TRIANGLE DE LA PHYSIQUE

An Advanced Research Cluster in Physics
at Palaiseau, Orsay and Saclay, south of Paris

PALM
Laboratoire d'Excellence
Physique : Atomes Lumière Matière

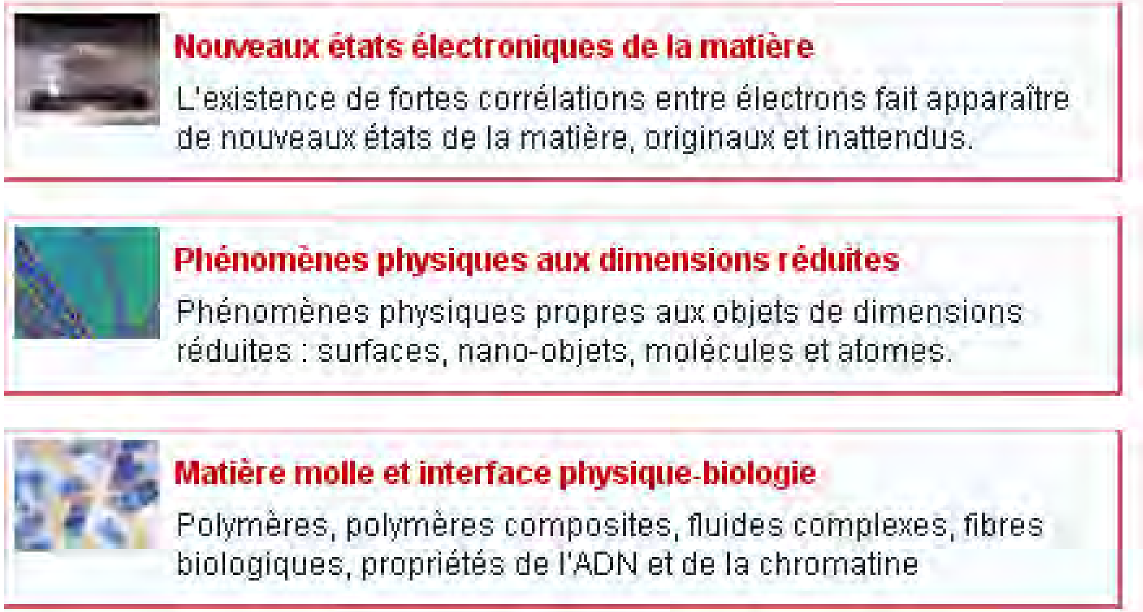
LPS
ORSAY

New States of matter probed by NMR, μSR, ARPES

Laboratoire de
Physique des
Solides

UMR 8502 - Université Paris-Sud, Bât. 510 - 91405 Orsay cedex

The LPS research themes



Nouveaux états électroniques de la matière

L'existence de fortes corrélations entre électrons fait apparaître de nouveaux états de la matière, originaux et inattendus.

Phénomènes physiques aux dimensions réduites

Phénomènes physiques propres aux objets de dimensions réduites : surfaces, nano-objets, molécules et atomes.

Matière molle et interface physique-biologie

Polymères, polymères composites, fluides complexes, fibres biologiques, propriétés de l'ADN et de la chromatine

NMR studies of correlated electron systems
From the Mott insulator to superconductivity through the cuprate pseudogap


P. Mendels


J. Bobroff


V. Brouet


P. Wzietek


F. Rullier-Albenque

RMN- μSR

ARPES

High pressures

Transport

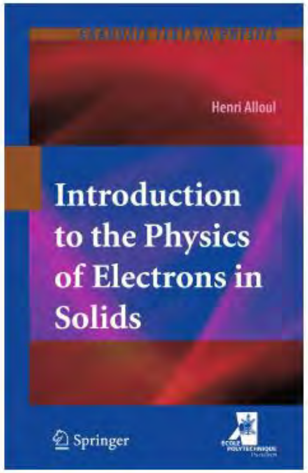
(SPEC /CEA Saclay)

Deceased march 20th 2016

G. Collin , N. Blanchard, D. Colson, A. Forget
(material synthesis and structures)

University of Kazan (Russia) : I. Mukhamedshin, A. Dooglav
University of Parma (Italy) : D. Pontiroli, M. Ricco
U. Fukuoka and Hyogo (Japan): Y. Ihara , T. Mito

Observation reveals Amazing Phenomena


Henri Alloul

Introduction to the Physics of Electrons in Solids

Springer

Introduction to the Physics of Electrons in Solids,
Editions de l'Ecole polytechnique (2007)
English edition , Springer (january 2011)

NMR in correlated electron systems
Illustration in the case of the cuprates

- ***Introduction to Magnetic resonance (NMR and ESR)***

  Hyperfine couplings , NMR shifts

- ***Magnetic spin susceptibilities in NMR***

  Metals and superconductors: Singlet spin pairing

  Impurity magnetism , RKKY , Transferred hyperfine couplings

- ***Magnetic spin susceptibilities in NMR : the cuprate case***

  Electronic structure . Single spin fluid in the normal state

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- ***Spin lattice relaxation T_1 and transverse relaxation T_2***

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  d- wave SC , magnetic correlations in the cuprate phase diagram

  Spin echoes and T_2: NMR applications

Conclusion: NMR is a powerful tool in Solid State Physics

ESR and NMR : SPIN RESONANCE IN THE PARAMAGNETIC REGIME

Angular momentum **magnetic moment**

Nuclear spin

Electron spin

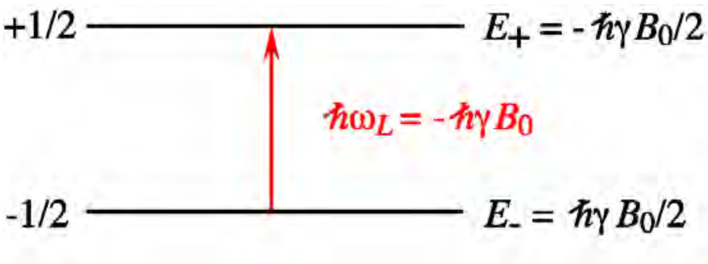
$\mu_n \approx 10^{-3} \mu_e$

Zeeman Effect

$$H_Z = -\mu.B_0 = -\hbar\gamma\,\mathbf{S}.\mathbf{B}_0 = -\hbar\gamma\,S_z.B_0$$

$\mathbf{B}_0 \,//\, z$

I = 1/2



Larmor frequency

$$\omega_L = -\gamma B_0$$

I > 1/2 **2I+1 equidistant levels levels** ($h\,\gamma_n B_0$)

Absorption spectoscropy

Electron spins: ESR ~ 30 GHz/Tesla **microwave frequencies**

Nuclear spins: NMR~ 10 MHz/Tesla **radiofrequencies**

Spins I

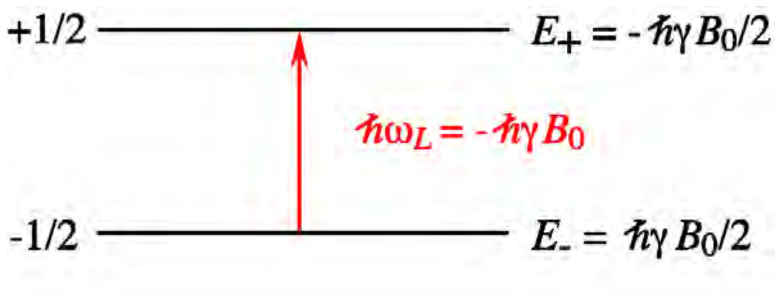
Gyromagnetic ratios γ_n

^{1}H	I=1/2	42,57 MHz/Tesla
^{2}H	I=1	6,53 MHz/Tesla
^{63}Cu	I=3/2	11,28 MHz/Tesl
^{65}Cu	I=3/2	12,08 MHz/Tesl

ESR and NMR : SPIN RESONANCE IN THE PARAMAGNETIC REGIME

$$\boxed{H_Z = -\mu.B_0 = -\hbar\gamma\,\mathbf{S.B_0} = -\hbar\gamma\, S_z.B_0}$$

$\mathbf{B_0\,//z}$



Exciting ac field

Act as a perturbation for H_Z

$$\boxed{H_{rf} = -\hbar\gamma\,\mathbf{S.B_1}\cos\omega_L t}$$

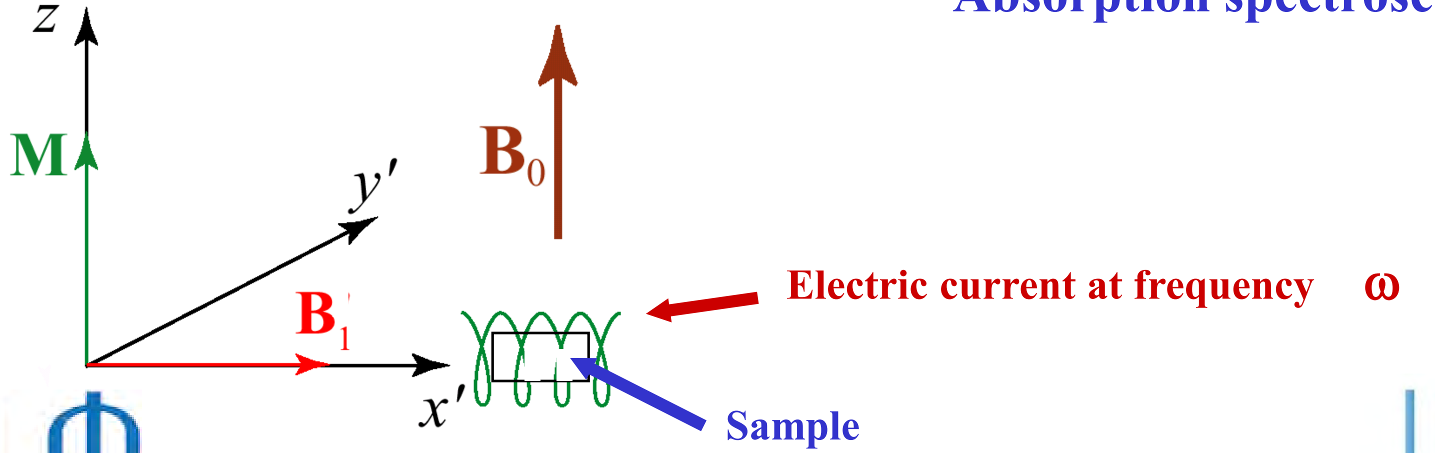
transitions $|\text{-}1/2\rangle \rightarrow |1/2\rangle$

if $\langle 1/2|H_{rf}|\text{-}1/2\rangle \neq 0$

$\Longleftrightarrow$

$\mathbf{B_1 \perp z}$

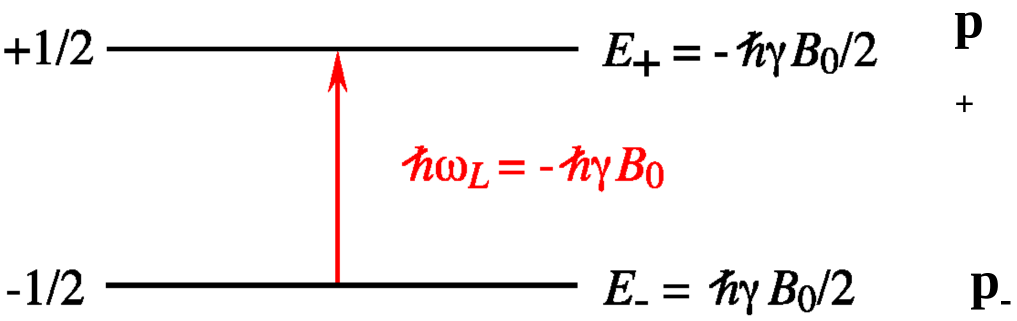
Absorption spectroscopy



NUCLEAR MAGNETISM

$$\boxed{H_Z = -\hbar\gamma\, \mathbf{S}.\mathbf{B}_0 = -\hbar\gamma\, S_z.B_0}$$

$$\omega_L = -\gamma\, B_0$$



Thermodynamic ensemble

$$\boxed{\langle\mu_z\rangle = N\mu_B \,\mathrm{th}\, \frac{\hbar\gamma B_0}{2k_B T}}$$

Curie susceptibility $\chi = C / T$

$$\hbar\gamma_n B_0 \approx 10^{-6}\,\mathrm{K} << k_B T \qquad \chi_n \approx 10^{-6}\,\chi_e$$

Very weak χ

Spectroscopic techniques : sensitivity

Radio Sources
Radio frequencies
(Electronic oscillators)

- **Stables (10^{-10})** **(monochromatic)**
- **coherent**
- **intense**

Radio, radar, television Technologies

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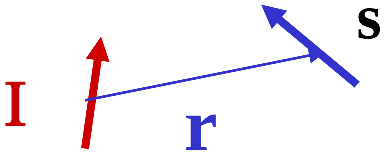
Hyperfine Interactions - NMR Frequency Shifts

Interactions between nuclear moments *I* and electronic moments *s* et *l*

Dipolar

$$H_{dd} = -\frac{\hbar^2\gamma_n\gamma_e}{r^3}\left\{\vec{I}.\vec{s} - 3\frac{(\vec{I}.\vec{r})(\vec{s}.\vec{r})}{r^2}\right\}$$



Orbital

$$H_{orb} = -\frac{\hbar^2\gamma_n\gamma_e}{r^3}\,\vec{I}.\vec{l}$$

- Filled atomic shells :

$$H_{orb} \equiv 0 \;;\; H_{dd} \equiv 0$$

Contact

$$H_c = \frac{8\pi}{3}\hbar^2\gamma_n\gamma_e\,\vec{I}.\vec{s}\,\delta(\vec{r})$$

- Paramagnetic or diamagnetic compounds:

$$H_T = H_Z + H_{dd} + H_{orb} + H_c = -\hbar\gamma_n\,\vec{I}.(\vec{B}_0 + \vec{B}_L)$$

$$\vec{B}_L = <\vec{B}_L> + \left[\vec{B}_L - <\vec{B}_L>\right]$$

Relaxation time

Mean field
Linear
response

$$<\vec{B}_L> \;\propto\; \chi B_0$$

Frequency shift

Local measurement of the electronic susceptibility

Insulators H_{orb}
Chemical shift
(orbital currents)

metals χ_{Pauli}
Knight shift
(unpaired electrons)

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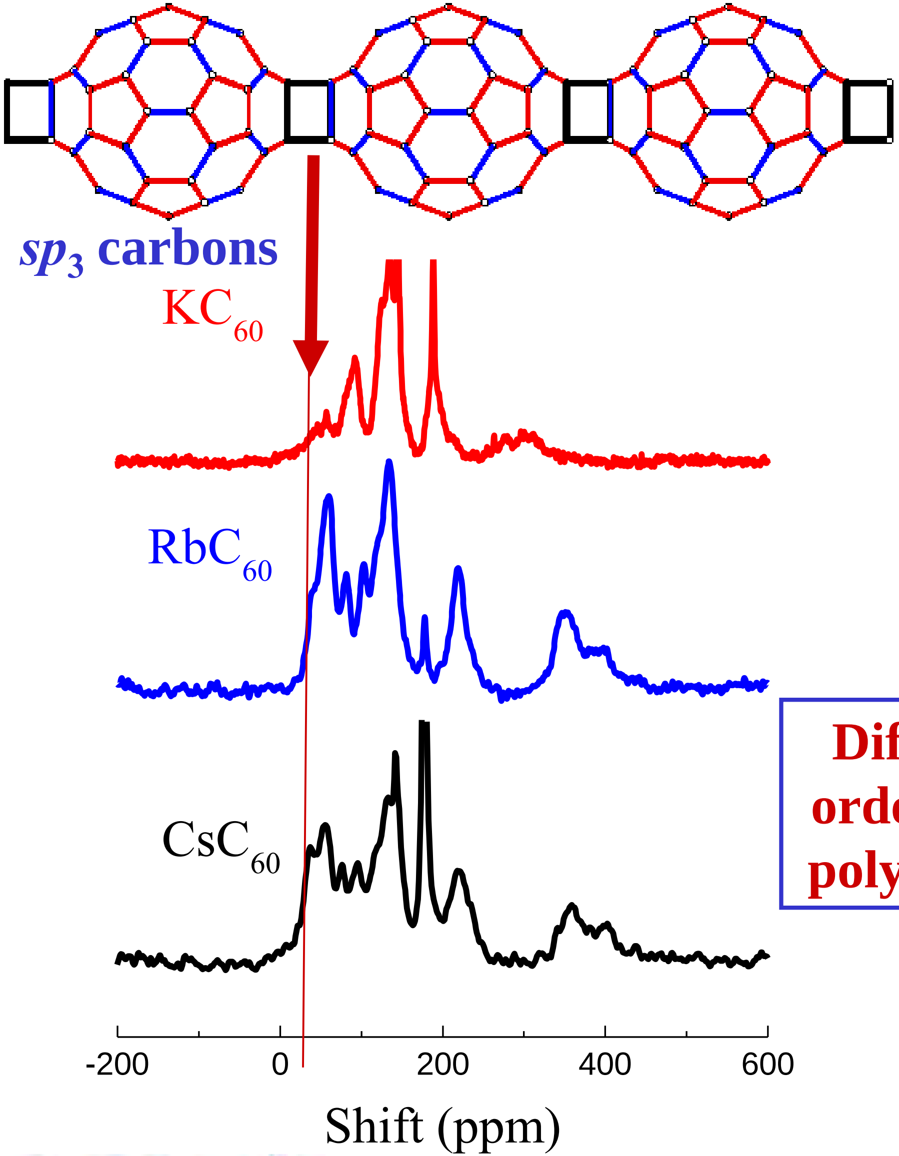
POLYMERIZED AC_{60} PHASES

1D metal

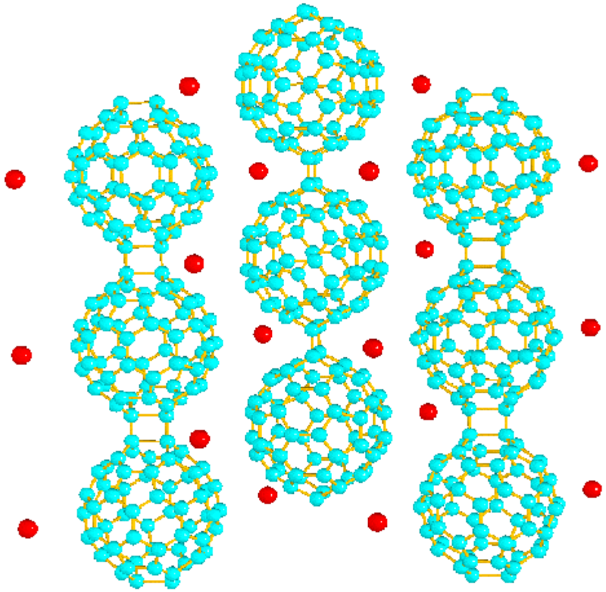


$$CsC_{60} \Rightarrow Cs^{+} + C_{60}^{\;-}$$

The ^{13}C site differenciation evidences the polymerization

Difference between KC_{60} and CsC_{60}

Different 3D ordering of the polymer chains



KNIGHT SHIFT IN METALS

Contact hamiltonian for the spin *I*
(for all the electrons of the metallic band)

$$H_c = \sum_i \frac{8\pi}{3}\hbar^2\gamma_n\gamma_e\,\vec{I}.\vec{s}_i\,\delta(\vec{r}_i)$$

$$H_c = \frac{8\pi}{3}\hbar^2\gamma_n\gamma_e\,\vec{I}.\sum_i \vec{s}_i\,\delta(\vec{r}_i) = \frac{8\pi}{3}\hbar\gamma_n\,\vec{I}.\vec{M}(0)$$

