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INTERNATIONAL CENTRE FOR THEORETICAL PHYSICS
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H4.SMR/1001-3

IX TRIESTE WORKSHOP ON
OPEN PROBLEMS IN
STRONGLY CORRELATED SYSTEMS

14 - 25 July 1997

RECENT DEVELOPMENT OF SUPERCONDUCTIVITY IN LADDER MATERIALS

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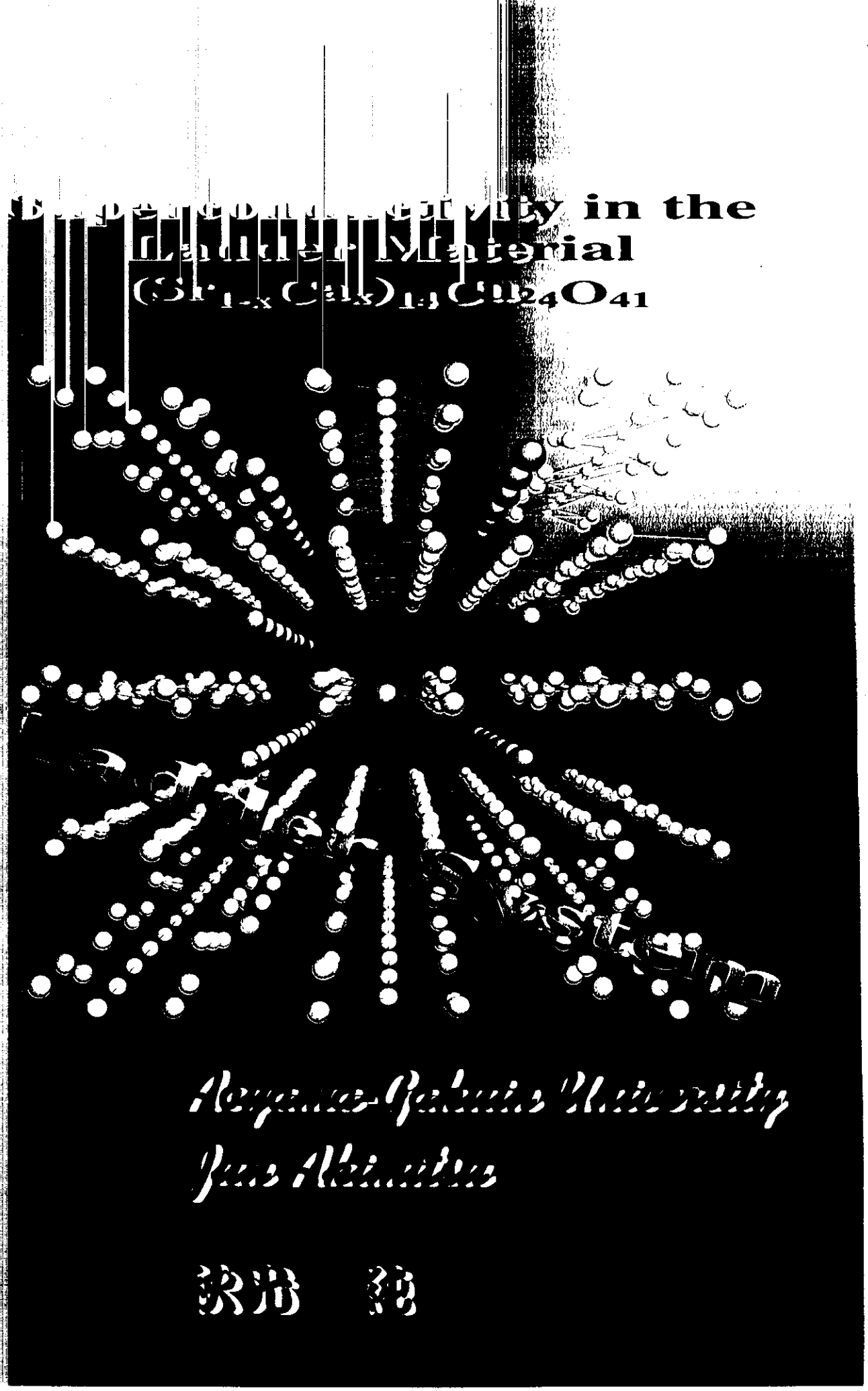
These are preliminary lecture notes, intended only for distribution to participants.

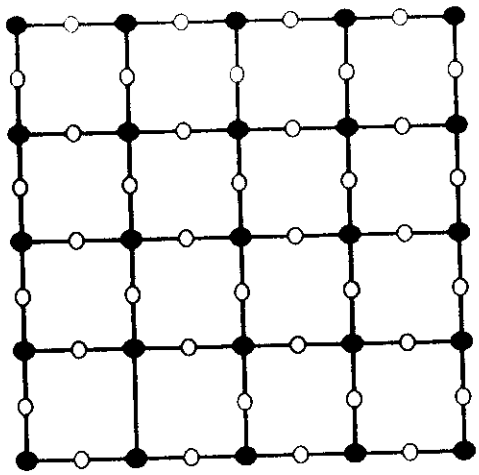
Superconductivity in the Ladder Material $(Sr_{1-x}Ca_x)_{14}Cu_{24}O_{41}$



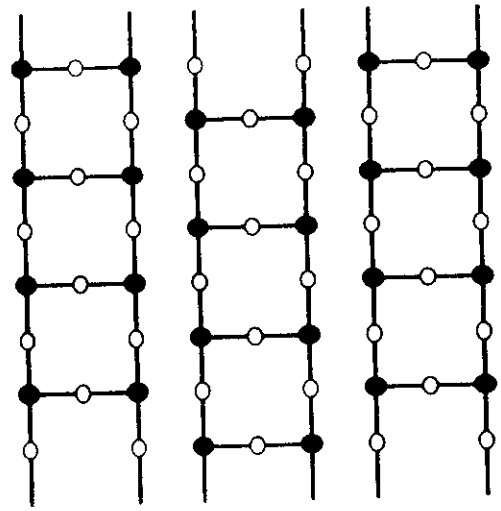
Aoyama Gakuin University
Jun Akimitsu

ISIS '99

CuO_2 planes are unique candidate for high-Tc superconductivity ?



CuO_2 plane

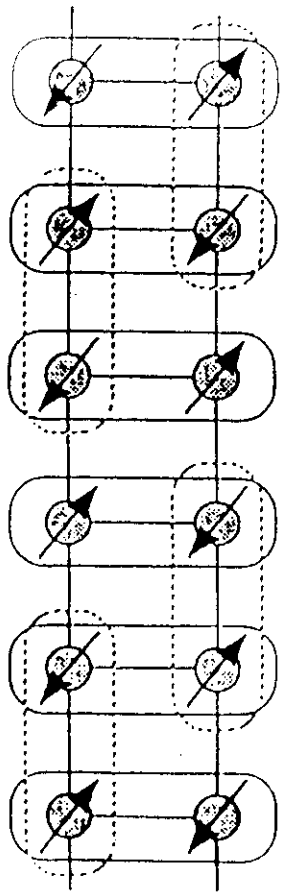


two-leg ladder

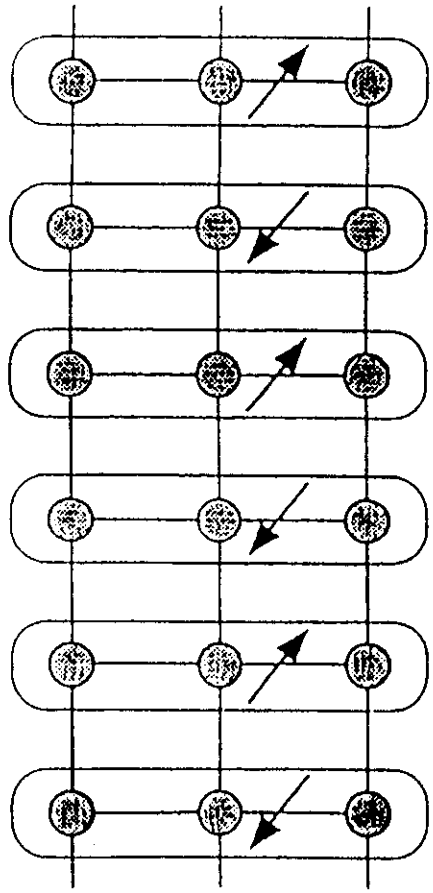
Theoretical Predictions

1) Ladders with even legs have a spin liquid state.

2) When lightly doped with holes the spin gap will remain and singlet superconductivity should occur.

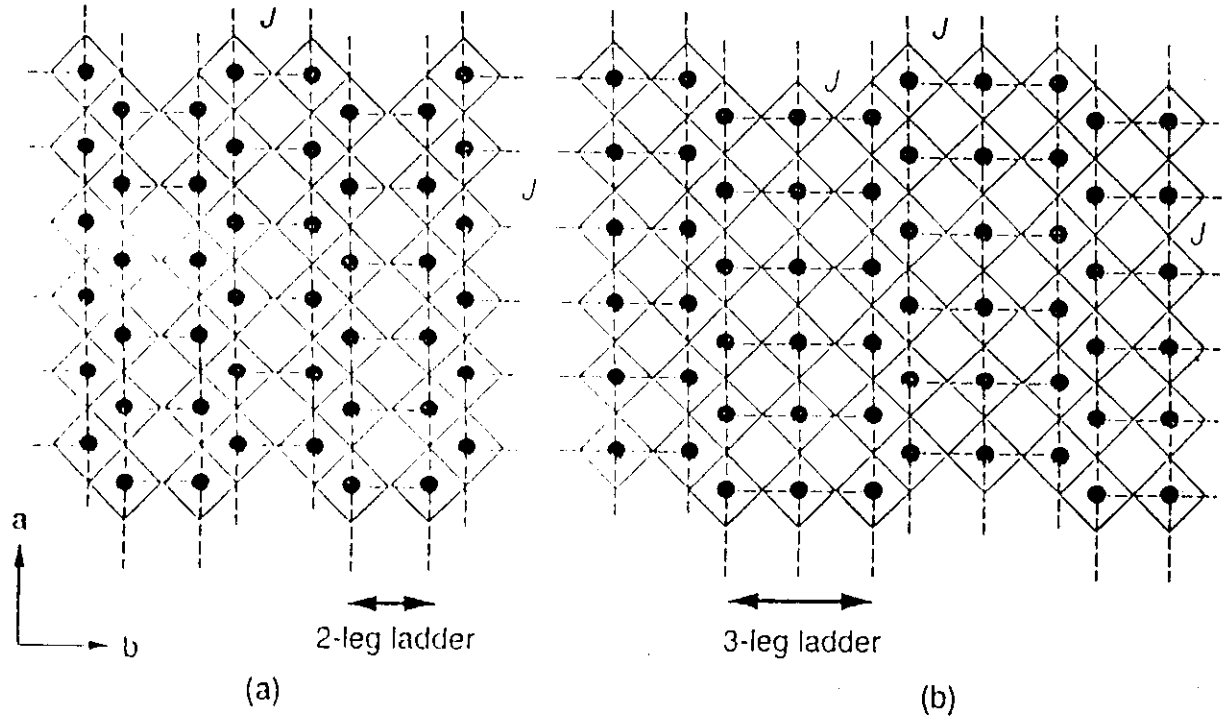


2-leg ladder

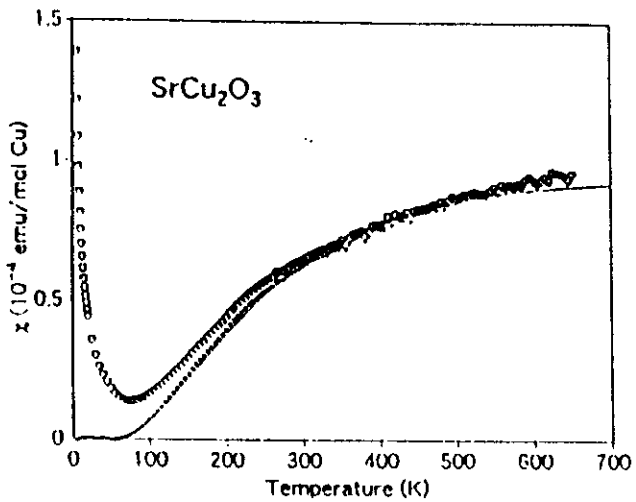


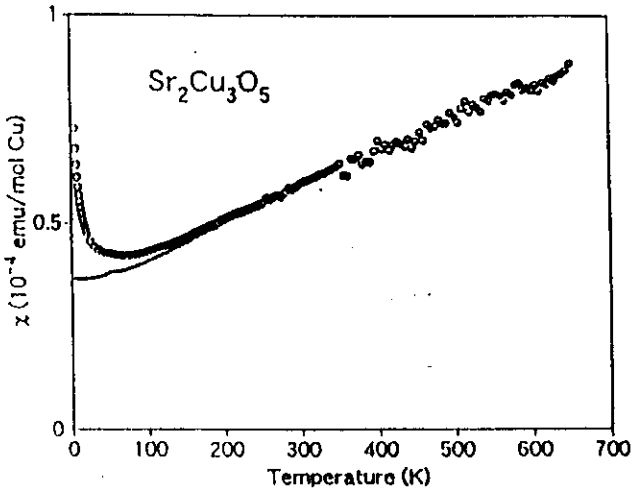
3-leg ladder

M. Ogata

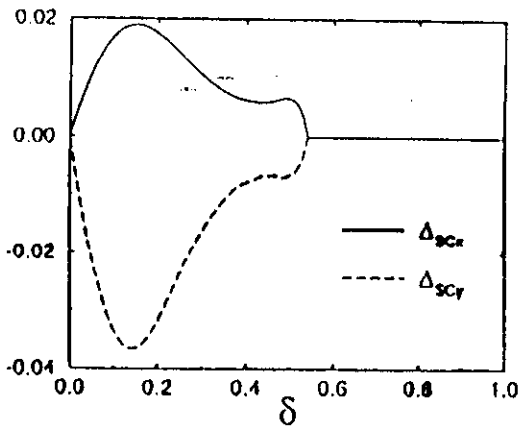


(a) (b)



