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SPRING COLLEGE IN CONDENSED MATTER
ON QUANTUM PHASES
(3 May - 10 June 1994)

METAL-INSULATOR TRANSITION

"Experimental Highlights"

Part II

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IV HIGHLIGHTS OF THERMODYNAMIC MEASUREMENTS

C = specific heat of electrons

χ susceptibility —"—

IV 1 In Fermi liquid:

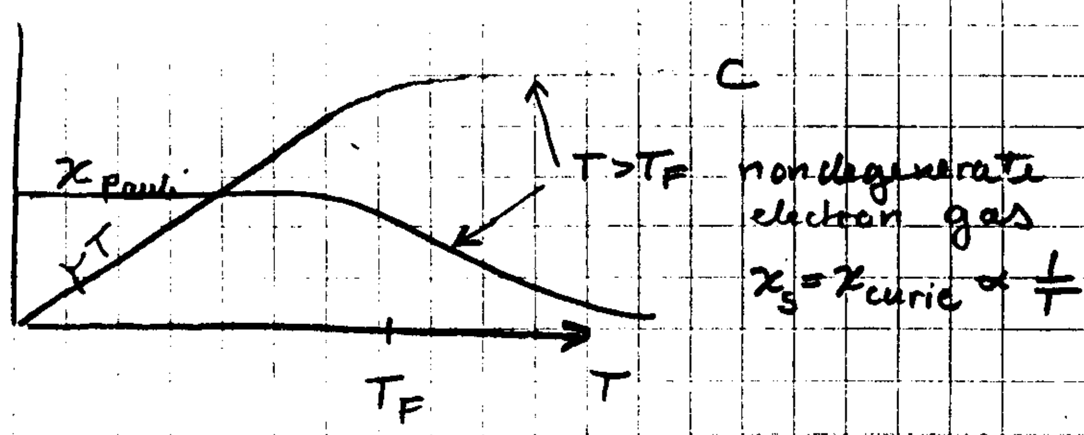
$$C = \gamma T \qquad \gamma = \tfrac{1}{2}\pi^2 n k_B / T_F$$

$$\chi_s = \chi_{Pauli} = \frac{3 n \mu_B^2}{2 k_B T_F} \quad \text{spin susceptibility}$$

$$\chi_{or} = -\frac{n \mu_B^2}{2 k_B T_F} \quad \text{orbital susceptibility}$$

ESR - measurements probe only χ_s

static magnetization measurements by SQUID or by other devices measure $\chi_{total} = \chi_s + \chi_{or}$, χ_s & χ_{or} are hard to separate



IV 2 Near MIT

Motivation for C & χ measurements near MIT came from the critical exponent puzzle in Si:P and from the predictions of scaling theories:

- In general universality class the scaling theory predicts quite strong increase of γ & χ_s toward lower temperatures near MIT. Also, γ & χ_s should behave critically at the transition n_c.

- On the other hand, in SO-universality class there should be neither 1/T-increase nor critical behavior in χ_s

Notice: There is no clear prediction for χ_{or} near MIT. It is better to measure χ_s by ESR than χ_{total} by SQUID, because the separation of χ_{or} and χ_s relies on the assumption that χ_{or} = constant thru MIT and as a function of T.

Notice: In the insulating phase for noninteracting "free" localized spins we expect:

$$C = 0 \quad !$$

$$\chi = \chi_{curie} = \frac{n\mu_B^2}{3k_BT} \quad !$$

IV 2. 1. Specific heat near MIT

Recent experimental results have been presented on page 45

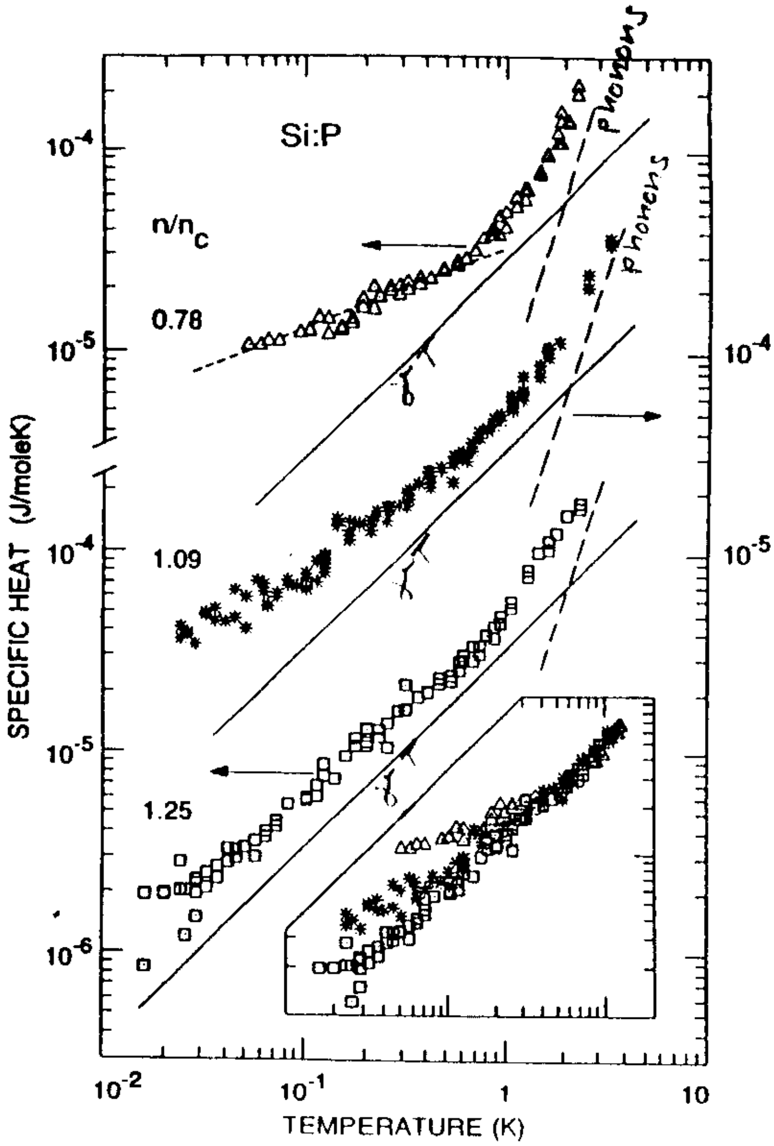
At lowest temperatures:

