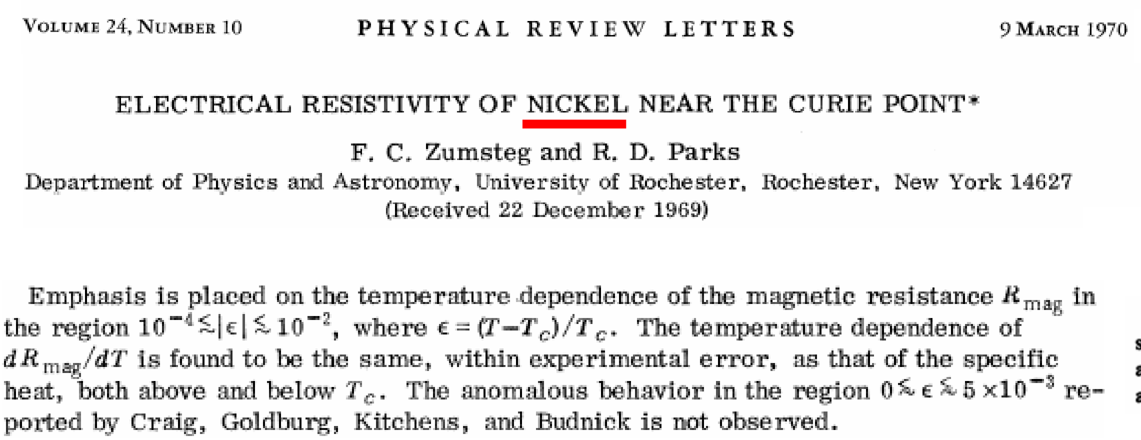
what happens when $\xi(T) \gg \ell$?

New contribution: scattering from short-range $2k_F$ spin fluctuations

$$\frac{\partial \rho}{\partial T} \propto \frac{\partial U}{\partial T} = C(T) \propto t^{-\alpha}$$

specific heat exponent

➔ anomaly entirely due to anomalous dimensions



Volume 24, Number 10 PHYSICAL REVIEW LETTERS 9 March 1970

ELECTRICAL RESISTIVITY OF NICKEL NEAR THE CURIE POINT*

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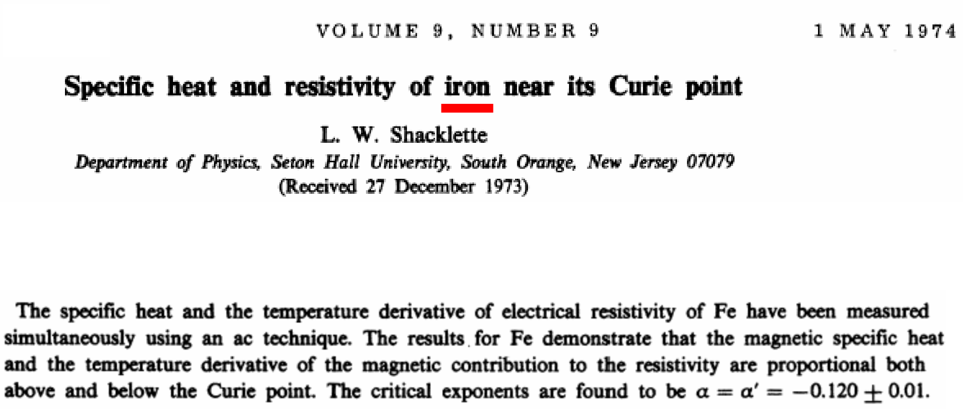
(Received 22 December 1969)

Emphasis is placed on the temperature dependence of the magnetic resistance $R_{\rm mag}$ in the region $10^{-4} \lesssim |\epsilon| \lesssim 10^{-2}$, where $\epsilon = (T - T_c)/T_c$. The temperature dependence of $dR_{\rm mag}/dT$ is found to be the same, within experimental error, as that of the specific heat, both above and below T_c. The anomalous behavior in the region $0 \lesssim \epsilon \lesssim 5\times 10^{-3}$ reported by Craig, Goldburg, Kitchens, and Budnick is not observed.



