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SMR.959 - 37

MINIWORKSHOP ON STRONG ELECTRON CORRELATIONS
"Disorder and Interaction in Quantum Systems and Their Classical Analogs"

(1 - 19 July 1996)

"Magnetic Properties of Low Dimensional Quantum Spin Systems CaV_nO_{2n+1} (n=2-4)"

Masatoshi Sato
Nagoya University
Department of Physics
Nagoya 464-01
Japan

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

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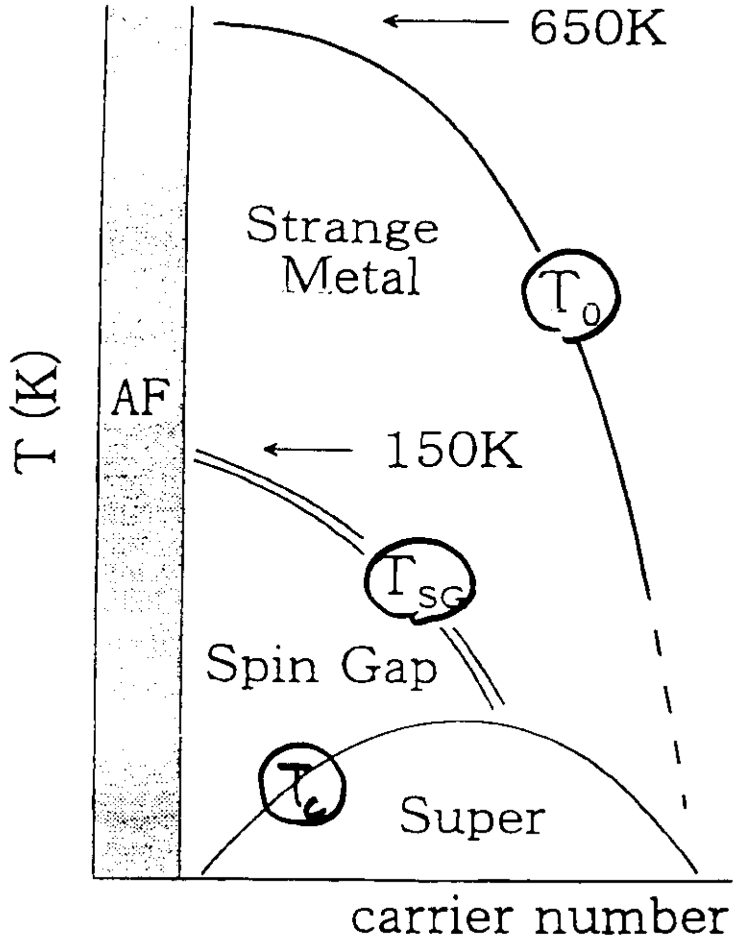
Magnetic Properties of Low Dimensional Quantum Spin Systems CaV_nO_{2n+1} ($n=2-4$)

Masatoshi SATO
Dept. of Phys. Nagoya Univ.

- Brief survey of anomalous metallic phase of Cu-oxides
- Expermental results of spin gap phase of CaV_4O_9

Co-workers
Nagoya Univ. Group.
ISSP Group

Anomalous Metallic Phase of High-T_c Oxides

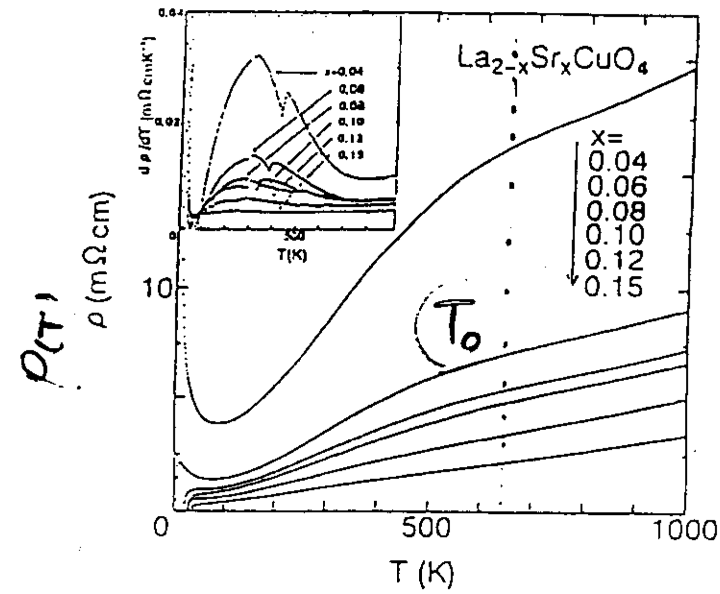


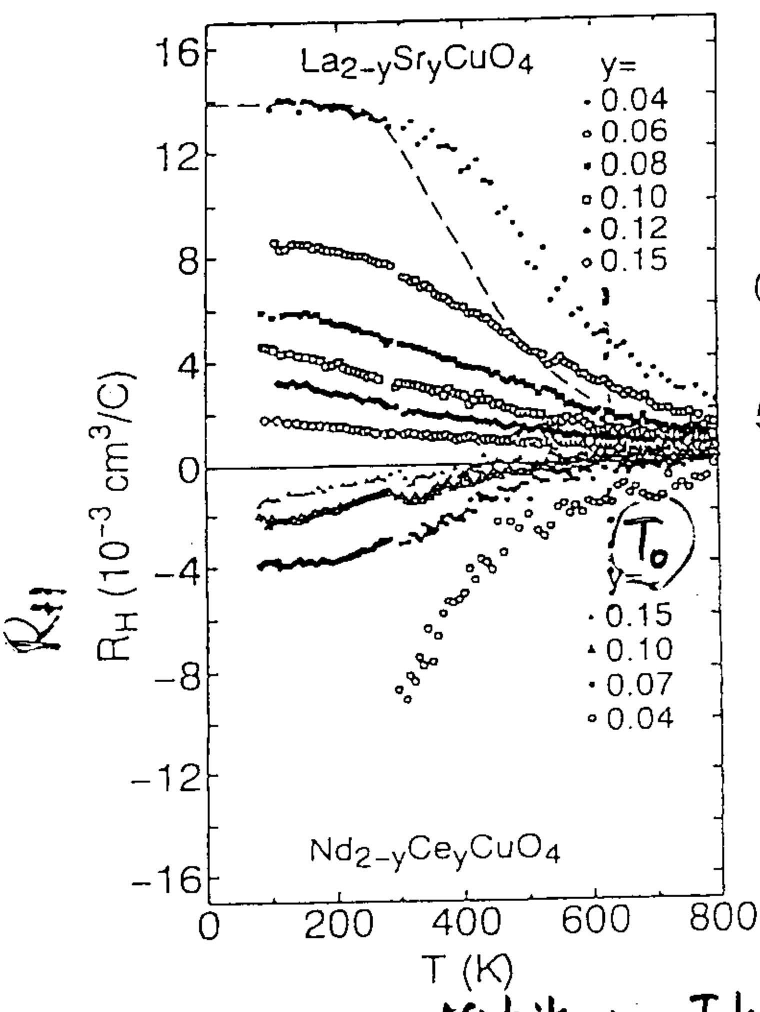
← 2D system near the Mott transition

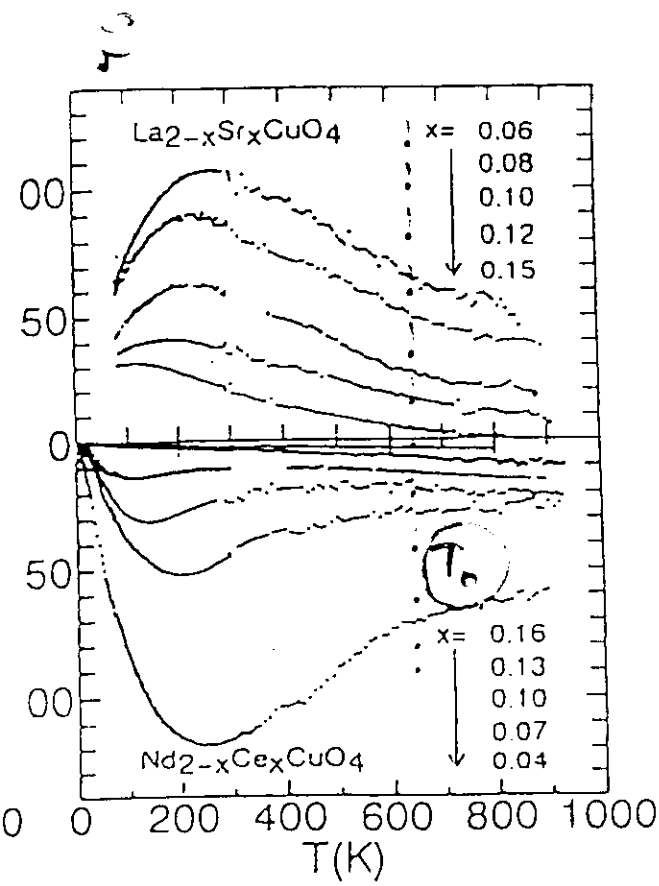
Anomalous Properties in Cu-Oxides

(I) Transport Anomalies at $T \sim T_0$ ($>$ 500K)

(& in x and K)

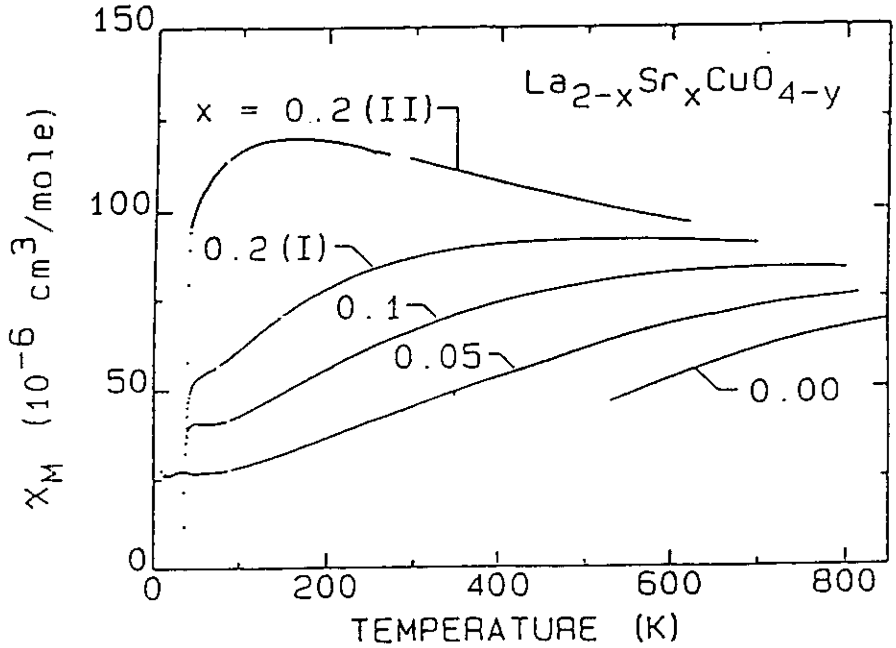






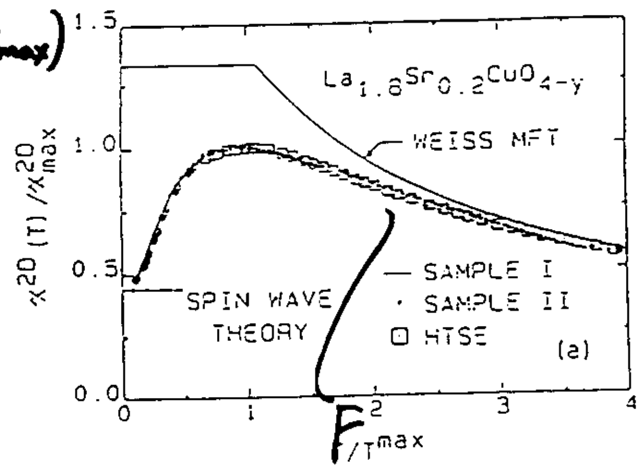
Nishikawa, Takada, M. S.

magnetic susceptibility χ



$\chi(T) = \chi_0 + (\chi_{max} - \chi_0) F(T/T_{max})$

D.C. Johnston

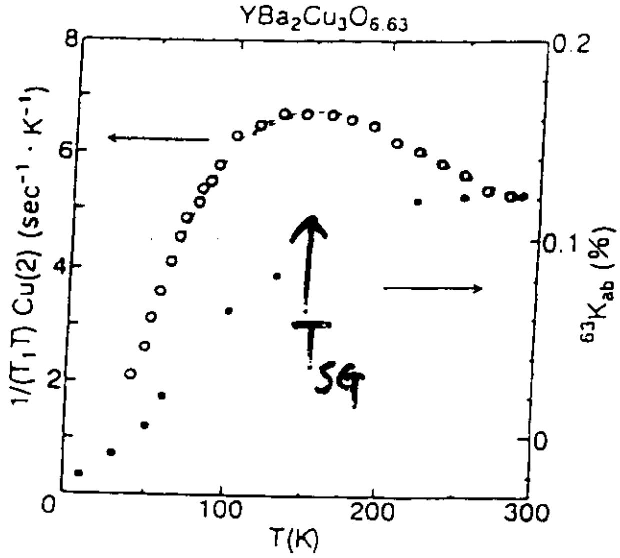


$T_{max} \sim T_0$

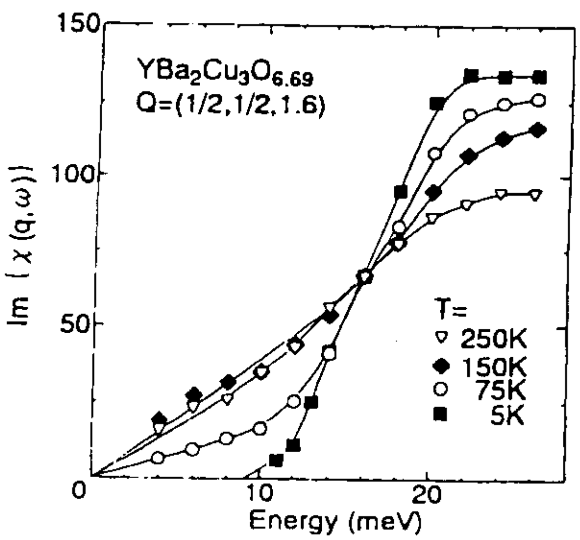
T. Nakano et al.

(R. Yoshizaki et al.)

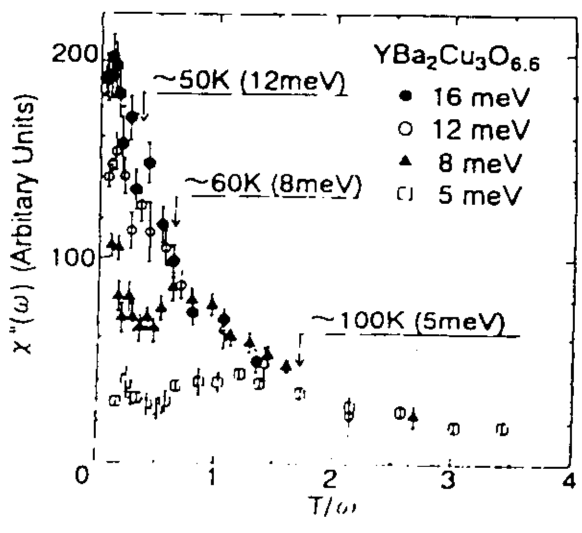
Spin gap



NMR $1/T_1T$
(Yasuoka, Takigawa)

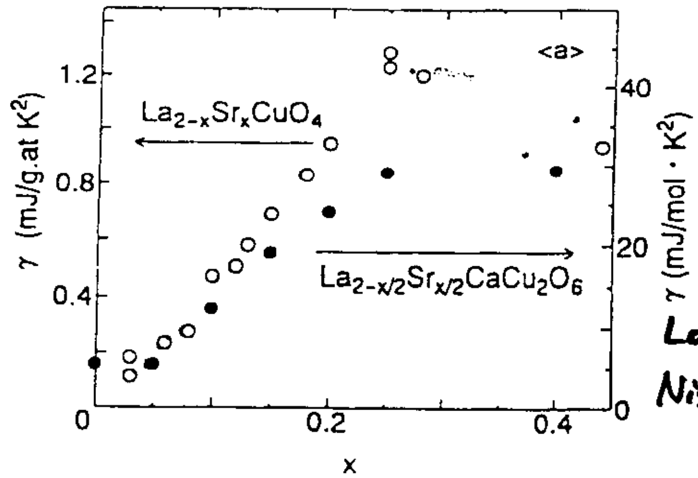


Neutron $\chi''(\omega)$
(Rossat-Mignod et al.)

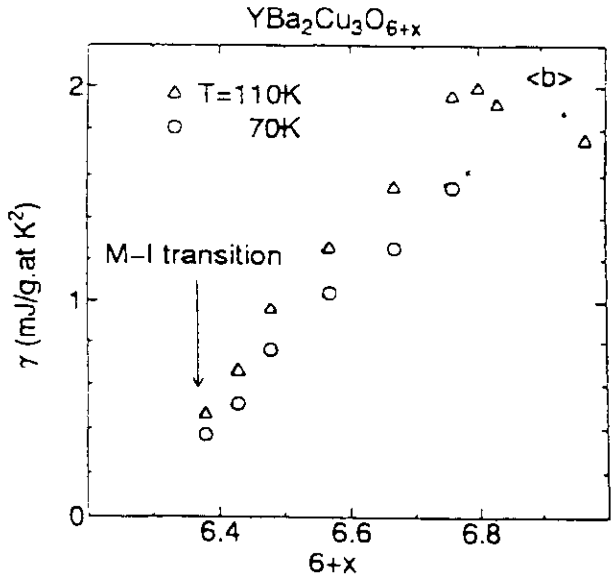


Our data

Anomalous behavior of γ



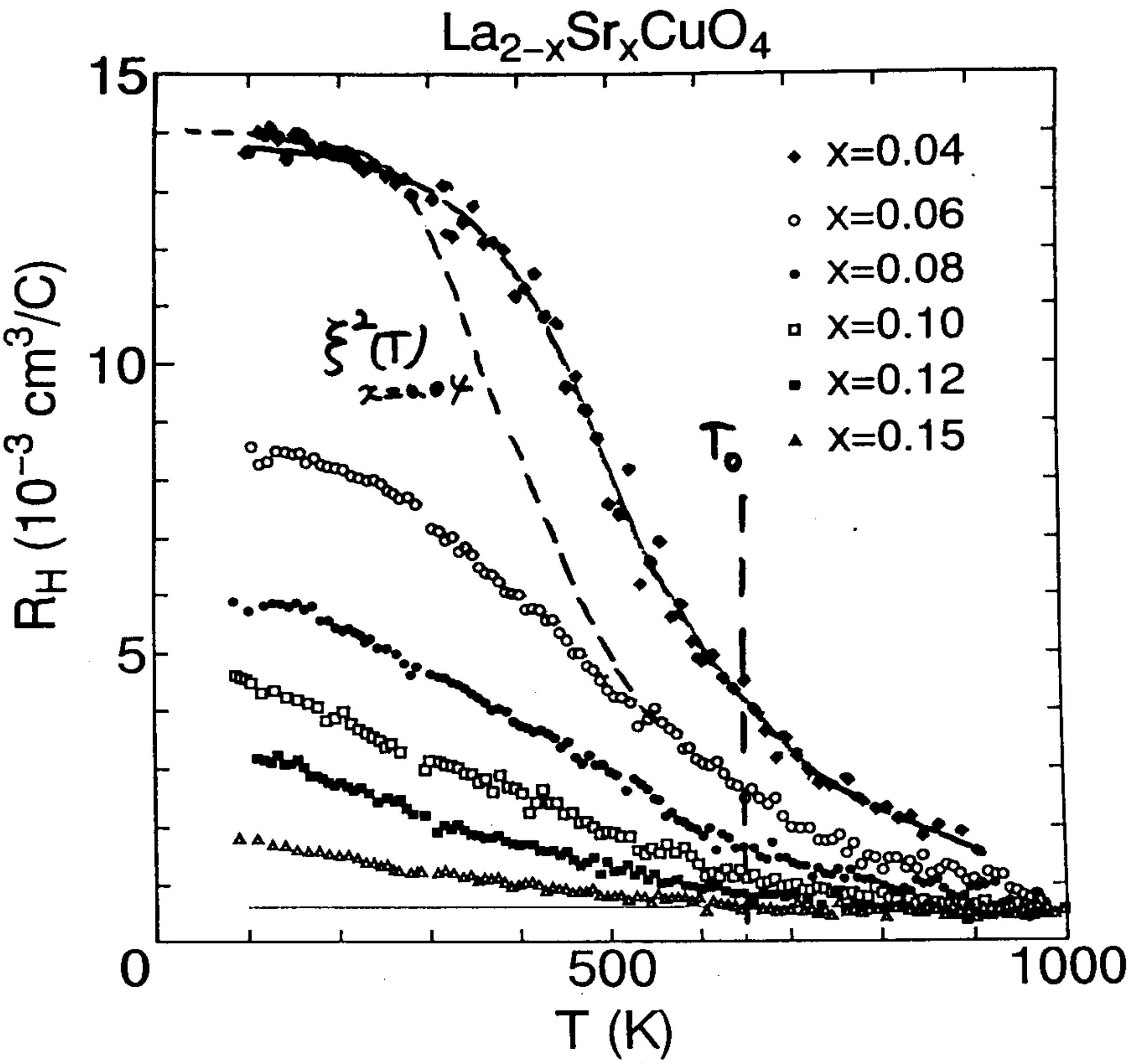
Loram et al,
Nishikawa et al,
(Nagoya)



