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SMR 1232 - 10

XII WORKSHOP ON
STRONGLY CORRELATED ELECTRON SYSTEMS

17 - 28 July 2000

Unconventional Magnetism and Superconductivity in Heavy Fermions $CeRhIn_5$, $CeIrIn_5$, $CeCoIn_5$ and related compounds

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Unconventional Magnetism and Superconductivity in Heavy Fermions $CeRhIn_5$, $CeIrIn_5$, $CeCoIn_5$ and related compounds

Roman Movshovich

Los Alamos National Laboratory

Synthesis & Characterization

H. Hegger - LANL
M. Jaime - LANL
E.G. Moshopoulou - LANL
P.G. Pagliuso - LANL
M.F. Hundley - LANL
J.L. Sarrao - LANL
J.D. Thompson – LANL

Z. Fisk NHMFL & LANL
C. Petrovic - FSU

F. Bouquet - Berkeley
R.A. Fisher - Berkeley
N.E. Phillips - Berkeley

Magnetic Spectroscopies

N. Curro - LANL
P.C. Hammel - LANL

R.H. Heffner - LANL

W. Bao - LANL

Electronic Structure

A.L. Cornelius - UNLV
D. Hall - NHMFL
R.G. Goodrich - LSU

A.J. Arko - LANL
J.J. Joyce - LANL

J.M. Wills - LANL

Outline

I. Context: Doniach phase diagram and $CeIn_3$

II. $Ce_xM_yIn_{3x+2y}$ - low-dimensional variants of $CeIn_3$?

[J.D. Thompson *et al.*, ICM/SCES-2000]

A. $CeRhIn_5$ (AFM, pressure-induced superconductivity)

[H. Hegger *et al.*, PRL **84**, 4986 (2000)]

B. Ce_2RhIn_8 (AFM, pressure-induced superconductivity)

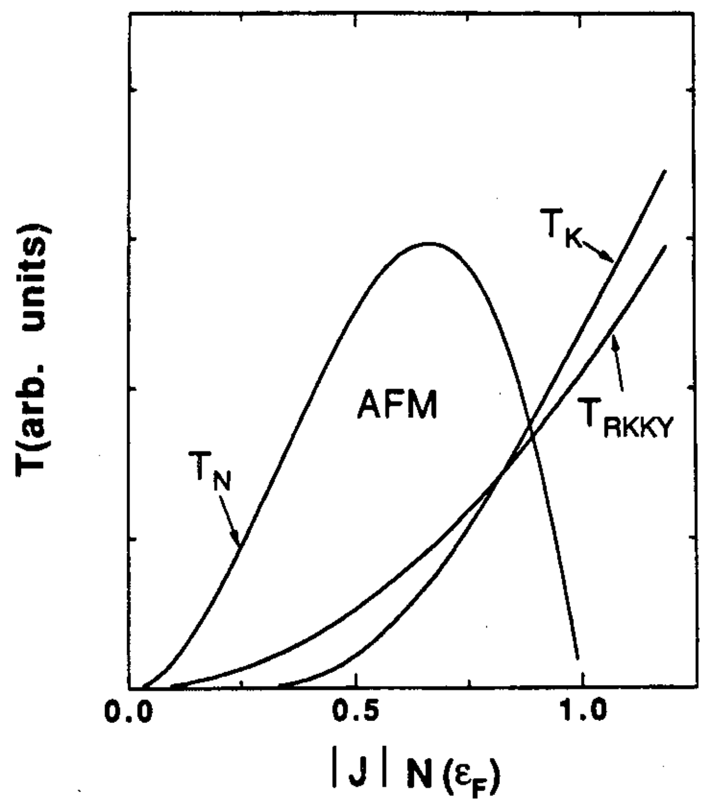
C. $CeIrIn_5$ ('unconventional' superconductor)

D. $Ce_{1-x}RE_xIr_{1-y}Rh_yIn_5$ studies

E. Ce_2IrIn_8 (paramagnet)

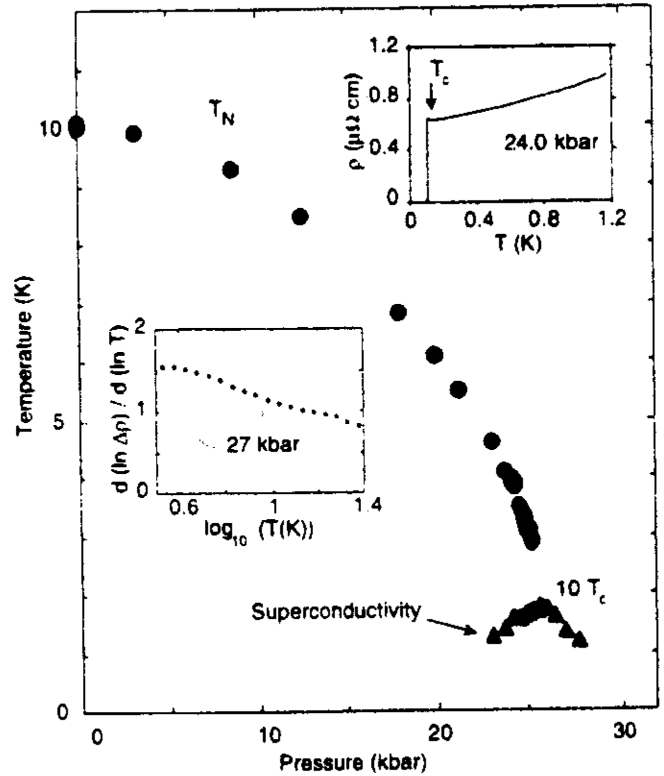
F. CeCoIn5 ('unconventional' superconductor)

The conventional view of magnetism giving way to superconductivity



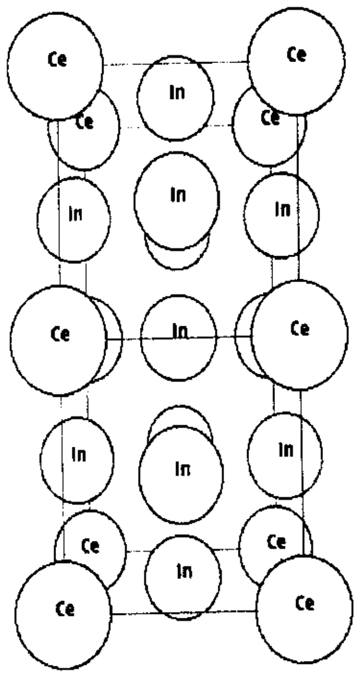
S. Doniach, in *Valence Instabilities and Related Narrow Band Phenomena*, ed. R.D. Parks (Plenum, New York, 1977) p. 169.

$CeIn_3$

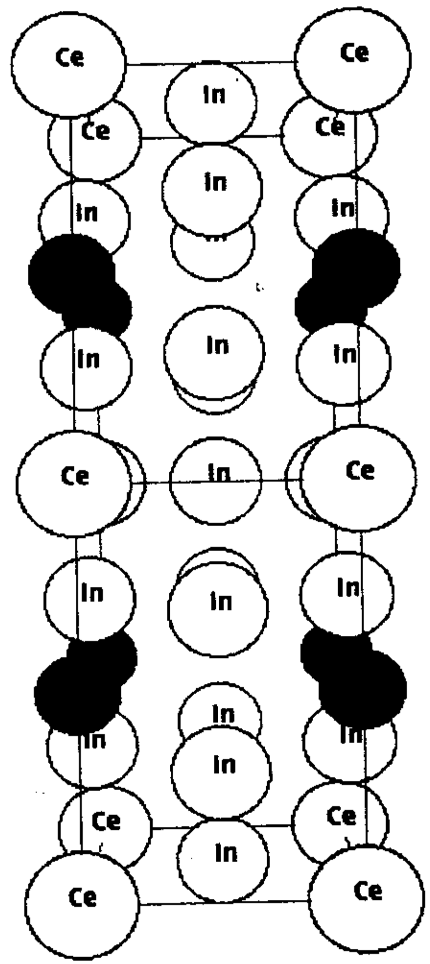


N.D. Mathur et al., Nature **394**, 39 (1998)

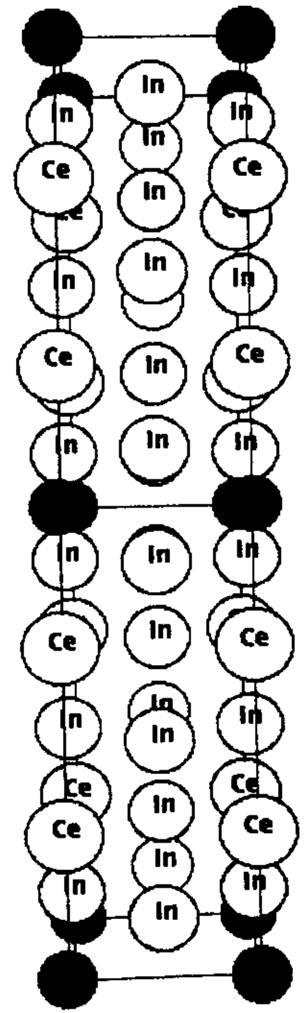
Crystal Structures



$CeIn_3$



$CeMIn_5$



Ce_2MIn_8

Lattice Parameters

Compound	a(Å)	c(Å)
$CeRhIn_5$	4.652	7.542
$CeIrIn_5$	4.668	7.515
$CeCoIn_5$	4.614	7.552
Ce_2RhIn_8	4.665	12.244
Ce_2IrIn_8	4.671	12.214

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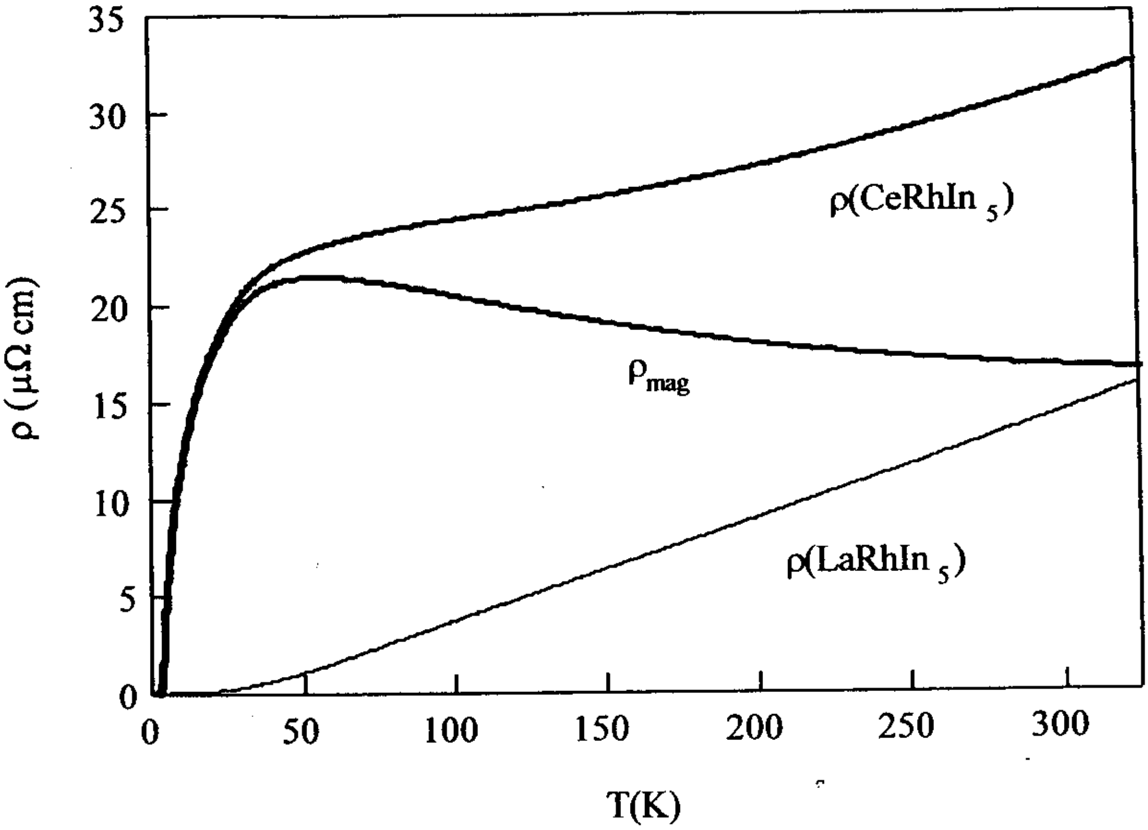
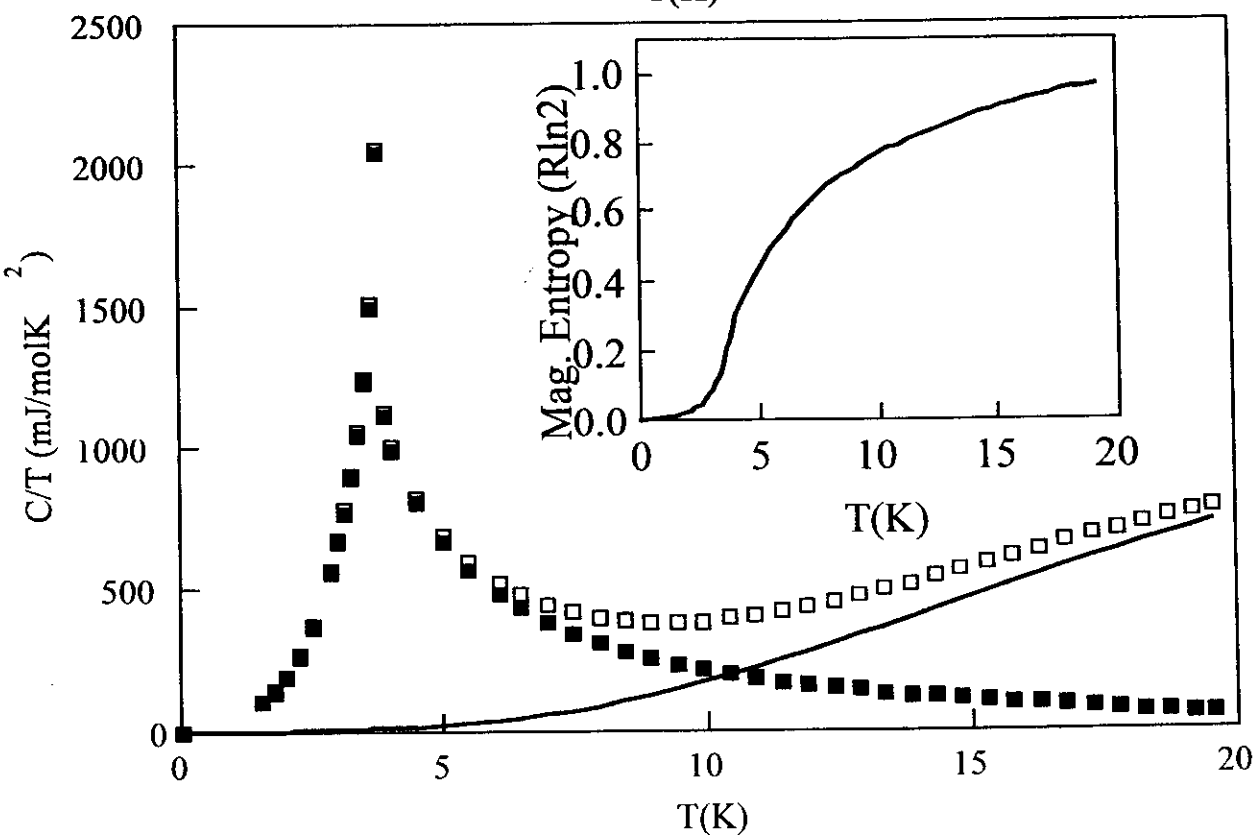
CeRhIn$_5$ - ρ(T), C/T