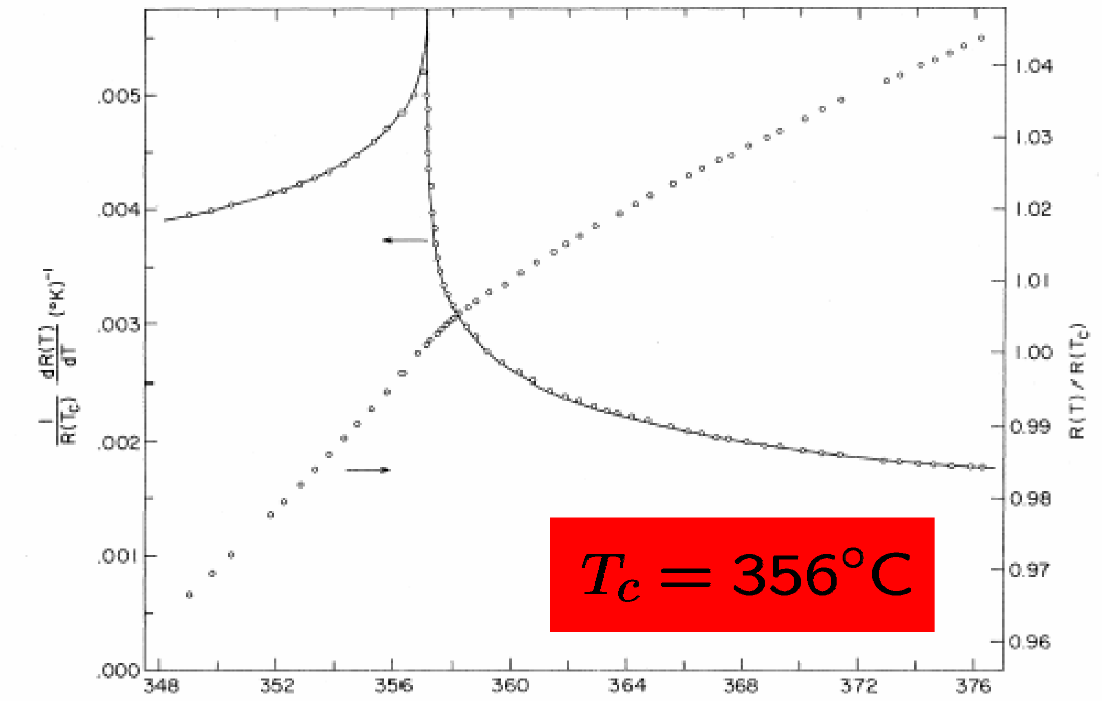
VOLUME 9, NUMBER 9 1 MAY 1974

Specific heat and resistivity of iron near its Curie point

L. W. Shacklette
Department of Physics, Seton Hall University, South Orange, New Jersey 07079

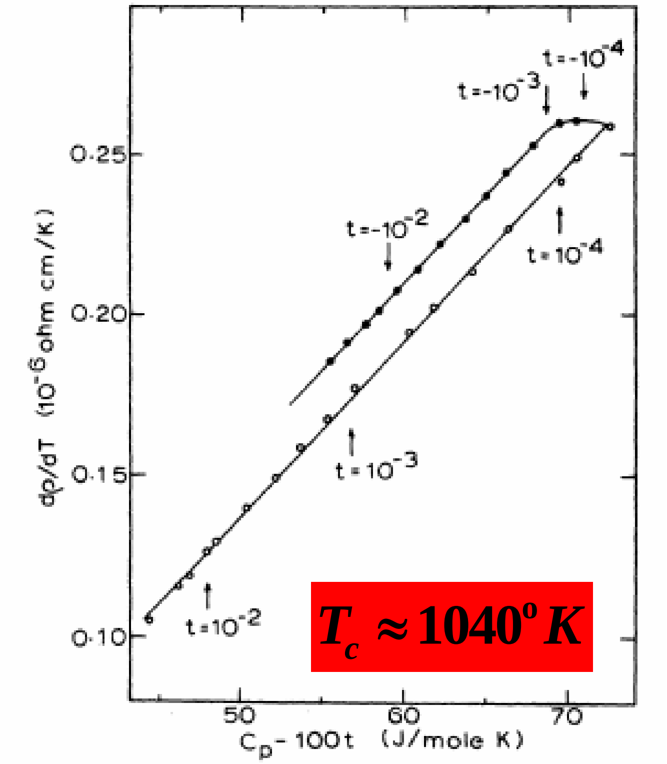
(Received 27 December 1973)

The specific heat and the temperature derivative of electrical resistivity of Fe have been measured simultaneously using an ac technique. The results for Fe demonstrate that the magnetic specific heat and the temperature derivative of the magnetic contribution to the resistivity are proportional both above and below the Curie point. The critical exponents are found to be $\alpha = \alpha' = -0.120 \pm 0.01$.



$T_c = 356°\mathrm{C}$

FIG. 1. Electrical resistivity $R(T)$ of nickel and dR/dT versus temperature in the region of the Curie point T_c. The solid lines represent fits of Eq. (1) to the data as discussed in text. For the sake of clarity only a small fraction of the data points is shown.