- $C > \gamma T$ and $\gamma_{eff} = C/T$ increases toward lower temperatures
- γ_{eff} increases also toward insulating phase, which has quite large specific heat.
- In the insulating phase $C \neq 0$
- In the high B-field measurments one can see a Schottky type specific heat peak.

The specific heat measurments are qualitatively in agreement with the scaling predictions of γ - enhancement.

Quantitative comparison is difficult!

(45)



Paalanen, Graebner, Bhatt & Sachdev PRL 63, 651 (1984)

- phonon specific heat $\propto T^3$ appears at higher temperatures
- electron specific heat dominates the low temperature behavior

Lakner & Löhneysen PRL 63, 648 (1989)

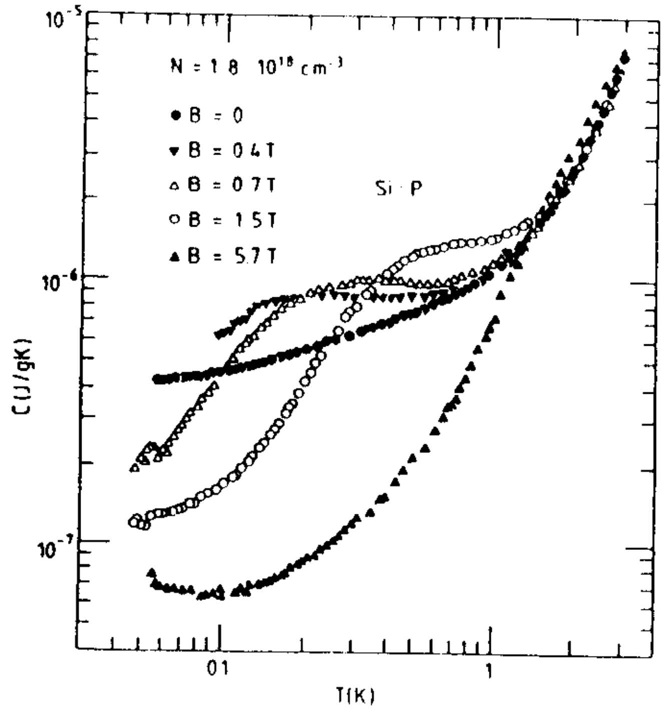
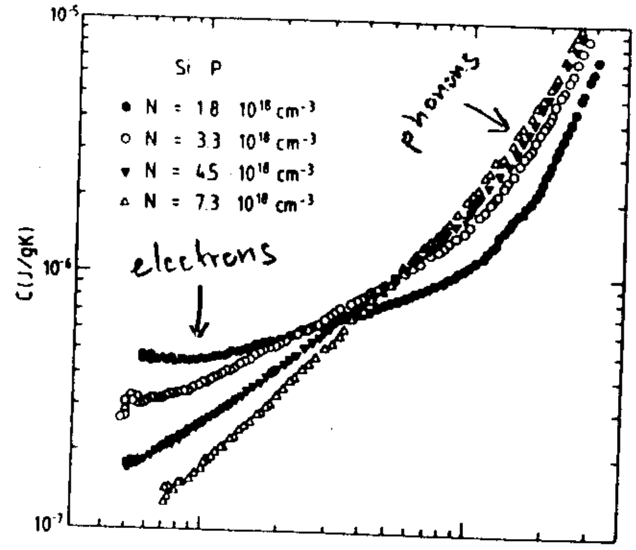


FIG. 3. Specific heat C in various magnetic fields B vs temperature T for one Si:P sample.