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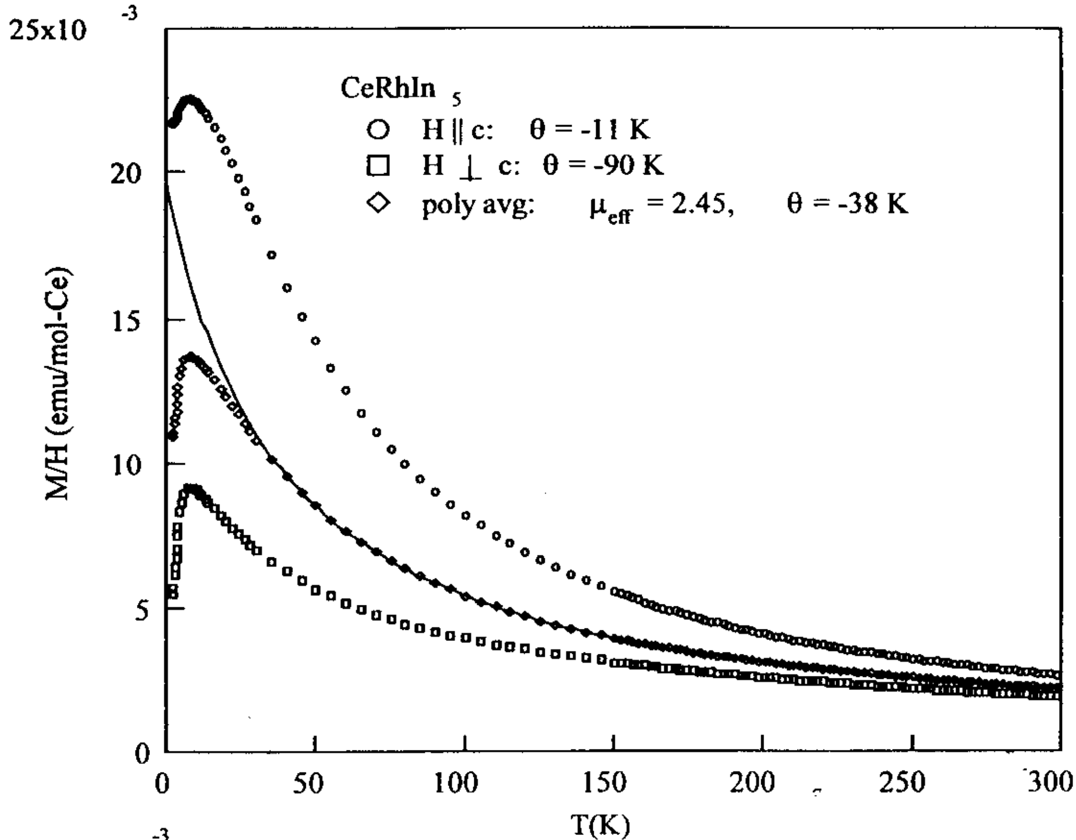
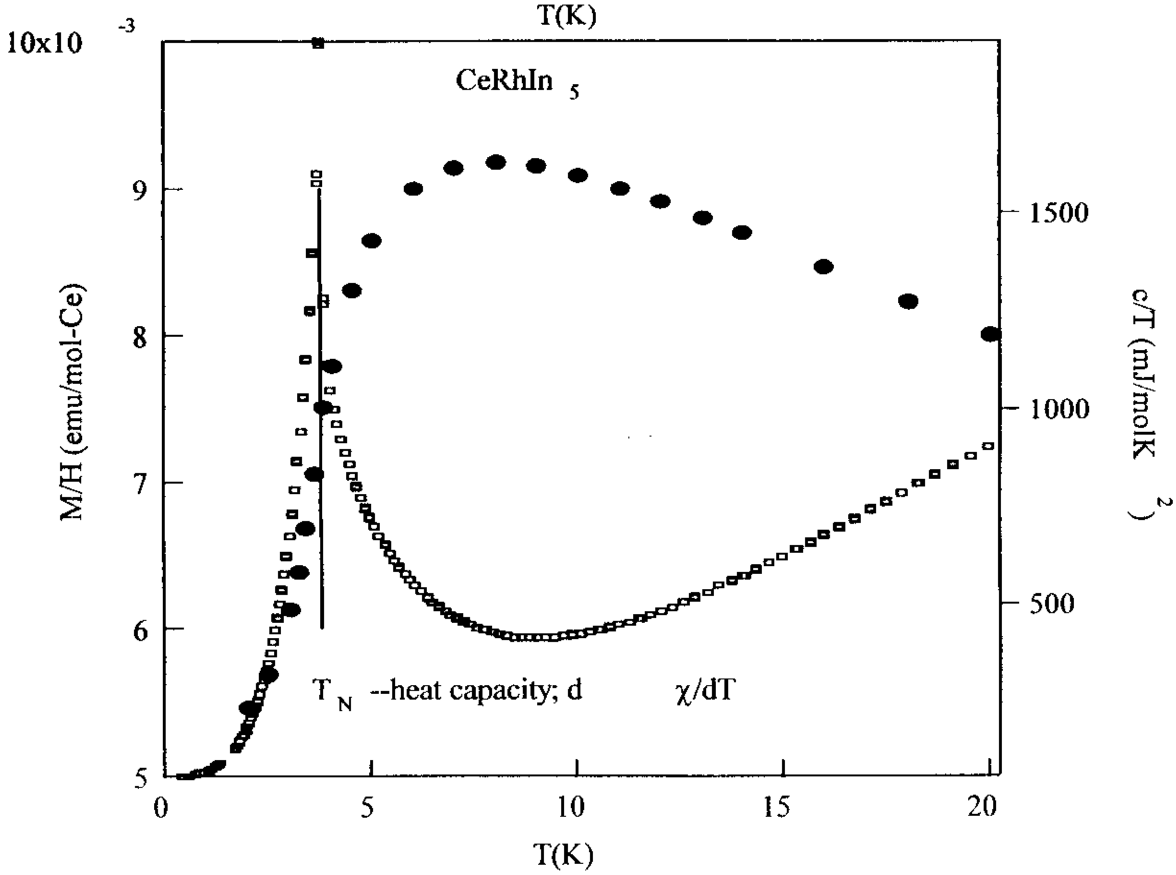
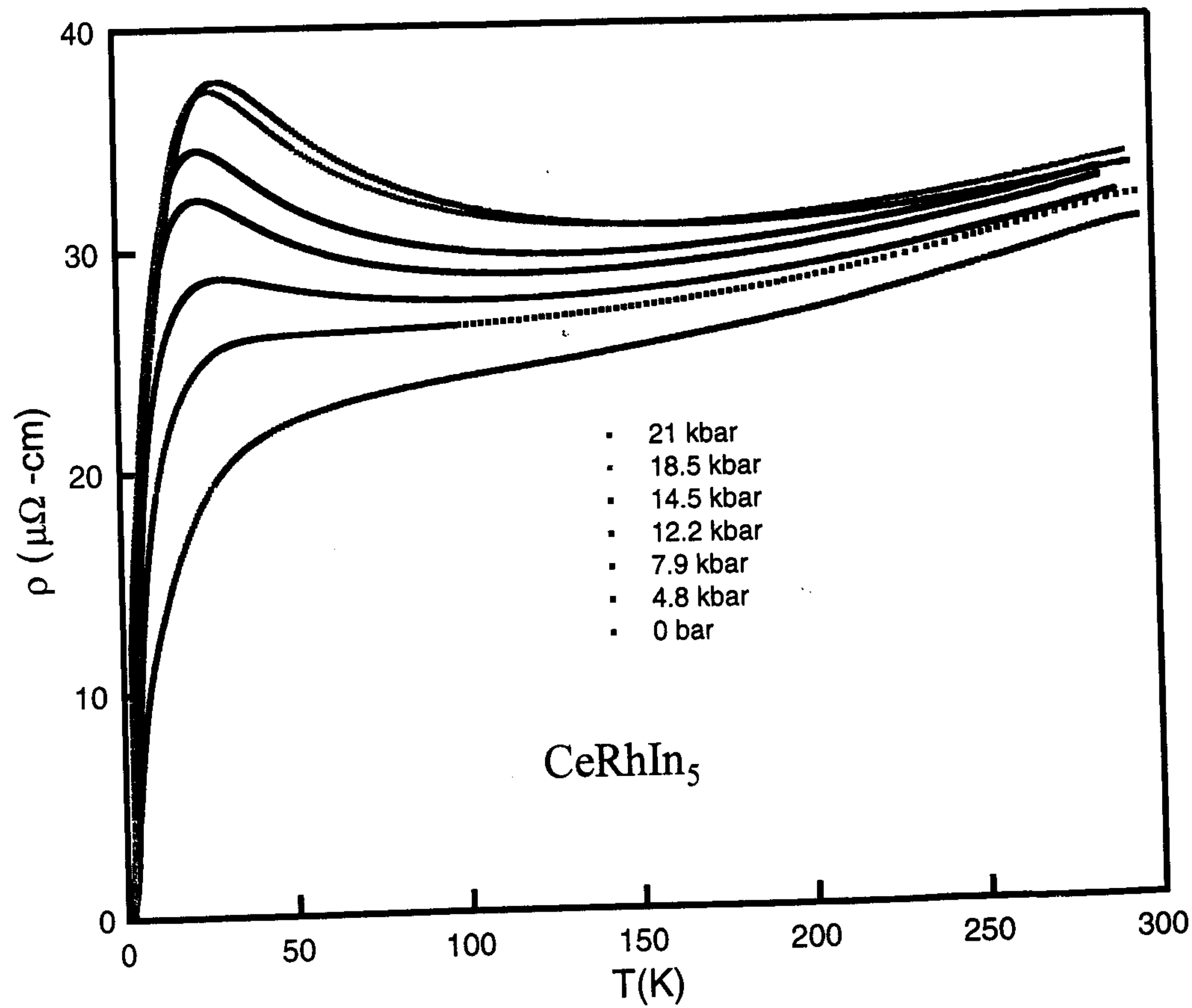
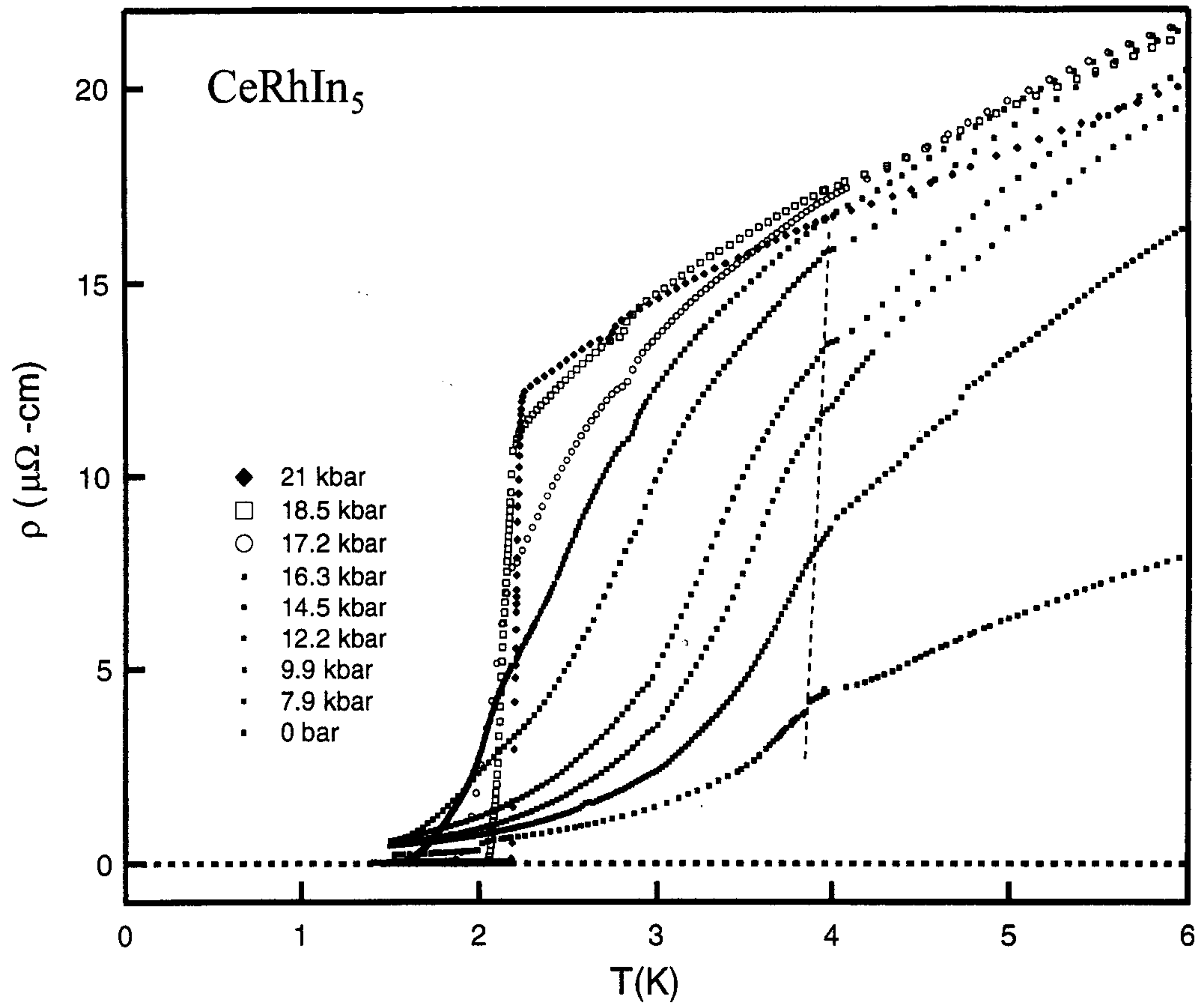
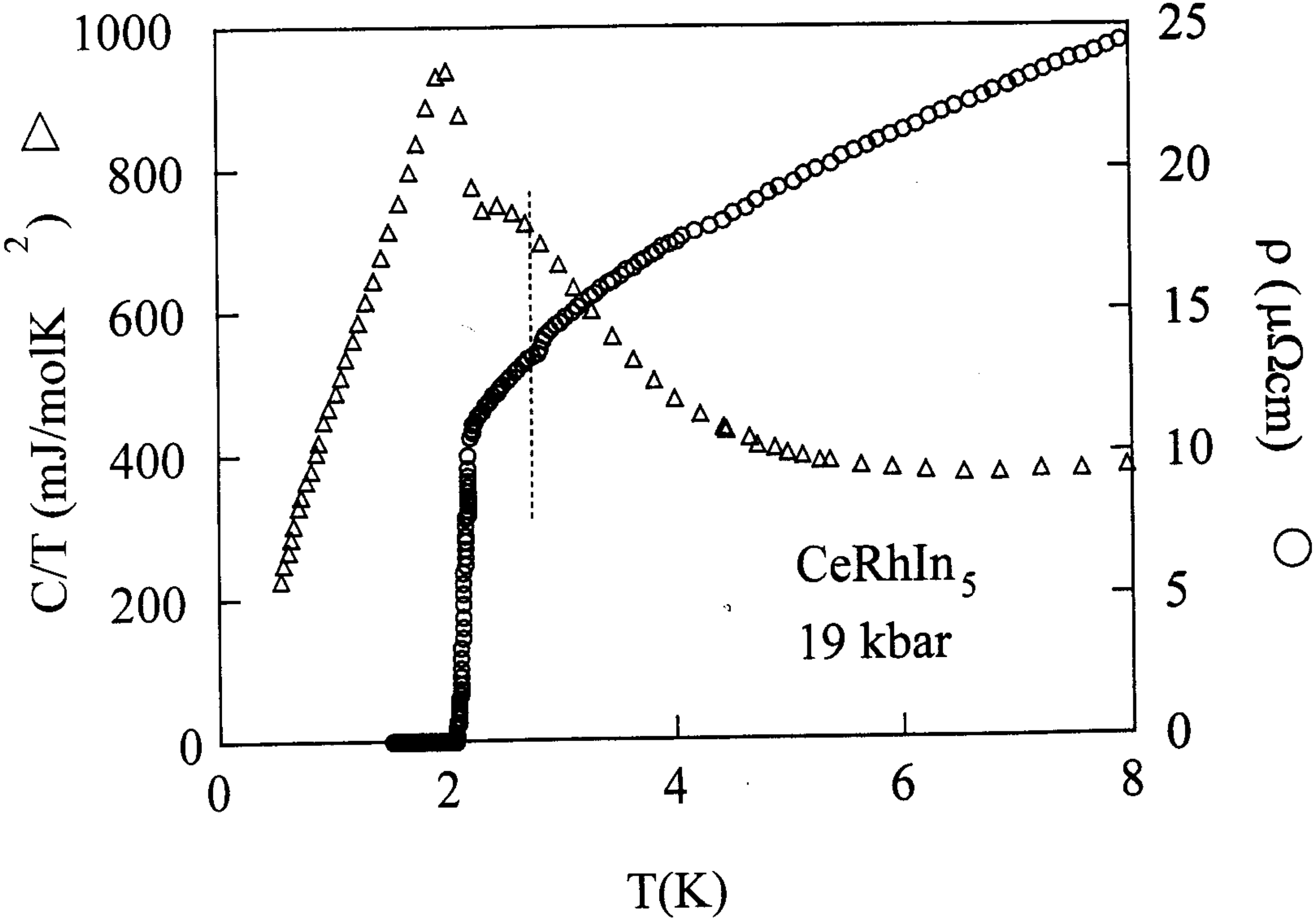

25x10 -3
CeRhIn 5
H || c: θ = -11 K
H ⊥ c: θ = -90 K
poly avg: μeff = 2.45, θ = -38 K
M/H (emu/mol-Ce)
T(K)
0
50
100
150
200
250
300
0
5
10
15
20


