The Abdus Salam International Centre for Theoretical Physics

United Nations Educational, Scientific and Cultural Organization

IAEA International Atomic Energy Agency

SMR/1855-6

School and Workshop on Highly Frustrated Magnets and Strongly Correlated Systems: From Non-Perturbative Approaches to Experiments

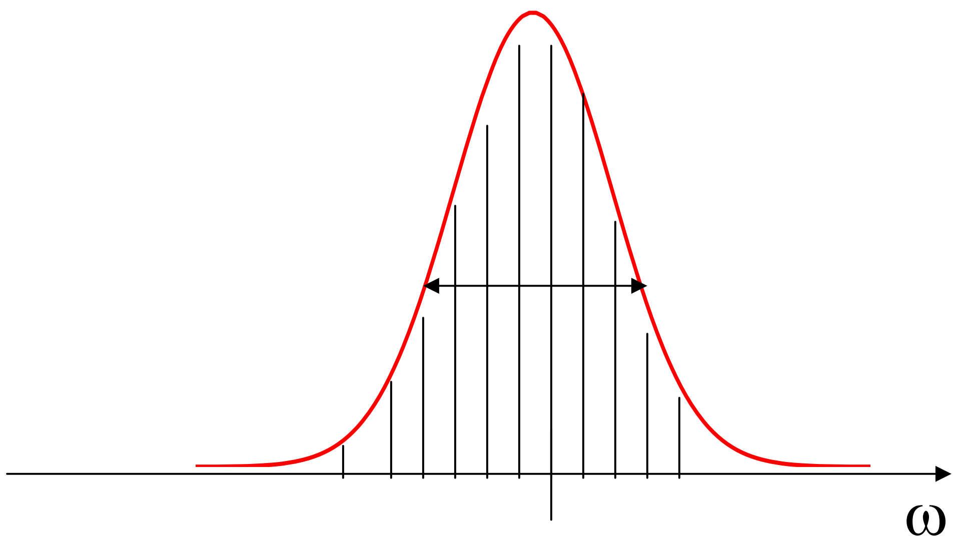
30 July - 17 August, 2007

Dynamical effects on the NMR spectra

Pietro Carretta

Dipartimento di Fisica "A. Volta"
Pavia, Italy

Dynamical effects on the NMR spectra



Due to the time dependence of the hyperfine hamiltonian one can observe a modification in the NMR spectra. Let us consider a rather standard situation where the rigid lattice NMR spectrum is a Gaussian and the local field at the nuclei is fluctuating. Then the FID signal is given by

$$G(t) \propto Tr\{e^{i\mathcal{H}'_P t/\hbar} I_x e^{-i\mathcal{H}'_P t/\hbar} I_x\}$$

where $\mathcal{H}'_P(t)$ is the time-dependent hamiltonian which can be considered as a perturbation of the Zeeman hamiltonian. Suppose that the time-dependence is induced by fluctuations of the local field at the nucleus (due to molecular motions, spin fluctuations, ionic diffusion, flux lines lattice motion in a superconductor, etc...). Then one can write

$$\mathcal{H}'_P(t) = -\hbar \sum_i I_z^i \Delta\omega_i(t) = -\hbar\gamma \sum_i I_z^i h_z^i(t)$$

where $\Delta\omega_i(t)$ describes the fluctuations in the resonance frequency of the i-th nucleus. If we consider a stationary gaussian distribution for the fluctuations with a mean-square amplitude $< \Delta\omega^2 >$, then one finds that

$$G(t) = G(0) exp\Big(- < \Delta\omega^2 > \int_0^t (t-\tau) g(\tau) d\tau \Big)$$

where $g(\tau) =< \Delta\omega(t+\tau)\Delta\omega(t) > / < \Delta\omega^2 >$ is the normalized correlation function describing the fluctuations of the frequency of the nuclei.

Now one can introduce the corresponding correlation time for the fluctuations

$$\tau_c = \int_0^\infty g(\tau)d\tau$$

which describes the characteristic decay time for $g(\tau)$. Without making any assumption on $g(\tau)$ one can distinguish two limiting cases:

a) Slow motions regime. Then one records the FID signal over a time $t \ll \tau_c$. Then from the equation describing $G(t)$, considering that $g(\tau) \simeq g(0) \simeq 1$, one has

$$G(t) = G(0)e^{-\frac{<\Delta\omega^2>t^2}{2}}$$

namely a Gaussian decay, as it should be expected as we have assumed a rigid lattice Gaussian distribution of the nuclear resonance frequencies. The corresponding spectrum is also a Gaussian with second moment $< \Delta\omega^2 >$.

b) Fast motions regime. The FID signal is recorded over a time $t \gg \tau_c$. Then one can set the upper limit of the integral in the $G(t)$ expression to ∞ and neglect τ with respect to t since $g(\tau)$ has already vanished over the time t. Then

$$G(t) = G(0)e^{-<\Delta\omega^2>t\tau_c} = G(0)e^{-\frac{t}{T_2'}}$$

where

$$\frac{1}{T_2'} =< \Delta\omega^2 > \tau_c = \gamma^2 \int_0^\infty < h_z(t)h_z(0) > dt$$

is the relaxation rate of the FID, namely of the transverse magnetization. One observes that now the FID decay is exponential and thus the corresponding NMR spectrum is a lorentzian with full width at half maximum equal to $1/T_2'$. Upon decreasing τ_c the linewidth decreases and one observes the motional narrowing of the NMR line.

If $g(\tau) = exp(-\tau/\tau_c)$ then one can write

$$G(t) = G(0)e^{-<\Delta\omega^2>\tau_c^2[exp(-t/\tau_c)-1+(t/\tau_c)]}$$

which nicely interpolates between fast and slow motions regime.

Li^+ diffusion

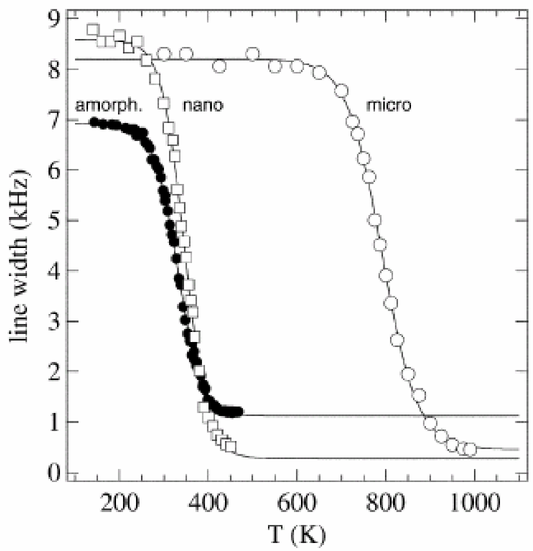
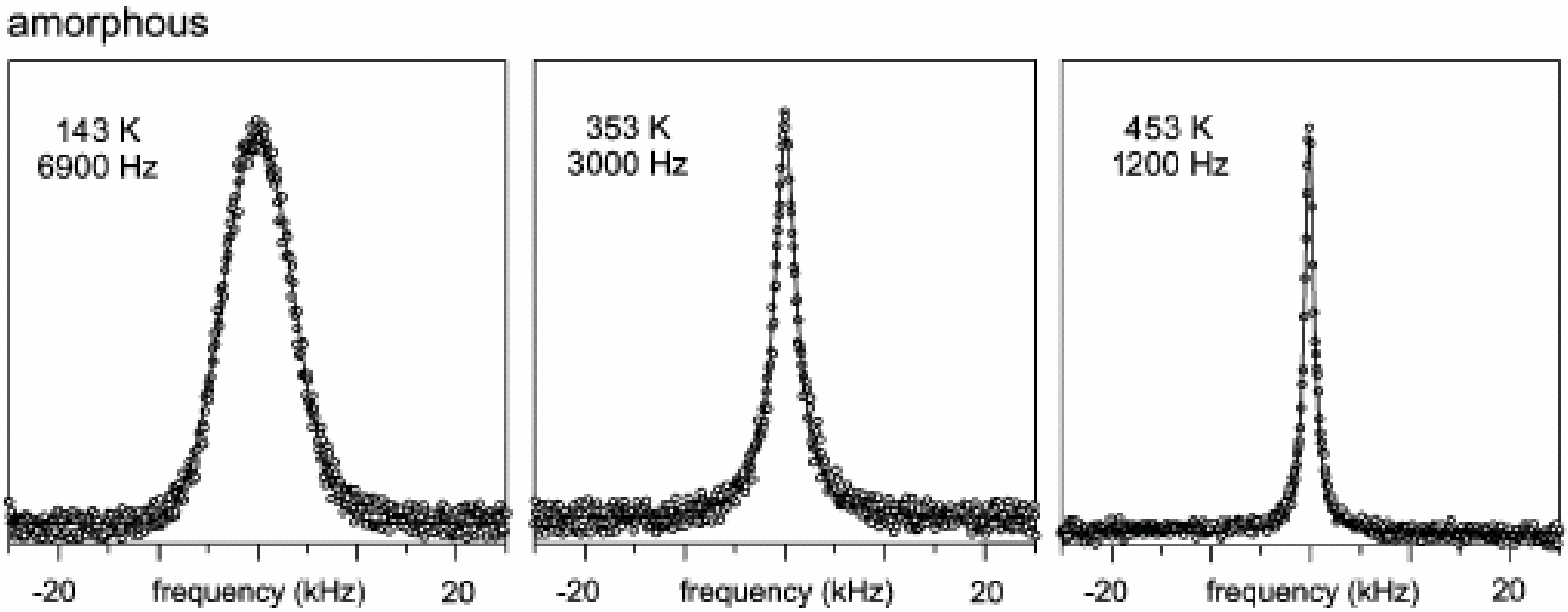


Fig. 4 Full width at half-maximum of the central transition line in the ^{7}Li-NMR spectra of amorphous, nano- and microcrystalline $LiNbO_3$ obtained at 78 MHz as a function of temperature. The data