IV 2.2. Susceptibility measurements

Some of the recent measurements
in doped semiconductors ($Si:P$, $Si:P,B$,
these are χ_s measurements by ESR)
and in an amorphous metal-semiconductor
alloy ($Nb_x Si_{1-x}$, SQUID measurement
of χ_{tot}, χ_s is estimated by subtracting
the χ_{or} "background")

— Near MIT, on both sides of n_c,
the low temperature susceptibility

$$\boxed{\chi_s(T) \propto T^{-\alpha}} \qquad \alpha < 1$$

quite universally:
in uncompensated $Si:P$ ($\mu < 1$?, general univ. class)
in compensated $Si:P,B$ ($\mu \simeq 1$, ?)
and in $Nb_x Si_{1-x}$ ($\mu = 1$, SO universality class)

- $\chi(T=0) \sim \infty$ already for $n > n_c$
$\Rightarrow$ no critical behavior at n_c

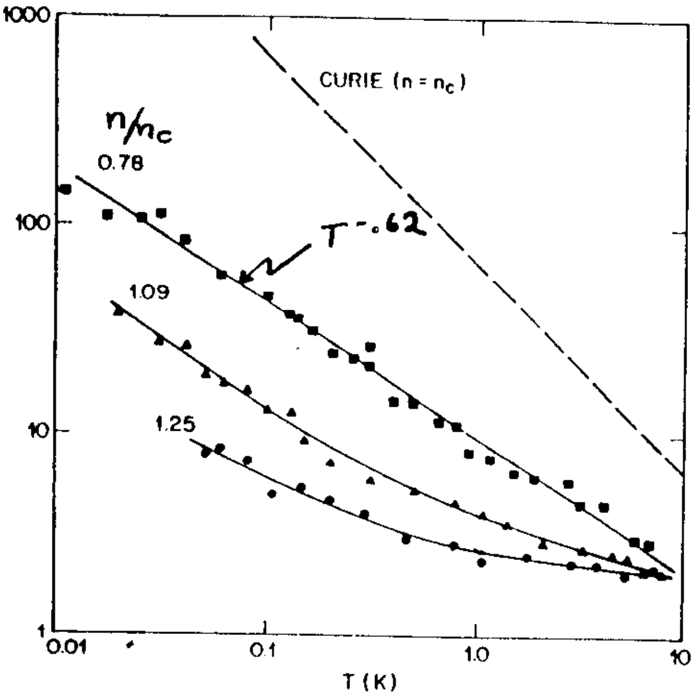
- $\chi_{comp} > \chi_{uncomp}$

This is in contradiction to the
predictions of scaling theory

- χ of $Nb_x Si_{1-x}$ behaves
very similarly to χ of $Si:P$.
$Nb_x Si_{1-x}$ is in SO-universality class.
This contradicts also scaling
predictions.

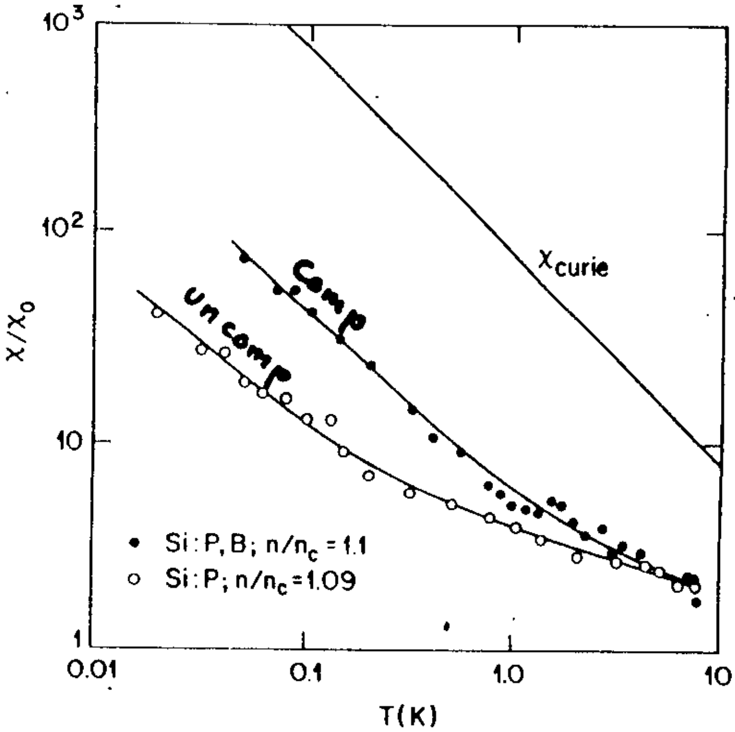
Si:P:

Paalanen, Sachdev, Bhatt & Ruckenstein
PRL **57**, 2061 (1986)



