Bulk Techniques
and
Muons

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International Advanced School on Muon Spectroscopy
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Local vs Non-local response

In general

$$\mathbf{M(q,\omega)=\chi(k,\Omega,q,\omega)\ H(k,\Omega)}$$

for homogeneous and stationary systems (see R.M.White *Quantum Theory of Magnetism*)
(often the case)

$$\mathbf{M(q,\omega)=\chi(q,\omega)\ H(q,\omega)}$$

$\Rightarrow$ Bulk techniques probe $\boldsymbol{\chi(0,\omega)}$ and $\mathbf{M(0,\omega)}$

Example: ac susceptibility probes $\boldsymbol{\chi(0,\omega)}$**,** typically for $(\omega/2\pi)< 1$ MHz

Local vs Non-local response

Local probes as muons are sensitive to the local field h(t)

$$\frac{1}{T_1} = \frac{\gamma_\mu^2}{2}\int e^{i\omega_L t}\{< h_x(t)h_x(0) > + < h_y(t)h_y(0) >\}\, dt$$

$$\mathbf{h}(t) = \sum_i \tilde{A}_{hyp_i}\cdot \mathbf{S}_i$$

$$h_\alpha(t) = \frac{1}{\sqrt{N}}\sum_{\mathbf{q}\in BZ}\sum_{i=1}^{4}\sum_{\beta=x,y,z} A_{hyp_i}^{\alpha\beta} S_{\mathbf{q}}^{\beta}(t) e^{i\mathbf{q}\cdot\mathbf{r}_i}.$$

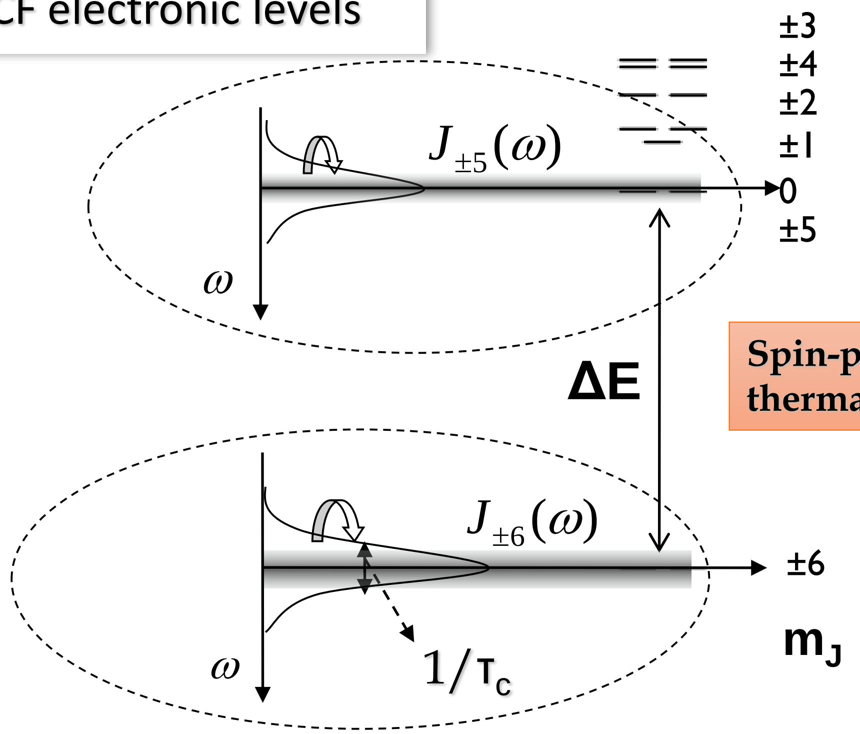
$$S^{\alpha\alpha}(\mathbf{q},\omega_L) = \int e^{i\omega_L t} < S_{\mathbf{q}}^{\alpha}(t) S_{-\mathbf{q}}^{\alpha}(0) > dt$$

$$\frac{1}{T_1} = \frac{\gamma_\mu^2}{2N}\sum_{\mathbf{q}\in BZ}(|\sum_{\beta=x,y,z} A_{\mathbf{q}}^{x\beta}|^2 + |\sum_{\beta=x,y,z} A_{\mathbf{q}}^{y\beta}|^2) S^{\alpha\alpha}(\mathbf{q},\omega_L)$$

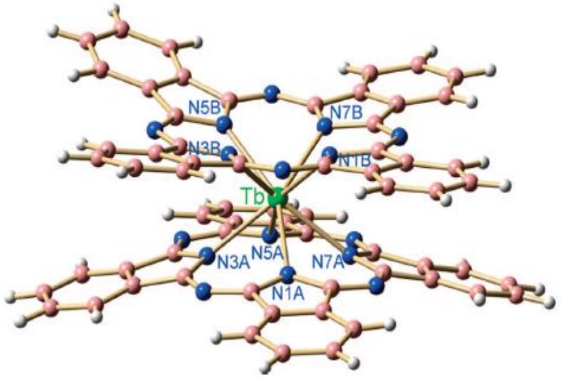
$$\boxed{\frac{1}{T_1} = \frac{\gamma_\mu^2}{2} k_B T \frac{1}{N}\sum_{\vec{q}}|A_{\vec{q}}|^2 \frac{\chi''(\vec{q},\omega_R)}{\omega_R}}$$