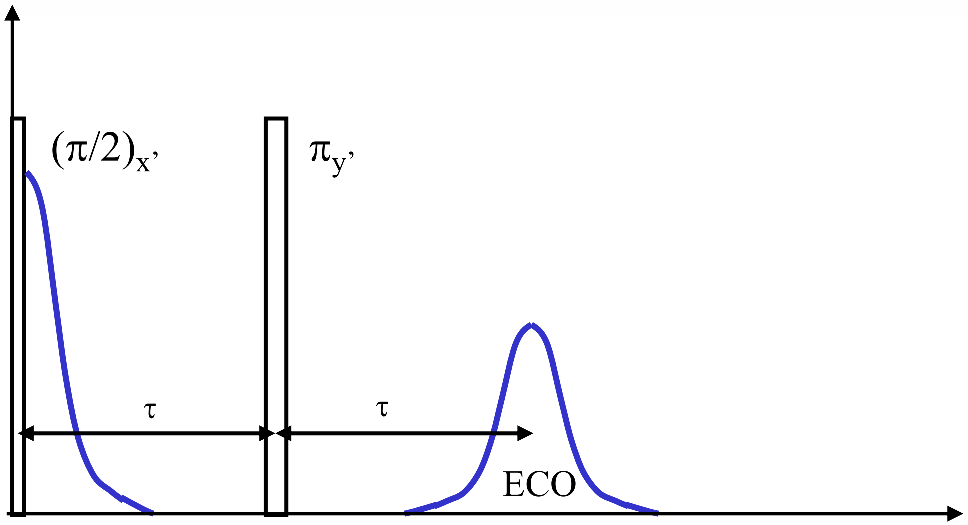


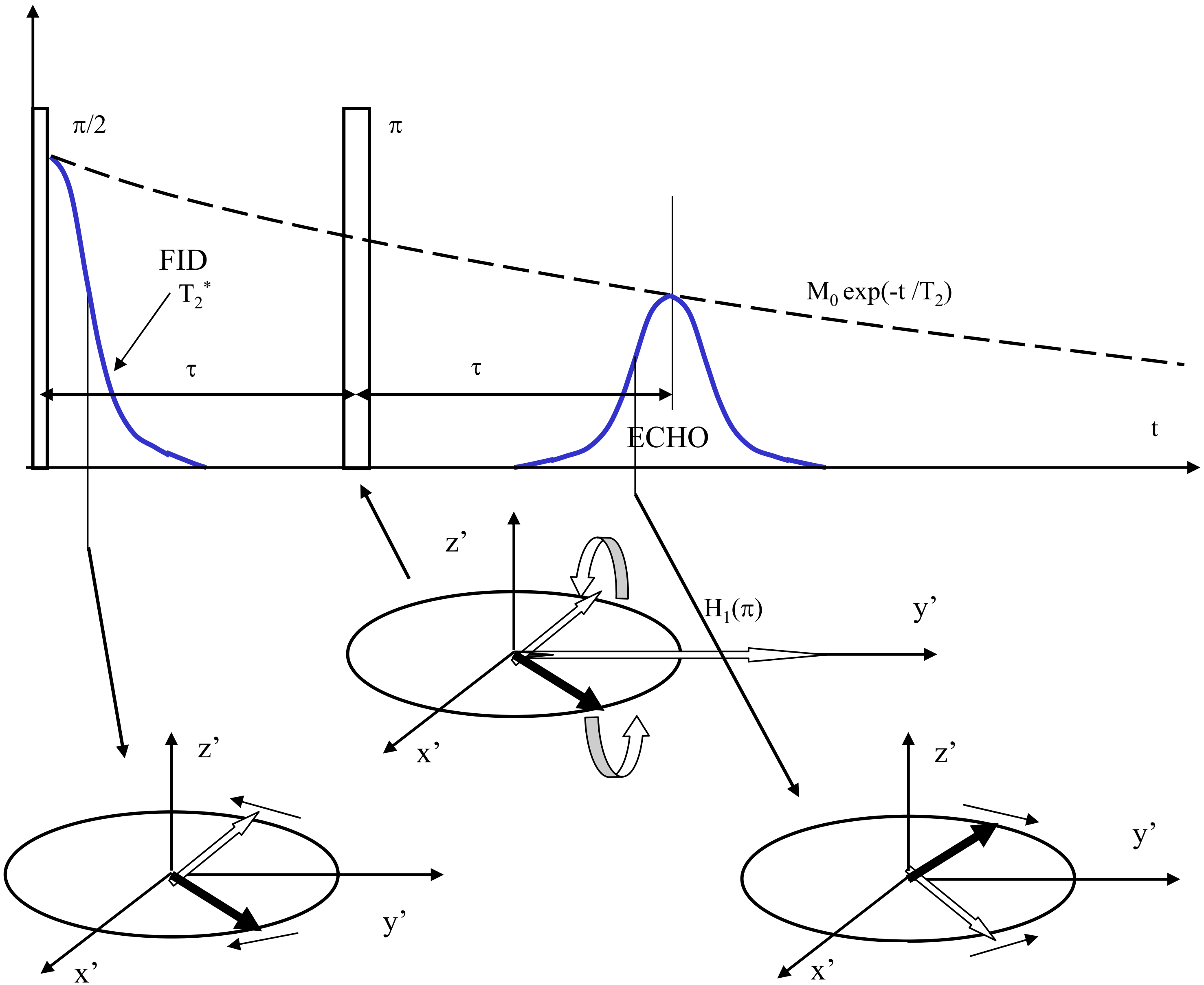
The echo signal

In general one observes that the decay of the FID signal is affected not only by intrinsic effects but also by extrinsic effects as magnetic field inhomogeneities associated, for example, with a distribution of paramagnetic shifts or simply to the inhomogeneity of the magnetic field generated by the magnet over the sample volume. Then one has an additional contribution to the decay of the FID, namely

$$G(t) = G(0)exp(-t/T_2')exp(-\gamma \Delta H t) = G(0)exp(-t/T_2^*)$$

with ΔH the magnetic field distribution. Sometimes T_2^* can be so short that it is not possible to record the FID signal. To avoid this problem one can use the **spin-echo** technique. Let us suppose that the magnetic field distribution is static and we apply the pulse sequence below.




π/2
π
FID
T_2^*
τ
τ
ECHO
M_0 exp(-t /T_2)
t
z'
H_1(π)
y'
x'
z'
y'
x'
z'
y'
x'

Dynamical effects on the echo amplitude

Let us now consider that the field distribution is no longer static but there are magnetic field fluctuations. Again we shall consider a gaussian stationary distribution function. If now one calculates the dephasing of the nuclear spins between the $\pi/2$ and π $(0-t)$ pulse and then between the π pulse and the echo $(t-2t)$ one derives that the echo amplitude at time $2t$ is given by

$$E(2t) = E(0)exp\left(-<\Delta\omega^2> [2\int_0^\infty (t-\tau)g(\tau)d\tau - \int_0^t \tau g(\tau)d\tau - \int_t^{2t} (2t-\tau)g(\tau)d\tau]\right)$$

Without making any assumption on $g(\tau)$, in the fast motions regime ($\sqrt{<\Delta\omega^2>}\tau_c \ll 1$) one finds that

$$E(2t) = E(0)e^{-<\Delta\omega^2>\tau_c 2t} = E(0)e^{-\frac{2t}{T_2'}}$$

namely the echo decays with the same characteristic time of the FID. In the very slow motions regime, i.e. $\sqrt{<\Delta\omega^2>}\tau_c \gg 1$ the echo sequence allows to rephase completely the nuclear magnetization and then

$$E(2t) \rightarrow E(0)$$

while the FID decays as $G(t) = G(0)exp(-<\Delta\omega^2> t^2/2)$. On the other hand, if $\sqrt{<\Delta\omega^2>}\tau_c \simeq 1$ one finds

$$E(2t) = E(0)e^{-\frac{<\Delta\omega^2>(2t)^3}{3\tau_c}}$$

If $g(\tau) = exp(-\tau/\tau_c)$ then

$$E(2t) = E(0)exp\left(-<\Delta\omega^2>\tau_c[2t-\tau_c(1-exp(-t/\tau_c))(3-exp(-\tau/\tau_c))]\right)$$

Echo amplitude

FID amplitude

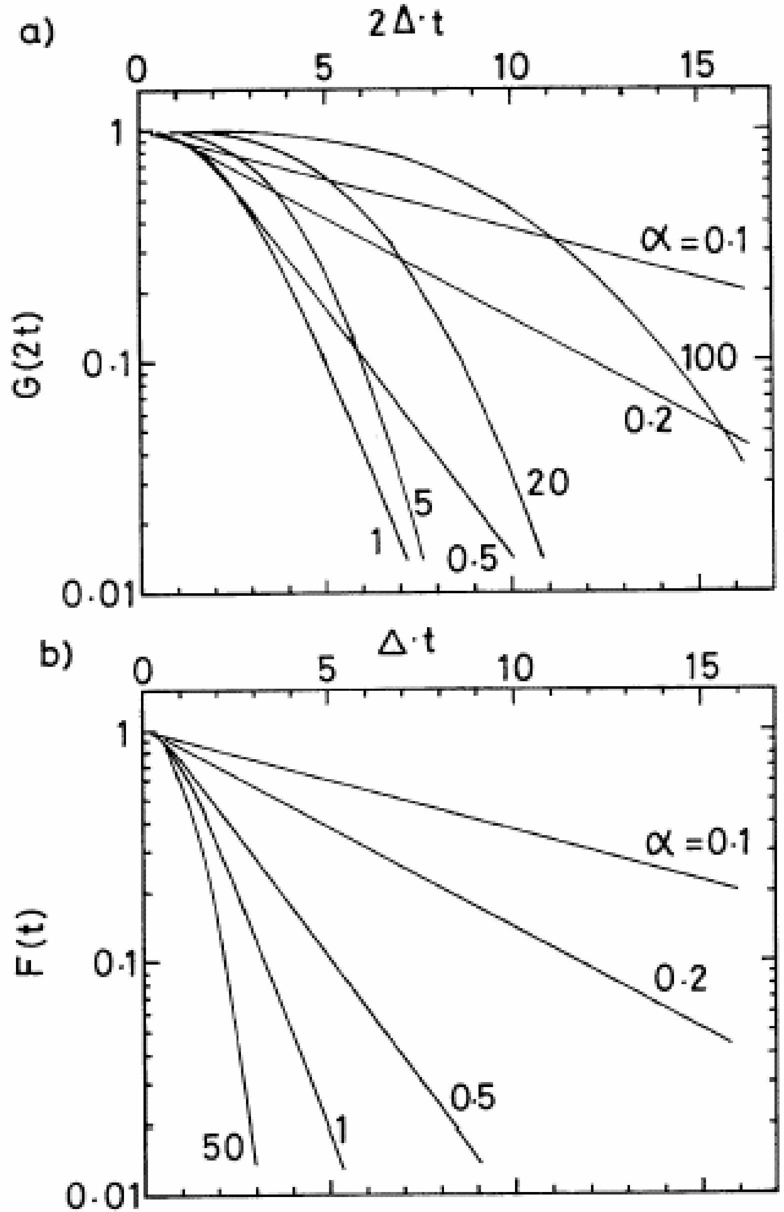
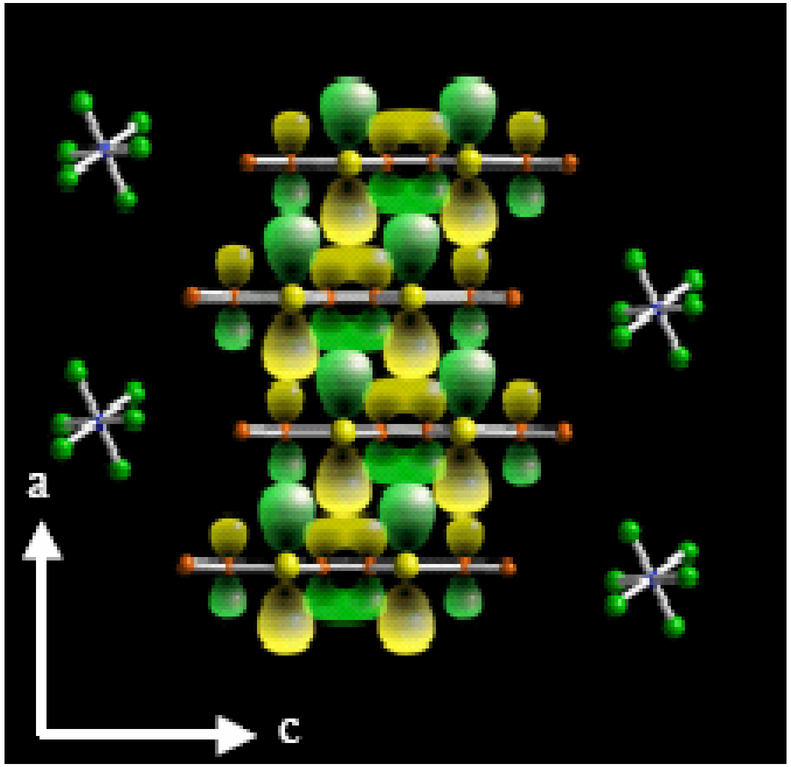


Fig. 6. The time dependences of the spin echo decay a) and the free induction decay b) calculated from eqs. (10) and (11) for various values of $\alpha = \Delta\tau_c = \sqrt{<\Delta\omega^2>}\tau_c$