$T_c \approx 1040^{\circ} K$

$\alpha \simeq 0.1$

$\alpha \simeq -0.1$

VOLUME 23, NUMBER 2 PHYSICAL REVIEW LETTERS 14 JULY 1969

EFFECT OF THE MOLECULAR FIELD ON THE ELECTRICAL RESISTIVITY NEAR A MAGNETIC TRANSITION: $GdNi_2$†

M. P. Kawatra, S. Skalski, J. A. Mydosh, and J. I. Budnick
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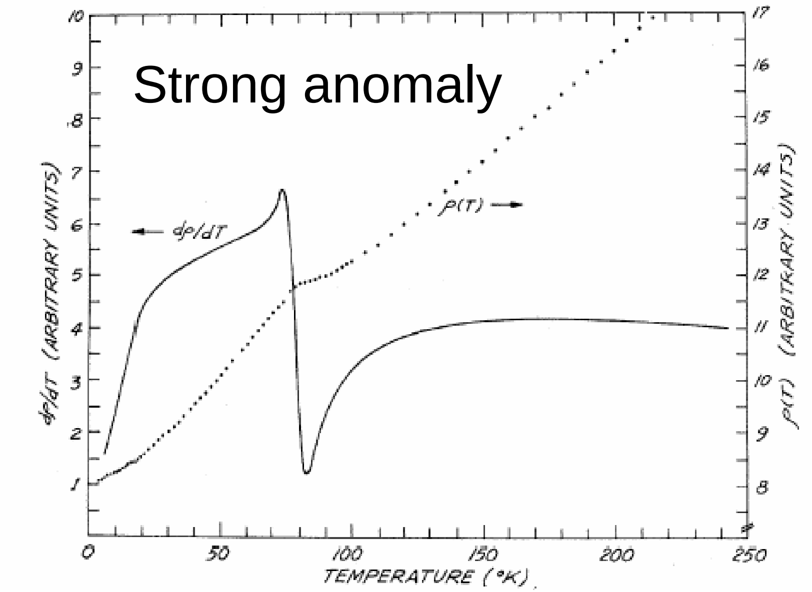
(Received 21 May 1969)

We have measured the temperature dependence of the electrical resistivity of the cubic, Laves-phase, ferromagnetic, intermetallic compounds $GdNi_2$, $GdPt_2$, and $GdRh_2$, and for $GdNi_2$, we have analyzed the temperature derivative of the electrical resistivity in the neighborhood of the magnetic transition. Above the Curie temperature our data are very well described by the molecular-field treatment of the long-range spin fluctuations of the short-range order, giving for the first time an experimental result in agreement with this treatment.



Strong anomaly

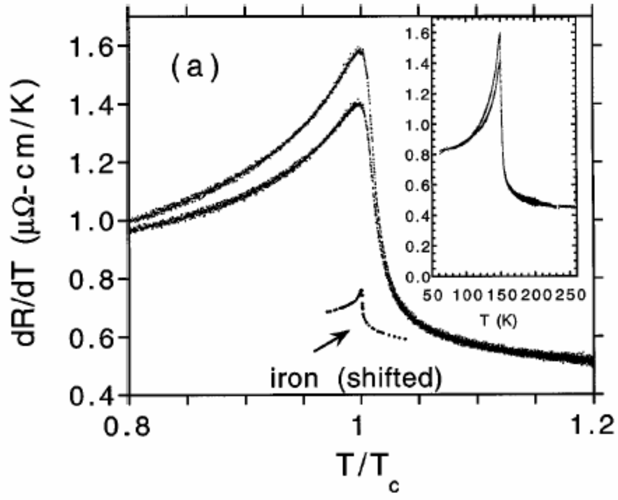
$T_c = 75\text{K}$

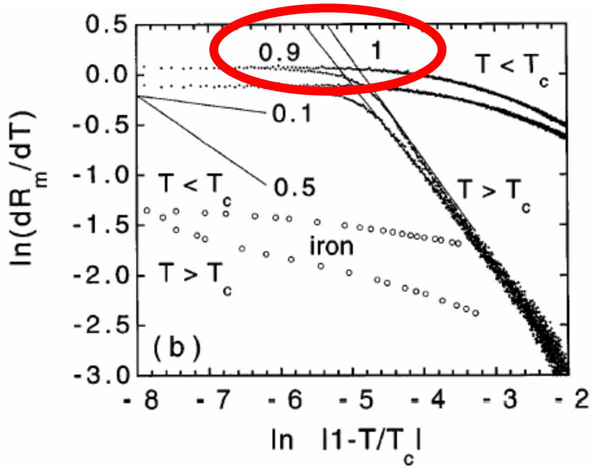
VOLUME 77, NUMBER 13 PHYSICAL REVIEW LETTERS 23 SEPTEMBER 1996

Anomalous Spin Scattering Effects in the Badly Metallic Itinerant Ferromagnet $SrRuO_3$