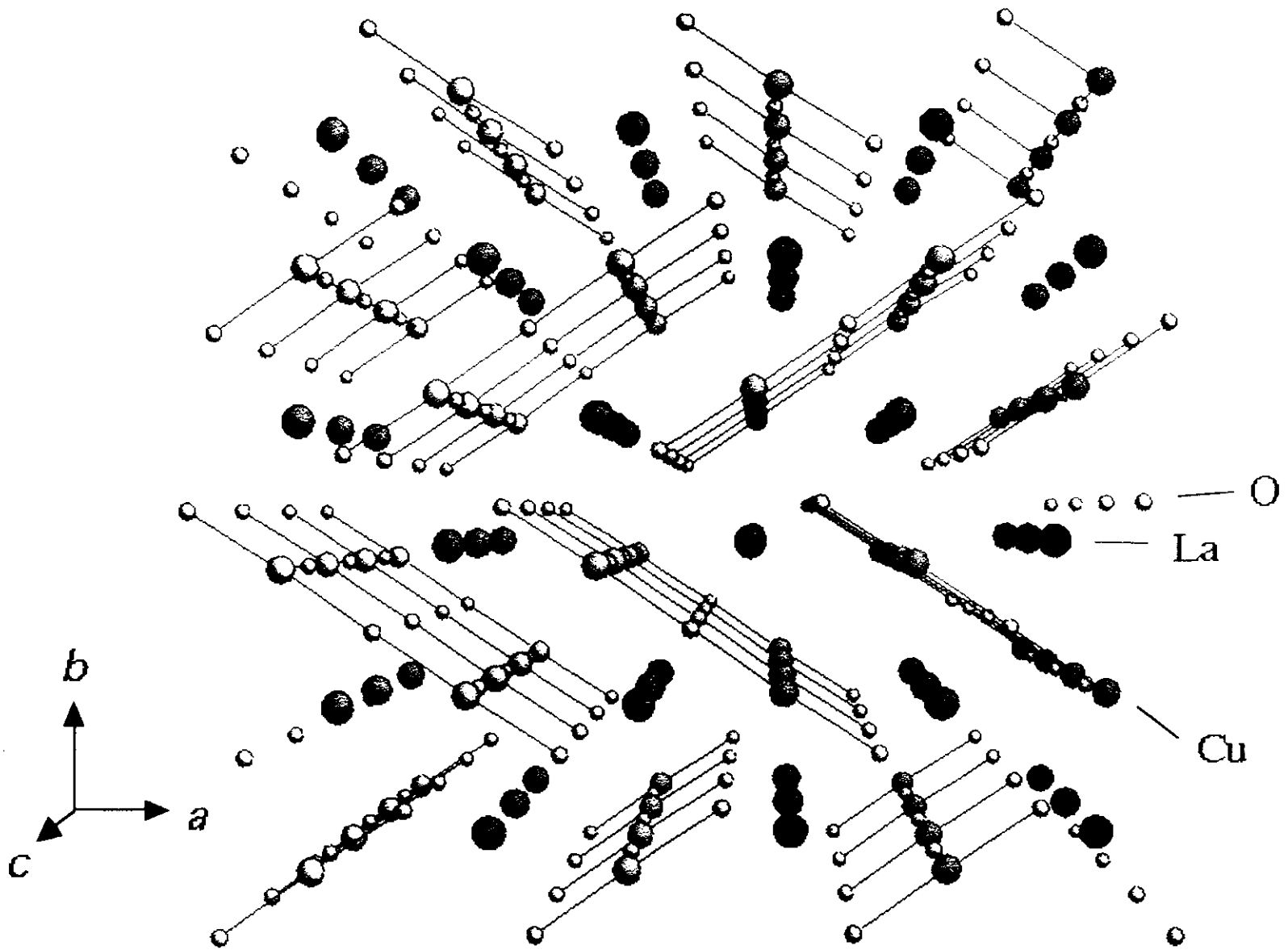


Azuma et al.

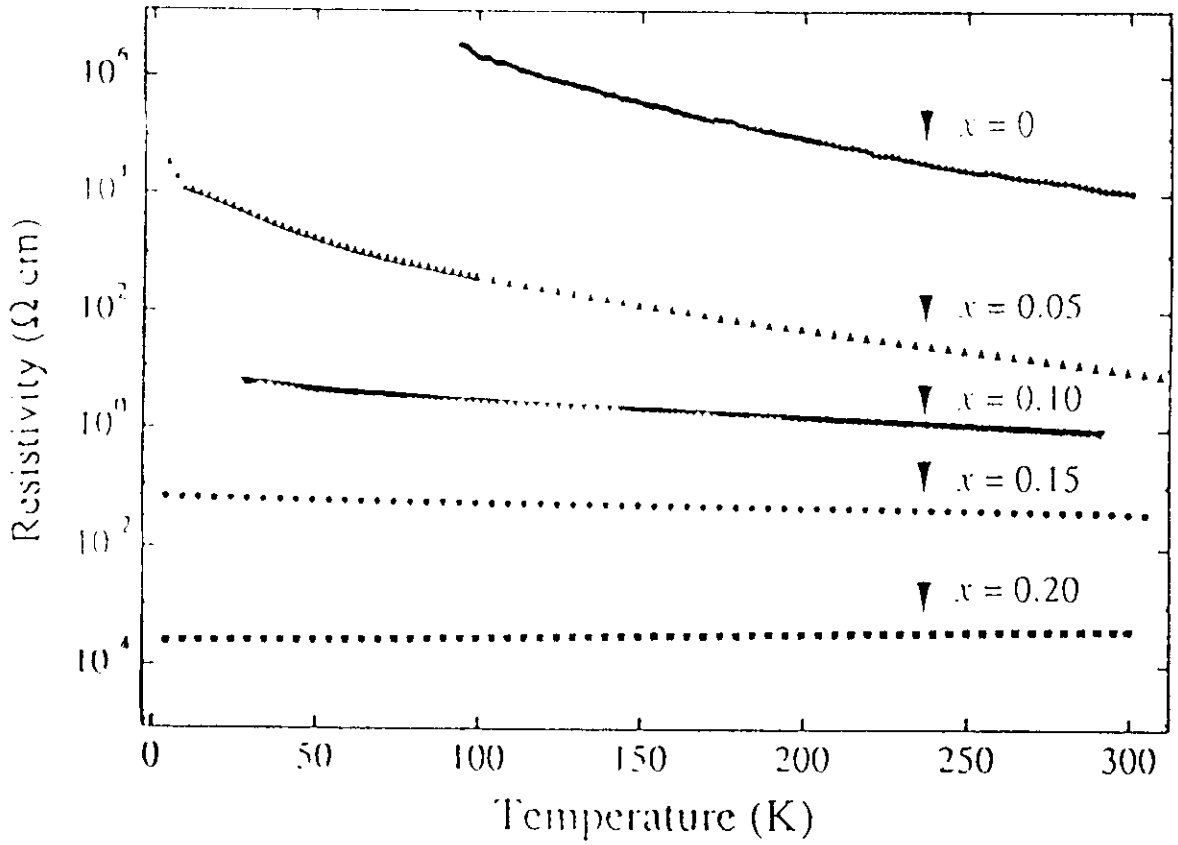


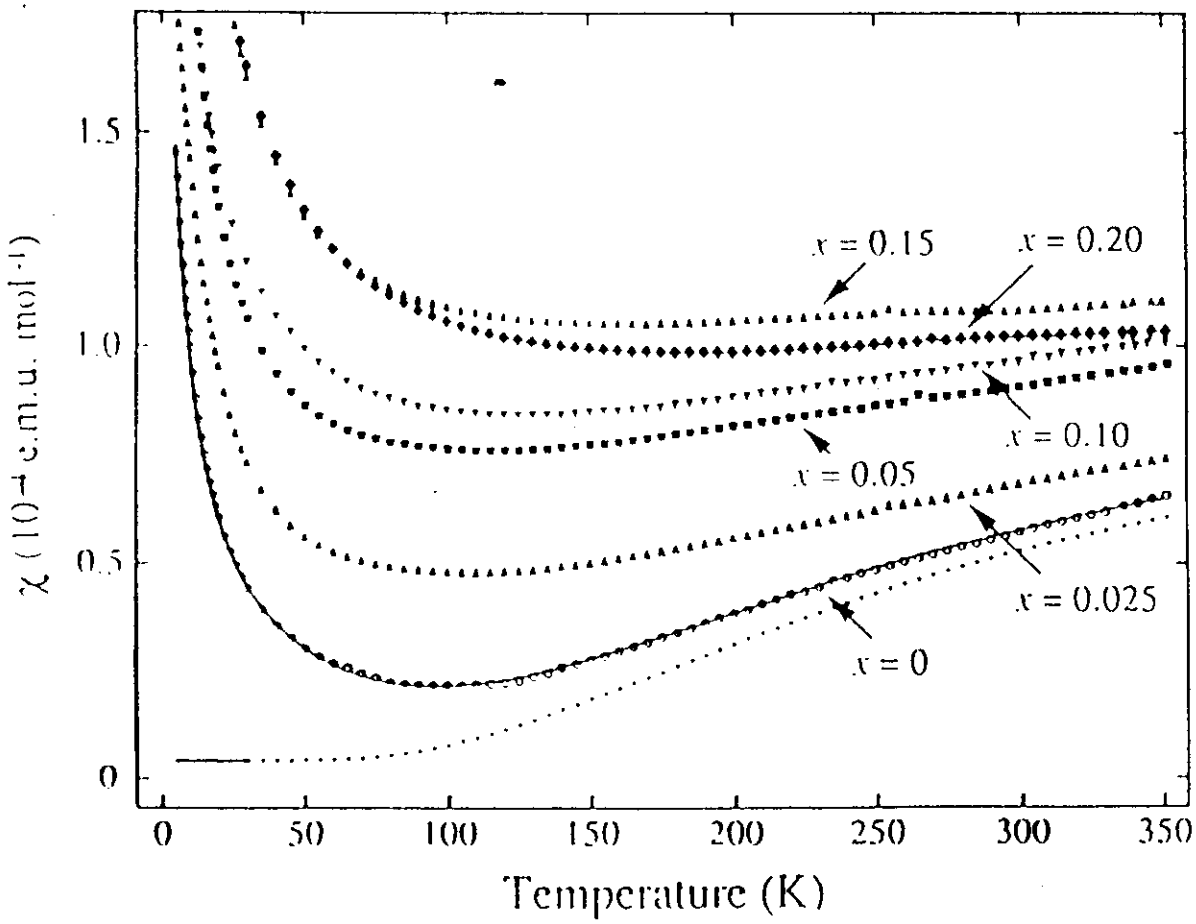
Sigrist et al.