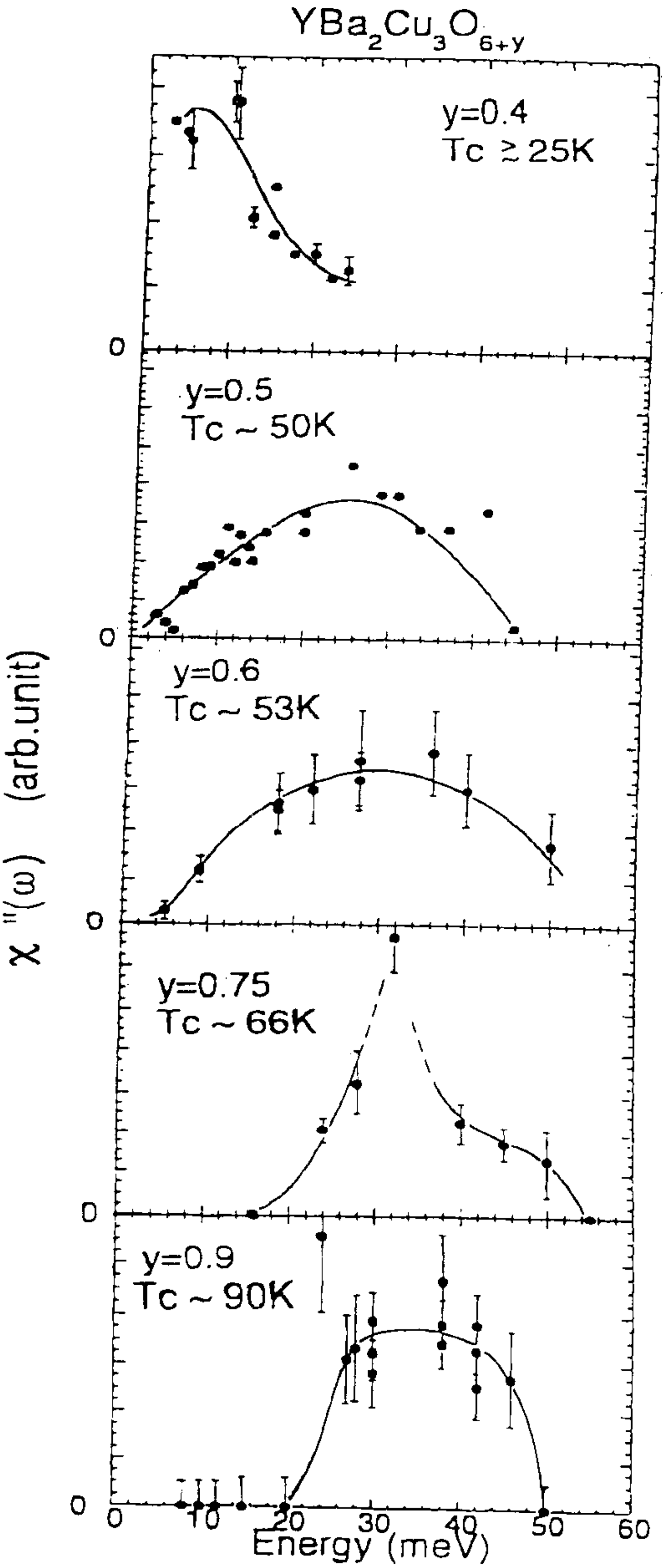
Loram et al.

γ decreases as the system approaches
M–I phase boundary.

What is the origin of the anomalous phase ?

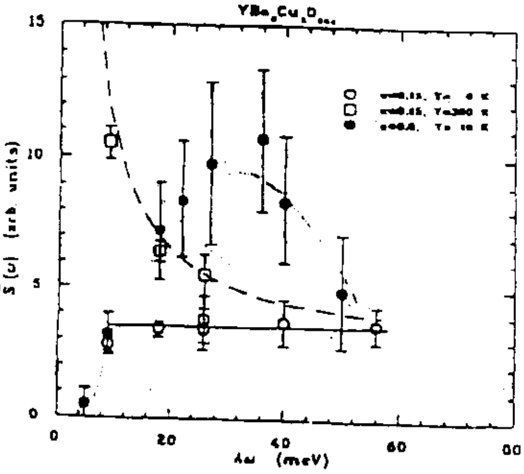


$\xi^2(T)$: G. Shirane et al.



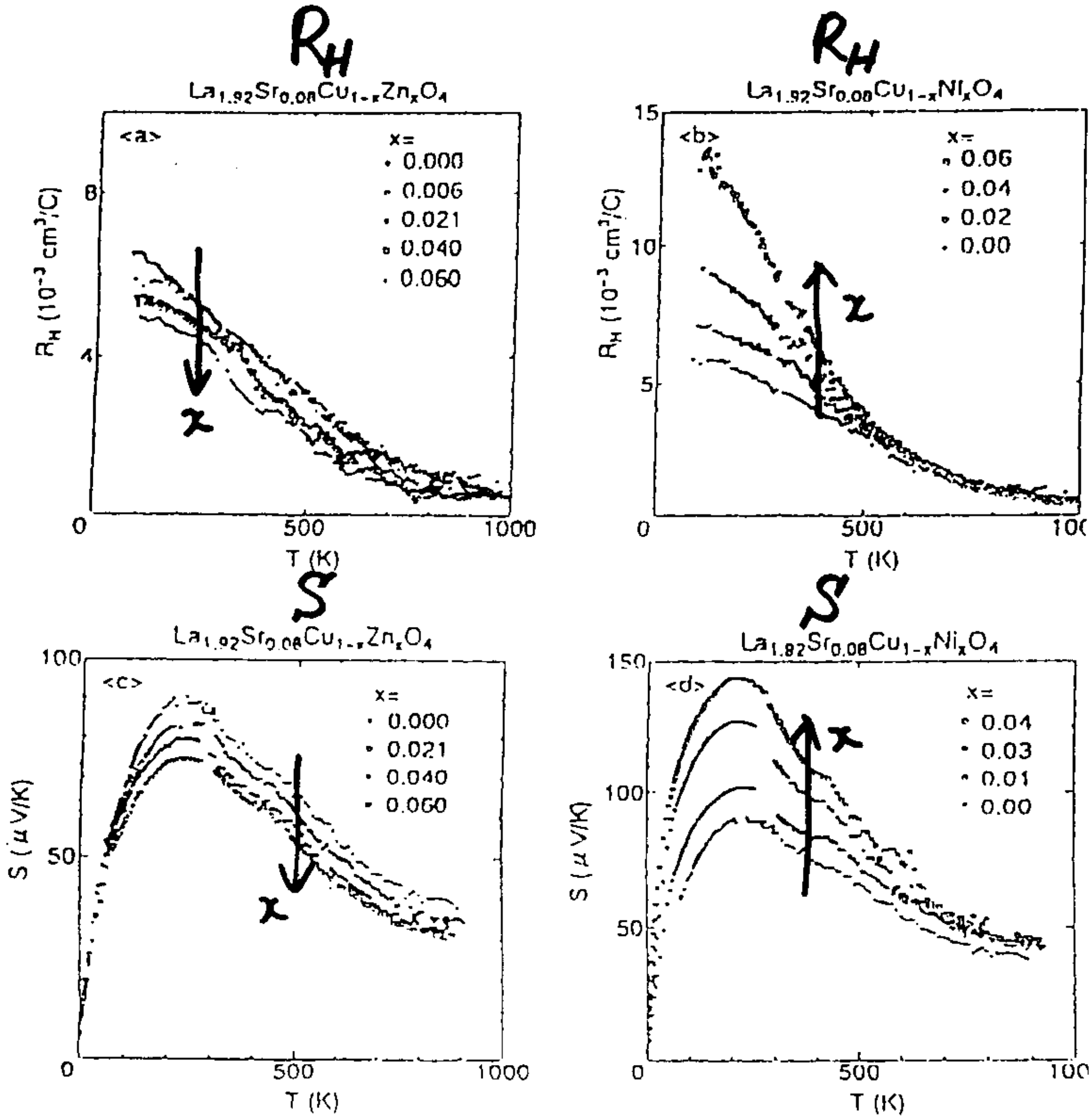
$\chi''(\omega)$ of YBCO

our data



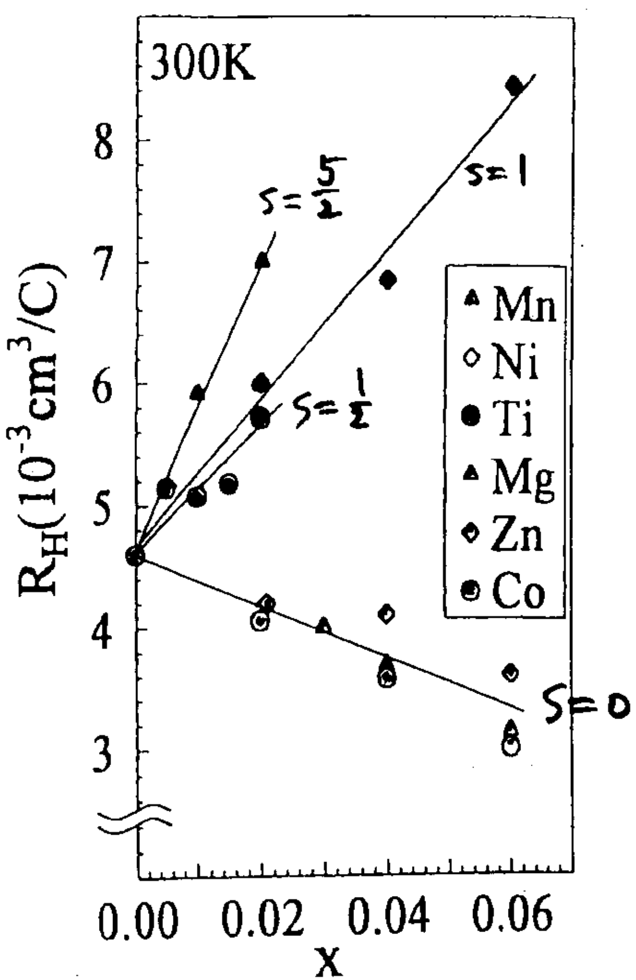
Doping effect on the anomalous behavior of S and R_H (La 214)

Zn-doped (S=0)　　　Ni-doped (S=1)

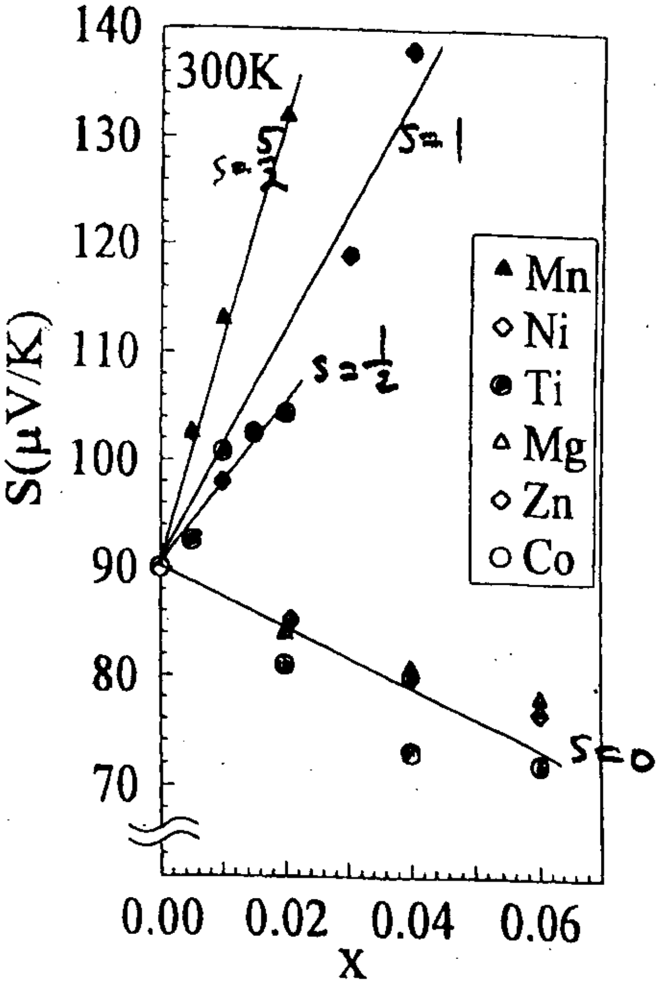


J. Takeda et al.
(Nagoya)

$La_{1.92}Sr_{0.08}Cu_{1-x}M_xO_4$ (M=Mn,Ni,Mg,Zn)
$La_{2-y}Sr_yCu_{1-x}Ti_xO_4$ (y-x=0.08)
$La_{2-y}Sr_yCu_{1-x}Co_xO_4$ (y-x=0.08)

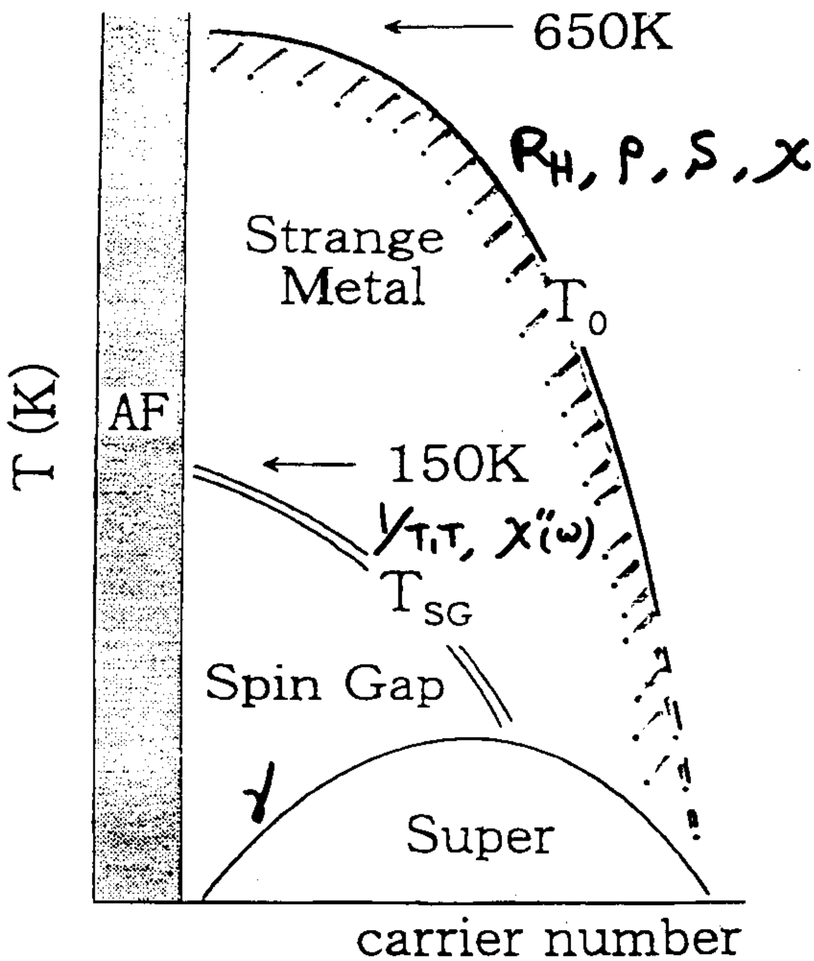


$La_{1.92}Sr_{0.08}Cu_{1-x}M_xO_4$ (M=Mn,Ni,Mg,Zn)
$La_{2-y}Sr_yCu_{1-x}Ti_xO_4$ (y-x=0.08)
$La_{2-y}Sr_yCu_{1-x}Co_xO_4$ (y-x=0.08)



Enhancement of anomalous behavior of R_H and S by magnetic impurities
suppression of anomalous behavior of R_H and S by nonmagnetic impurities

Anomalous metallic phase



Characteristics of 2D electrons with
large spatial spin correlation,
low energy spin fluctuations,
& no long range magnetic ordering.

(⇑ near the Mott insulating phase)

In order to clarify what characteristics of electron systems with 2D nature and near the Mott M–I phase boundary are relevant to High-T_c, studies on non-Cu system with similar characteristics are interesting.

$BaCo_{1-x}Ni_xS_2$

$La_{1+\alpha-x}Sr_xVS_{3+\alpha}$

$La_3Ni_2O_{7-\delta}$

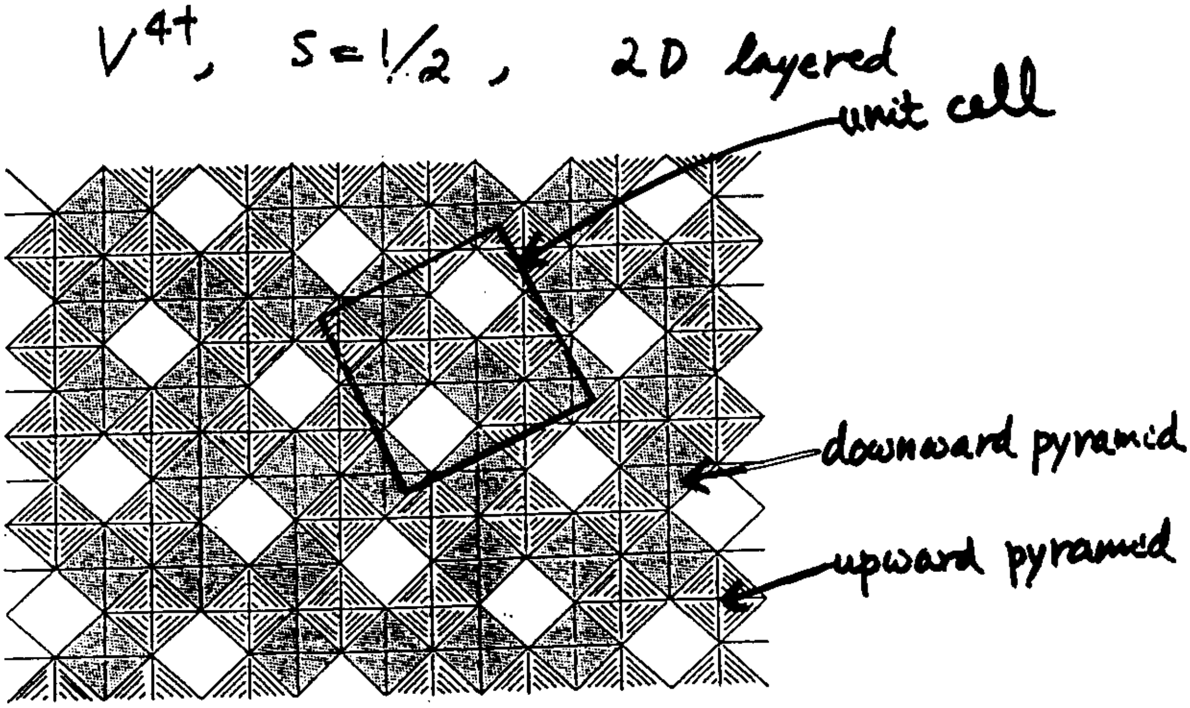
$La_4Ni_3O_{10-\delta}$

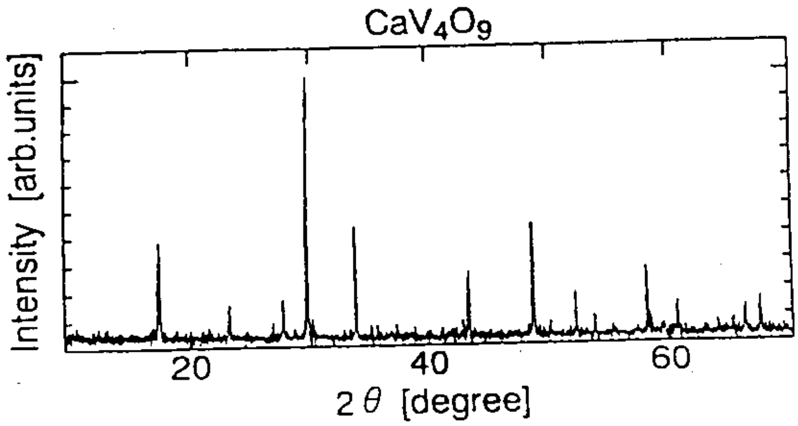
$\underline{CaV_3O_7}$

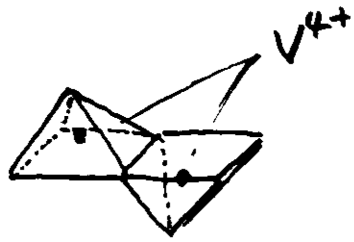
$\underline{CaV_4O_9}$

CaV_4O_9 ($\leftarrow CaV_nO_{2n+1}$ $n=2,3,4$)