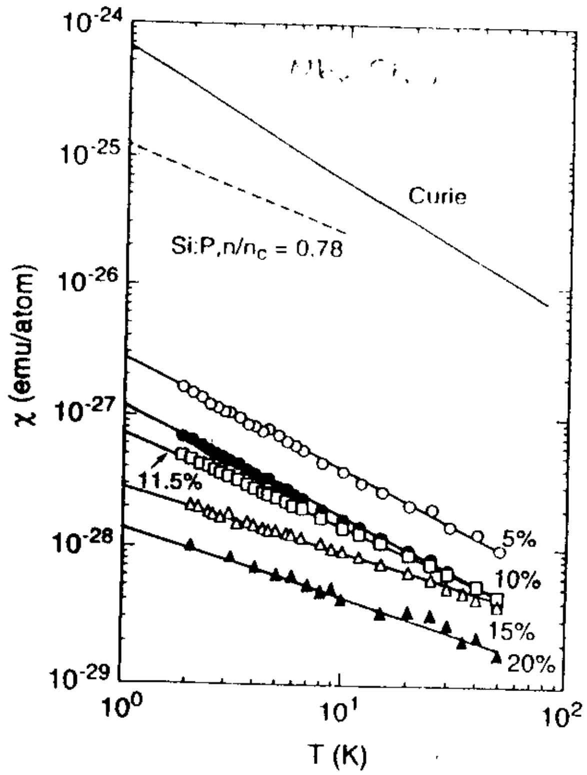
Si:P; B

Hirsch, Holcomb, Bhatt & Paalanen, PRL **68**, 1418 (1992)

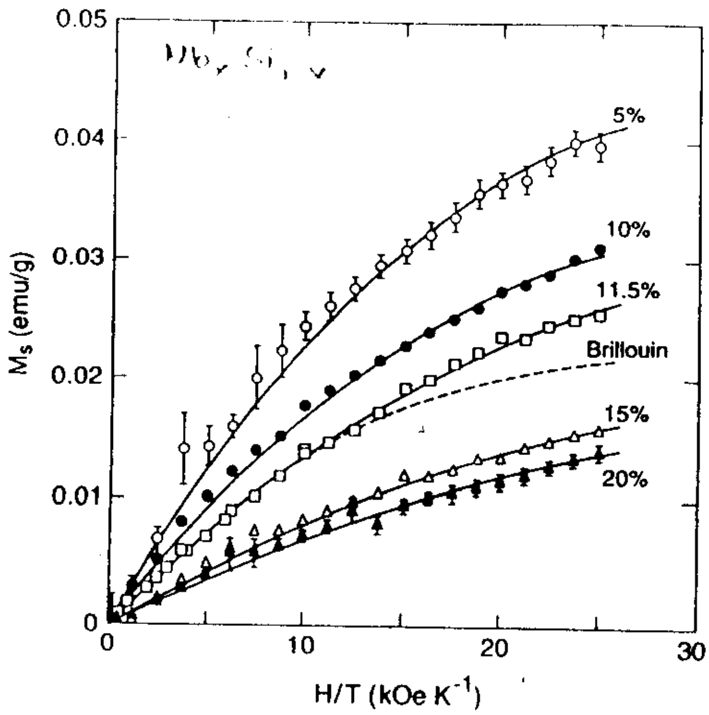


$Nb_x Si_{1-x}$: Allen, Paalanen & Bhatt Europhys Lett. **21**, 927 (1993)

χ versus T

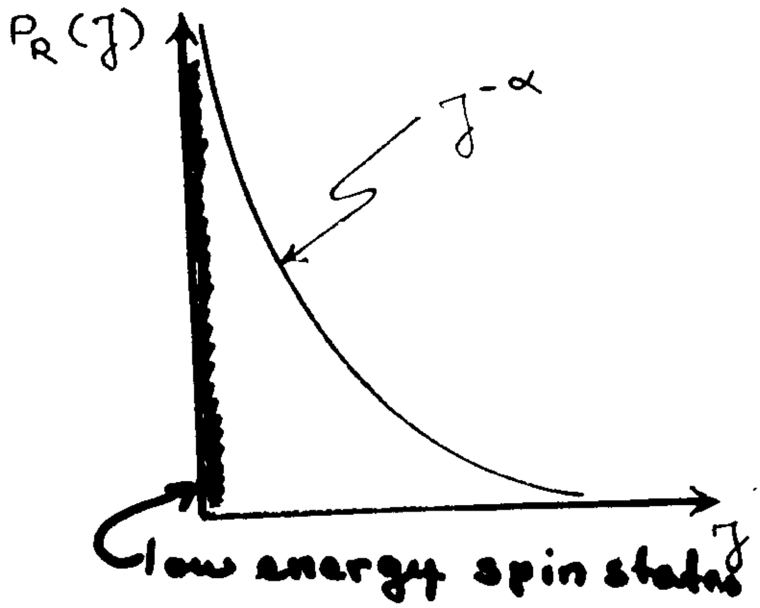


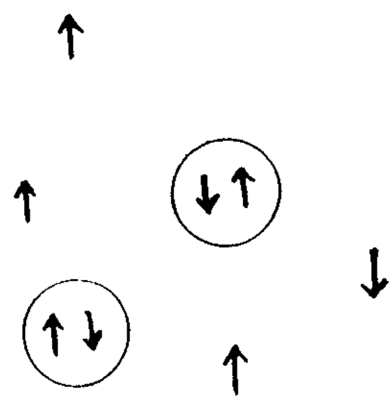
Magnetization as a function of magnetic field