10x10 -3
CeRhIn 5
M/H (emu/mol-Ce)
c/T (mJ/molK 2)
T N --heat capacity; dχ/dT
T(K)
0
5
10
15
20
5
6
7
8
9
500
1000
1500

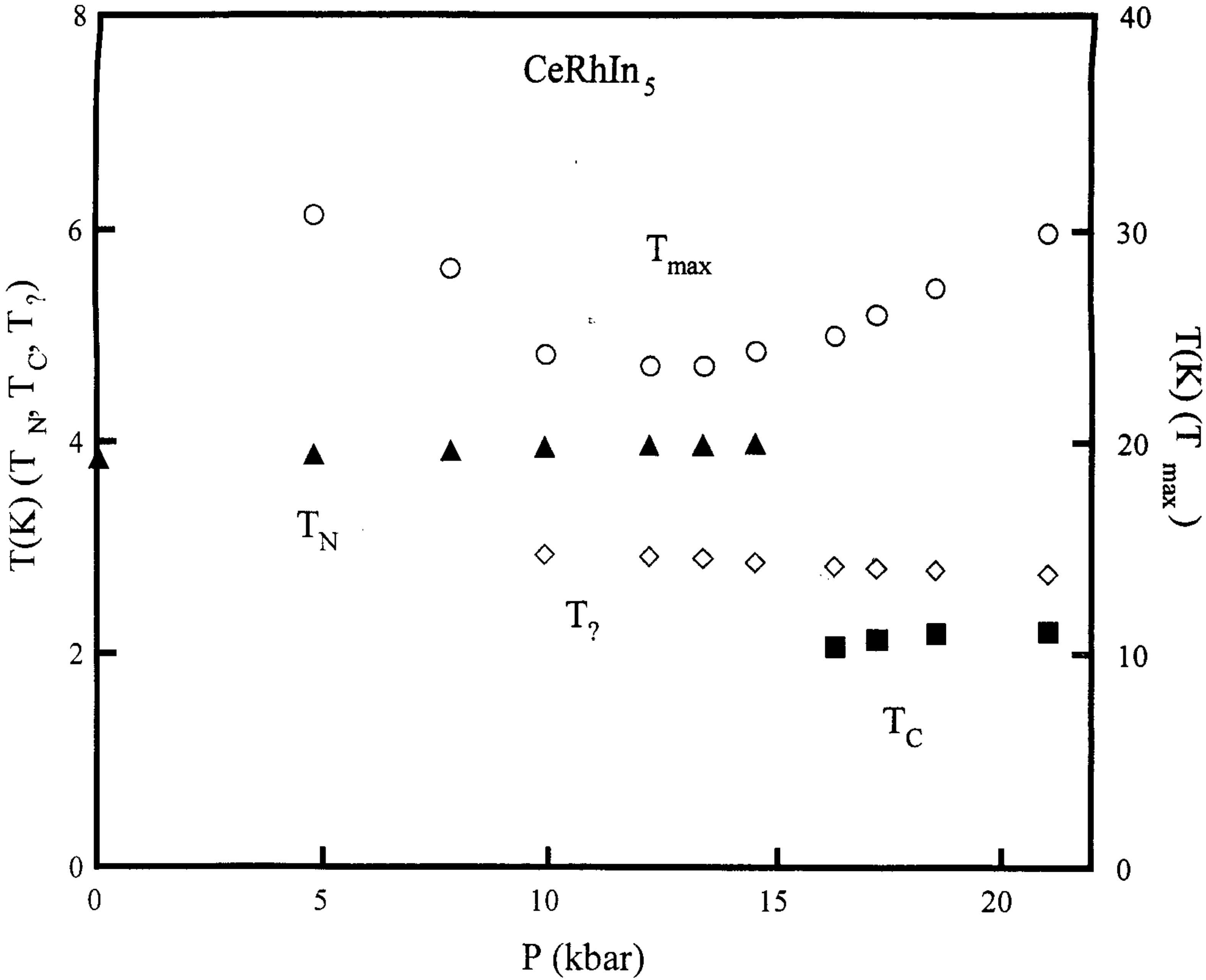

40
30
20
10
0
ρ (μΩ -cm)
0
50
100
150
200
250
300
T(K)
21 kbar
18.5 kbar
14.5 kbar
12.2 kbar
7.9 kbar
4.8 kbar
0 bar
CeRhIn5

8


CeRhIn$_5$
ρ (μΩ -cm)
T(K)
21 kbar
18.5 kbar
17.2 kbar
16.3 kbar
14.5 kbar
12.2 kbar
9.9 kbar
7.9 kbar
0 bar
0
5
10
15
20
0
1
2
3
4
5
6


C/T (mJ/molK^2) △
ρ (μΩcm) ○
T(K)
CeRhIn$_5$
19 kbar
1000
800
600
400
200
0
0
2
4
6
8
25
20
15
10
5
0

[redacted]


CeRhIn5
T_max
T_N
T_?
T_C
T(K) (T_N, T_C, T_?)
T(K) (T_max)
P (kbar)
0
2
4
6
8
0
10
20
30
40
0
5
10
15
20

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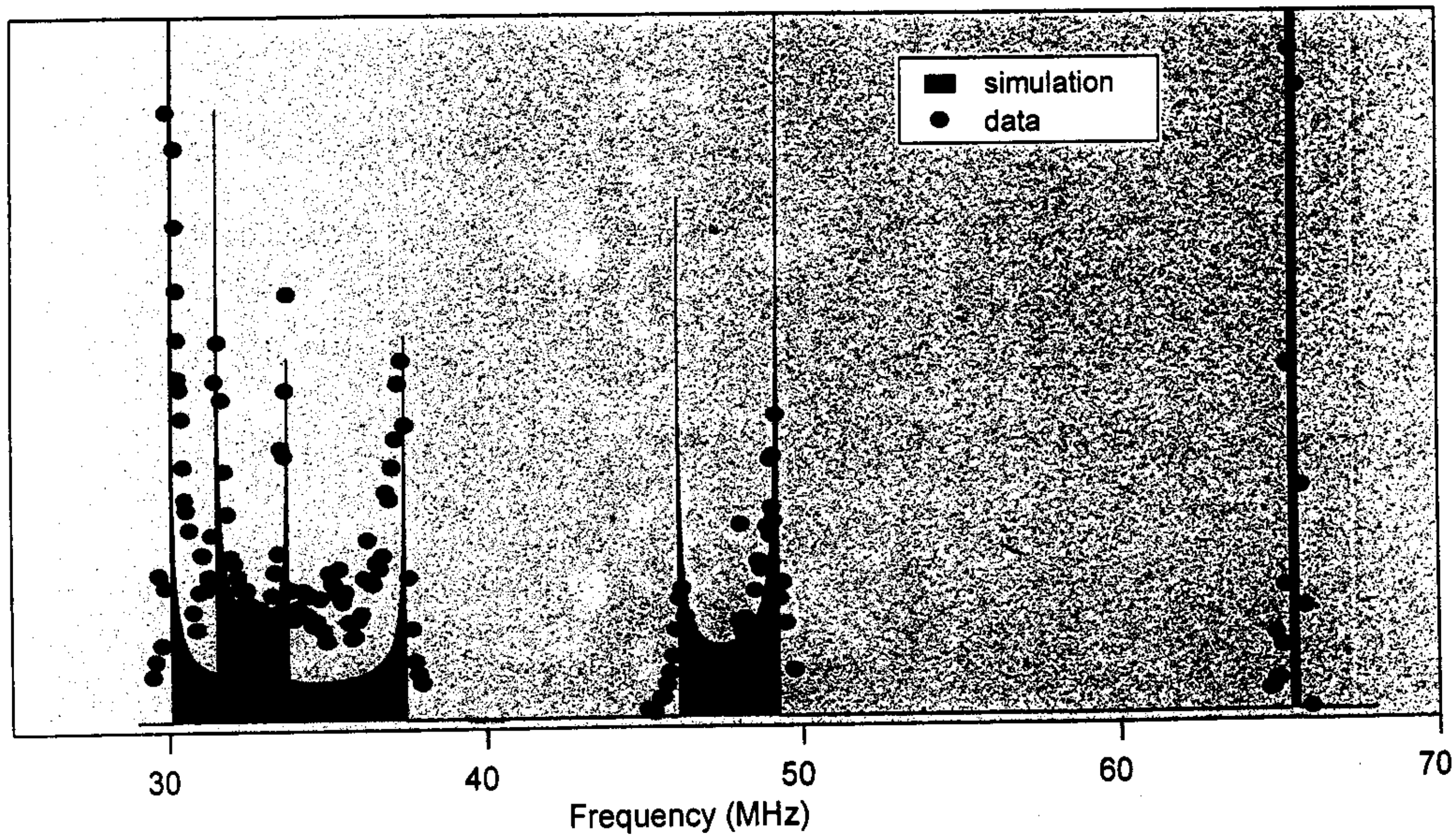
Magnetic Structure - $CeRhIn_5$

NQR spectrum in AF ordered state of In(2) site



Spiral spin structure along c

Neutrons suggest 3 rotations in 10 lattice constants

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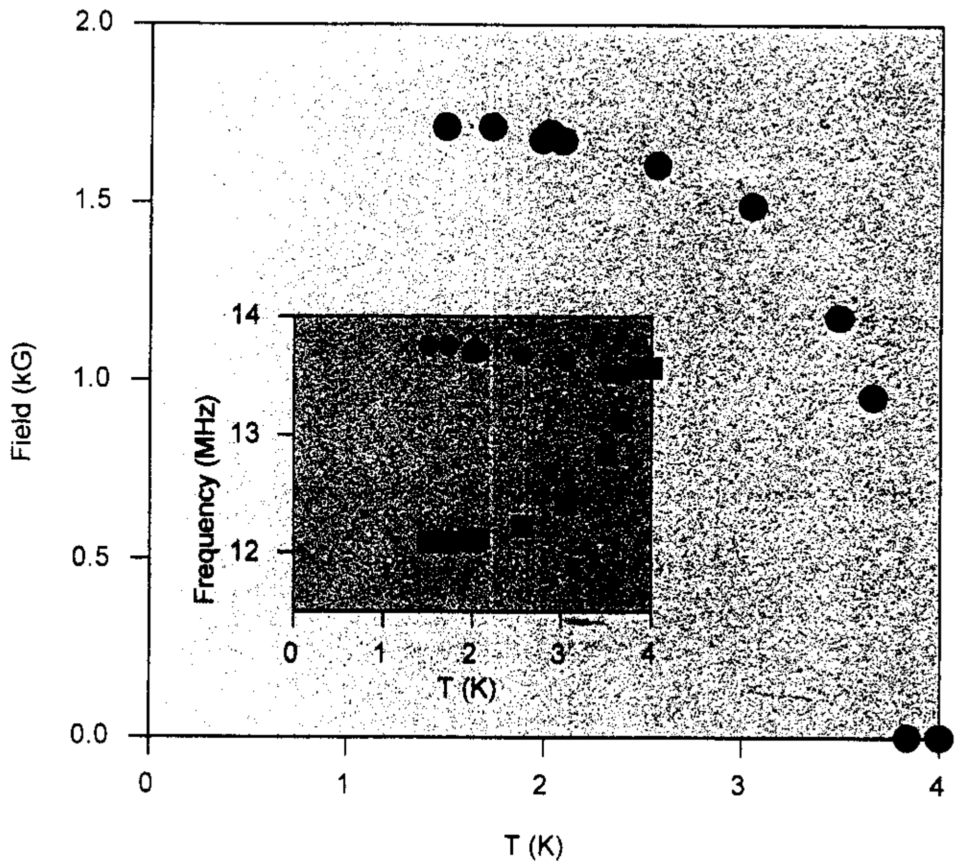
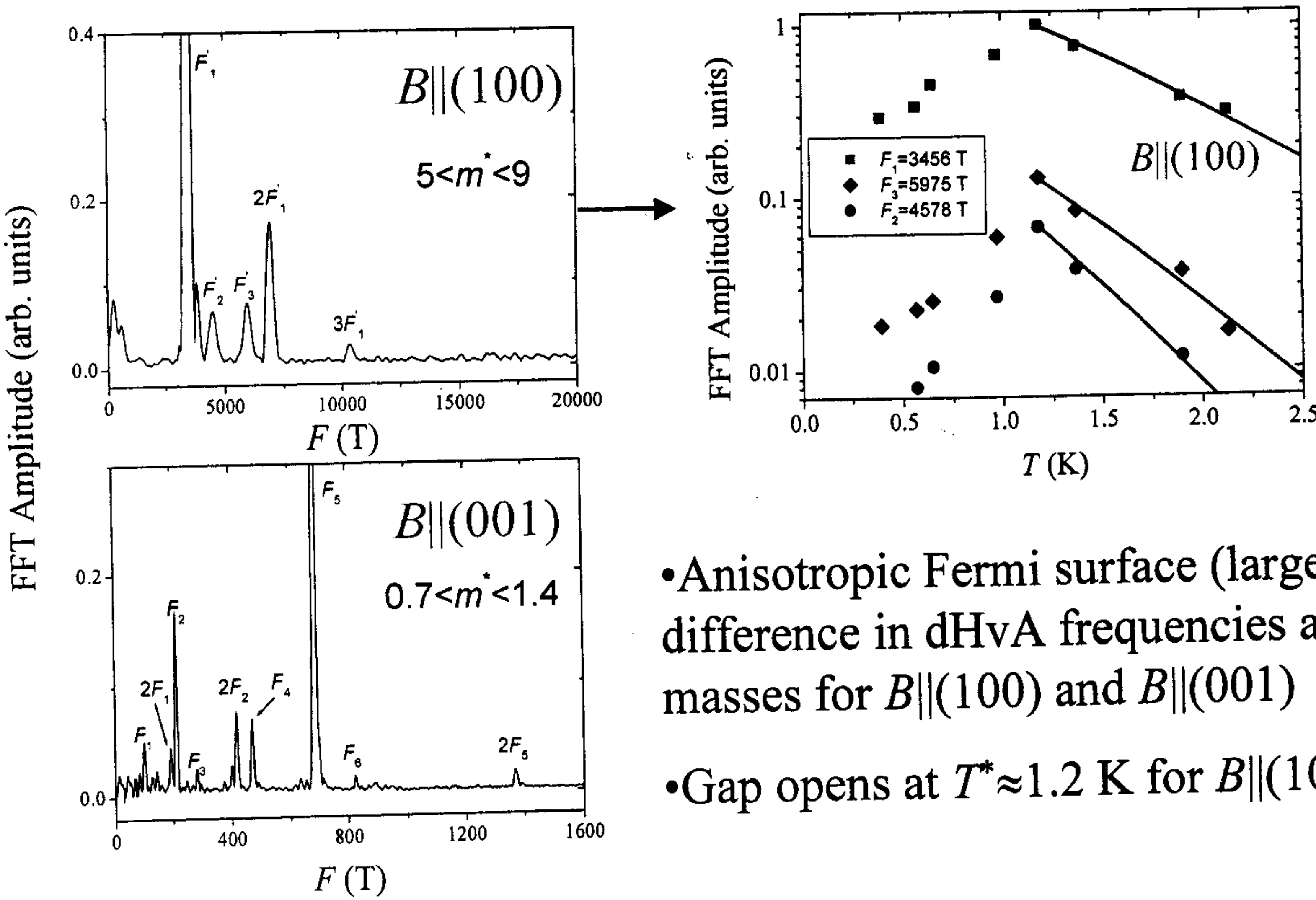
Magnetic Structure - $CeRhIn_5$ from In NQR (Curro et al.)

In(1) site -- internal field



- Antiferromagnetic order
  ($\mu_{ord} \sim 0.1\ \mu_B$)
- Moments lie in the plane
- Order parameter evolution
  $\propto (1-T/T_N)^{0.25}$

Anisotropic Fermi Surface of $CeRhIn_5$ (Cornelius et al.)



- Anisotropic Fermi surface (large difference in dHvA frequencies and masses for $B||(100)$ and $B||(001)$)
- Gap opens at $T^* \approx 1.2$ K for $B||(100)$

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$CeRhIn_5$: 2-d $CeIn_3$?