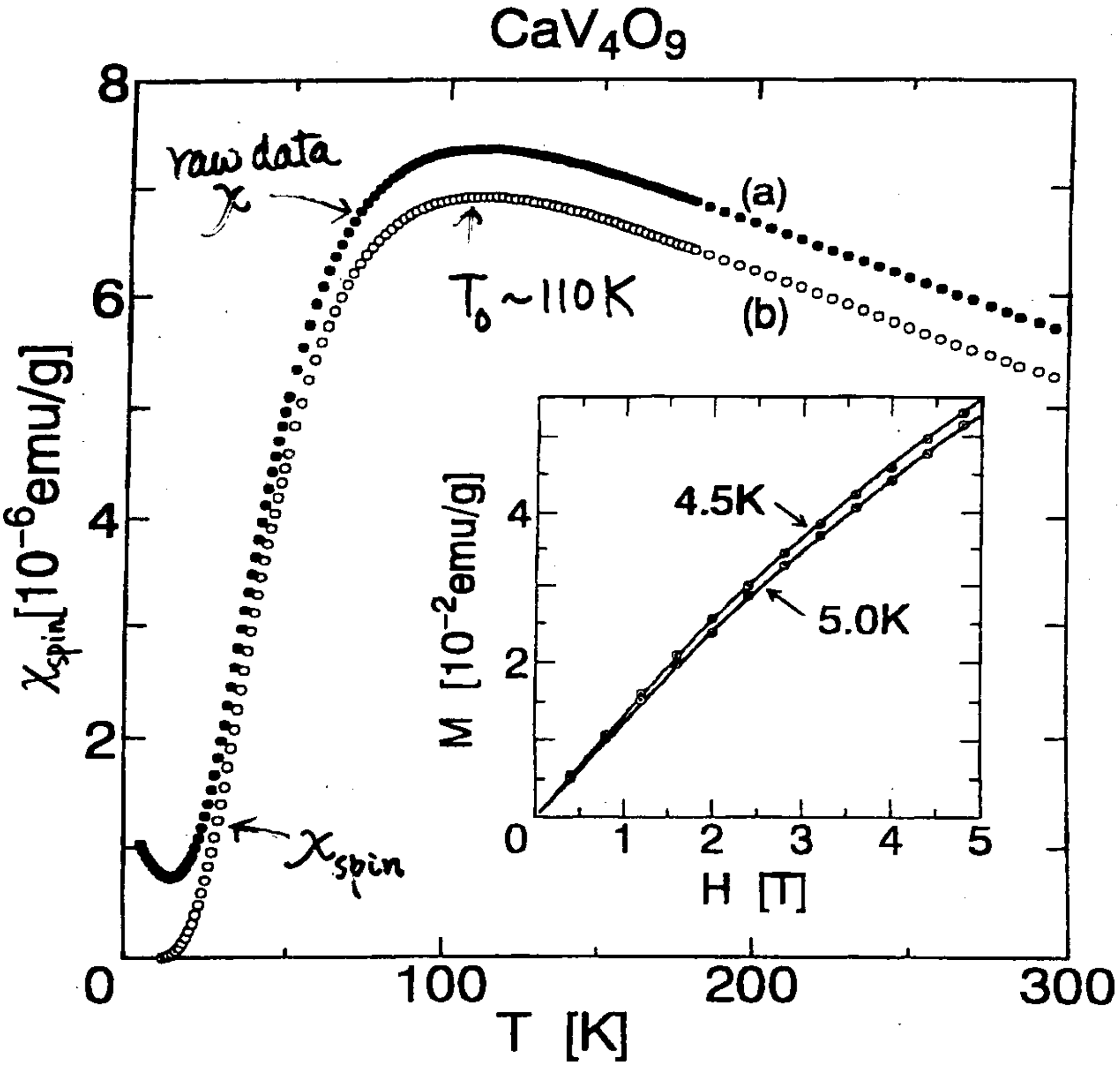
V^{4+}, $S=1/2$, 2D layered







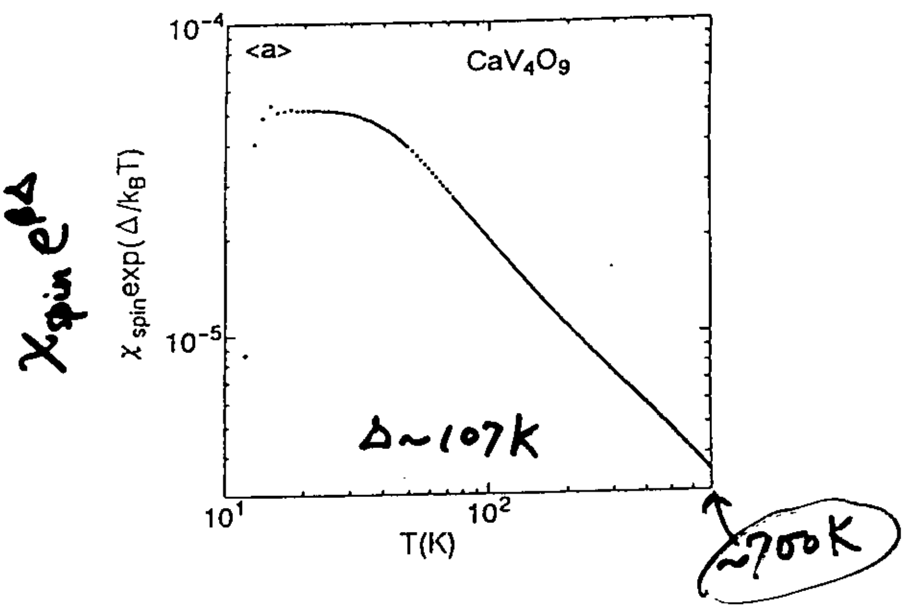
static magnetic susceptibility

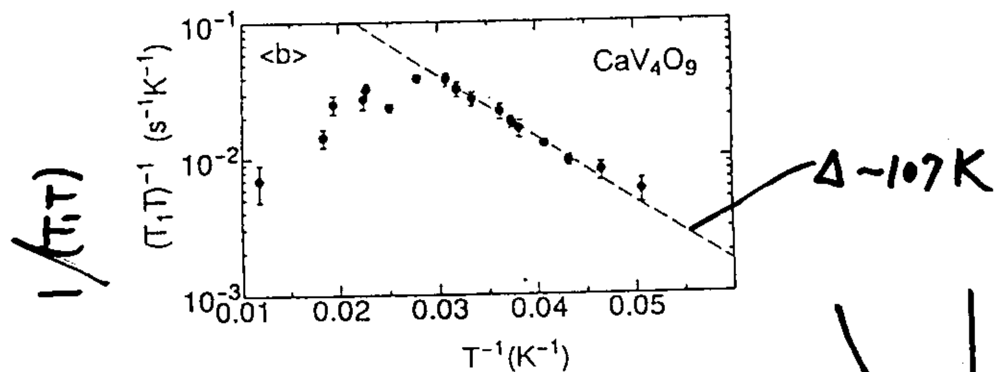


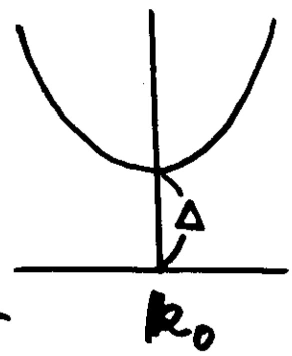
$$\chi = \chi_{spin} + \chi_0 + \alpha B_J\left(\frac{\mu H}{k_B T}\right)$$

↑ J=1

Taniguch et al.







$$\chi_{spin} \sim \text{const.} \times e^{-\Delta/k_BT}$$

$$1/(T_1T) \sim \text{const.} \times e^{-\Delta/k_BT}$$

⇓

2D spin gap system!

T dep. of χ and $1/T_1$

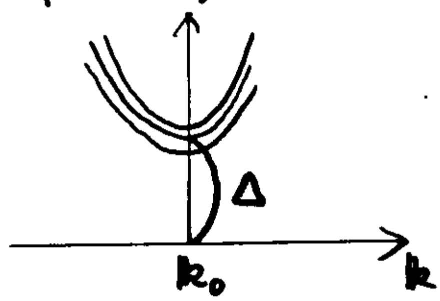
(i) $\chi \sim T^{d/2-1} e^{-\beta\Delta}$ (d : dim) ($T \ll \Delta$)

$$Z \cong \prod_k \left\{ 1 + e^{-\beta(\varepsilon_k + g\mu_B H)} + e^{-\beta\varepsilon_k} + e^{-\beta(\varepsilon_k - g\mu_B H)} \right\}$$

$$F = -\frac{1}{\beta}\ln Z \sim -\frac{1}{\beta}\sum_k \{1 + 2\cosh(\beta g\mu_B H)\} e^{-\beta\varepsilon_k}$$

$$\sum_k \longrightarrow \int N(\varepsilon)\, d\varepsilon$$

$N(\varepsilon)$: d-dependent



(ii) $\dfrac{1}{T_1 T} \sim e^{-\beta\Delta}$ (d=2)

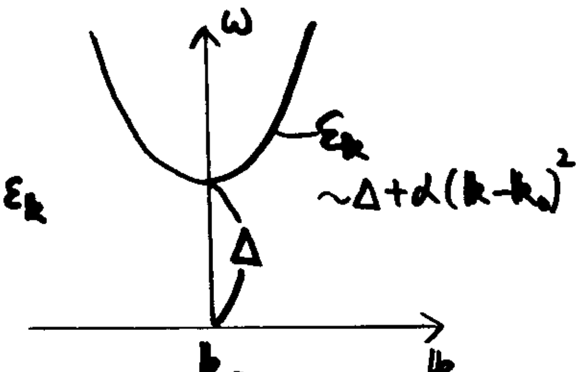
excited state $|k\rangle$

nuclear spin relaxation ← scattering

$|k\rangle \longrightarrow |k+q\rangle \quad q\sim 0$

$$\frac{1}{T_1} \propto \sum_{q(\sim 0)} S(q,\omega)$$

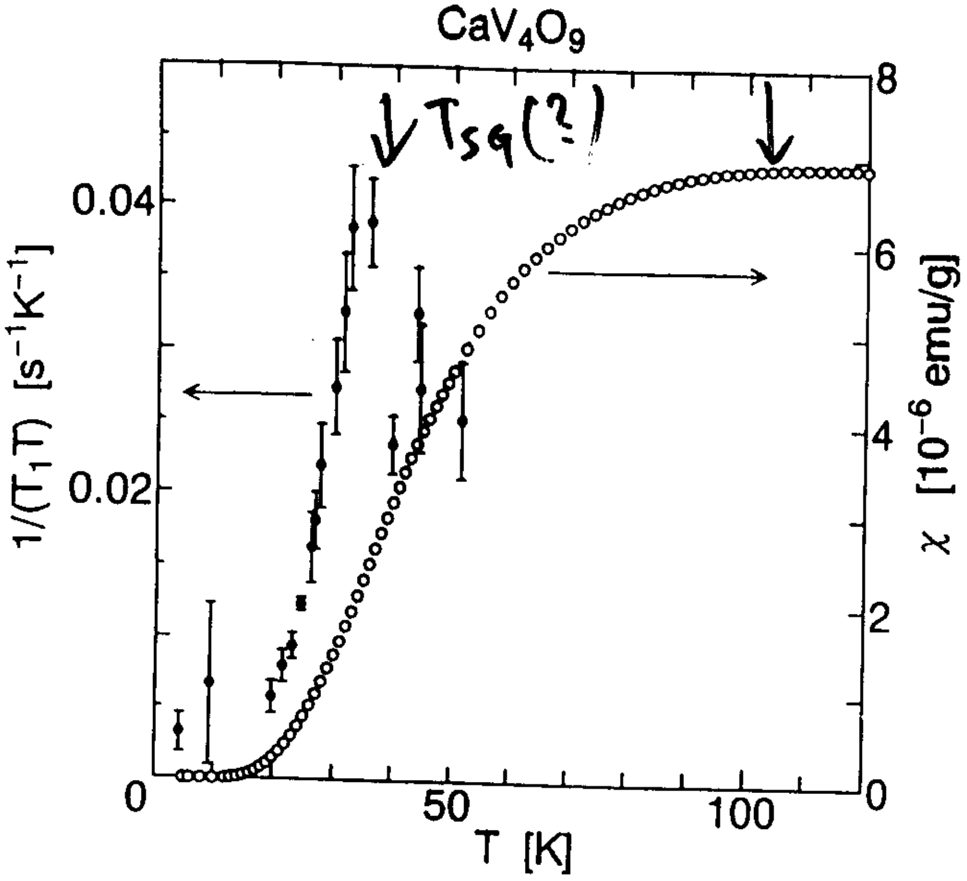
$$\sim \sum_q \sum_k \left|\langle k+q | S_q | k\rangle\right|^2 \times \delta(\varepsilon_{k+q} - \varepsilon_k - \hbar\omega_0) e^{-\beta\varepsilon_k}$$

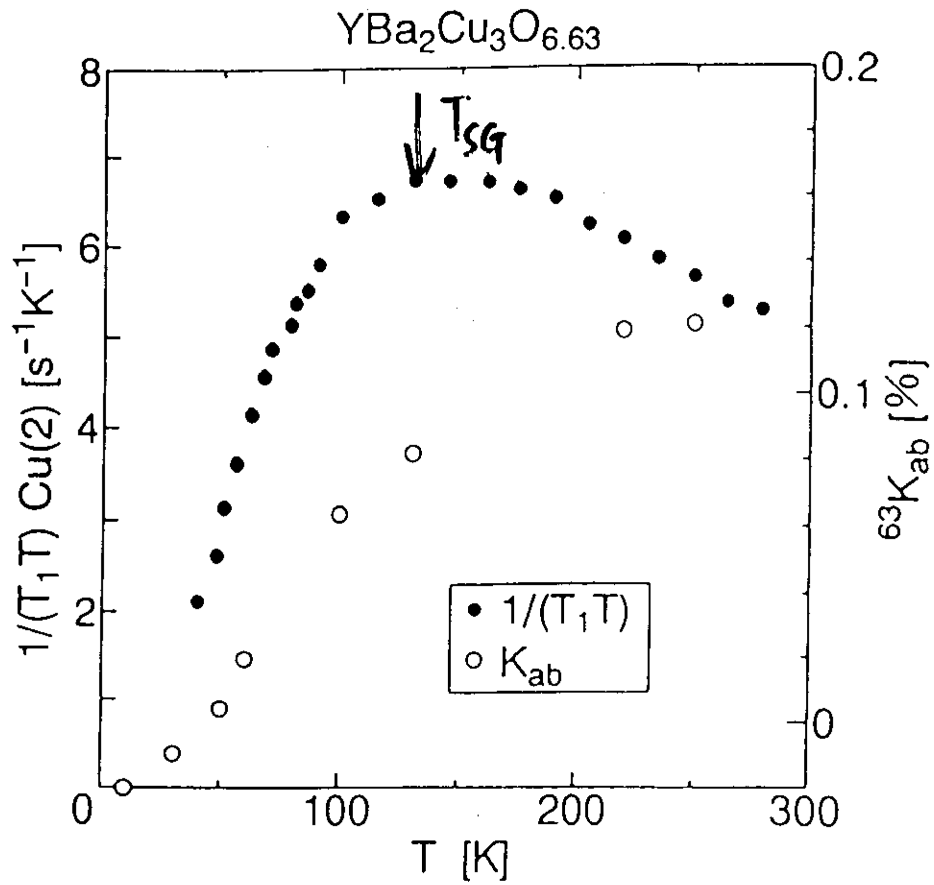


$\omega_0 \sim 0$

$$\sim \text{const.} \times \sum_k e^{-\beta\varepsilon_k}$$

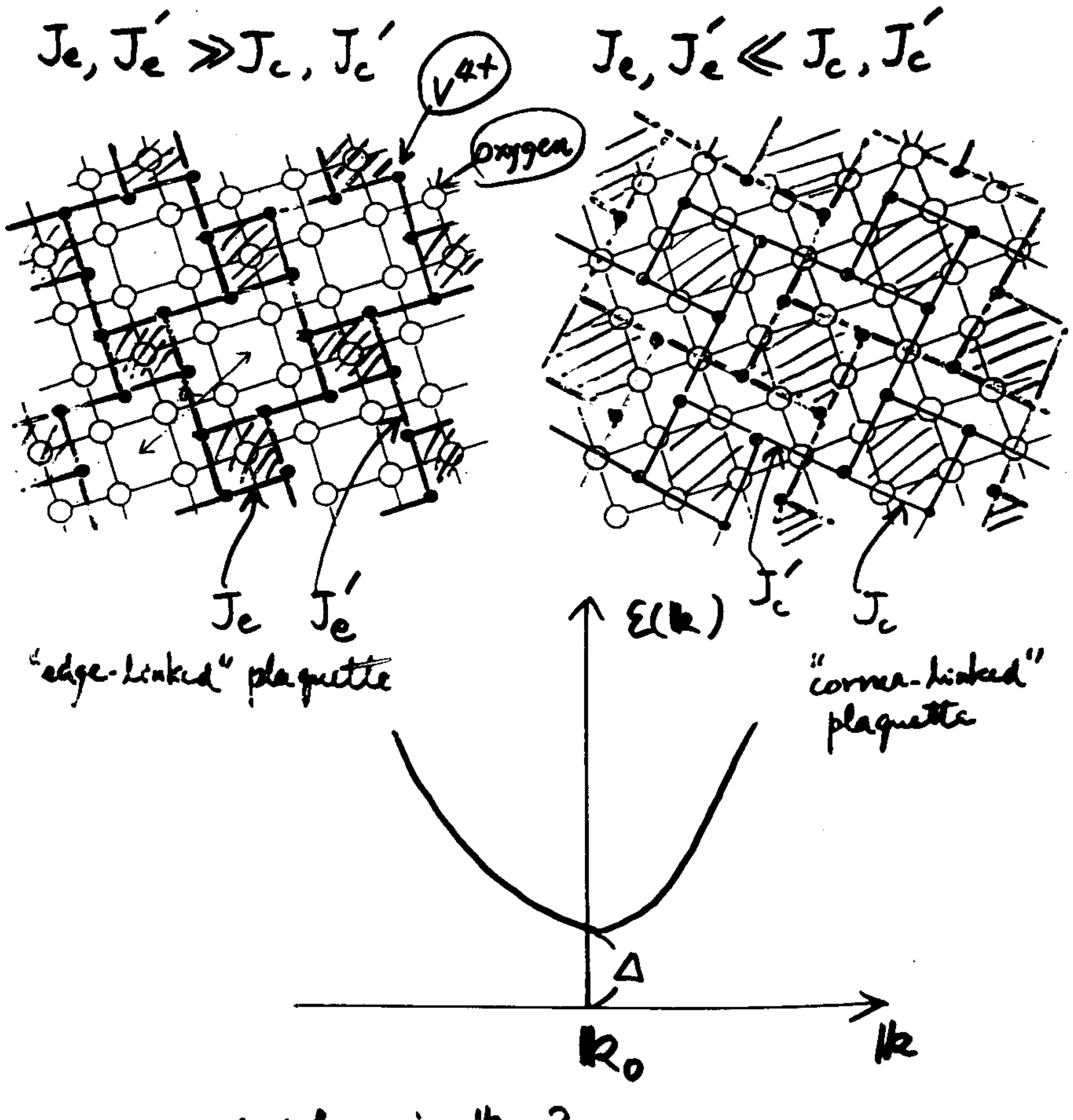
$$\sim \int_\Delta^\infty e^{-\beta\varepsilon} d\varepsilon \sim \frac{1}{\beta} e^{-\beta\Delta}$$


CaV4O9
1/(T1T) [s-1K-1]
0.04
0.02
0
50
100
T [K]
χ [10-6 emu/g]
8
6
4
2
0
TSG(?)