L. Klein, J. S. Dodge, C. H. Ahn, G. J. Snyder, T. H. Geballe, M. R. Beasley, and A. Kapitulnik
Edward L. Ginzton Laboratories, Stanford University, Stanford, California 94305
(Received 6 May 1996)

$SrRuO_3$ is an itinerant ferromagnet with $T_c \sim 150$ K. While the magnetization shows critical behavior that is well fit with universal critical exponents, the temperature derivative of the resistivity shows an unusually strong divergence as $T \to T_c^+$ with critical exponents higher than 0.9 and very weak divergence as $T \to T_c^-$. At low temperatures, the resistivity rapidly increases with temperature, and an unusual correlation with magnetization is found. We argue that the two phenomena stem from the fact that $SrRuO_3$ is an inherently bad metal. [S0031-9007(96)01229-X]





$T_c = 150\text{K}$

Diluted Magnetic Semiconductors

APPLIED PHYSICS LETTERS VOLUME 83, NUMBER 22 1 DECEMBER 2003

Capping-induced suppression of annealing effects on $Ga_{1-x}Mn_xAs$ epilayers

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(Received 11 July 2003; accepted 26 September 2003)

We have studied the effects of capping ferromagnetic $Ga_{1-x}Mn_xAs$ epilayers with a thin layer of undoped GaAs, and we find that even a few monolayers of GaAs have a significant effect on the ferromagnetic properties. In particular, the presence of a capping layer only 10 monolayers thick completely suppresses the enhancement of the ferromagnetism associated with low temperature annealing. This result, which demonstrates that the surface of a $Ga_{1-x}Mn_xAs$ epilayer strongly affects the defect structure, has important implications for the incorporation of $Ga_{1-x}Mn_xAs$ into device heterostructures. © *2003 American Institute of Physics.* [DOI: 10.1063/1.1629376]

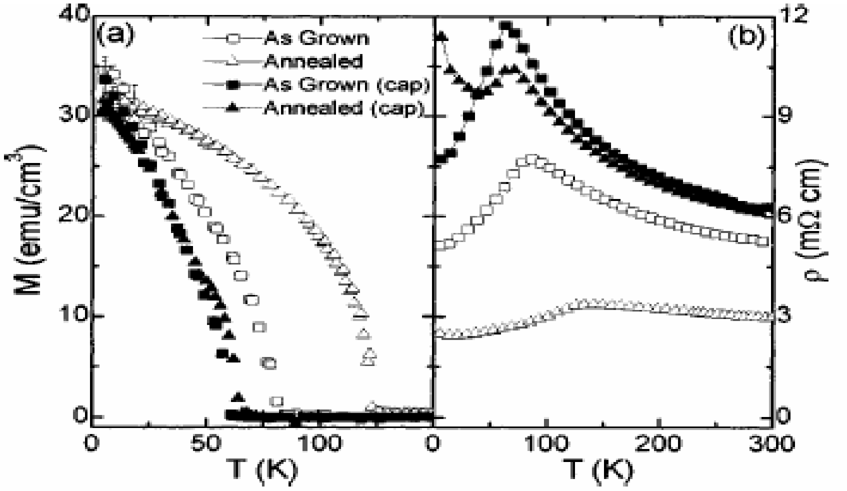

FIG. 1. Magnetization (a) and resistivity (b) as a function of temperature ($T>5$ K) for annealed and as-grown 50-nm-thick $Ga_{1-x}Mn_xAs$ samples. Results shown are from series A samples with (closed symbols) and without (open symbols) 10-ML-thick GaAs capping layers. The addition of the capping layer is shown to reduce T_C for both as-grown and annealed samples. In addition, the capping layer increases the resistivity for both as-grown and annealed samples over a significant portion of the temperature range probed.

APPLIED PHYSICS LETTERS VOLUME 83, NUMBER 20 17 NOVEMBER 2003

Enhancement of Curie temperature in $Ga_{1-x}Mn_xAs/Ga_{1-y}Al_yAs$ ferromagnetic heterostructures by Be modulation doping

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(Received 5 May 2003; accepted 25 September 2003)