M(0) magnetization density operator at the nuclear site

Bloch electronic states

$$\left|\vec{k},\vec{s}\right\rangle = u_{\vec{k}}(\vec{r})\,e^{i\vec{k}\vec{r}}\,\psi_{\vec{s}}$$

$$\vec{M}(0) = \left\langle \left|u_{\vec{k}}(\vec{r})\right|^2 \right\rangle_{k_F} \chi_P\; B_0 \qquad \chi_P = \frac{1}{2}(\hbar\gamma_e)^2\,n(E_F)$$

Pauli susceptibility of the electronic band

with $A = \frac{8\pi}{3}\hbar^2\gamma_n\gamma_e\left\langle \left|u_{\vec{k}}(\vec{r})\right|^2 \right\rangle_{k_F}$ **one might write**

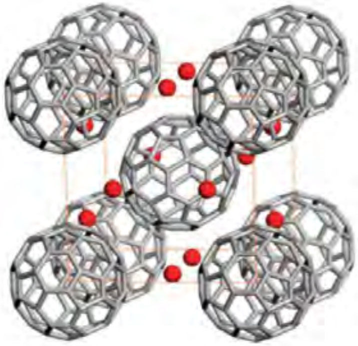
$$\boxed{H_c = A\;\vec{I}.\sum_i \vec{s}_i\,\delta(\vec{r}_i)}$$

- **The electrons are then considered as free electrons**
- **The hyperfine coupling *A* contains informations on the electronic band structure**

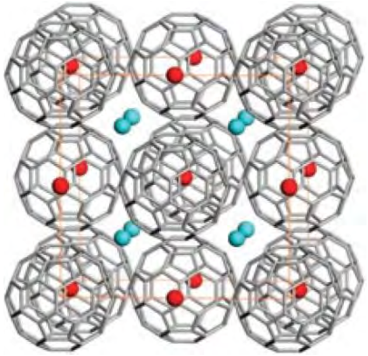
$$\boxed{K = \frac{\langle B_L\rangle}{B_0} = \frac{A}{\hbar^2\gamma_e\gamma_n}\,\chi_P}$$

Knight shift

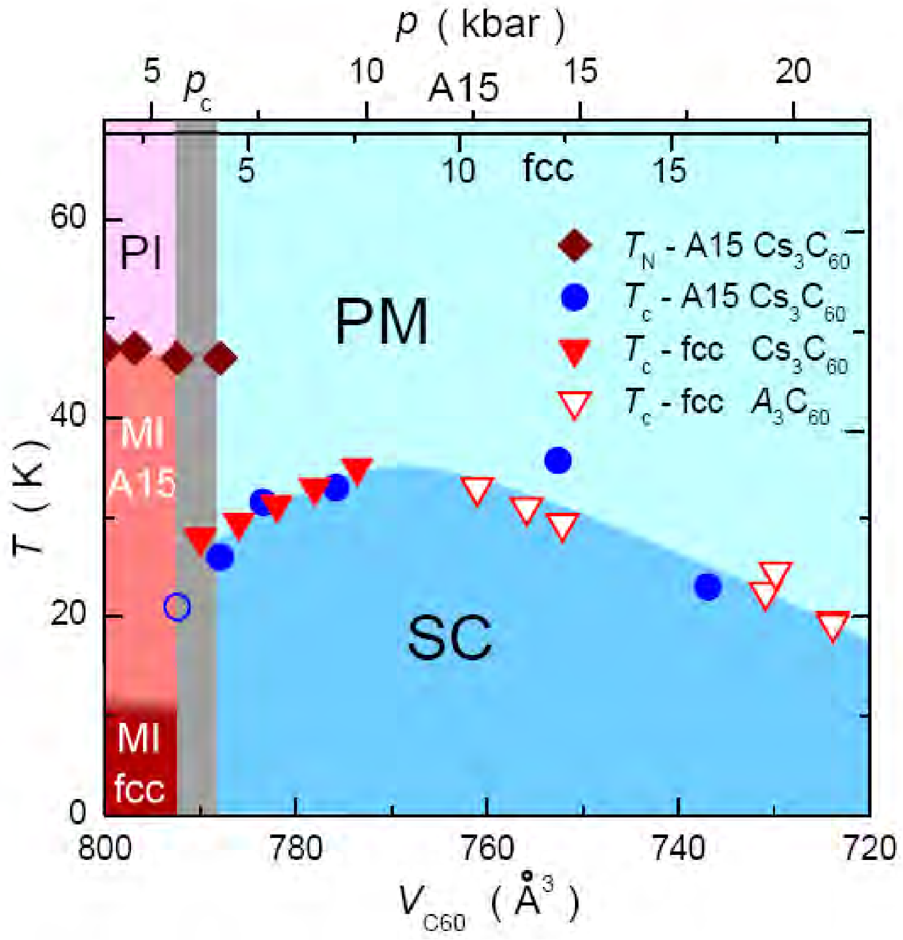
Multiple phases in the samples: ^{133}Cs NMR is very helpful



A15 Cs_3C_{60}



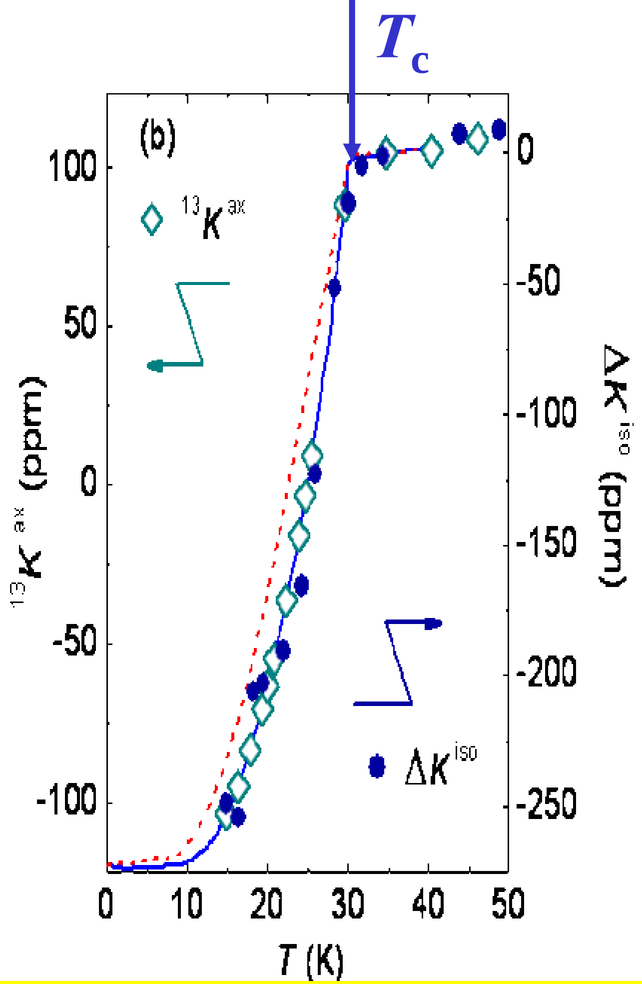
fcc Cs_3C_{60}



Differences allow selective NMR experiments

Crystal structure has no incidence on the SC side

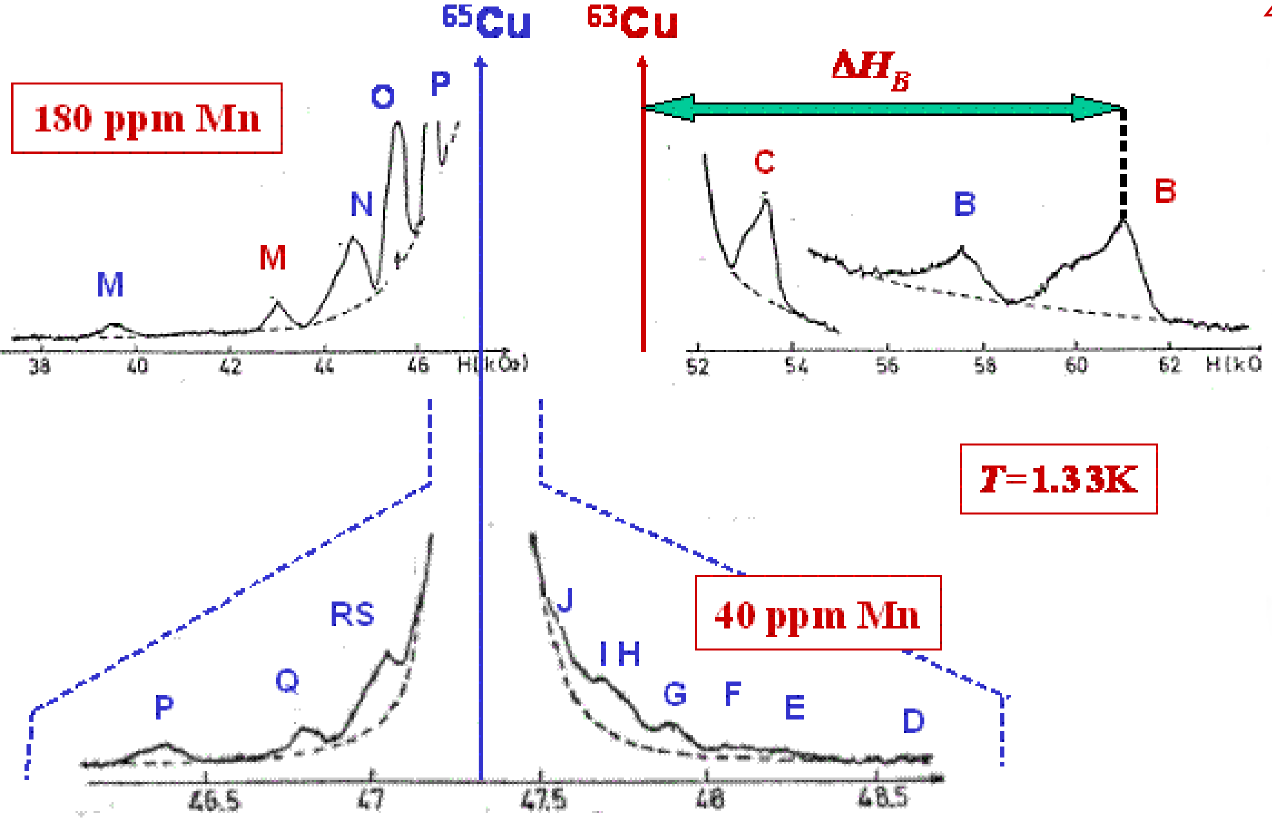
Knight Shift in the SC state

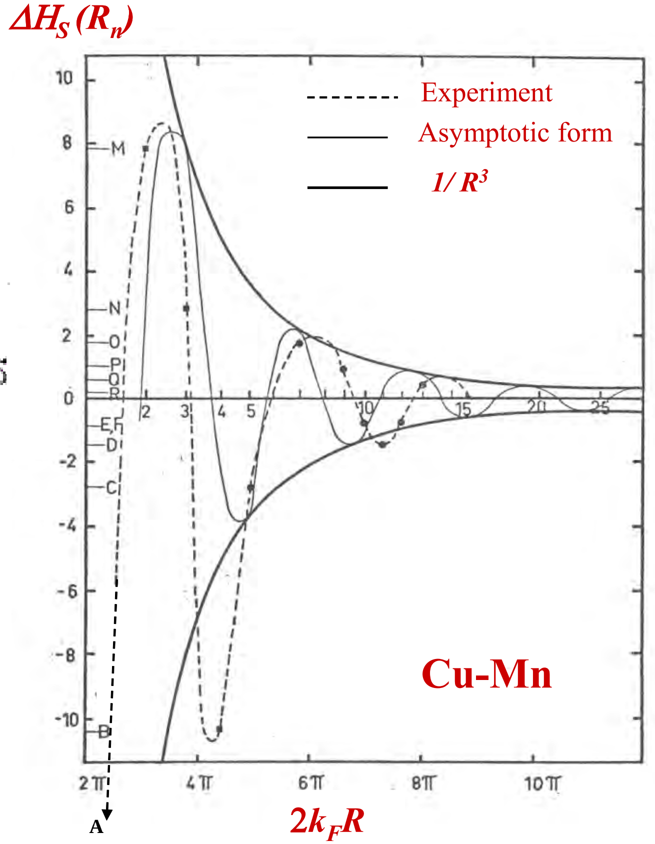


Vanishing of χ_P in the superconducting state
Cooper pairs are in a singlet state

P. Wzietek et al PRL 2014

Magnetic Impurities in normal metals
RKKY oscillations

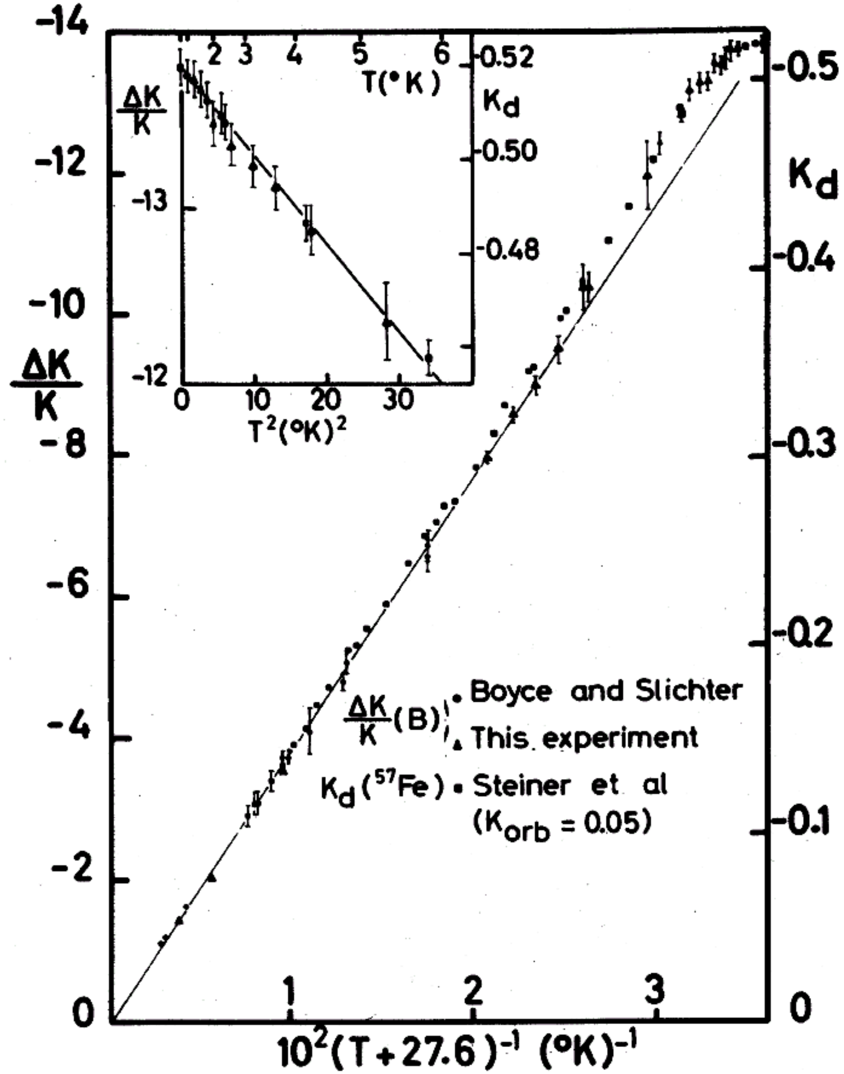




Transferred hyperfine couplings
Nuclear spins can sense the magnetism on their neighbour atomic sites

H. Alloul, Autumn School on correlated electrons
Julich ,15 /09/ 2016

Magnetic Impurities in normal metals
Kondo effect



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Magnetic susceptibilities

SQUID Measures

always

Ion cores **orbital** **Spin**

$$\chi_{\alpha}^{m}(T) = \chi^{dia} + \chi_{\alpha}^{orb} + \chi_{\alpha}^{s} + (\chi^{imp})$$

$$= \chi^{dia} + \sum_{i}\left[\chi_{i,\alpha}^{orb} + \chi_{i,\alpha}^{s}(T)\right]$$

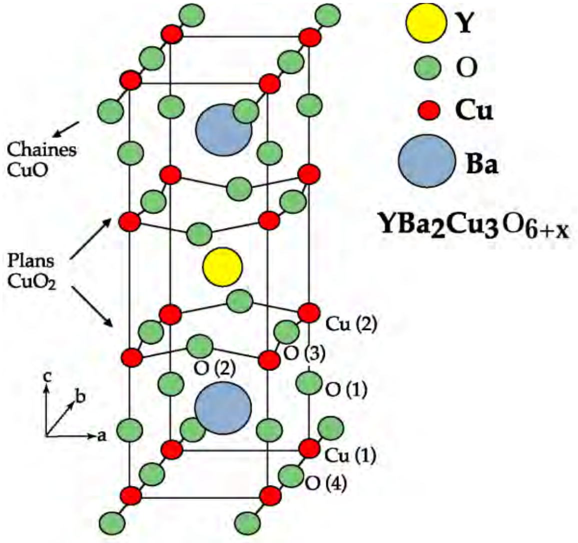
α =(x,y,z)

i = atomic sites

NMR shift measures on each nuclear site i

$$K_{i,\alpha}(T) = K_{i}^{dia} + K_{i,\alpha}^{orb} + K_{i,\alpha}^{s}(T)$$

$$= K_{i}^{dia} + A_{i,\alpha}^{orb}\chi_{i,\alpha}^{orb} + A_{i,\alpha}^{s}\chi_{i,\alpha}^{s}(T)$$