YBa2Cu3O6.63
1/(T1T) Cu(2) [s-1K-1]
8
6
4
2
0
100
200
300
T [K]
0.2
0.1
0
63Kab [%]
TSG
1/(T1T)
Kab

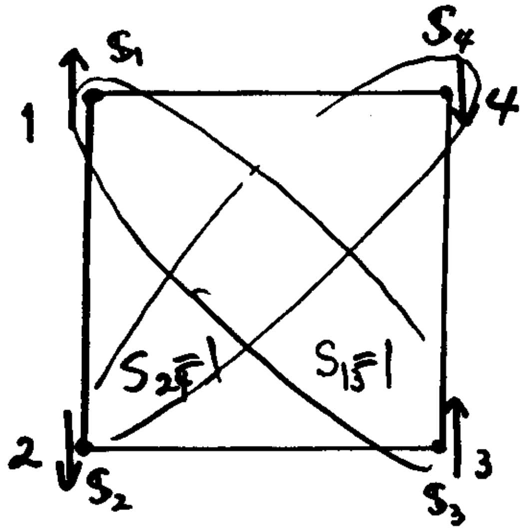
What is the origin of spin gap?

⟶ plaquette unit ?

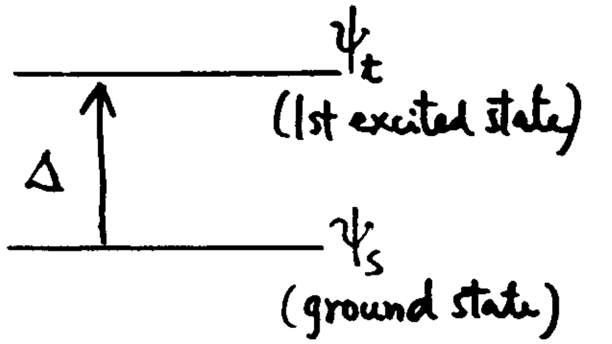


- where is $\mathbf{k}_0$?
- Structure factor distribution for neutron magnetic scattering ?

Isolated plaquette



$$\mathbf{S}_{13} = \mathbf{S}_1 + \mathbf{S}_3$$
$$\mathbf{S}_{24} = \mathbf{S}_2 + \mathbf{S}_4$$



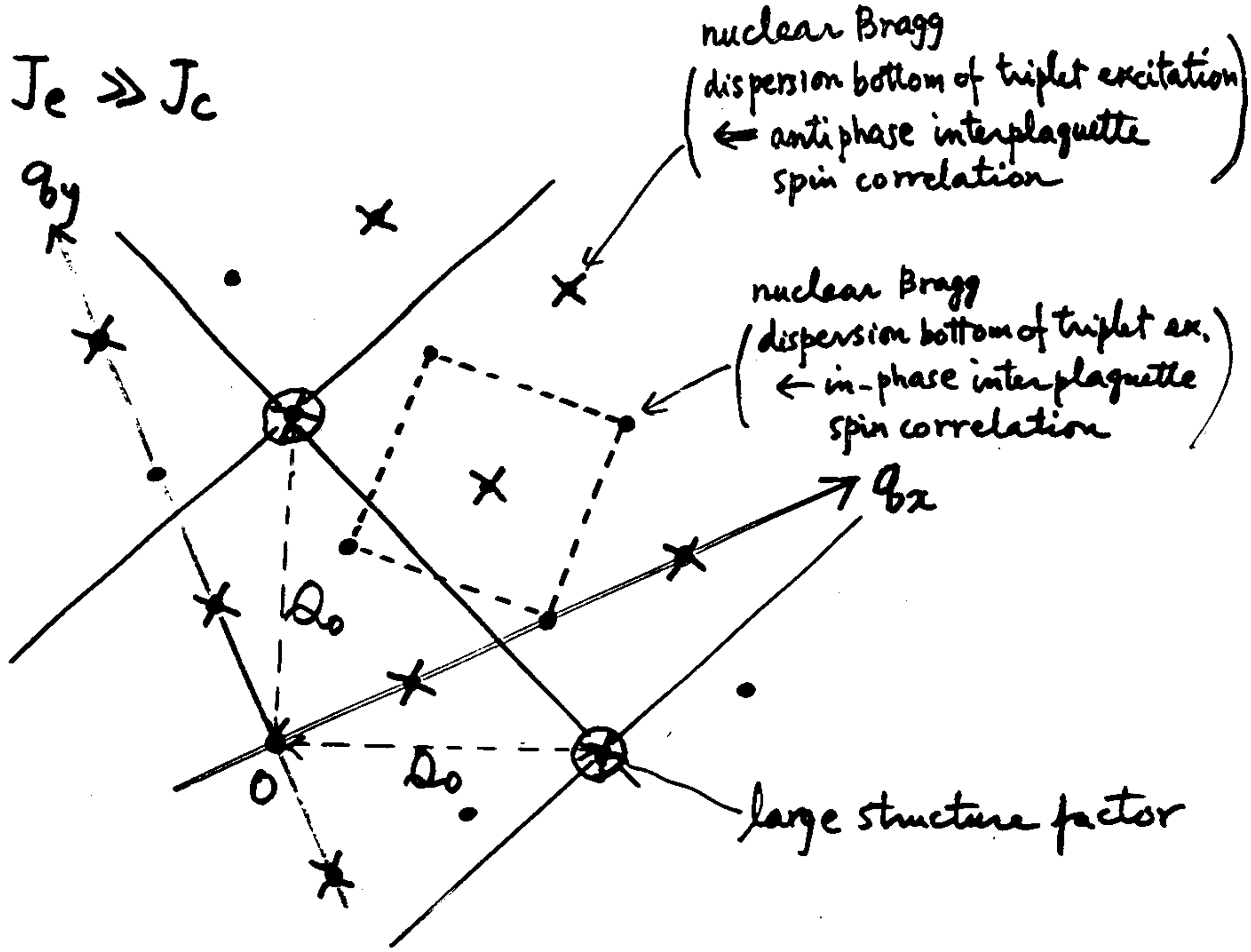
$S=1 \; (\Leftarrow \mathbf{S}_{13} + \mathbf{S}_{24})$

$S=0 \; (\Leftarrow \mathbf{S}_{13} + \mathbf{S}_{24})$

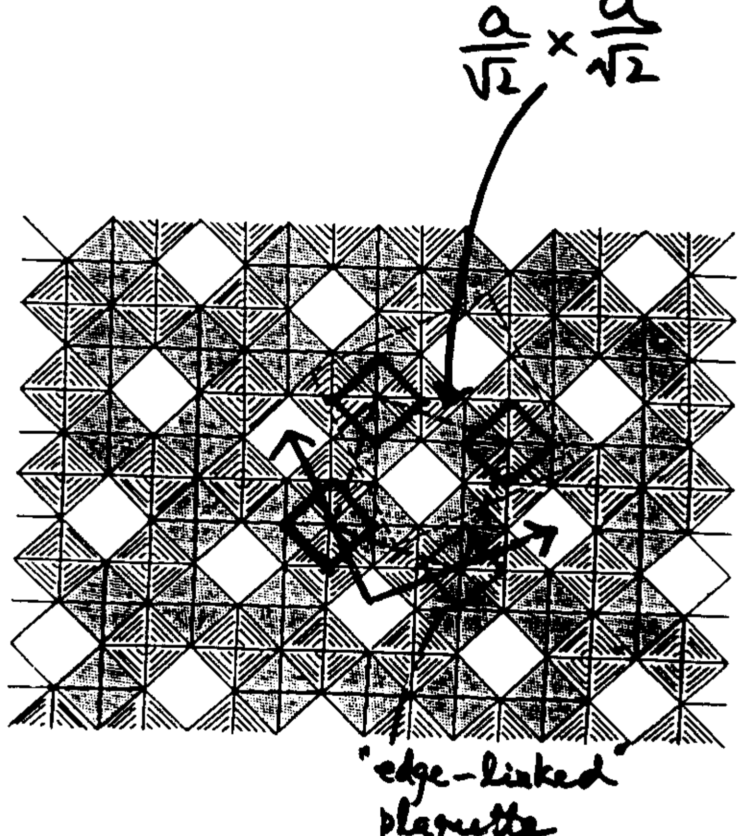
$$\psi_s \propto \left\{ \alpha_1\beta_2\alpha_3\beta_4 + \beta_1\alpha_2\beta_3\alpha_4 - \frac{1}{2}\left(\alpha_1\alpha_2\beta_3\beta_4 + \beta_1\alpha_2\alpha_3\beta_4 + \alpha_1\beta_2\beta_3\alpha_4 + \beta_1\beta_2\alpha_3\alpha_4\right) \right\}$$

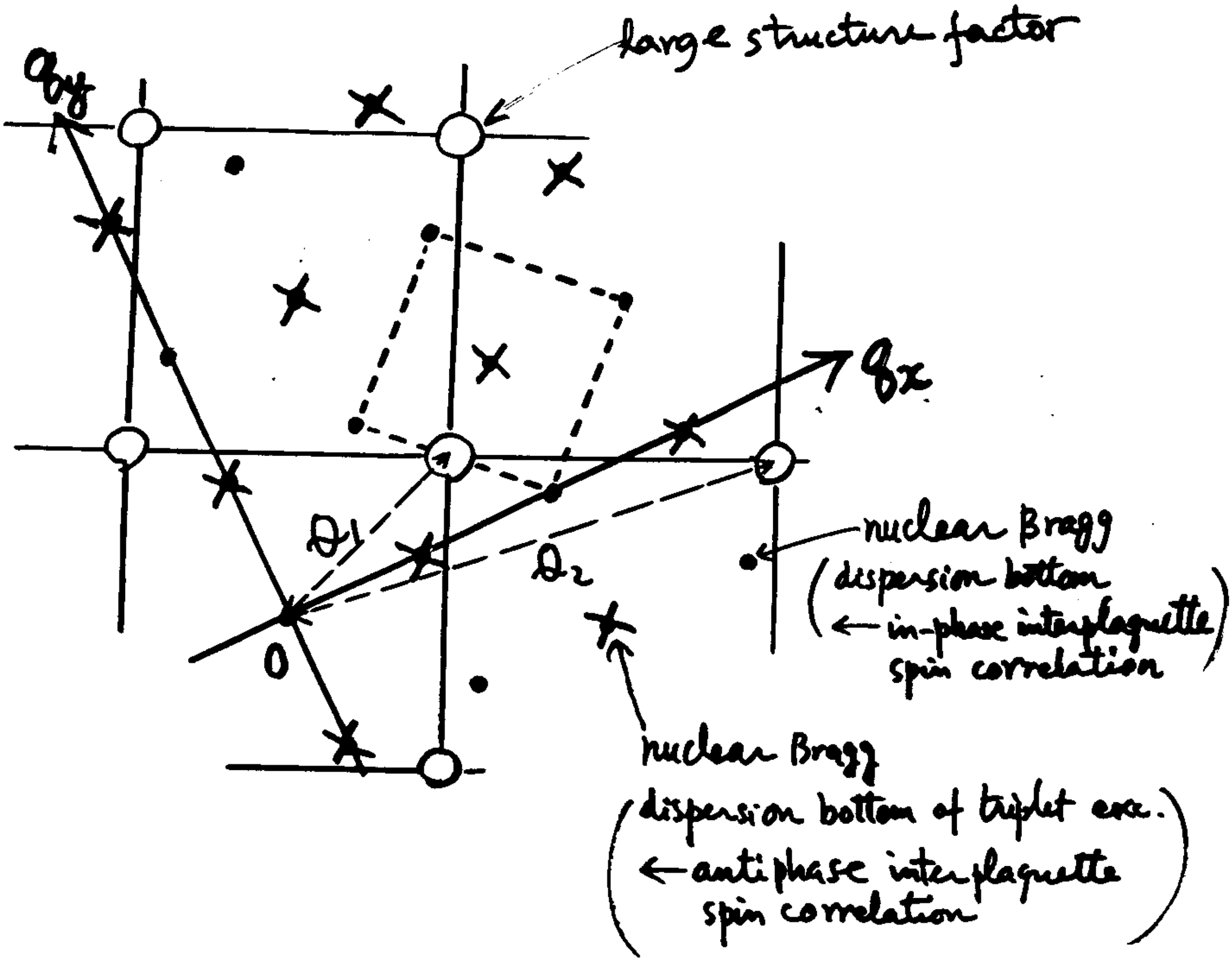
$$\psi_t \propto \left(\alpha_1\beta_2\beta_3\beta_4 + \beta_1\beta_2\alpha_3\beta_4 - \beta_1\alpha_2\beta_3\beta_4 - \beta_1\beta_2\beta_3\alpha_4\right)$$

$J_e \gg J_c$

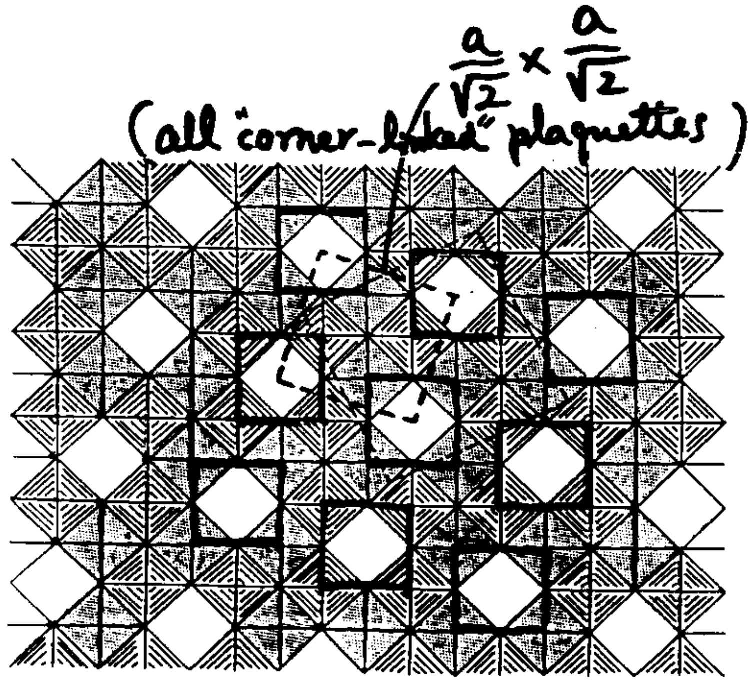


CASE I

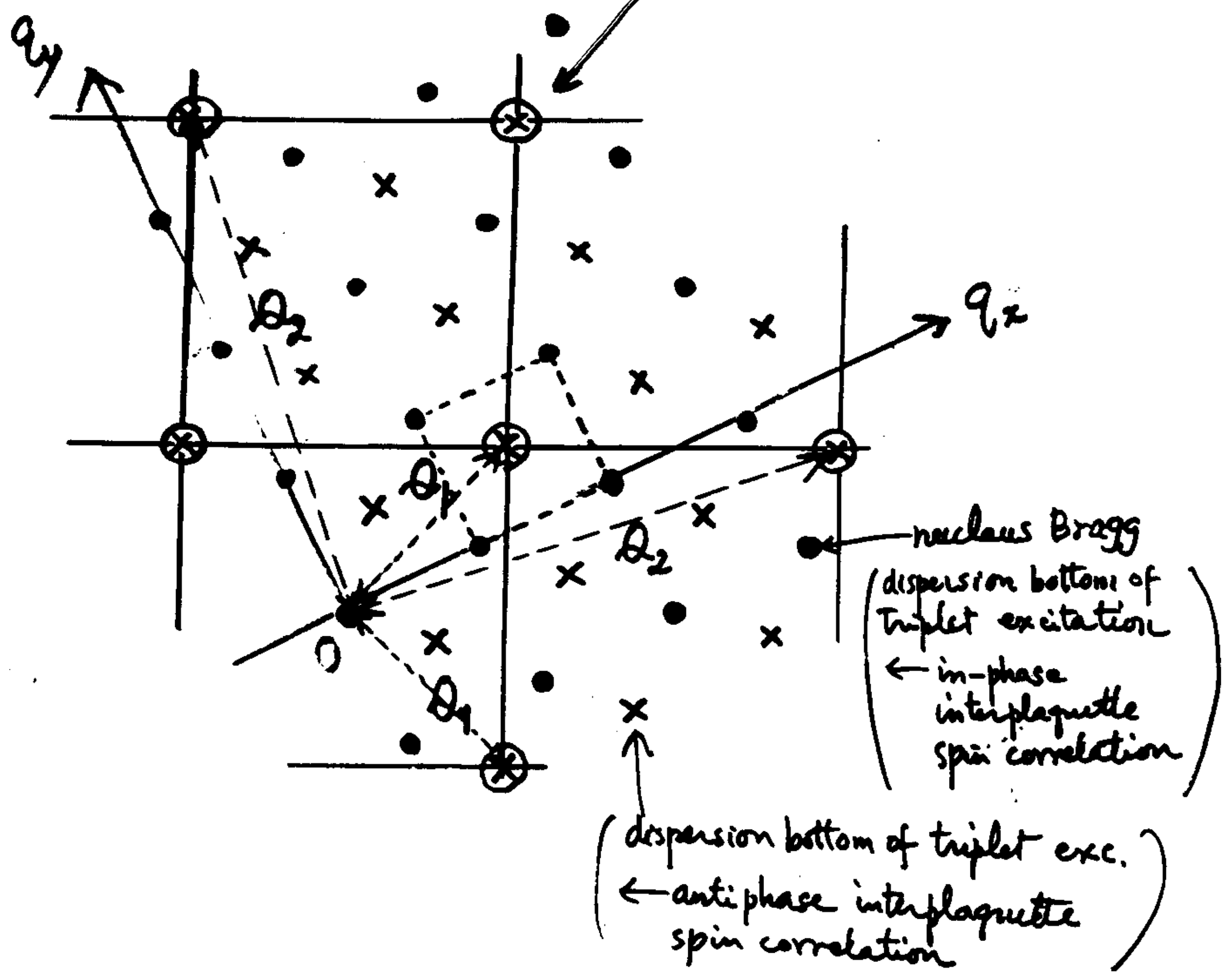



large structure factor
q_y
q_x
Q_1
Q_2
0
nuclear Bragg
(dispersion bottom
← in-phase interplaquette
spin correlation)
nuclear Bragg
(dispersion bottom of triplet exc.
← antiphase interplaquette
spin correlation)

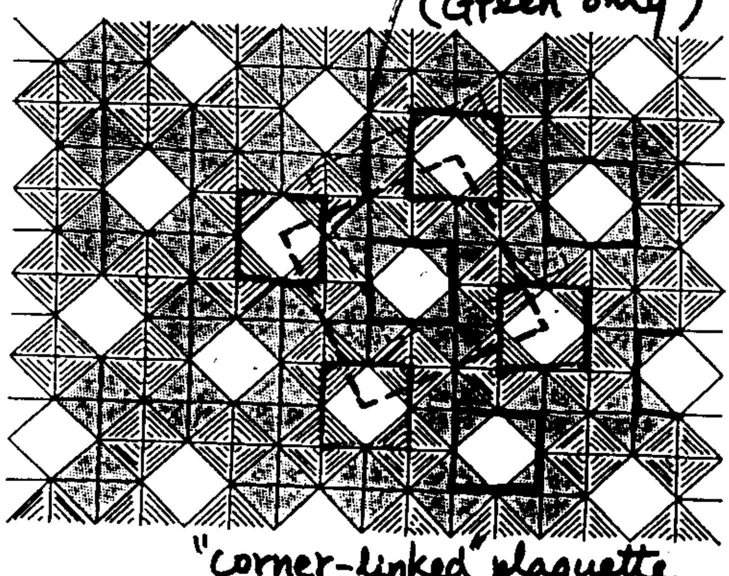
CASE III


$\frac{a}{\sqrt{2}} \times \frac{a}{\sqrt{2}}$
(all "corner-linked" plaquettes)