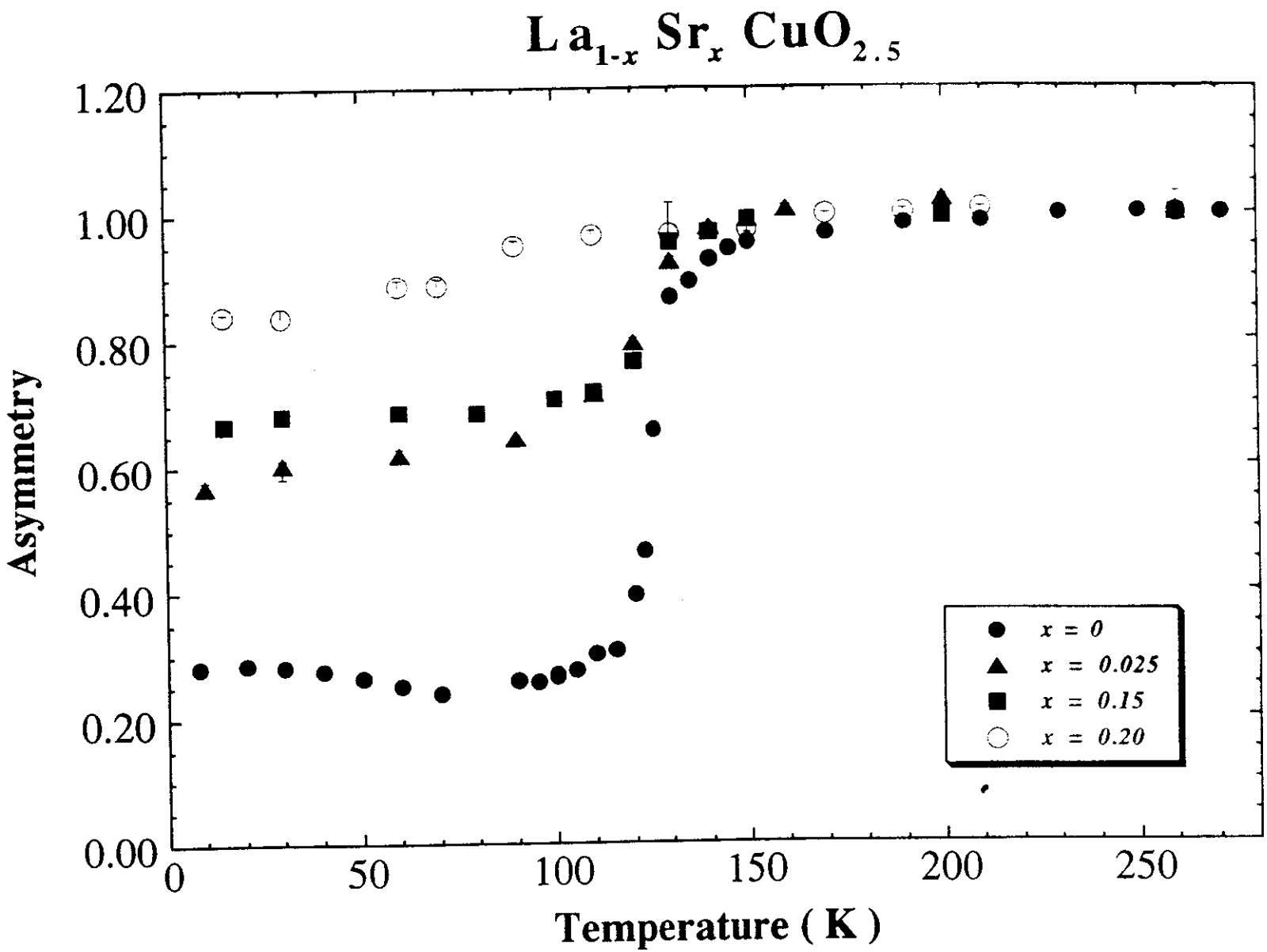
Crystal Structure of $LaCuO_{2.5}$

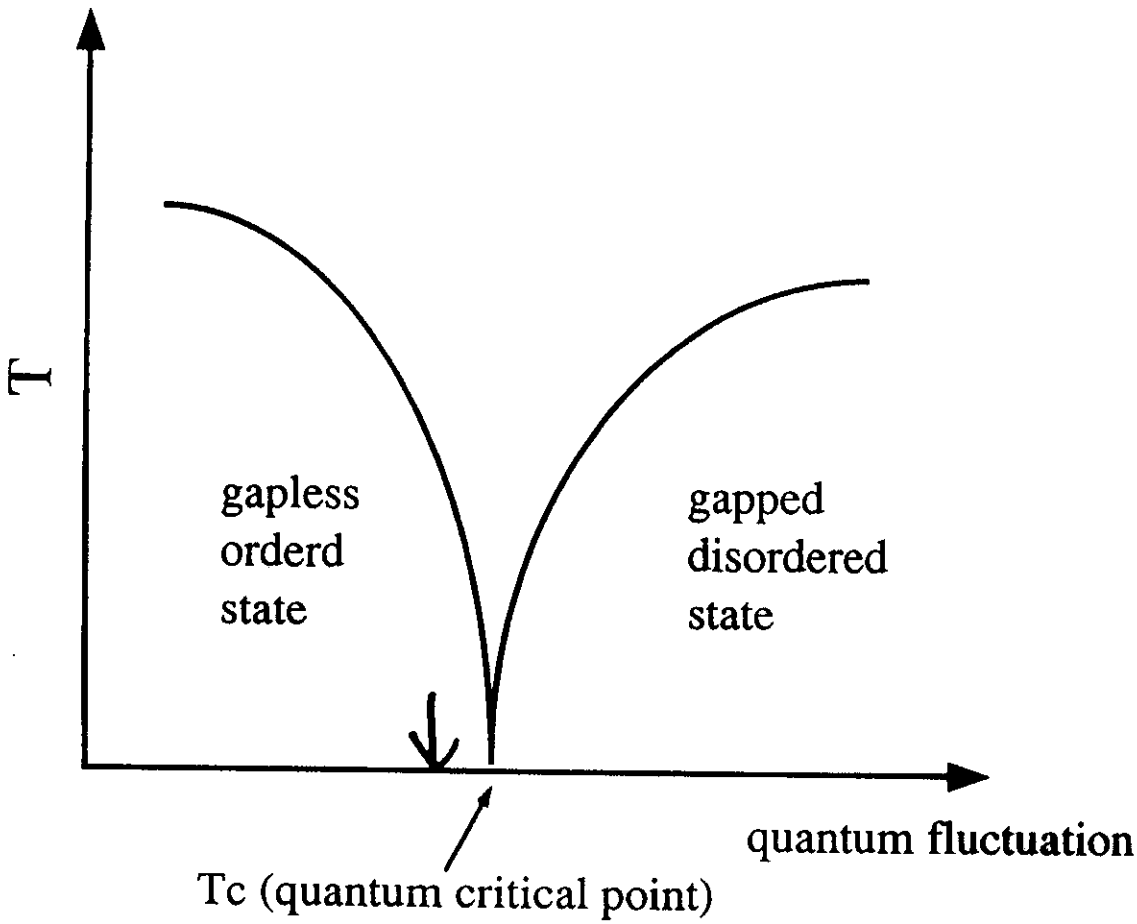


$La_{1-x}Sr_xCuO_{2.5}$

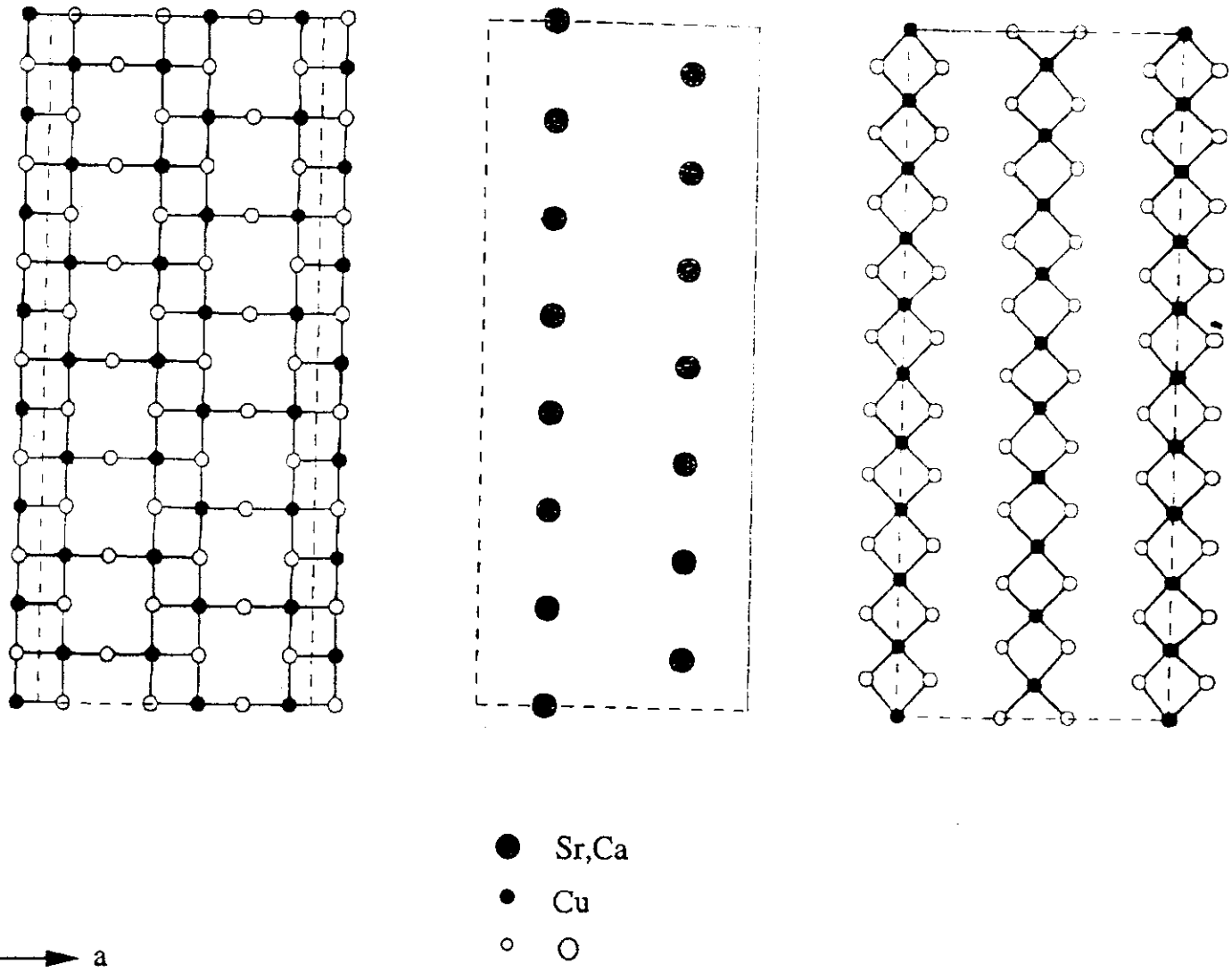


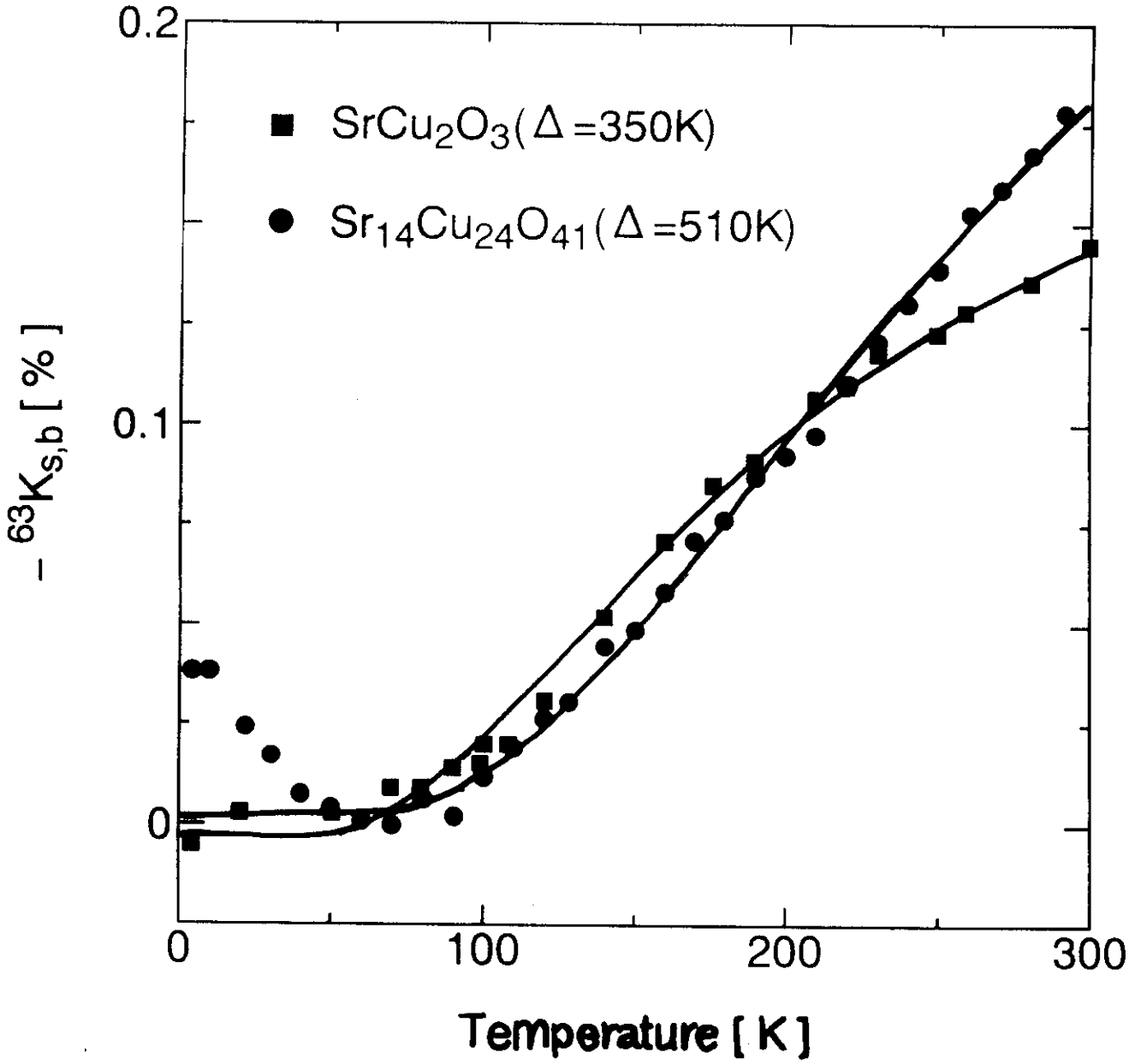



La1-x Srx CuO2.5
Asymmetry
Temperature (K)
1.20
1.00
0.80
0.60
0.40
0.20
0.00
0
50
100
150
200
250
x = 0
x = 0.025
x = 0.15
x = 0.20



B. Normand et al


c
a
Sr,Ca
Cu
O



$$K_s(T) = \frac{A}{\sqrt{T}} \exp\left(-\frac{\Delta}{k_B T}\right)$$

Troyer et al.

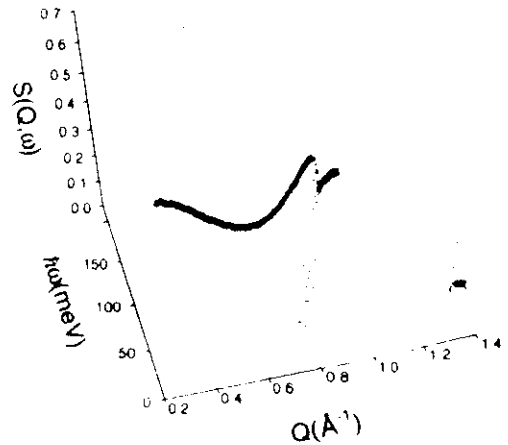