Effect of molecular dynamics on the echo decay rate



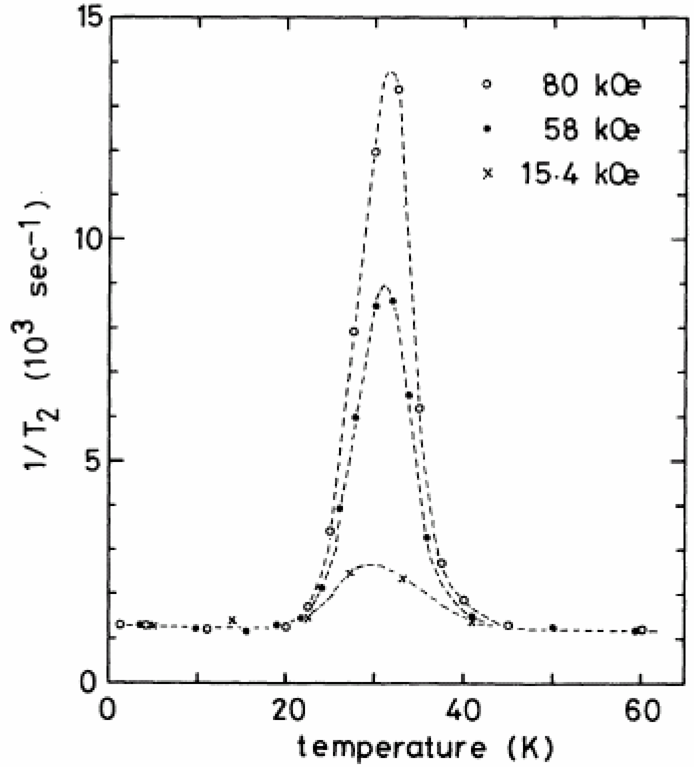
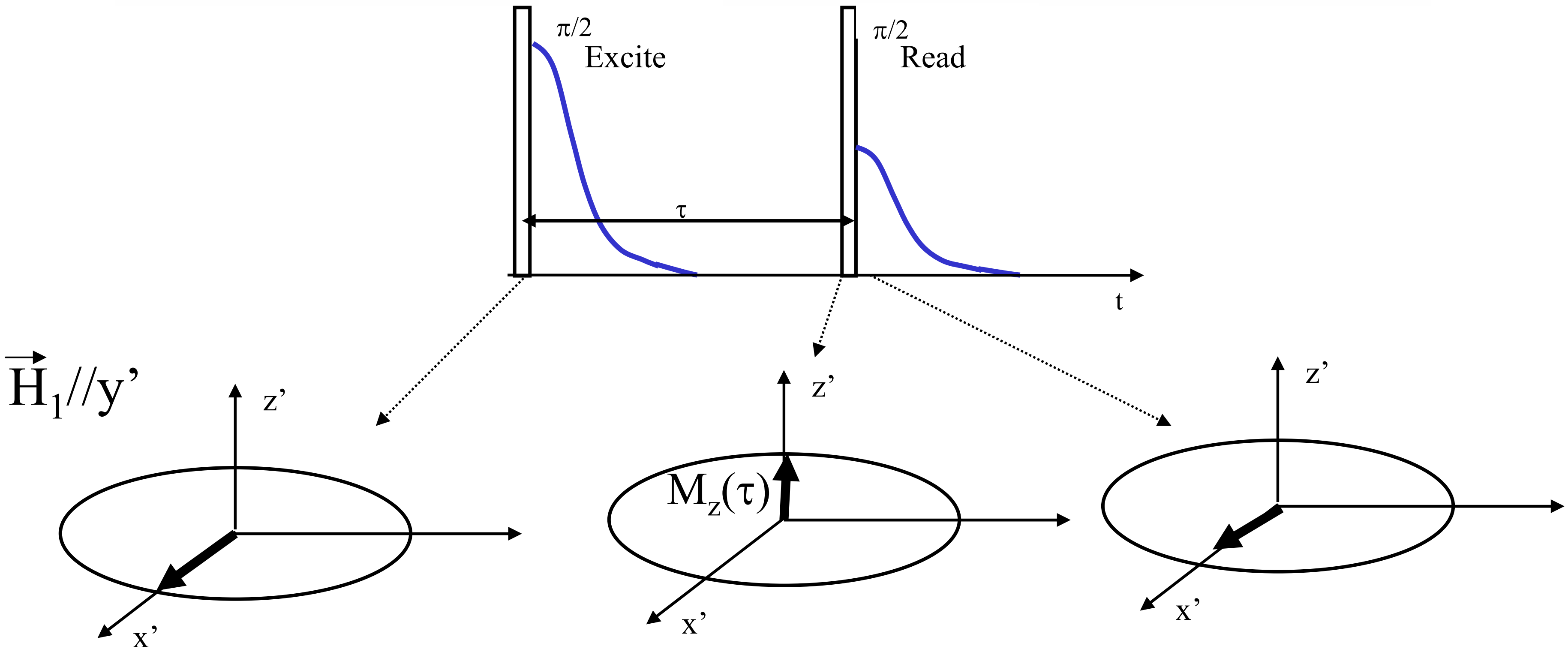


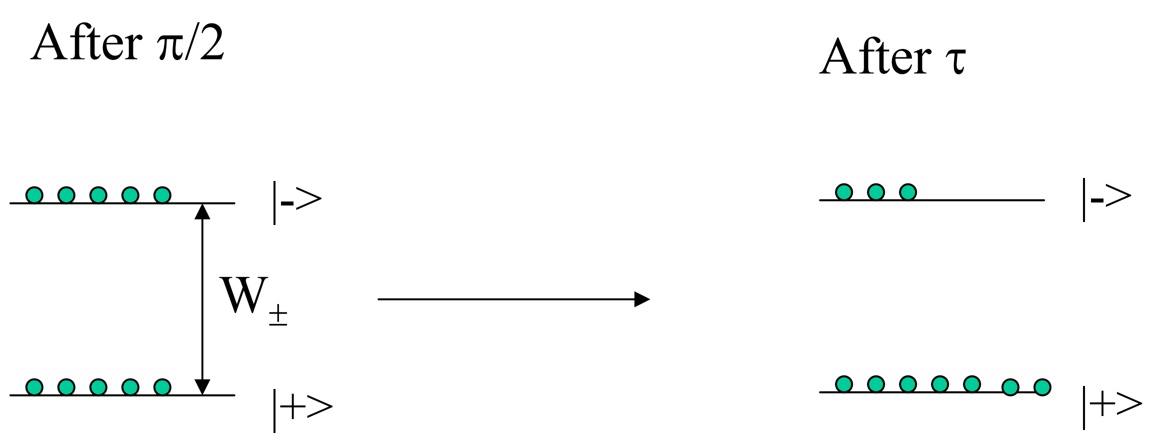
Fig. 3. The temperature dependence of the spin echo decay rate ($1/T_2$) of ^{77}Se in a powder sample of $(TMTSF)_2ClO_4$ at several magnetic fields. The lines are guide to eyes.

Nuclear spin-lattice relaxation rate $1/T_1$

As we have seen in Bloch equations the longitudinal component of nuclear magnetization relaxes back to its equilibrium value, determined by the temperature of the lattice, with a characteristic relaxation time T_1. A simple RF pulse sequence which allows one to determine T_1 is shown below. After flipping the magnetization along x' with a $\pi/2$ pulse one waits for a delay τ and then applies a second $\pi/2$ pulse. The second $\pi/2$ will flip back along x' the fraction of magnetization which during the time τ has relaxed back to equilibrium. One can repeat the same experiment for different τ values and then derive T_1.



The recovery of nuclear magnetization towards equilibrium is determined by the transition probability among the hyperfine levels associated with the time-dependent part of the hamiltonian, namely by the lattice excitations. The effect of the previous pulse sequence on the longitudinal magnetization can also be understood from the study of the statistical populations on the hyperfine levels. If we consider for simplicity nuclei with $I = 1/2$, then $M_z(\tau) \propto N_+ - N_-$, the difference of population between the two levels.



$M_z(\tau=0) = 0 = N_+ - N_-$

$M_z(\tau) > 0$

In general for nuclei with spin I one has $2I+1$ states and one has to solve a system of $2I+1$ differential equations

$$\frac{dN_m}{dt} = \sum_{n \neq m} (N_n W_{nm} - N_m W_{mn})$$

to derive the time evolution of the population difference between the two levels which are being irradiated. For the simple case of $I = 1/2$ one finds that

$$M_z(\tau) = M_z(\tau \to \infty)(1 - e^{-\frac{\tau}{T_1}})$$

or equivalently

$$y(\tau) = \frac{M_z(\infty) - M_z(\tau)}{M_z(\infty)} = e^{-\frac{\tau}{T_1}}$$

with

$$\frac{1}{T_1} \equiv 2W_{\pm}$$

For $I > 1/2$ one has to consider all possible transitions which are driven by the time-dependent part of the hamiltonian. If the fluctuations are associated with an effective fluctuating magnetic field (e.g electron spin fluctuations) then just transitions with $\Delta m = \pm 1$ have to be considered in solving the system of differential equations. If the fluctuations are the ones of the electric field gradient, since $\mathcal{H}_{EFG}$ is quadratic in the spin components, one has to consider also $\Delta m = \pm 2$ transitions. In general one finds a recovery law for nuclear magnetization

$$y(\tau) = \sum_j c_j e^{-\frac{\alpha_j \tau}{T_1}}$$

still with $1/T_1 = 2W_{\pm}^{I=1/2}$.

I=3/2

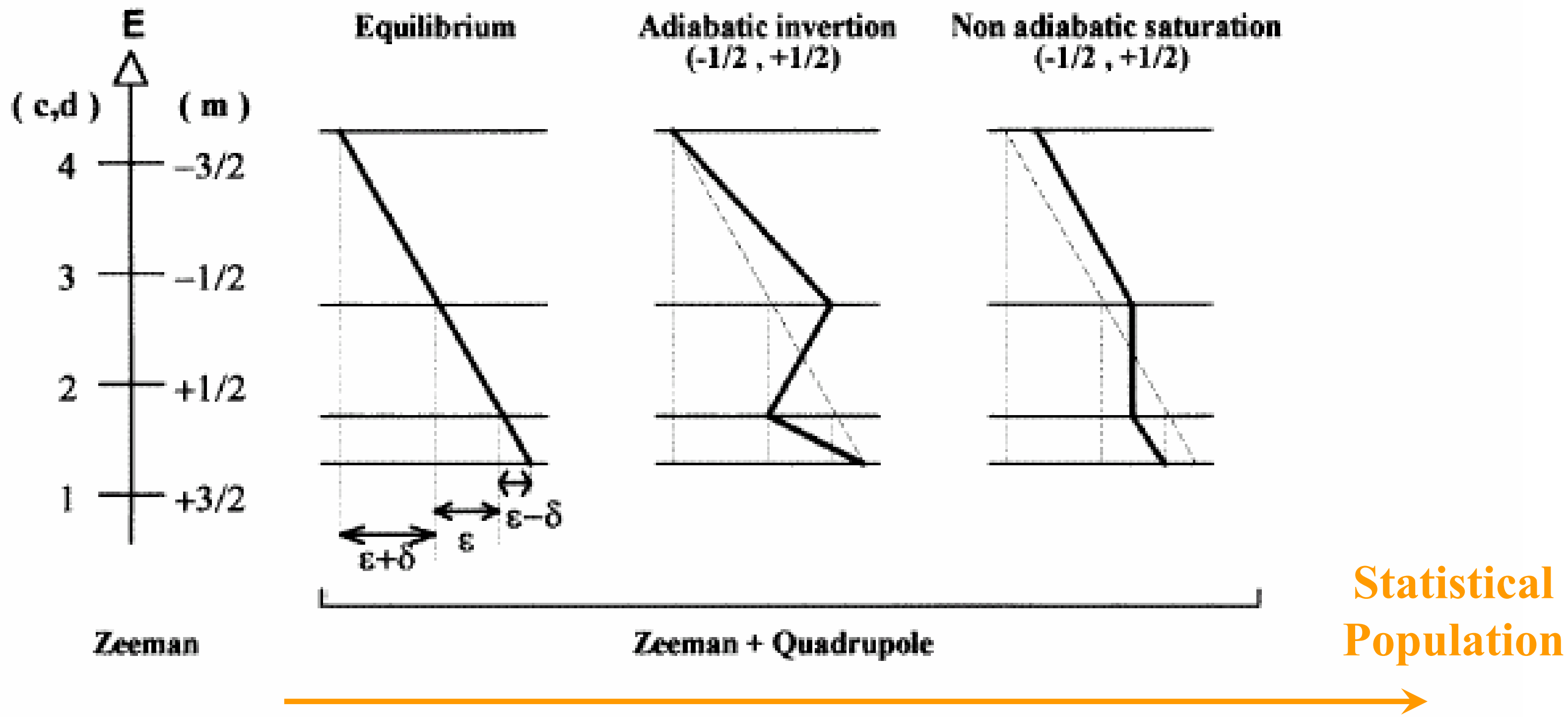


Table 2. Recovery laws of the spin–lattice relaxation. $X = 2Wt$ and by definition $T_1^{-1} = 2W$.