$J_c \gg J_e$



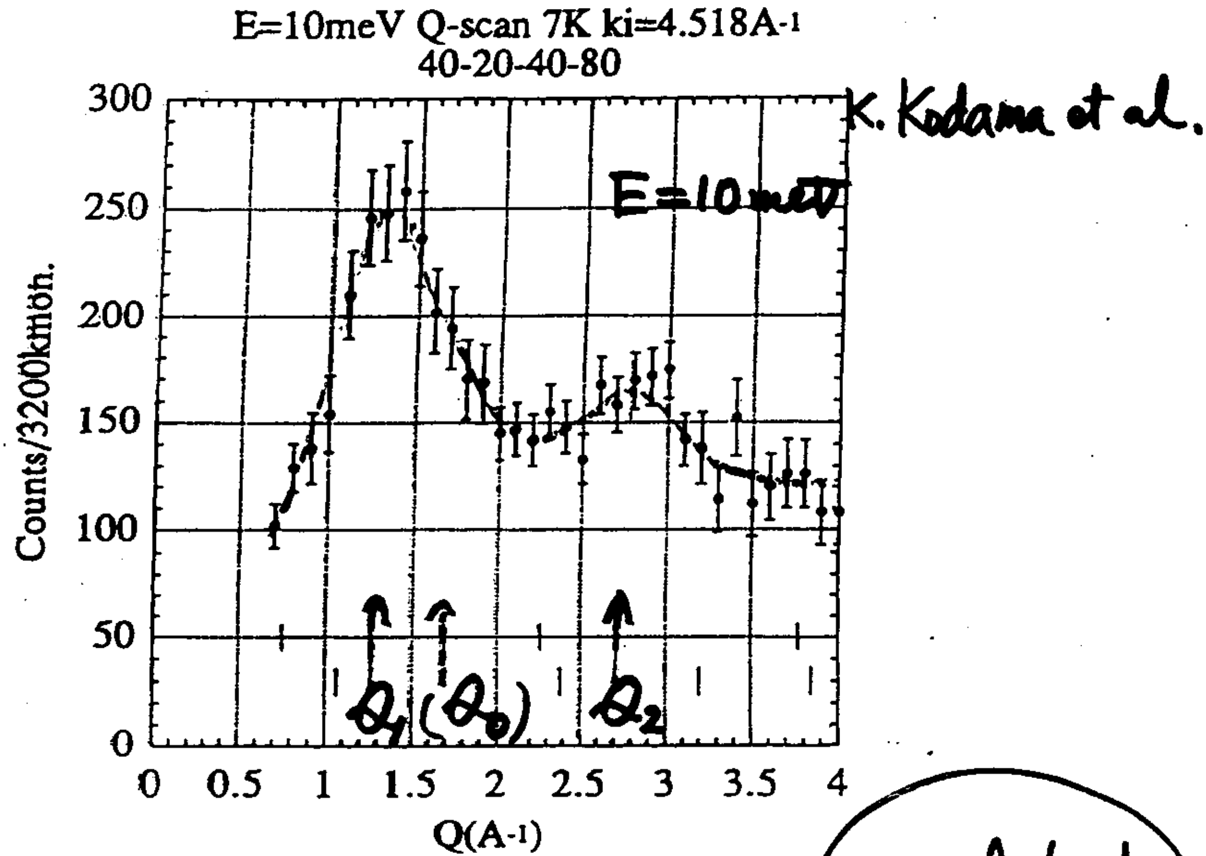
CASE II

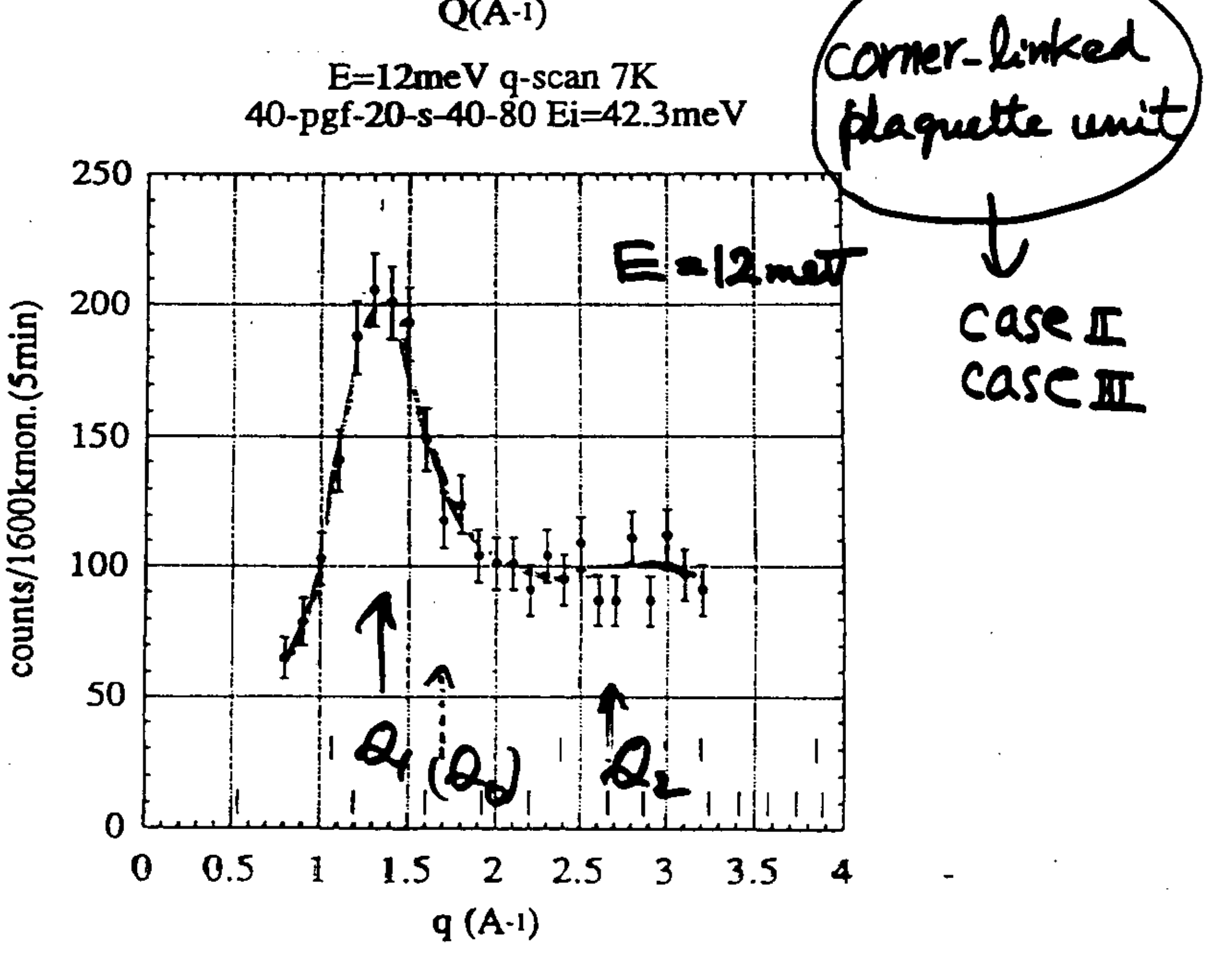


"corner-linked" plaquette

Neutron Inelastic Measurements

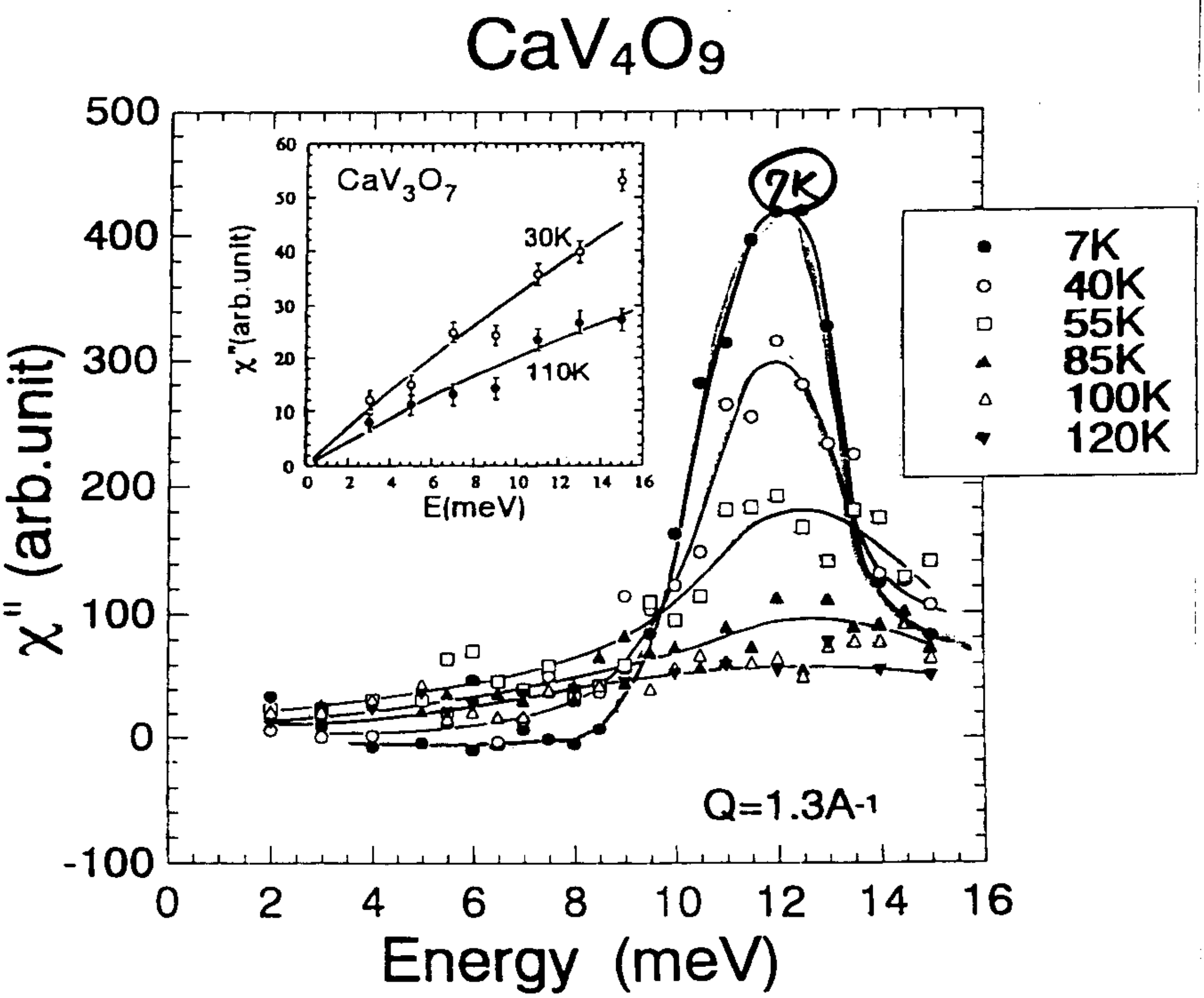
powder





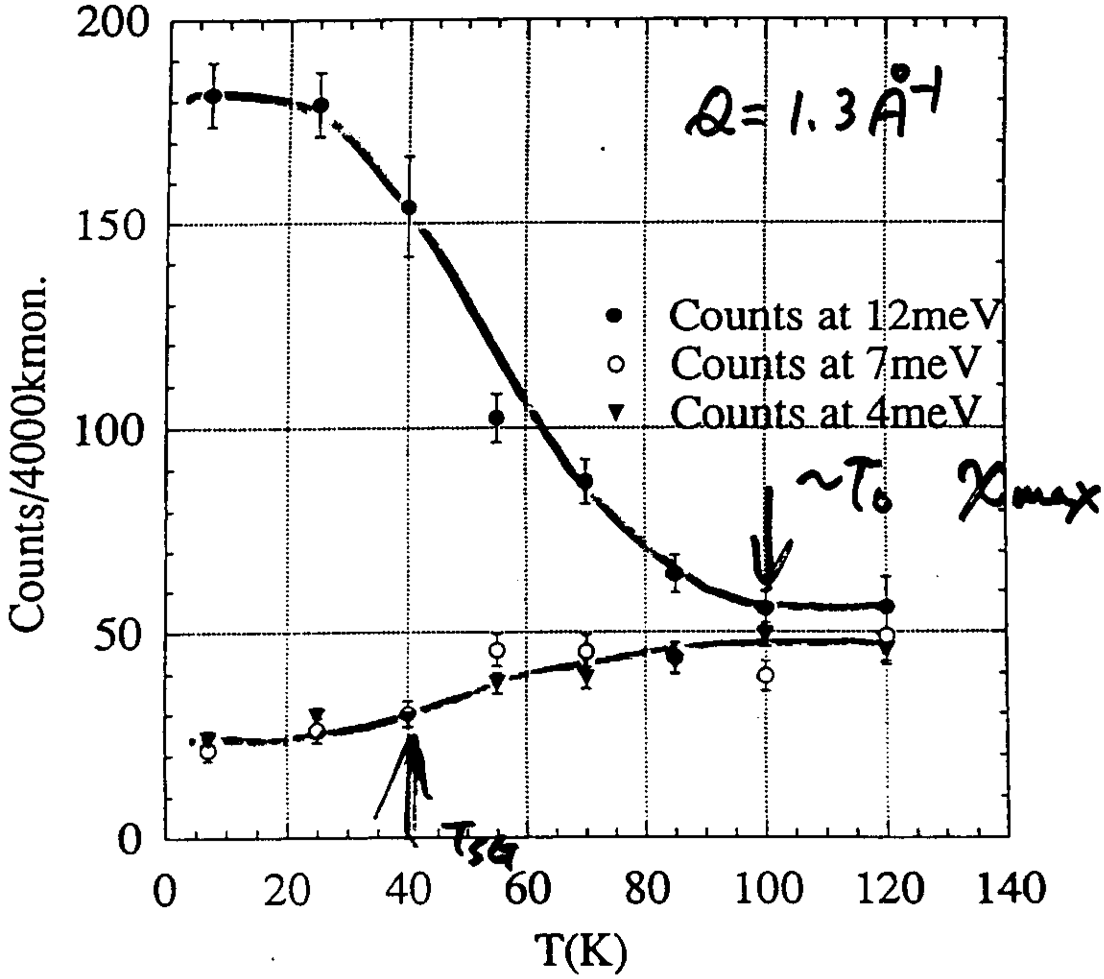
powder data

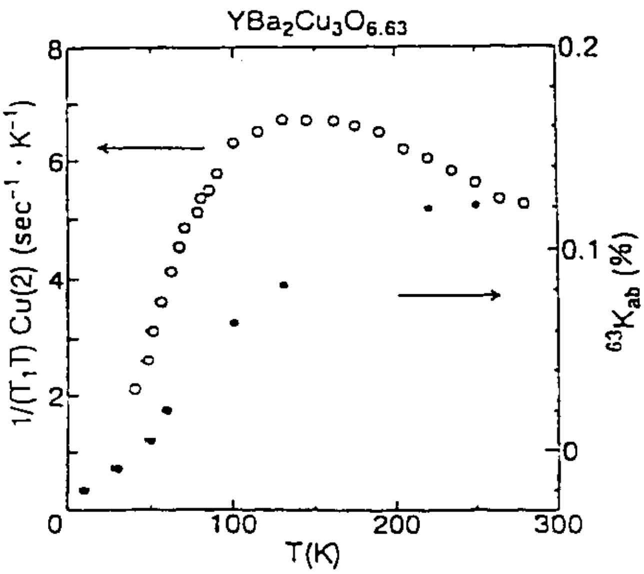
$Q = 1.3\,\text{Å}^{-1}$ ($\sim Q_1$)