Local magnetic measurement
on each nuclear site i

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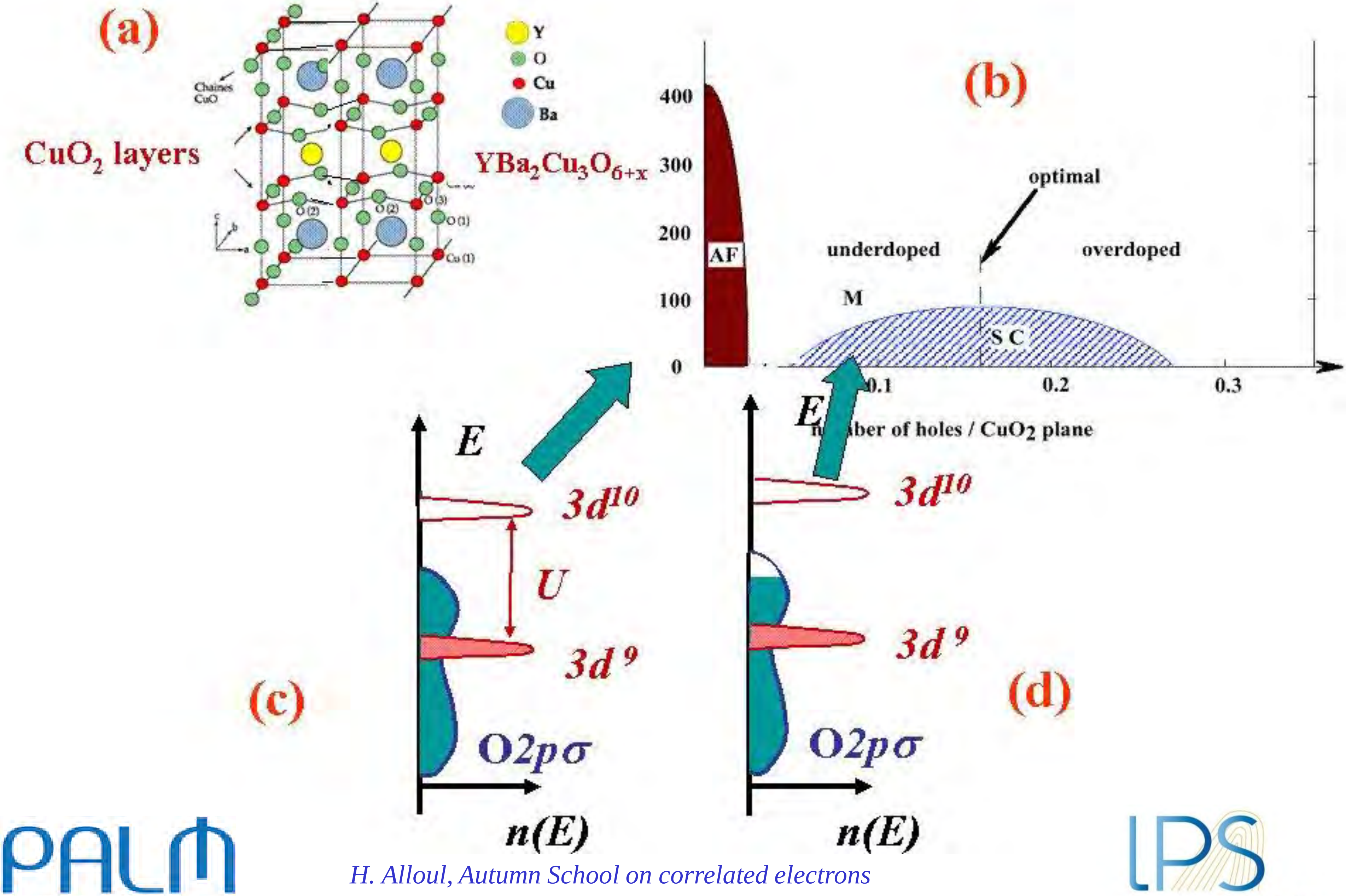
Phase Diagram and Band Structure



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^{89}Y NMR shift in the metallic state

H.A , T. Ohno and P. Mendels, PRL 1989

CuO$_2$ plane

- ΔK

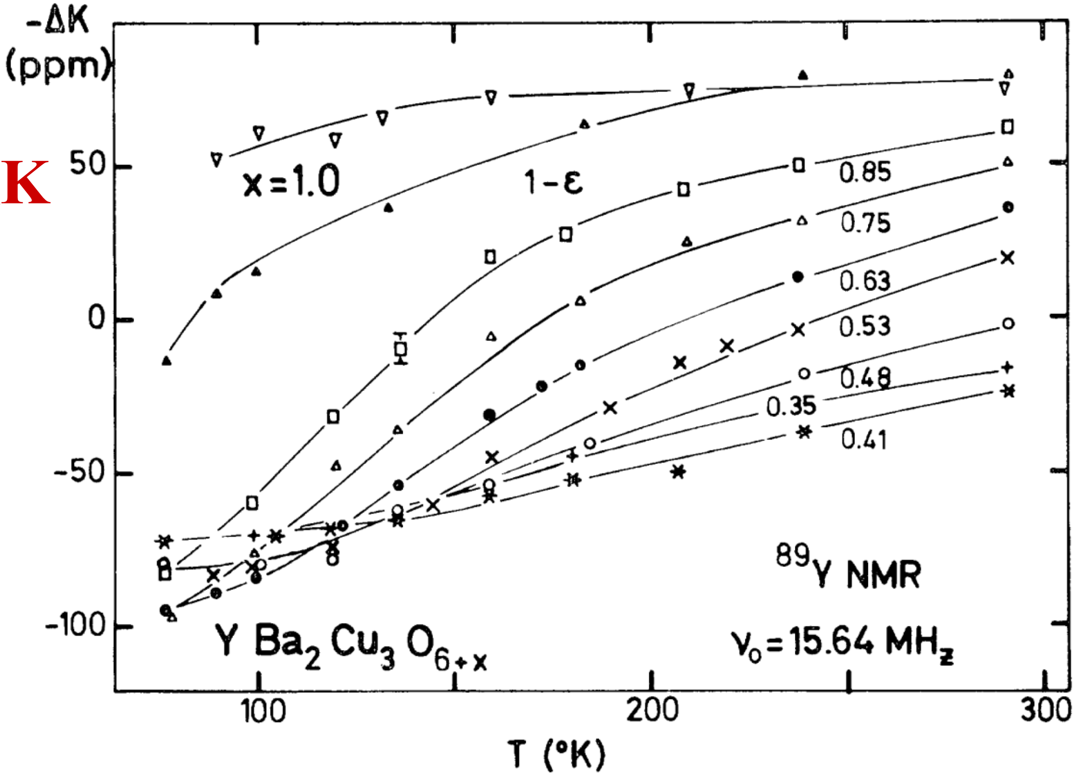
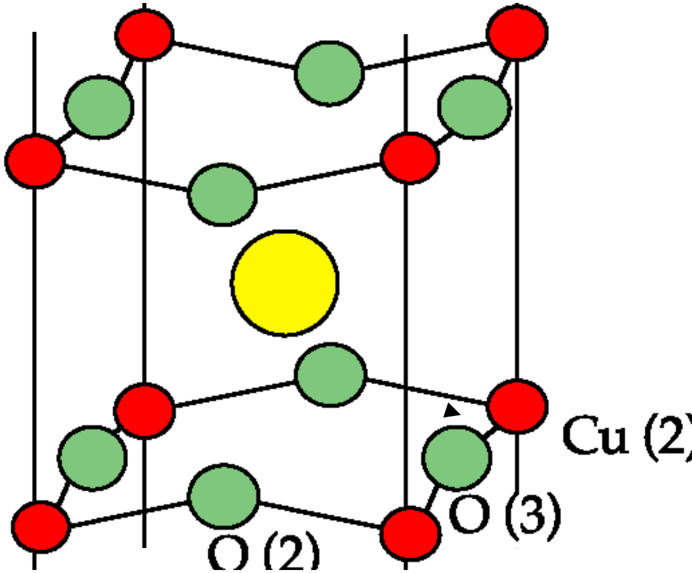


FIG. 1. The shift ΔK of the ^{89}Y line, referenced to YCl$_3$ plotted vs T, from 77 to 300 K. The lines are guides to the eye.



CuO$_2$ plane

$$K_{i,\alpha}(T) = K_i^{dia} + A_{i,\alpha}^{orb}\chi_{i,\alpha}^{orb} + A_{i,\alpha}^{s}\chi_{i,\alpha}^{s}(T)$$

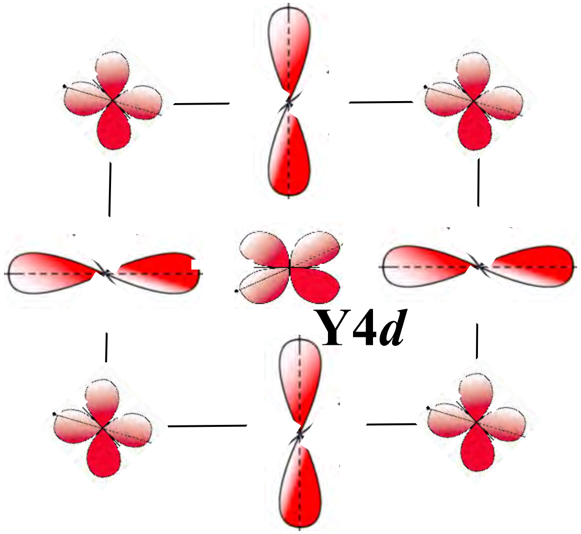
Local magnetic measurement

But transferred hyperfine couplings

Sign of ^{89}Y NMR shift

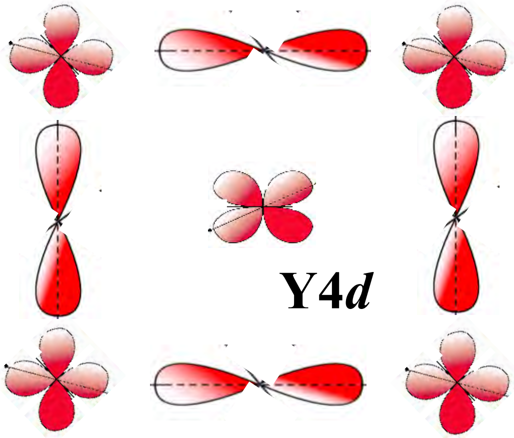
Negative sign comes from Y4*d* orbitals: core polarization

pπ Y4*d*



Very weak

pσ Y4*d*



OK

So negative sign comes from pσ -Y4*d* hybridization

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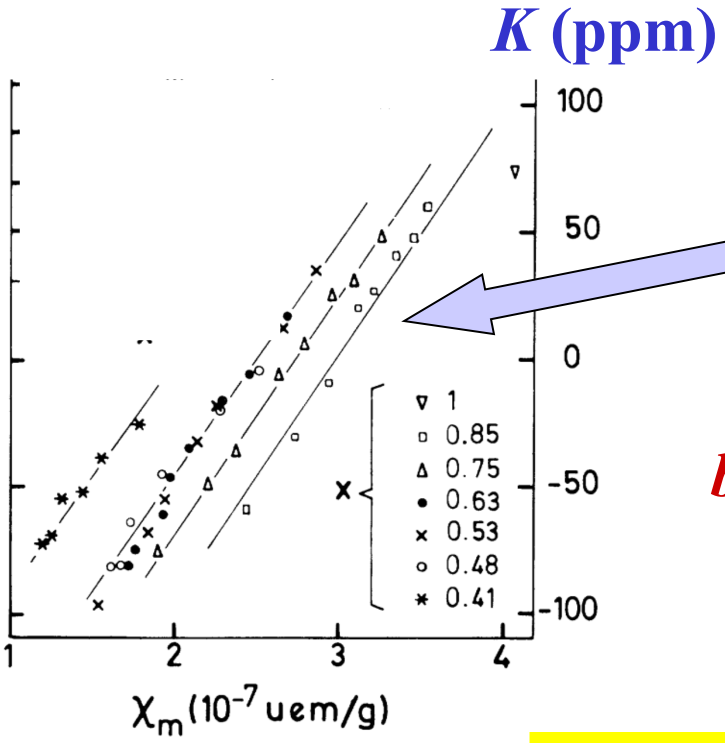
Julich ,15 /09/ 2016

Is there an independent oxygen band at the Fermi level?

H.A. , T. Ohno and P. Mendels, PRL 1989



$$K^s(T) = A\ \chi^s(T)$$

does not change with hole doping

A is driven

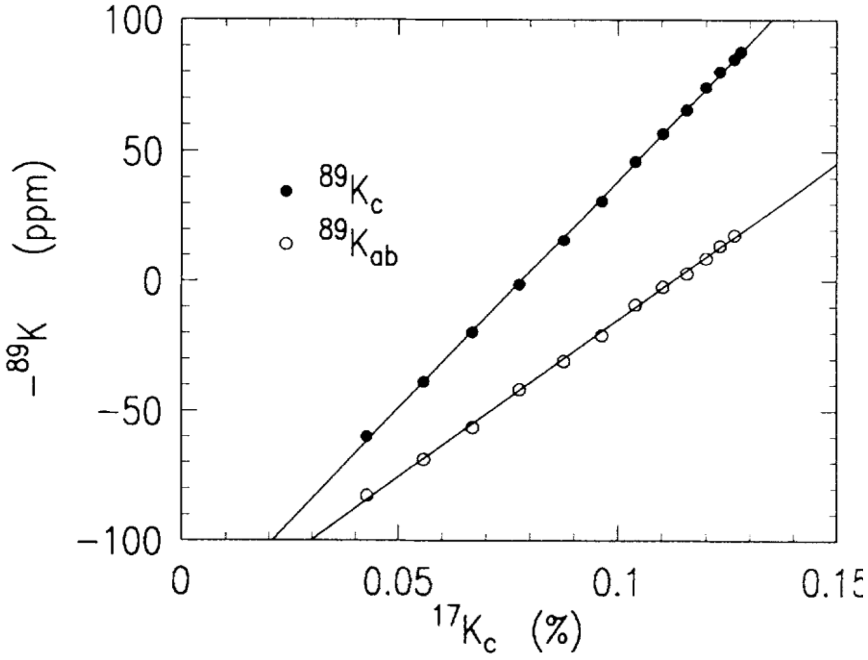
by (Y4d-O2pσ)–Cu(3d) covalency

So there is no independent oxygen spin degree of freedom at E_F

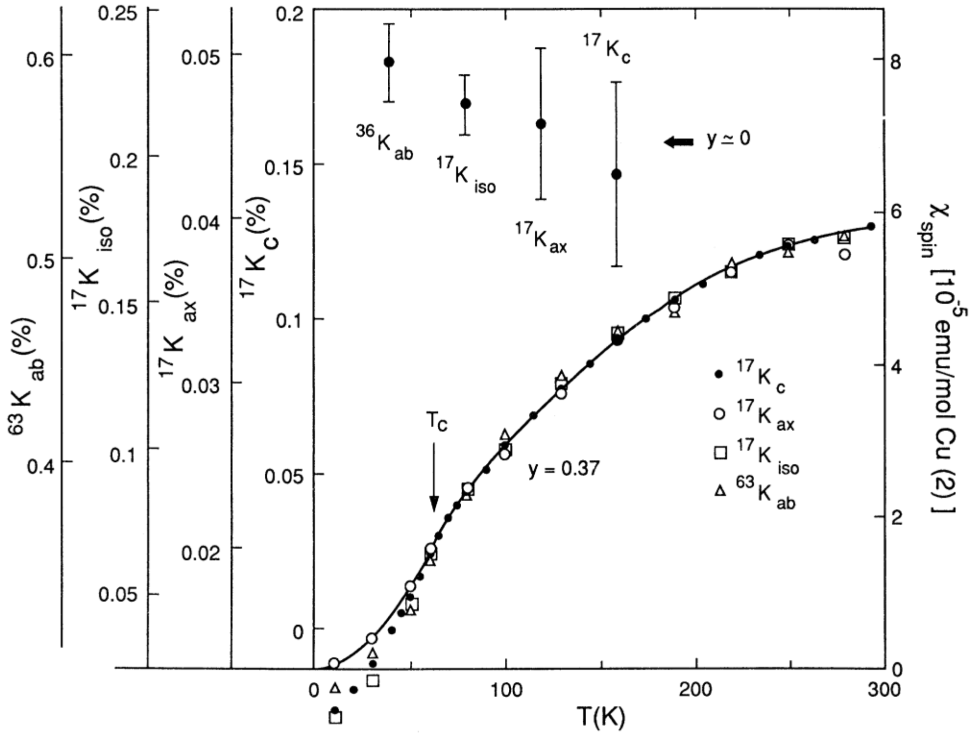
Single spin fluid behaviour

$YBCO_{6.63}$ $$K_{i,\alpha}(T) = K_i^{dia} + A_{i,\alpha}^{orb}\chi_{i,\alpha}^{orb} + A_{i,\alpha}^{s}\chi_{i,\alpha}^{s}(T)$$

M. Takigawa et al 1991, 1993



^{89}Y versus ^{17}O



^{63}Cu versus ^{17}O

A single T dependence for $K_{i,a}(T)$: due to $\chi_{Cu}(T)$

Notice: this allows determinations of the shift references for all nuclei

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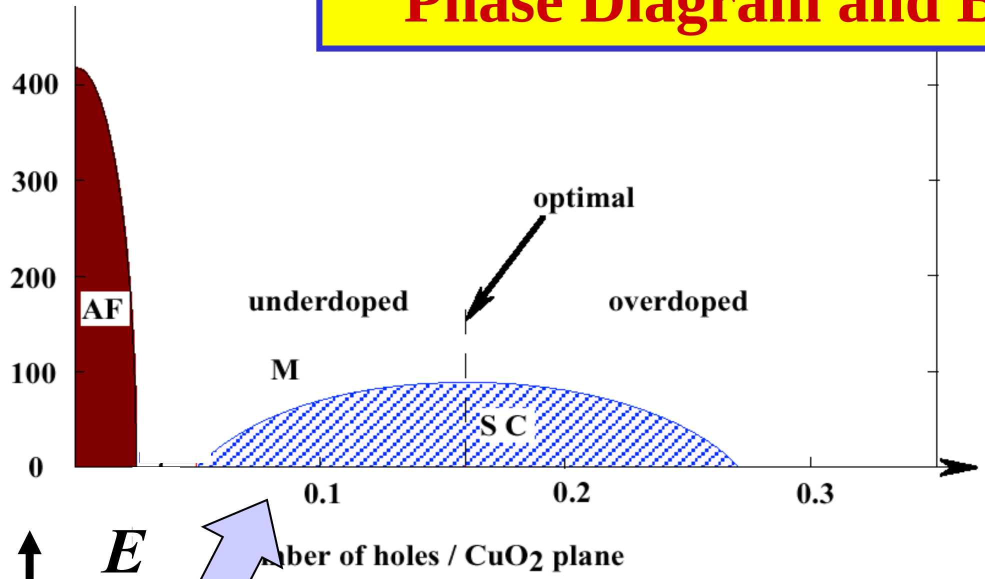
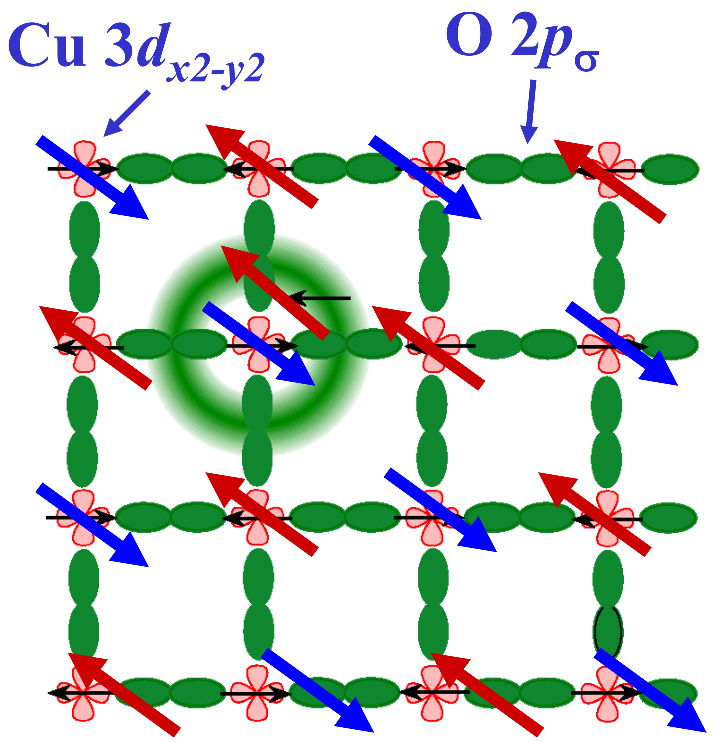
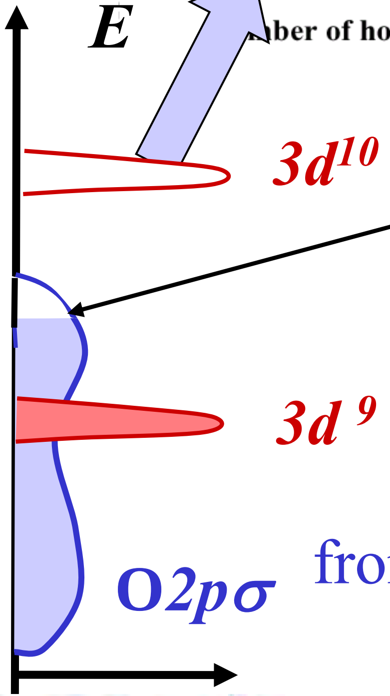
Phase Diagram and Band Structure



Two types of holes ?