Example: ac-susceptibility vs μSR in Single Molecule Magnets

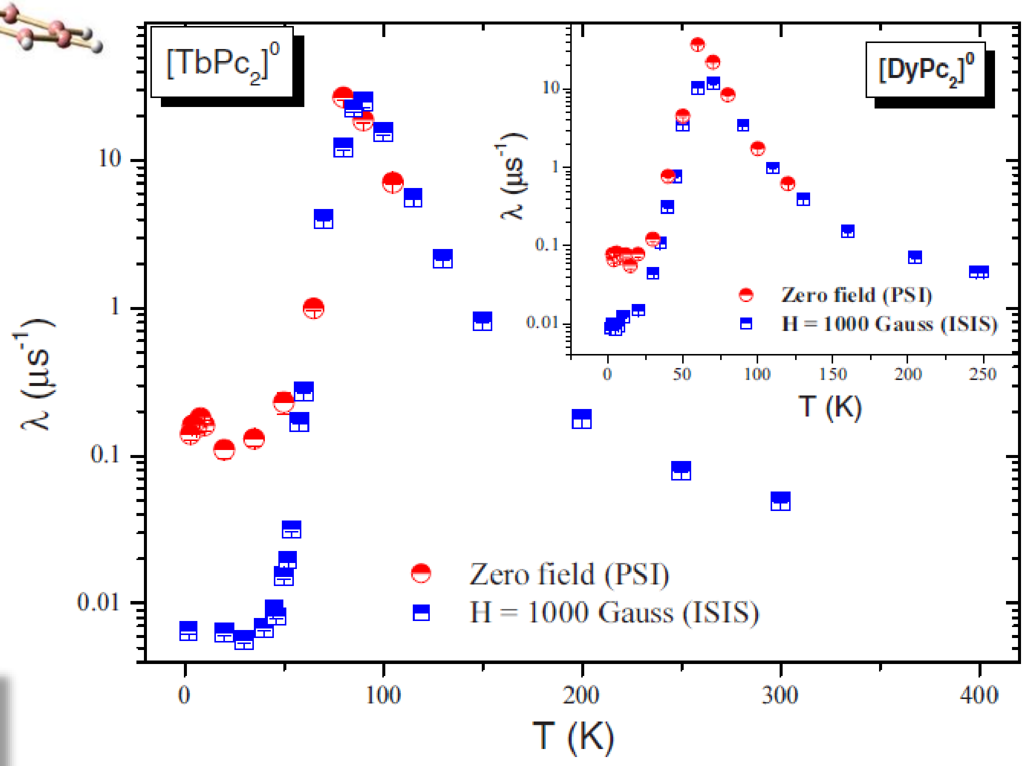
Tb^{3+} CF electronic levels



Spin-phonon thermal excitations

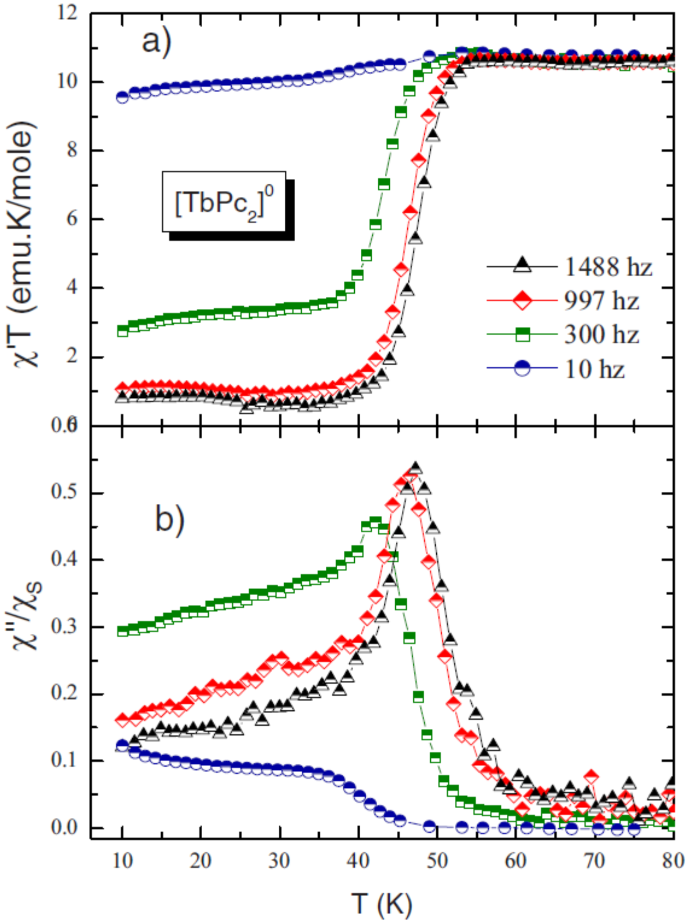


F. Branzoli et al., PRB**82**, 134401 (2010)



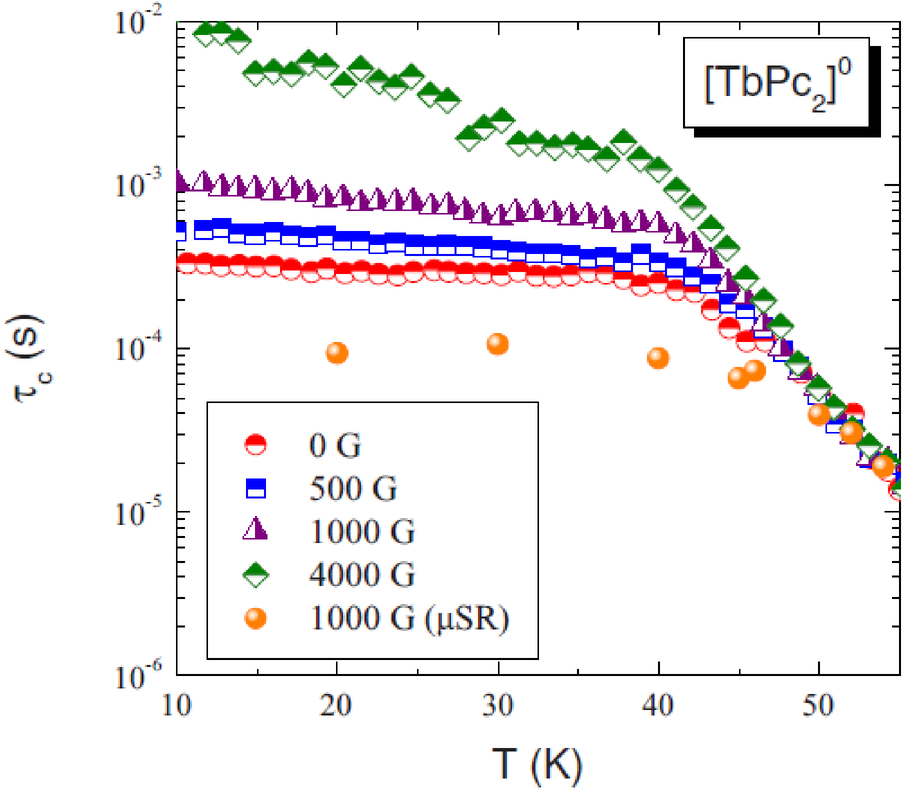
$$\frac{1}{T_1} = \frac{\gamma^2\langle\Delta h_\perp^2\rangle}{Z}\sum_{m=-6}^{+6}\frac{\tau_m e^{-E_m/kT}}{1+\omega_L^2\tau_m^2} \longrightarrow \frac{1}{T_1} = \frac{\gamma^2}{2}\langle\Delta h_\perp^2\rangle\frac{2\tau_c}{1+\omega_L^2\tau_c^2}$$