K. Kodama et al.

T-dep at 12meV,7meV data



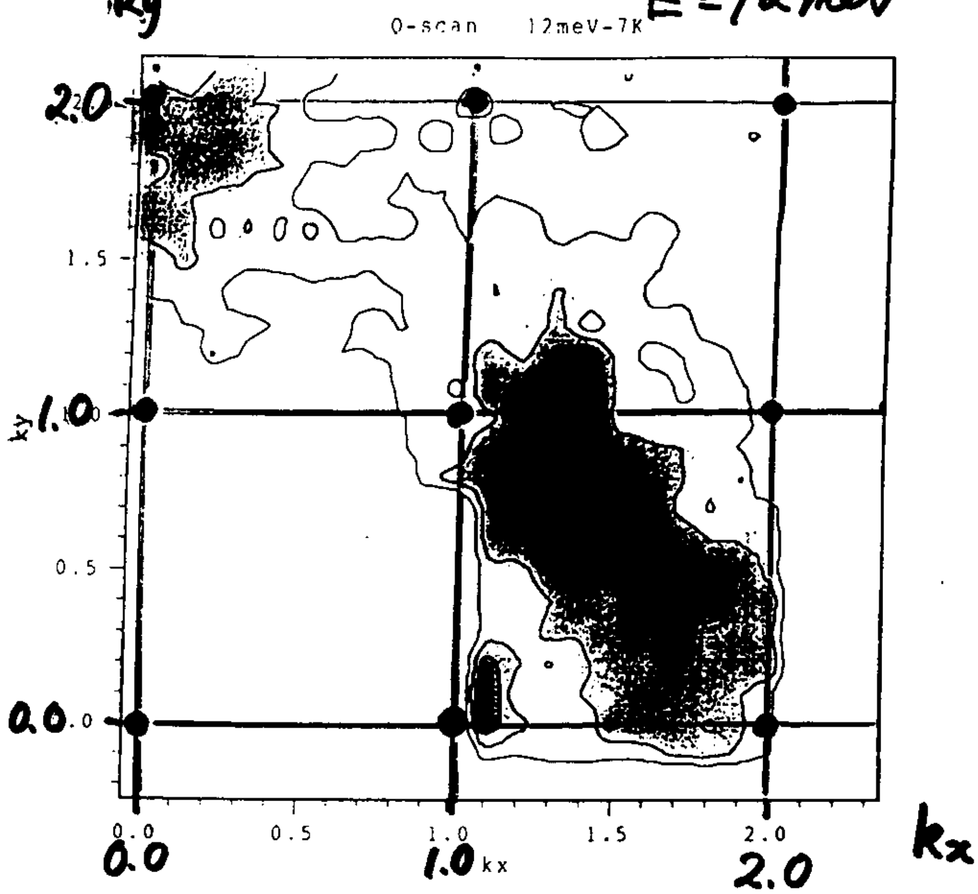


Single crystal study

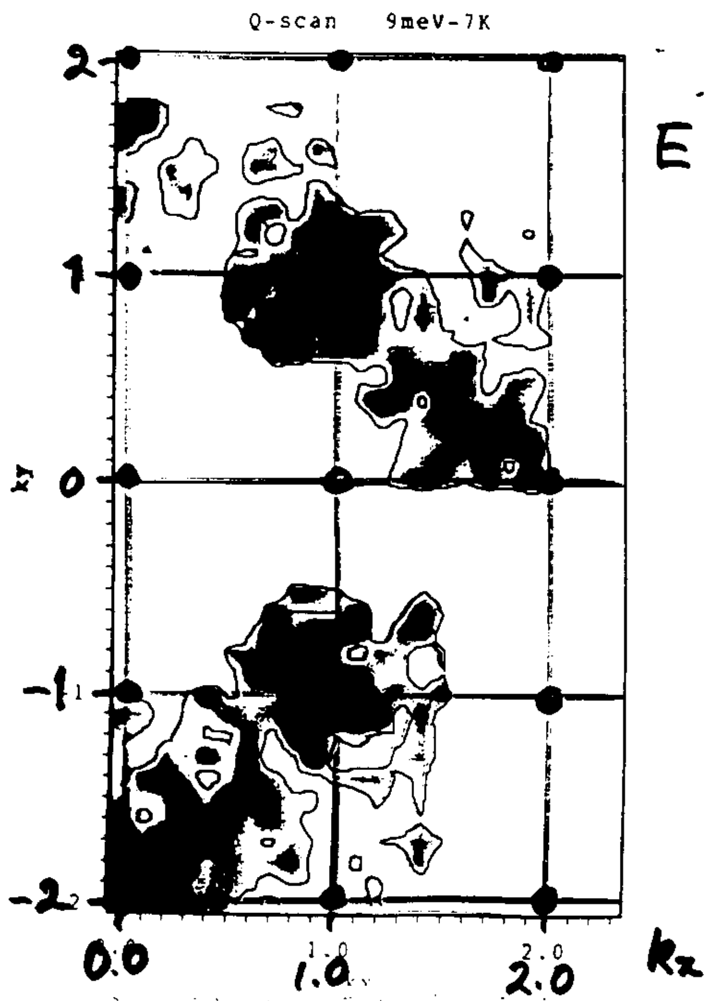
CaV_4O_9

Intensity map

E = 12 meV

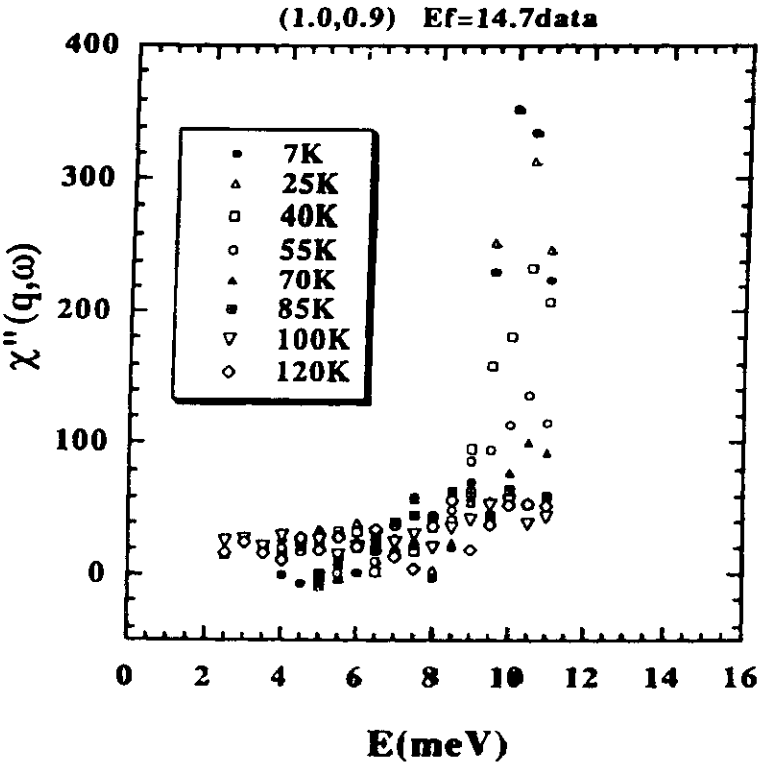


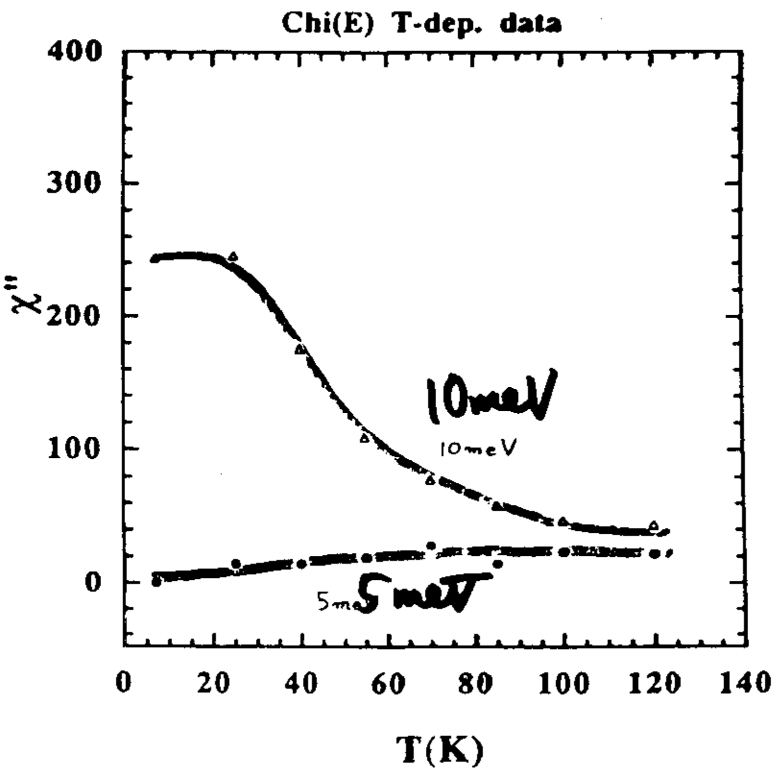
E = 9 meV



K. Kodama et al.

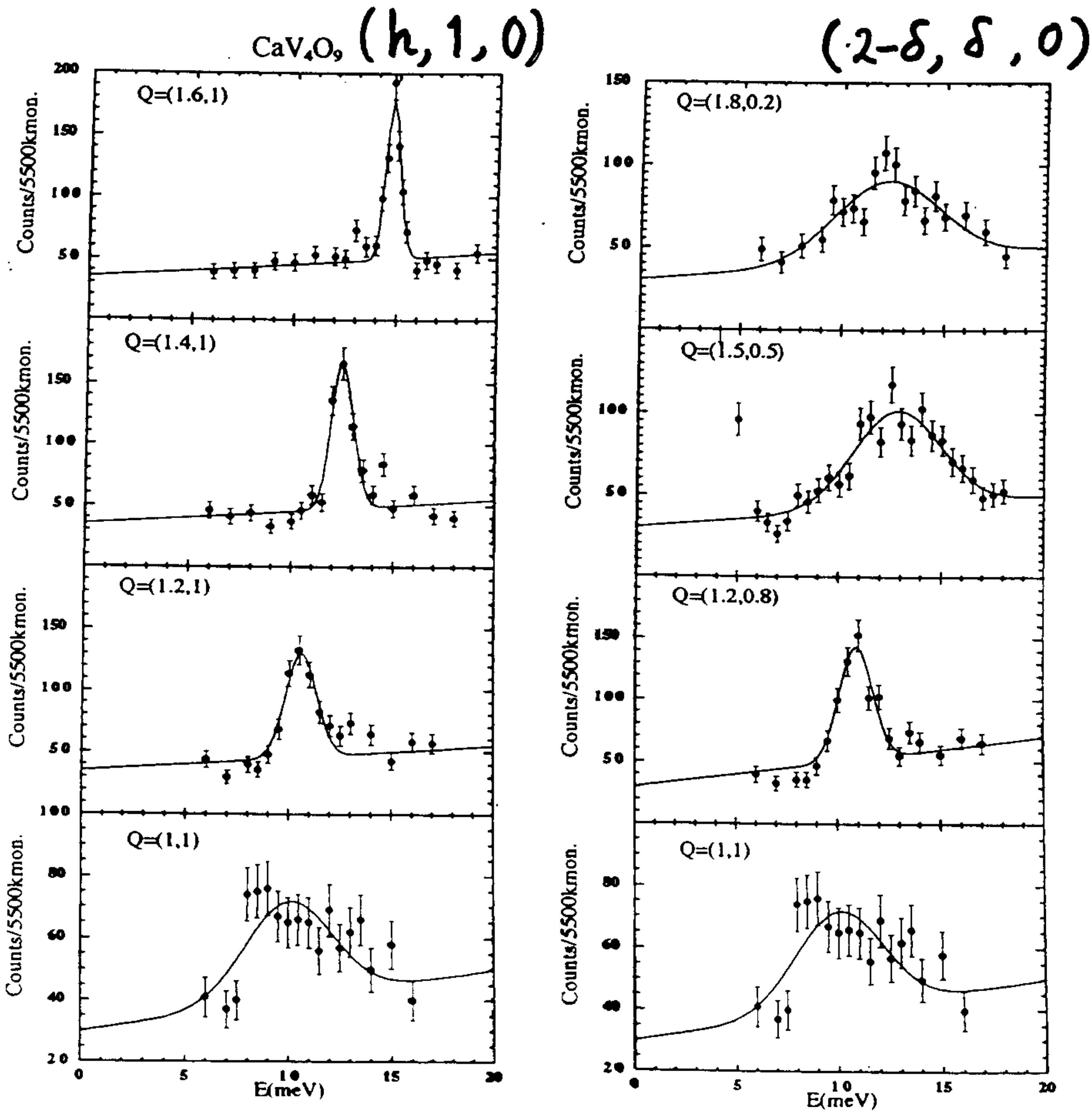
Single crystal data

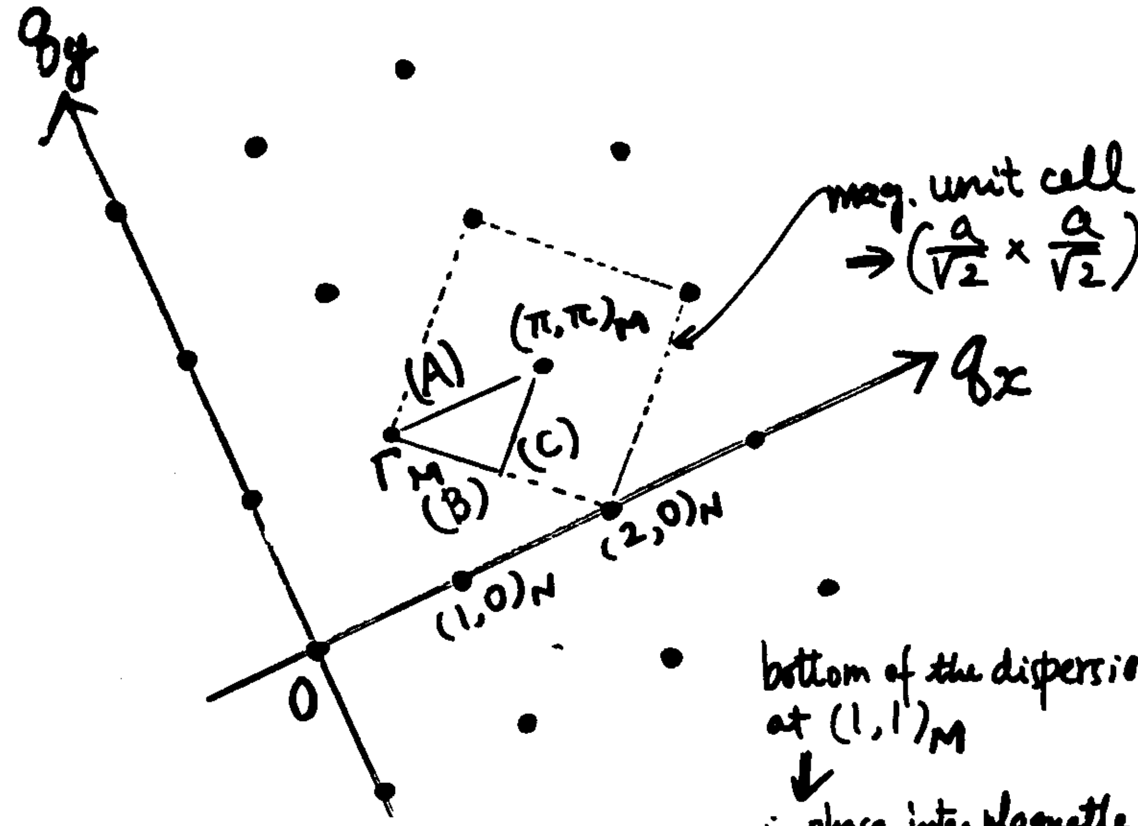




essentially similar to corresponding powder data

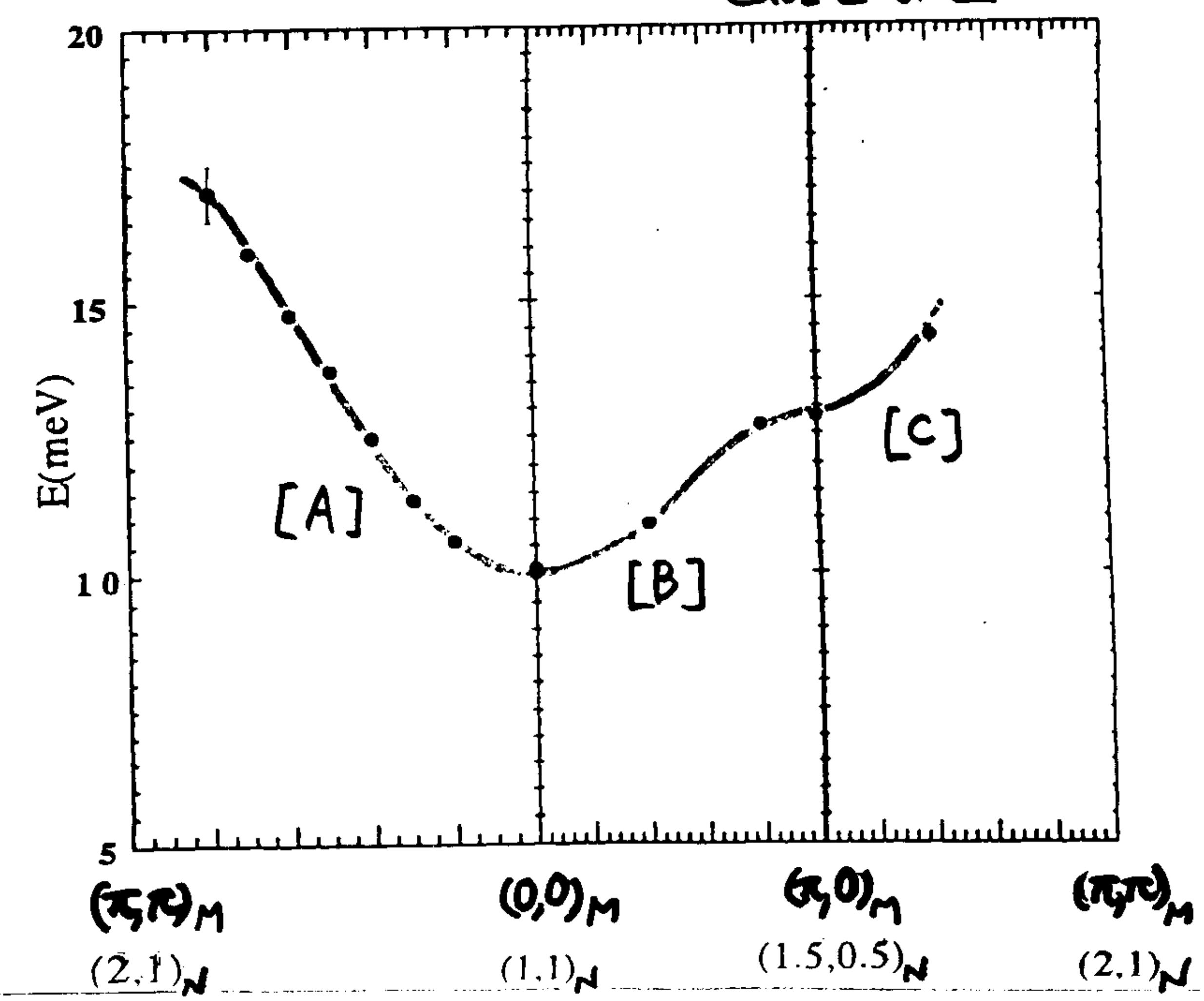
Example results of dispersion study



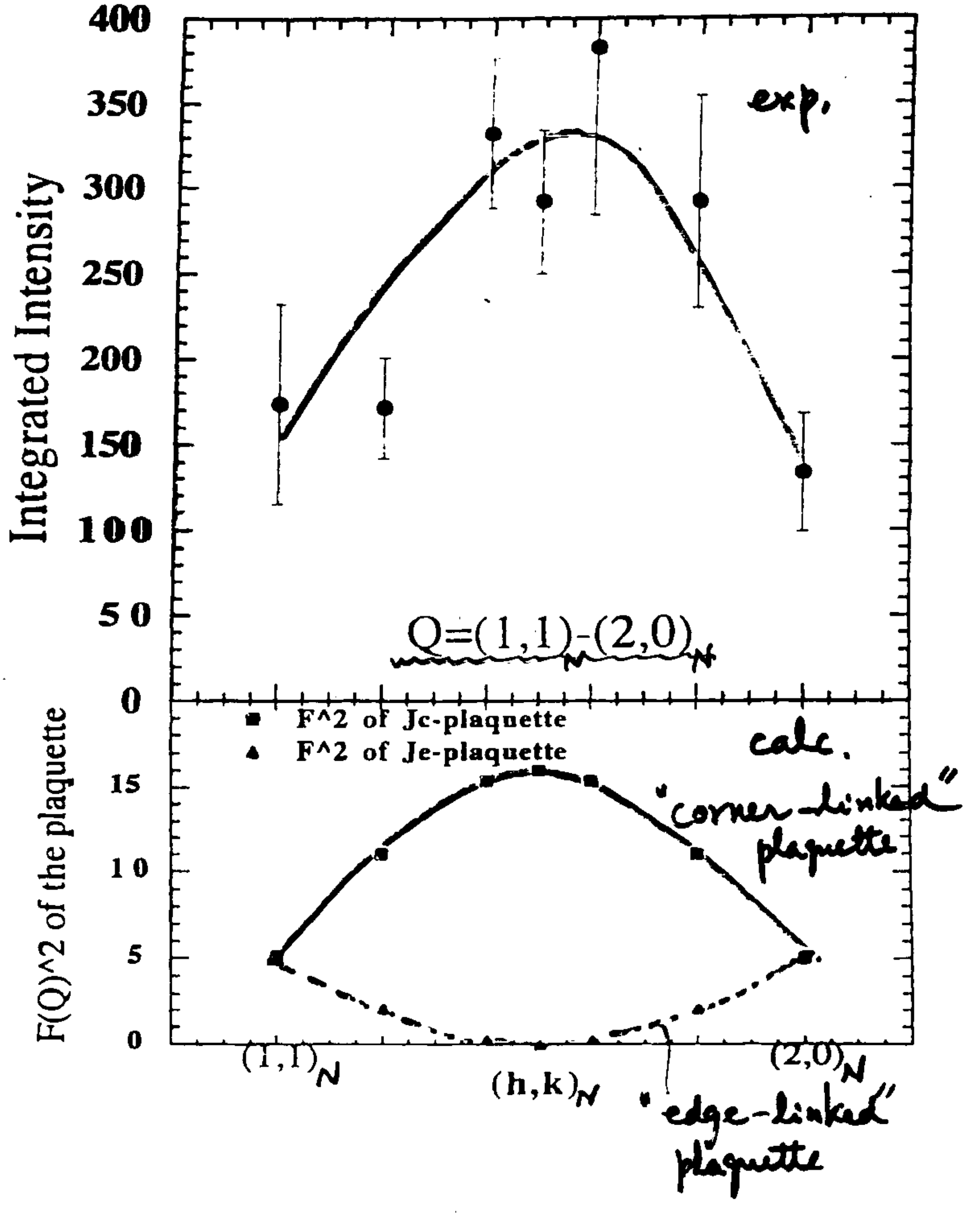


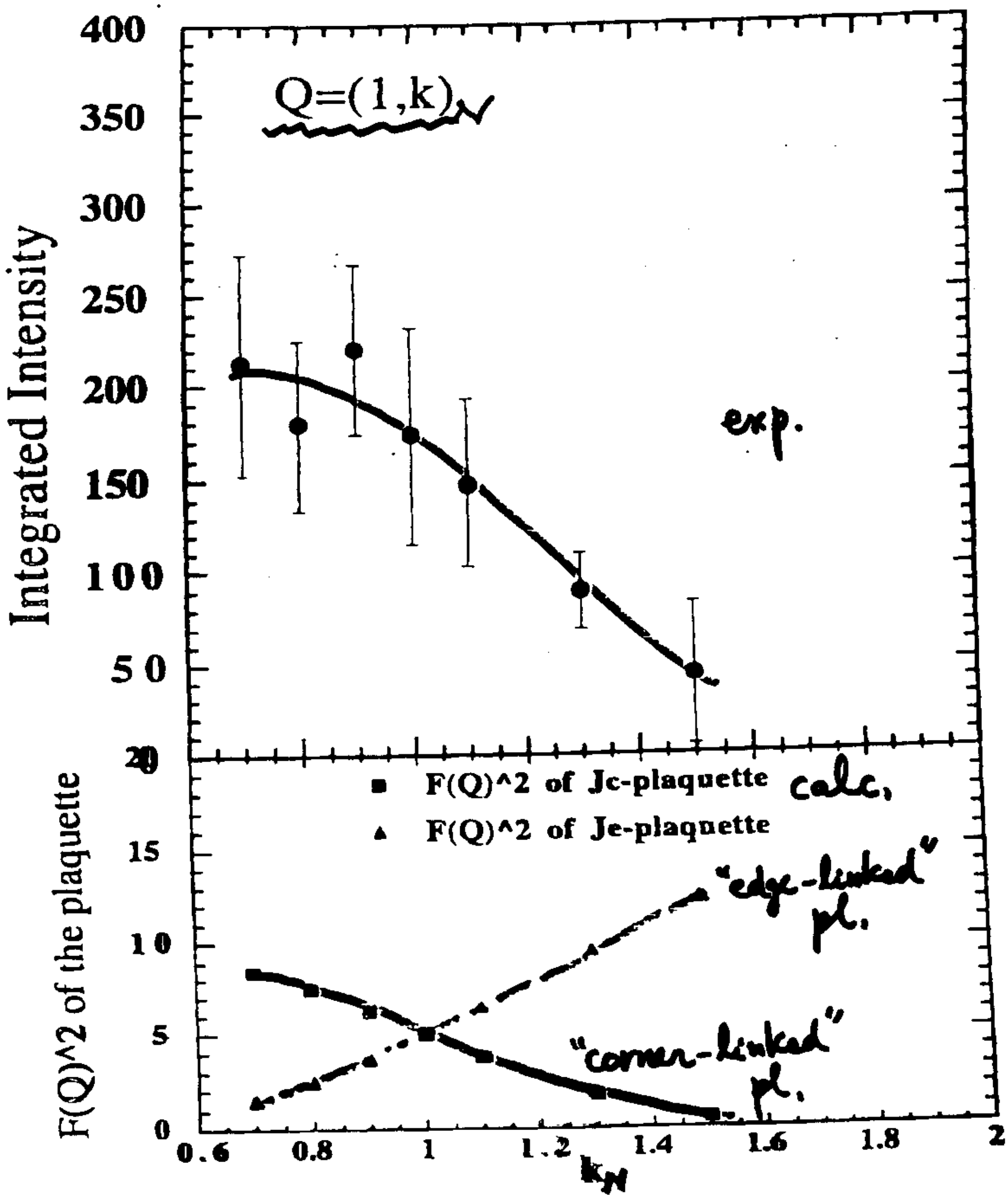
bottom of the dispersion at $(1,1)_M$
↓
in-phase interplaquette spin correlation
⇓
CASE I or III