Empirical analogy with $CeIn_3$

Identify χ_{max} with 'remnant' 3d order in $CeIn_3$

$T_N(CeIn_3$ @ 14 kbar$) = 8$ K

$T_N(CeIn_3) = 0$ at 25 kbar (~14kbar +13 kbar, where $\chi_{max}(CeRhIn_5)=0$)

'Remnant' T_N -> 0 produces enhanced quantum fluctuations and increasing low-T ρ

2-d, S=1/2 Heisenberg antiferromagnet

- No long range order for T > 0 K
- Peak in $\chi(T)$ at $T(\chi_{max}) = 0.93$ J w/ value $\chi_{max} = 0.0938Ng^2\mu_B^2/J$
- Deviations from pure 2-d give ordering at $T_N \sim S(S+1)J$

For $CeRhIn_5$,

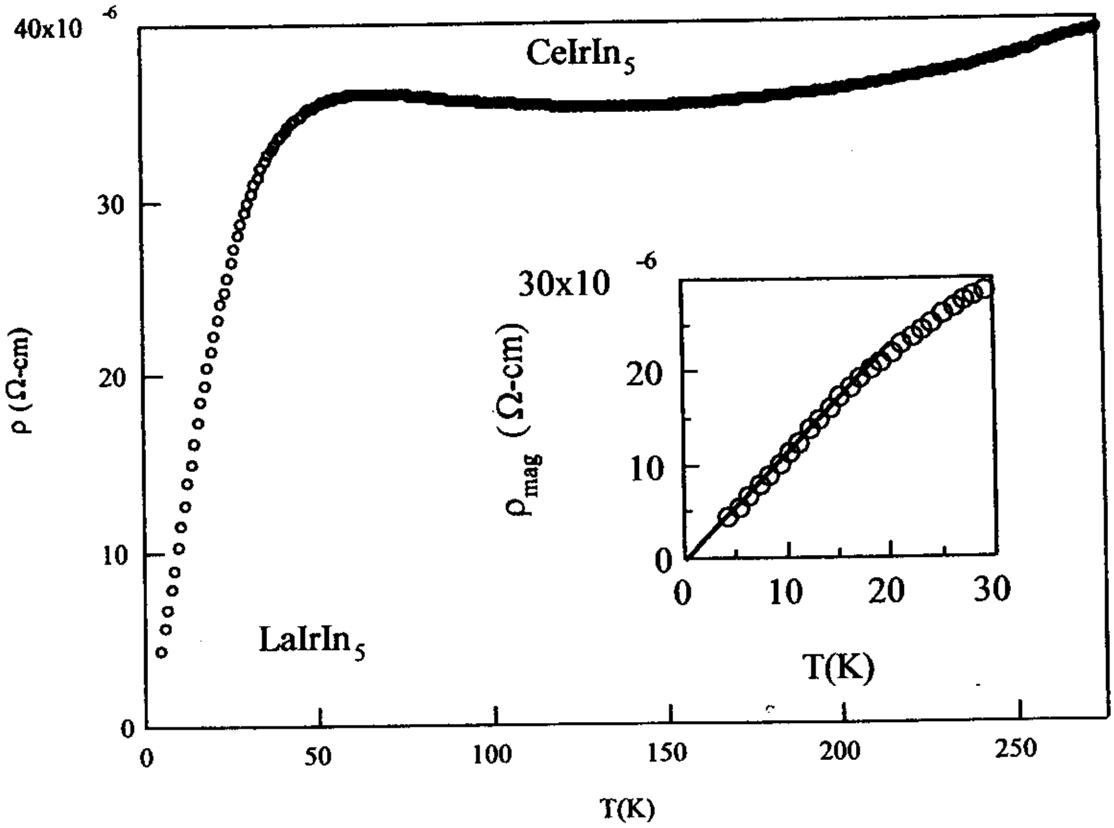
$T(\chi_{max})$ => J = 8 K, χ_{max} => J = 10 K, predicted T_N = 3.0 –3.7 K

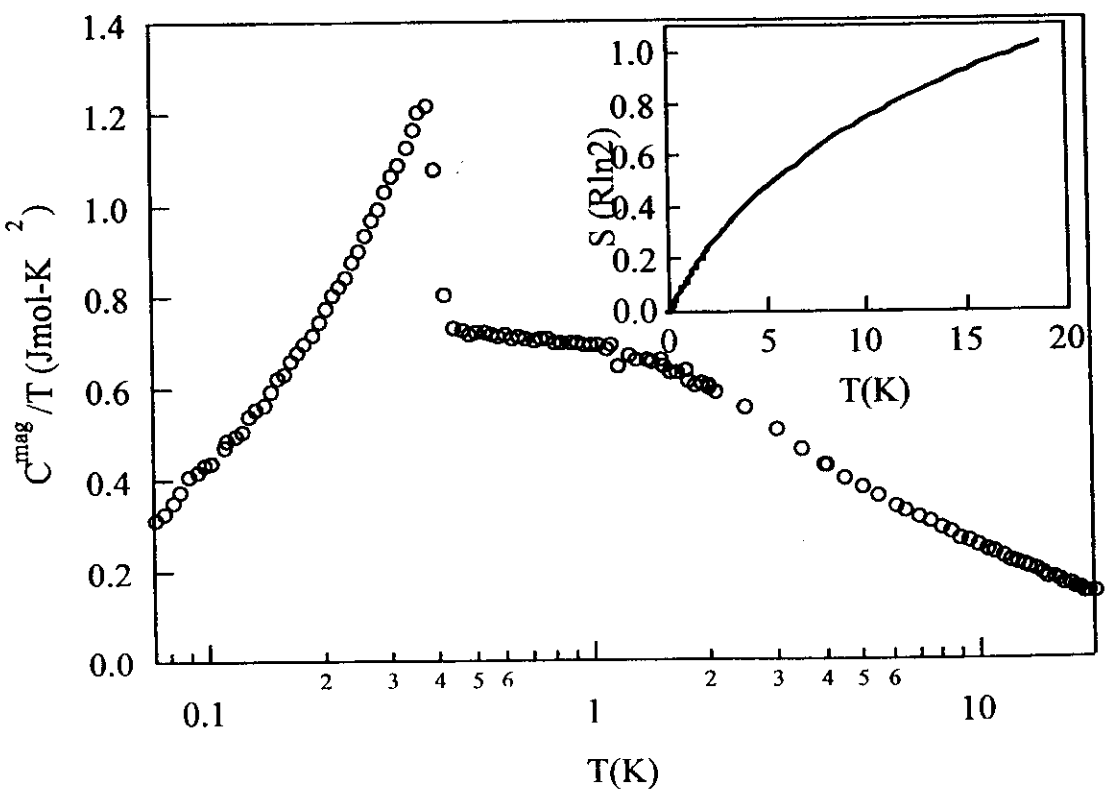
($CeIn_3$: T_N = J = 10 K)

However, no apparent maximum in $c_p(T)$ at $T(\chi_{max})$

So, perhaps, strong pressure dependence of J_{perp} causes 2d-3d crossover

$CeIrIn_5$ - ρ(T), C/T





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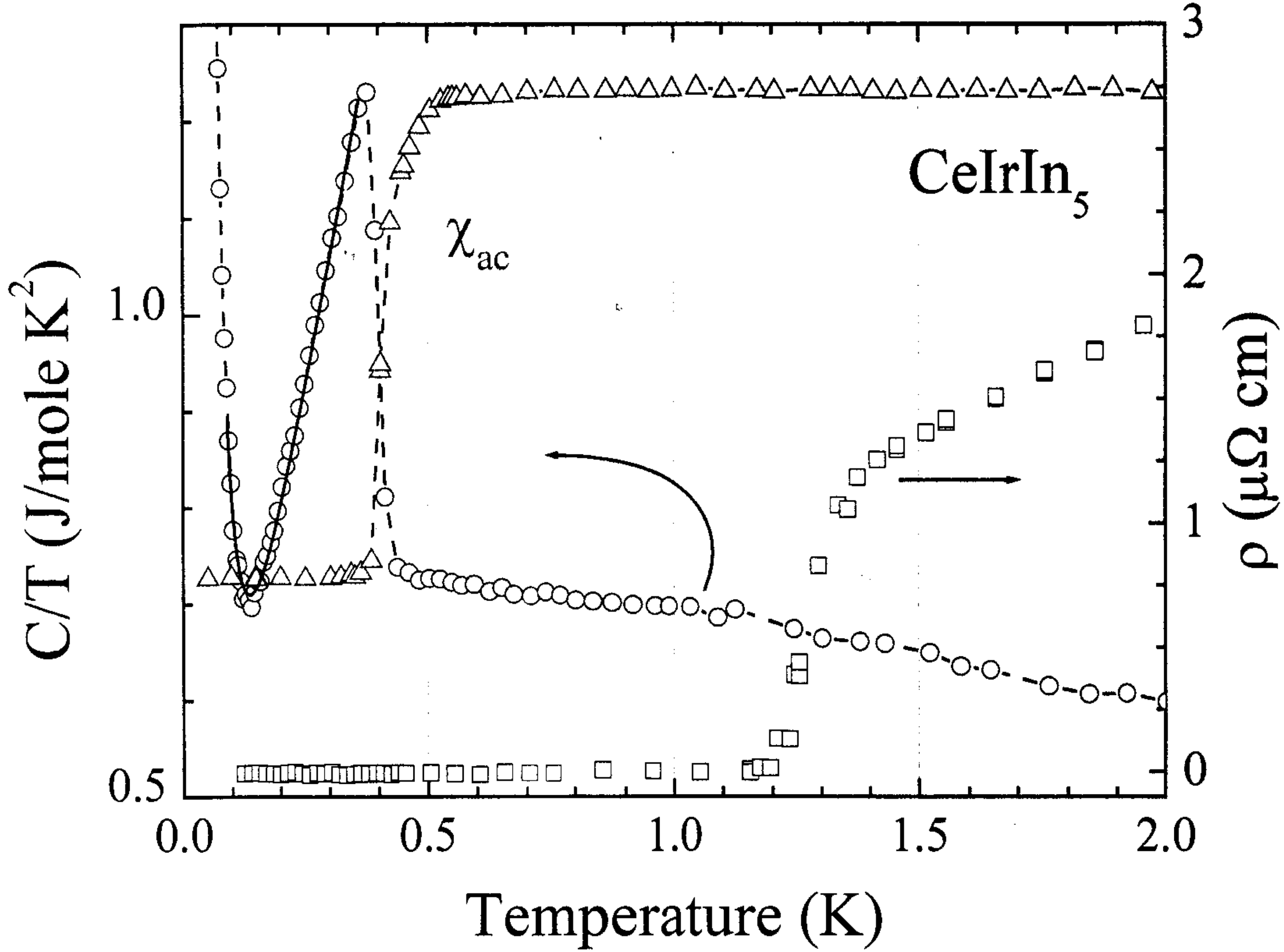
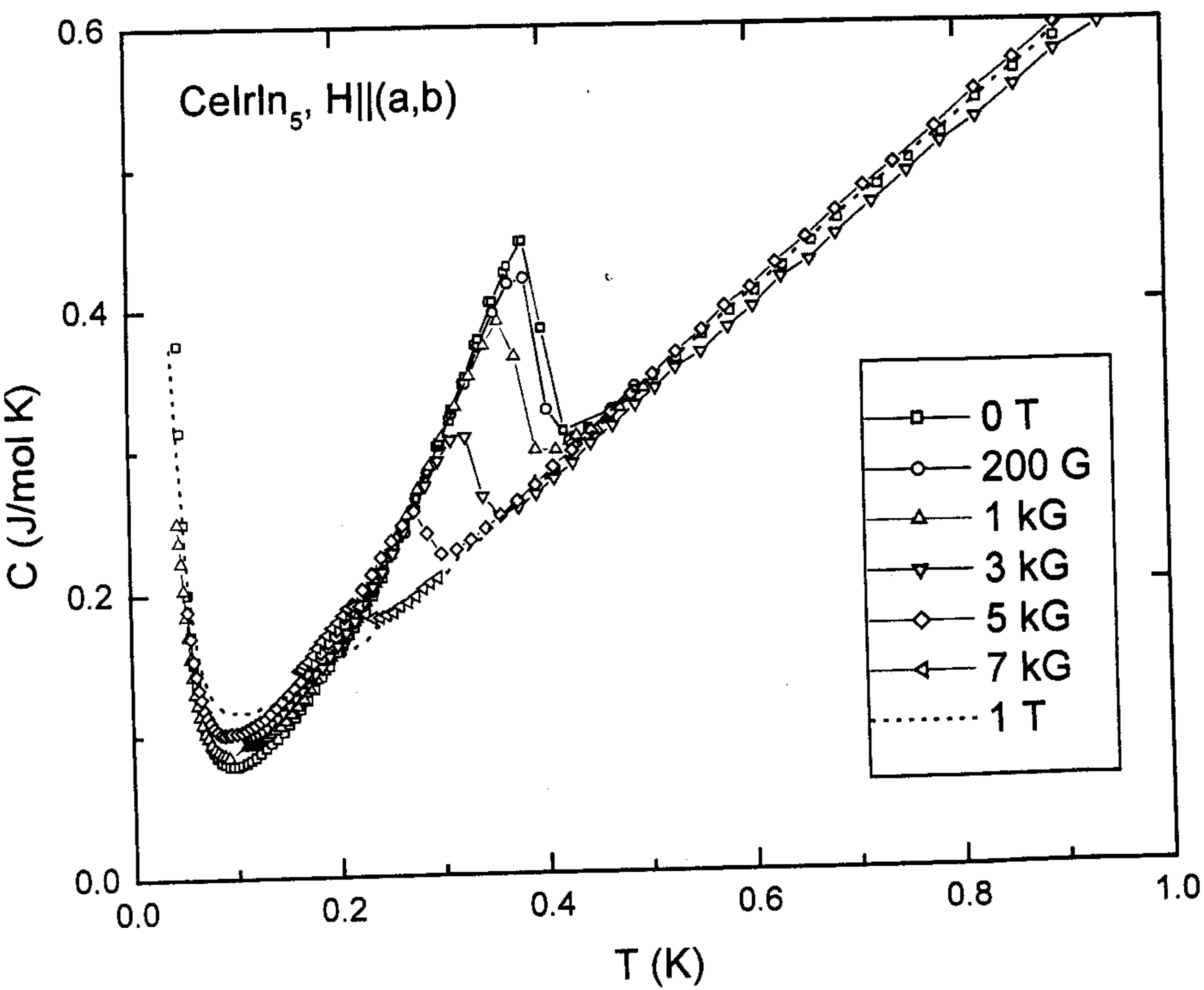
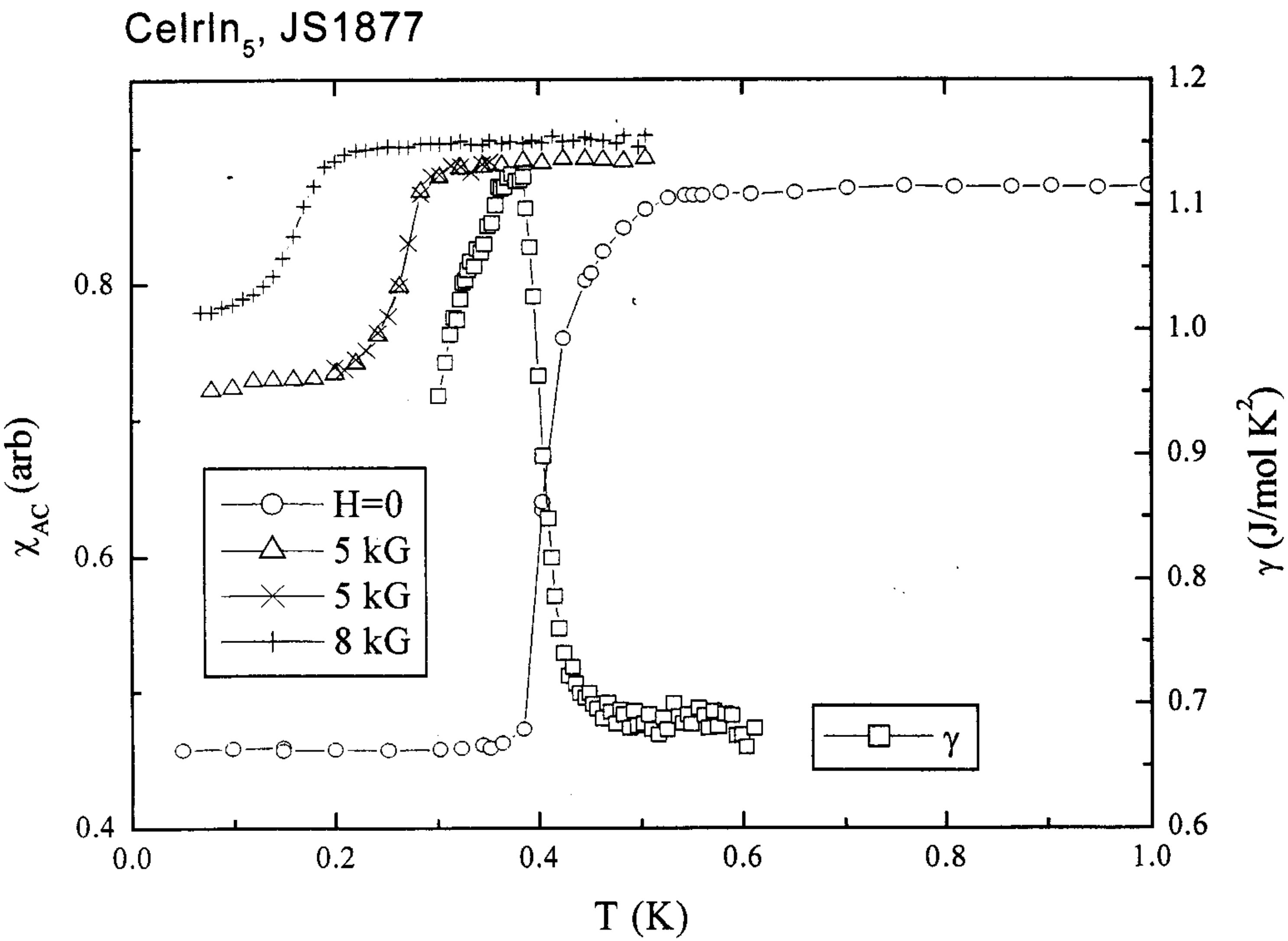
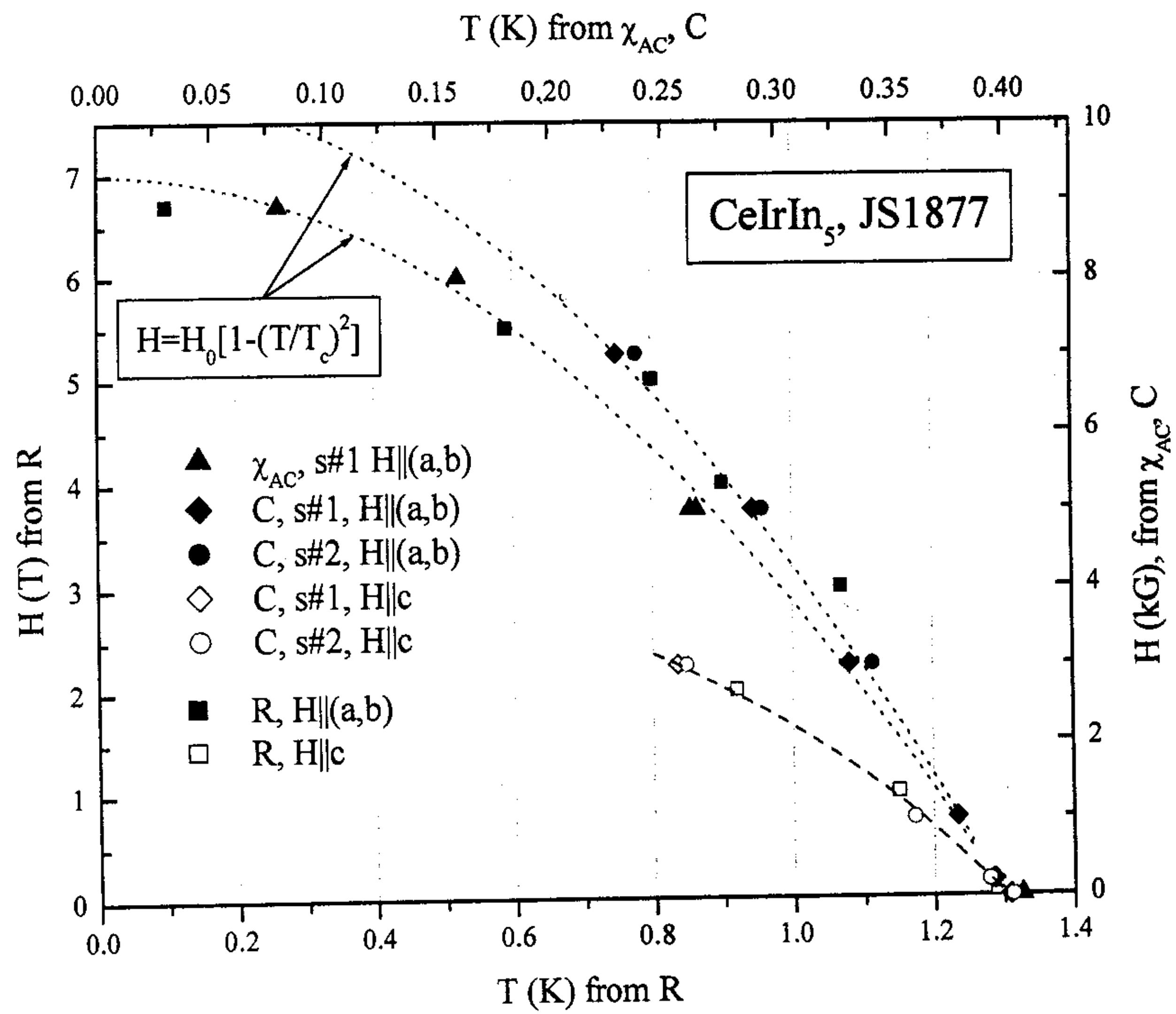