Excitations from the Spin Ladder - Conclusions

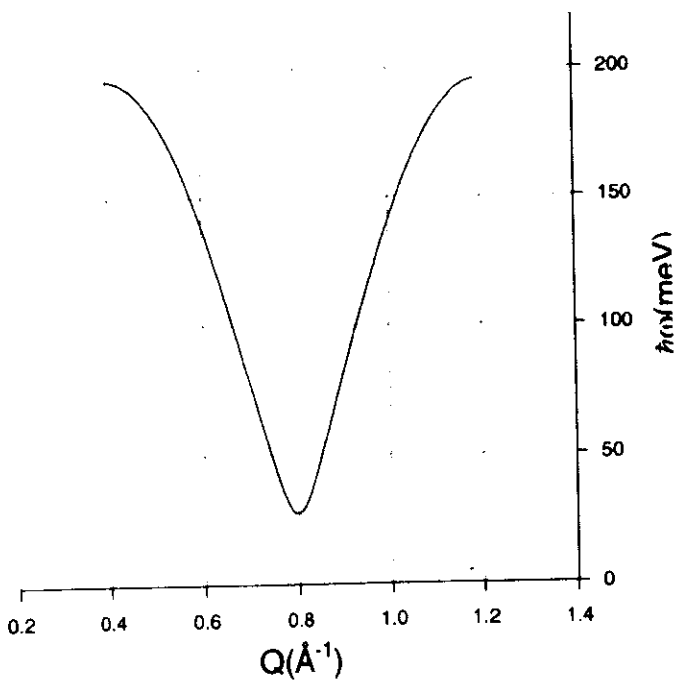
$(Sr_{14}Cu_{24}O_{41})$

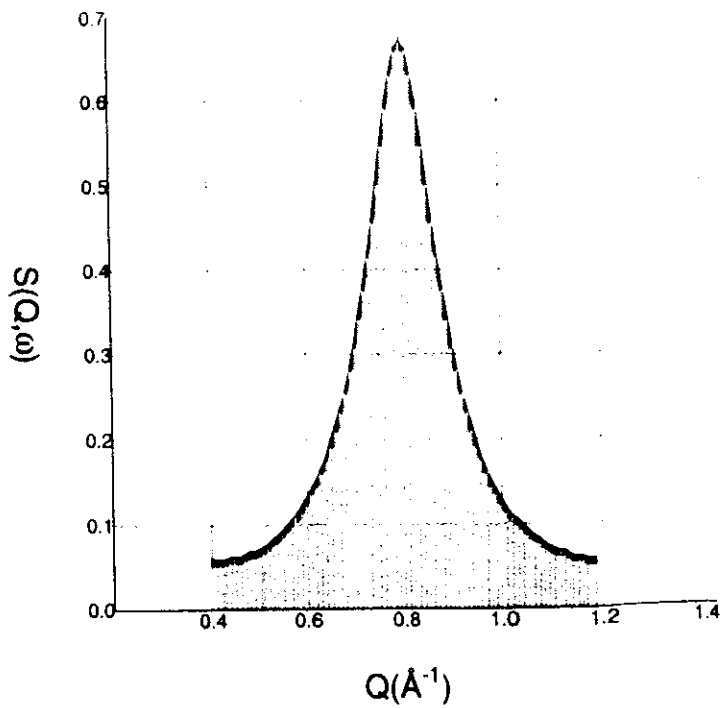
- Band minima at π and 3π
- Spin gap = 36 ± 0.1 meV
- Band maximum = 193.5 ± 2.4 meV

$J \sim 1500\,K$

- κ=0.1 Å^{-1} ≡ 16 rungs.







Trial to hole doping in ladder compound

- $Sr_{14-x}Ca_xCu_{24}O_{41}$

  Yamane et. al., J Ceramic. Soc Jpn. **98** (1990) 105.

  S. A. Carter et. al., Phys. Rev. Lett. **77** (1995) 1378.

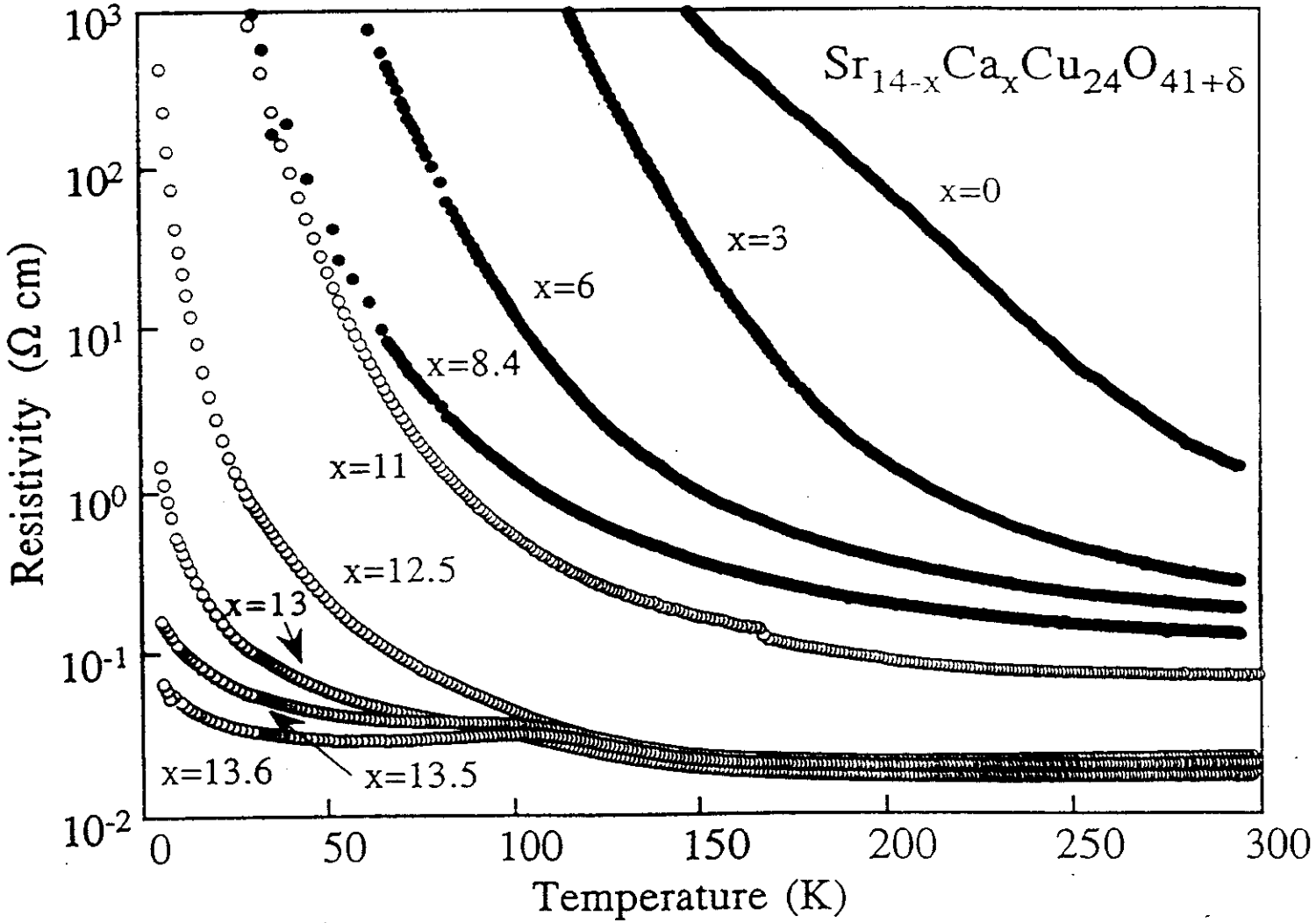
  Kato et. al., Physica C **258** (1996) 284.