IV3 INSULATING PHASE OF SI:P

- Random Heisenberg Antiferromagnet
  - $$H = \sum_{i,j} J(r_{ij}) \vec{S}_i \cdot \vec{S}_j$$
  - $$J(r) = 1.636(r/a_B^*)e^{-2r/a_B^*} Ry^*$$
  - Not a spin-glass!!
- Elegant solution by *BHATT* and *LEE*
  - Remove strongest coupled pairs
  - Removed pairs renormalize J of the remaining pairs
- Renormalized J-distribution





INSULATING PHASE OF SI:P

Random Heisenberg Antiferromagnet

- Renormalized J-distribution
  - $P_R(J) \propto J^{-\alpha}$
  - $\alpha \approx .62$ for $n \lesssim n_c$
  - $\chi \propto T^{-\alpha}$
  - $\gamma = C/T \propto T^{-\alpha}$
  - Wilson ratio

$$\left(\frac{\chi}{\chi_0}\right) / \left(\frac{\gamma}{\gamma_0}\right) = \frac{\pi^2}{3(1 - \alpha) ln 2} \approx 10$$

- This model explains in the insulating SI:P:
  - Susceptibility; K. Andres et al
  - High field magnetization; M. Sarachik et al
  - ESR linewidth; Murayama et al Paalanen et al
  - T_1 of ^{29}Si NMR; Paalanen et al Holcomb et al

IV 4 Local Moment Formation in Disordered Metal

- Scaling theories fail to produce enough magnetism near MIT

- In the insulating phase, just below n_c, there are local magnetic moments in the disordered system. The disordered metallic system just above n_c might also have local moment formation

  - rare sights far away from neighbours

  - Low Kondo Temperature due to low local density of states

Milovanovic, Sachdev & Bhatt PRL 63, 82, 1989
Bhatt & Fisher PRL 68, 3072 (1992)
Dobrosavljevic et al 69, 1113 (1992)

IV 5 Two Fluid Model

The coexistance of local moments and delocalized electrons can be phenomenologically modelled by so called "two fluid model".

TWO FLUID MODEL

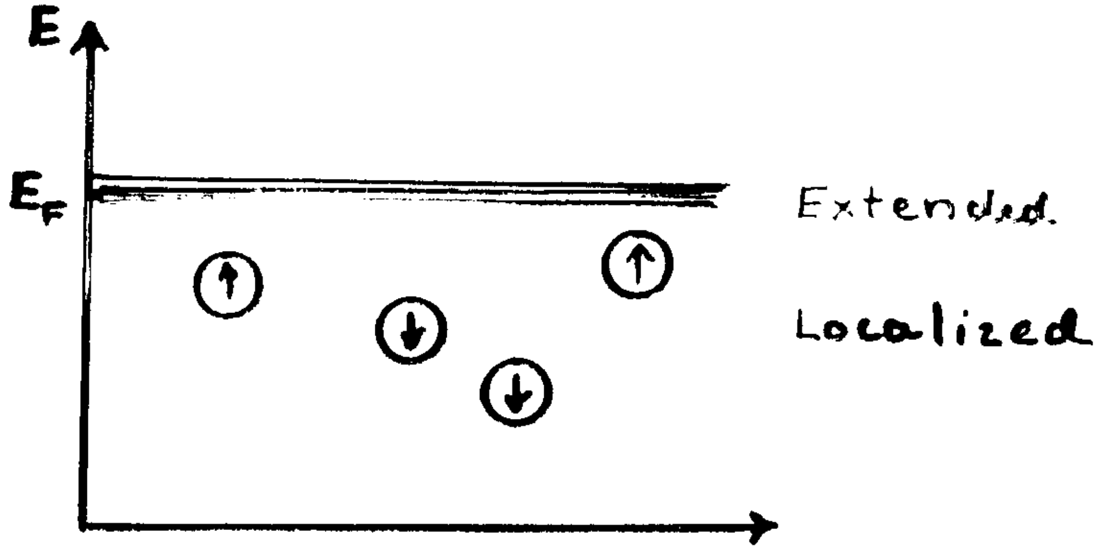
of localized moments and free electrons ($n > n_c$)

- Interaction between localized moments and itinerant electrons is weak
- In first order the interactions between local moments described by Bhatt and Lee model
- In first order the free electrons described by the Fermi-liquid theory

$$\chi/\chi_0 = m^*/m + \frac{\pi^2}{3(1-\alpha)\ln 2}\left(\frac{T}{T_0}\right)^{-\alpha}$$

$$\gamma/\gamma_0 = m^*/m + \left(\frac{T}{T_0}\right)^{-\alpha}$$

- T_0 only adjustable parameter containing the number of localized moments!!



