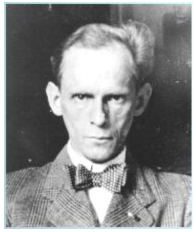
Zastosowanie techniki μSR w badaniach własności magnetyków molekularnych.

Piotr M. Zieliński
NZ35
IFJ PAN

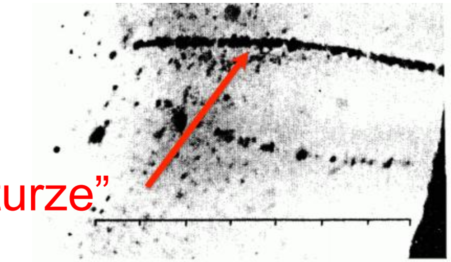
1. Fundamenty spektroskopii mionów
2. Typowy eksperyment
3. Zjawiska krytyczne i μSR
4. Przykłady otrzymanych wyników
5. Podsumowanie

Historia mionów

1933



Paul Kunze
Z. Phys., 83 (1933) 1



,,cząstka o nieznanej naturze"

1936

1937 PHYSICAL REVIEW VOLUME 51

Note on the Nature of Cosmic-Ray Particles

SETH H. NEDDERMEYER AND CARL D. ANDERSON
California Institute of Technology, Pasadena, California
(Received March 30, 1937)

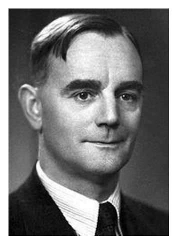
Seth Neddermeyer

mesotron $m \approx 240\ m_e$
meson miu Yukawy ? (100 MeV)

Carl Anderson

1947, 1949





Nature, **160** (1947), 486, *Observations on the tracks of slow mesons in photographic emulsions* $\pi \to \mu$

Brown et al., Nature, **163** (1949), 47, *Observations with electron-sensitive plates exposed to cosmic radiation*

$\pi \to \mu \to e$

Cèsar Lattes, Giuseppe Occhialini, Cecil F. Powell

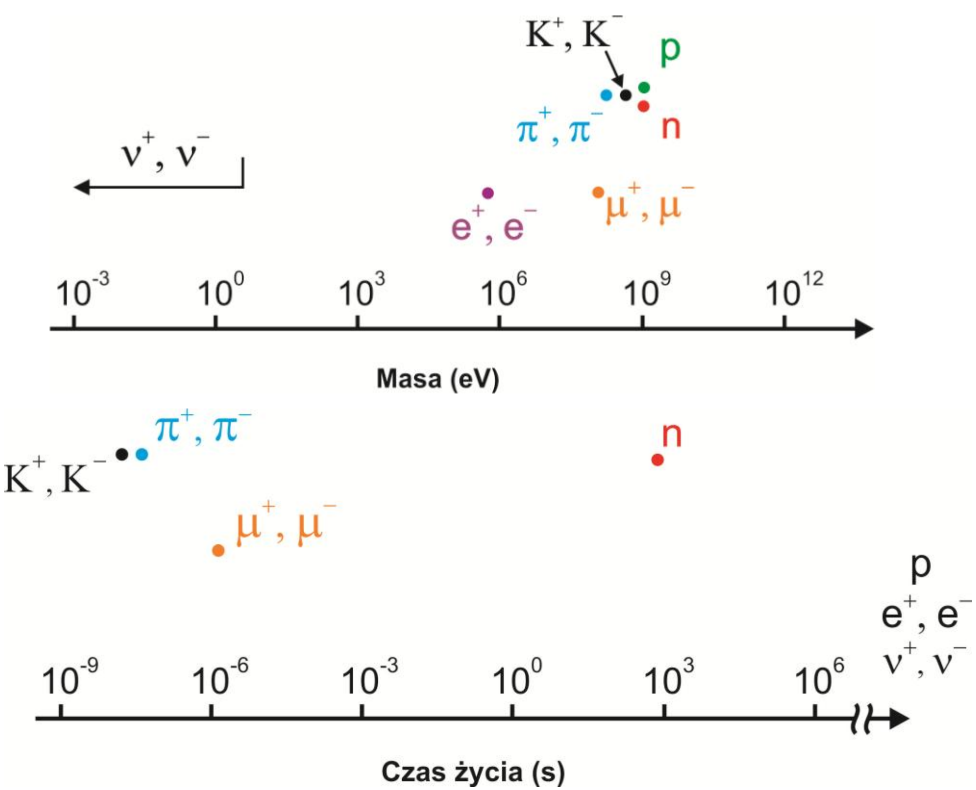
1956

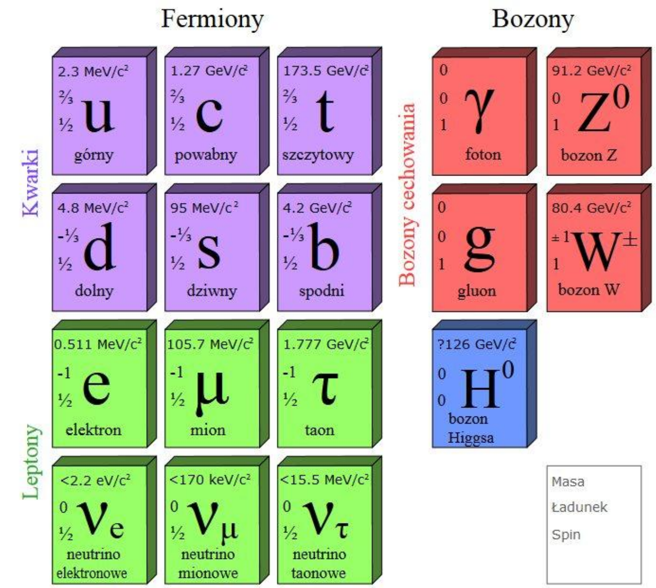

Physical Review, **104** (1956), 254, *Question of parity conservation in weak interactions*
Physical Review, **105**(1957), 1671, *Parity nonconservation and a two-component theory of the neutrino*