a.i.$(+1/2, -1/2)$	$\Delta I_{23}^{*} \propto \frac{1}{10}e^{-X} + \frac{9}{10}e^{-6X}$
a.i.$(\pm 1/2, \pm 3/2)$	$\Delta I_{12,34}^{*} \propto \frac{1}{10}e^{-X} + \frac{5}{10}e^{-3X} + \frac{4}{10}e^{-6X}$
n.a.s.$(+1/2, -1/2)$	$\Delta I_{23}^{*} \propto \frac{4}{10}e^{-X} + \frac{6}{10}e^{-6X}$
Sudden turn on of H_0	$\Delta I_{12,23,34}^{*} \propto e^{-X}$
Inversion $(\pm 3/2, \pm 1/2)$ (NQR)	$\Delta I_{12,34}^{*} \propto e^{-3X}$

I=5/2, NMR, 1/2↔-1/2 transition

$$\frac{M(t)-M(\infty)}{M(\infty)}=0.0286\exp(-2W_M t)+0.178\exp(-12W_M t)+0.793\exp(-30W_M t) .$$

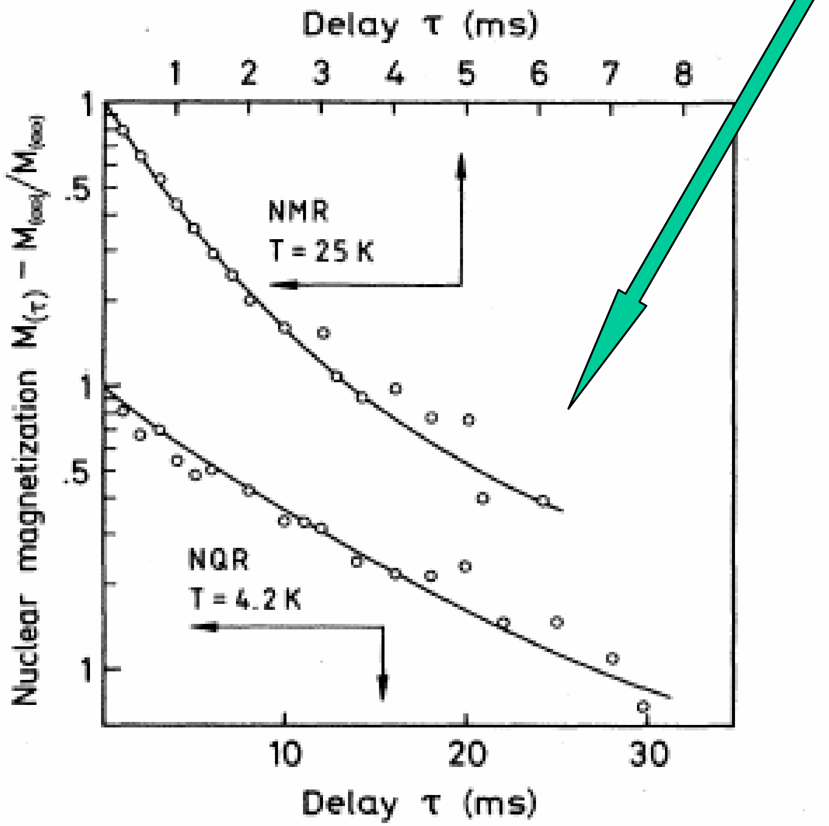


FIG. 2. Typical fits of the reduced nuclear magnetization recovery curve vs delay τ according to Eq. (2) for the NMR case ($W_M = 32\ s^{-1}$) and according to Eq. (3) for the NQR case ($W_M = 6\ s^{-1}$).

Let us suppose that the time-dependent part of the hamiltonian is associated with an effective magnetic field fluctuation

$$\mathcal{H}_P(t) = -\gamma\hbar \boldsymbol{I}\boldsymbol{h}(t)$$

which can be considered as a perturbation of the main Zeeman hamiltonian. Then, starting from time-dependent perturbation theory one can estimate $W_{\pm}$. If the correlation function

$$g(\tau) =< < +|\mathcal{H}_P(\tau)|- >< -|\mathcal{H}_P(0)|+ > >$$

describing the fluctuations of $\mathcal{H}_P(t)$ decays with a correlation time $\tau_c \ll T_1$ and $T_1\omega_0 \gg 1$ then one can write that

$$\frac{1}{T_1} = \frac{\gamma^2}{2}\int_{-\infty}^{+\infty} e^{i\omega_0 t} < h_+(t)h_-(0) > dt$$

This fundamental expression shows that $1/T_1$ is driven by the transverse components of the fluctuating field at the nucleus, to comply with magnetic-dipole selection rules, and that $1/T_1$ is proportional to the Fourier transform of the correlation function at the resonance frequency, to comply with energy conservation, or, in other terms, to the spectral density at ω_0.

Suppose that $< h_+(t)h_-(0) >=< \Delta h_\perp^2 > exp(-t/\tau_c)$. Then from the previous expression one derives that

$$\frac{1}{T_1} = \frac{\gamma^2}{2} < \Delta h_\perp^2 > \frac{2\tau_c}{1+\omega_0^2\tau_c^2}$$

One can distinguish three regimes:

a) Fast motions, $\omega_0\tau_c \ll 1$, then

$$\frac{1}{T_1} = \gamma^2 < \Delta h_\perp^2 > \tau_c$$

Then one notices that if the fluctuations are isotropic so that $< \Delta h_\perp^2 >= 2 < \Delta h_z^2 >$ then if $\omega_0\tau_c \ll 1$ and $\sqrt{< \Delta\omega^2 >}\tau_c \ll 1$ one finds $1/T_1 = 2/T_2'$.

b) Slow motions, $\omega_0\tau_c \gg 1$, then

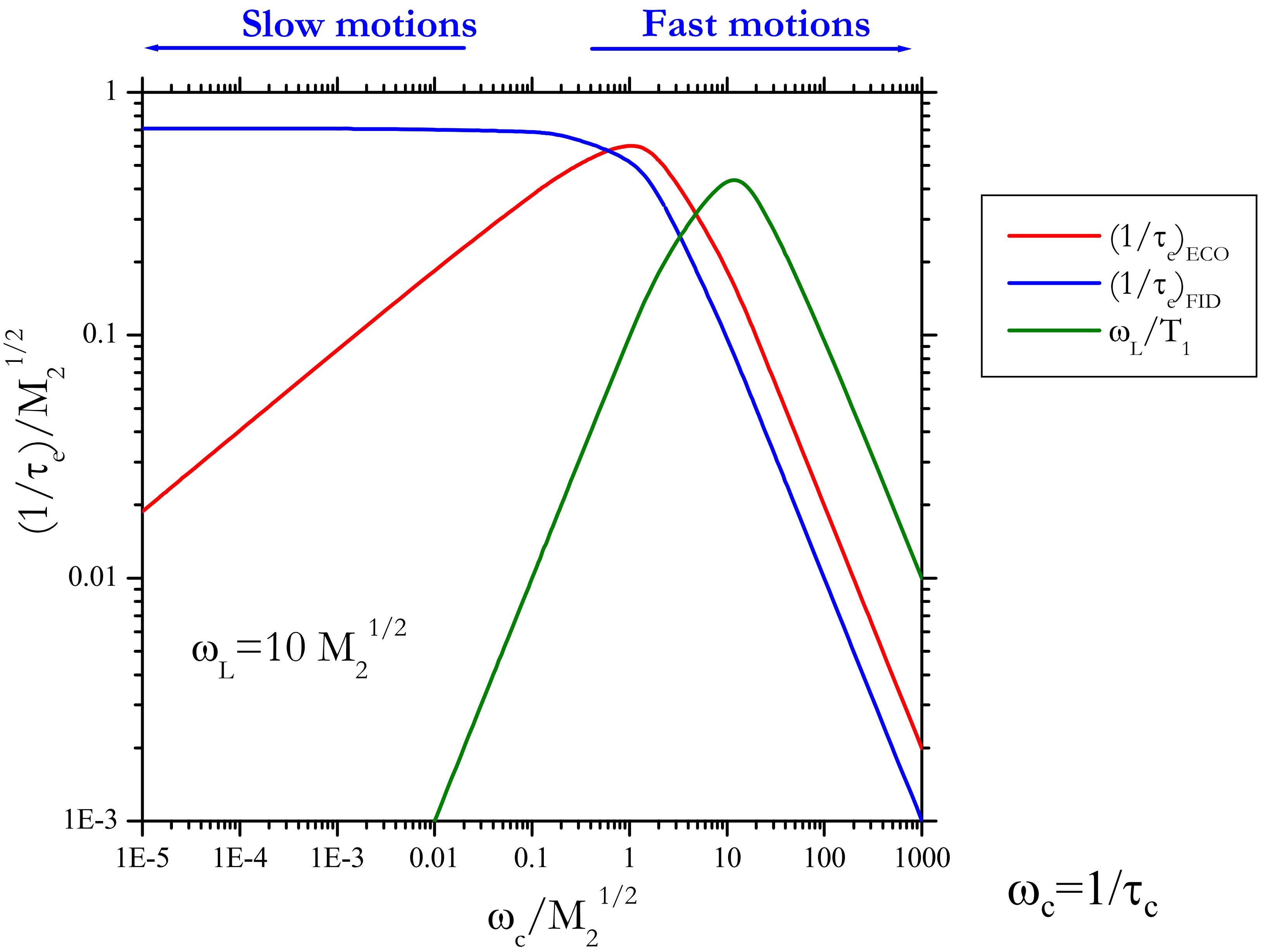
$$\frac{1}{T_1} = \gamma^2 < \Delta h_\perp^2 > \frac{1}{\omega_0^2\tau_c}$$

c) $\omega_0\tau_c = 1$ then

$$\frac{1}{T_1} = \frac{\gamma^2}{2} < \Delta h_\perp^2 > \frac{1}{\omega_0}$$

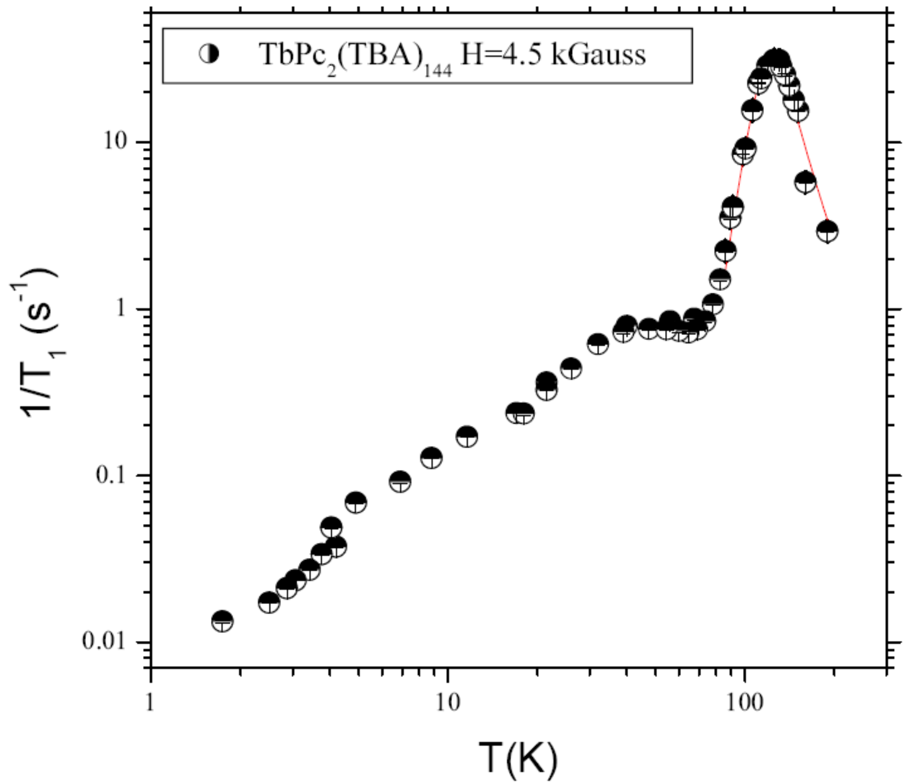
and one has a maximum in $1/T_1$, as it has to be expected since the highest transition probability would take place when the characteristic frequency for the fluctuations corresponds to the resonance frequency.