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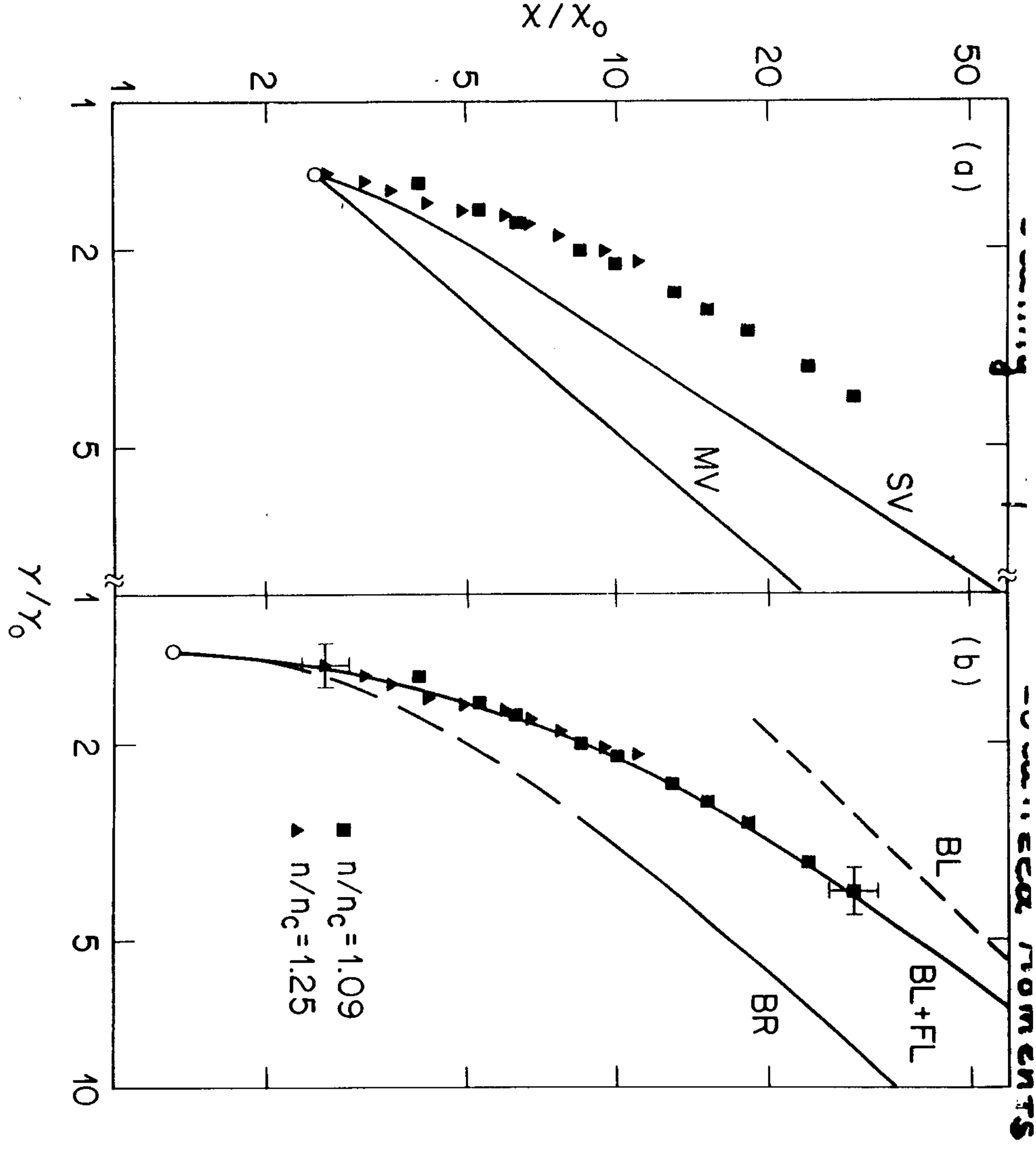
<u>χ & C measurements in Si:P : PRL 61, 597(</u>

Test of scaling theory and
two fluid model with local moments near MI
Two fluid model on right is better.