Tsung-Dao Lee, Chen-Ning Yang

Własności mionów

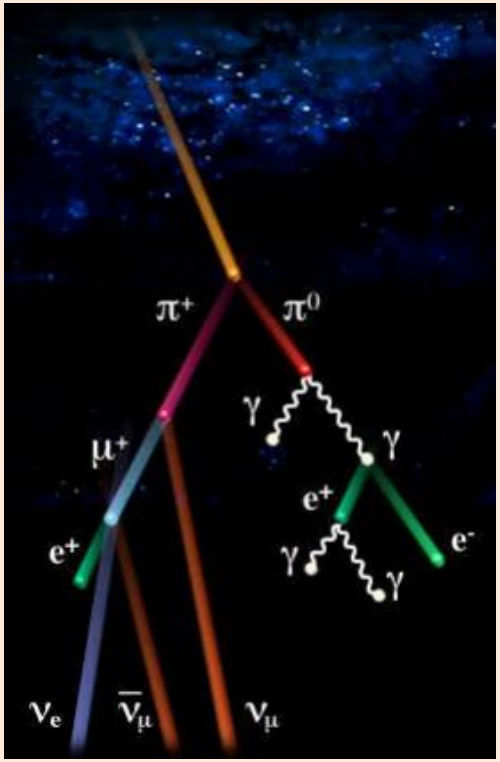
Wielkość	**Symbol**	μ
Masa spoczynkowa	$m_\mu c^2$	105.6583715(35) MeV
	m_μ	$1.883531475 \times 10^{-28}$ kg
Masa	m_μ	0.1126095272(28) m_p
	m_μ	206.7682843(52) m_e
Ładunek	Q	$\pm 1.60219 \times 10^{-19}$
Spin	S_μ	$1/2$ ($\hbar$)
Moment magnetyczny	μ_μ	$4.84197044(12)\times 10^{-3} \mu_B$
Stosunek żyromagnetyczny	γ_μ	$135{,}5\times 2\pi$ MHz/T
Średni czas życia swobodnego mionu	τ_μ	$2.1969811(22)\times 10^{-6}$ s





Źródła mionów

Promieniowanie kosmiczne



- Pierwotne P.K.

P (~90%), He(~9%), e.

10^{11} GeV

- Wtórne P.K.

π, κ, Λ, …

- przy powierzchni

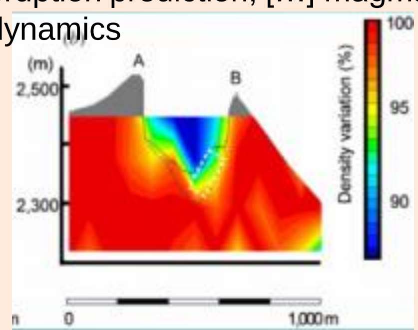
μ(~70%) e^- (30%)

4 GeV, 1μ/cm2/min

Search for hidden chambers in the pyramids

Alvarez, Science, **167** (1970) 832.

[…] Inner structure, […] volcanic eruption prediction, […] magma dynamics



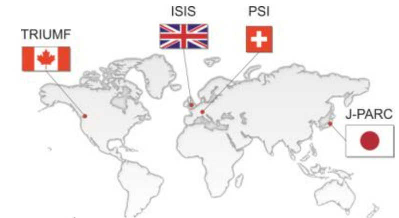
Tanaka, Nature Comm., **5** (2014), 3381