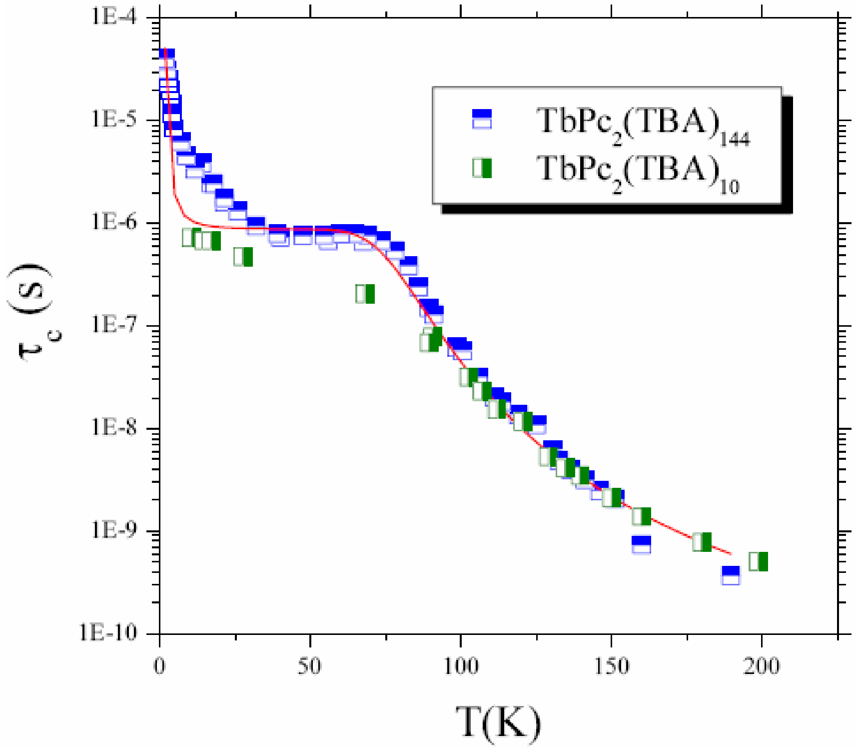
Effect of the dynamics on T1, echo and FID decay



$\omega_c=1/\tau_c$

^{1}H NMR in $TbPc_2$





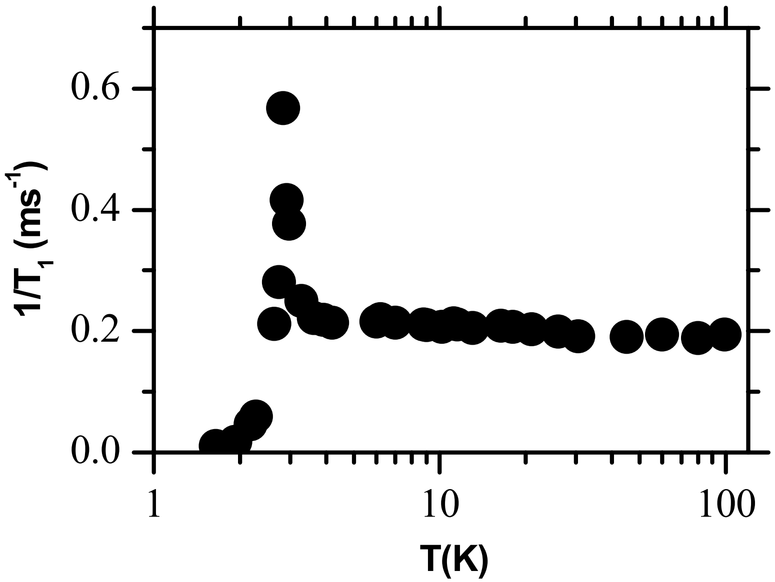
Example: a paramagnet

If the fluctuations are associated with electron spin fluctuations $h(t) = \sum_i \tilde{A}_i S_i(t)$. At high temperature, namely $k_B T \gg J$ (J the exchange coupling among the spins), the correlation function for the spin components is

$$< S^i_{x,y,z}(t) S^i_{x,y,z}(0) >= |S_{x,y,z}|^2 e^{-\frac{\omega_e^2 t^2}{2}}$$

with $\omega_e = (J/\hbar)\sqrt{2zS(S+1)/3}$ the Heisenberg exchange frequency. Then

$$\frac{1}{T_1} = \frac{\gamma^2}{2} \sum_i \left([A^i_{xx}]^2 + \ldots \right) \frac{S(S+1)}{3} \frac{\sqrt{2\pi}}{\omega_e}$$



Frustrated 2DHAF S=1/2

If collective spin excitations are present then one has that

$$\boldsymbol{h}(t) = \frac{1}{\sqrt{N}} \sum_{\boldsymbol{q}} \sum_{i} e^{i\boldsymbol{q}\boldsymbol{r}_i} \tilde{A}_i \boldsymbol{S}_{\boldsymbol{q}}(t)$$

then, by writing the transverse components of $\boldsymbol{h}(t)$ in $1/T_1$ expression one finds that

$$\frac{1}{T_1} = \frac{\gamma^2}{2} \frac{1}{N} \sum_{\boldsymbol{q}} \left(|A_{\boldsymbol{q}}|^2 S_{\alpha\alpha}(\boldsymbol{q}, \omega_0) \right)_{\perp}$$

where $|A_{\boldsymbol{q}}|^2$ is the form factor giving the hyperfine coupling of the nuclei with the spin excitations at wave-vector $\boldsymbol{q}$. $S_{\alpha\alpha}(\boldsymbol{q}, \omega_0)$ is the component of the dynamical structure factor at the resonance frequency. The term $\perp$ indicates that one has to consider the products $|A_{\boldsymbol{q}}|^2 S_{\alpha\alpha}(\boldsymbol{q}, \omega_0)$ associated with the perpendicular components of the hyperfine field at the nucleus.

From the fluctuation-dissipation theorem, by recalling that usually $k_B T \gg \hbar\omega_0$ one can also write

$$\frac{1}{T_1} = \frac{\gamma^2}{2} \frac{k_B T}{\hbar} \frac{1}{N} \sum_{\boldsymbol{q}} \left(|A_{\boldsymbol{q}}|^2 \frac{\chi''_{\alpha\alpha}(\boldsymbol{q}, \omega_0)}{\omega_0} \right)_{\perp}$$

Increasing ξ

$1/T_1 = (\gamma^2/2N)\, \Sigma_{\mathbf{q}} |A_{\mathbf{q}}|^2 S(\mathbf{q},\omega_R)$

$$\frac{1}{T_1} = \frac{\gamma^2}{2}\frac{1}{N}\sum_{\vec{q}} (2|S_{\vec{q}}|^2/\Gamma_{\vec{q}}) \times \{A_\perp - 2B[\cos(q_x a) + \cos(q_y b)]\}^2$$

$$|S^\alpha_{\vec{q}}|^2 = |S^\alpha_{q_{\mathrm{AF}}}|^2 f(q\xi) = \epsilon \frac{S(S+1)}{3}\left(\frac{\xi}{a}\right)^{2-\eta} f(q\xi),$$

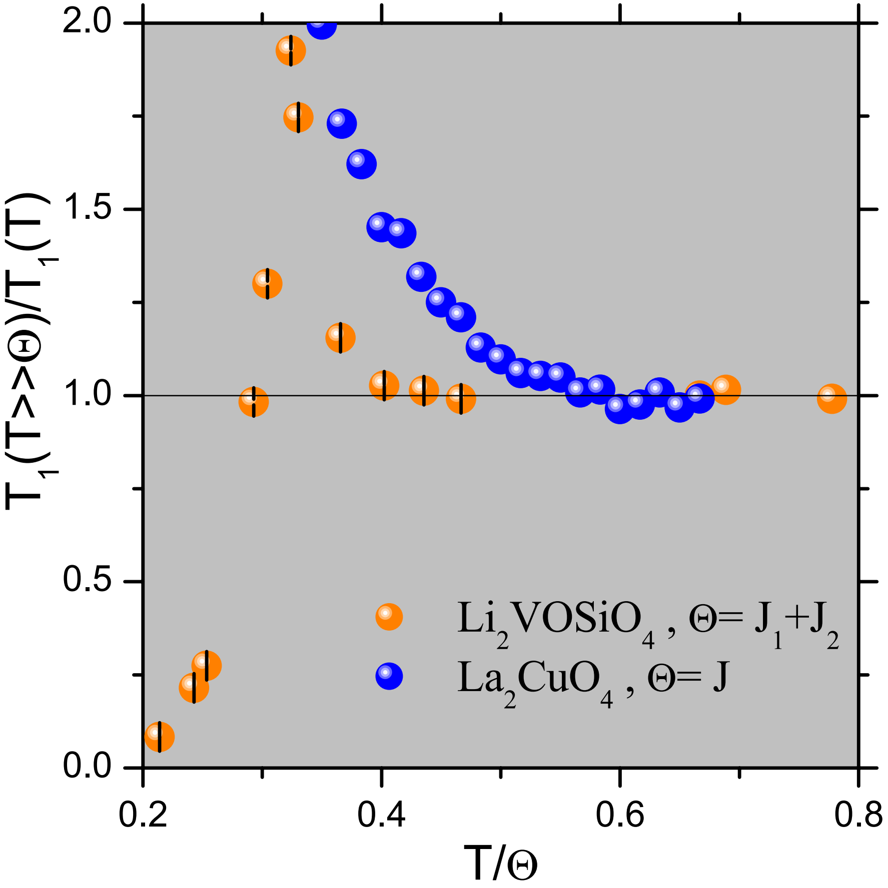
$$\Gamma_{\vec{q}} = \Gamma_{q_{\mathrm{AF}}} g(q\xi) = (2\omega_e/\sqrt{2\pi})\left(\frac{\xi}{a}\right)^{-z} g(q\xi),$$