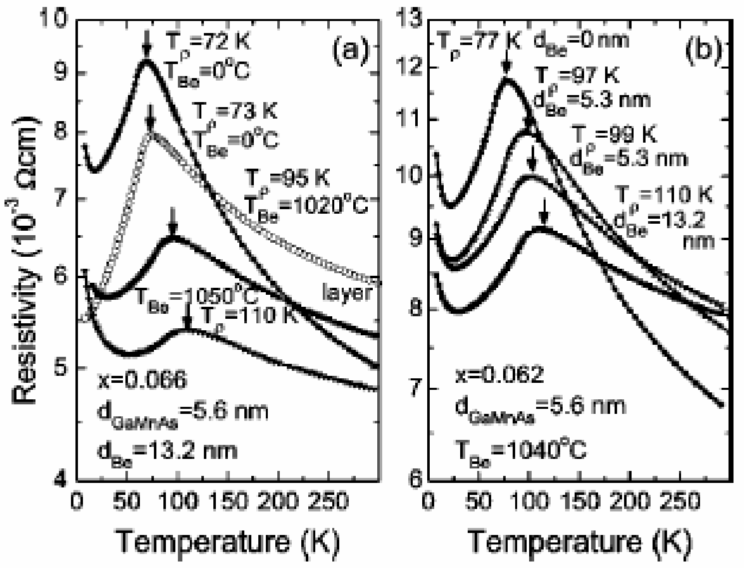
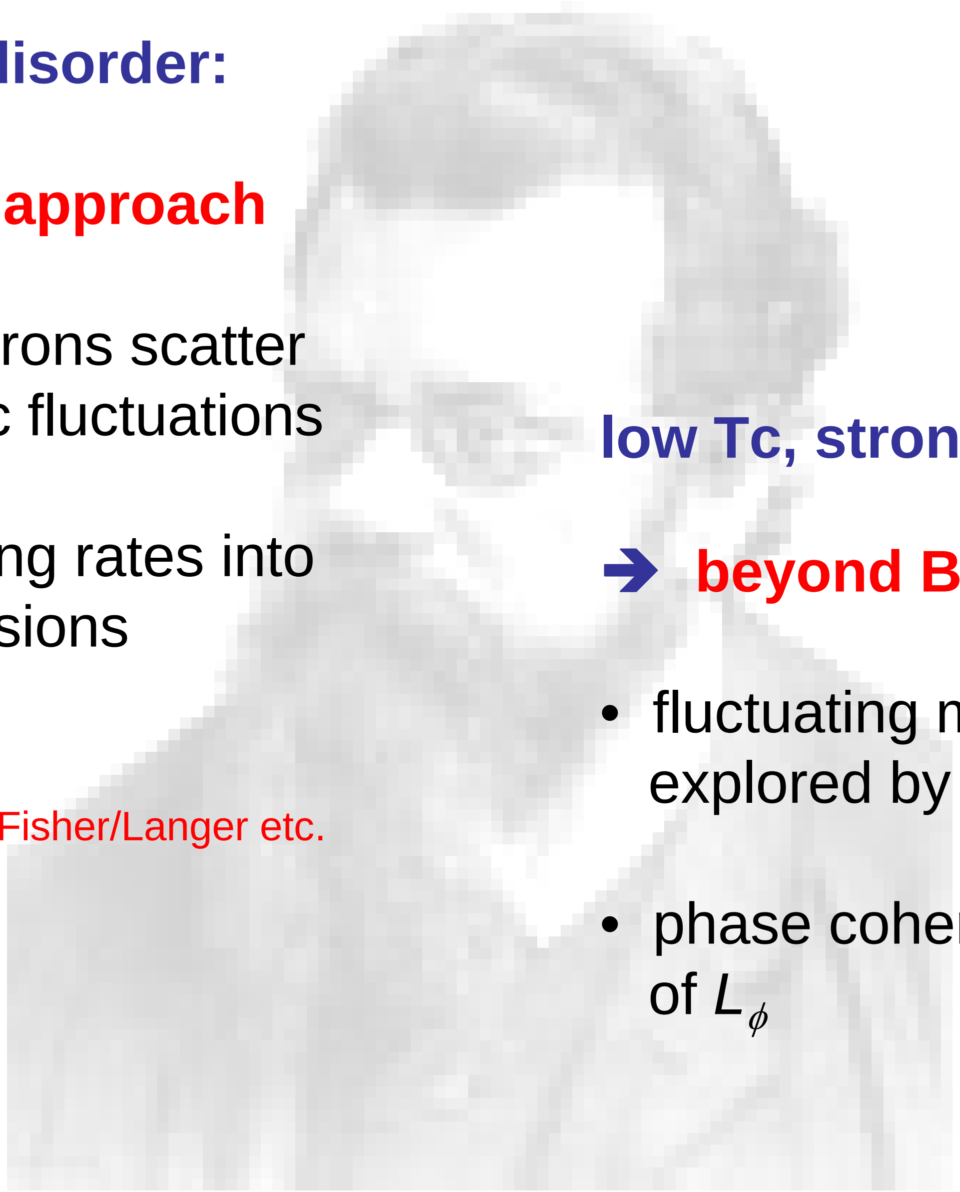