NO!!
Strong O2*p* - Cu *3d*
hybridization
Magnetic correlations

The holes steal spins
from the copper hole background

There is a single spin fluid
Zhang Rice spin singlets
Cu3*d* - O2*p*σ

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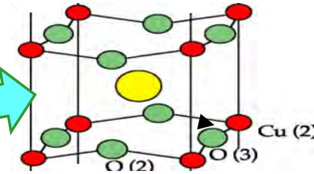
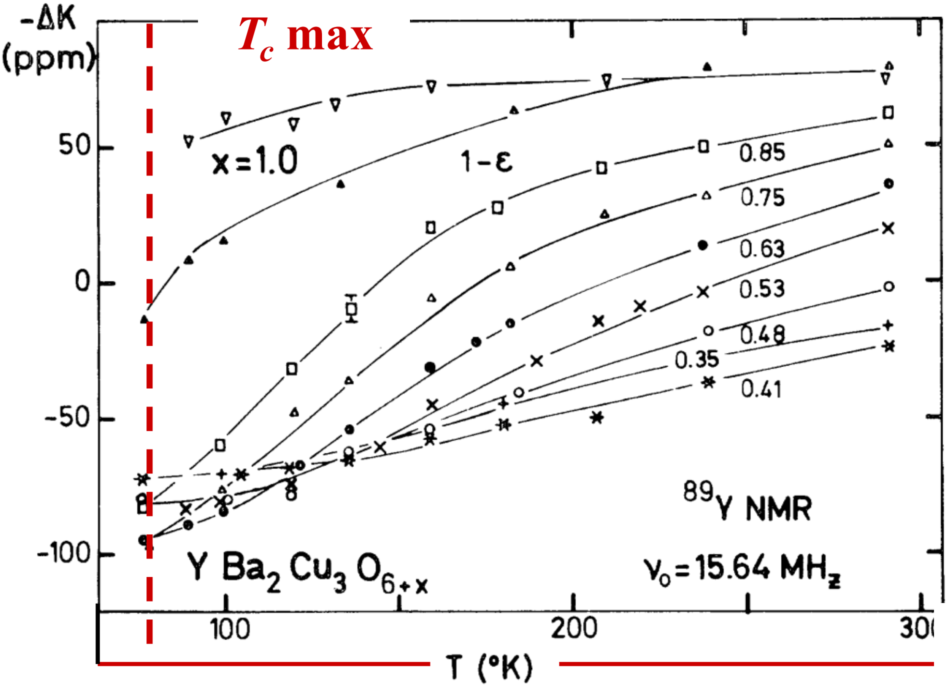
What about the origin of this large decrease at low T?

$YBa_2Cu_3O_{6+x}$

^{89}Y NMR shift

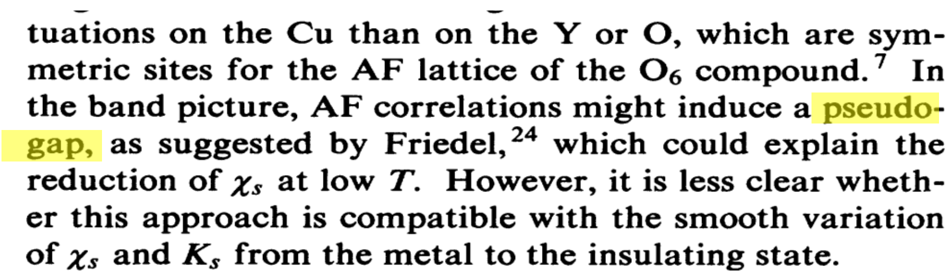




Large decrease (nearly full loss) of $\chi^s(T)$ above T_c

Pseudogap in the electronic excitations

H.A, T. Ohno and P. Mendels, PRL 1989



tuations on the Cu than on the Y or O, which are symmetric sites for the AF lattice of the O_6 compound.[7] In the band picture, AF correlations might induce a pseudogap, as suggested by Friedel,[24] which could explain the reduction of χ_s at low T. However, it is less clear whether this approach is compatible with the smooth variation of χ_s and K_s from the metal to the insulating state.

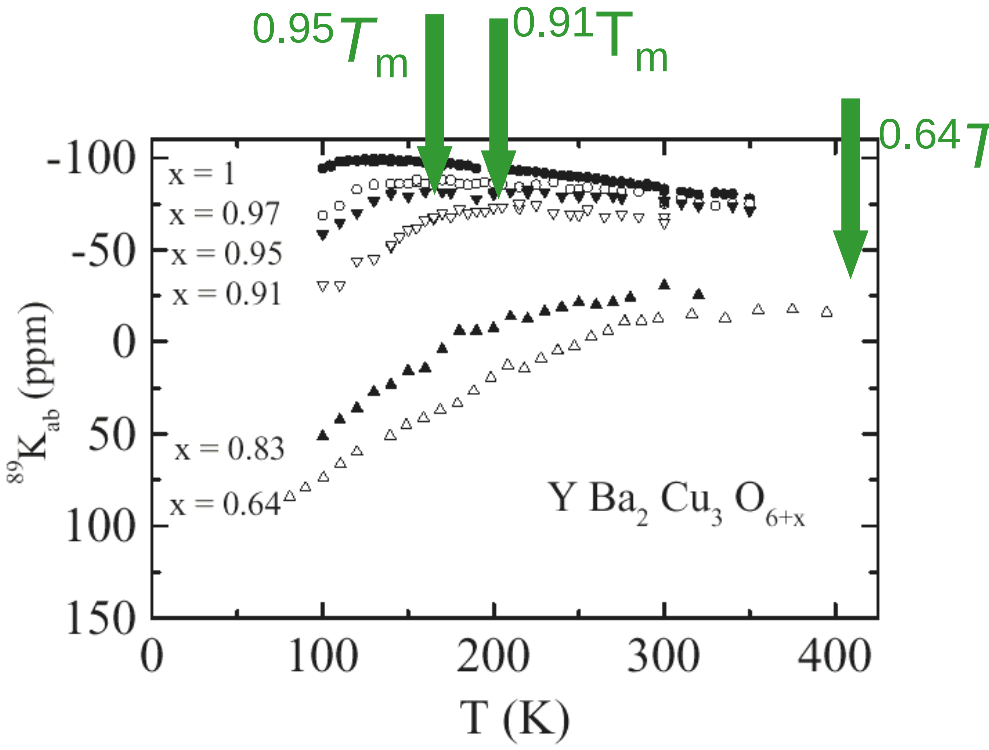
$$K = \sigma + A\,\chi_s(T)$$

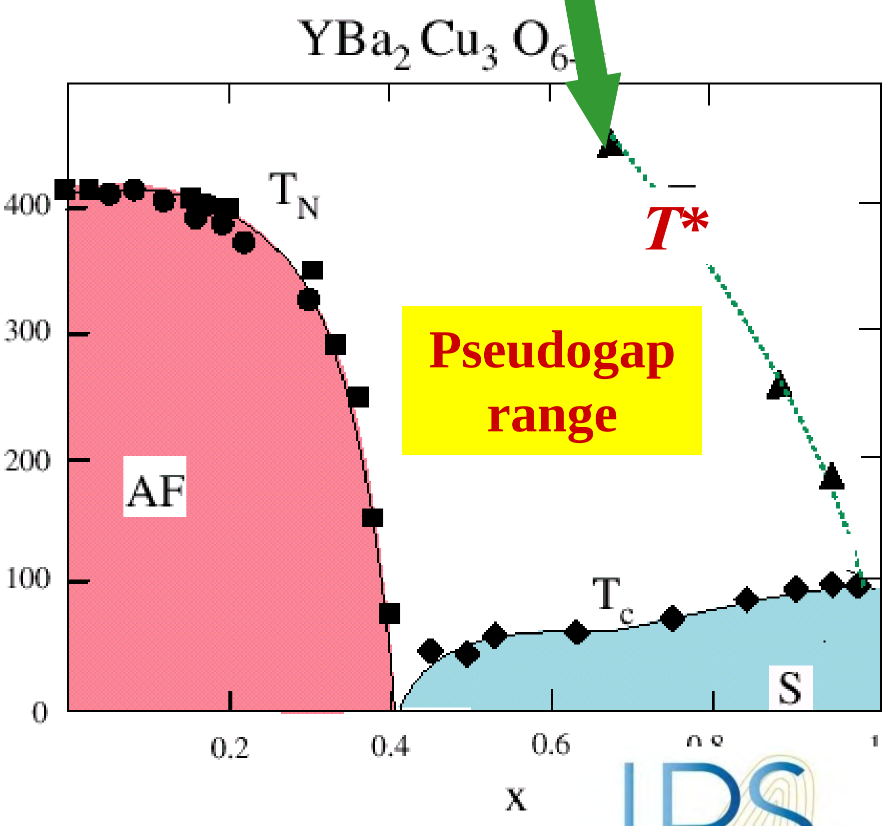
In usual metals χ_s is T independent (as for $x=1$) and vanishes at T=0 in the SC