Nagamine, (1995),

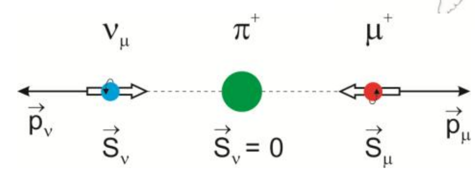
DOI: 10.1016/0168-9002(94)01169-9

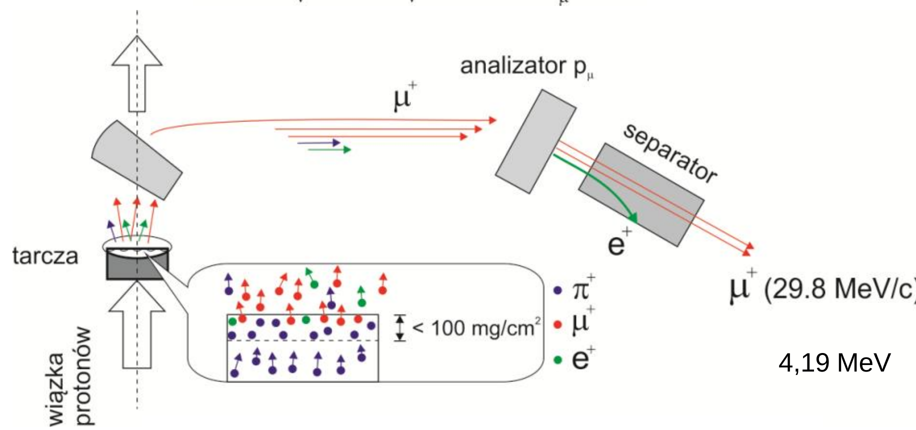
Akceleratory protonów

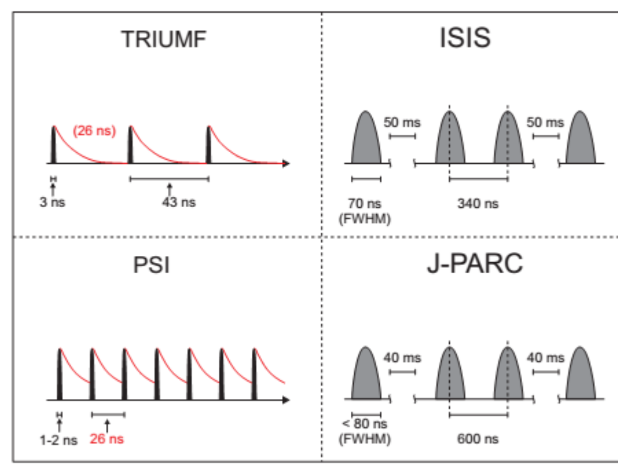
100μA, 500 MeV



$$p + p \rightarrow \pi^+ + p + n$$
$$p + n \rightarrow \pi^+ + n + n$$



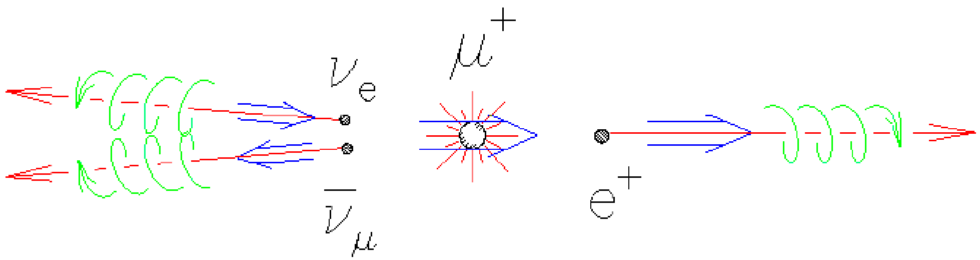


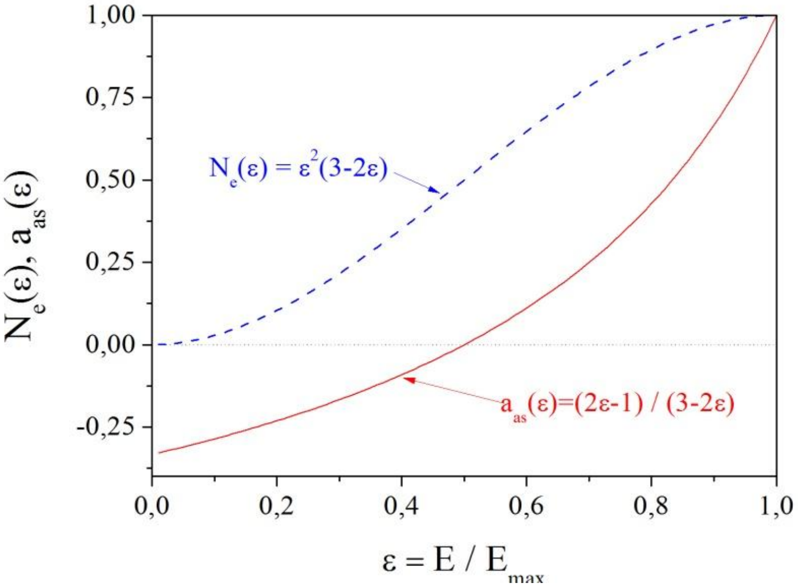


Rozpad mionów

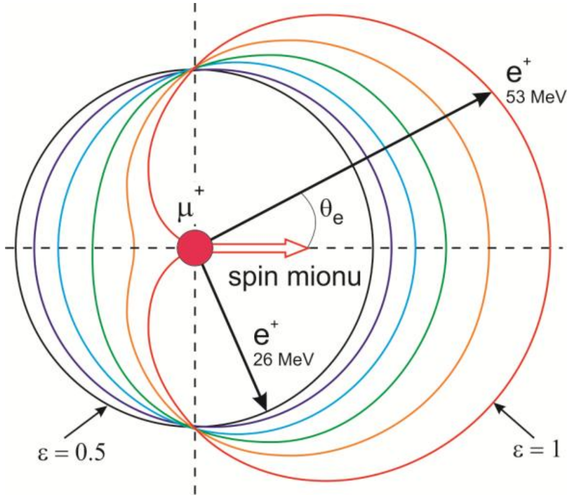
$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

$$\mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu$$





$$W(\theta) \propto [1 \pm a_{as}(\varepsilon) \cos\theta]$$



$$N_e(E_e) \propto [1 \pm a_{as}(E_e) \cos\theta]$$

$$a_{as}(E_e) = (E_e^{max} - 2E_e)/(3E_e^{max} - 2E_e)$$

$$E_e^{max} = \frac{m_\mu c^2}{2} = 52{,}83\ MeV$$

„It seems possible that polarized positive and negative muons will become a powerful tool for exploring magnetic fields in nuclei [...], atoms, and interatomic regions." (Garwin et al., Phys. Rev. 1957)

μSR – muon Spin Rotation, Relaxation, …

Możliwości

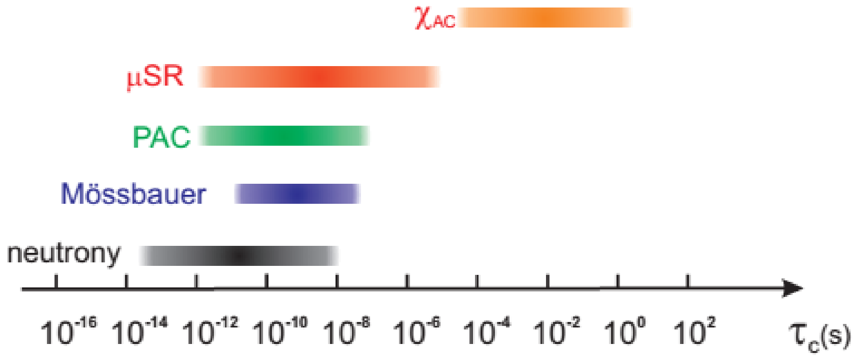
Struktura, dynamika materii skondensowanej

10 mK do 1000 K
~ 1,5 Gpa
8 T
1 h

Ograniczenia

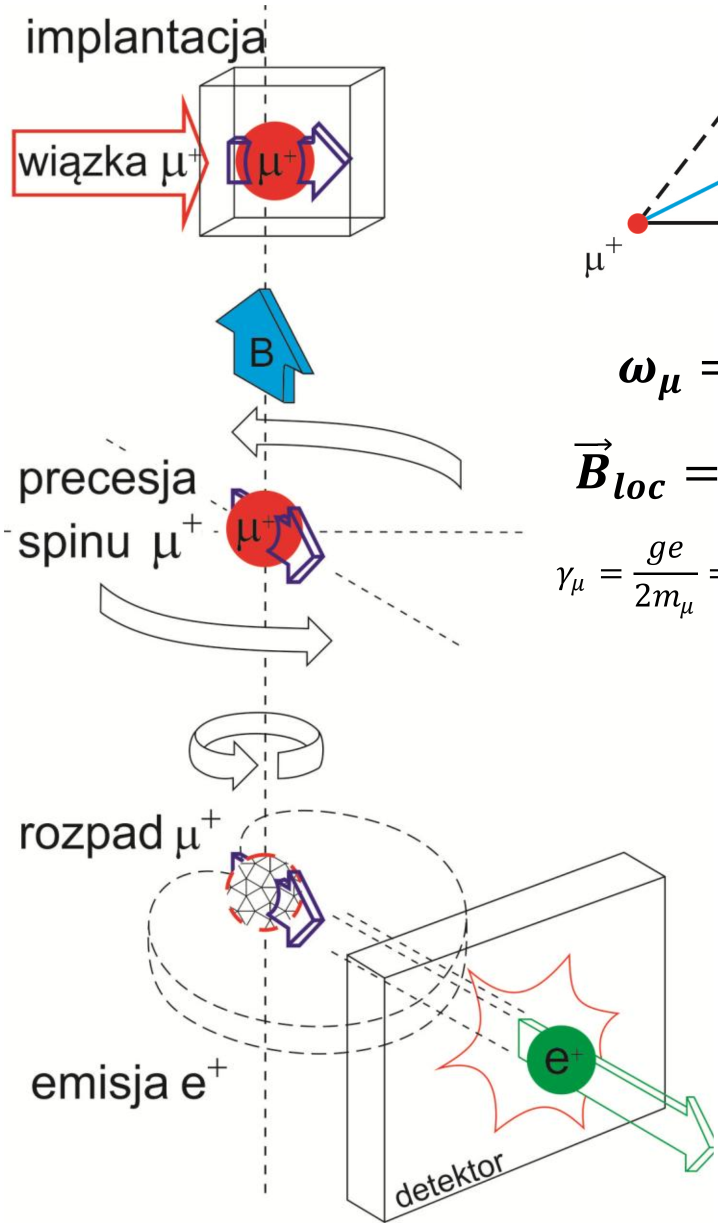
Rozmiar / Masa próbki

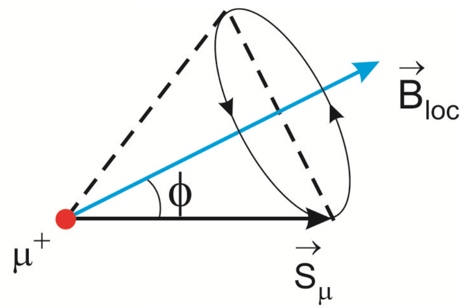
6,5 mm^2 , 0.07 mm
Najczęściej:
180 mg /cm^2 wiązki
Grubość:
> 1mm (mat. organiczne ρ ~ 1g/cm^3)
100 – 300 μm (metale przejściowe)



… Resonace (ALC, RF-μSR, techniki stroboskopowe).