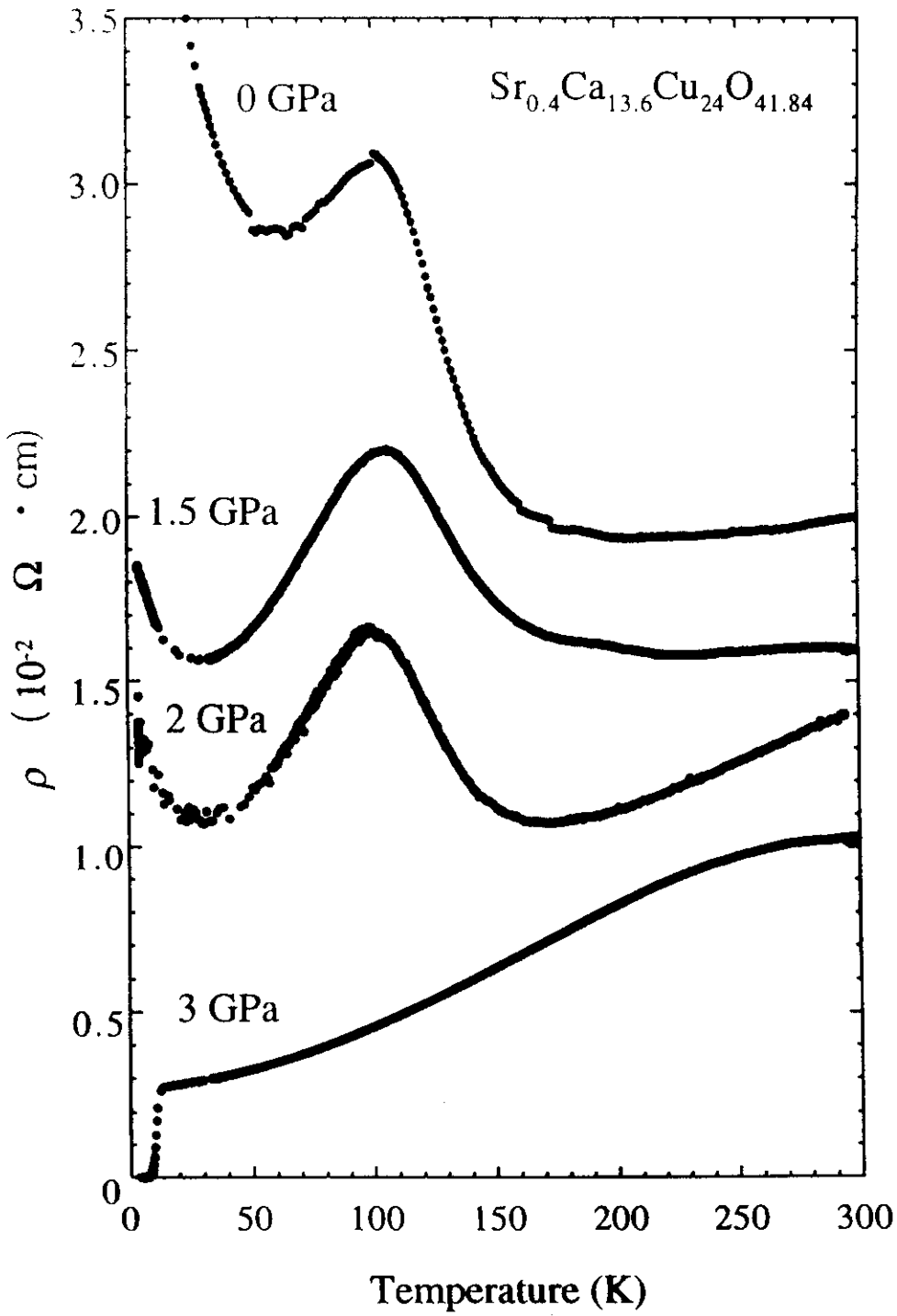
- $Sr_{5.6}Ca_{8.4}Cu_{24-x}Co_xO_{41}$

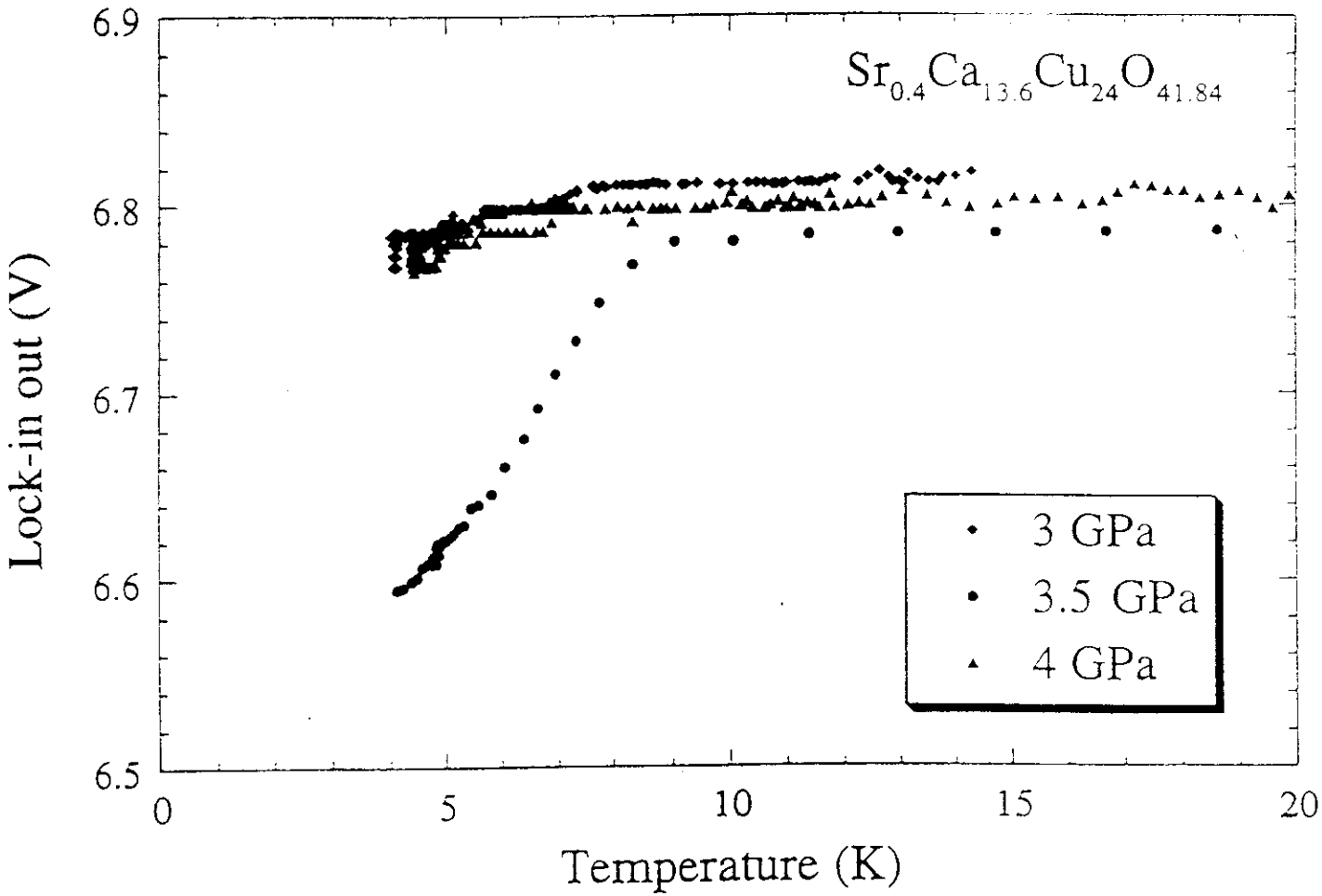
  Uehara et. al., Physica C **255** (1995) 193.

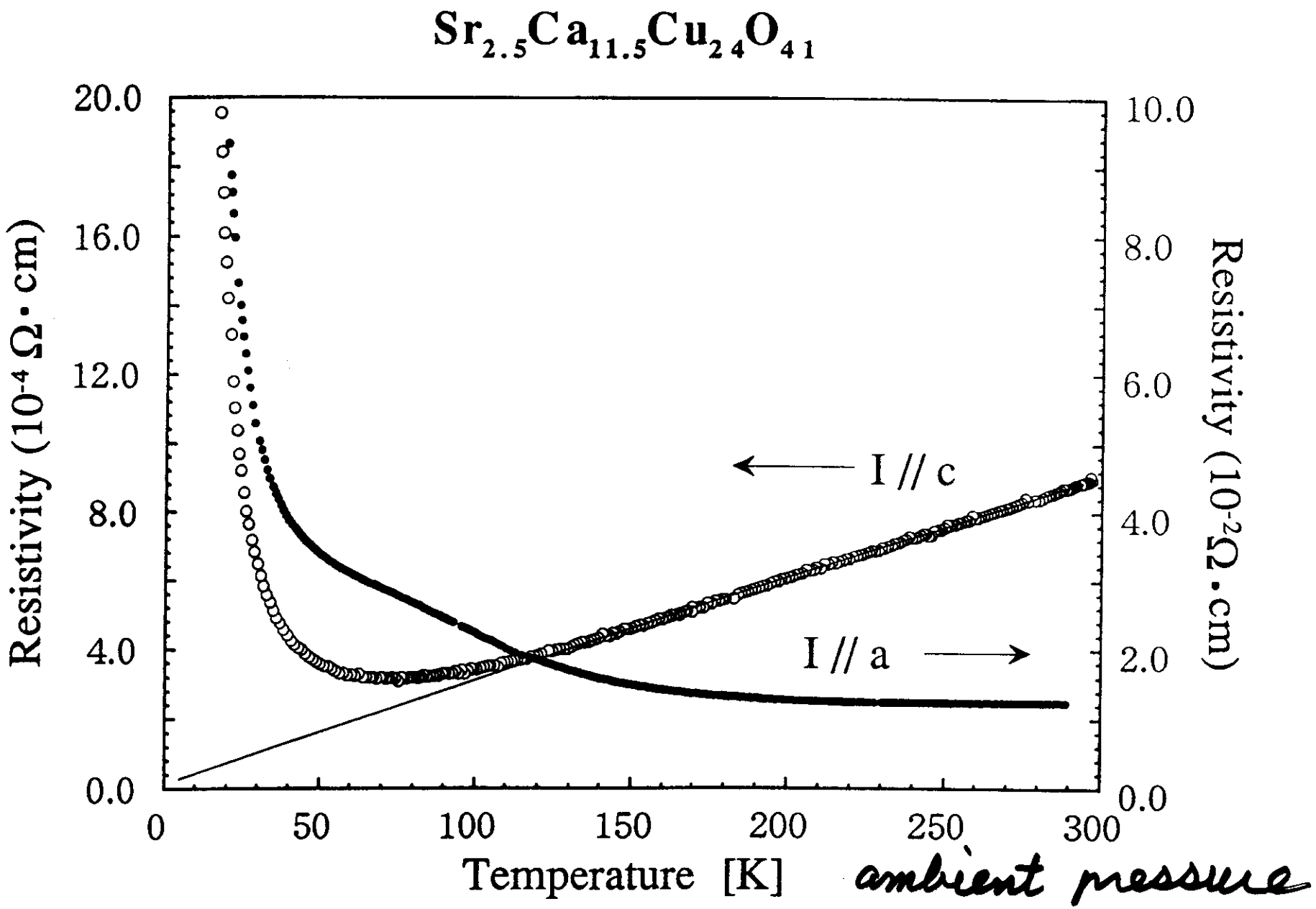
- $La_{1-x}Sr_xCuO_{2.5}$

  Hiroi et. al. Nature 377 (1995) 41.


$Sr_{14-x}Ca_xCu_{24}O_{41+\delta}$
Resistivity (Ω cm)
Temperature (K)
10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
0
50
100
150
200
250
300
x=0
x=3
x=6
x=8.4
x=11
x=12.5
x=13
x=13.5
x=13.6

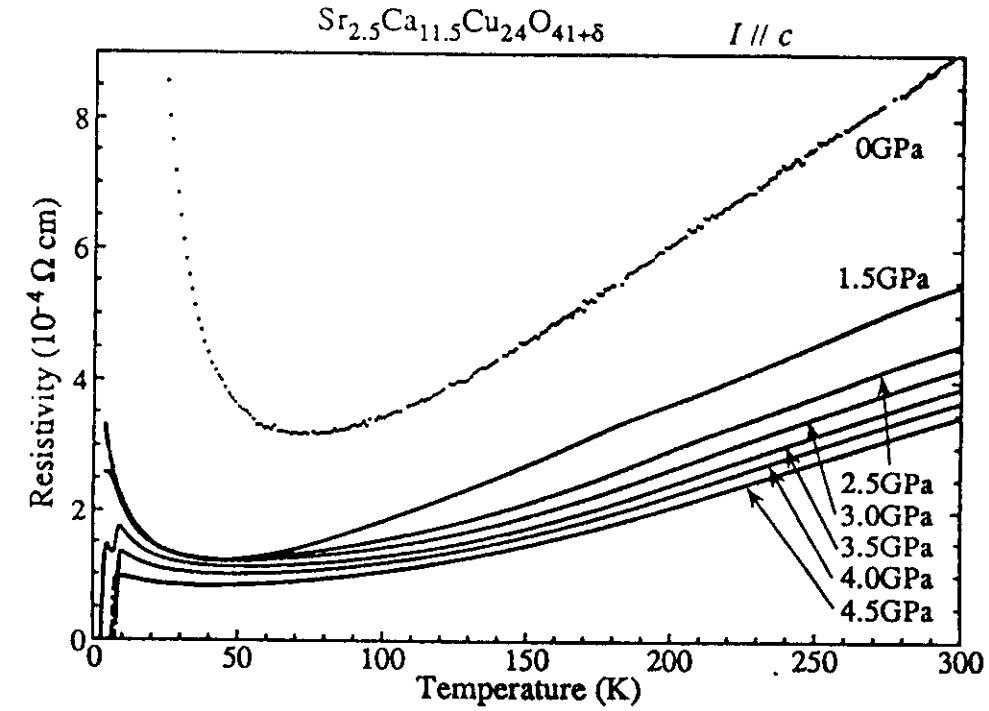

0 GPa
$Sr_{0.4}Ca_{13.6}Cu_{24}O_{41.84}$
1.5 GPa
2 GPa
3 GPa
ρ (10⁻² Ω · cm)
Temperature (K)
0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
0
50
100
150
200
250
300