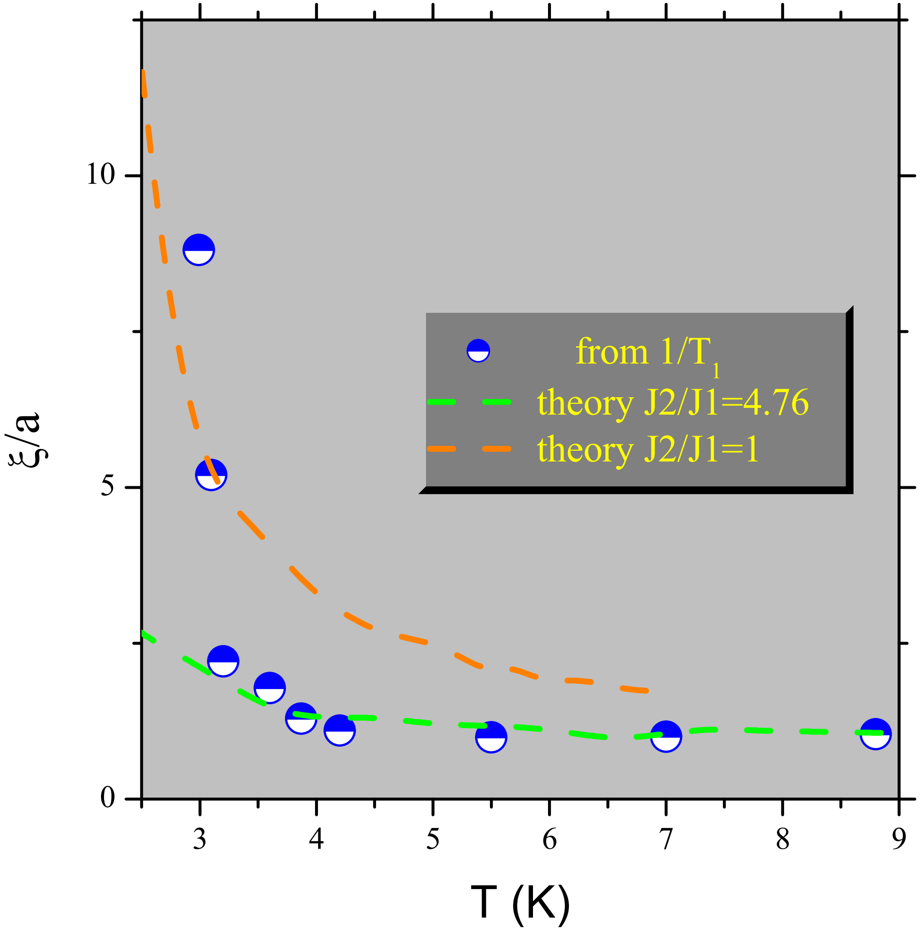
For $\xi >> 1$

$1/T_1 \propto \xi^{z+2-d}$

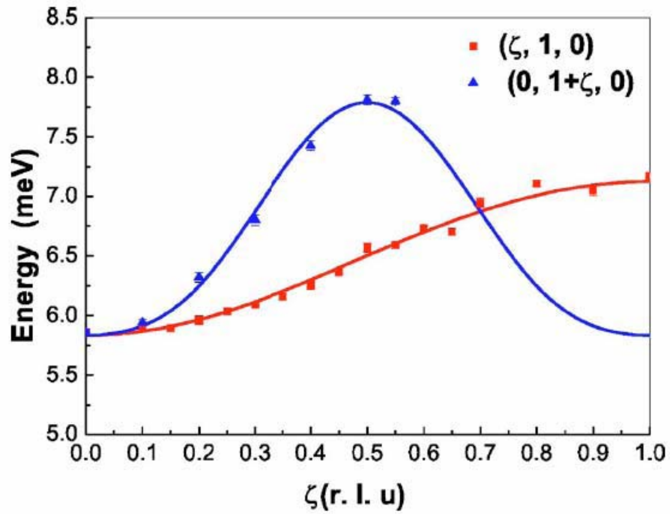
In 2D $1/T_1 \propto e^{2\pi\rho_s/T}$

N. Papinutto et al. PRB71, 174425 (05)





Example: Spin waves and Spin gaps



D. Beeman and P. Pincus, Phys. Rev. 166, 359 (1968)

$$S_j^+ = S_{jx} + iS_{jy} = (2S/N)^{1/2}\{\sum_{\mathbf{k}} \exp(-i\mathbf{k}\cdot\mathbf{r}_j)b_{\mathbf{k}} - (4SN)^{-1}\sum_{\mathbf{k},\mathbf{k}',\mathbf{k}''}\exp[i(\mathbf{k}-\mathbf{k}'-\mathbf{k}'')\cdot\mathbf{r}_j]b_{\mathbf{k}}^\dagger b_{\mathbf{k}'} b_{\mathbf{k}''} + \cdots\},$$

$$S_j^- = S_{jx} + iS_{jy} = (2S/N)^{1/2}\{\sum_{\mathbf{k}} \exp(i\mathbf{k}\cdot\mathbf{r}_j)b_{\mathbf{k}}^\dagger - (4SN)^{-1}\sum_{\mathbf{k},\mathbf{k}',\mathbf{k}''}\exp[i(\mathbf{k}+\mathbf{k}'-\mathbf{k}'')\cdot\mathbf{r}_j]b_{\mathbf{k}}^\dagger b_{\mathbf{k}'}^\dagger b_{\mathbf{k}''} + \cdots\},$$

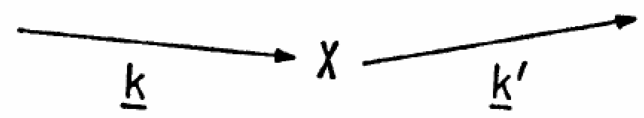
$$S_{jz} = S - N^{-1}\sum_{\mathbf{k},\mathbf{k}'}\exp[i(\mathbf{k}-\mathbf{k}')\cdot\mathbf{r}_j]b_k^\dagger b_{k'},$$

$$\frac{1}{T_1} \equiv 2W_\pm \qquad W = (2\pi/\hbar)\sum_f |\langle f|\mathcal{H}'|i\rangle|^2\,\delta(E_i - E_f)$$

$$\mathcal{H}' = \tfrac{1}{2}AI^+(2S/N)^{1/2}\sum_{\mathbf{k}} b_{\mathbf{k}}^\dagger.$$

Two problems:

- Spin gap is not compatible with direct relaxation processes → Raman processes



- During the relaxation process no electron spin flip → hyperfine coupling is a tensor

$$[S_z + I_z, \mathcal{H}] \neq 0 \qquad A_{xz} I_x S_z \neq 0$$

$$\mathcal{H}' = -(A/2N) I^{+} \sin\theta \sum_{\mathbf{k}.\mathbf{k}'} b_{\mathbf{k}}{}^{\dagger} b_{\mathbf{k}'}.$$

$$(1/T_1) = (4\pi/\hbar)(A/2N)^2 \sin^2\theta \times \sum_{\mathbf{k},\mathbf{k}'} n_{k'}(1+n_k)\delta(E_k - E_{k'} - AS)$$

3D Feromagnet

$$T_1^{-1} = \frac{4\pi}{\hbar}\left(\frac{A}{2N}\right)^2 \sin^2\theta \, \frac{V^2}{(2\pi)^6}(4\pi)^2 \int_0^{k_{\max}} \int_0^{k_{\max}} k^2 dk\, k'^2 dk'$$

$$\times \frac{\exp(E_k/k_BT)}{[\exp(E_k/k_BT)-1]^2}\,\delta(E_k - E_{k'}), \qquad (2.15)$$

For small k, $E_k \approx \Delta + 2JSk^2a^2$. $k_BT \ll 2JS$

$$T_1^{-1} = \frac{A^2}{\hbar^2\omega_e}\frac{\sin^2\theta}{2(2\pi)^3}\left(\frac{k_BT}{\hbar\omega_e}\right)^2 \int_{x_0}^{\infty}\frac{dx}{e^x - 1}\,.$$

$1/T_1 \rightarrow T^2$ for $k_BT >> \Delta$

$$x_0 = \Delta / k_BT$$

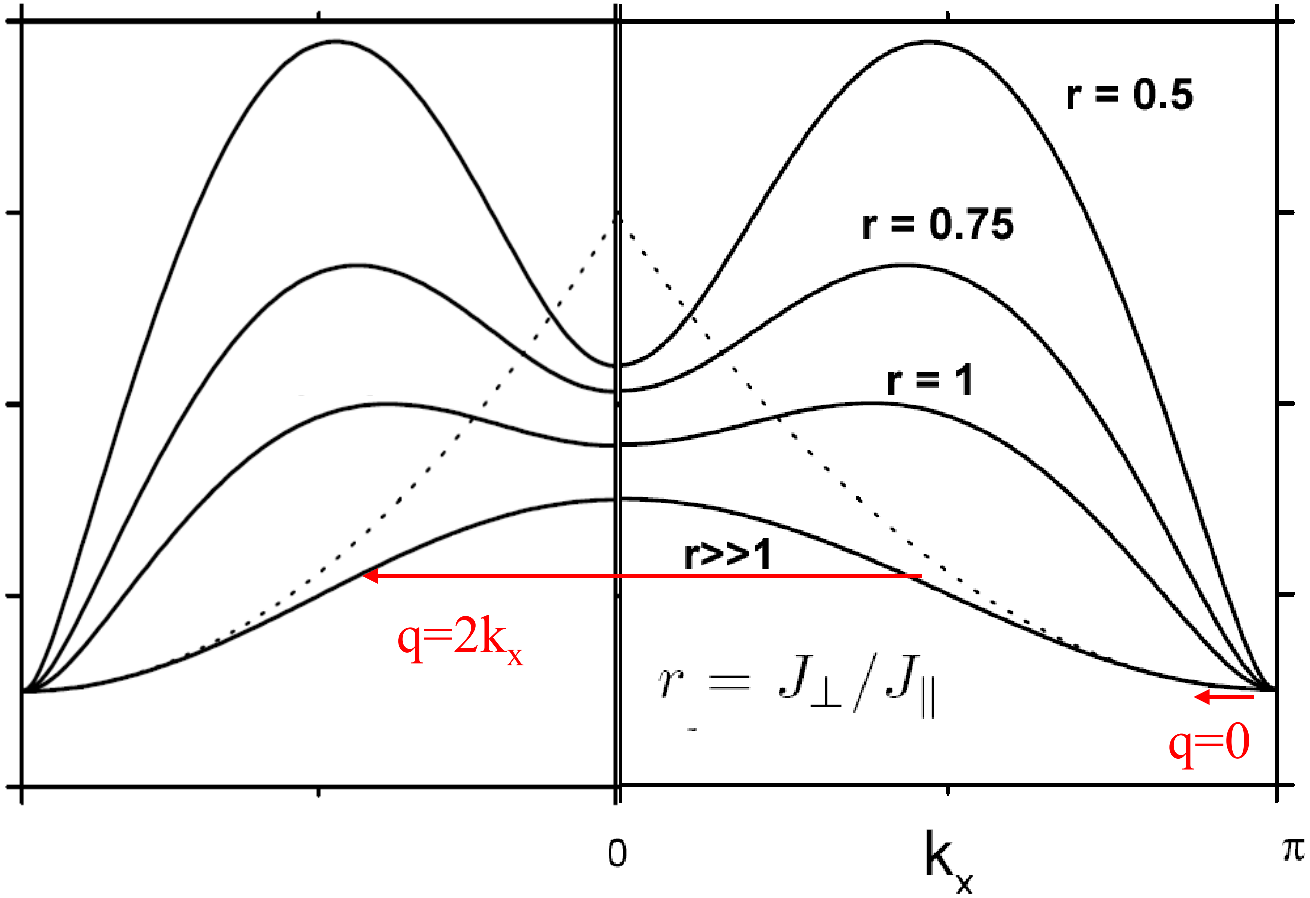
$1/T_1 \rightarrow \exp(-\Delta/T)$ for $k_BT << \Delta$