Example: ac-susceptibility vs μSR in Single Molecule Magnets



$$\chi''(\omega) = \frac{\chi_S \omega \tau_c}{1 + \omega^2 \tau_c^2}$$

F. Branzoli et al., PRB**82**, 134401 (2010)

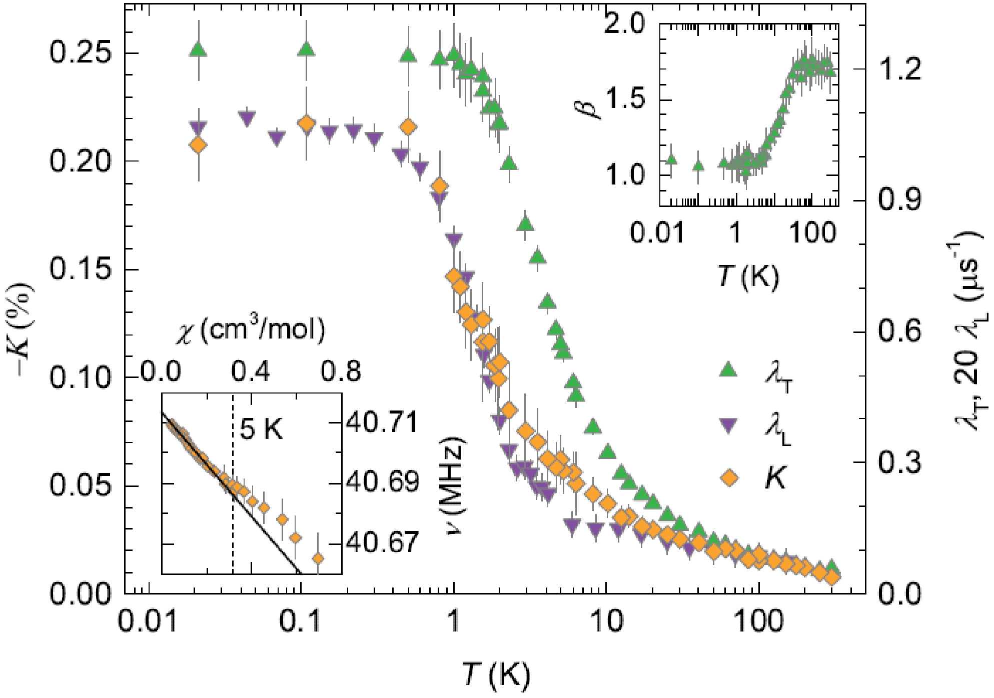


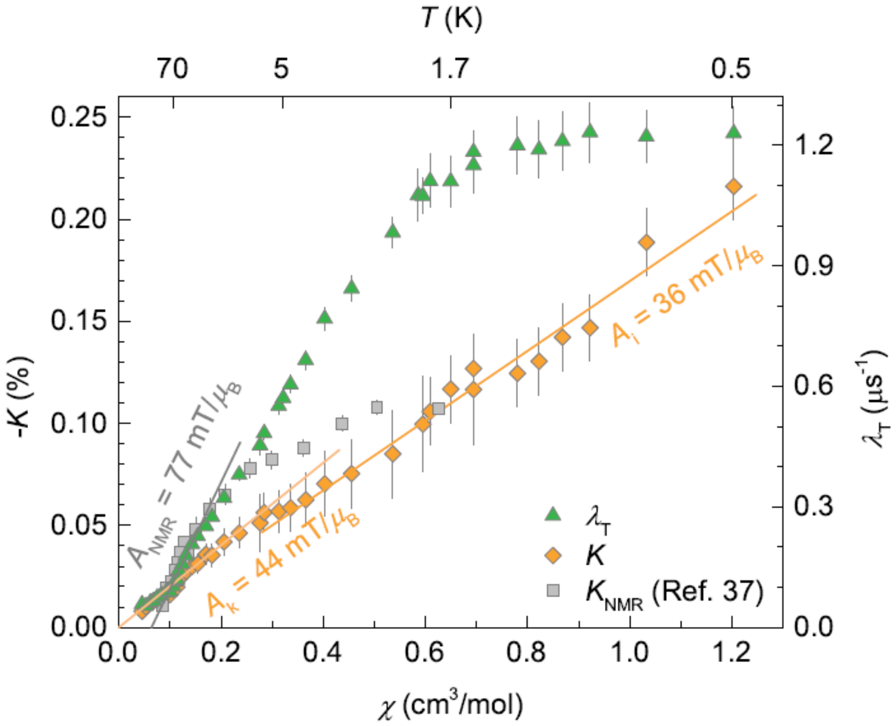
Discrepancy between ac-susceptibility and μSR correlation times suggest the presence of correlations among Tb^{3+} moments in the lattice, i.e. q≠0 modes.

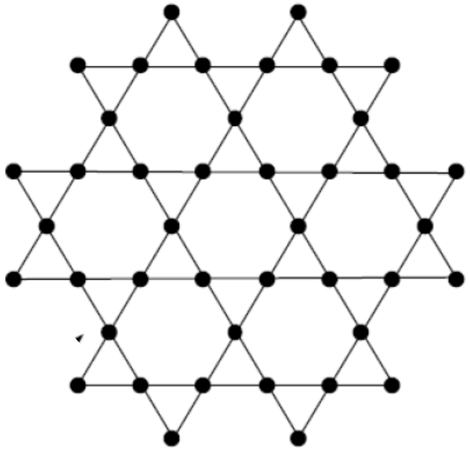
Static Magnetization/Susceptibility $\chi(0,0)$ and the muon Knight shift

With µSR shift one probes the intrinsic local susceptibility due only to those electron spins coupled to the muon, i.e. not the extrinsic impurity contribution. In clean systems the shift mesurement allows to derive the hyperfine coupling.