$Sr_{0.4}Ca_{13.6}Cu_{24}O_{41.84}$
Lock-in out (V)
6.9
6.8
6.7
6.6
6.5
0
5
10
15
20
Temperature (K)
3 GPa
3.5 GPa
4 GPa


$Sr_{2.5}Ca_{11.5}Cu_{24}O_{41}$
Resistivity ($10^{-4}\ \Omega \cdot cm$)
Resistivity ($10^{-2}\ \Omega \cdot cm$)
20.0
16.0
12.0
8.0
4.0
0.0
10.0
8.0
6.0
4.0
2.0
0.0
0
50
100
150
200
250
300
Temperature [K]
I // c
I // a
ambient pressure

$Sr_{14-x}Ca_xCu_{24}O_{41+\delta}$ (at room temperature)

x	$\frac{\rho_{\perp} \text{ ladder}}{\rho_{//} \text{ ladder}}$	$\frac{\rho_b}{\rho_{//} \text{ ladder}}$
0	3.5	7500
11.5	20	5000


$Sr_{2.5}Ca_{11.5}Cu_{24}O_{41+\delta}$ *I // c*
Resistivity (10^{-4} Ω cm)
Temperature (K)
0GPa
1.5GPa
2.5GPa
3.0GPa
3.5GPa
4.0GPa
4.5GPa

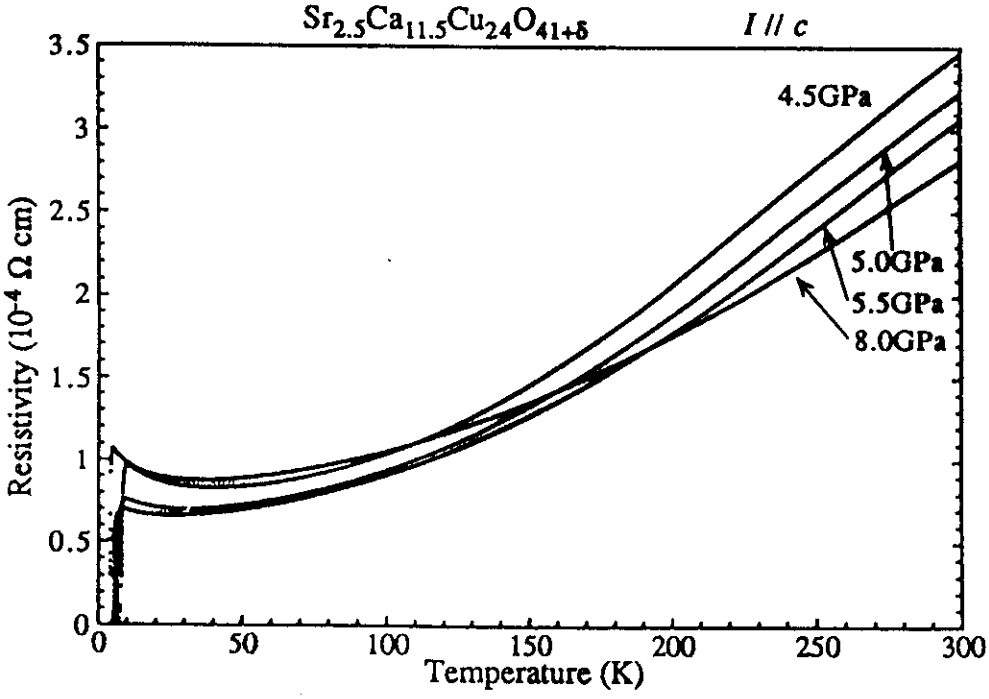
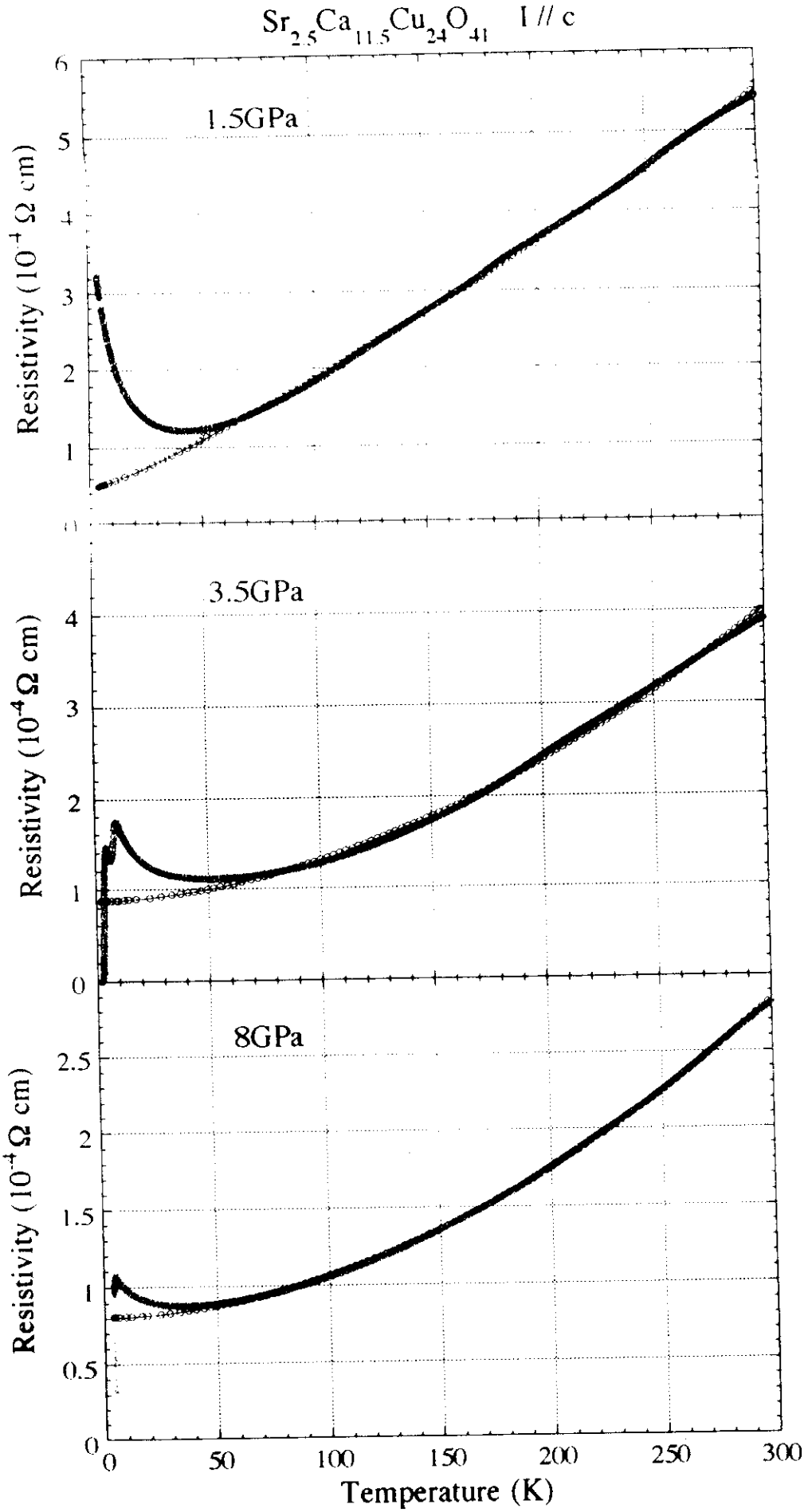
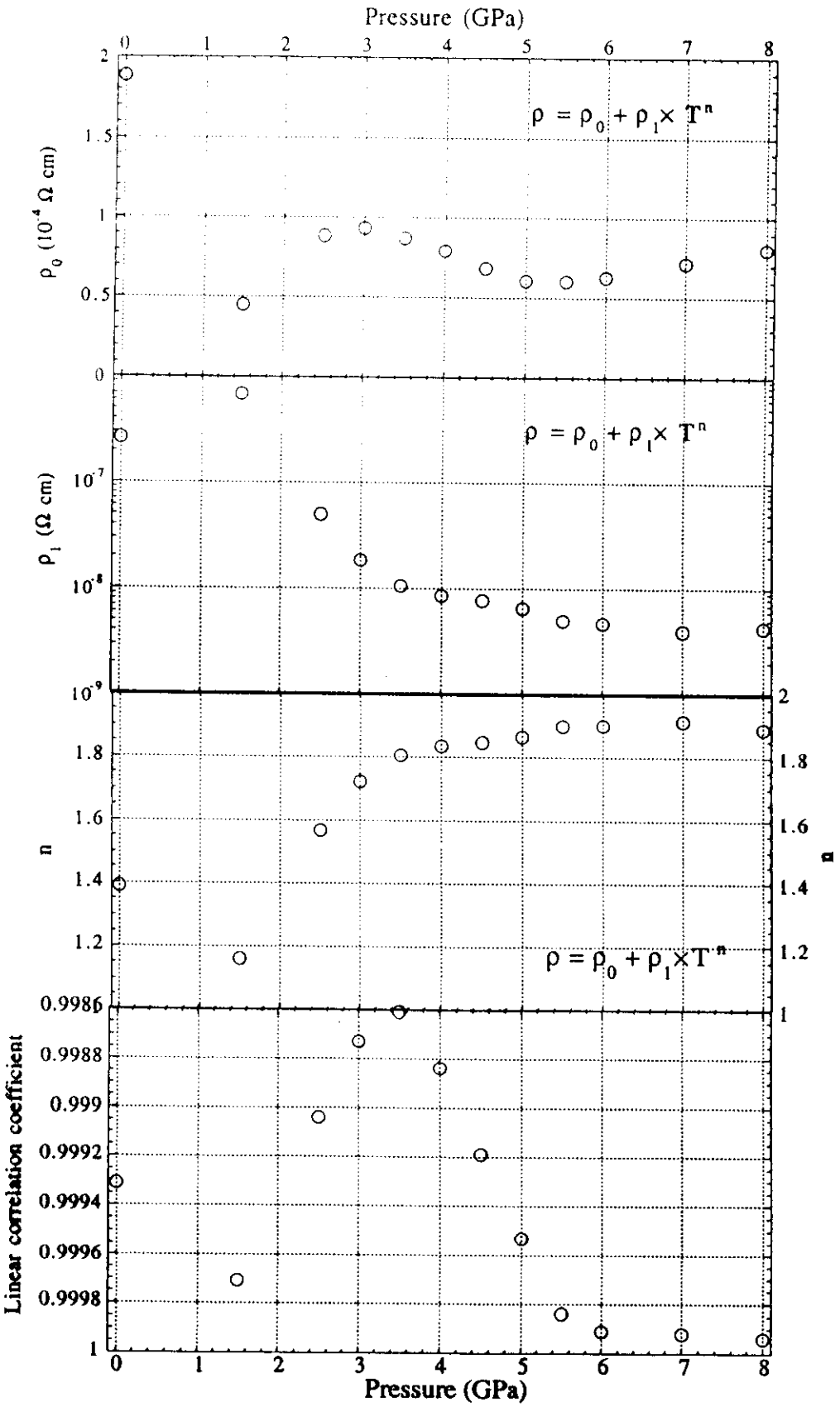

$Sr_{2.5}Ca_{11.5}Cu_{24}O_{41+\delta}$ *I // c*
Resistivity (10^{-4} Ω cm)
Temperature (K)
4.5GPa
5.0GPa
5.5GPa
8.0GPa