CaV_4O_9

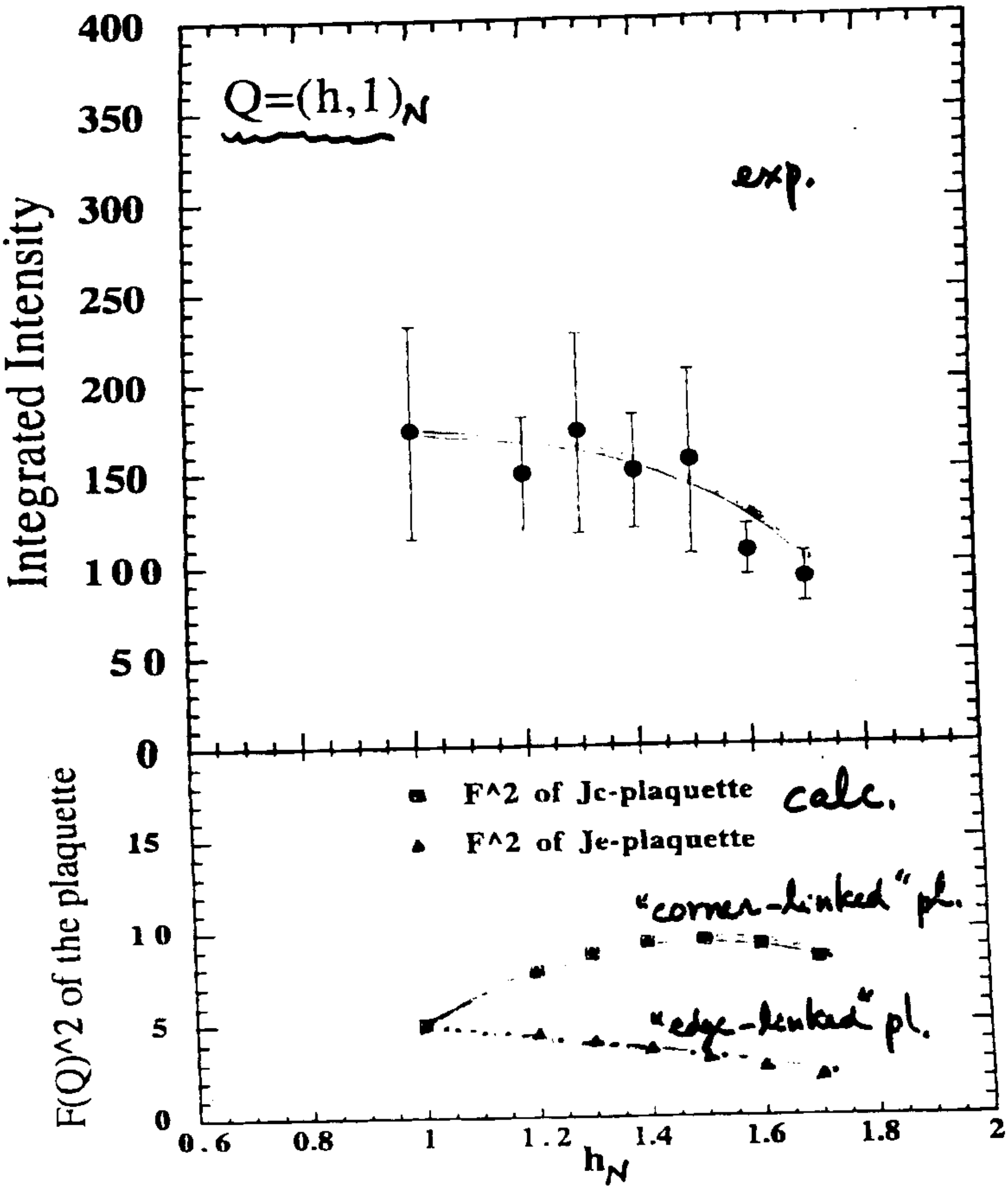


Structure factor of neutron scattering





Q=(1,k)
Integrated Intensity
400
350
300
250
200
150
100
50
exp.
F(Q)^2 of the plaquette
20
15
10
5
0
F(Q)^2 of Jc-plaquette
F(Q)^2 of Je-plaquette
calc.
"edge-linked" pl.
"corner-linked" pl.
0.6
0.8
1
1.2
1.4
1.6
1.8
2

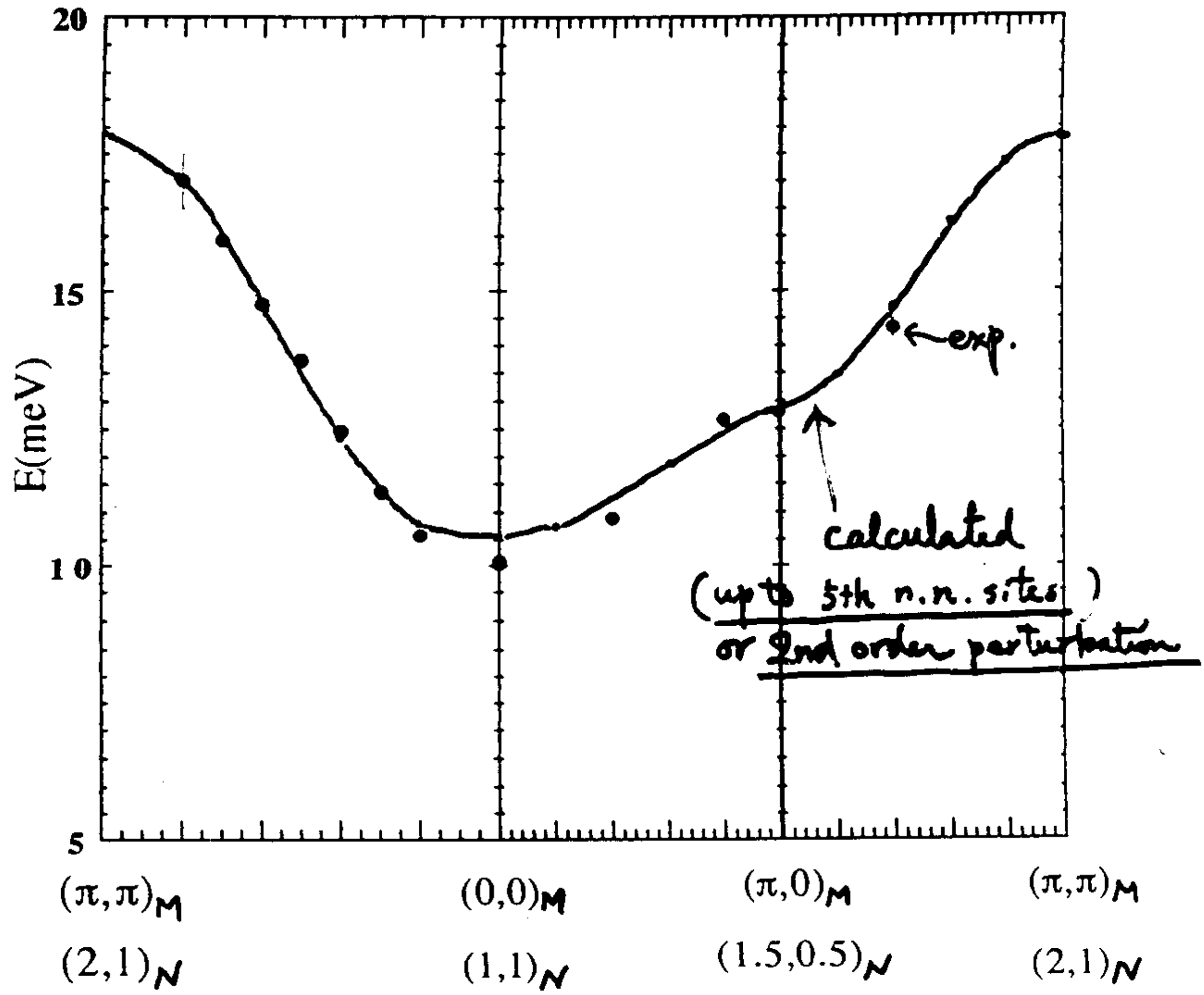


discrepancy
from higher order effect ?

$$\varepsilon_t(k) - \varepsilon_s = J_c + \frac{J_c'}{3}(\cos k_x a + \cos k_y a) + \left(-\frac{J_e}{3} + \frac{J_e'}{6}\right) \times 4 \cos\frac{k_x a}{2} \cos\frac{k_y a}{2}$$
$$+ \cdots\cdots$$

four parameters J_c, J_c'
J_e, J_e'

CaV_4O_9

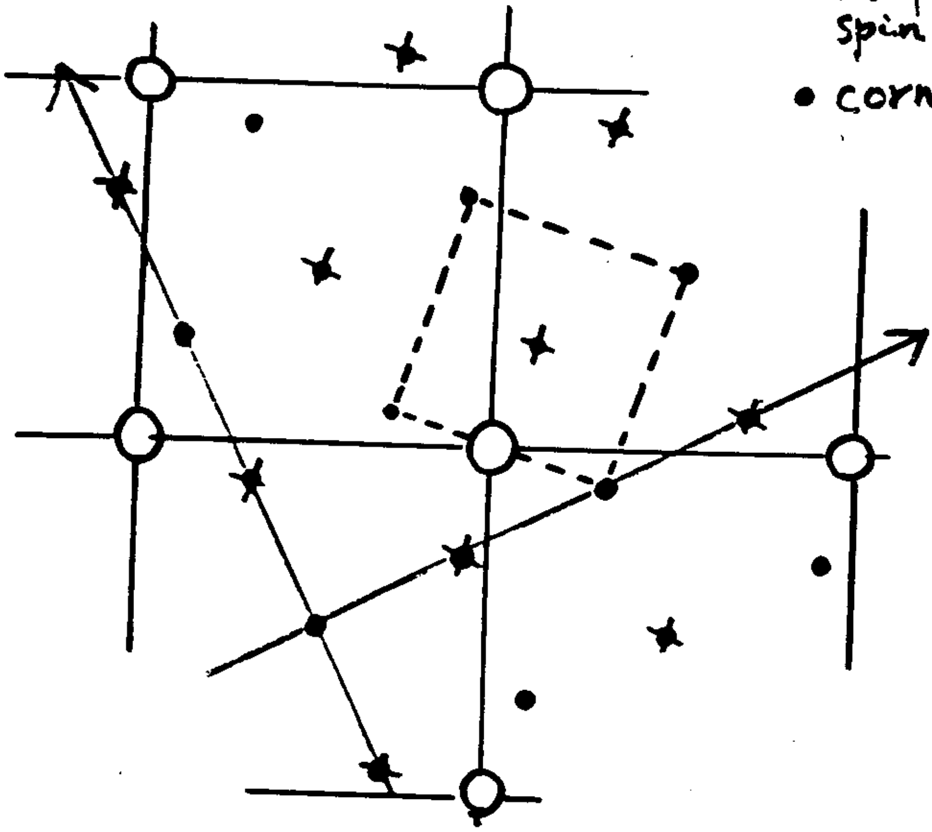


J_c	14.9 meV	J_c	13.4
J_c'	1.3	J_c'	1.5
$J_e = J_e'$	5.9	J_e	1.3
		J_e'	−3.7

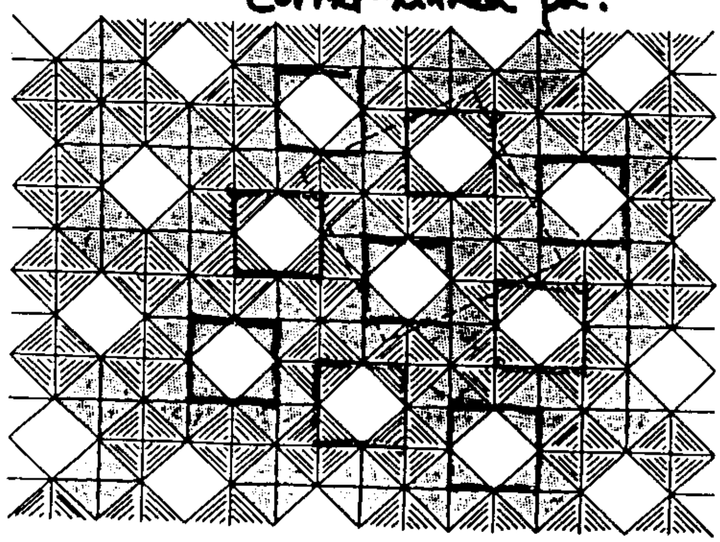
K. Kodama, H. Harashina, M.S.

CASE III

⟸ • mag. unit cell $\frac{a}{\sqrt{2}} \times \frac{a}{\sqrt{2}}$
• in-phase interplaquette spin correlation
• corner-linked plaquette

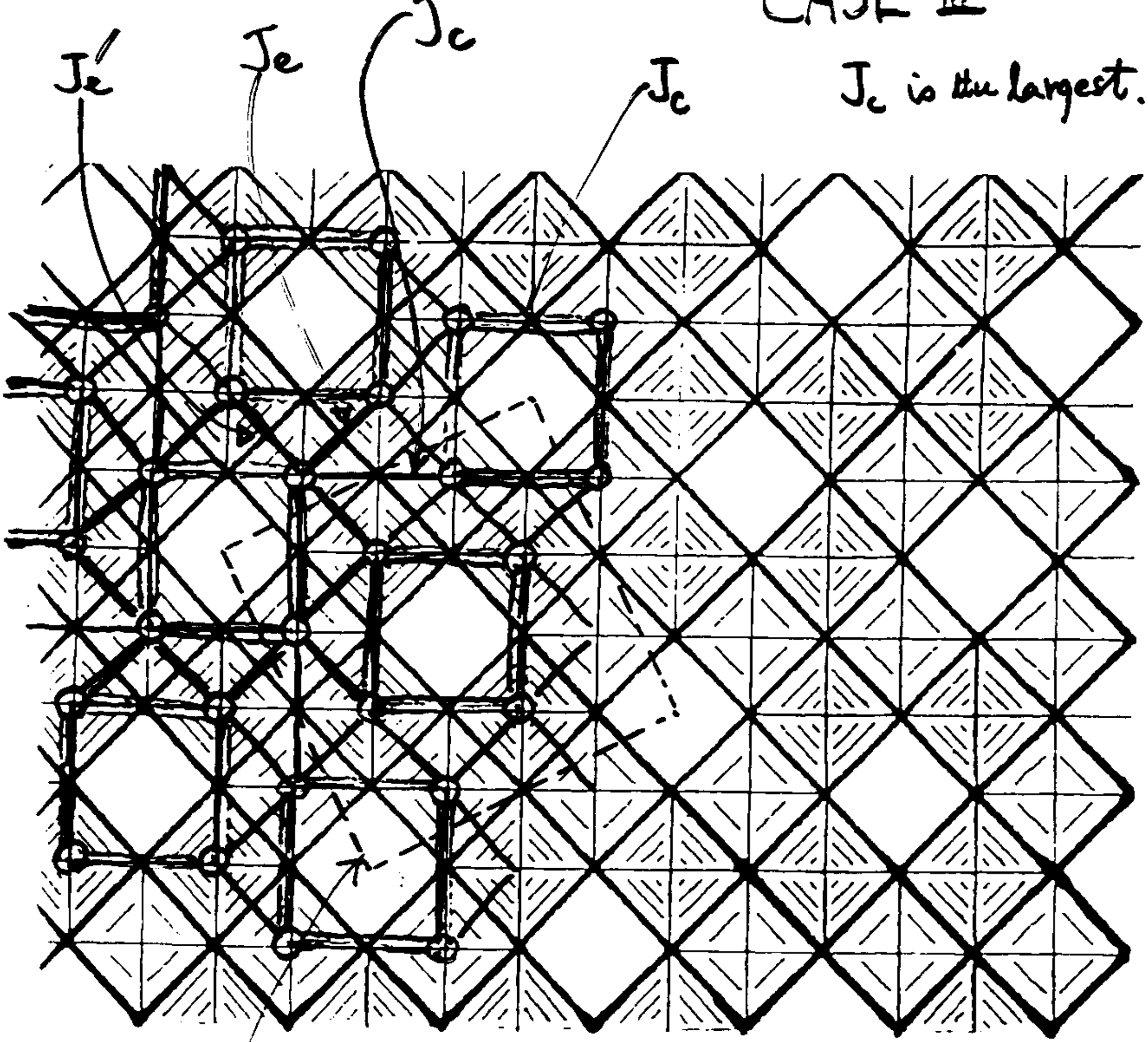


"corner-linked" pl.



CASE III

J_c is the largest.