$$\tilde{\Delta K} = \frac{\sum_k \tilde{A}_k < \boldsymbol{S}_k >}{H_0} \; .$$



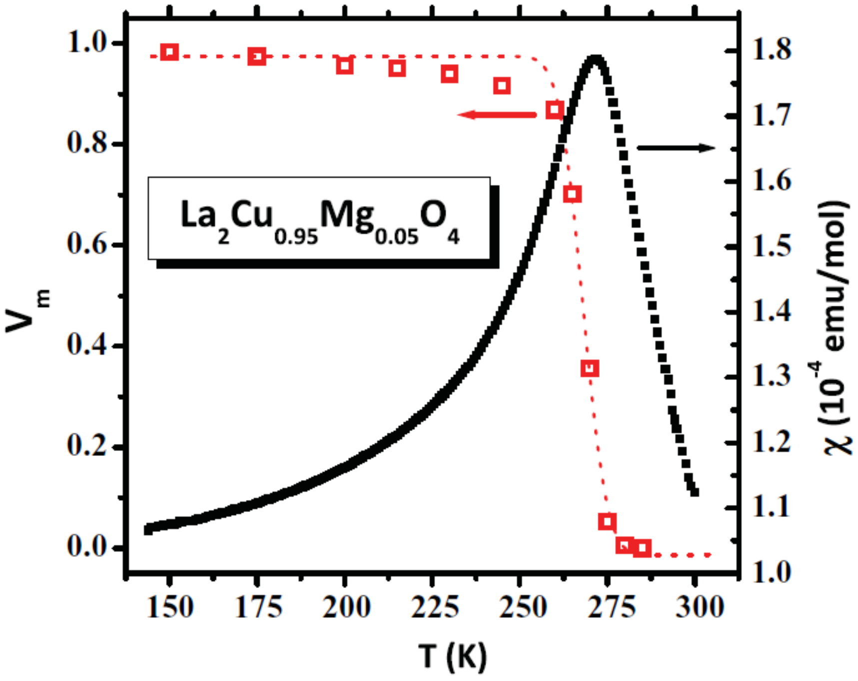


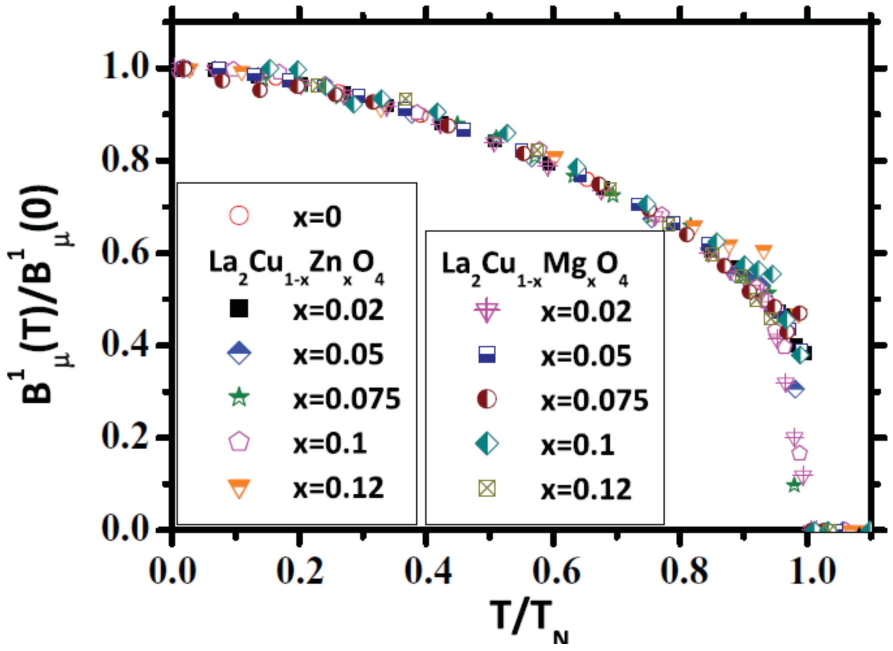


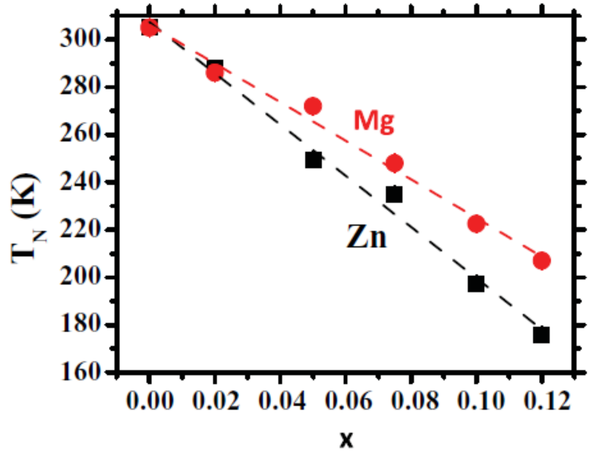
M.Gomilsek et al., PRB **94**, 024438 (2016)

In antiferromagnets or helimagnets (Q≠0) one needs a local probe to measure the sublattice magnetization