CeIrIn$_5$
χ_{ac}
C/T (J/mole K^2)
ρ (μΩ cm)
Temperature (K)
0.0
0.5
1.0
1.5
2.0
0.5
1.0
0
1
2
3

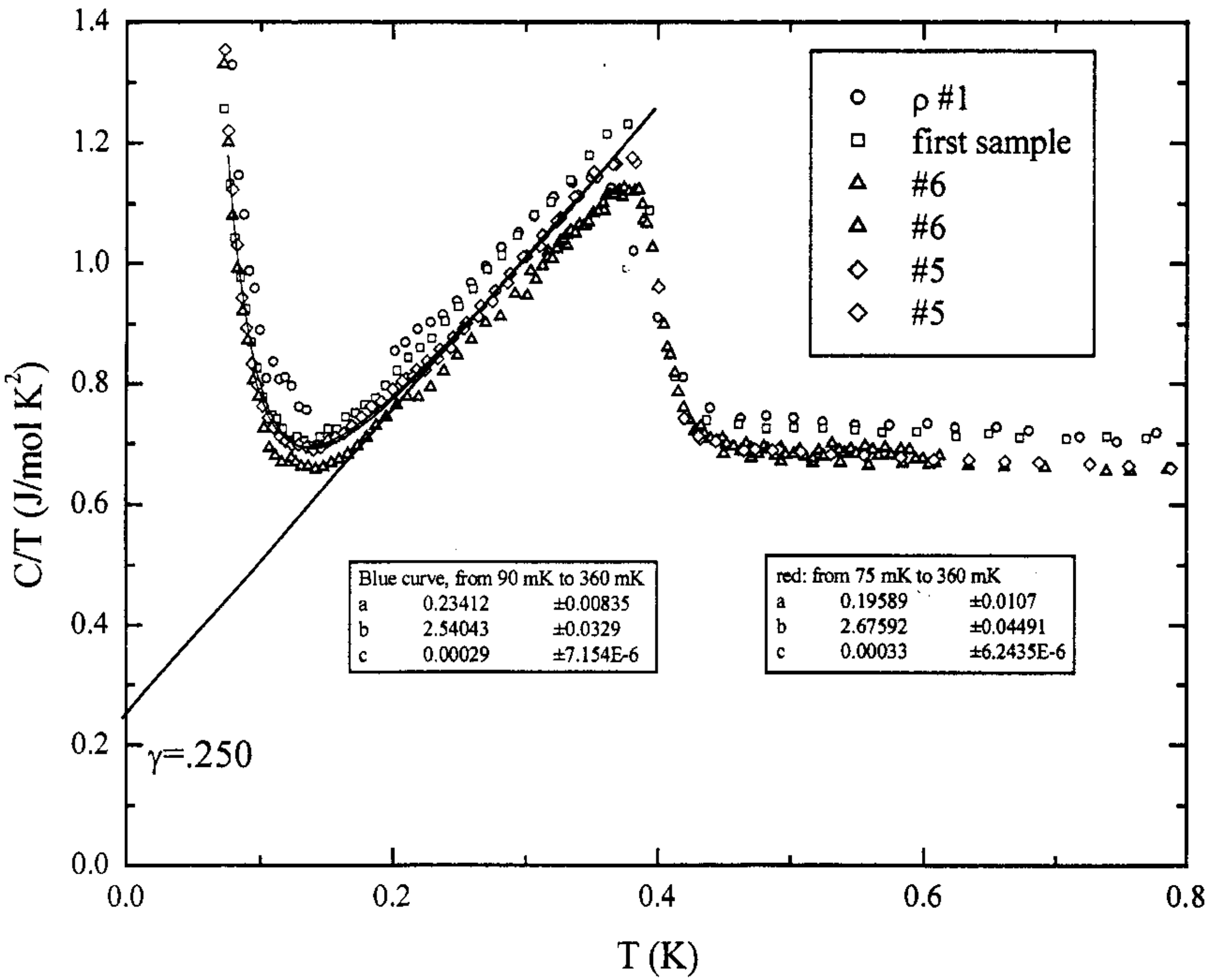
[redacted]


CeIrIn$_5$, H||(a,b)
C (J/mol K)
T (K)
0.0
0.2
0.4
0.6
0.8
1.0
0 T
200 G
1 kG
3 kG
5 kG
7 kG
1 T

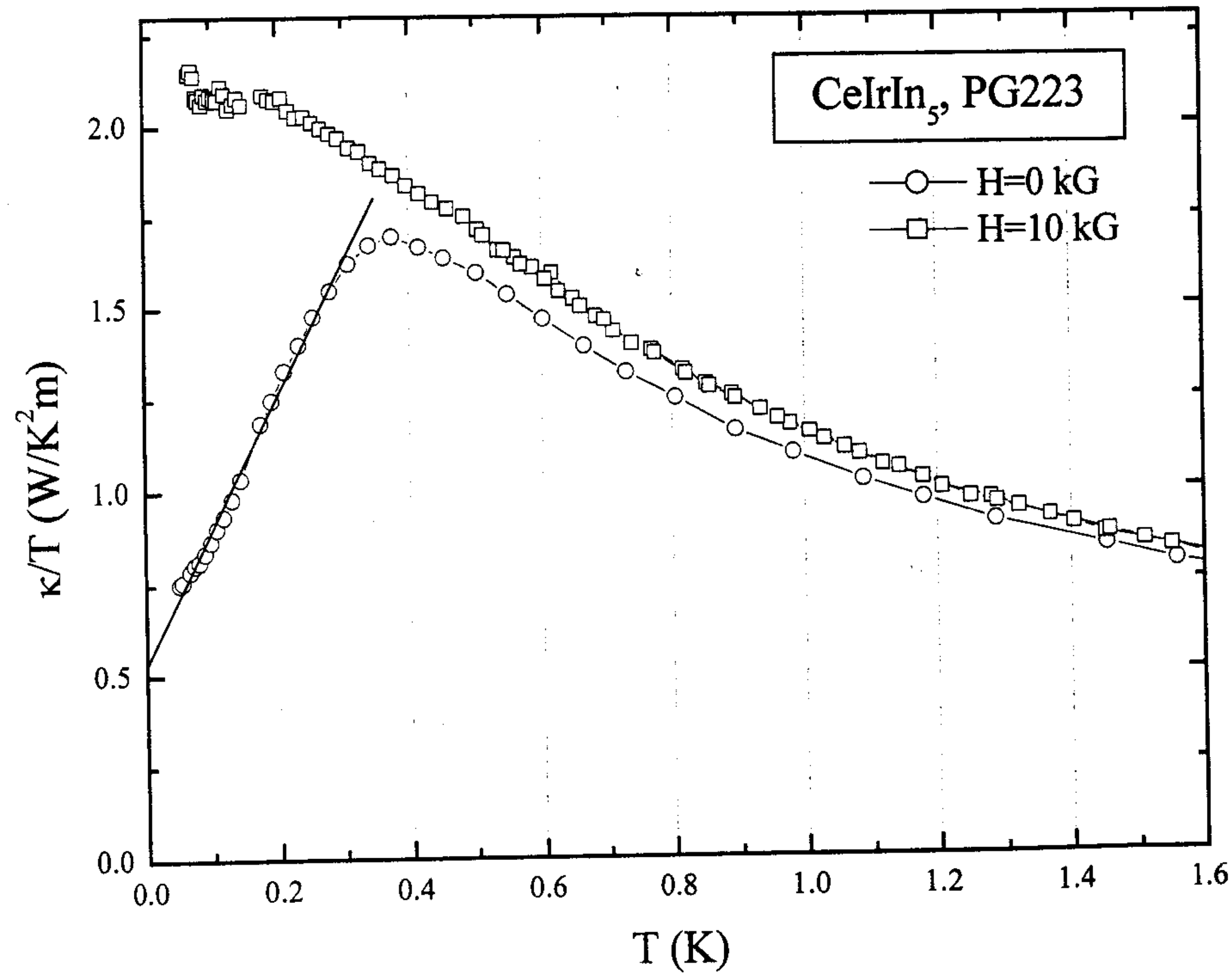

CeIrIn5, JS1877
H=0
5 kG
5 kG
8 kG
γ
χAC (arb)
γ (J/mol K2)
T (K)
0.0
0.2
0.4
0.6
0.8
1.0
0.4
0.6
0.8
0.6
0.7
0.8
0.9
1.0
1.1
1.2



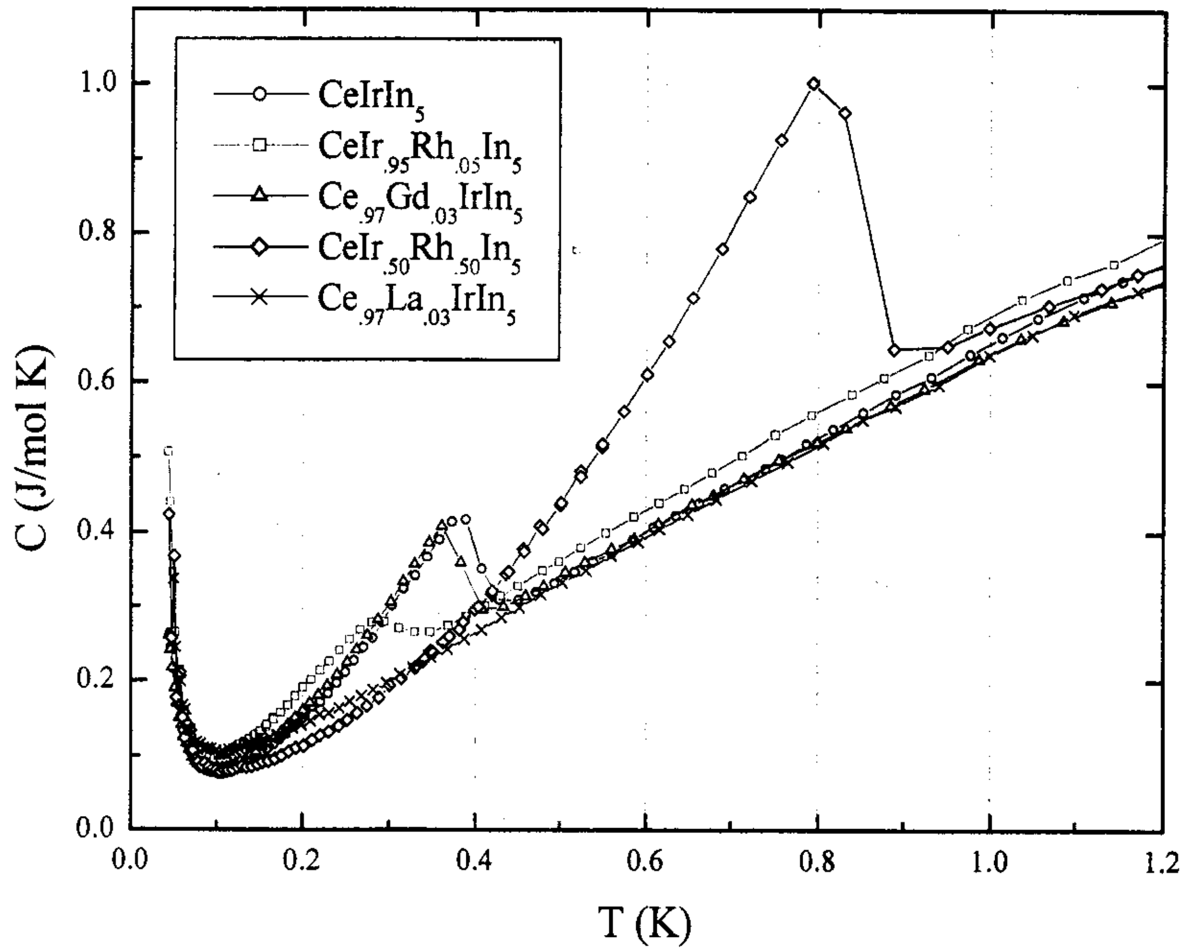
T (K) from χ_{AC}, C
0.00
0.05
0.10
0.15
0.20
0.25
0.30
0.35
0.40
H (T) from R
0
1
2
3
4
5
6
7
H (kG), from χ_{AC}, C
0
2
4
6
8
10
T (K) from R
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
$CeIrIn_5$, JS1877
$H=H_0[1-(T/T_c)^2]$
χ_{AC}, s#1 H||(a,b)
C, s#1, H||(a,b)
C, s#2, H||(a,b)
C, s#1, H||c
C, s#2, H||c
R, H||(a,b)
R, H||c