Fig 2


$Sr_{2.5}Ca_{11.5}Cu_{24}O_{41}$ I // c
1.5GPa
3.5GPa
8GPa
Resistivity (10^{-4} Ω cm)
Temperature (K)
0
50
100
150
200
250
300

$$\rho = \rho_0 + \rho_1 \times T^n$$

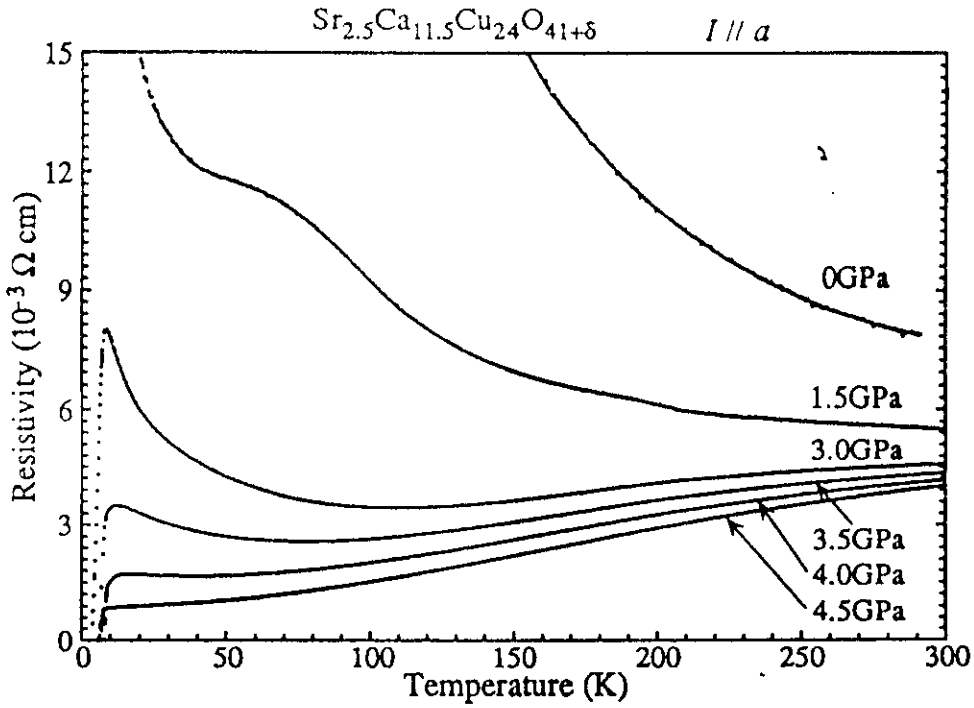


ρ_0

ρ_1

n

fitting error bar


$Sr_{2.5}Ca_{11.5}Cu_{24}O_{41+\delta}$ *I // a*
Resistivity (10^{-3} Ω cm)
Temperature (K)
0GPa
1.5GPa
3.0GPa
3.5GPa
4.0GPa
4.5GPa

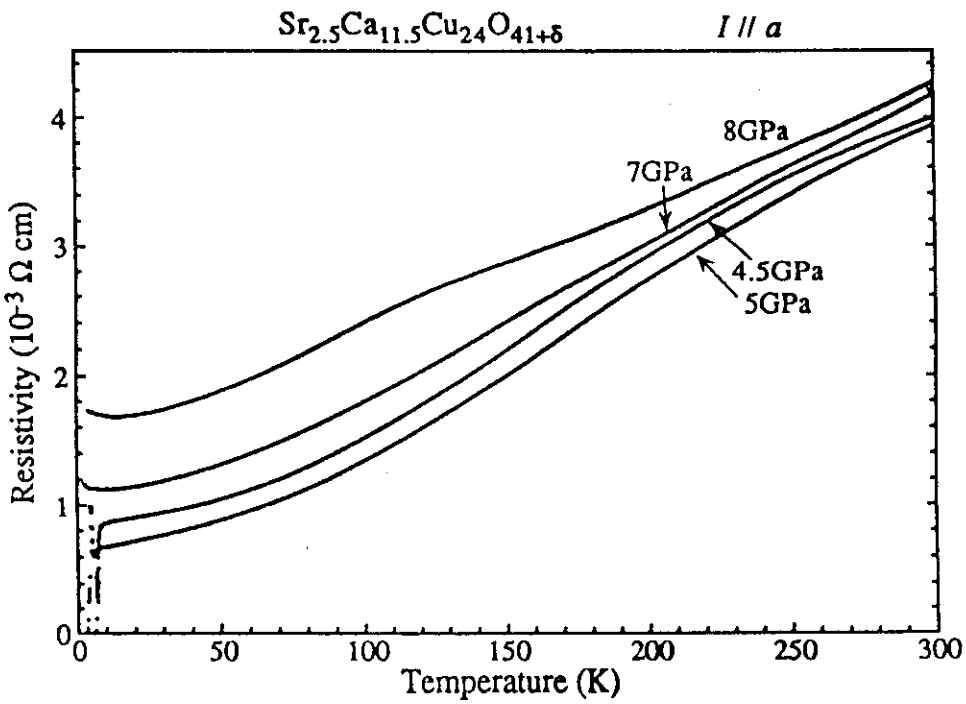

$Sr_{2.5}Ca_{11.5}Cu_{24}O_{41+\delta}$ *I // a*
Resistivity (10^{-3} Ω cm)
Temperature (K)
8GPa
7GPa
4.5GPa
5GPa

Fig 4

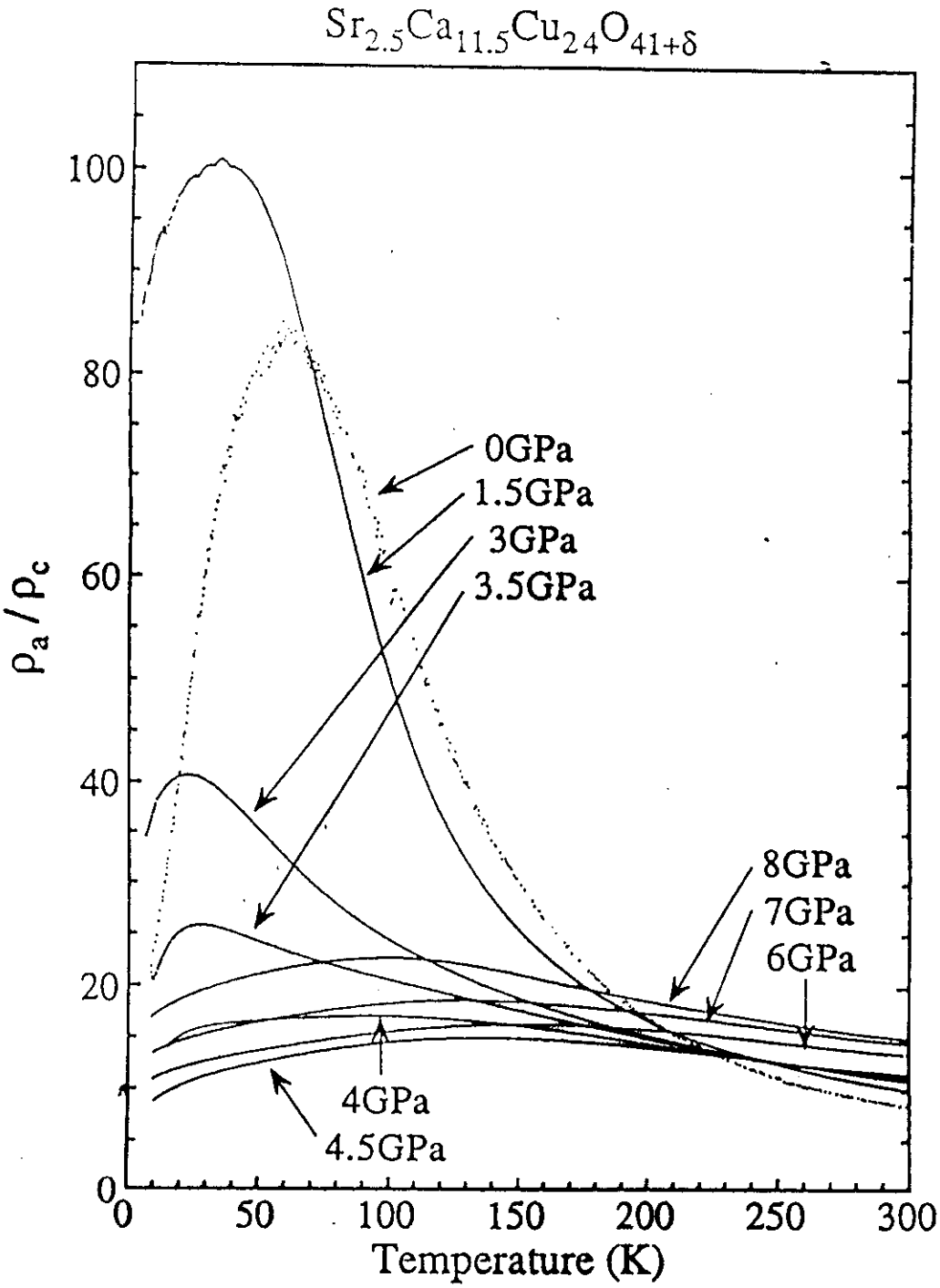
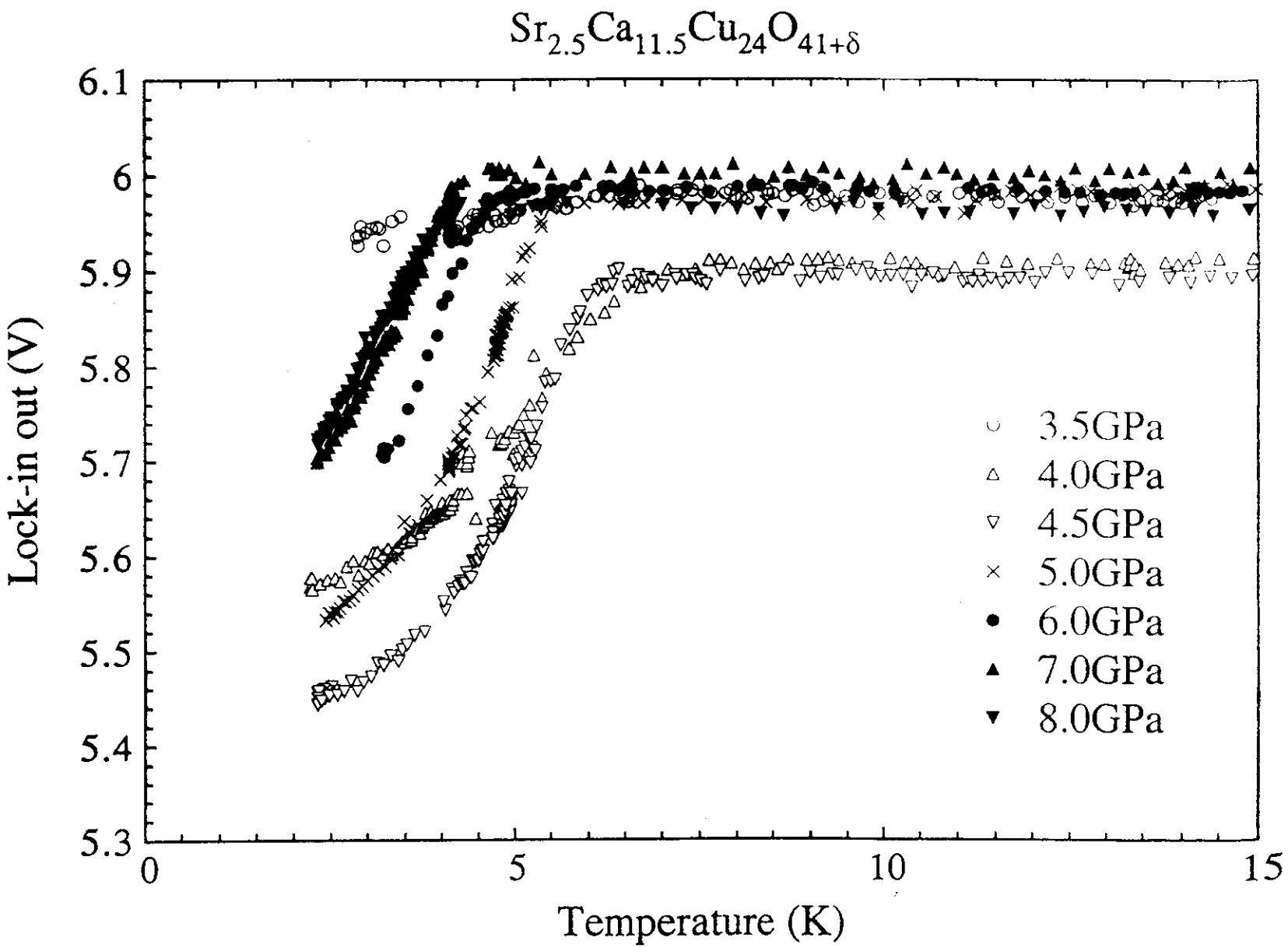

$Sr_{2.5}Ca_{11.5}Cu_{24}O_{41+\delta}$
ρ_a / ρ_c
100
80
60
40
20
0
0
50
100
150
200
250
300
Temperature (K)
0GPa
1.5GPa
3GPa
3.5GPa
4GPa
4.5GPa
8GPa
7GPa
6GPa

Fig.8


$Sr_{2.5}Ca_{11.5}Cu_{24}O_{41+\delta}$
Lock-in out (V)
Temperature (K)
6.1
6
5.9
5.8
5.7
5.6
5.5
5.4
5.3
0
5
10
15
3.5GPa
4.0GPa
4.5GPa
5.0GPa
6.0GPa
7.0GPa
8.0GPa

Results on single crystal measurements

1. Temperature dependence of ρ_c gradually changes from T-linear to T^2 with pressure increase.

2. ρ_a/ρ_c is 10 ~ 20 and is almost temperature independent in the superconducting region. (The stage is 2-D!)