Schemat

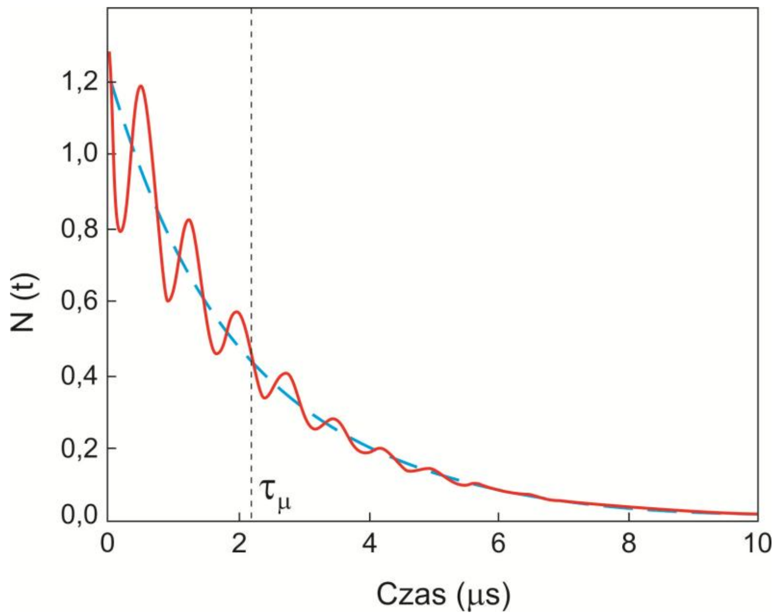




$$\boldsymbol{\omega_\mu = \gamma_\mu B_{loc}}$$

$$\boldsymbol{\vec{B}_{loc} = \vec{B}_{ext} + \vec{B}_0}$$

$$\gamma_\mu = \frac{ge}{2m_\mu} = 2\pi \cdot 135{,}5\ \frac{MHz}{T}$$



$$N_{F,B}(t) = N_0 exp(-t/\tau_\mu)[1 \pm a_0 P_\alpha(t)]$$

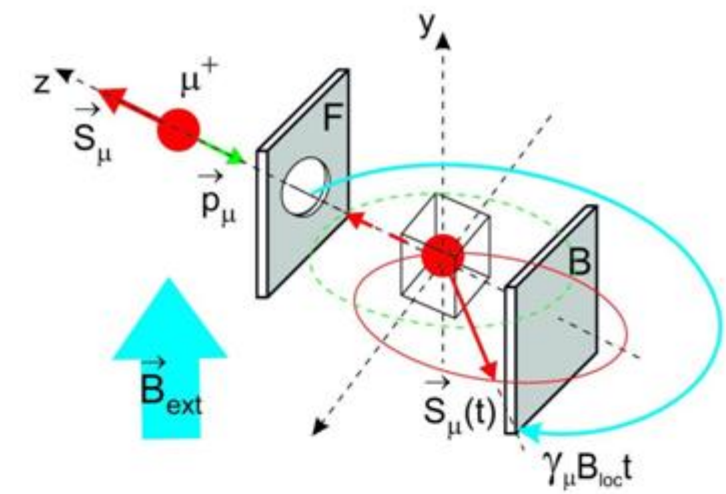
$$\alpha = x, y, z$$

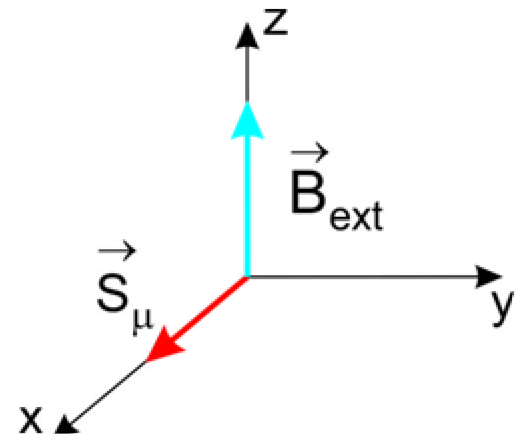
$$\boldsymbol{A(t) = a_0 P_\alpha(t) = \frac{N_F(t) - N_B(t)}{N_F(t) + N_B(t)}}$$

$$a_0 \sim 0.25$$

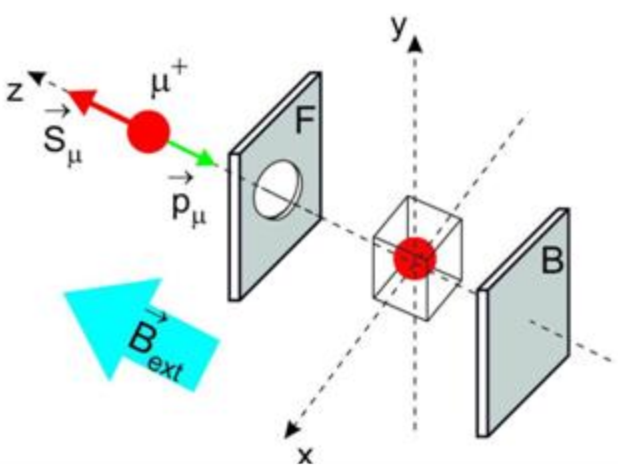
Geometria

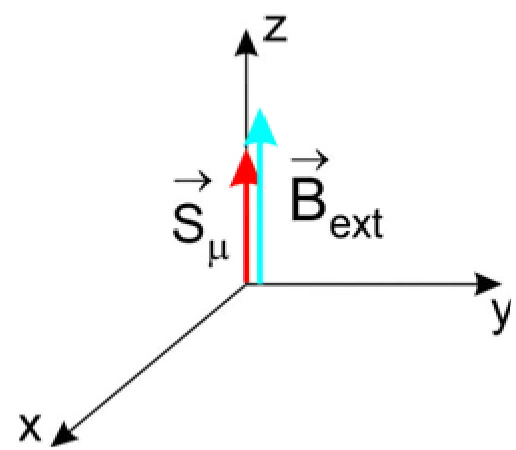
TF rotacja spinu mionów





LF (ZF) relaksacja spinu mionów





Analiza

$$\vec{B}_{loc} = \vec{B}_{ext} + \vec{B}_0$$

$$\vec{B}_0 = \vec{B}_{dip} + \vec{B}_{Lor} + \vec{B}_{dem} + \vec{B}_{hyp}$$

$$P_\alpha(t) = \int f(\vec{B}_{loc})\left[sin^2\theta + cos^2\theta \cos\left(\gamma_\mu B_{loc} t\right)\right] d\vec{B}_{loc}$$

$$P_{\vec{\imath}_\mu,\vec{\imath}_p}(t) = \frac{\langle \vec{S}_\mu(t) \rangle}{S_\mu(0)} \cdot \vec{u}_p$$