ρ #1
first sample
#6
#6
#5
#5
Blue curve, from 90 mK to 360 mK
a 0.23412 ±0.00835
b 2.54043 ±0.0329
c 0.00029 ±7.154E-6
red: from 75 mK to 360 mK
a 0.19589 ±0.0107
b 2.67592 ±0.04491
c 0.00033 ±6.2435E-6
γ=.250
C/T (J/mol K²)
T (K)


CeIrIn5, PG223
H=0 kG
H=10 kG
κ/T (W/K2m)
T (K)
0.0
0.5
1.0
1.5
2.0
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6

Doping studies of $CeIrIn_5$



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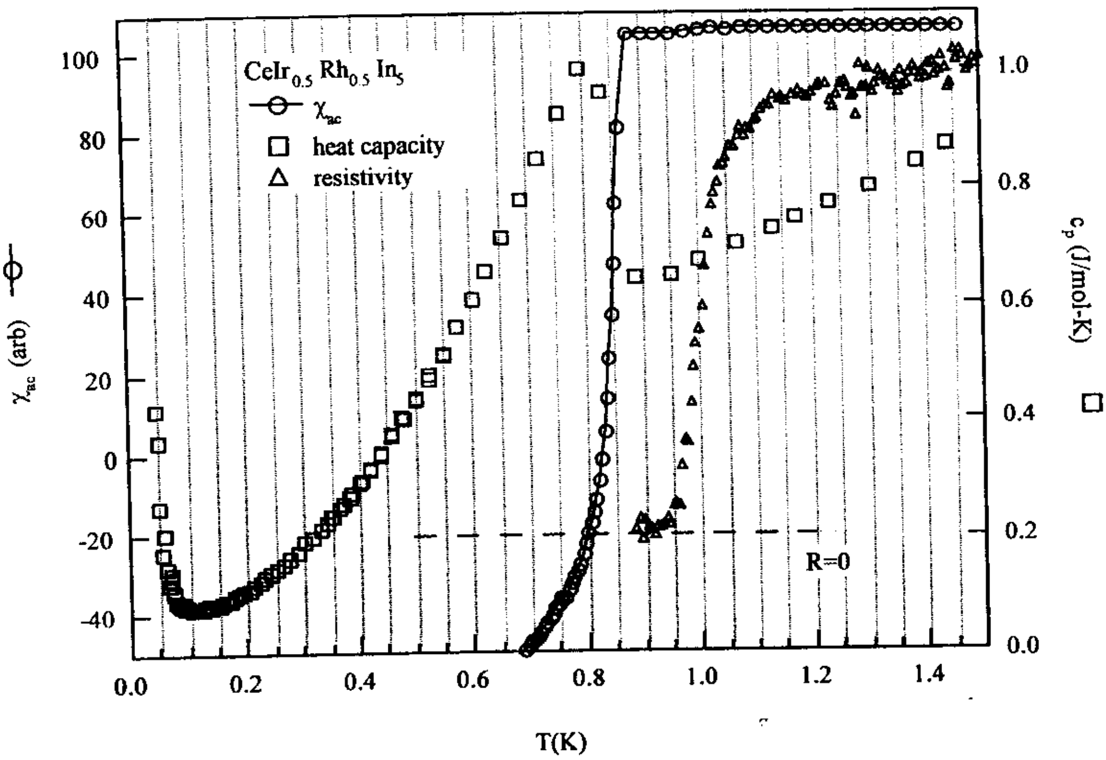
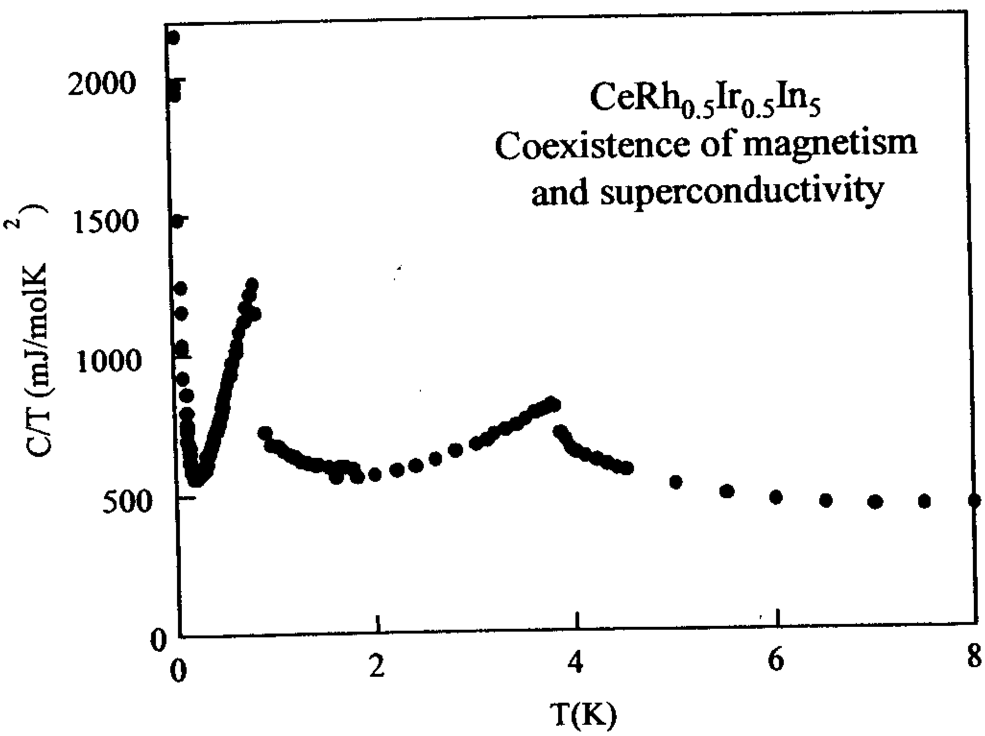
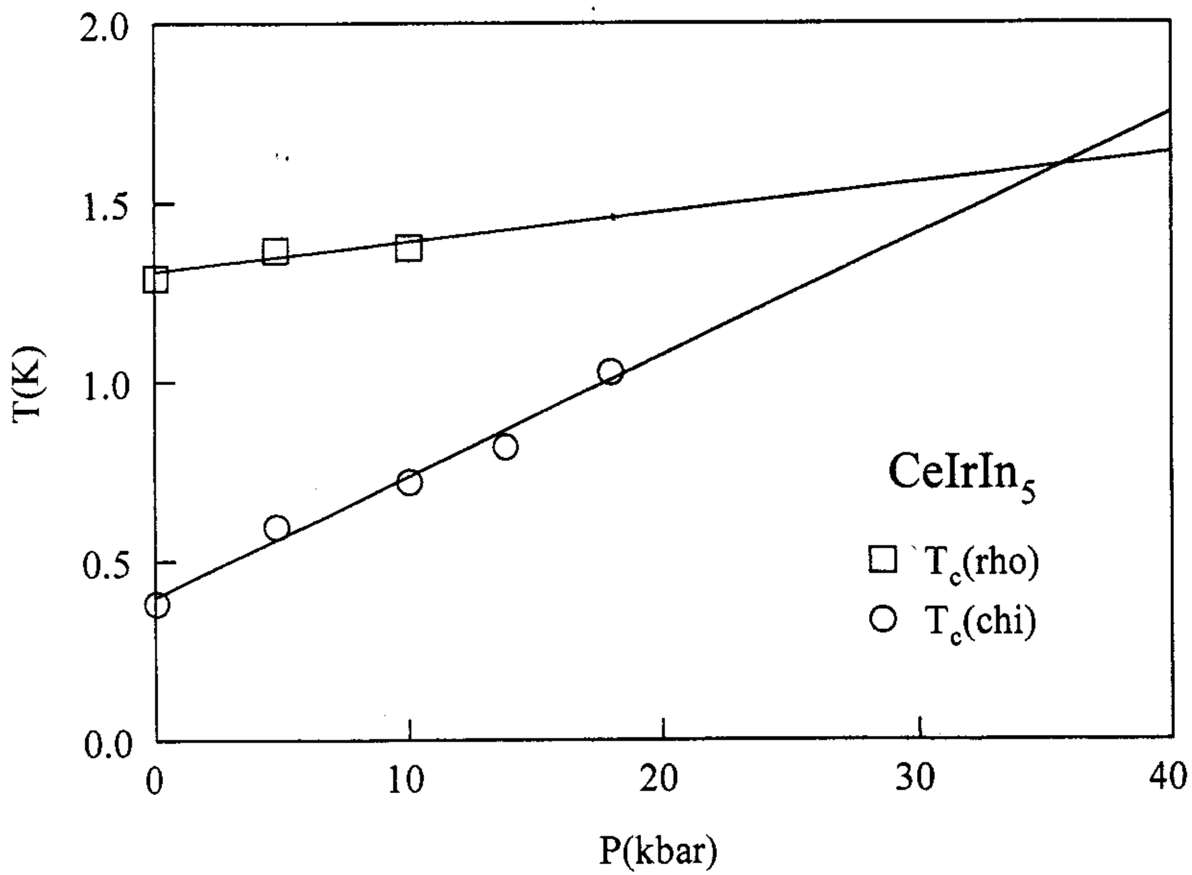
$CeRh_{0.5}Ir_{0.5}In_5$







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Scenarios for $CeIrIn_5$ 'separated' superconductivity

- Extrinsic effect
  Unlikely

- 2d-3d crossover
  But, estimated coherence length from $\partial H_{c2}/\partial T \sim 50$ Å

- 2-band superconductivity
  Why no diamagnetic signature?

- Intrinsic zero resistance without diamagnetism?

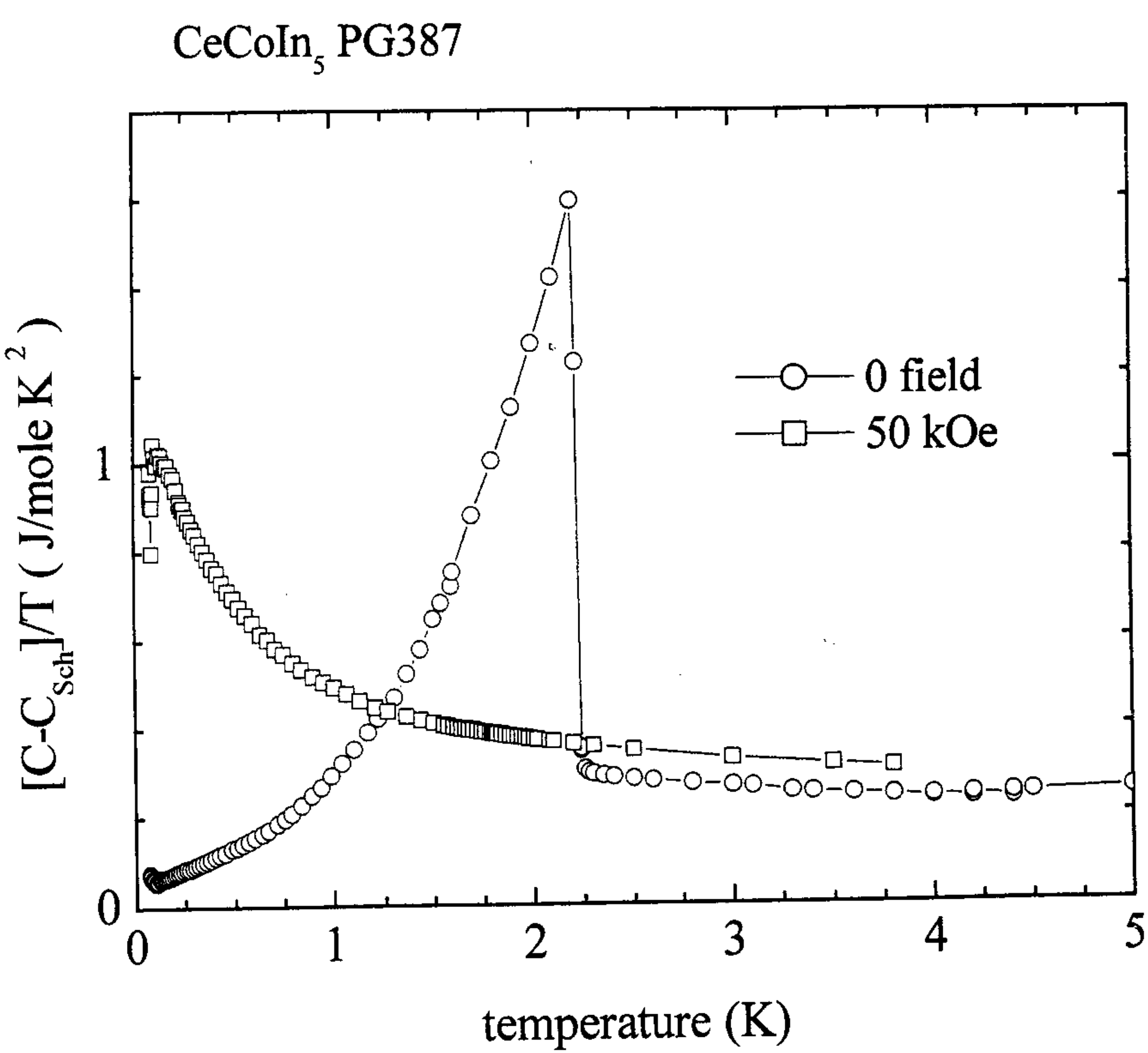
Measurements in Progress

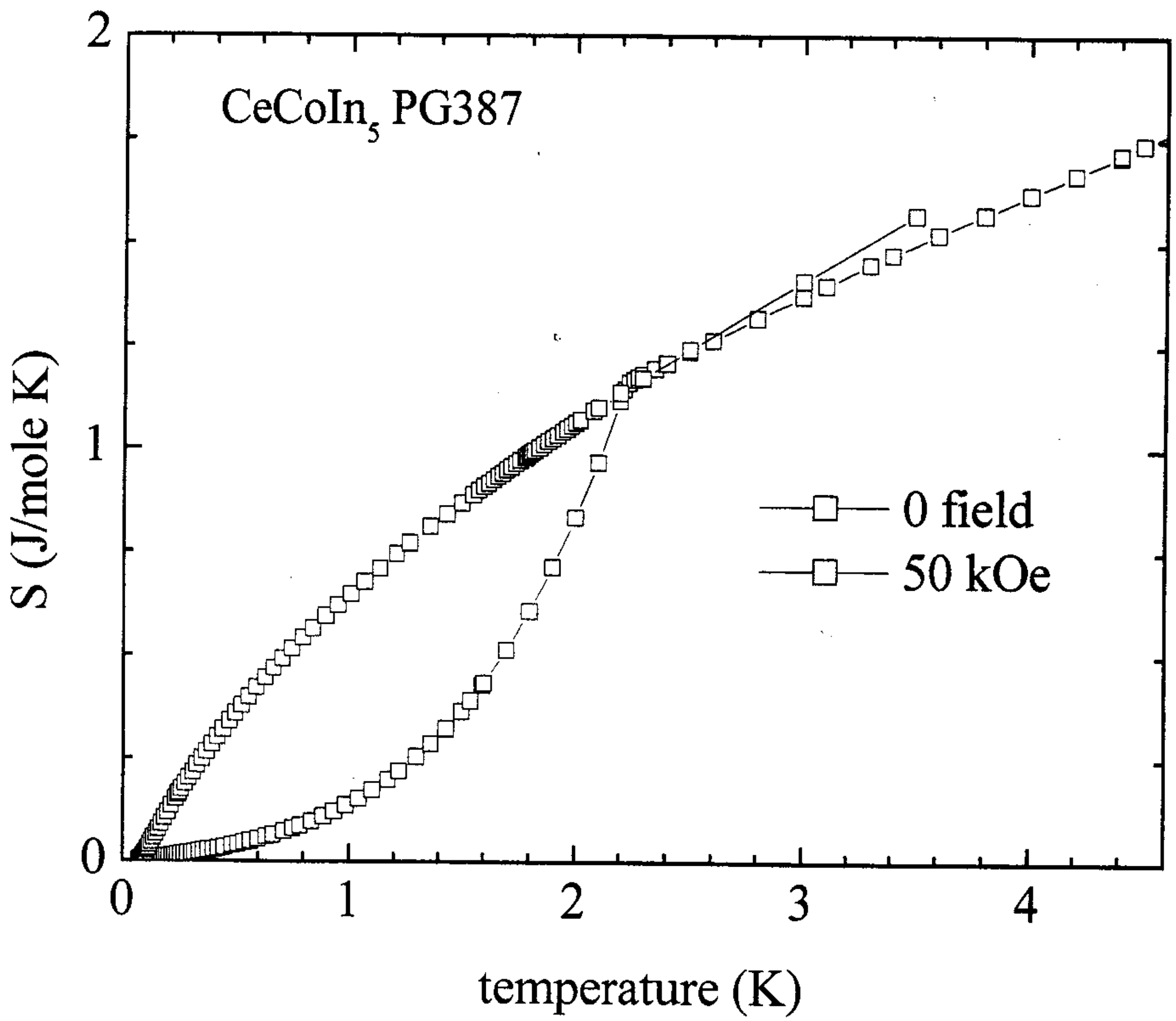
Response to pressure
Preliminary result: $\partial T_c(\chi)/\partial P > 0$; $\partial T_c(\rho)/\partial P = 0$