Example: Zn and Mg doped La_2CuO_4

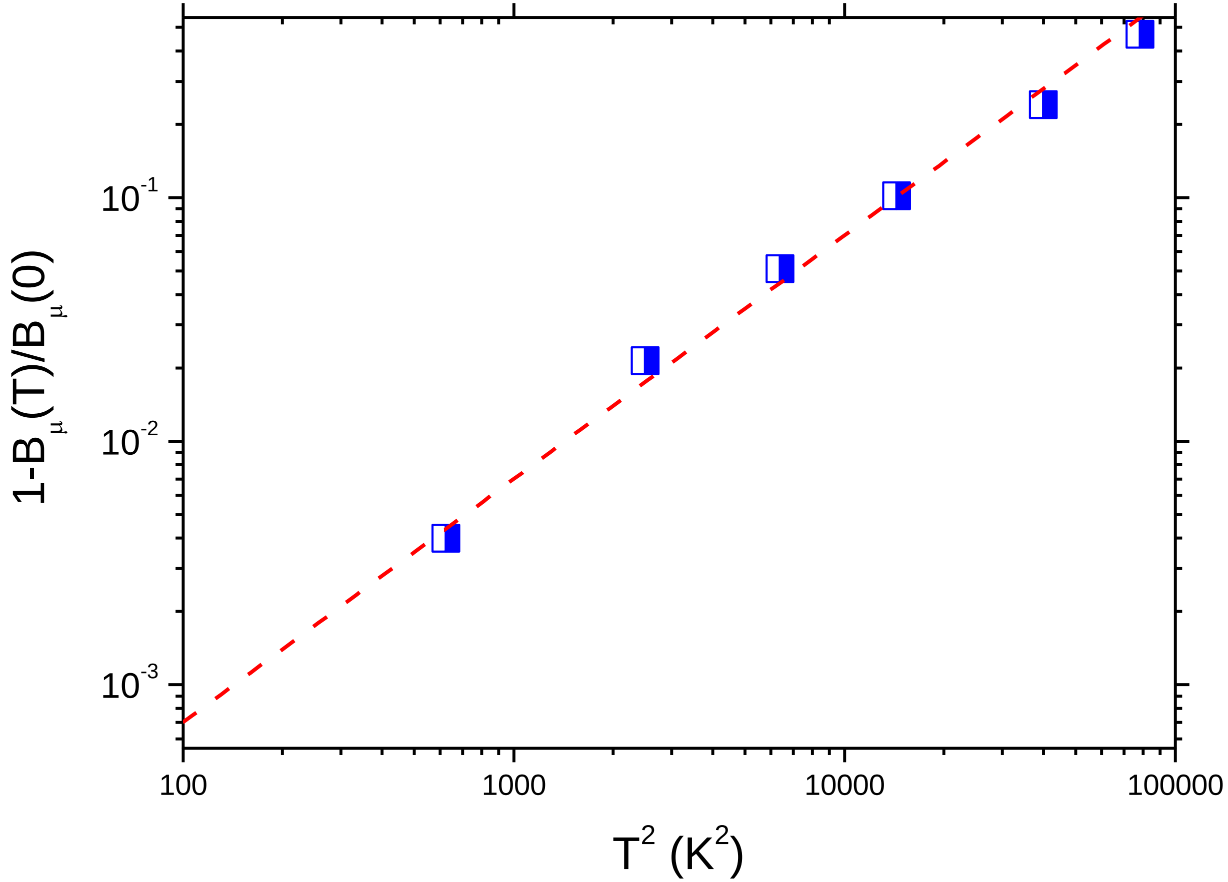






Derive critical exponents and information on spin waves

La_2CuO_4

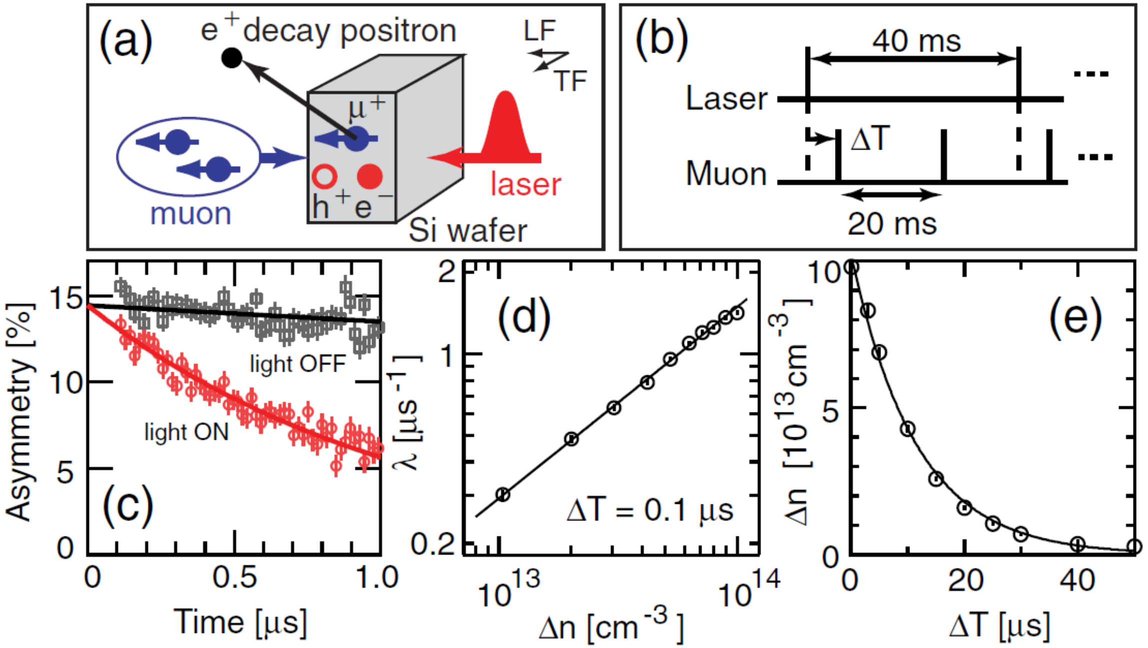


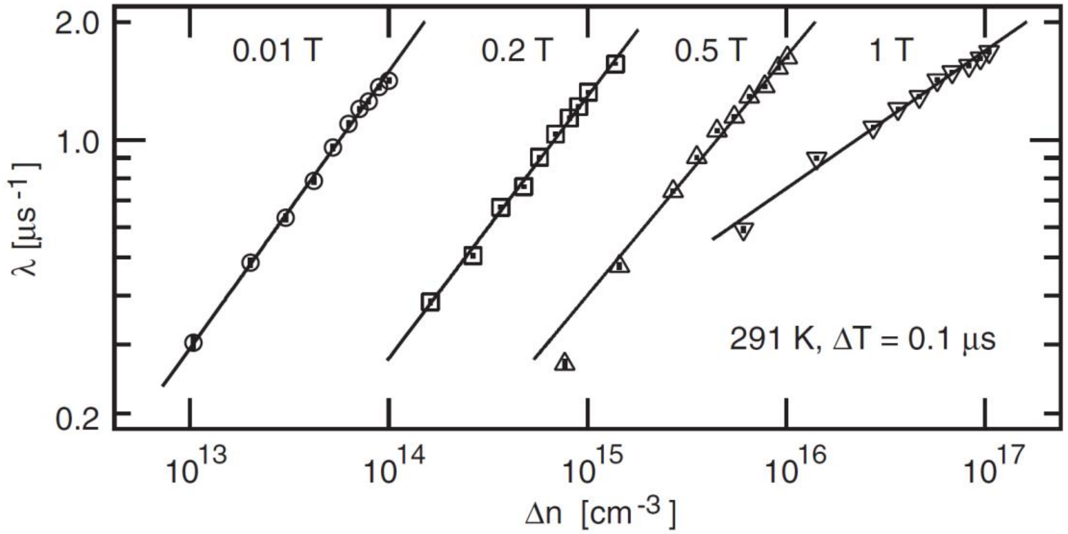
PRL **119,** 226601 (2017) PHYSICAL REVIEW LETTERS week ending 1 DECEMBER 2017

Photoexcited Muon Spin Spectroscopy: A New Method for Measuring Excess Carrier Lifetime in Bulk Silicon

K. Yokoyama,[1,2,*] J. S. Lord,[2] J. Miao,[1,3] P. Murahari,[1] and A. J. Drew[1,2,3,†]

Measurement of the bulk lifetime of photoinduced carriers in Si, µSR is not affected by surface effects as photoconductance/luminescence techniques which are typically used to measure carrier lifetimes.

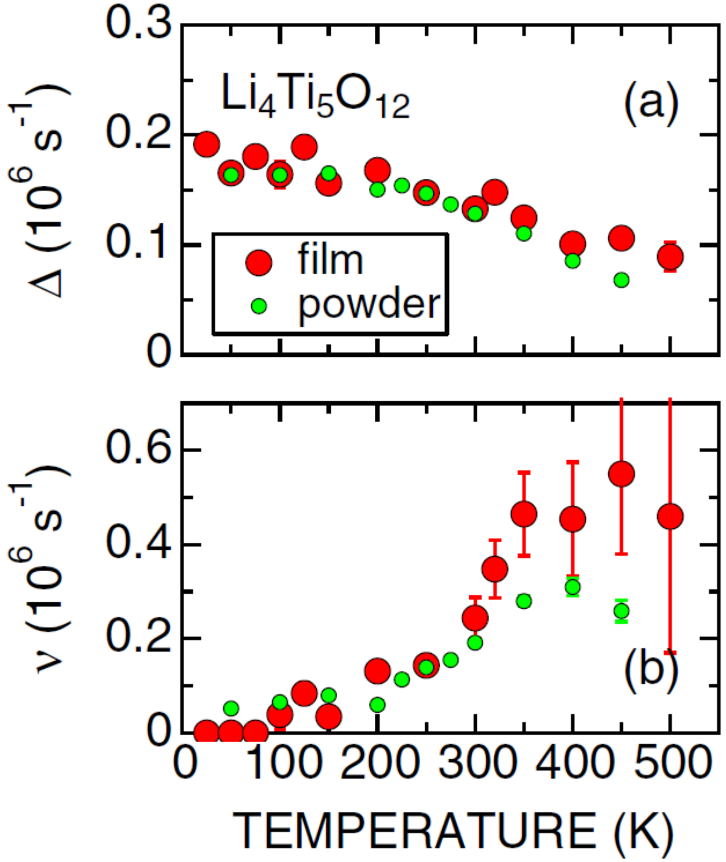




Ionic dynamics from conductivity measurements and from μSR

Local probes as muons probe ionic intersite hopping even if this does not give rise to a neat ionic current hence often a local fast dynamic can be detected by μSR and not by conductivity measurements.

J.Sugiyama et al., PRB**92**, 014417 (2015)



Sample	Case	D_{Li} at 300 K (10^{-11} cm^2/s)	E_a (eV)
$Li_4Ti_5O_{12}$	**1**	2.29 ± 0.11	0.09 ± 0.02
powder	(2)	6.94 ± 0.12	0.161 ± 0.005
$Li_4Ti_5O_{12}$	**1**	3.2 ± 0.8	0.12 ± 0.02
film	(2)	4.9 ± 1.1	0.16 ± 0.03
$LiTi_2O_4$	**1**	3.6 ± 1.1	0.17 ± 0.06
film	(2)	6 ± 3	0.15 ± 0.08

Activation energies for AC conductivity at different frequencies.