Phase Diagram and Pseudogap

^{89}Y NMR shift

Low *T* decrease of the susceptibility:
opening of the pseudogap



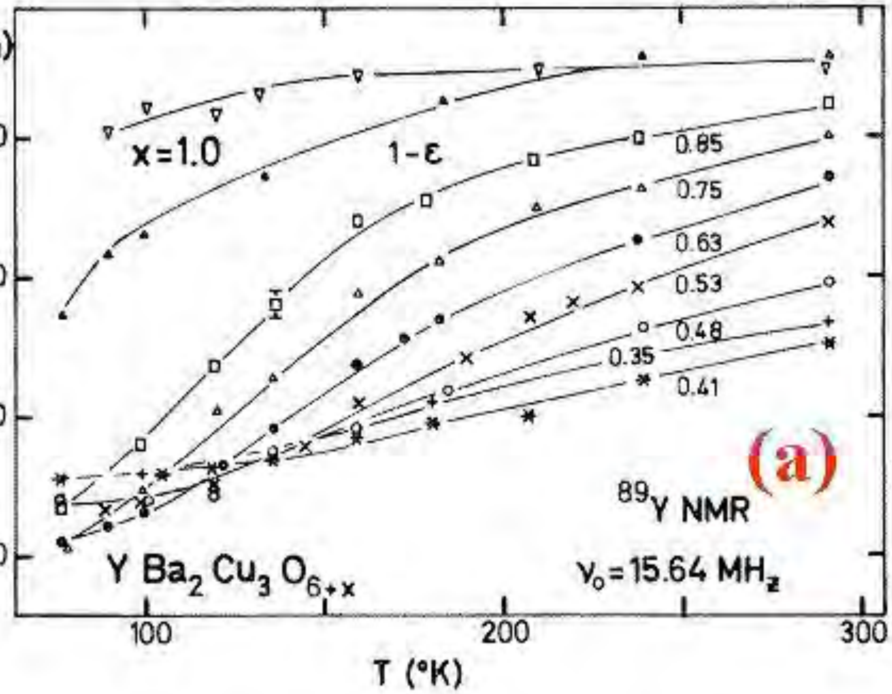


Alloul et al

The pseudogap is generic in the various families of cuprates

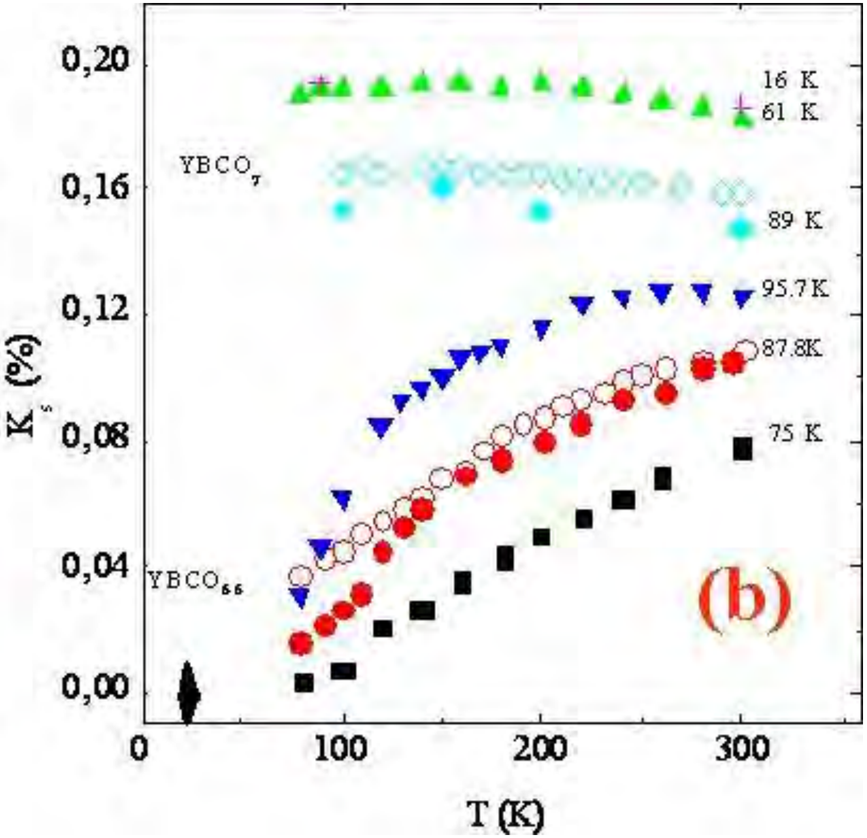
YBCO : two CuO_2 layer

H.Alloul , T. Ohno and P. Mendels, PRL 1989



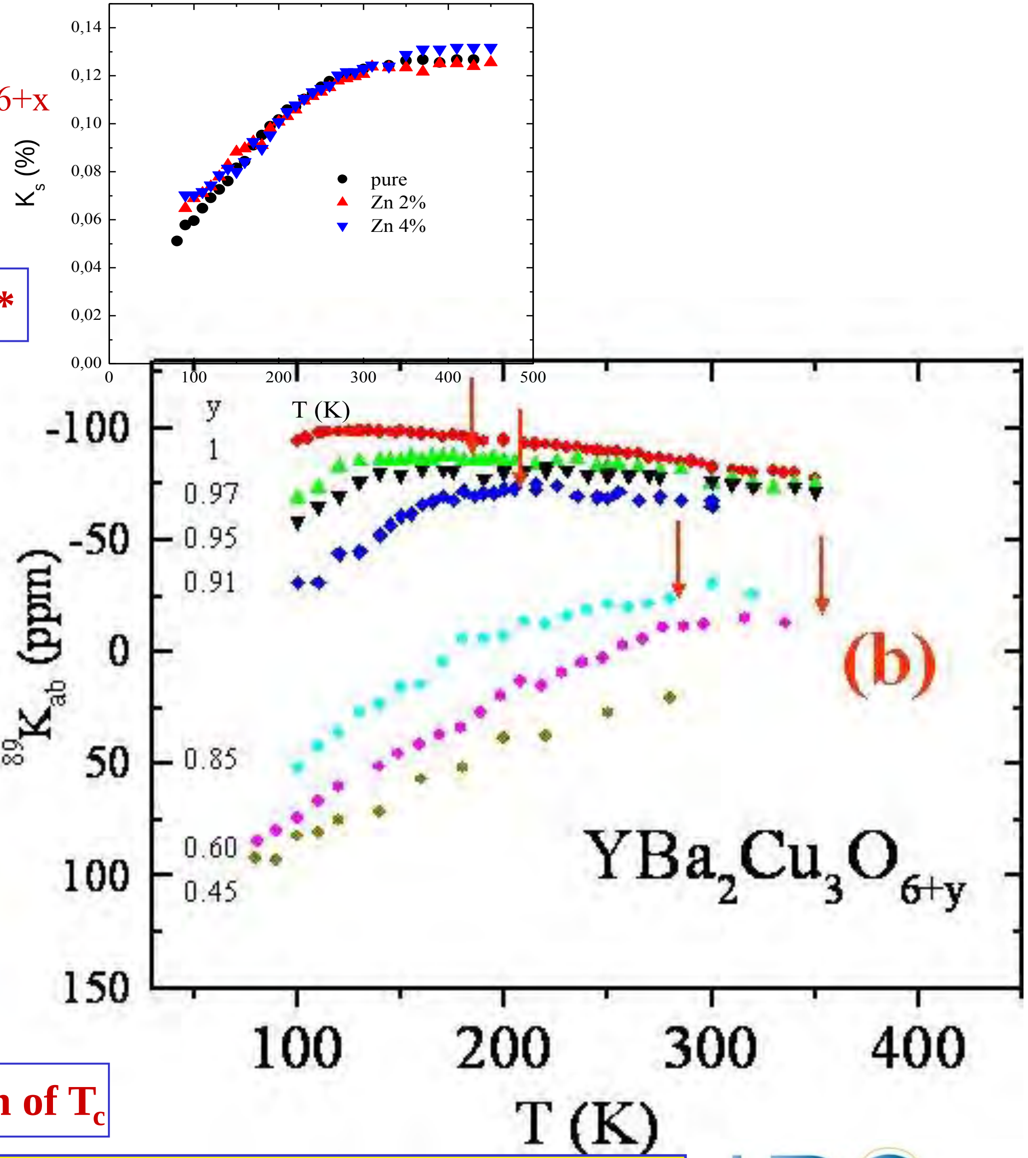
Hg1201 : one CuO_2 layer

J. Bobroff, H.A,… PRL 1997



Incidence of non magnetic impurities on the SC and pseudogap

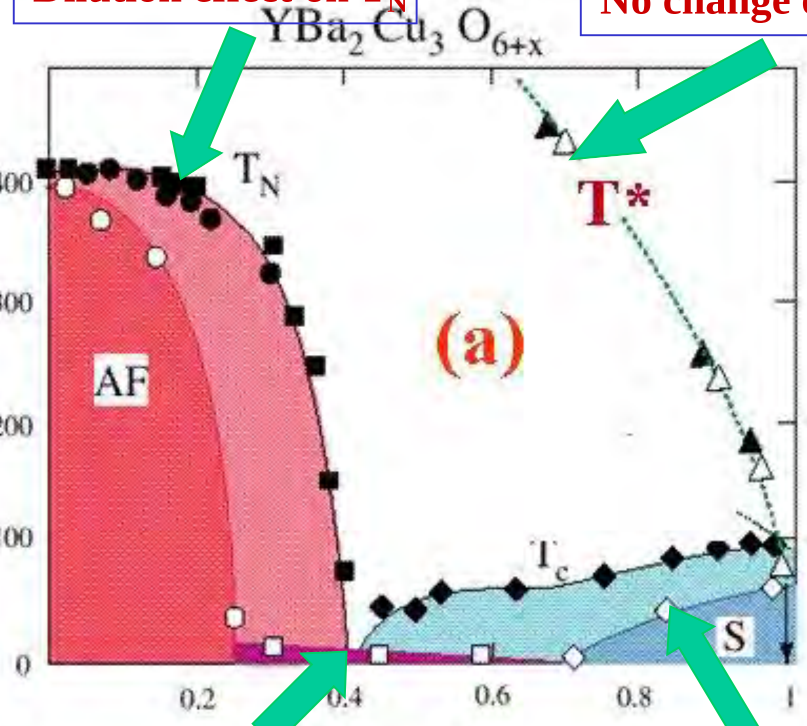
$YBCO_{6+x}$ + 4%Zn → $YBCOZ_{6+x}$



H. Alloul et al , PRL 67, 3140 (1991)

Dilution effect on T_N

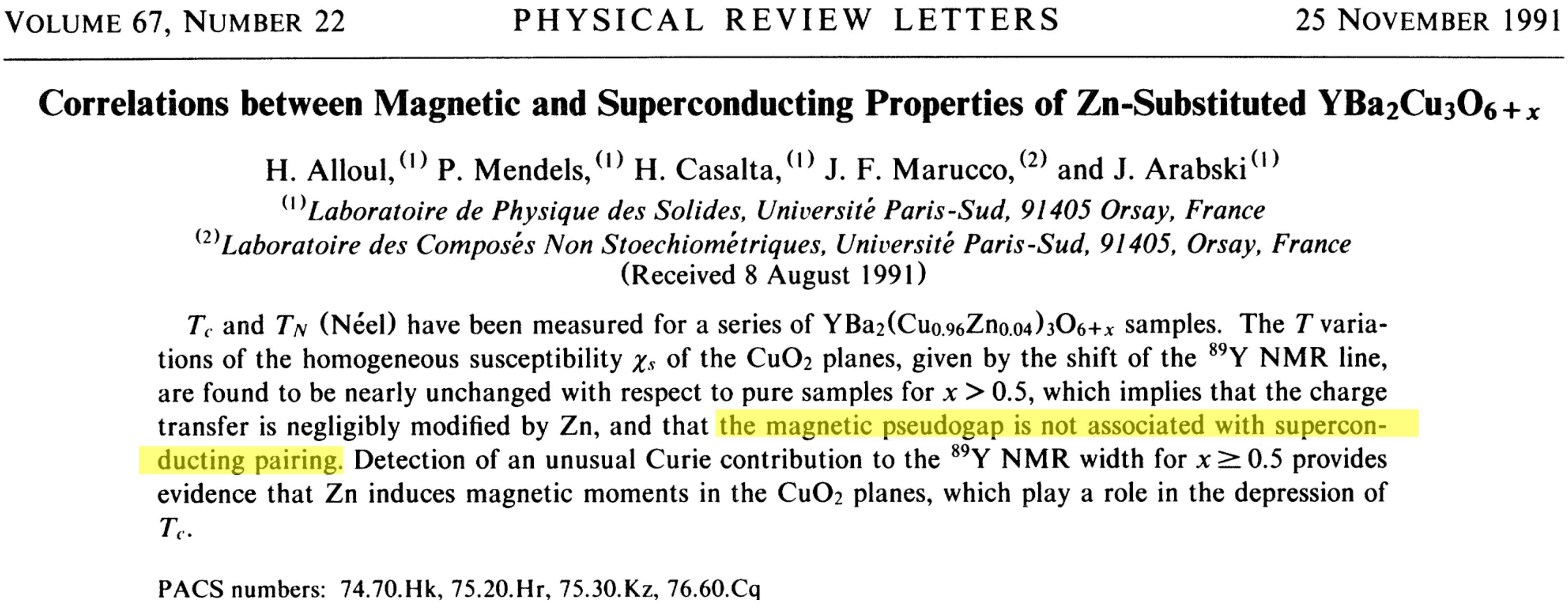
No change of T*



Increase of the disordered magnetism range

Large depression of T_c

The pseudogap is robust and insensitive to disorder



VOLUME 67, NUMBER 22 PHYSICAL REVIEW LETTERS 25 NOVEMBER 1991

Correlations between Magnetic and Superconducting Properties of Zn-Substituted $YBa_2Cu_3O_{6+x}$

H. Alloul,(1) P. Mendels,(1) H. Casalta,(1) J. F. Marucco,(2) and J. Arabski(1)
(1)*Laboratoire de Physique des Solides, Université Paris-Sud, 91405 Orsay, France*
(2)*Laboratoire des Composés Non Stoechiométriques, Université Paris-Sud, 91405, Orsay, France*

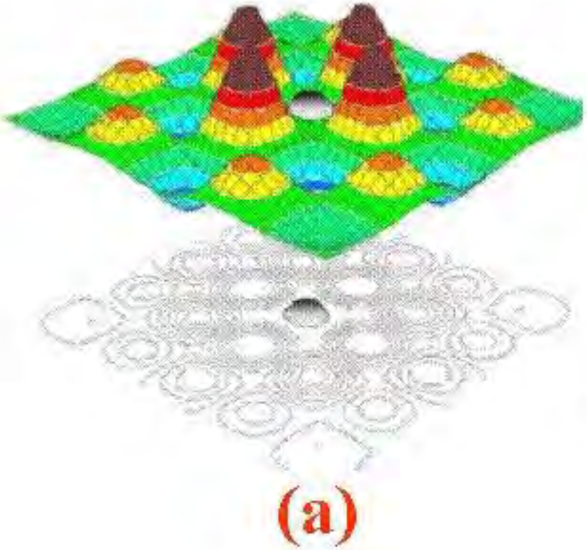
(Received 8 August 1991)

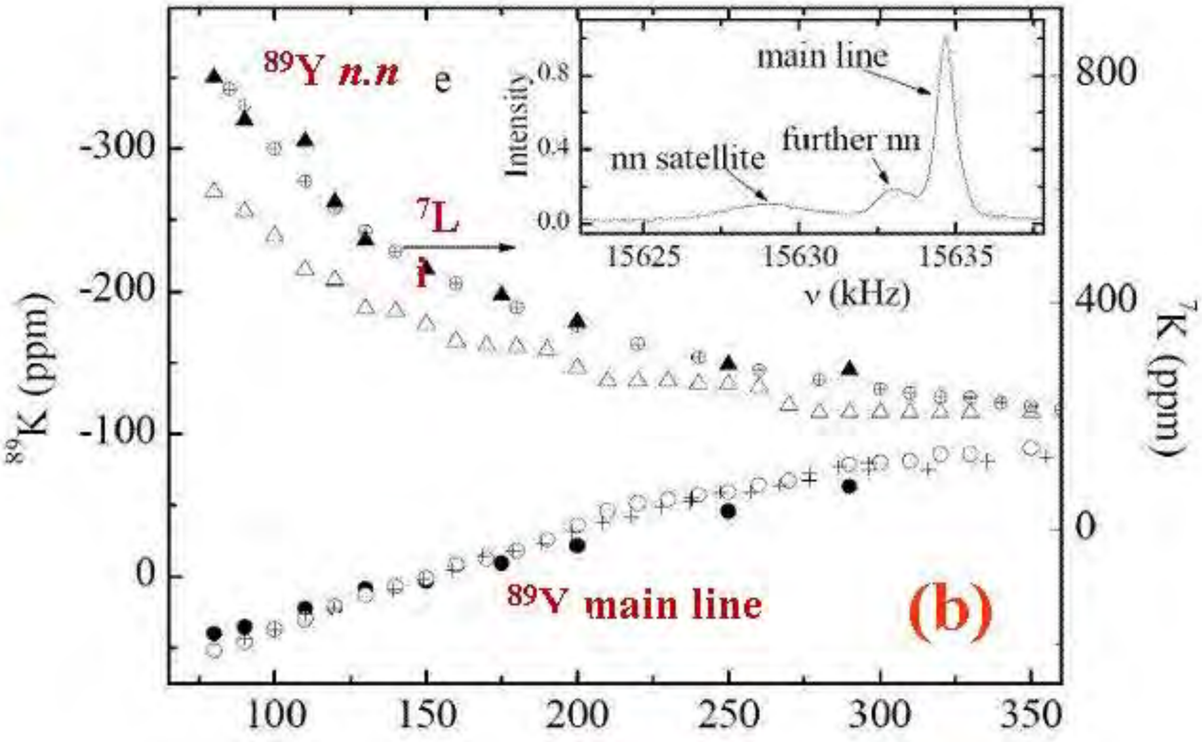
T_c and T_N (Néel) have been measured for a series of $YBa_2(Cu_{0.96}Zn_{0.04})_3O_{6+x}$ samples. The T variations of the homogeneous susceptibility χ_s of the CuO_2 planes, given by the shift of the ^{89}Y NMR line, are found to be nearly unchanged with respect to pure samples for $x > 0.5$, which implies that the charge transfer is negligibly modified by Zn, and that the magnetic pseudogap is not associated with superconducting pairing. Detection of an unusual Curie contribution to the ^{89}Y NMR width for $x \geq 0.5$ provides evidence that Zn induces magnetic moments in the CuO_2 planes, which play a role in the depression of T_c.

PACS numbers: 74.70.Hk, 75.20.Hr, 75.30.Kz, 76.60.Cq

Pseudogap and correlations : Mott physics?

Local magnetic response induced by non magnetic Zn

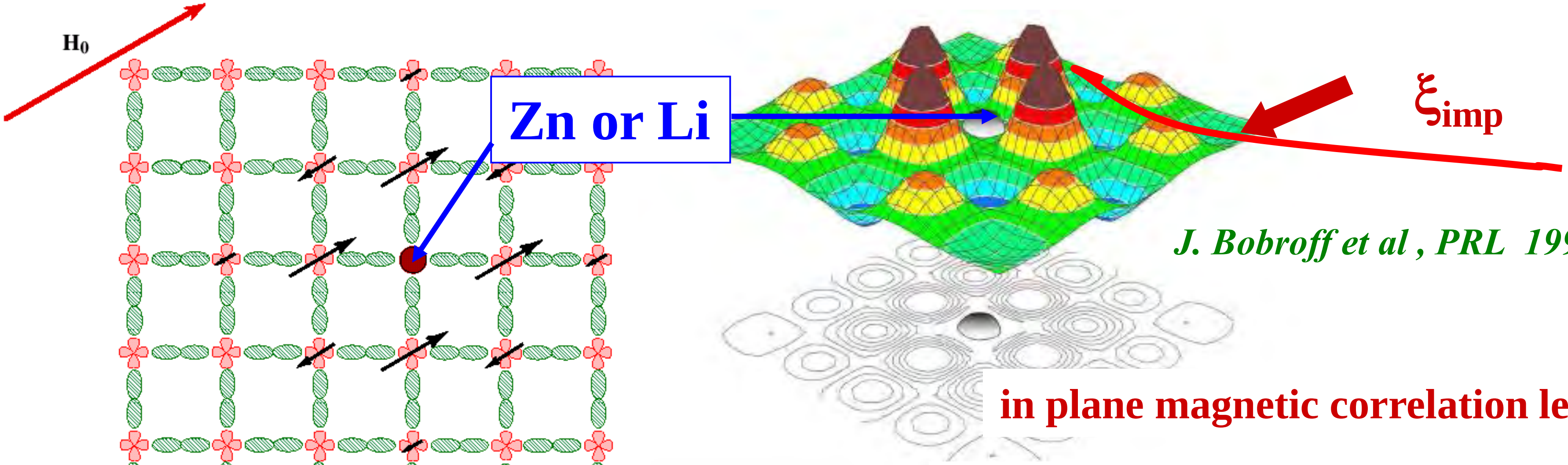




Importance of correlations : magnetism induced by non magnetic substitutions

H. Alloul, P. Mendels et al PRL 1991; A. Mahajan, H. A et al PRL 1993

Review: H.A, J. Bobroff, M. Gabay and P. Hirschfeld. Review of Modern Physics (2009).



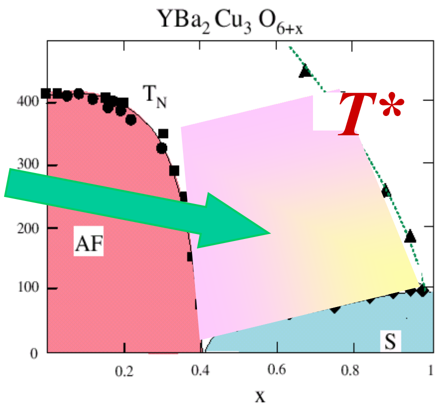
Zn or Li

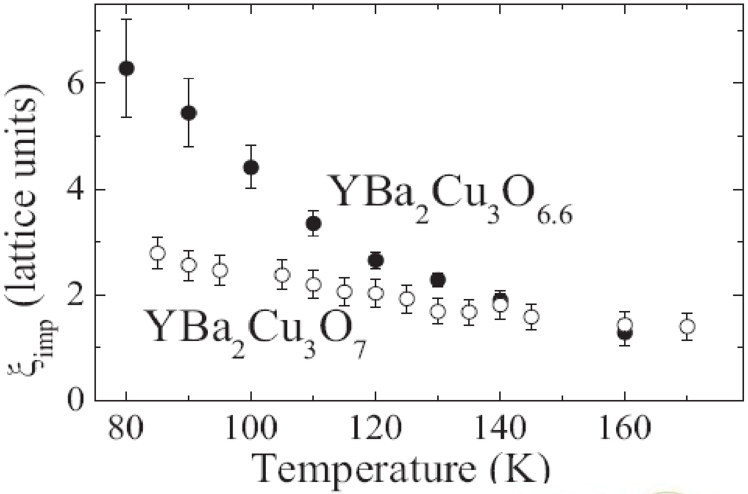
ξ_{imp}

J. Bobroff et al , PRL 1999

in plane magnetic correlation length

Correlations persist up to optimal doping



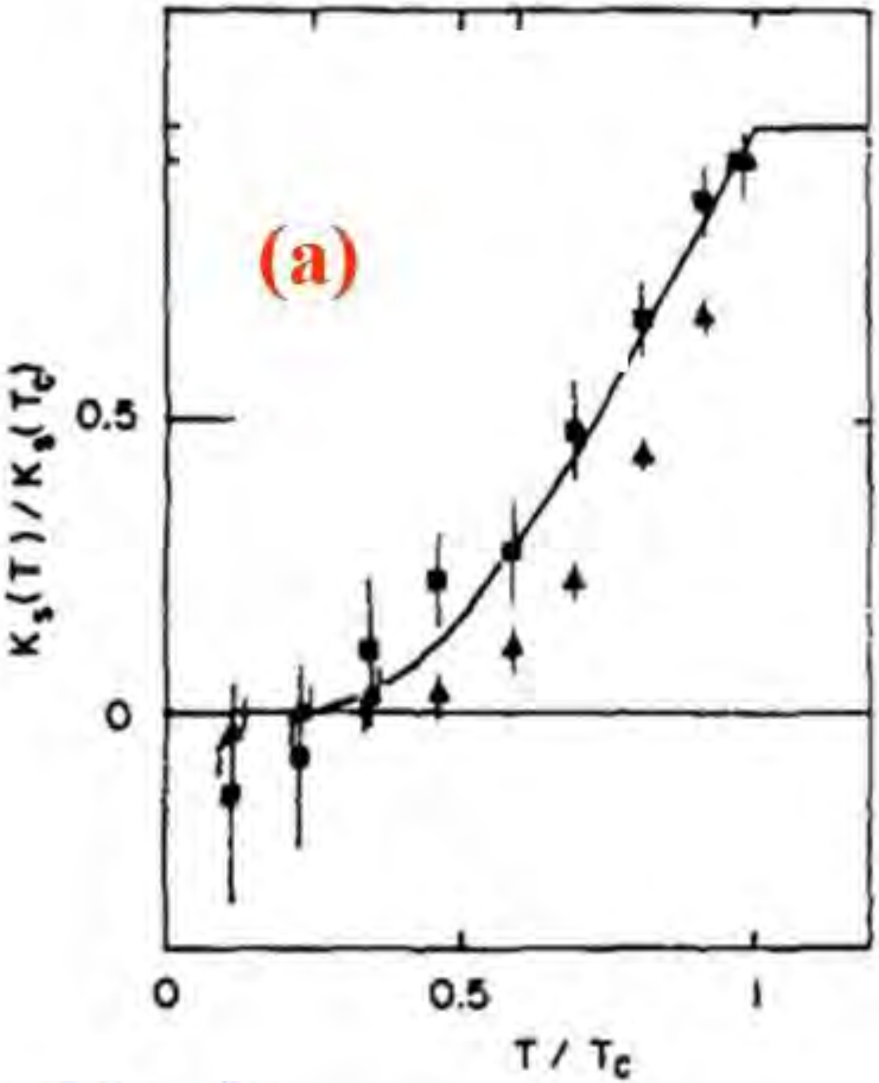


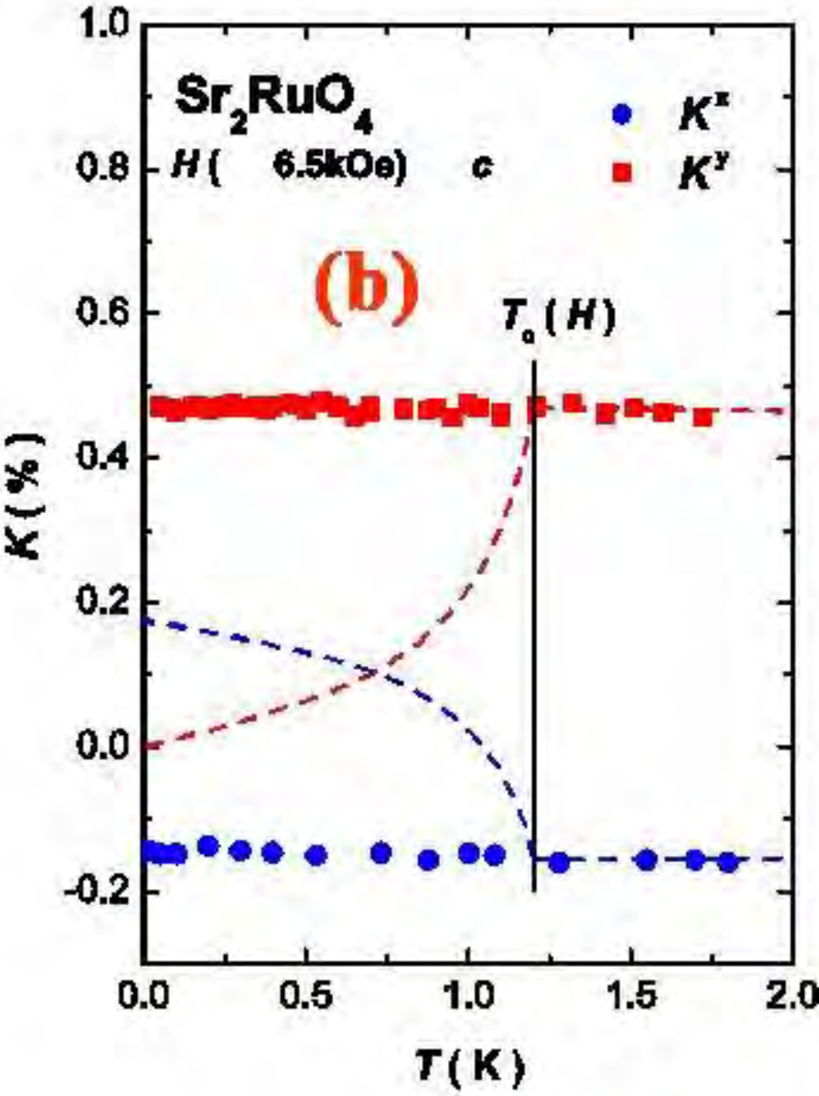
NMR in correlated electron systems
Illustration in the case of the cuprates