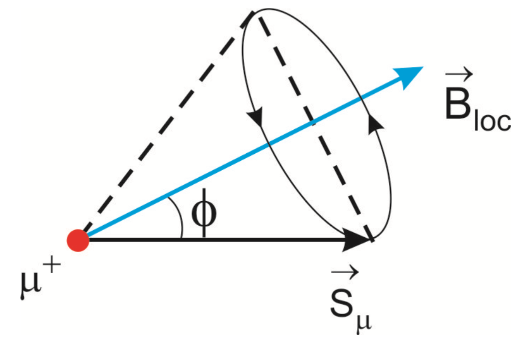
$$\vec{\imath}_\mu = \frac{\vec{S}_\mu(0)}{S_\mu(0)}$$

Próbka jednodomenowa, monokrystaliczna

$$f(\vec{B}_{loc}) = \delta(t)$$

$$P_Z(t) = cos^2\theta + sin^2\theta \cos\left(\omega_\mu t\right)$$

$$\omega_\mu = \gamma_\mu B_{loc} = 2\pi\nu_\mu \left[\left(B^X_{loc}\right)^2 + \left(B^Y_{loc}\right)^2 + \left(B^Z_{loc}\right)^2\right]^{1/2}$$



$$\mu_\mu = \gamma_\mu \hbar S_\mu$$

Próbka polikrystaliczna, B_{ext}=0, faza uporządkowana magnetycznie

$$P_Z(t) = \frac{1}{3} + \frac{2}{3}\cos\left(\omega_\mu t\right)$$

$$P_Z(t) = A_Z + A_{osc} \cos\left(\omega_\mu t\right)$$

$$A_Z(b) = \frac{3}{4} - \frac{1}{4b^2} + \frac{(b^2-1)^2}{8b^3} log\left|\frac{b+1}{b-1}\right|$$

$$A_{osc}(b) = 1 - A_Z(b)$$

Teoria zjawisk krytycznych

$$f(\tau) \propto \tau^k \quad \tau \to 0 \qquad k = \lim_{\tau\to 0} \frac{log f(\tau)}{log\tau}$$

$$\tau = \frac{|T - T_{kr}|}{T_{kr}}$$

Model magnetyka molekularnego

$$\mathcal{H} = -2\sum_{i<j}\left(J_{ij,x}S_{i,x}S_{j,x} + J_{ij,y}S_{i,y}S_{j,y} + J_{ij,z}S_{i,z}S_{j,z}\right)$$

$$S_{i,k} \ \ (k = x, y, z)$$

Liczba niezerowych składowych spinu określa wymiar ***n*** parametru porządku

- model Heisenberga, $n = 3$.
  $J_{ij,x} = J_{ij,y} = J_{ij,z}$ (izotropowy model Heisenberga).
  $J_{ij,x} \neq J_{ij,y} \neq J_{ij,z}$ (anizotropowy model Heisenberga).
- model XY, $n = 2$.
  $J_{ij,x} = J_{ij,y}$ i $J_{ij,z} = 0$ (izotropowy model XY).
  $J_{ij,x} \neq J_{ij,y}$ i $J_{ij,z} = 0$ (anizotropowy model XY).
- model Isinga, n=1.
  $J_{ij,x} = J_{ij,y} = 0$ i $J_{ij,z} \neq 0$.

Z pomiarów μSR bezpośrednio:

ZF

$$B(T) = B(0)\left[1 - \left(\frac{T}{T_{kr}}\right)^{\sigma}\right]^{\beta}$$

$$\lim_{\tau \to 0} M \propto \tau^{\beta}$$

TF

$$\frac{f - f_0}{f_0} \sim x(T) \sim \left(\frac{T}{T_C} - 1\right)^{-\gamma}$$

$$\lim_{\tau \to 0} \chi_0 \propto \tau^{-\gamma}$$

LF

$$\tau \sim \left(\frac{T}{T_C} - 1\right)^{-w}$$

$$\lambda_Z \propto \tau^{w}$$

Pozostałe wykładniki krytyczne

z relacji skalowania, np. :