3. With Ca concentration increases,

   (1) maximum T_c is increased.

   (2) optimum pressure is decreased.

   (3) superconducting region become narrower.

Questions

1. Has any crystallographic phase change occurred under pressure ?

2. Where are the holes located-ladders or chains ?

3. T_c (=12K) should be higher ?

4. The relationship between the spin gap and superconductivity.

5. Why an another ladder compound $La_{1-x}Sr_xCuO_{2.5}$ does not show superconductivity.

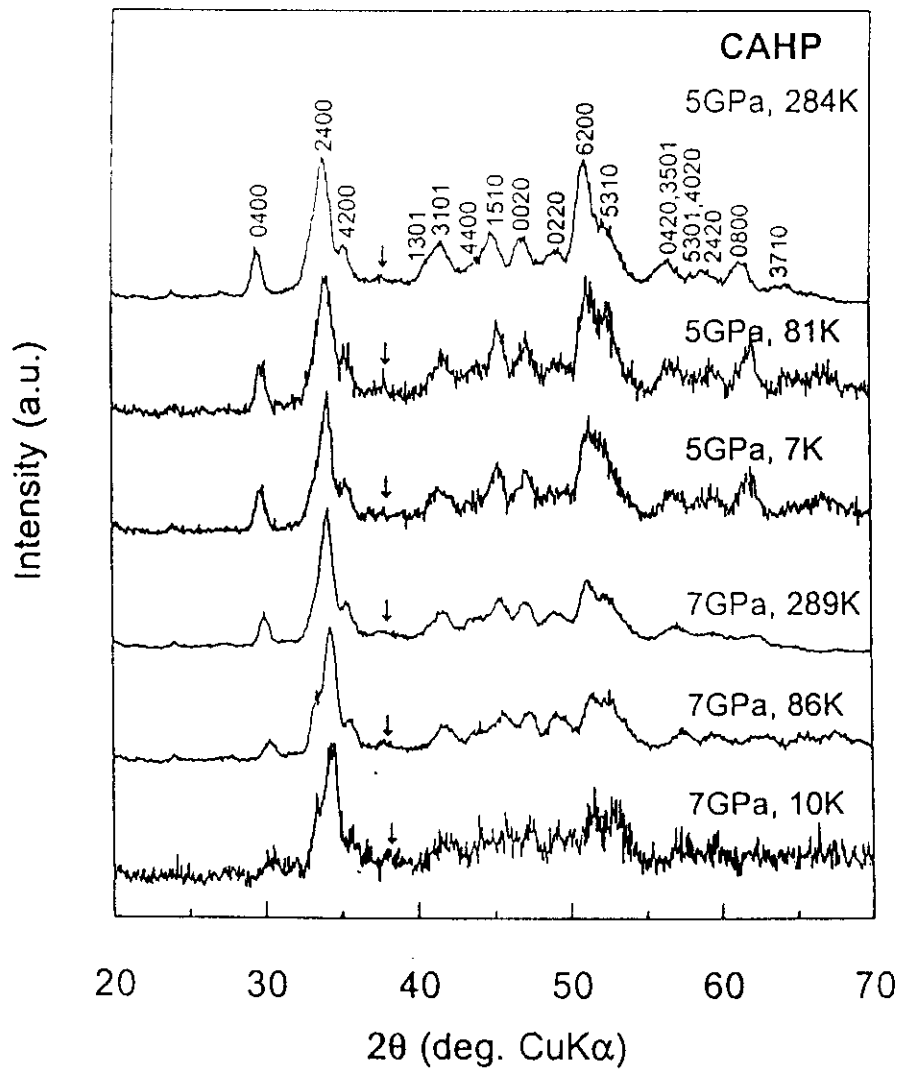
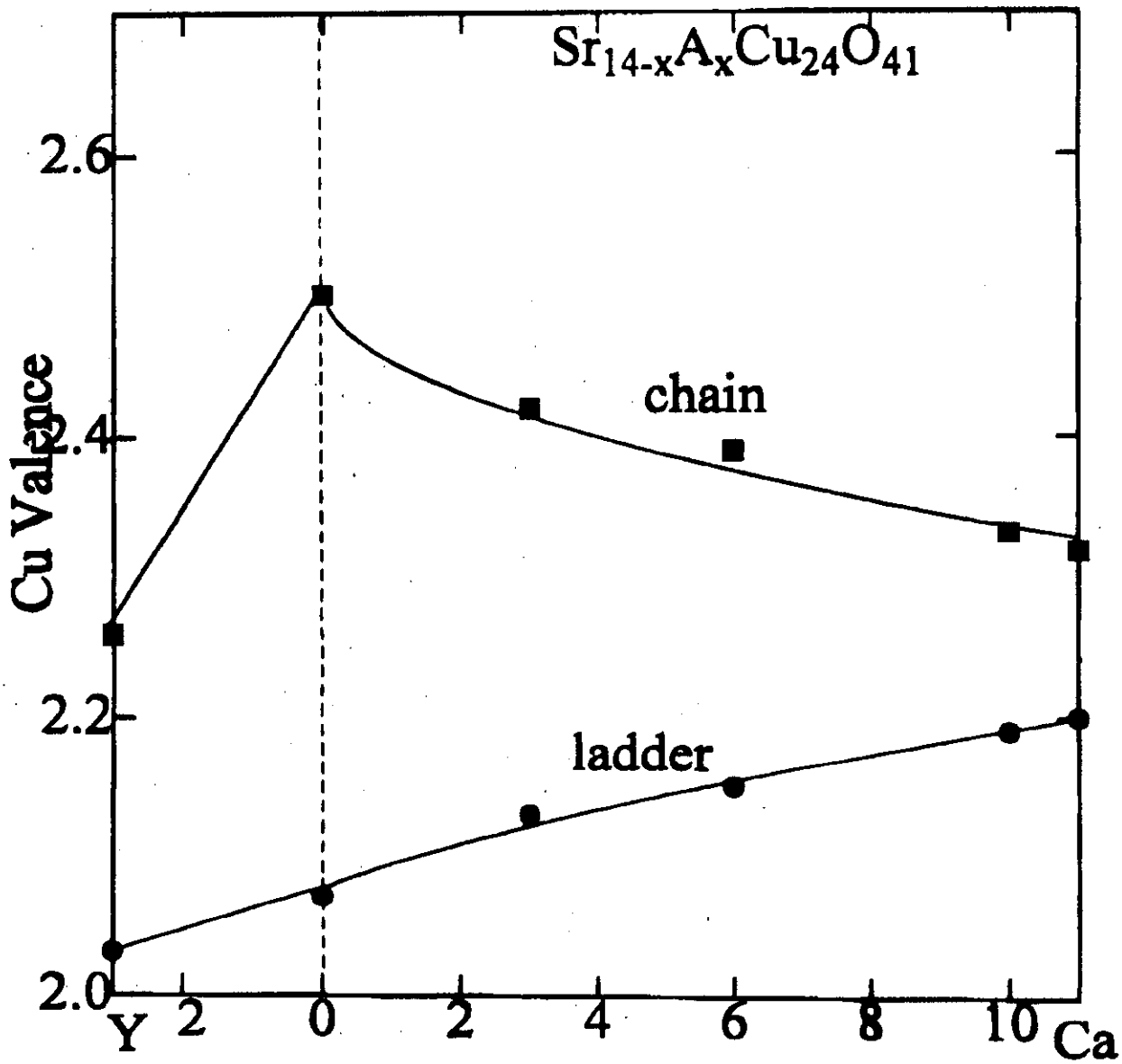
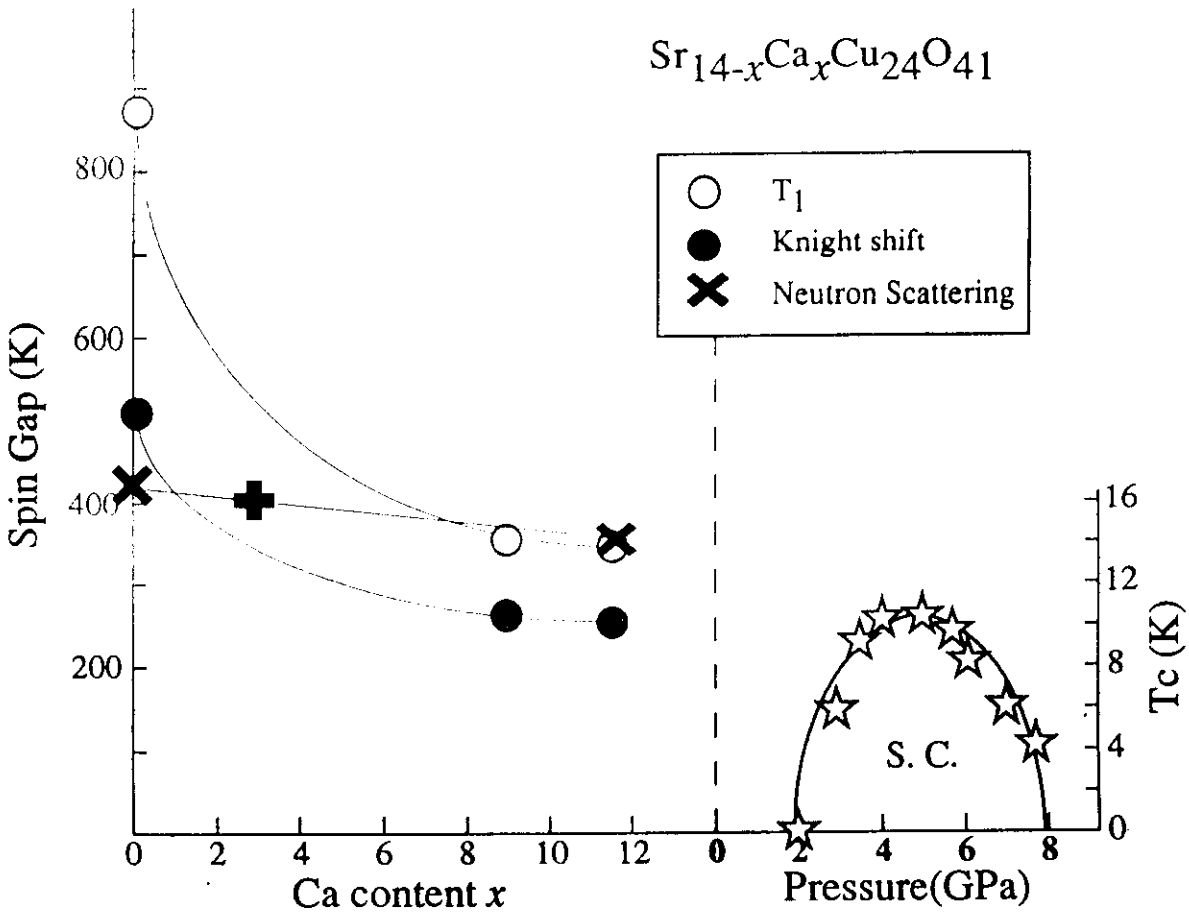


Fig. 8 M. Isobe et al.



Motoyama et al



Spin Gap (K)	Ca content x ($Sr_{14-x}Ca_xCu_{24}O_{41}$)			
	0	2.8	9	11.5
T_1 [1)]	860		360	350
Knight Shift [1)]	510		280	270
Neutron Scat.	420	410 [2)]		380

1) K. Magishi *et.al* submitted to P. R. B

2) R. S. Eccleston *et.al* Phys. Rev. B 53(1996)14721

Is there any difference between high-Tc cuprate and ladder ?

Charge ?

spin ?