- ***Introduction to Magnetic resonance (NMR and ESR)***
  - Hyperfine couplings , NMR shifts
- ***Magnetic spin susceptibilities in NMR***
  - Metals and superconductors: Singlet spin pairing
  - Impurity magnetism , RKKY , Transferred hyperfine couplings
- ***Magnetic spin susceptibilities in NMR : the cuprate case***
  - Electronic structure . Single spin fluid in the normal state
- ***The pseudogap and the phase diagram***
  - Pseudogap and disorder. Impurities reveal the magnetic correlations
- ***Spin lattice relaxation T_1 and transverse relaxation T_2***
  - Dynamic susceptibilities and spin lattice relaxation
  - d- wave SC , magnetic correlations in the cuprate phase diagram
  - Spin echoes and T_2: NMR applications

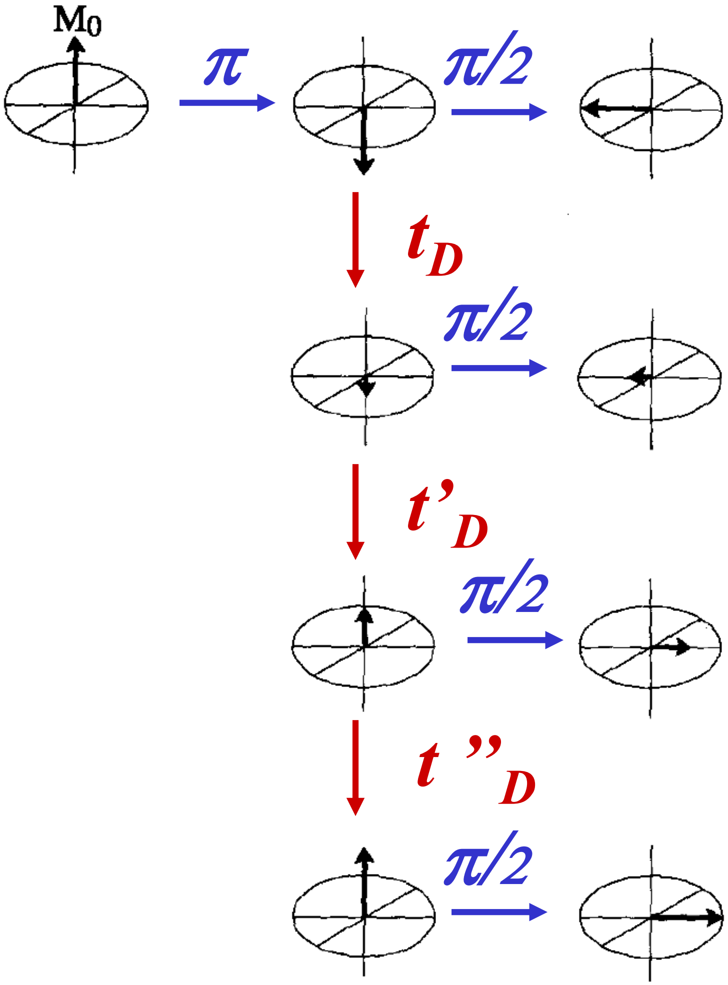
Conclusion: NMR is a powerful tool in Solid State Physics

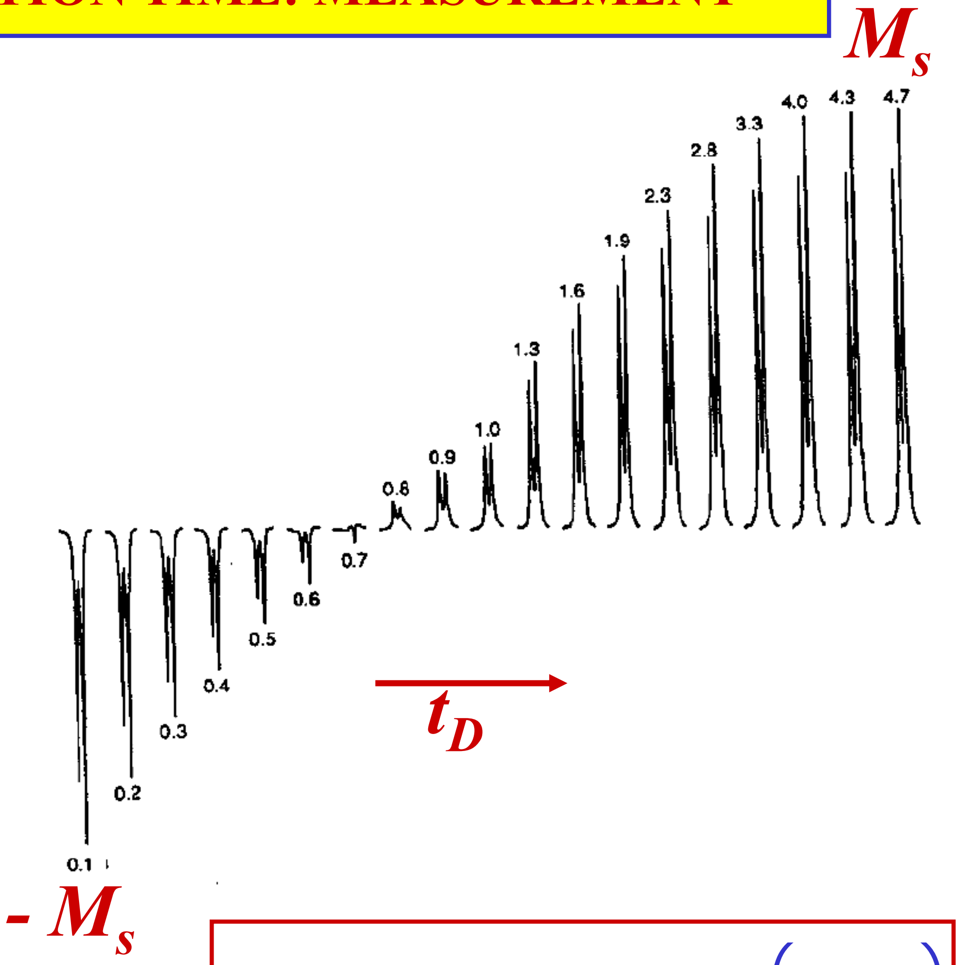
Exotic superconductivities; singlet or triplet?





SPIN LATTICE RELAXATION TIME: MEASUREMENT

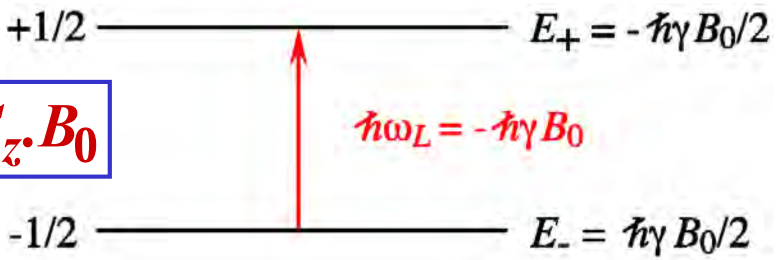




$(\pi - t_D - \pi/2)$ **sequence**

$$M(t_D) = M_s - 2M_s \exp\left(-\frac{t}{T_1}\right)$$

Physical Origin of the Spin Lattice Relaxation



$$\boxed{H_Z = -\hbar\gamma S_z . B_0}$$

B_0 // z

transitions $|-1/2\rangle \rightarrow |1/2\rangle$

if $\langle 1/2 | H_{rf} | -1/2 \rangle \neq 0$

$B_1 \perp z$

rf excitting field perturbation for H_Z

$$\boxed{H_{rf} = -\hbar\gamma\, \mathrm{S.B}_1 \cos \omega_L t}$$

$$\vec{B}_L = < \vec{B}_L > + \left[\vec{B}_L - < \vec{B}_L > \right]$$

Relaxation: transverse components of the fluctuating field at the Larmor frequency

Transition probability

$$\boxed{\frac{1}{T_1} = \gamma_n^2 \int_{-\infty}^{\infty} < B_L^+(t)\, B_L^-(0) > \exp(-i\omega_n t)\, dt}$$

Correlation function of the local field

T_1 results from the coupling with the equilibrium fluctuations of the electron spins degrees of of freedom

T_1 IN A METAL: KORRINGA LAW

$$H = H_Z + H_c = -\hbar\gamma_n \vec{I}\cdot\vec{B}_0 + A\,\vec{I}\cdot\sum_i \vec{s}_i\,\delta(\vec{r}_i) \qquad \vec{B}_L = -\frac{A}{\hbar\gamma_n}\sum_i \vec{s}_i\,\delta(\vec{r}_i) = -\frac{A}{\hbar^2\gamma_e\gamma_n}\vec{M}(0)$$

$$\frac{1}{T_1} = \gamma_n^2\int_{-\infty}^{\infty}< B_L^+(t)\,B_L^-(0) > \exp\left(-i\omega_n t\right)dt \qquad \boxed{\frac{1}{T_1} = \frac{A^2}{\hbar^4\gamma_e^2}\int_{-\infty}^{\infty}< \vec{M}^+(t)\,\vec{M}^-(0) > \exp\left(-i\omega_n t\right)dt}$$

Fluctuation-dissipation theorem (Transverse dynamic χ of the electron gas)

$$\chi_T''(\omega_n) = \frac{1}{2\hbar}\left(1-\exp\frac{\hbar\omega_n}{k_BT}\right)\int_{-\infty}^{\infty}< \vec{M}^+(t)\,\vec{M}^-(0) > \exp\left(-i\omega_n t\right)dt$$

with $\hbar\omega_n << k_BT$

$$\boxed{\frac{1}{T_1} = \frac{2A^2}{\hbar^2\gamma_e^2}k_BT\frac{\chi_T''(\omega_n)}{\omega_n}}$$

For a fermion gas $\chi_T(\omega) = \frac{1}{2}\hbar^2\gamma_e^2\left\{n(E_F) + i\pi\,\hbar\omega\,n^2(E_F)\right\}$

$$\boxed{\frac{1}{T_1} = \frac{\pi}{\hbar}A^2 n^2(E_F)k_BT} \qquad \boxed{K = \frac{A}{\hbar^2\gamma_e\gamma_n}\chi_P = \frac{A\gamma_e}{2\gamma_n}n(E_F)} \qquad \boxed{T_1TK^2 = \frac{\hbar}{4\pi k_B}\left(\frac{\gamma_e}{\gamma_n}\right)^2}$$

Korringa law for a metal

Spin lattice relaxation in a free electron metal

$$\frac{1}{T_1}=\frac{2A^2}{\hbar^2\gamma_e^2}k_BT\,\frac{\chi_T''(\omega_n)}{\omega_n}$$

$$\chi_T''(\omega_n)=\sum_q\chi_T''(q,\omega_n)$$

Al metal

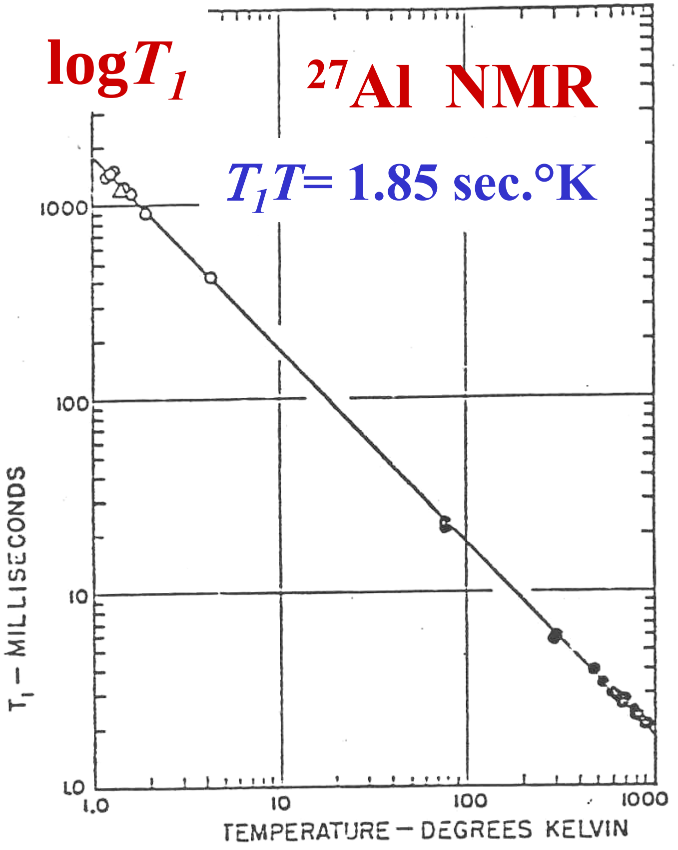
For a free electron gas χ ''(q, ω_n) is q independent

$$\chi_T(\omega)=\frac{1}{2}\hbar^2\gamma_e^2\left\{n(E_F)+i\pi\hbar\omega n^2(E_F)\right\}$$

$$\frac{1}{T_1}=\frac{\pi}{\hbar}A^2n^2(E_F)k_BT$$

$$K=\frac{A}{\hbar^2\gamma_e\gamma_n}\chi_P=\frac{A\gamma_e}{2\gamma_n}\,n(E_F)$$