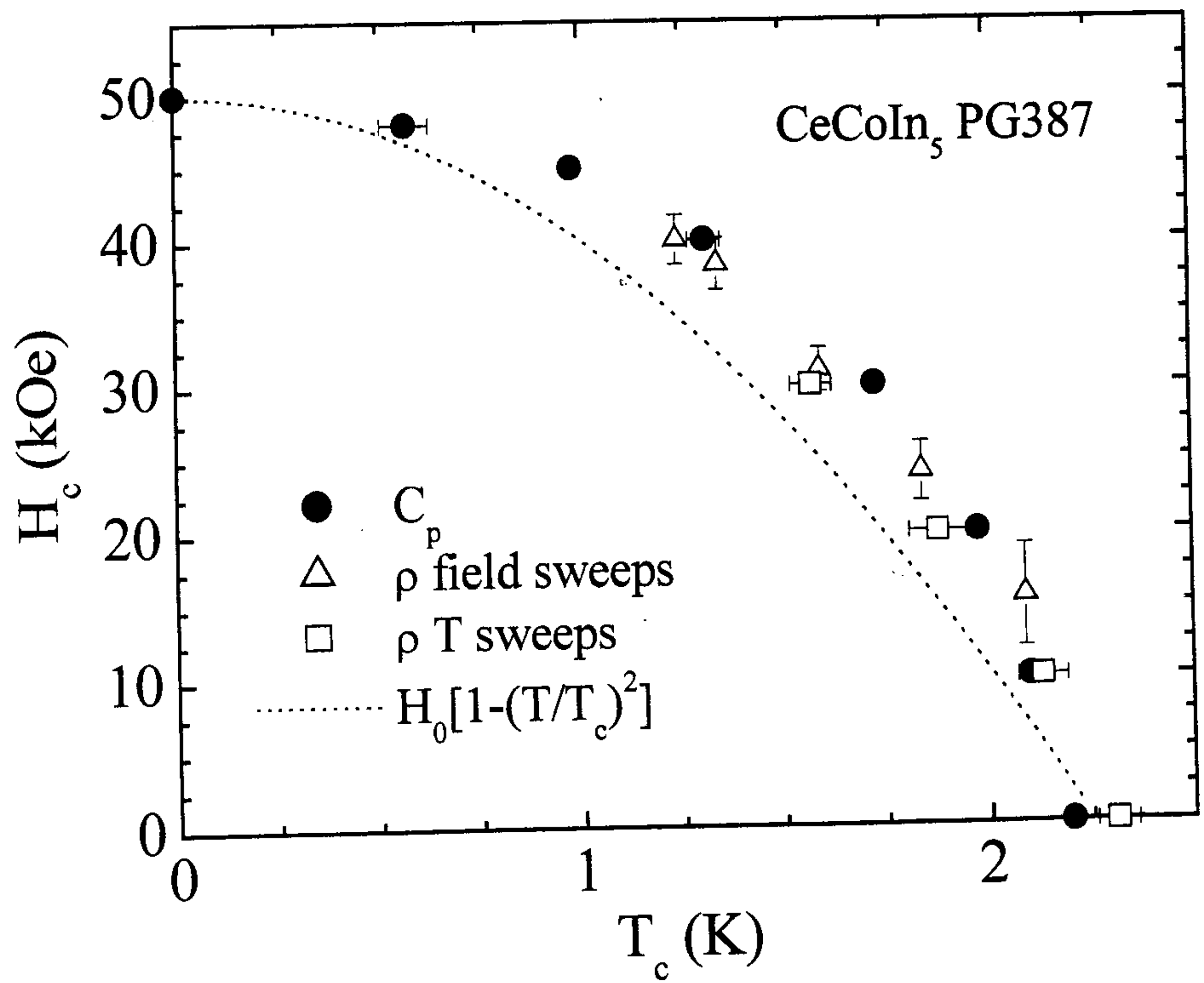
Response to doping
$CeIr_{1-x}Rh_xIn_5$: $T_c(CeIr_{0.5}Rh_{0.5}In_5) \sim 0.8$ K
Magnetic and non-magnetic dopants for Ce – in progress

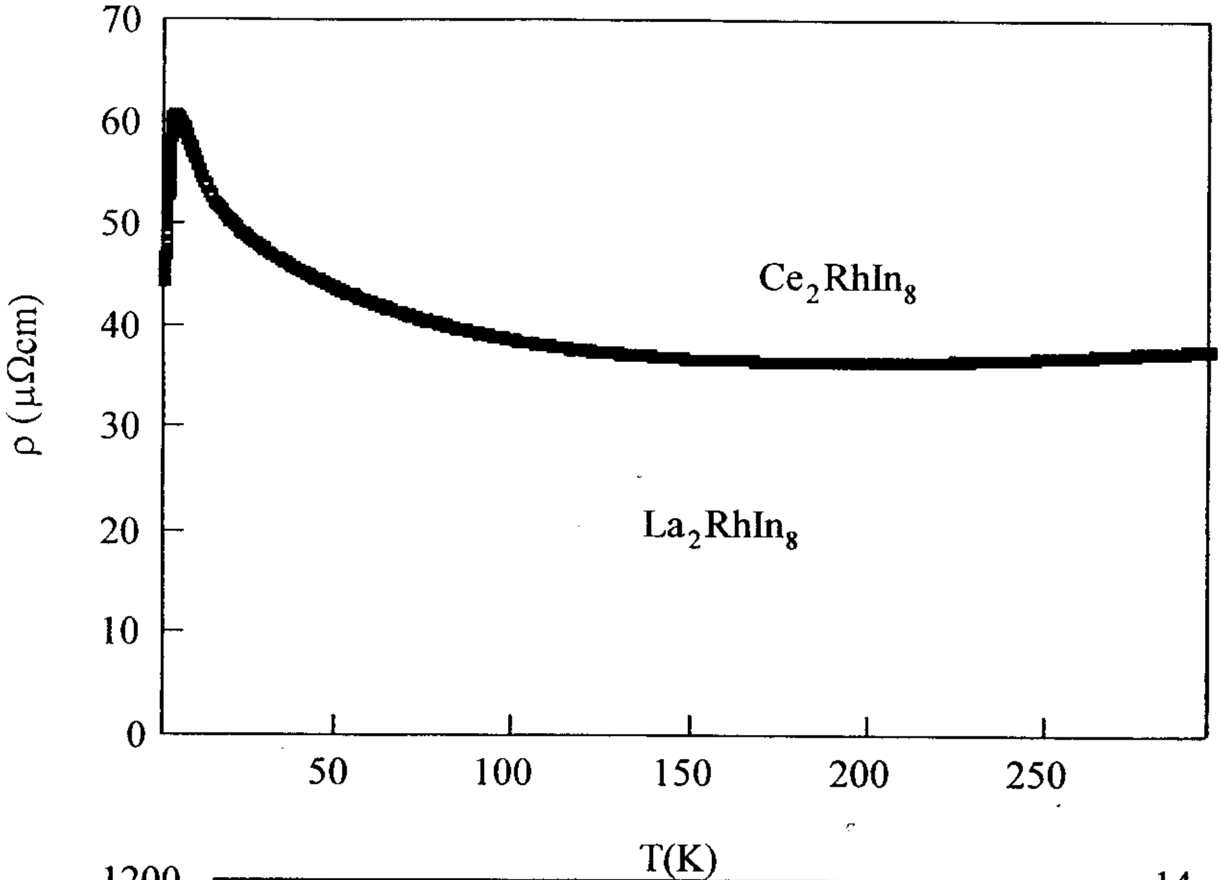
- $CeIrIn_5$ – ambient pressure heavy fermions superconductor with $T_c = 0.40$ K.
- $aT+bT^2$ temperature dependences of both specific heat and thermal conductivity indicate lines of nodes in the superconducting energy gap.
- Strong response (suppression of superconductivity) to non-magnetic La impurities

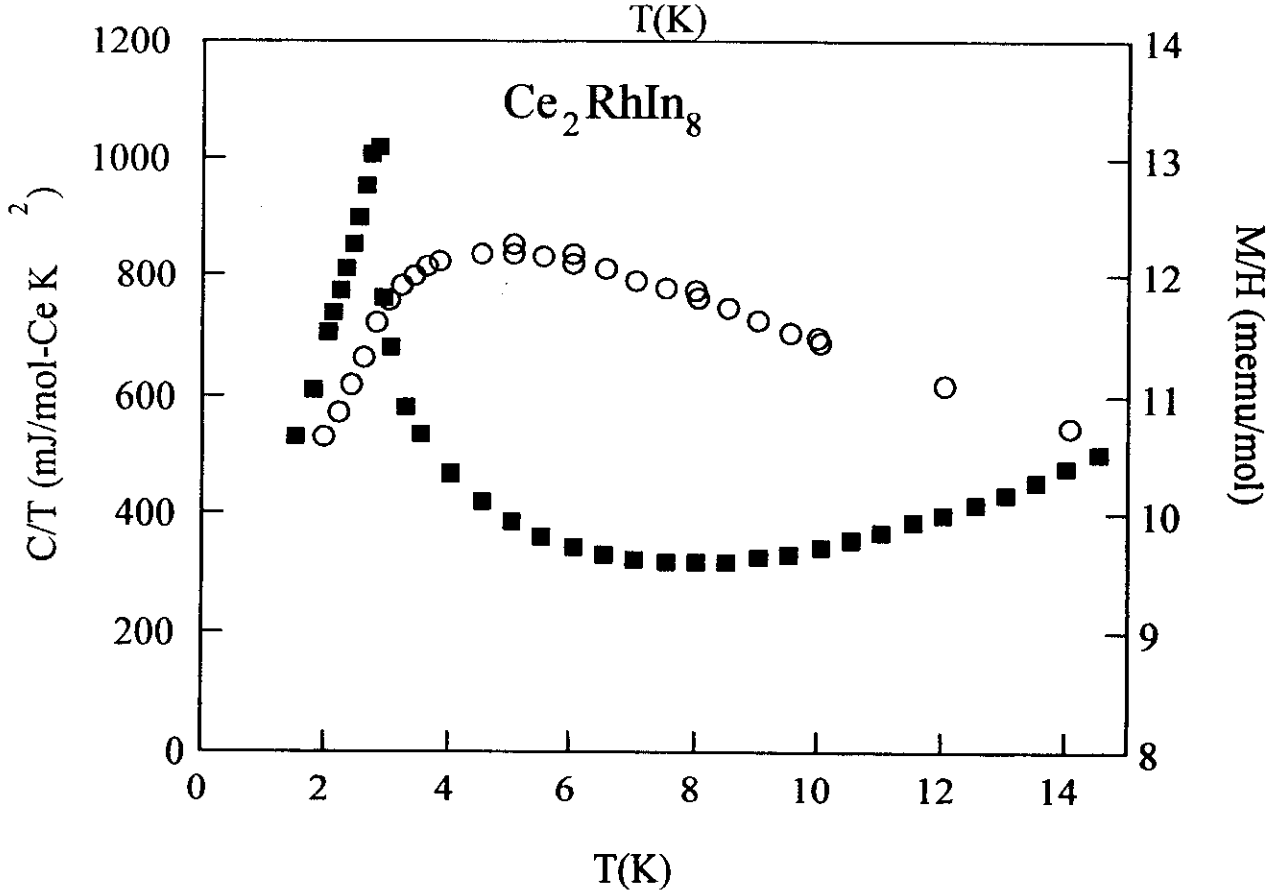
$CeIrIn_5$ – Unconventional HF superconductor

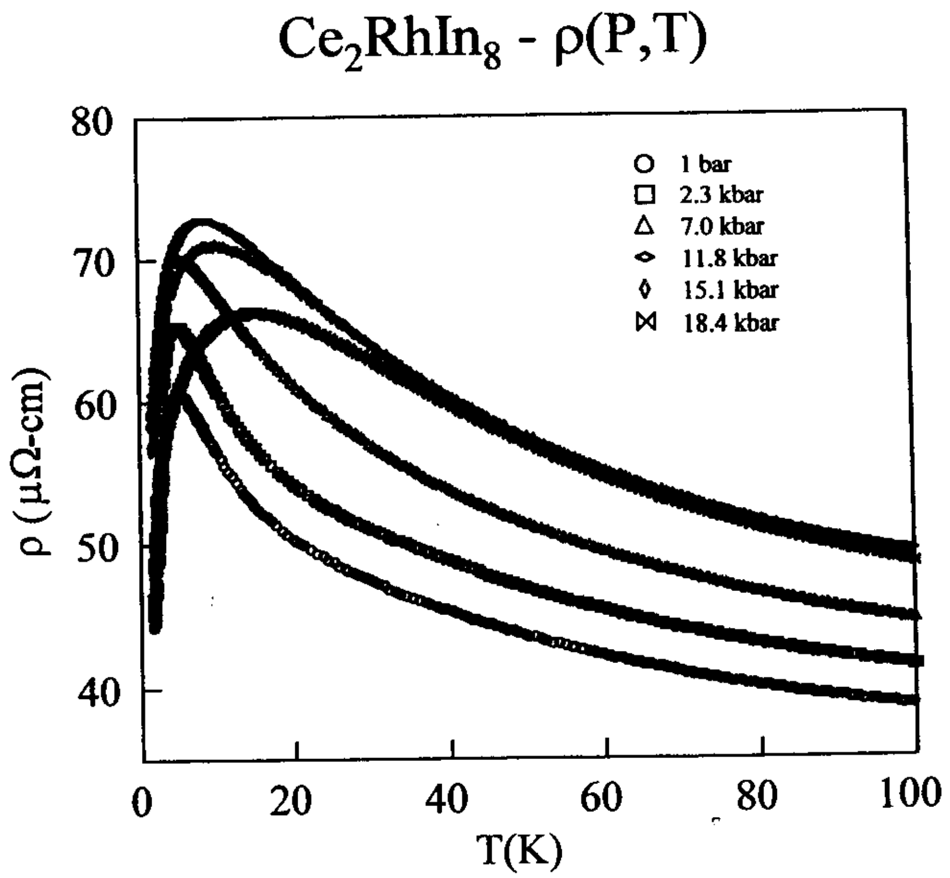

CeCoIn5 PG387
0 field
50 kOe
[C-CSch]/T (J/mole K 2)
0
1
0
1
2
3
4
5
temperature (K)


CeCoIn5 PG387
S (J/mole K)
temperature (K)
0 field
50 kOe
0
1
2
0
1
2
3
4

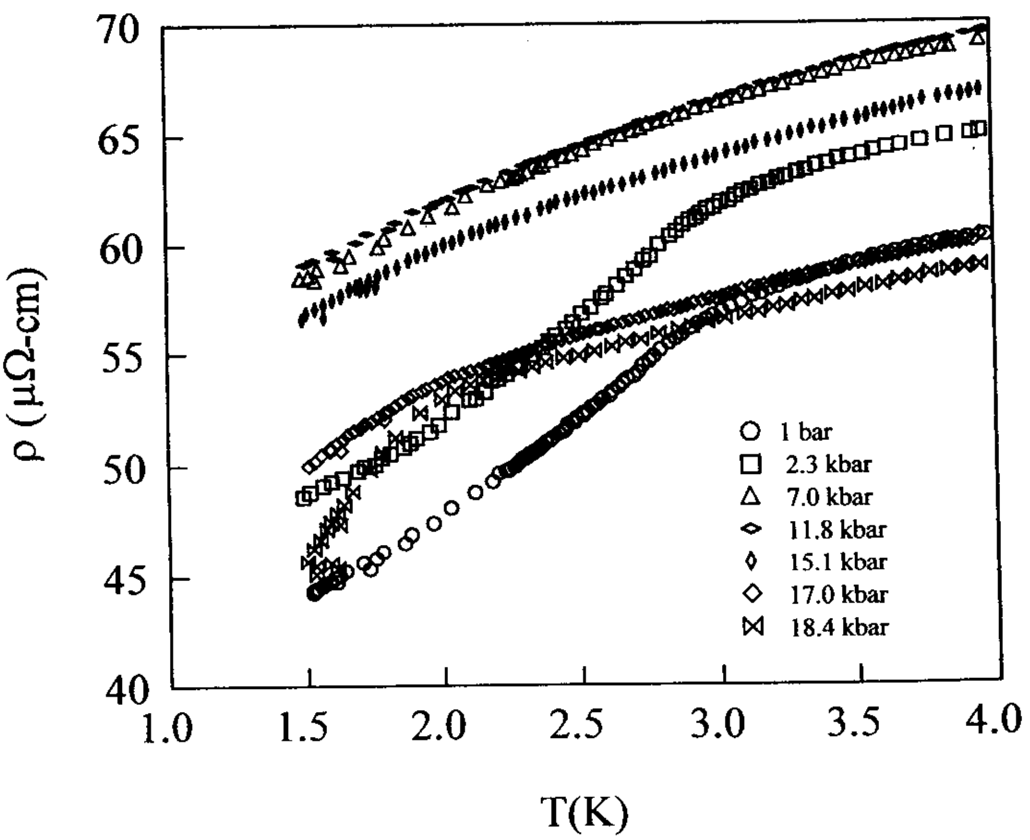

CeCoIn5 PG387
Cp
ρ field sweeps
ρ T sweeps
H0[1-(T/Tc)2]
Hc (kOe)
Tc (K)
50
40
30
20
10
0
0
1
2