FIG. 1. Temperature-dependent zero-field resistivities $\rho(T)$ for $Ga_{1-x}Mn_xAs/Ga_{0.76}Al_{0.24}As$ heterojunctions remotely doped with Be acceptors: (a) series 1, with $x=0.066$, $d_{Be}=13.2$ nm, and various T_{Be}; (b) series 2, with $x=0.062$, $T_{Be}=1040$ °C, and various d_{Be}. Sample parameters and peak resistivity values ($T_\rho \sim T_C$) are indicated. Also shown as the open points in (a) are data for a $Ga_{0.94}Mn_{0.06}As$ epilayer with no GaAlAs barrier.

$T_c \sim$ 100K



high T_c, weak disorder:

➔ Boltzmann approach

- “ballistic“ electrons scatter from magnetic fluctuations
- insert scattering rates into Drude expressions

de Gennes/Friedel; Fisher/Langer etc.

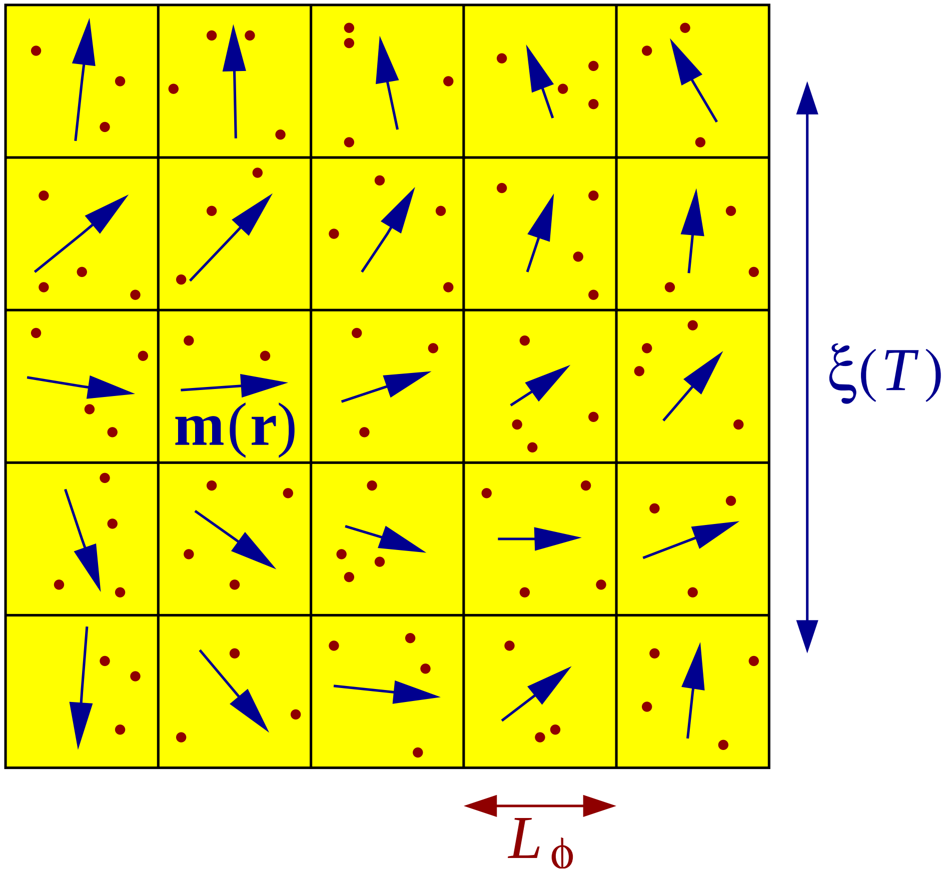
low Tc, strong disorder:

➔ beyond Boltzmann

- fluctuating magnetization ***m(r)*** is explored by diffusive carriers
- phase coherence up to lengths of L_ϕ

PRL **94**, 036602 (2005)

Model for $\xi(T) \gg \ell_{\text{el}}$



inhomogeneous resistor network of blocks of size L_ϕ

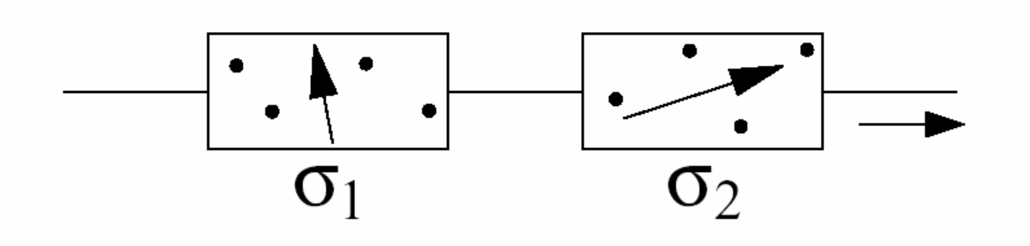
➔ magnetic fluctuations enter resistivity via Kirchoff's laws