$$\alpha = 2 - 2\beta - \gamma$$

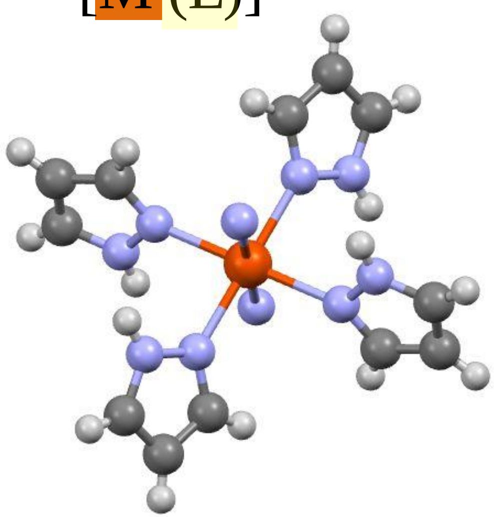
$$\nu = \frac{2 - \alpha}{d}$$

Substancje

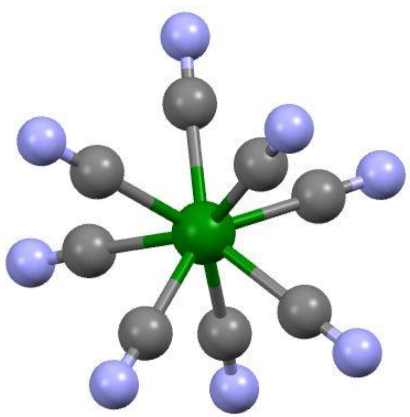
Badane związki

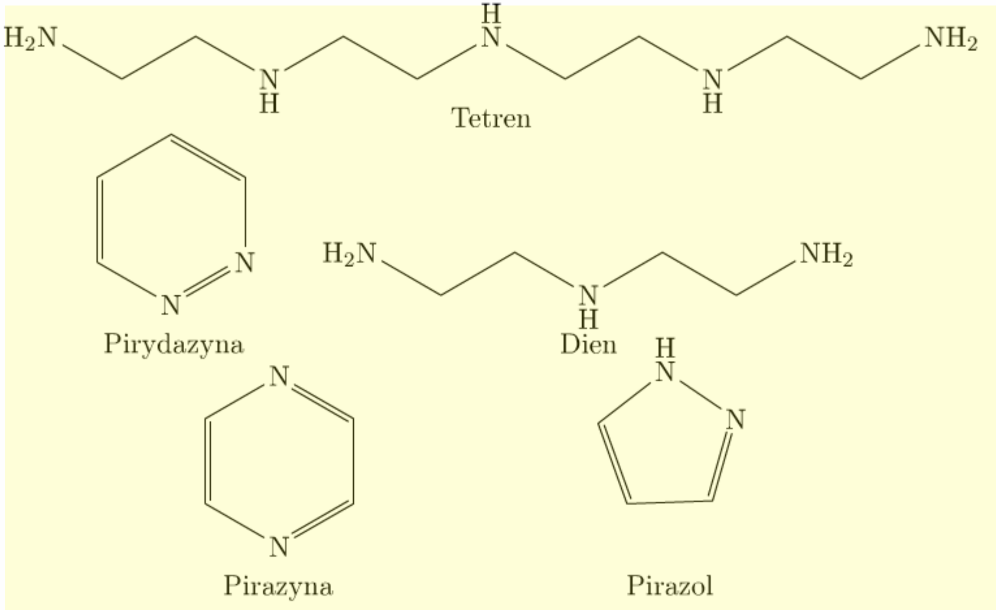
1. $\{(\mathrm{tetrenH_5})_{0.8}\mathrm{Cu^{II}_4}[\mathrm{W^{V}(CN)_8}]_4 \cdot 7\mathrm{H_2O}\}_n$ – (Cu4W4)
2. $\{\mathrm{Cu^{II}_{2+x}Cu^{II}_4}[\mathrm{W^{V}(CN)_8}]_{4-2x}[\mathrm{W^{IV}(CN)_8}]_{2x}\} \cdot 4\mathrm{H_2O}$ – Cu7W4)
3. $\{[\mathrm{Mn^{II}(pirydazyna)(H_2O)_2}][\mathrm{Mn^{II}(H_2O)_2}][\mathrm{Nb^{IV}(CN)_8}] \cdot 2\mathrm{H_2O}\}_n$ – (Mn2Nb)
4. $\{(\mathrm{dienH_3})\mathrm{Cu^{II}_3}[\mathrm{Mo^{V}(CN)_8}]_3 \cdot 4\mathrm{H_2O}\}$ – (Cu3Mo3)
5. $\{\mathrm{Cu^{II}_3(pirazyna)}[\mathrm{W^{V}(CN)_8}]_2\}$ – (Cu3W)
6. $\{[\mathrm{Fe^{II}(pirazol)_4}]_2[\mathrm{Nb^{IV}(CN)_8}] \cdot 4\mathrm{H_2O}\}_n$ – (Fe2Nb)

$[\mathrm{M'(L)}]^{n+}$

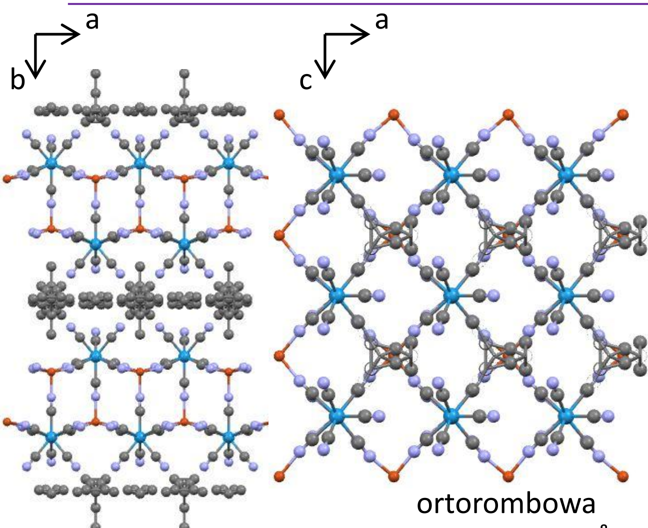


$[\mathrm{M(CN)_8}]^{3-/4-}$





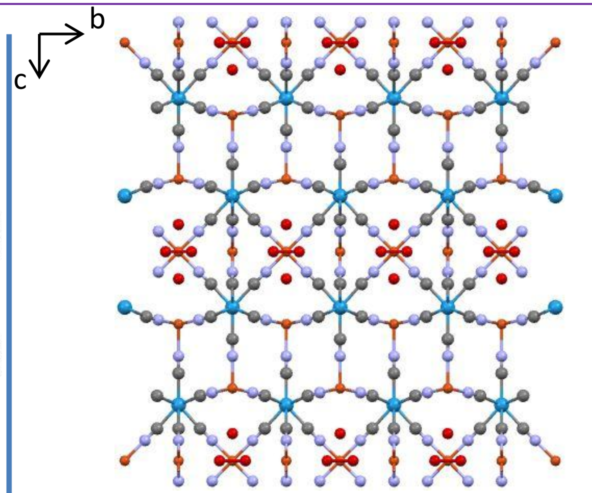
Substancje



Cu4W4
$Cmc2_1$

● W^{V} (S=1/2)
● Cu^{II} (S=1/2)

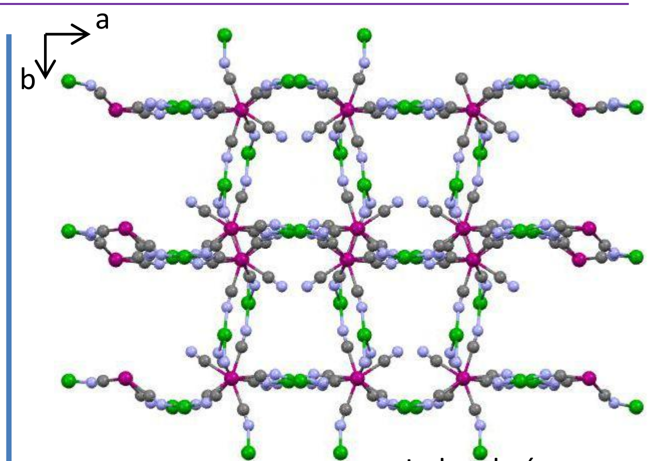
ortorombowa
a = 7.3792(6) Å
b = 32.096(2) Å
c = 7.0160(6) Å



Cu7W4
I4/mmm

● W^{V} (S=1/2)
● Cu^{II} (S=1/2)

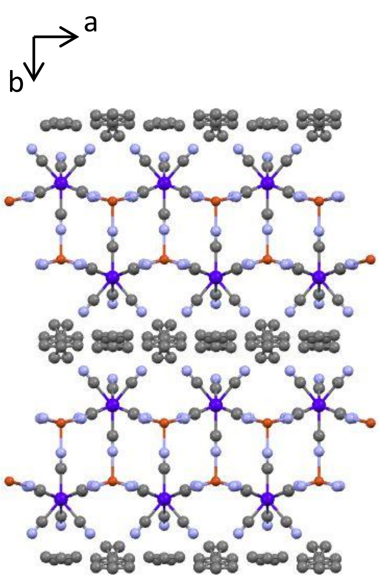
Tetragonalna
a = 7.22858(9) Å
b = 7.22858(9) Å
c = 28.282(5) Å