70
60
50
40
30
20
10
0
ρ (μΩcm)
Ce$_2$RhIn$_8$
La$_2$RhIn$_8$
50
100
150
200
250
T(K)

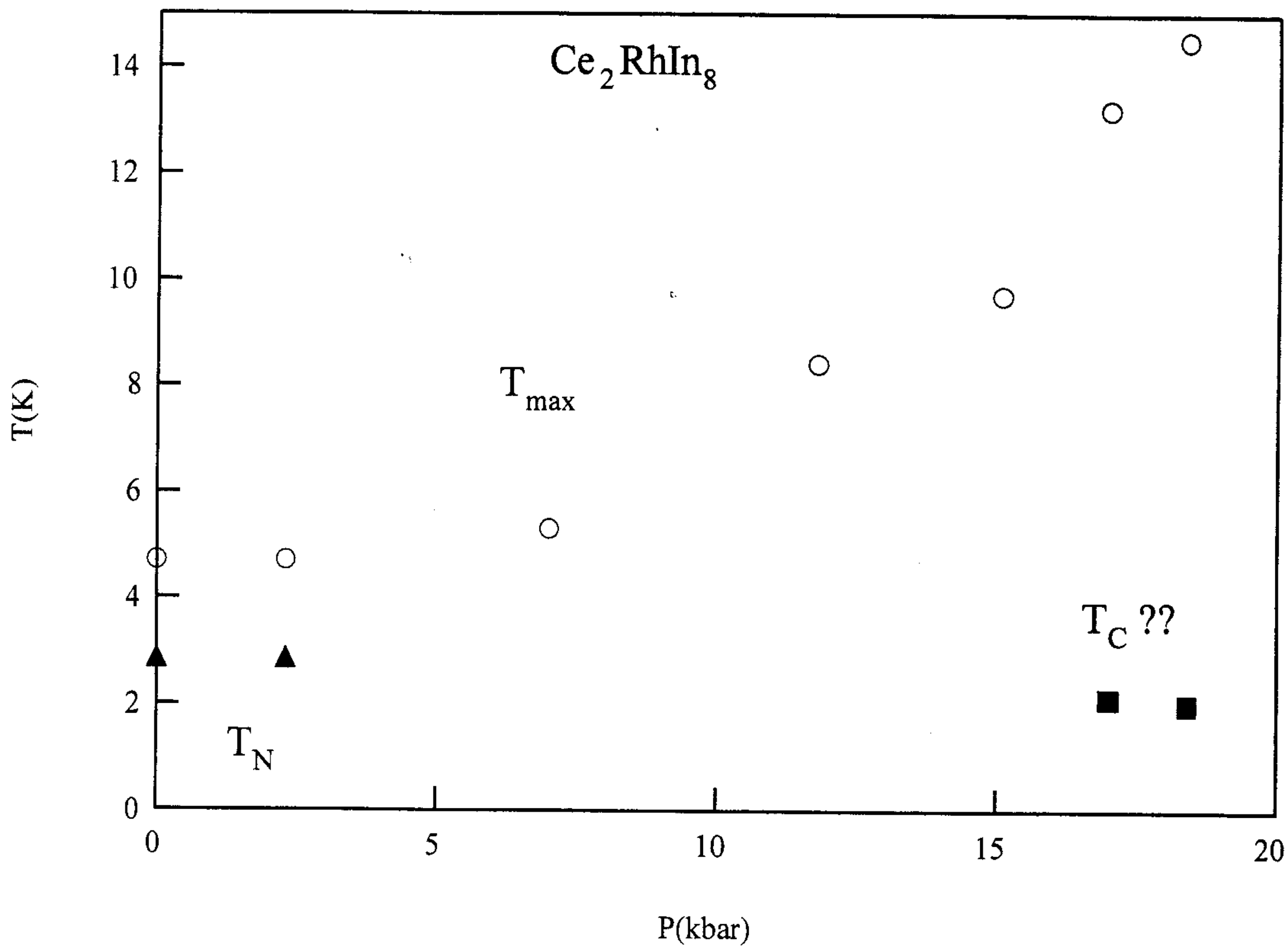

1200
1000
800
600
400
200
0
C/T (mJ/mol-Ce K^2)
Ce$_2$RhIn$_8$
14
13
12
11
10
9
8
M/H (memu/mol)
0
2
4
6
8
10
12
14
T(K)



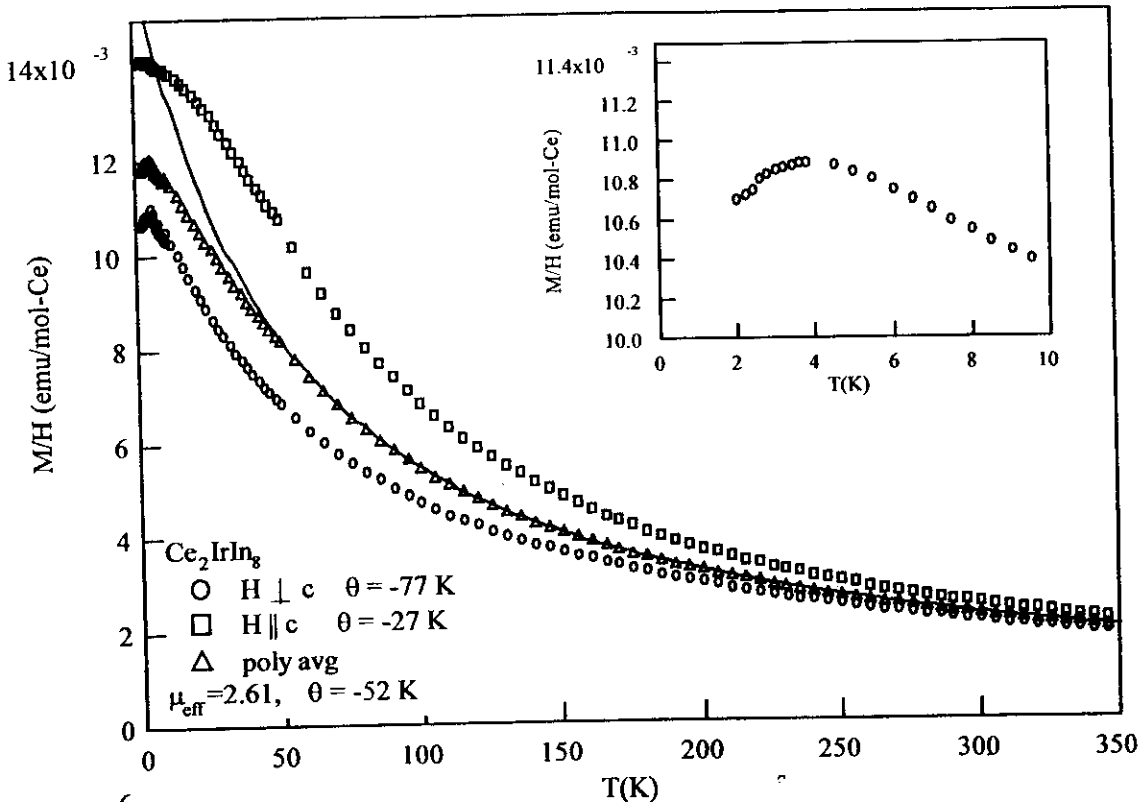
Ce_2RhIn_8 - ρ(P,T)
80
70
60
50
40
ρ (μΩ-cm)
0
20
40
60
80
100
T(K)
1 bar
2.3 kbar
7.0 kbar
11.8 kbar
15.1 kbar
18.4 kbar



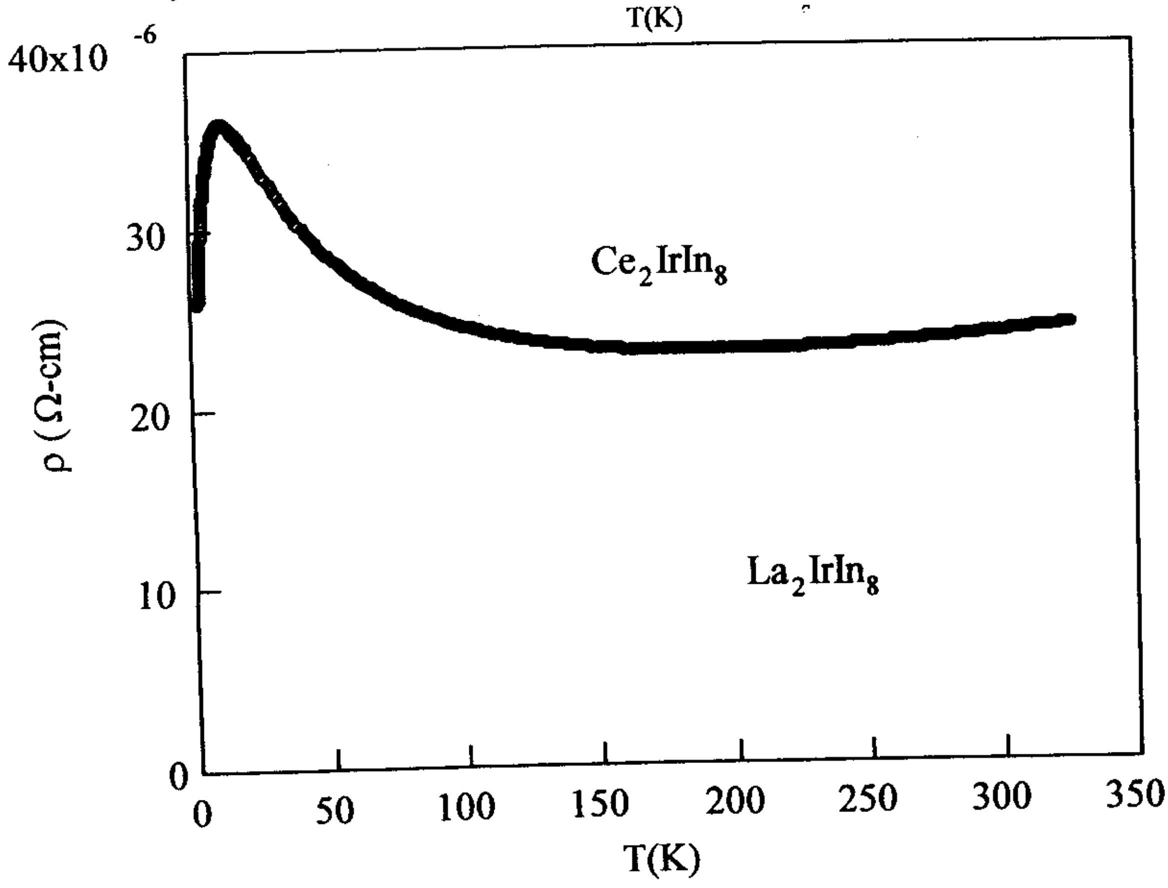
70
65
60
55
50
45
40
ρ (μΩ-cm)
1.0
1.5
2.0
2.5
3.0
3.5
4.0
T(K)
1 bar
2.3 kbar
7.0 kbar
11.8 kbar
15.1 kbar
17.0 kbar
18.4 kbar


Ce2RhIn8
Tmax
TN
TC ??
T(K)
P(kbar)
0
2
4
6
8
10
12
14
0
5
10
15
20

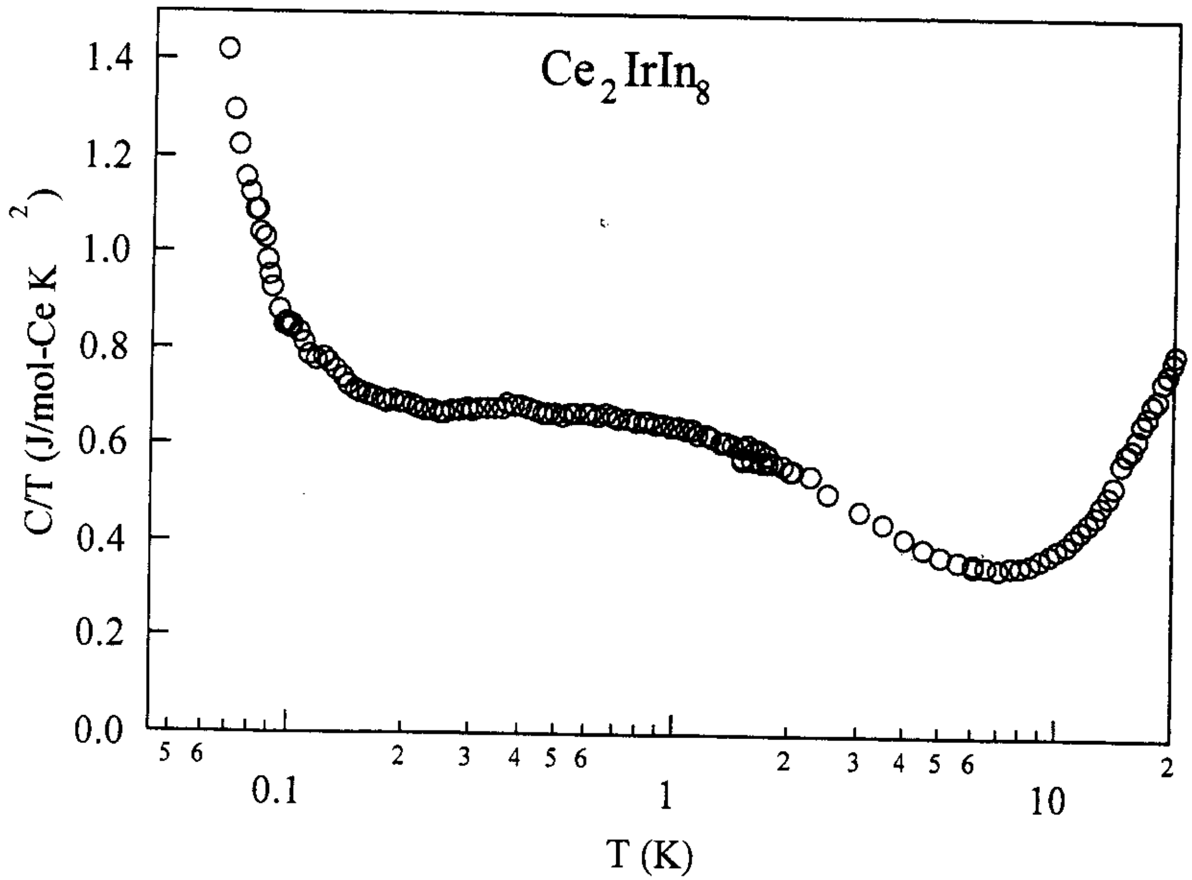
Ce$_2$IrIn$_8$



M/H (emu/mol-Ce)
T(K)
Ce2IrIn8
H ⊥ c θ = -77 K
H ∥ c θ = -27 K
poly avg
μeff=2.61, θ = -52 K



ρ (Ω-cm)
T(K)
Ce2IrIn8
La2IrIn8


Ce2IrIn8
C/T (J/mol-Ce K 2)
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
5 6
0.1
2 3 4 5 6
1
2 3 4 5 6
10
2
T (K)

Summary of $Ce_xM_yIn_{3x+2y}$ Properties

	T(ρ=max)	T(χ=max)	γ/Ce	T_N	p_c	T_c
$CeRhIn_5$	53 K	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Ce_2RhIn_8	4.8	4.5	300	2.8	17 (?)	2.0 (?)
$CeIrIn_5$	53	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Ce_2IrIn_8	11	3.7	700	--	--	--
$CeCoIn_5$			300-1000			2.3