Spin Gap determination

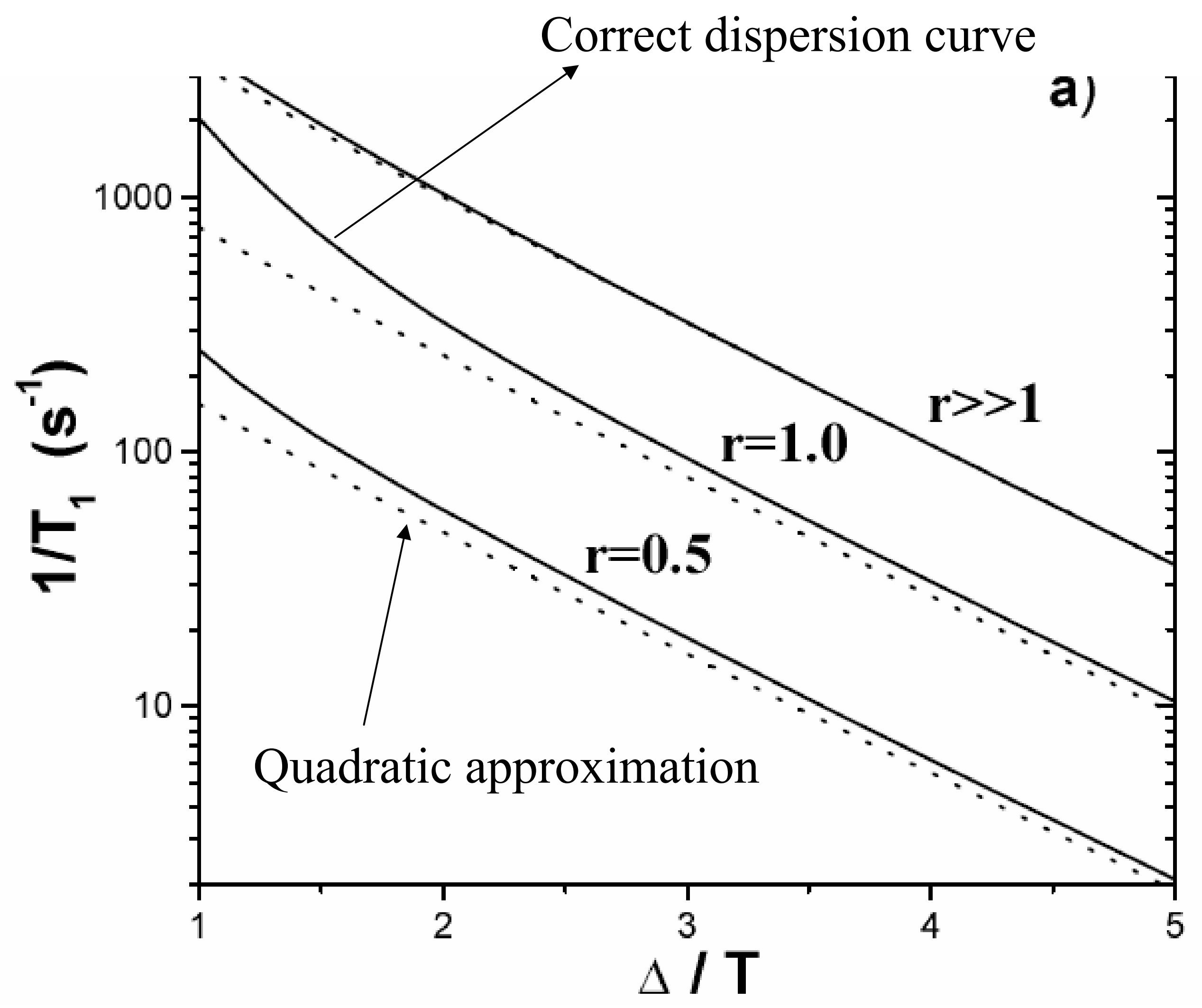
R. Melzi and PC, Cond-mat/9904074

	ΔT_1	$\Delta\chi$	$\Delta T_1/\Delta\chi$
$Sr_{14}Cu_{24}O_{41}$ (2-leg-ladder)	650 K	450 K	1.45 Refs.7-10
$Sr_{14}Cu_{24}O_{41}$ (dimerized chain)	120 K	120 K	1 Refs.7-10
$VO(HPO_4)0.5H_2O$ (dimerized chain)	75 K	75 K	1 Ref. 16
Cu(CHN)Cl (2-leg-ladder)	11 K	11 K	1 Ref. 15
CaV_2O_5 (dimers)	650 K	660 K	1
$SrCu_2O_3$ (2-leg-ladder)	700 K	450 K	1.55 Ref. 5
$AgVP_2S_6$ (S=1 chain)	400 K	320 K	1.25 Ref. 6
YBa_2NiO_5 (S=1 chain)	200 K	100 K	2.0 Ref. 13

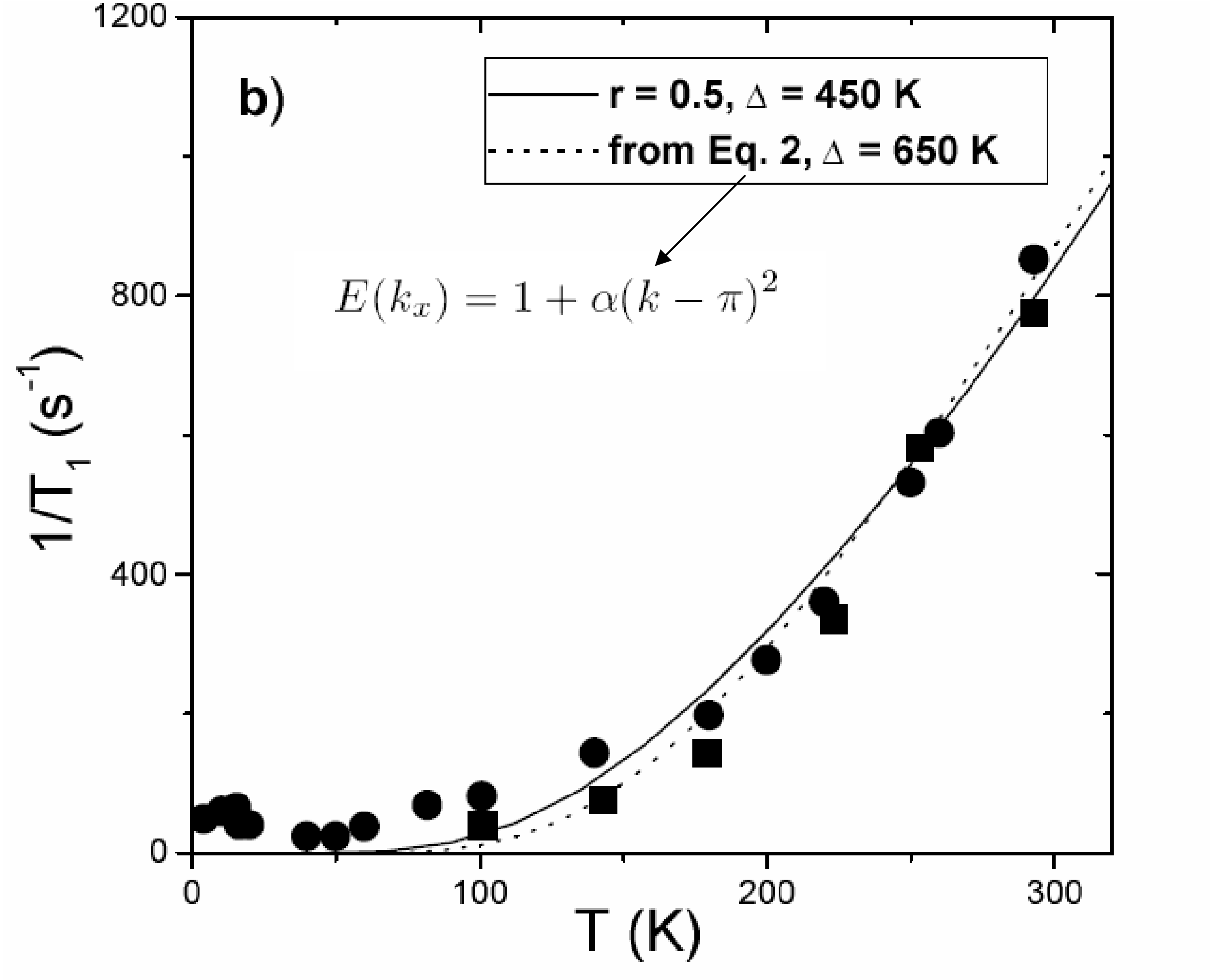
Example:Spin Ladders



$$1/T_1 = \frac{3\gamma^2 A_o^2}{\pi^2} \frac{\hbar}{k_B \Delta} \int_0^\pi dk_x \frac{e^{-E(k_x)/T}}{\sqrt{v^2(k_x) + 2\omega_o \frac{\partial v(k_x)}{\partial k_x}}}$$


Correct dispersion curve
a)
1000
100
10
1/T1 (s-1)
r>>1
r=1.0
r=0.5
Quadratic approximation
1
2
3
4
5
Δ / T

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

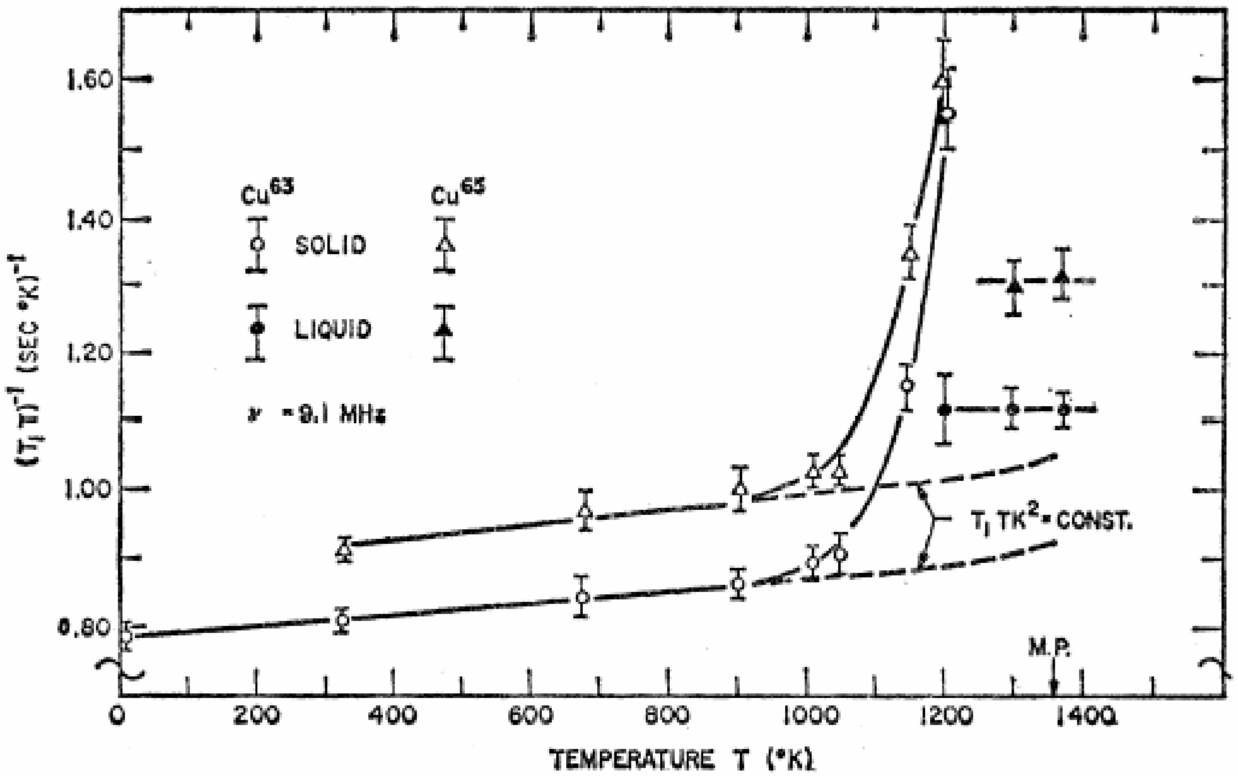


Example: a metal

By using the correspondent expression for the dynamical spin susceptibility in a metal one finds

$$\frac{1}{T_1} = (\frac{16}{3})^2 \pi^3 \hbar^2 \gamma^2 \mu_B^2 (|\psi(0)|^2)_{FS} D^2(E_F) k_B T \propto \Delta K^2$$

FIG. 2. Product $1/T_1T$ for Cu^{63} and Cu^{65} in liquid and solid Cu as a function of temperature. Solid circles below the melting point (M.P.) are for liquid in the supercooled state. The rapid rise in $1/T_1T$ above 1000°K is attributed to motional relaxation which couples to the spins mainly through the quadrupolar interaction. The dashed line indicates our estimate of the correct extrapolation of the magnetic relaxation rate from lower temperatures. The point at 4.2°K is that of B. C. de Torné, Compt. Rend. **250**, 512 (1960).