Mn2Nb
$P2_1/c$

● Mn^{V} (S=5/2)
● Nb^{IV} (S=1/2)

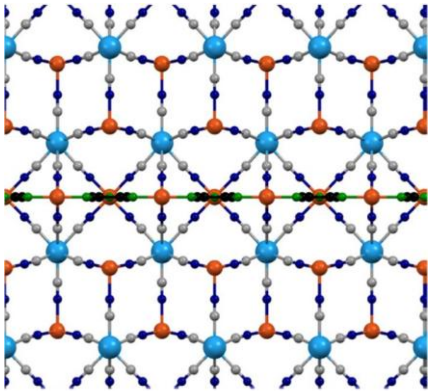
Jednoskośna
a = 10.6052(1) Å
b = 15.5751(2) Å
c = 14.3869(2) Å
β = 108.285(1) °



Cu3Mo3
$Cmc2_1$

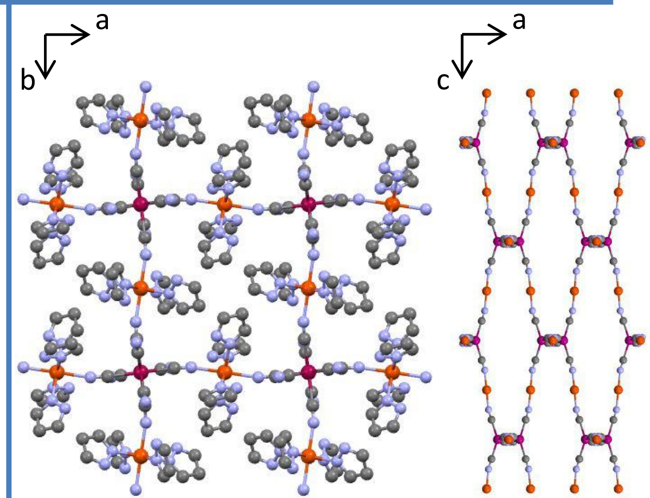
● Mo^{V} (S=1/2)
● Cu^{II} (S=1/2)

Ortorombowa
a = 7.340(15) Å
b = 31.667(5) Å
c = 7.0119(15) Å



Cu3W2

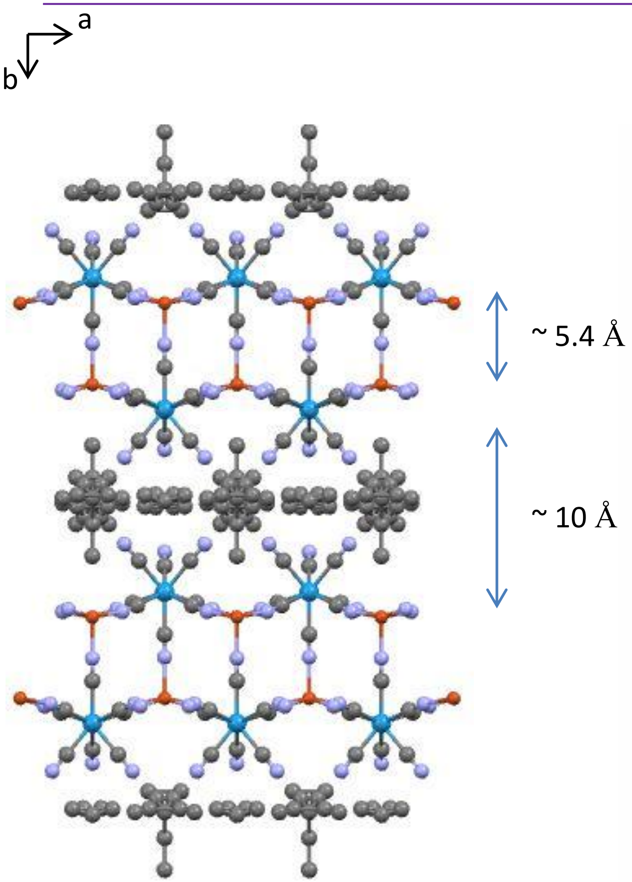
● W^{V} (S=1/2)
● Cu^{II} (S=1/2)



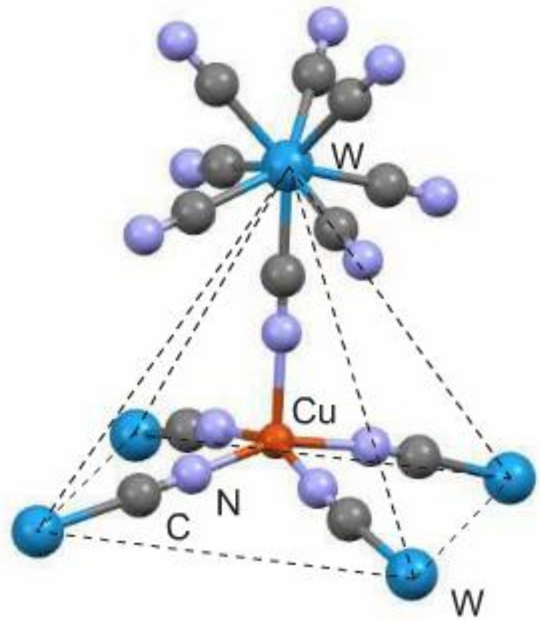
Fe2Nb
$I4_1/a$

● Fe^{II} (S=2)
● Nb^{IV} (S=1/2)

Tetragonalna
a=b = 21.659(5) Å
c = 9.618(5) Å



$\{(tetrenH_5)_{0.8}Cu^{II}_4[W^V(CN)_8]_4 \cdot 7H_2O\}_n$

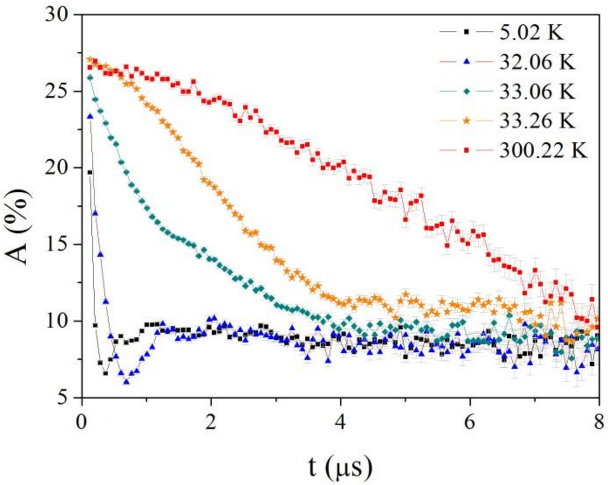


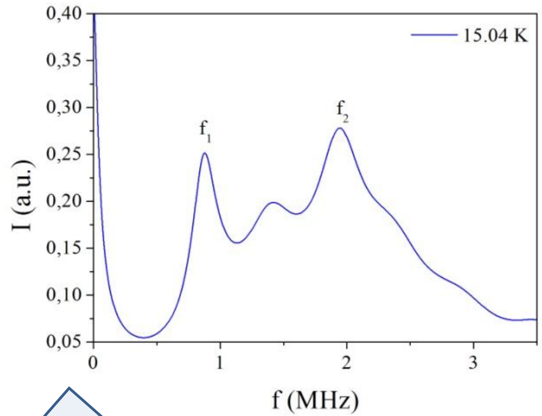
ortorombowa
a = 7.3792(6) Å
b = 32.096(2) Å
c = 7.0160(6) Å