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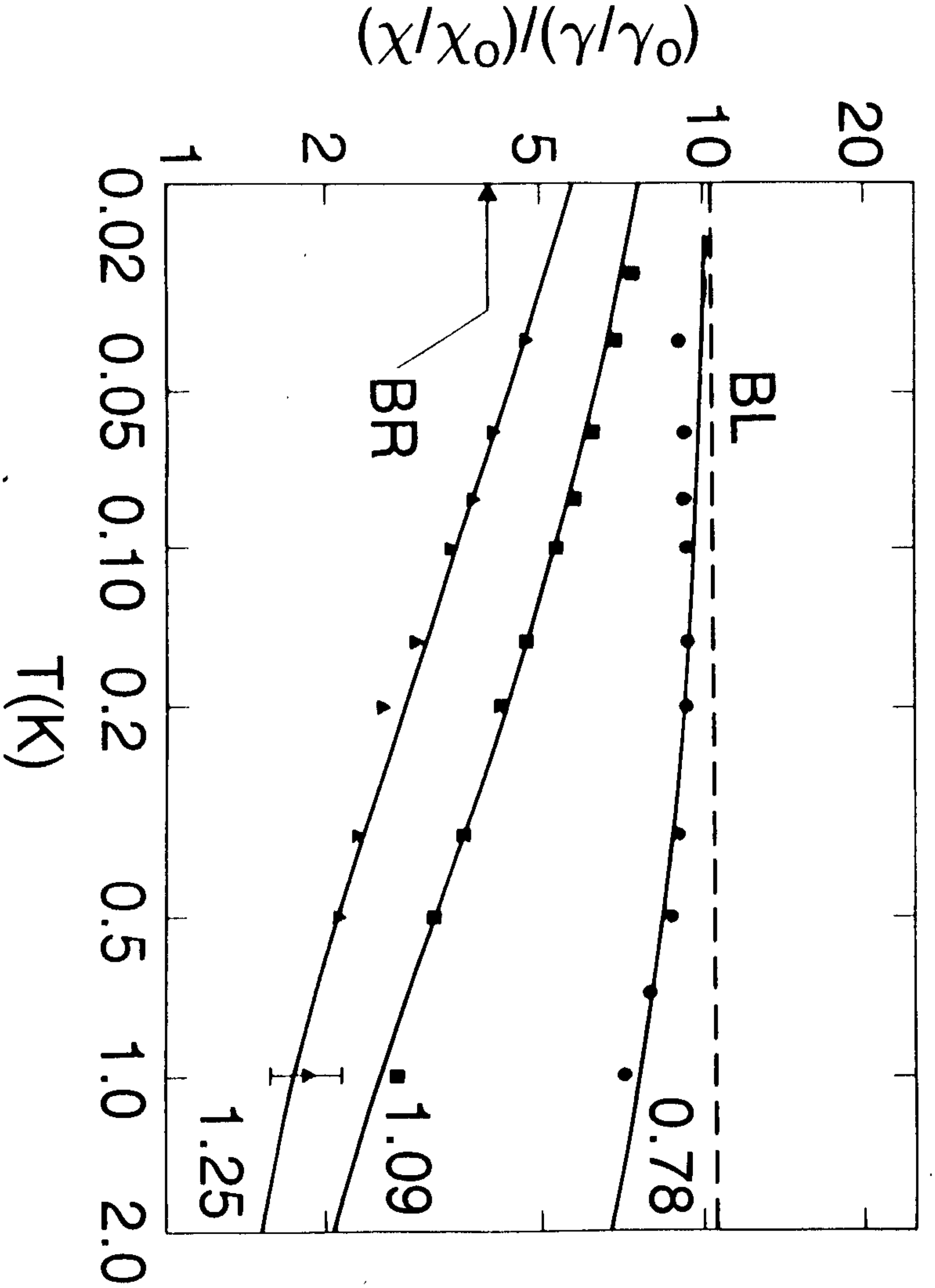
Wilson ratio for Si:P near MIT
[PRL 61, 597 (1988)]
The solid lines are from two fluid model with one fitting parameter.



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Two fluid model, where local moments have wide distribution of J-couplings following the Bhatt & Lee distribution $P_R(J) \propto J^{-\alpha}$, seems to explain the thermodynamic properties of Si:P and also $Nb_x Si_{1-x}$.

Further confirmation of low lying spin states is gain by ^{29}Si NMR measurements.

The spin lattice relaxation time (T_1) follows in good Fermi liquids Korringa law