IMPORTANT:

1) compute effective resistivity of network

2) perform average over impurity and spin configurations

Cartoon model



Boltzmann

averaging leads to both resistors being equal to

$$1/\bar{\sigma}$$

resistance of “network“

$$2/\bar{\sigma}$$

beyond Boltzmann

resistance of “network“

$$(\sigma_1+\sigma_2)/\sigma_1\sigma_2 \simeq \underbrace{2/\bar{\sigma}}_{\text{Boltzmann}} + \boxed{\delta\sigma^2/2\bar{\sigma}^3}$$

Boltzmann

extra term with *non-zero* average

Effective resistivity of inhomogeneous conductors

inhomogeneous conductor $\sigma = \sigma(\mathbf{r})$

Ohm‘s law

$$\begin{aligned} \mathbf{j}_0 &= \sigma_0 \mathbf{E}_0 + \langle \delta\sigma(\mathbf{r}) \delta\mathbf{E}(\mathbf{r}) \rangle \\ \delta\mathbf{j}(\mathbf{r}) &= \delta\sigma(\mathbf{r}) \mathbf{E}_0 + \sigma_0 \delta\mathbf{E}(\mathbf{r}) \end{aligned}$$

$$\left.\begin{array}{ll} \text{continuity} & \nabla \cdot \delta\mathbf{j} = 0 \\ & \\ \text{Maxwell} & \nabla \times \delta\mathbf{E} = 0 \end{array}\right\} \quad \delta\mathbf{E}(\mathbf{q}) = -\hat{\mathbf{q}}\,\hat{\mathbf{q}} \cdot \mathbf{E}_0 \delta\sigma(\mathbf{q}) / \sigma_0$$

analogous calculation for dielectric constant: Landau/Lifshitz

Effective conductivity: $\mathbf{j}_0 = \sigma_{\text{eff}} \mathbf{E}_0$

$$\boxed{\sigma_{\text{eff}} = \sigma_0 - \frac{\langle [\delta\sigma(\mathbf{r})]^2 \rangle}{3\sigma_0}}$$

- ➢ *independent* of geometry of conductivity variations
- ➢ dependent on magnitude of conductivity variation *only*

Effective conductivity due to spin fluctuations

block-specific random impurity + spin configuration

$$\delta\sigma(\mathbf{r}) \simeq \frac{1}{L_\phi}\left(\frac{e^2}{h}\right)\delta g(\mathbf{r}, E_F; \mathbf{m}(\mathbf{r}))$$

due to *universal conductance fluctuations*

⇒

$$\sigma_{\text{eff}} = \sigma_0 - \frac{\langle[\delta\sigma(\mathbf{r})]^2\rangle}{3\sigma_0}$$

involves much-studied correlator of universal conductance fluctuations

Two spin subbands

dominant effect of impurity spins on carriers:
effective Zeeman field from exchange interaction
proportional to the magnetization $m(\mathbf{r})$

coarse grained
over cube of size L_ϕ

UCF

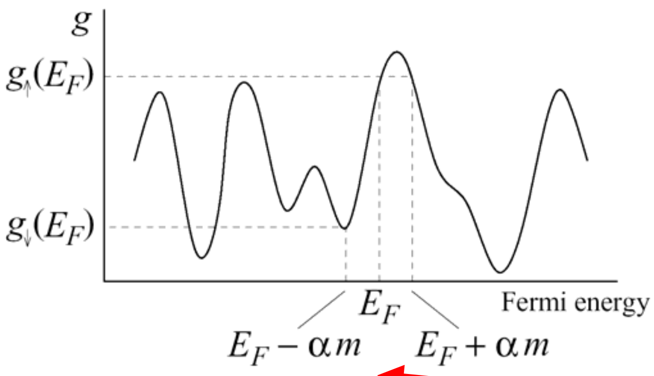


FIG. 2: Sample-specific variation of $g(E_F)$ for a block of the resistor network (universal conductance fluctuations) in the absence of spin. The conductances for each spin direction are obtained by including equal, but opposite exchange-induced Zeeman shifts of the Fermi energy. As indicated, this leads to a difference in the conductances for the two spin directions.