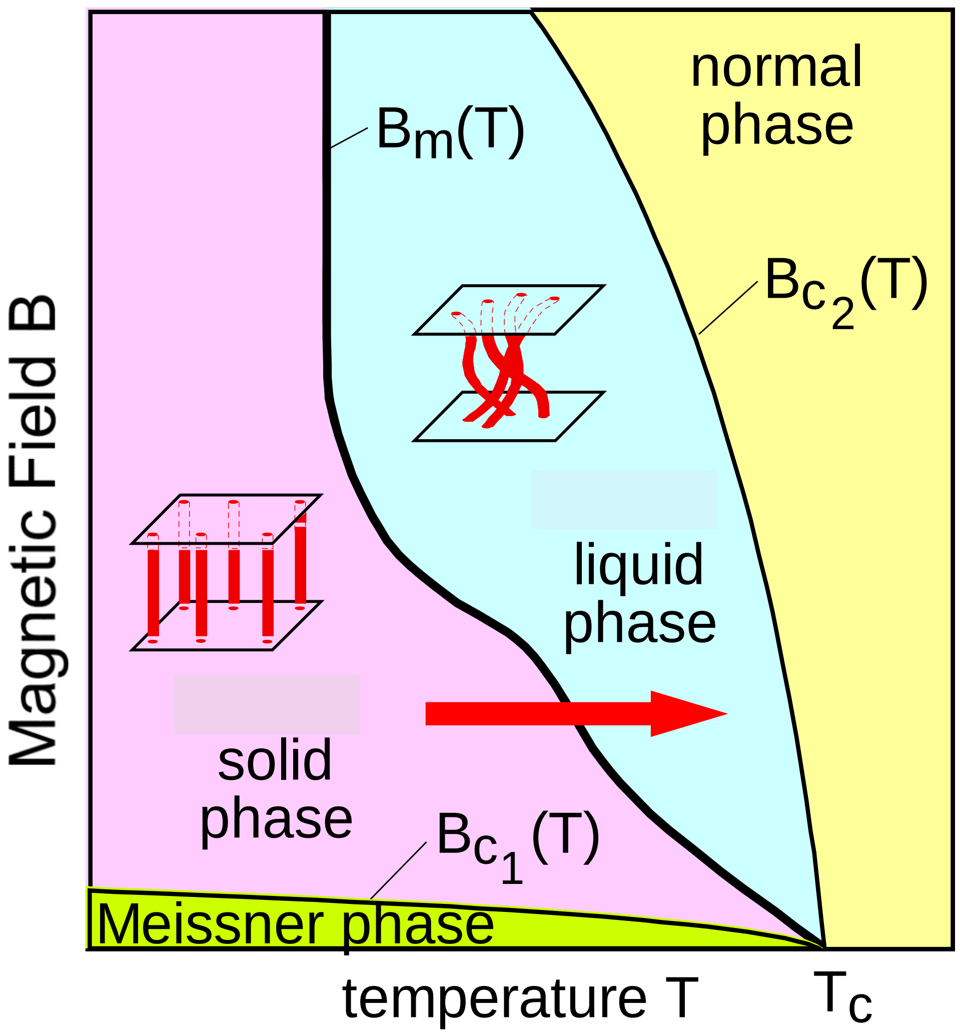
Sample	Frequency (kHz)	Activation Energy (eV)
LTO	1.5	0.39
	4.5	0.25
	7.5	0.23

$$\sigma = \sigma_0 \exp\left(-\frac{E_a}{K_B T}\right)$$

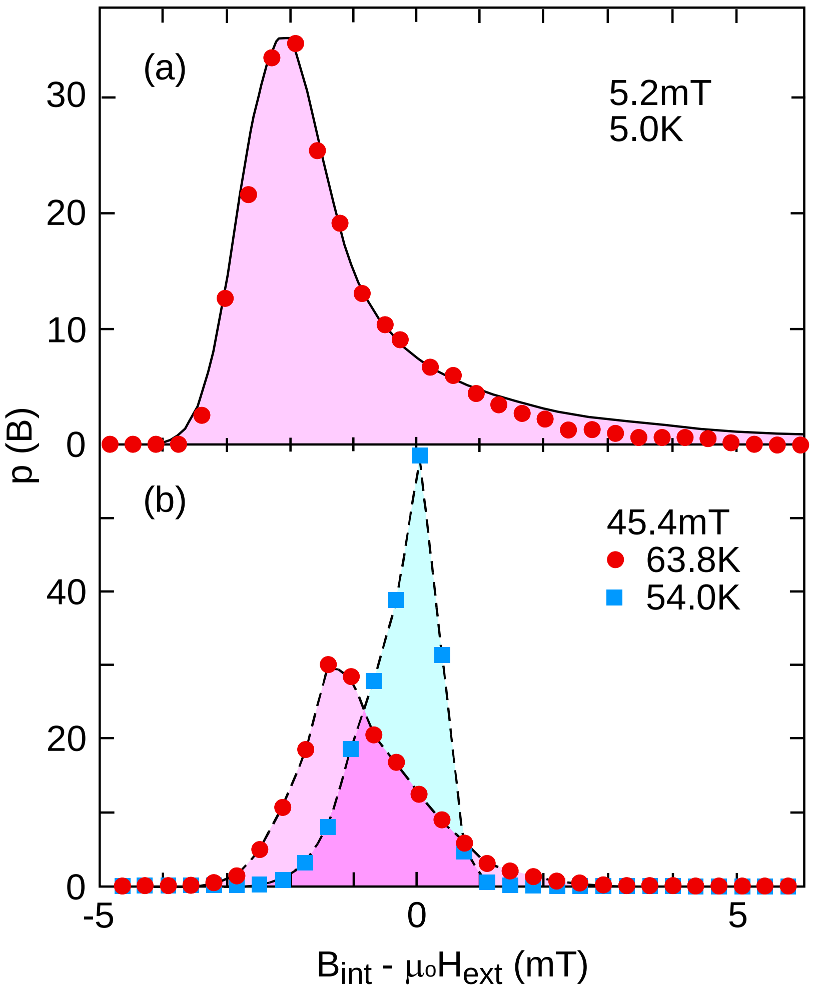
B.V.Babu et al., Results in Physics 9, 284 (2018)