Strongly Correlated Metals

$$\frac{1}{T_1} = \frac{\gamma^2 A^2}{2} k_B T \frac{1}{N} \sum_{\vec{q}} \frac{\chi''(\vec{q},\omega_R)}{\omega_R}.$$

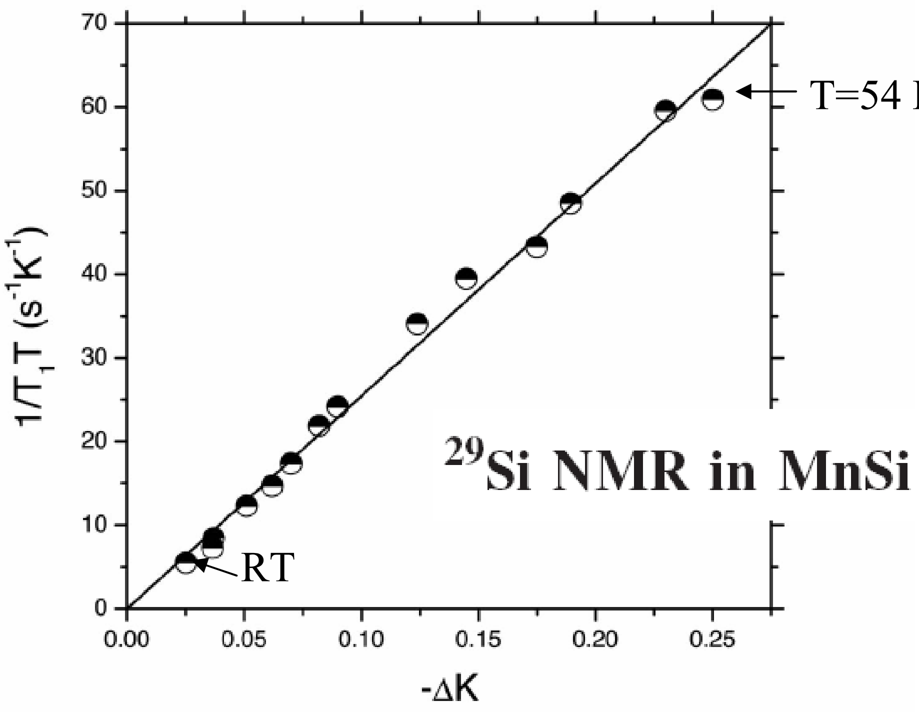
Example: Moriya SCR Theory

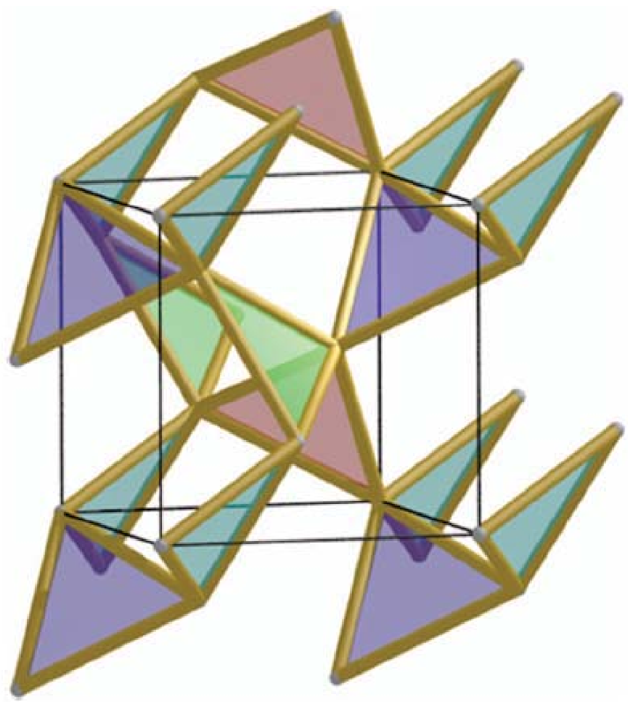
T. Moriya, *Spin Fluctuations in Itinerant Electron Magnetism* (Springer, Berlin, 1985).

$$\chi(q,\omega) = \frac{\pi T_0}{\alpha_Q T_A}\left(\frac{x}{k_B 2\pi T_0 x(y+x^2) - i\omega\hbar}\right),$$

$$\frac{1}{T_1} \simeq \gamma^2 A^2 \frac{3\hbar}{8\pi}\left(\frac{T}{T_0}\right)\chi(0,0). \longrightarrow \frac{1}{T_1 T} \simeq \gamma^2 A \frac{3\hbar}{16\pi\mu_B}\left(\frac{1}{T_0}\right)\Delta K.$$

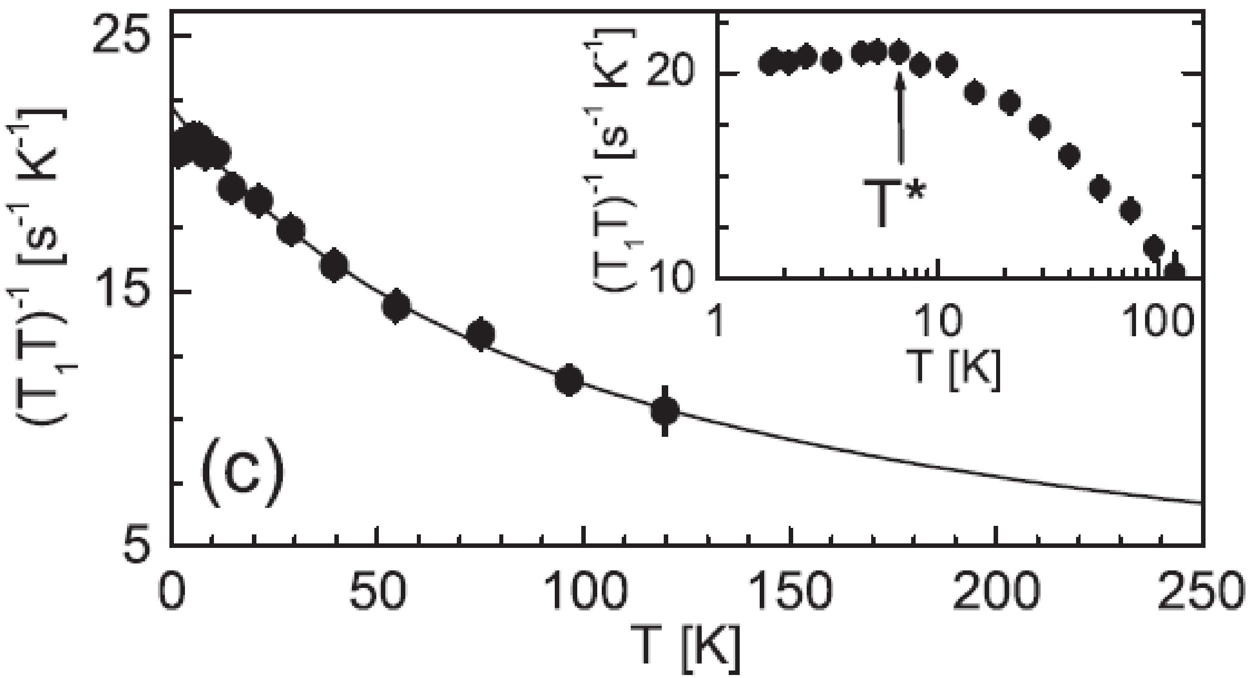
CORTI *et al.* PHYSICAL REVIEW B **75**, 115111 (2007)





^{59}Co NMR study of CoO_2

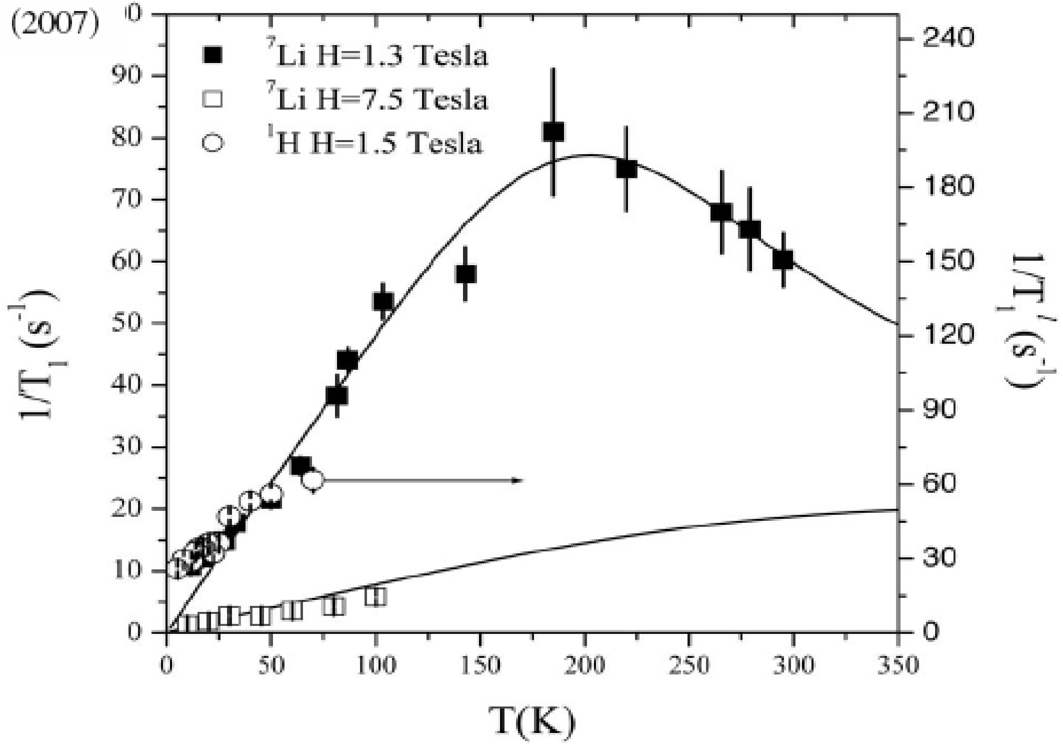
C. de Vaulx et al. PRL **98,** 246402 (2007)



A metal ??

FILIBIAN *et al.*

PHYSICAL REVIEW B **75**, 085107 (2007)



$$\left(\frac{1}{T_1}\right)_A = \int_{-\Delta}^{+\Delta} p(E_A) 1/T_1(E_A) dE_A$$

$$= \frac{\gamma^2}{2} \frac{\langle \Delta h_\perp^2 \rangle T}{\omega_N \Delta} [\arctan(\omega_N \tau_0 e^{(\langle E_A \rangle + \Delta)/T}) - \arctan(\omega_N \tau_0 e^{(\langle E_A \rangle - \Delta)/T})].$$

When $T_{1,2}$ are too short…

For certain nuclei T_1 is usually so short to prevent its measurement directly. However, in certain cases, it can be still possible to estimate it. Let us call S the spin of the fast relaxing nuclei and I the spin of another species of nuclei which one can suitably investigate. If S and I spins are coupled through nuclear dipole-dipole interaction, then the flip of spin S due to T_1^S processes is detected as a fluctuation of the local field at the I nuclear spin. Namely, one detects a dynamic with a correlation time $\tau_c = T_1^S$. This dynamic can manifest itself on the decay of the echo amplitude, for instance. If $\sqrt{< \Delta\omega_I^2 >}T_1^S \ll 1$, where $< \Delta\omega_I^2 >$ is the second moment of the frequency distribution associated with the nuclear dipole interaction between S and I spins, then the decay of the echo amplitude of I spins is given by

$$E(2t) = E(0)e^{-<\Delta\omega_I^2>T_1^S 2t}$$

and then one can estimate T_1^S.

Estimate of ^{51}V T_1 from ^{95}Mo T_2 in $MoVO_5$

PC et al., PRB **66**, 094420 (2002)