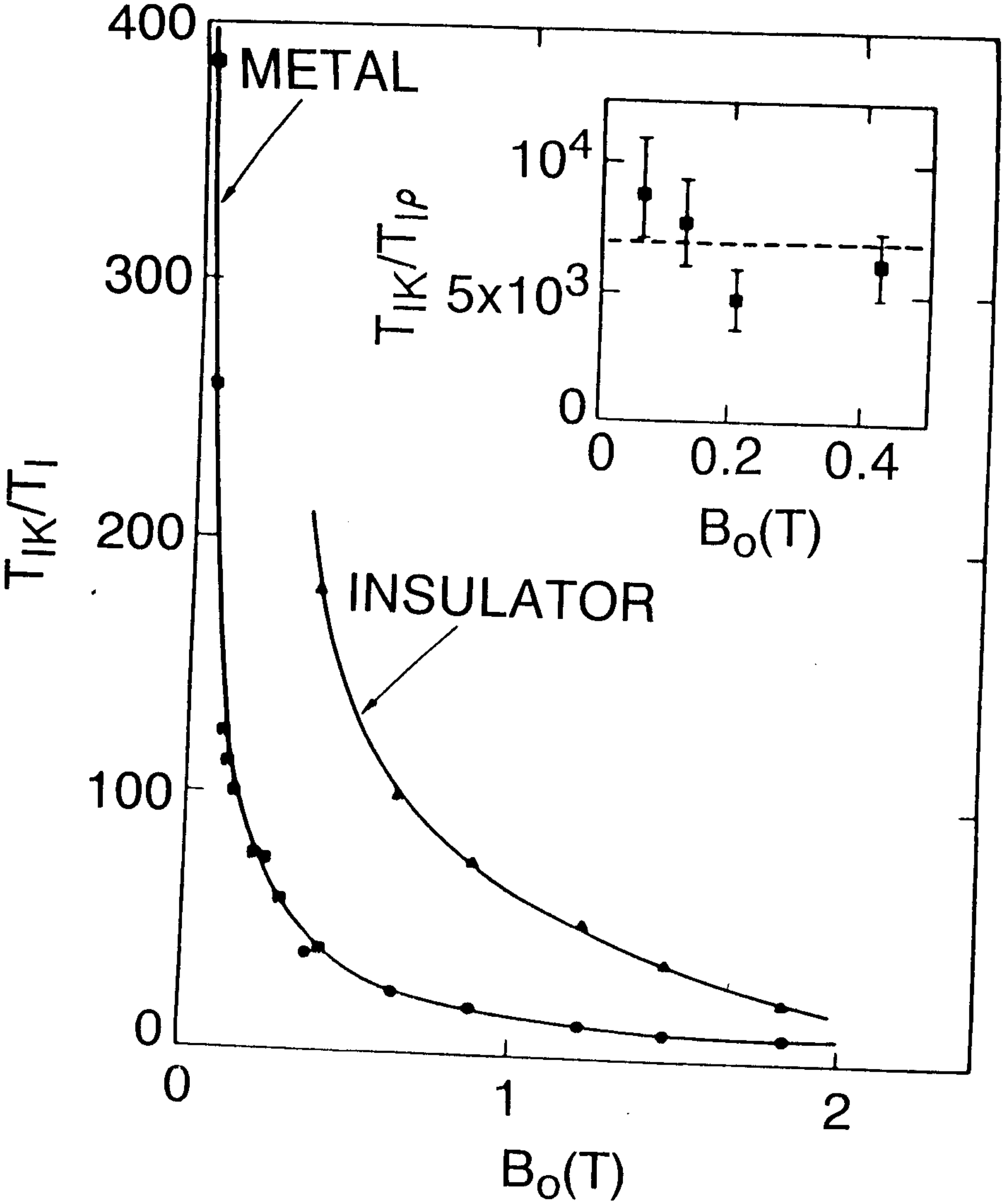
$$T_{1K} \propto \frac{1}{T}$$

and T_{1K} is independent of magnetic field B.

On page 55 we have compared the measured T_1 with the predicted T_{1K} and find huge enhancement in the relaxation rate T_1^{-1} compared to T_{1K}^{-1}

The ratio T_{1K}/T_1 is also B-dependent.

This all is consistent with the local moment picture



400
300
200
100
0
METAL
INSULATOR
T_IK/T_I
0
1
2
B_o(T)
10^4
5x10^3
0
T_IK/T_1ρ
0
0.2
0.4
B_o(T)

V CONCLUDING REMARKS

V 1. Critical behavior of σ at MIT

$[\sigma \propto (n-n_c)^{\mu}]$

Theory situation:

- one parameter scaling theory including disorder & e-e interactions exists
- theory predicts 8 universality classes with different critical behaviors. Very rich!
- in some cases we have estimations for μ in lowest order ε $(d-2)$ expansion

  spin-orbit
  spin-flip
  Magnetic field } universality classes have $\mu = 1$

  general universality class $\mu = ?$ (we don't know)

- in single electron theory without e-e interactions $\mu \geq 2/3$ (Harris criterion)

Experimental situation:

Si:P (uncompensated):

- $\mu \simeq 0.5$ (?)
- presumably in general univ. class (?)
- T-dependence complicated (?)
- In high B $\mu \to 1$ (OK)
- compensation $\mu \to 1$ (OK)

Shawdak et al
Holcomb et al

Crossover from one univ. class to another?

Si : B : (uncompensated p-type)

- SO - univ. class
- $\mu \simeq 0.5$ (?)
- high B, $\mu \to 1$ (OK)

Shcadule et. al

AlGaAs :

- SO - univ. class
- $\mu \simeq 1$ (OK)
- $\Delta\sigma \propto +\sqrt{T}$ (OK)

Katsumoto

$Nb_x Si_{1-x}$

- SO - univ. class
- $\mu \simeq 1$ (OK)

V 2. Critical behavior of R_H at MIT

THEORY : Both single electron & interaction calculations are predicting critical behavior for R_H

EXPERIMENTS :

- R_H is hard to measure (harder than σ_{xx})
- Most experiments show critical R_H at MIT
- Si:As, Si:P, Ar:Ga, In_2O_2 show noncritical behavior (?)

V 3 Thermodynamic properties

- C & χ don't show critical behavior at n_c
- C & χ are dominated by the contributions from <u>isolated spins</u>
- The magnetic fluctuations due to isolated spins are also seen in spin-lattice relaxation time T_1 of the nuclei in the material. T_1 is enhanced over the Korringa prediction for Fermi liquid.