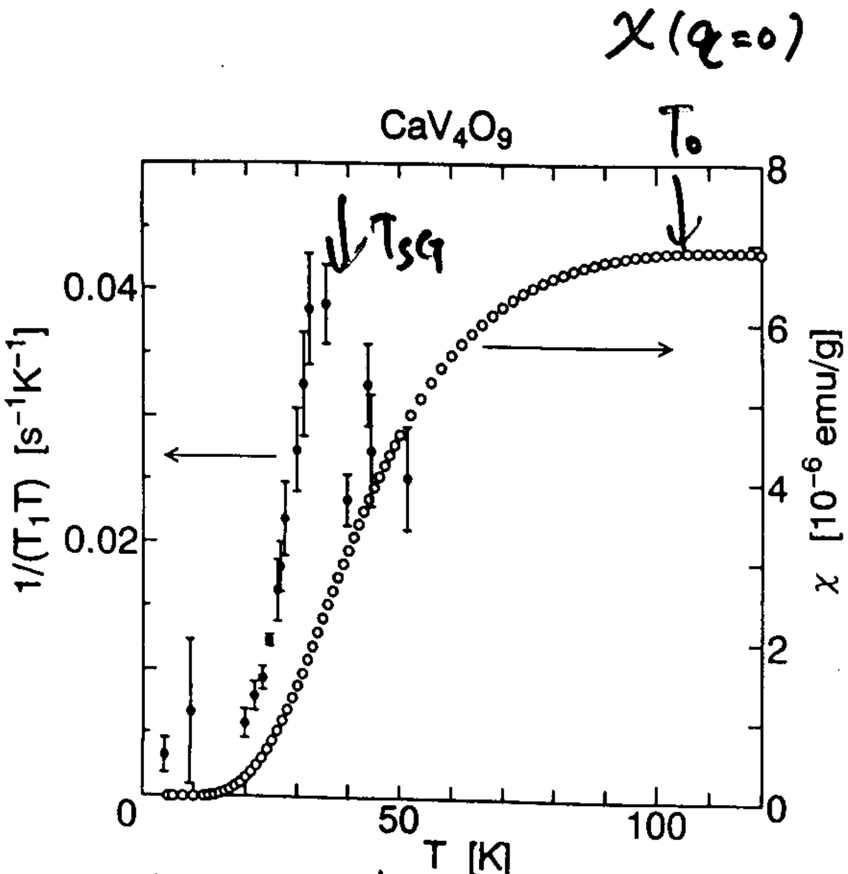
nuclear unit cell

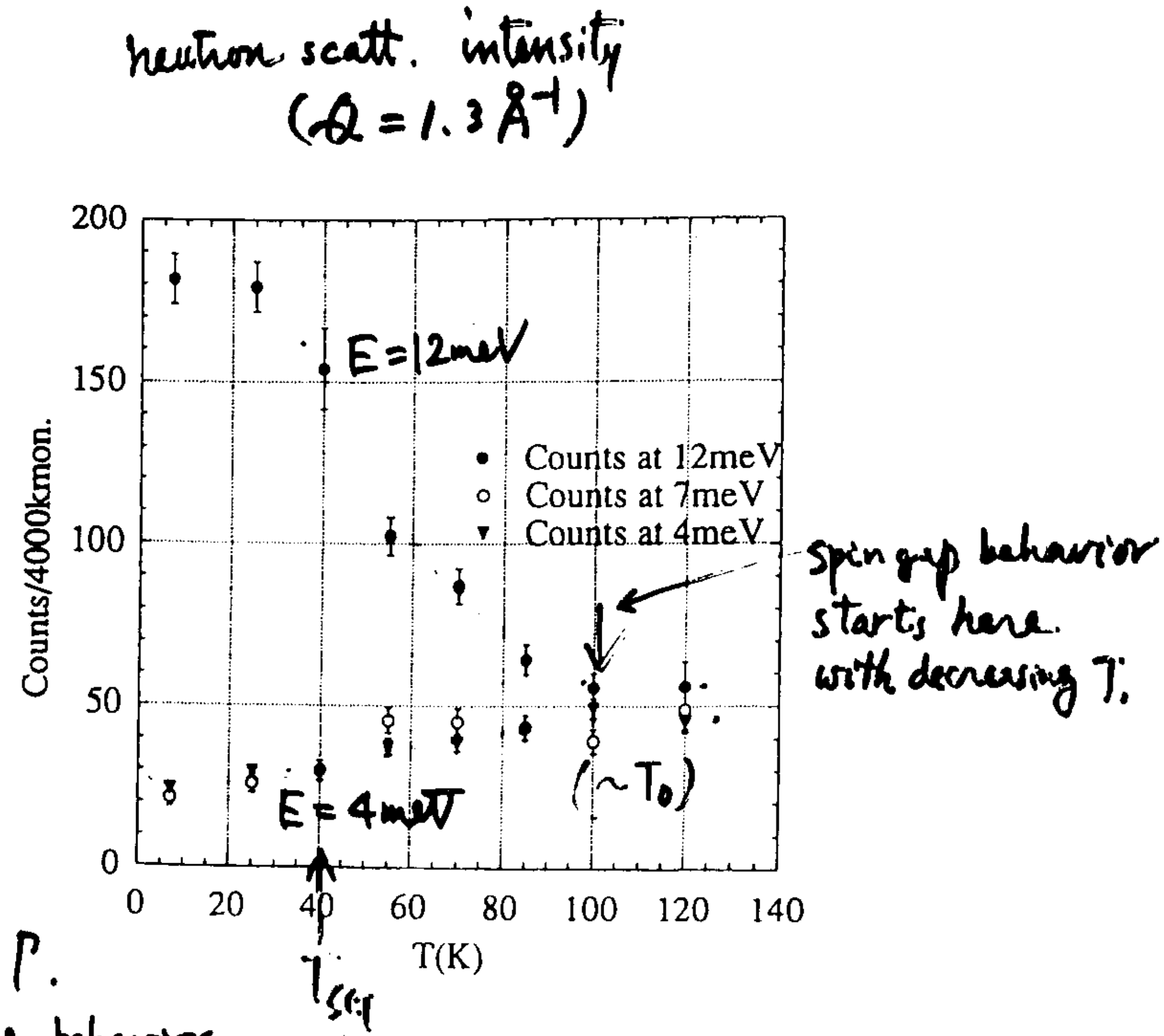
Physical picture of spin gap phase

J_e o------o (×2)

J_e' o.......o (×1)
(o.......o)

J_c' o.....o (×1)
(o.....o)



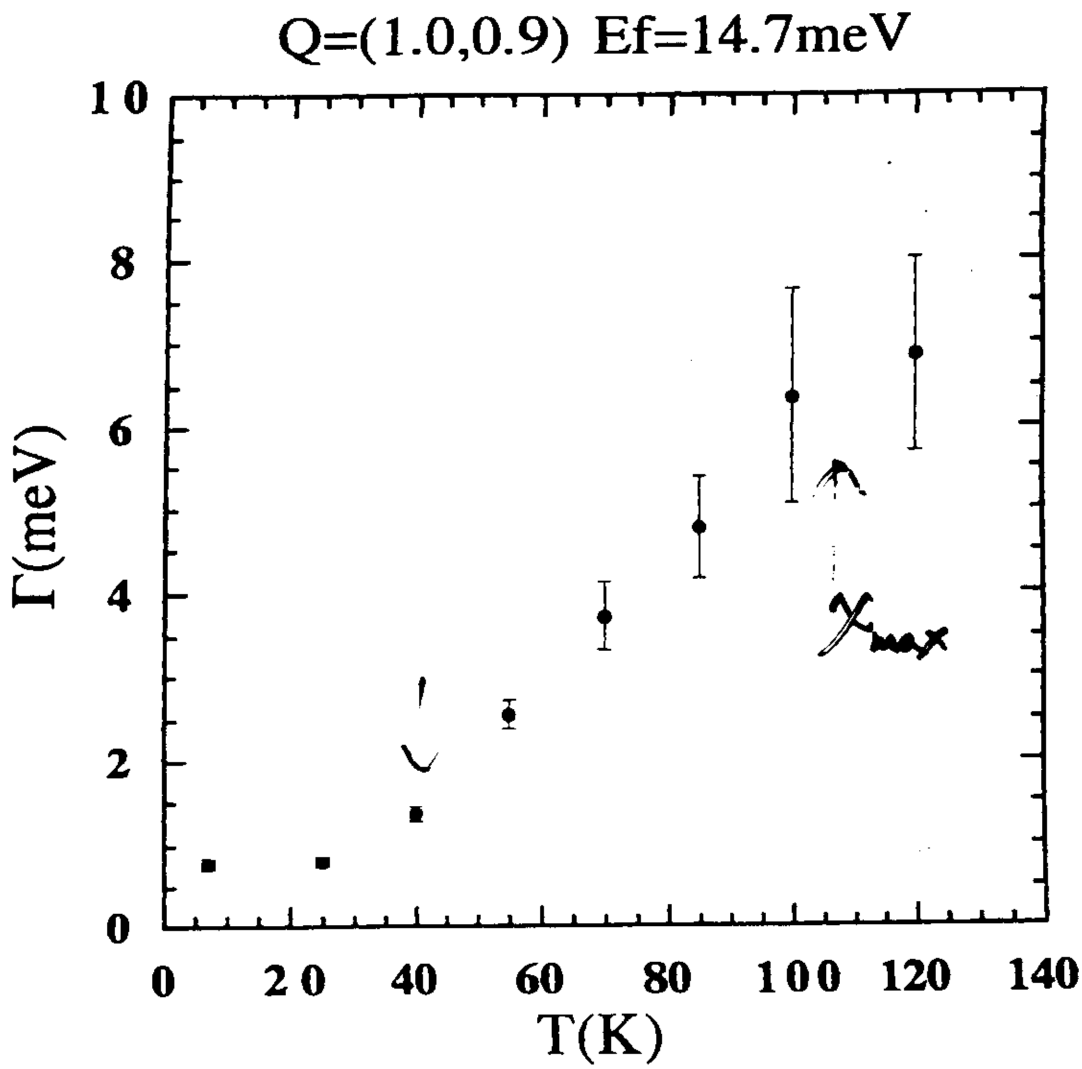


dispersion bottom of s→t excitation at Γ.

T-dep. of $1/T_1T$ is dominated by the mag. behavior at $q=0$, at least at low T.

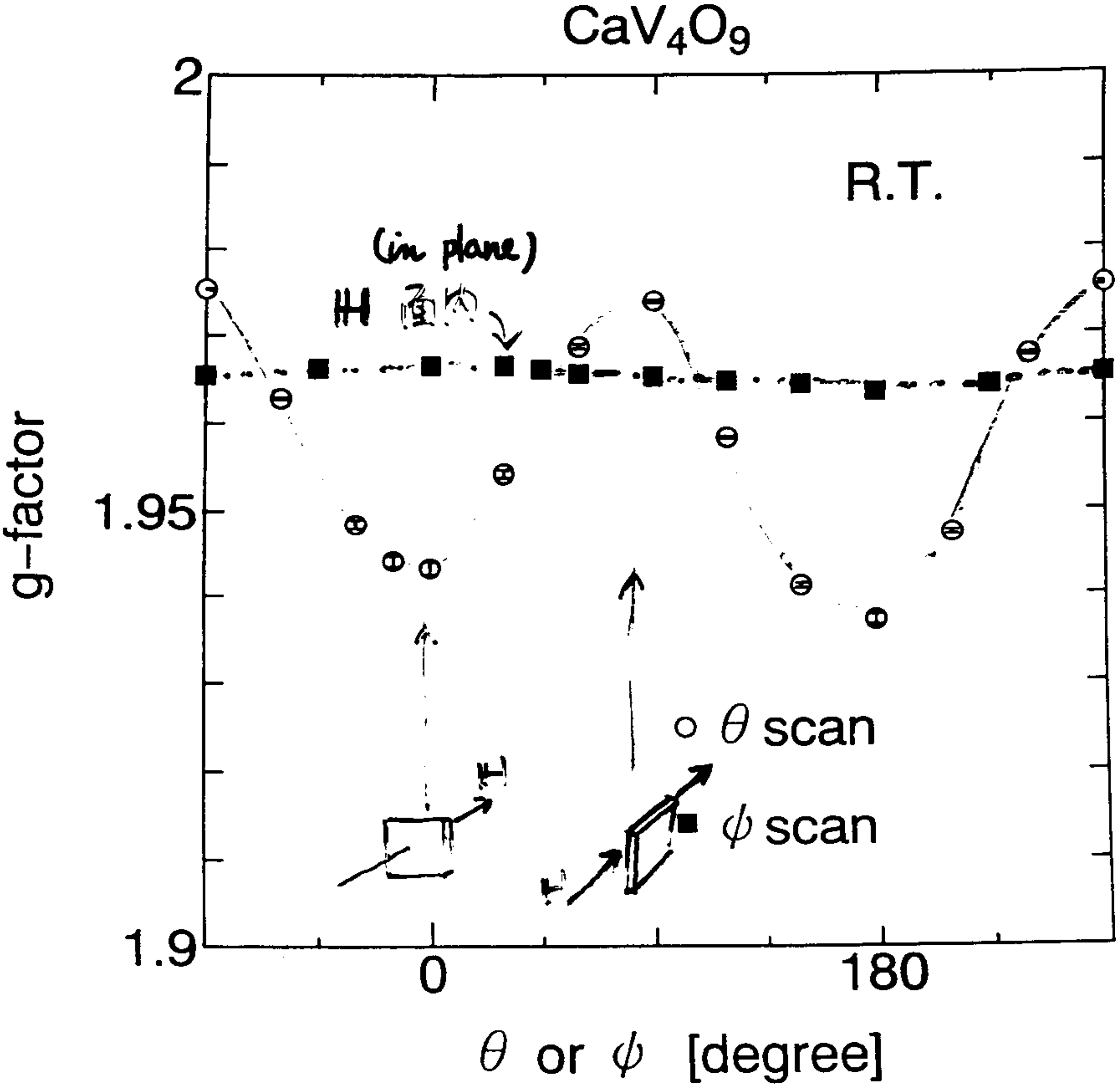
$$\left\{ \begin{matrix} \chi_{spin} \\ 1/(T_1T) \end{matrix} \right\} \propto e^{-\beta\Delta} \text{ (at low T)} \qquad T_{SG} < T_c \quad ?$$

Width of the singlet → triplet excitation
(at k_0)



ESR

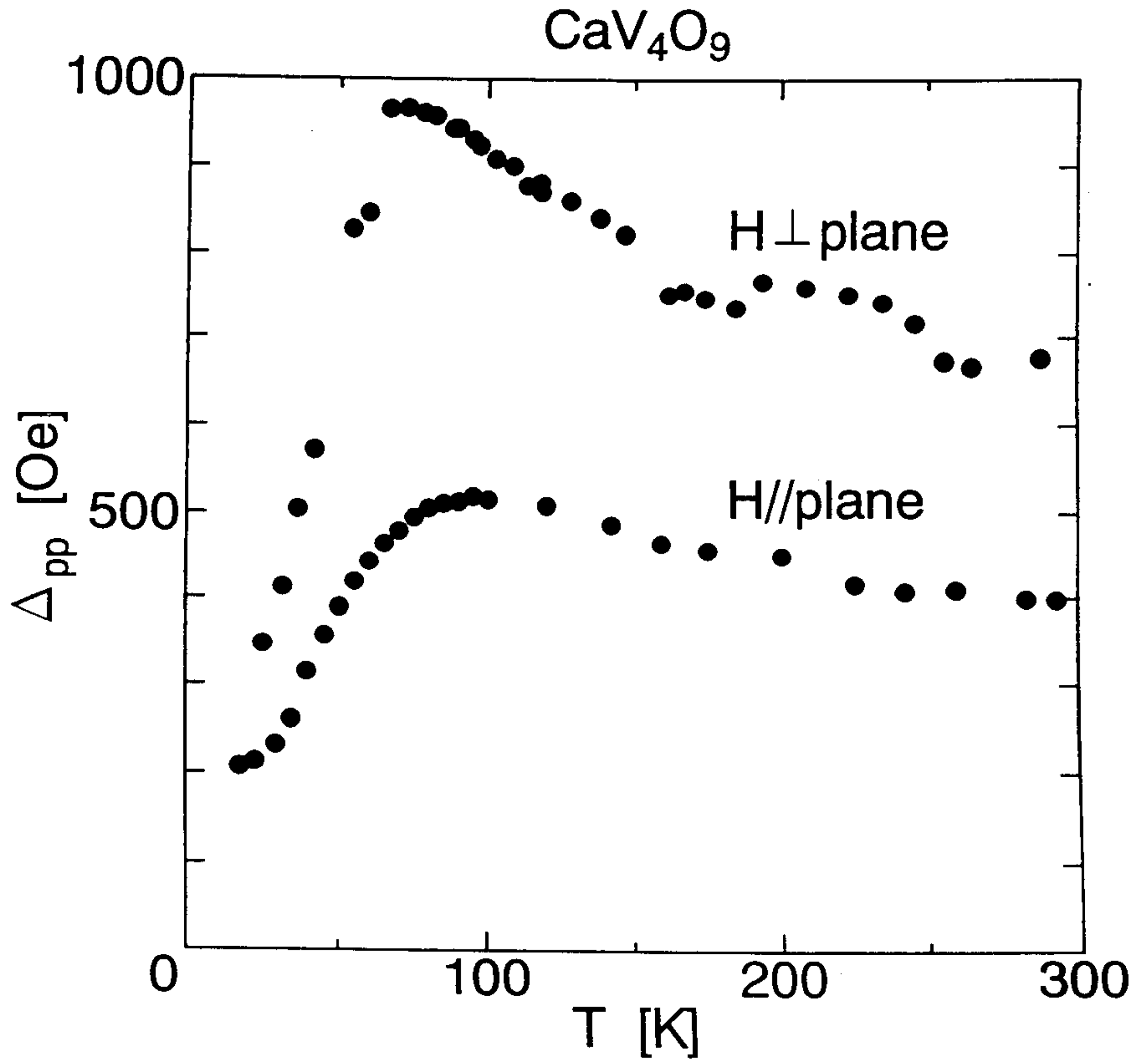
anisotropy of g-factor



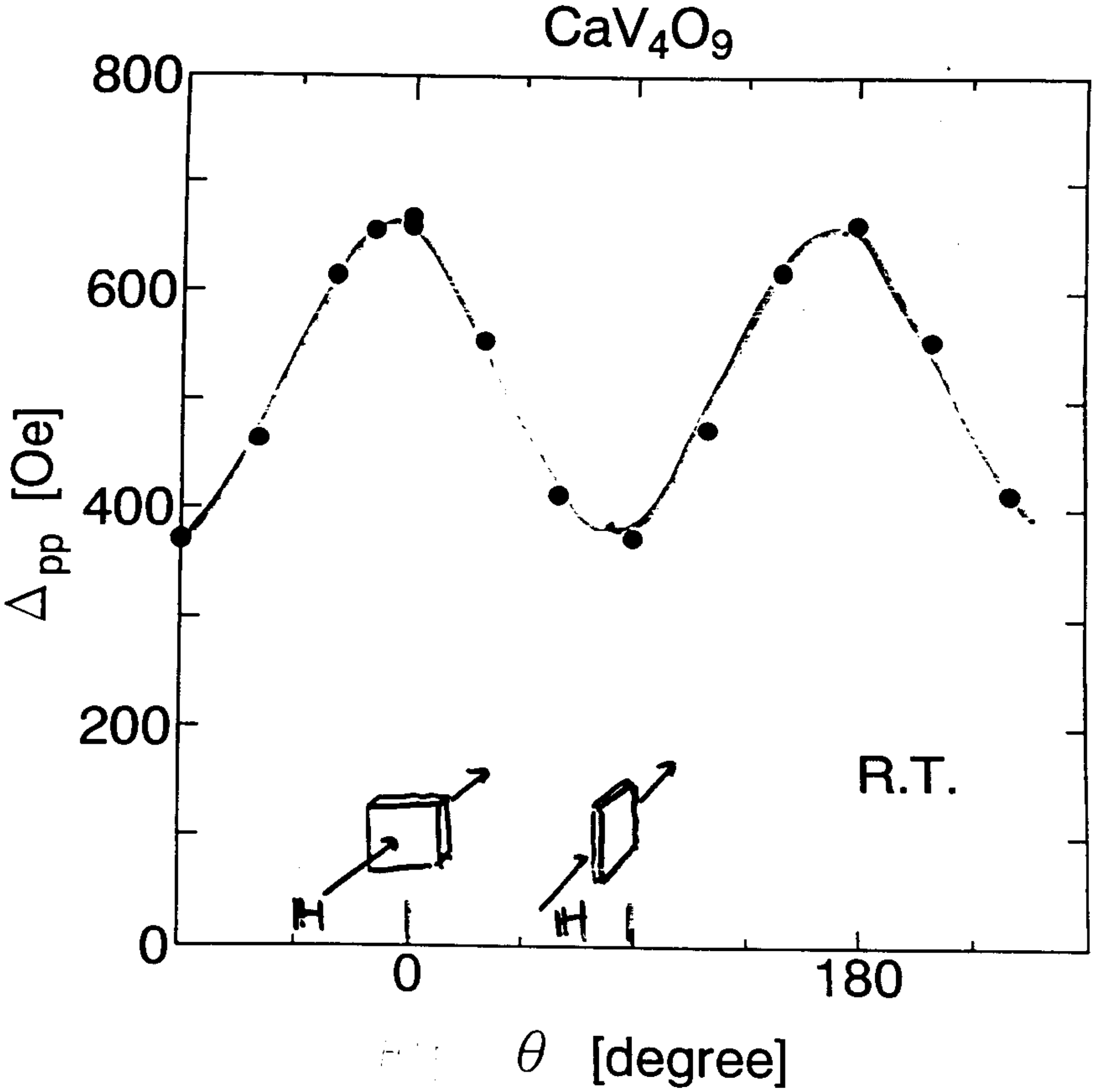
In what orbit does the electron exist?

S. Taniguchi et al.

ESR width



anisotropy of ESR width



θ : angle between H and C.

Summary

CaV_4O_9

2D SPIN GAP SYSTEM

$\Delta \sim 10$ meV

"corner-linked" plaquette

observation of the dispersion of magnetic excitations

↓

dispersion bottom at Γ

(different from the case of high-T_c)

A physical picture of the spin gap phase has been presented.