$$T_1TK^2=\frac{\hbar}{4\pi k_B}\left(\frac{\gamma_e}{\gamma_n}\right)^2=S_0$$



$\log T_1$

T_1T= 1.85 sec.°K

$\log(1/T)$

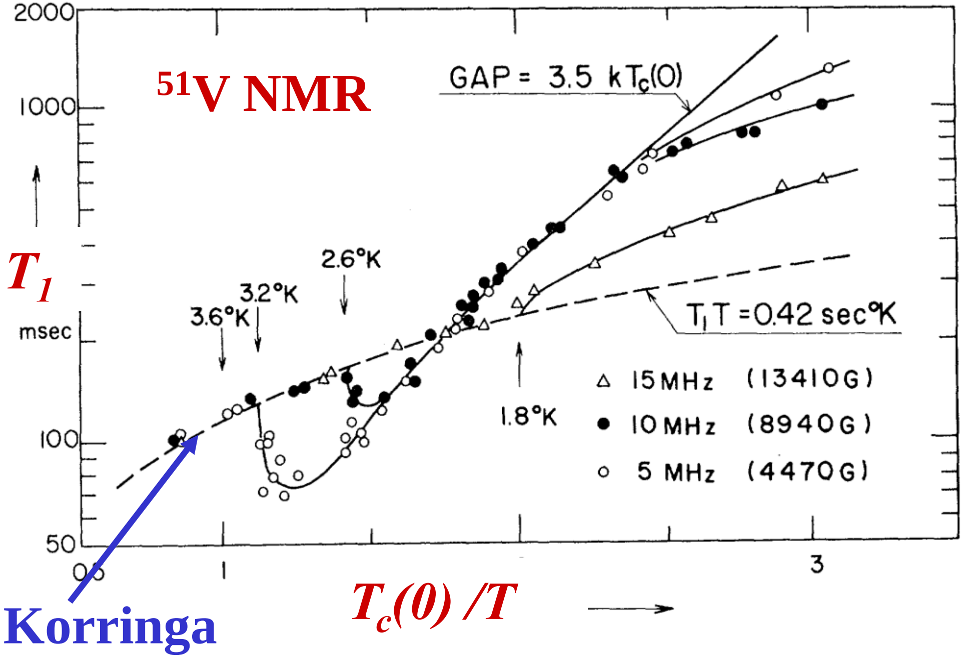
Korringa law for a metal

Thermometry

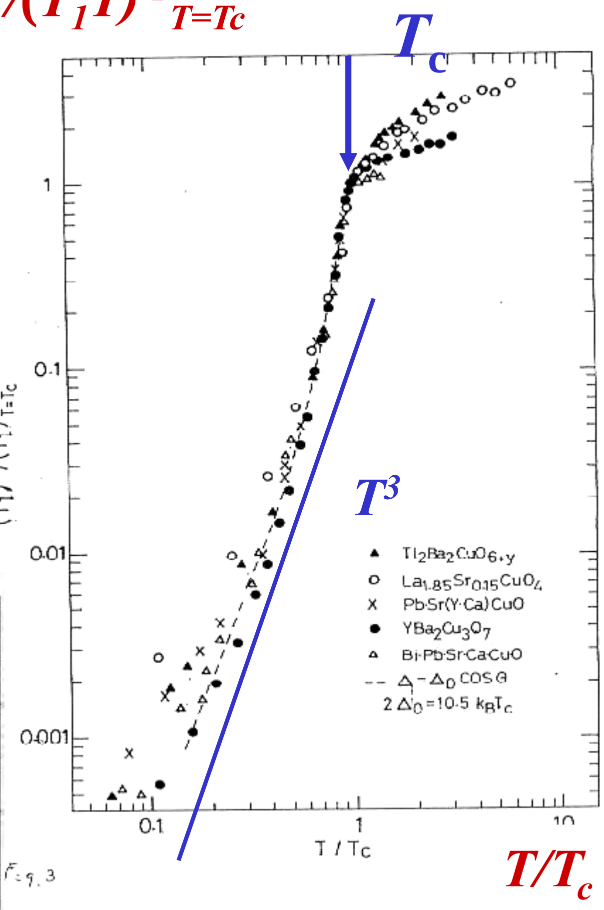
T_1 in the superconducting state

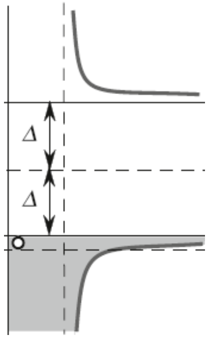
V_3Sn

Cuprates

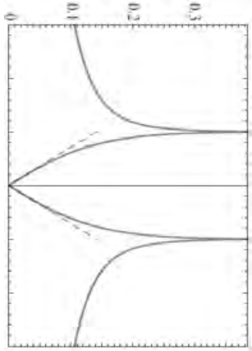


$(T_1T)^{-1}/(T_1T)^{-1}_{T=Tc}$





s wave superconductor



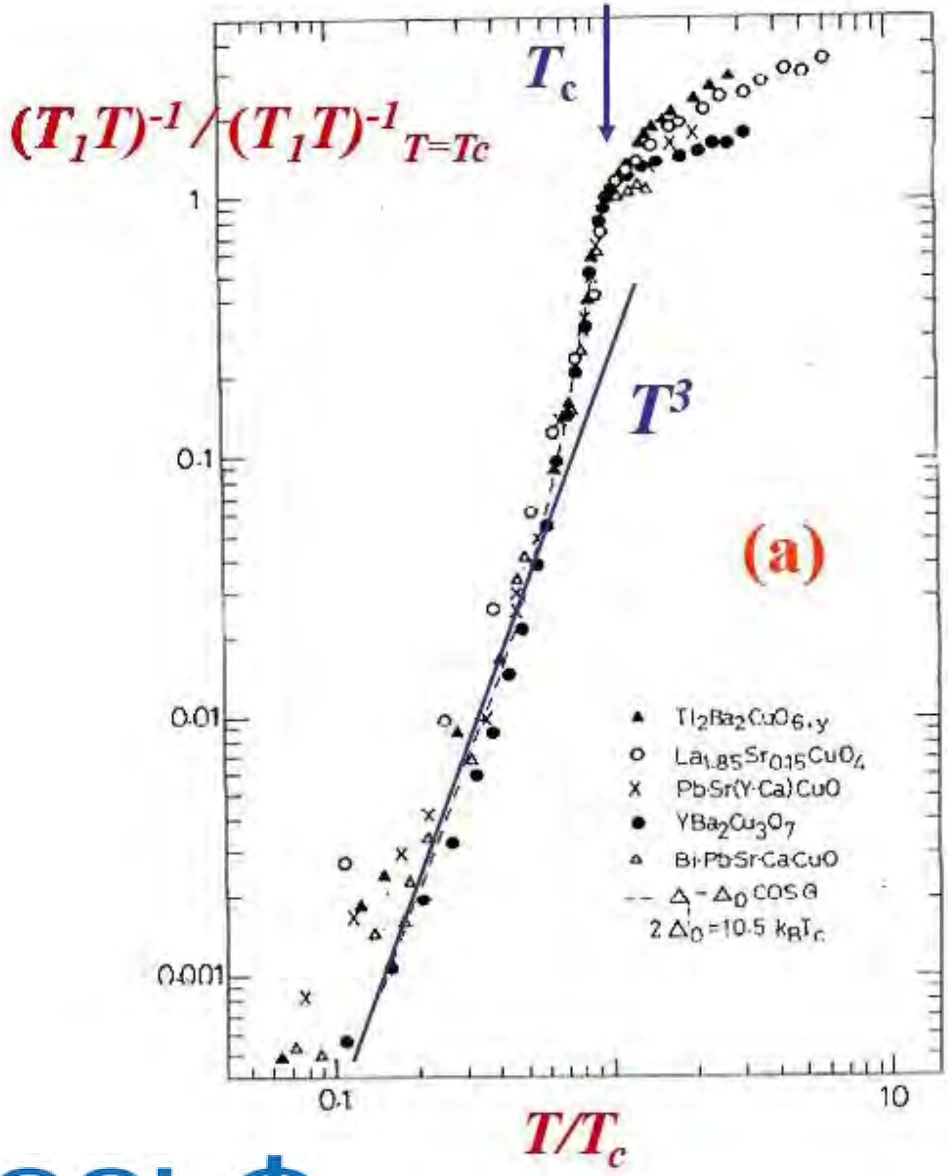
$$(T_1T)^{-1} \sim \ exp\ (-\Delta/k_BT)$$

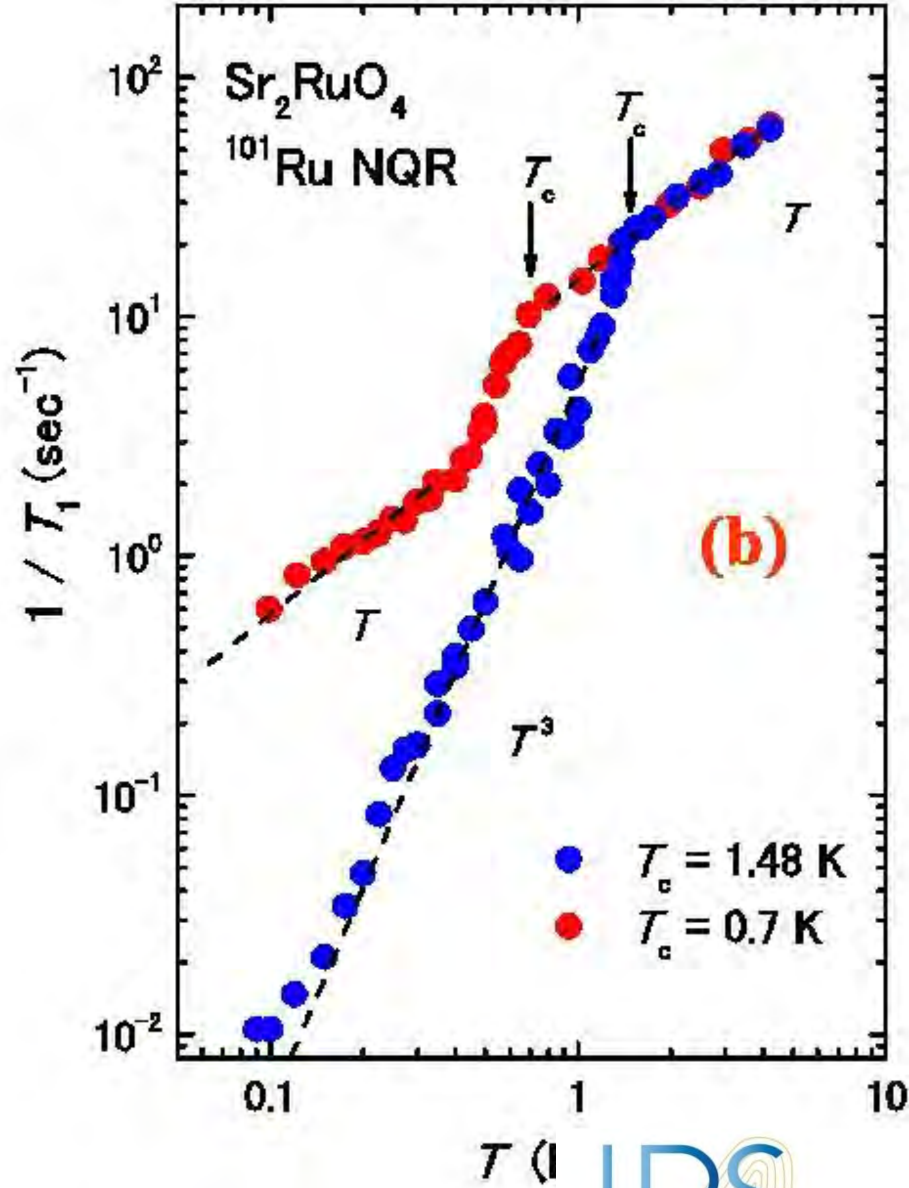
for $T<<T_c$

T_1 minimum below T_c
(Hebel-Slichter peak in $1/T_1$)

***d* wave superconductivity**
T^3 variation for $T<<Tc$

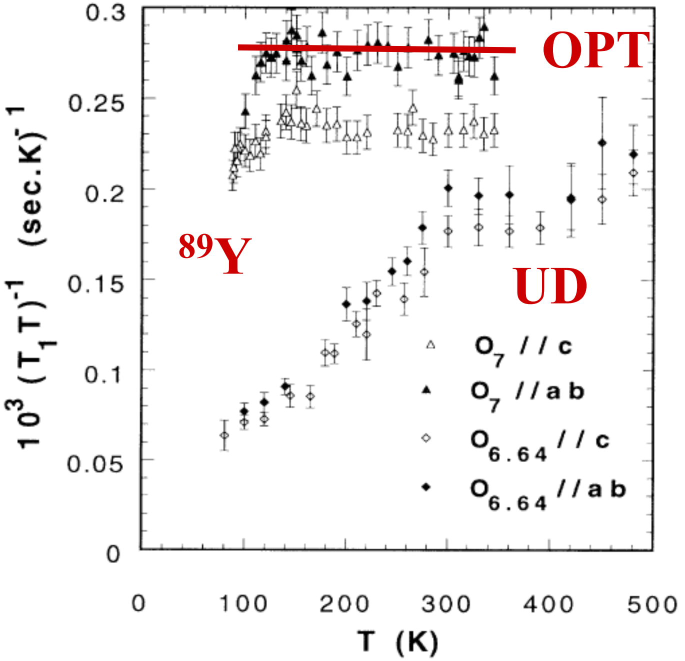
H. Alloul, Autumn School on correlated electrons
Julich ,15 /09/ 2016

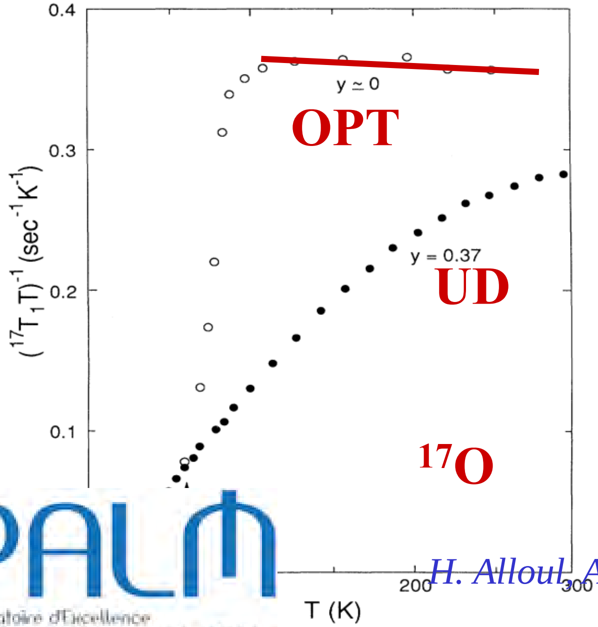

(T1T)-1 / (T1T)-1 T=Tc
Tc
T3
(a)
1
0.1
0.01
0.001
0.1
10
T/Tc
▲ Tl2Ba2CuO6+y
○ La1.85Sr0.15CuO4
× PbSr(Y·Ca)CuO
● YBa2Cu3O7
△ Bi·Pb·Sr·CaCuO
-- Δ = Δ0 cos θ
2Δ0 = 10.5 kBTc


Sr2RuO4
101Ru NQR
Tc
Tc
T
T
T3
(b)
1 / T1 (sec-1)
102
101
100
10-1
10-2
0.1
1
10
T (I
● Tc = 1.48 K
● Tc = 0.7 K

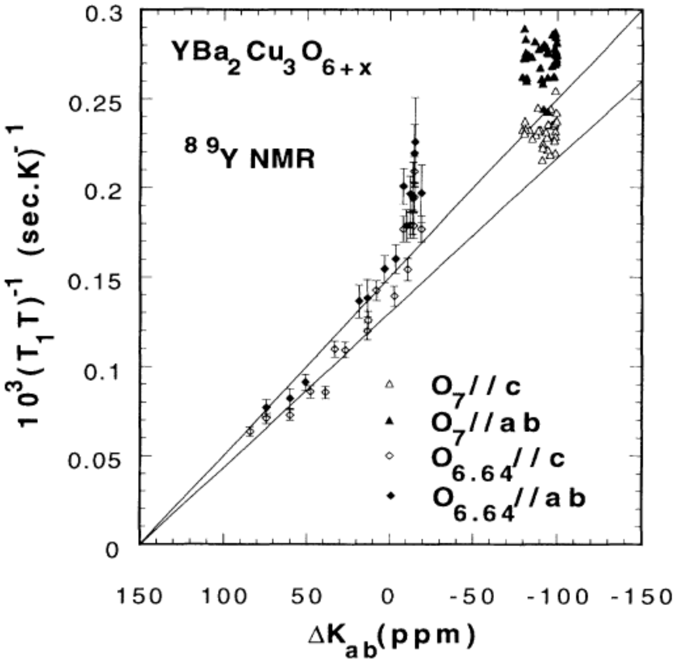
Comparison of $(T_1 T)^{-1}$ on ^{89}Y and ^{17}O above Tc

$(T_1T)^{-1}$





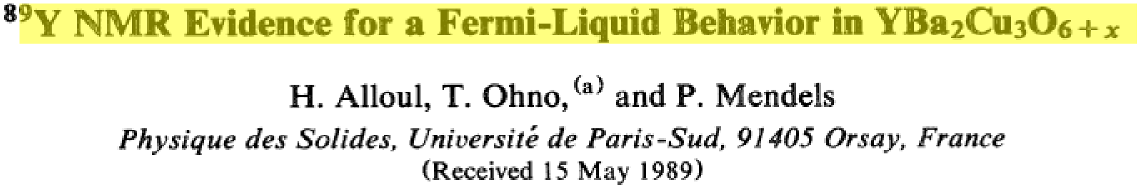
In YBCO$_7$ T_1T is nearly constant on ^{17}O and ^{89}Y
Like in a free electron metal



In YBCO$_{6.6}$

$$\boxed{\frac{1}{T_1T} \propto K}$$

Metallic like component



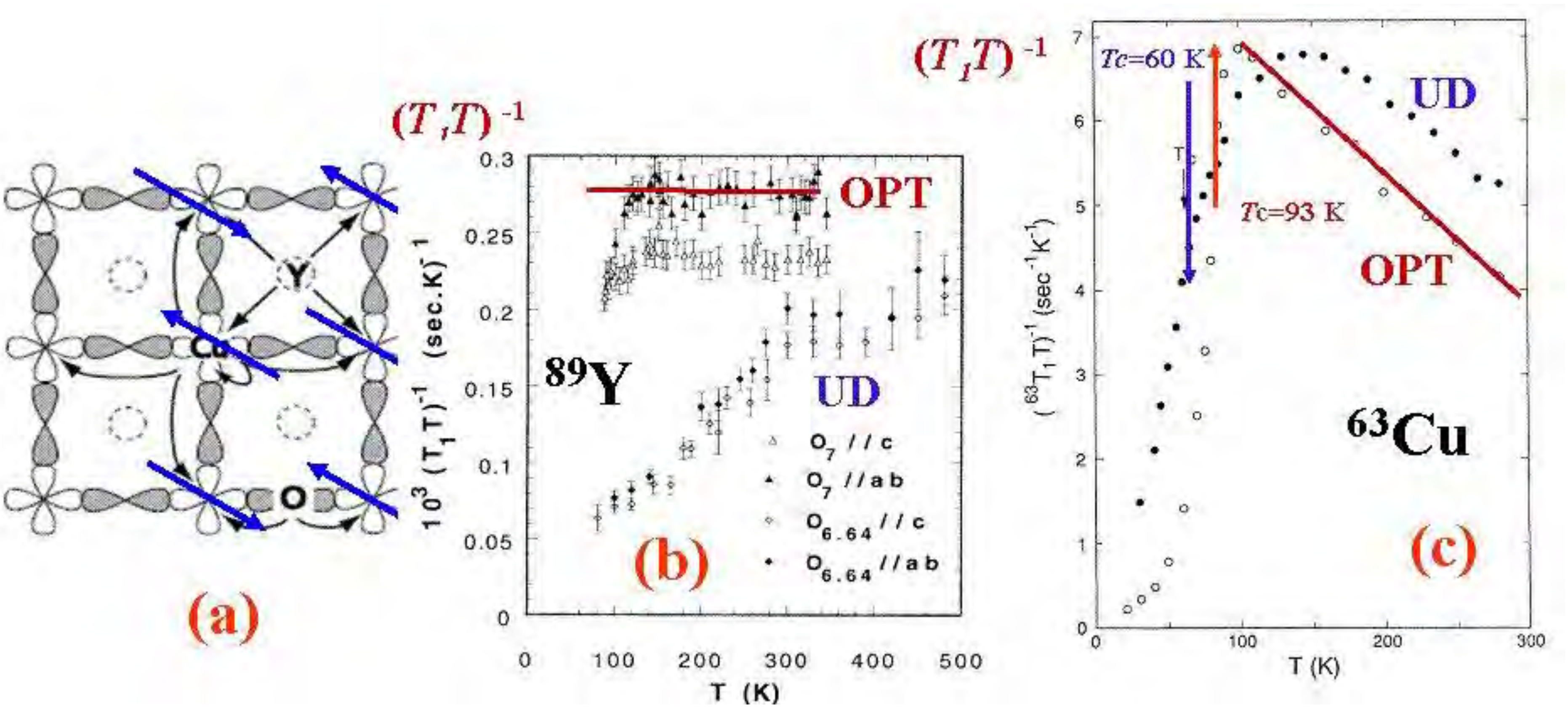
^{89}Y NMR Evidence for a Fermi-Liquid Behavior in $YBa_2Cu_3O_{6+x}$

H. Alloul, T. Ohno,(a) and P. Mendels

Physique des Solides, Université de Paris-Sud, 91405 Orsay, France

(Received 15 May 1989)

Distinct behaviour of $(T_1T)^{-1}$ on the Cu site: AF correlations



In YBCO$_7$ T_1T is nearly constant on ^{89}Y and ^{17}O but increases at low T for ^{63}Cu