equal, but opposite energy shifts
for spin-up and spin-down carriers

$$\pm\alpha m(\mathbf{r})$$

Deviation from Boltzmann resistivity

independent of
magnetization

$$\rho_{\rm eff} - \rho_0 = \frac{2\rho_0^3}{3L_\phi^2}\{\langle[\delta g(\mathbf{r}, E_F + \alpha m(\mathbf{r}))]^2\rangle + \langle[\delta g(\mathbf{r}, E_F - \alpha m(\mathbf{r}))]^2\rangle$$
$$+2\langle\delta g(\mathbf{r}, E_F + \alpha m(\mathbf{r}))\delta g(\mathbf{r}, E_F - \alpha m(\mathbf{r}))\rangle\}\}$$

critical temperature dependence
contained in this correlator

$$F(\alpha m(\mathbf{r})/E_c)$$

with (E.g. Lee, Stone, Fukuyama)

$$F(x) = F(0)\begin{cases} (1 - C_1 x^2) & x \ll 1 \\ C_2 x^{-1/2} & x \gg 1 \end{cases}$$

average w/ Landau
functional

$$m(\mathbf{r}) \rightarrow \langle m^2(\mathbf{r})\rangle^{1/2}$$

$$\begin{aligned}\rho_{\rm eff} - \rho_0 &= \frac{2\rho_0^3}{3L_\phi^2}\left[F(x_0) - F'(x_0)x_0\frac{\pi L_\phi}{4\xi(T)}\right] \\ &= \frac{2\rho_0^3}{3L_\phi^2}\left[F(x_0) - F'(x_0)x_0\frac{\pi L_\phi\sqrt{t}}{4a}\right],\end{aligned}$$

stronger, mean-field singularity than Fisher/Langer or de Gennes/Friedel !!

Strong spin-orbit scattering

$$\begin{aligned}
\rho_{\mathrm{eff}} - \rho_0 &= \frac{2\rho_0^3}{3L_\phi^2}\left[H(y_0) - H'(y_0)y_0\frac{\pi L_\phi}{4\xi(T)}\right] \\
&= \frac{2\rho_0^3}{3L_\phi^2}\left[H(y_0) - H'(y_0)y_0\frac{\pi L_\phi\sqrt{t}}{4a}\right]
\end{aligned}$$

opposite sign compared to two spin subbands

➔ anomaly is **increase** in resistivity

Summary

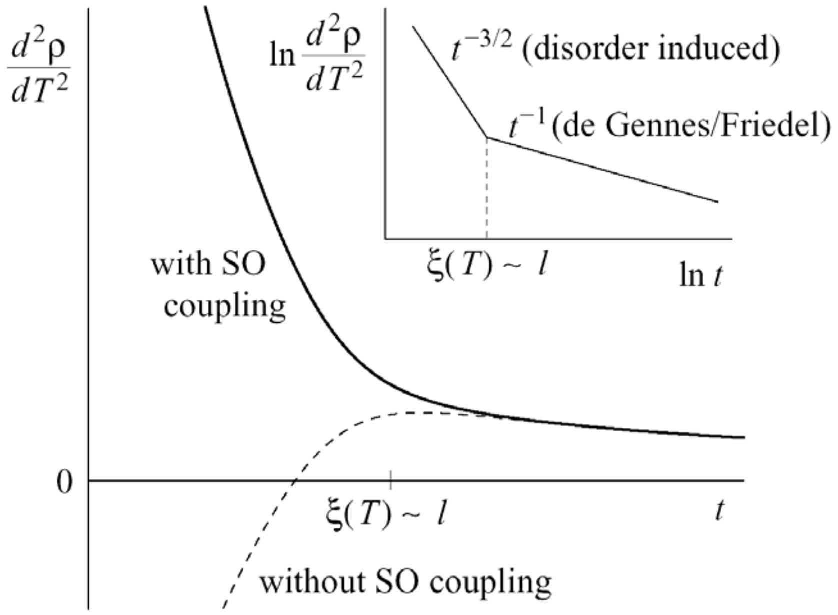


FIG. 3: Resistive anomaly within mean-field theory for $L_\phi \sim \ell$ (schematic) with (full line) and without (dashed line) SO coupling. The anomaly is described by the de Gennes-Friedel mechanism for $\xi(T) \ll \ell$, while the disorder-induced mechanism of this paper dominates closer to T_c where $\xi(T) \gg L_\phi$. When $L_\phi \gg \ell$, there is an additional intermediate regime. Inset: anomaly with SO coupling in a log-log plot.

Scenario:

- magnetic fluctuations lead to inhomogeneous resistor network (conductance fluctuations)
- enter resistivity through Kirchoff
- stronger singularity at T_c

Relevant to

- low Curie temperature
- strong disorder