Flux lines thermal dynamics in superconductors studied with μSR

high-T_c type II superconductor

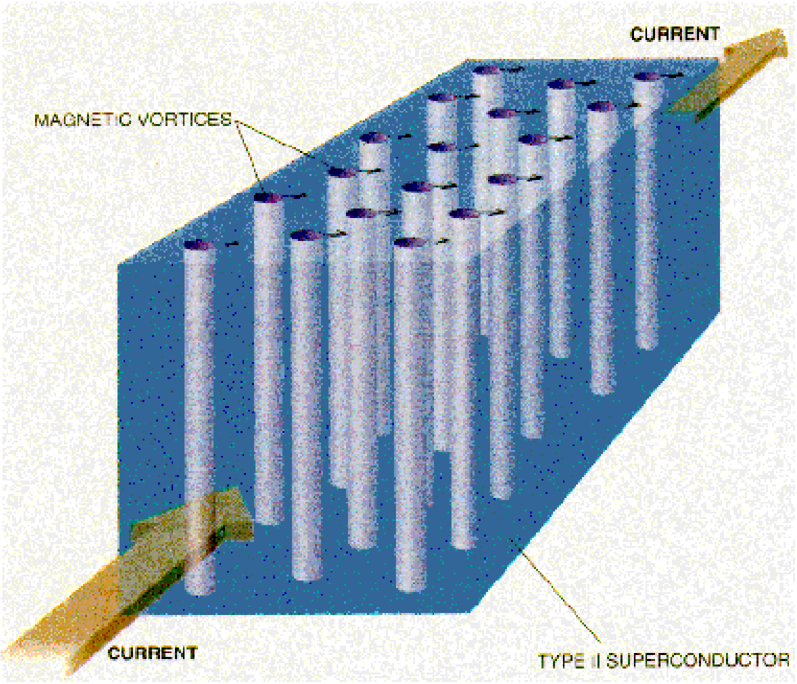


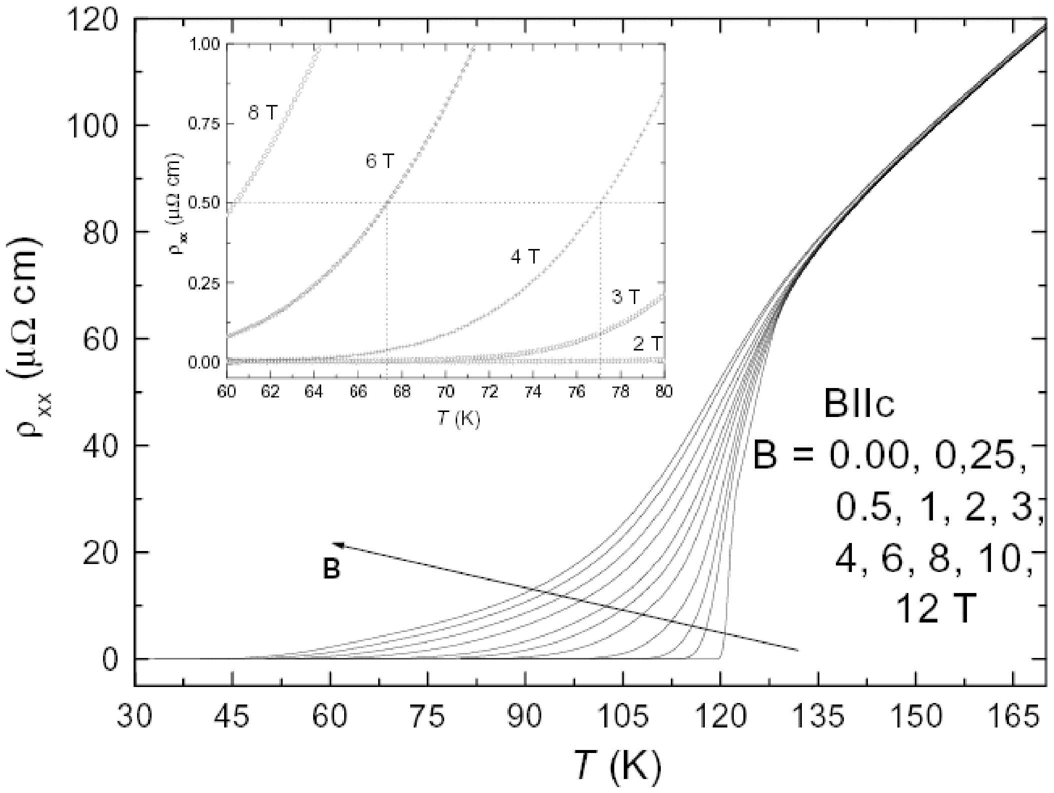
$Bi_{2.15}Sr_{1.85}CaCu_2O_{8+\delta}$



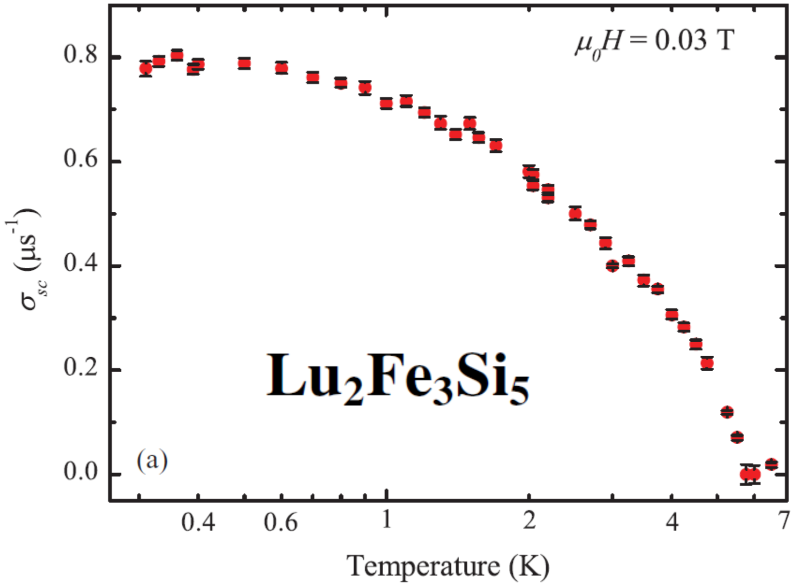
S.L.Lee et al., PRL**75**, 922 (1995)

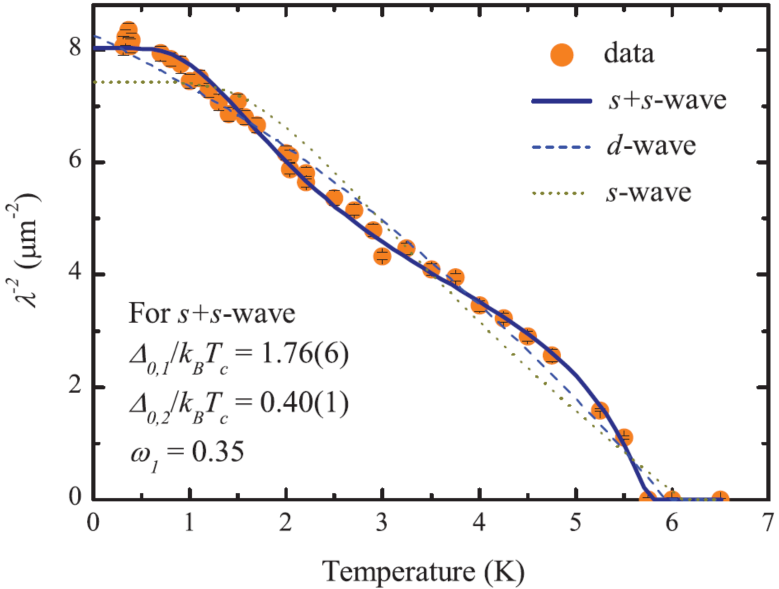
Flux line bundles drift under a Lorentz force