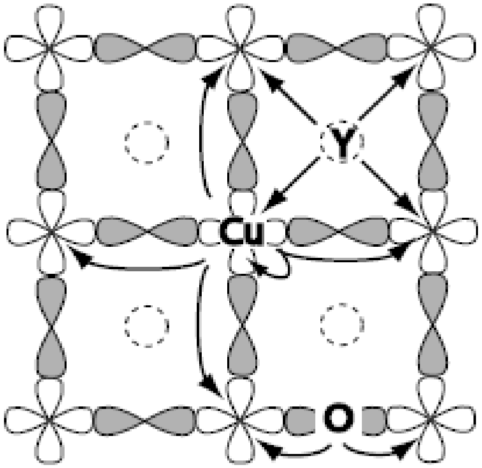
O and Y are insensitive to AF correlations while Cu probes them fully

Increase of AF correlations at low *T*
Even more for the underdoped case

T_1 for nuclei coupled to neighbouring sites

Non local hyperfine coupling
q dependence of the HF coupling

$$A^s_{O,\alpha}(\mathbf{q}) = A^s_{O,\alpha}\sum_{\mathbf{r}_i}\exp(i\ \mathbf{q}.\mathbf{r}_i)$$



^{89}Y $$A^s_{Y,\alpha}(q) = 8D_\alpha\left(\cos q_x a/2\ \ \cos q_y a/2\right)$$

^{17}O $$A^s_{O,\alpha}(q) = 2C_\alpha \cos q_x a/2$$

^{63}Cu $$A^s_{Cu,\alpha}(q) = A_\alpha + 2B_\alpha\left(\cos q_x a + \cos q_y a\right)$$

For Y and O, *A*(q) vanishes for q_{AF}= (π/a,π/a)
The AF fluctuations are filtered out by A(q)

$$\frac{1}{T_1} = \frac{2k_BT}{\hbar^2\gamma_e^2}\sum_{q} A^2(q)\ \chi_\perp''(q,\omega_n)/\omega_n$$

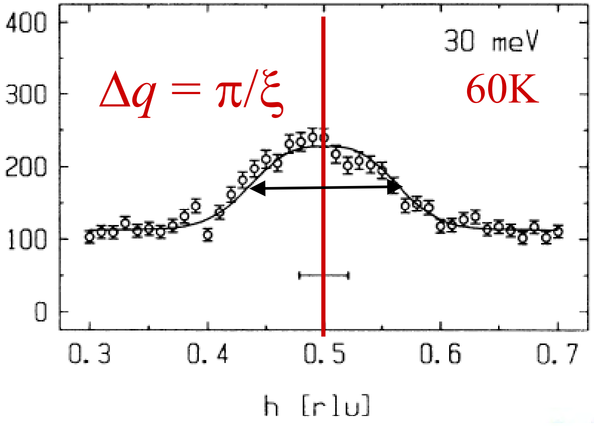
ξ(*T*) is the AF correlation length probed by ^{63}Cu NMR

$\omega \to 0$

Neutron scattering

$\chi_\perp''(q,\omega_n)$

YBCO$_{6.6}$



$\Delta q = \pi/\xi$

60K

q

(π/a,π/a)

Some conclusions

- *Magnetic spin susceptibilities in NMR :*
  - Singlet spin pairing
  - Single spin fluid in the normal state
  - The pseudogap is generic and robust to disorder
- *Dynamic susceptibilities and spin lattice relaxation :*
  - Magnetic correlations up to the Optimal doping
  - Metallic like at $q=0$, AF correlations for $q=(\pi/a , \pi/a)$
  - d- wave SC
- *The pseudogap and questions on the phase diagram*
  - Importance of disorder in the phase diagram
  - MIT and SG phases governed by disorder
- *SC Fluctuations and pseudogap* *(Conf: Florence Rullier Albenque)*
  - SC Fluctuations follow Tc versus hole doping , remain with disorder
  - A preformed pair scenario does not apply
  - Pseudogap is intimately linked with magnetism (competing order?)
  - NMR will be helpful to check possible models

More

- *Totally missing in my talk:*

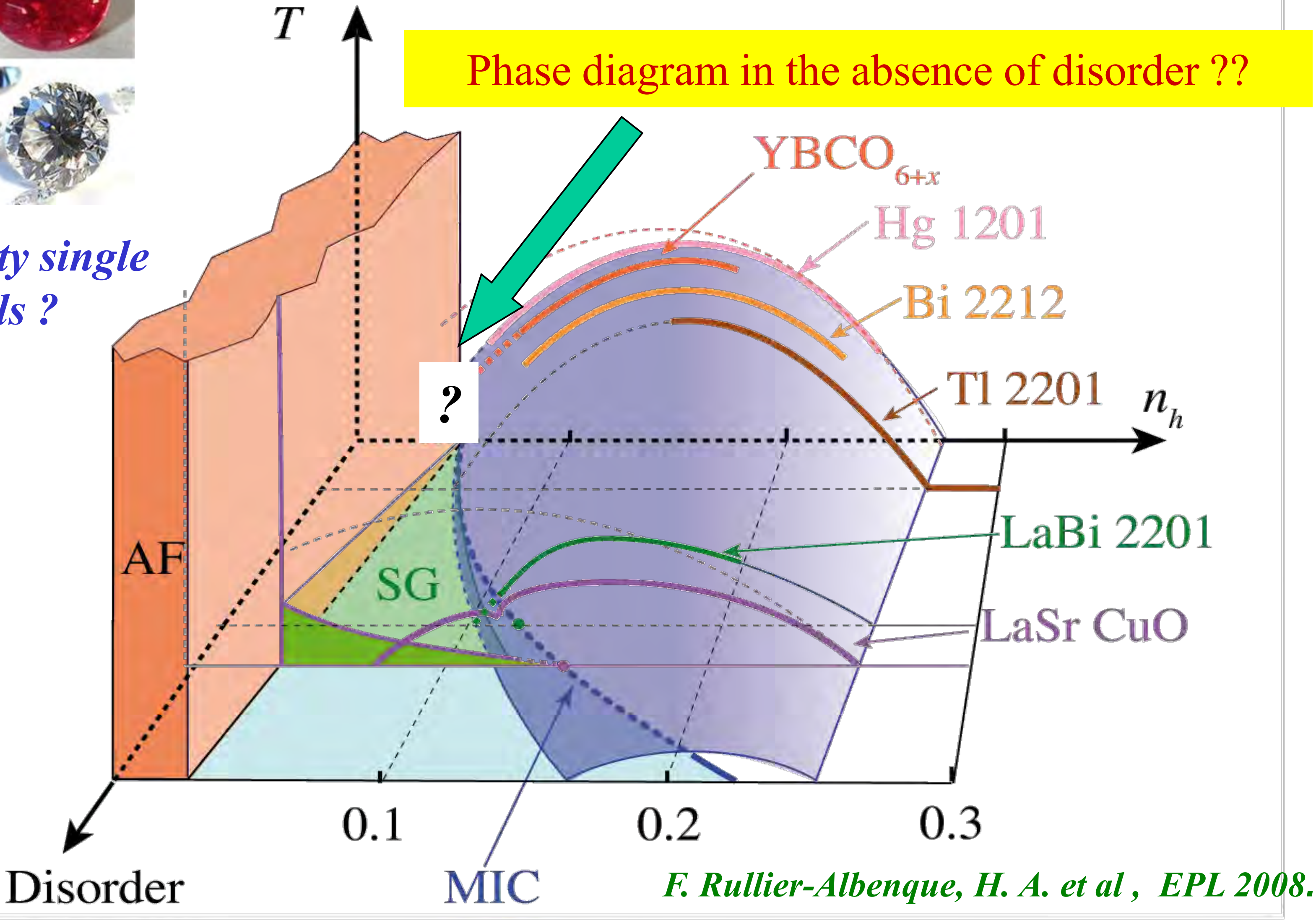
Quadrupolar effects
coupling of the nuclear spin with the charge distribution:
charge order, structurql transitions etc

- *Other examples of NMR studies :*

H. Alloul, “NMR studies of electronic properties of solids”, Scholarpedia, 9(9):32069 (2014)
H. Alloul, “NMR in strongly correlated materials”, Scholarpedia, 10(1):30632 (2015)

The various cuprate families

High quality single crystals ?



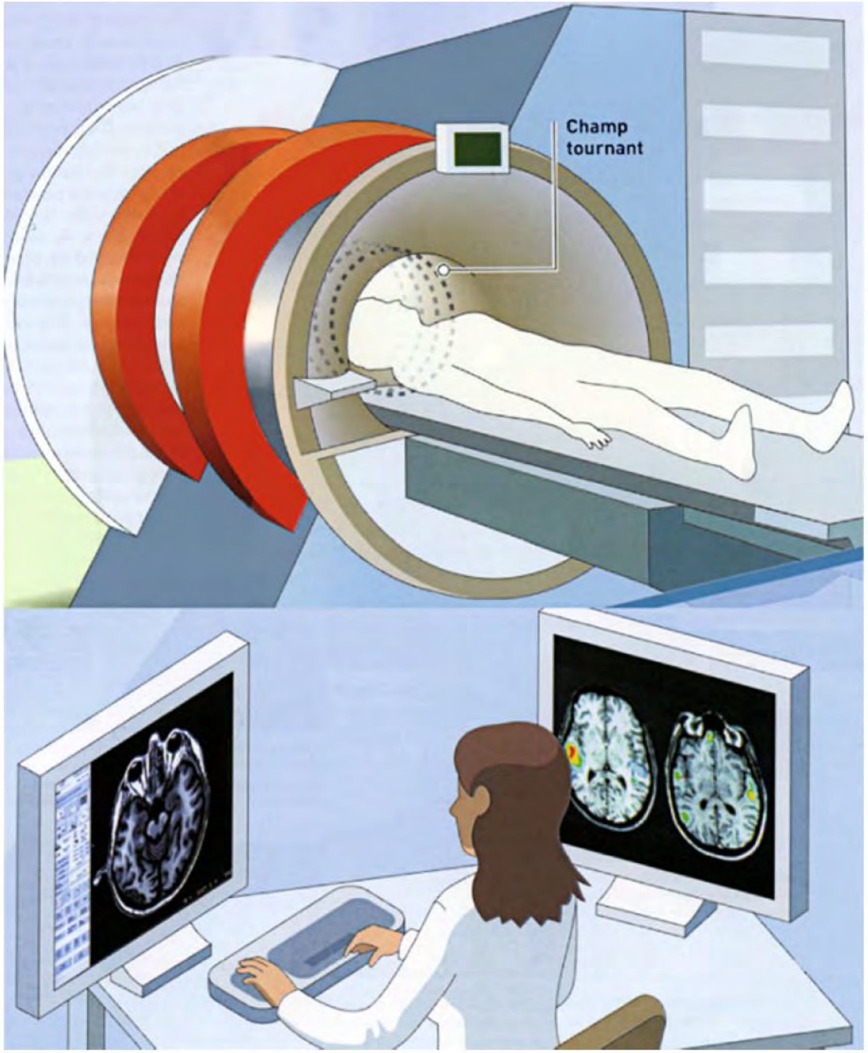
Phase diagram in the absence of disorder ??

F. Rullier-Albenque, H. A. et al , EPL 2008.

SG and MIT are determined by disorder

Magnetic Resonance Imaging (MRI)

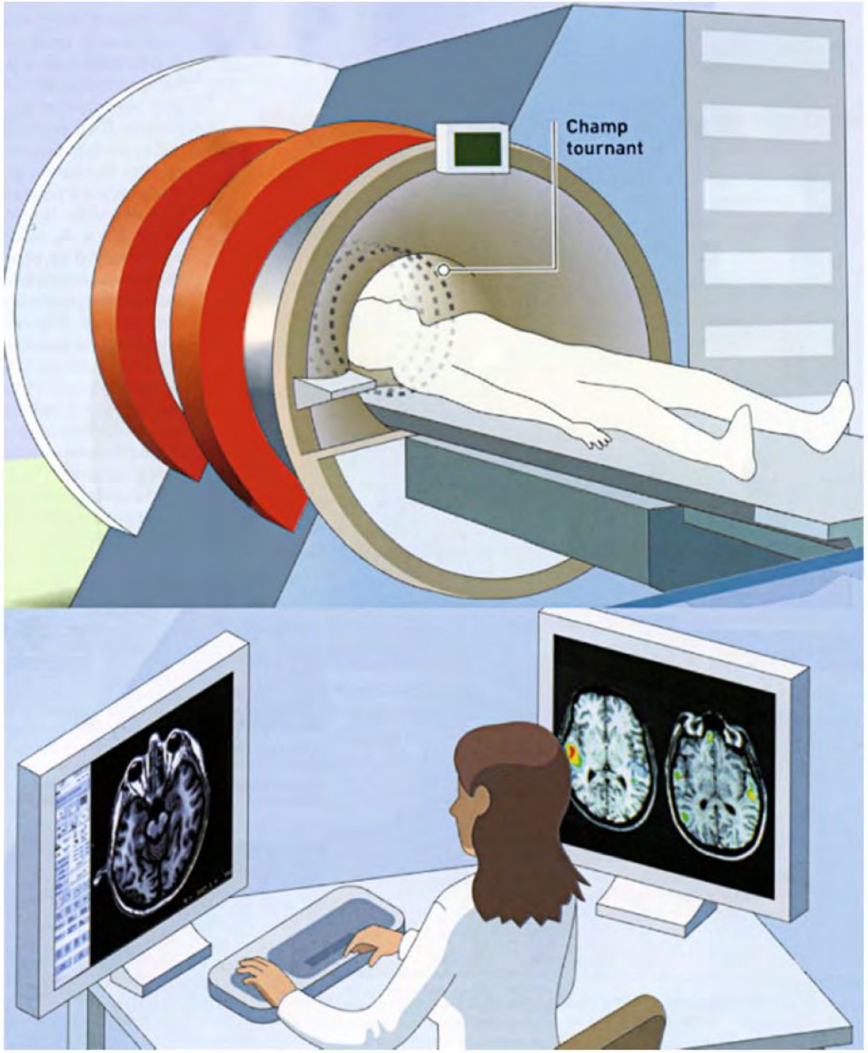
What is imaged here?



Magnetic Resonance Imaging (MRI)

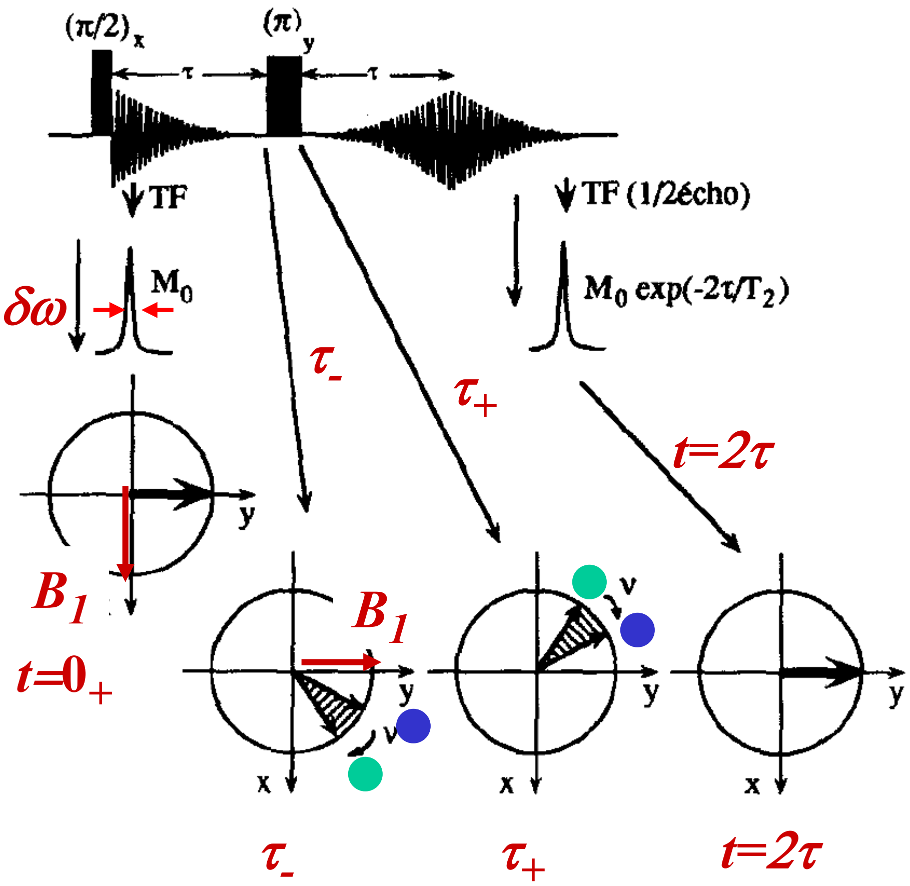
What is imaged here?

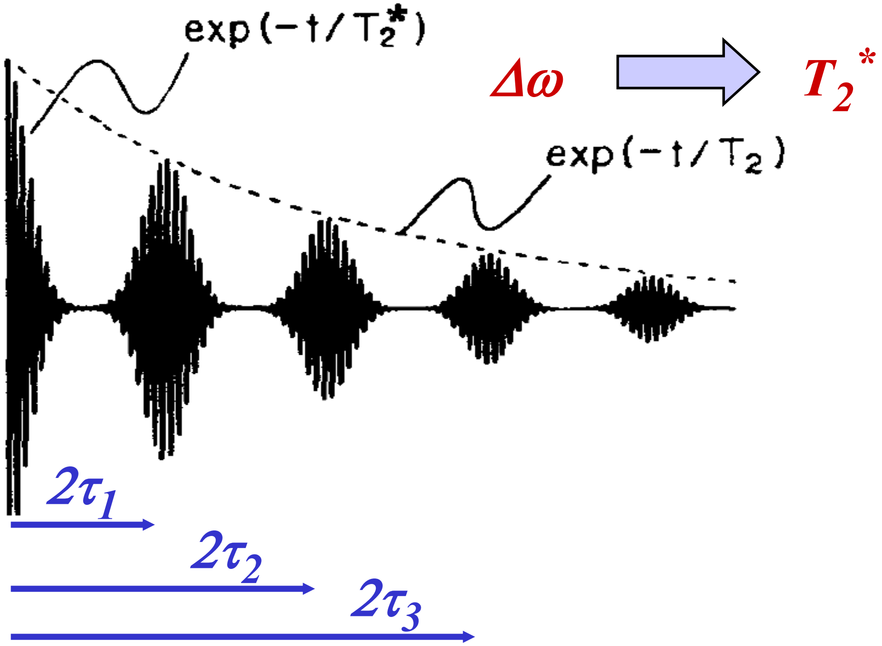
^{1}H proton NMR Intensity, But also T_2



SPIN ECHOES

δω **Distribution of Larmor frequencies**





Echo intensity varies with τ

$T_2^* < T_2 < T_1$

T_2 transverse relaxation time