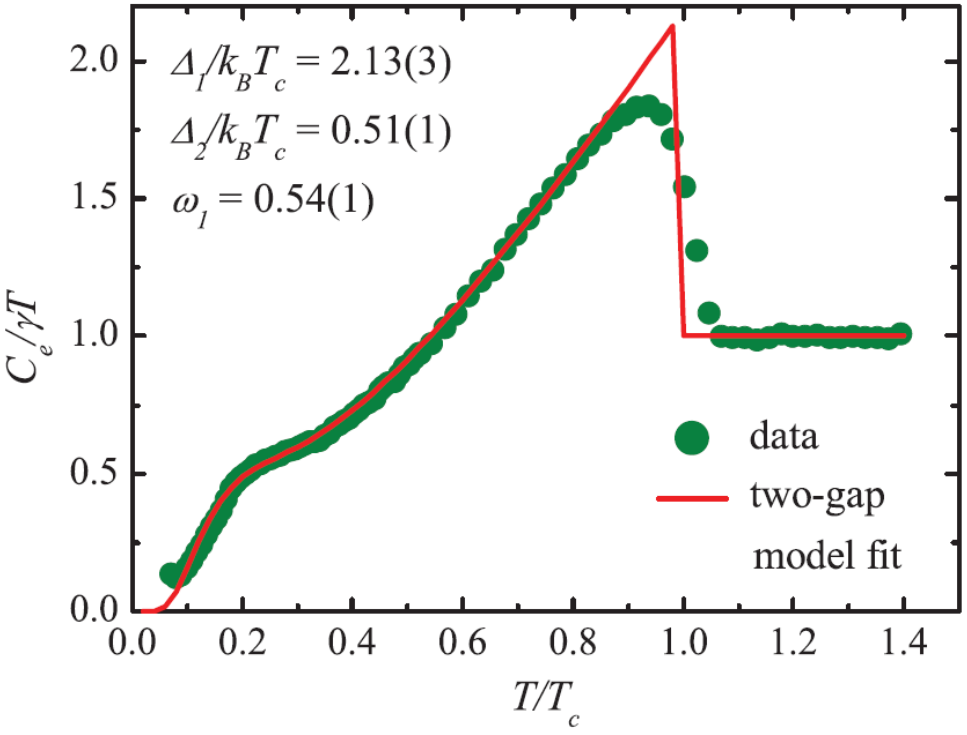


Multigap superconductor studied with Specific Heat and from μSR





P.K.Biswas et al., PRB**83**, 054517 (2011)

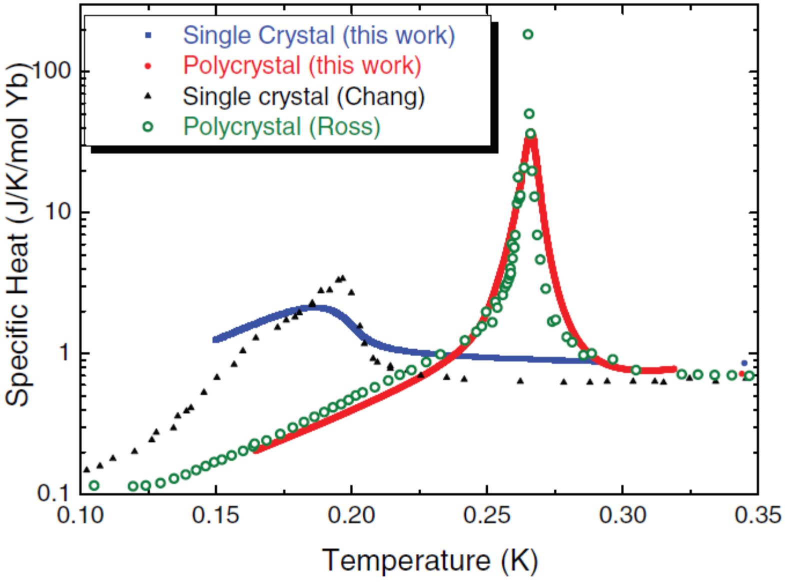


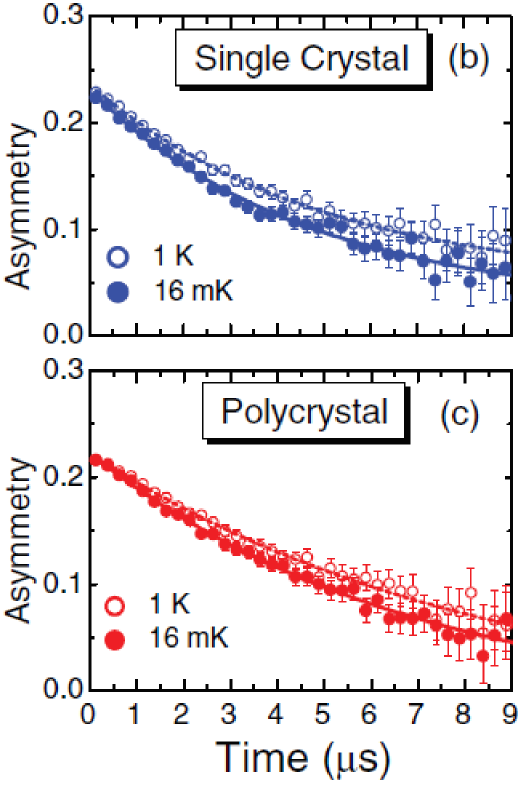
Unconventional Ground-States in Frustrated Magnets

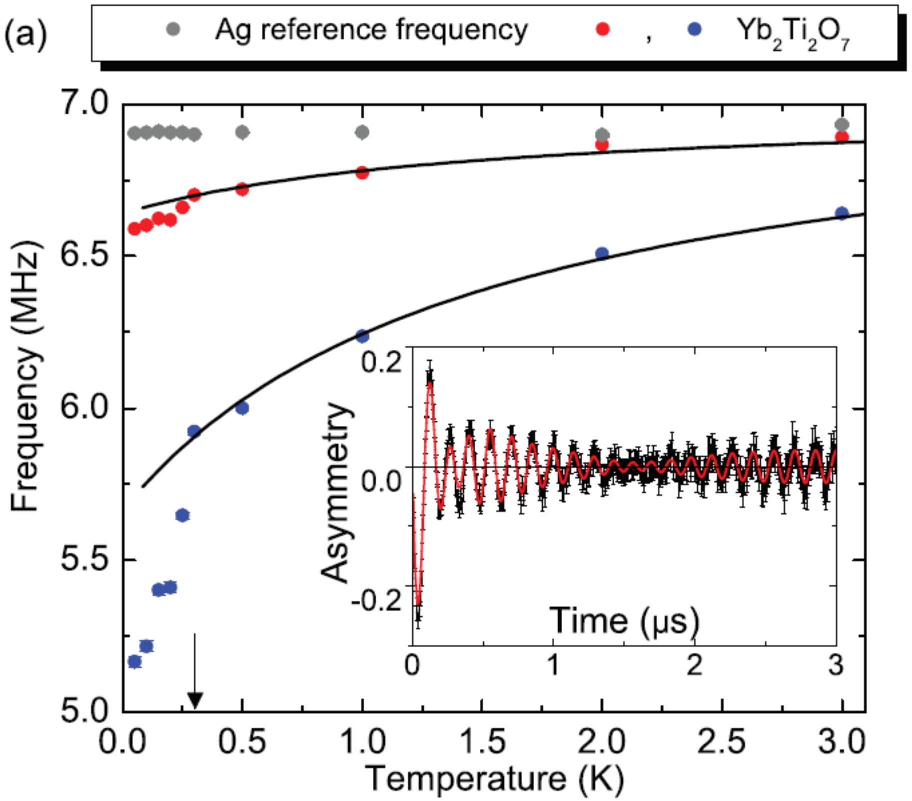
PHYSICAL REVIEW B **88**, 134428 (2013)

Unconventional magnetic ground state in $Yb_2Ti_2O_7$

R. M. D'Ortenzio,[1] H. A. Dabkowska,[2] S. R. Dunsiger,[3] B. D. Gaulin,[1,2,4] M. J. P. Gingras,[4,5,6] T. Goko,[7] J. B. Kycia,[5] L. Liu,[7]
T. Medina,[1] T. J. Munsie,[1] D. Pomaranski,[5] K. A. Ross,[8,9] Y. J. Uemura,[7] T. J. Williams,[1] and G. M. Luke[1,2,4,*]







In general, bulk tecniques provide information which is complementary to the one local microscopic techniques as µSR can access and often they provide the necessary and unavoidable preliminary characterization of the materials before a µSR experiment is performed.