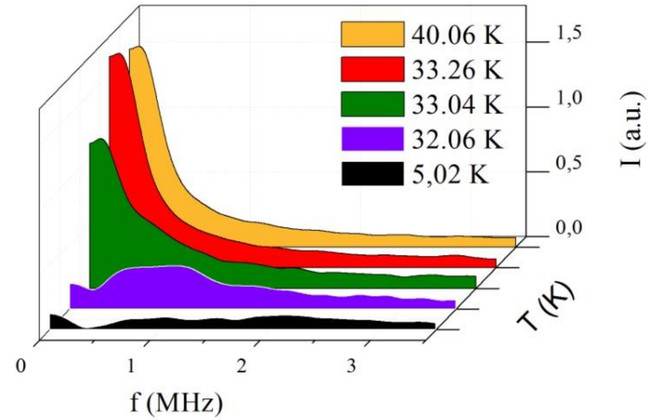
ISIS-RAL
MuSR,
m ≈ 1 g; polikrystaliczna
ZF 5-300 K
LF 0-200 G

● W^V (S=1/2)
● Cu^{II} (S=1/2)

Cu4W4 ZF



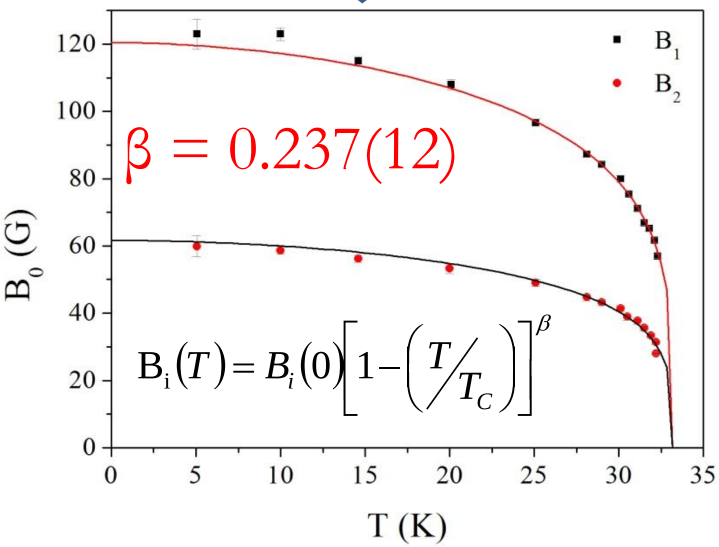


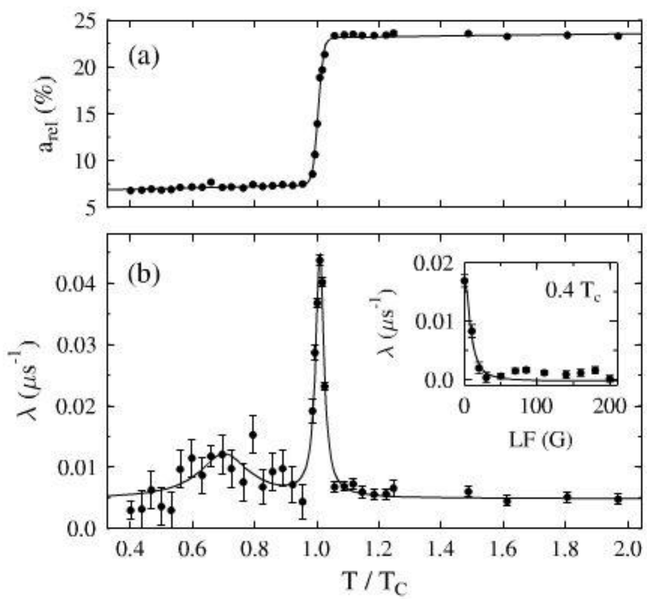


$$A(t) = A_1 \cos(\omega_1 t) e^{-\lambda_1 t} + A_2 \cos(\omega_2 t) e^{-\lambda_2 t}$$

$$\omega_i = \gamma_\mu B_0$$

$$T_C = 33.16(1)\ K$$





$$A(t) = a_{rel} e^{-\lambda t} \quad T < T_C$$

$$A(t) = a_{rel} e^{-\lambda t} P_Z^{KT}(\Delta, B, t) \quad T > T_C$$

$$\lambda = \frac{2\Delta^2 \tau}{1 + (\gamma_\mu B_{LF} \tau)^2}$$

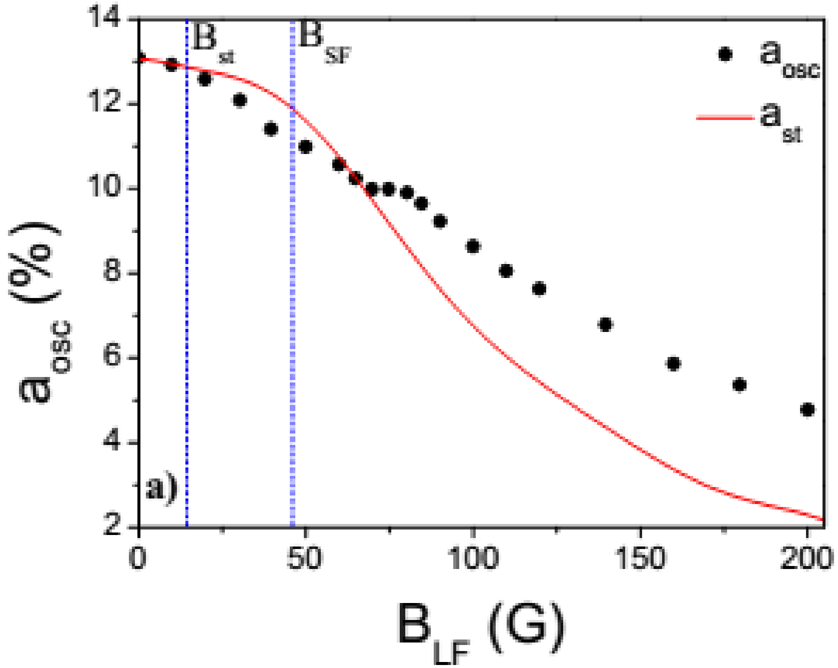
$\beta = 0.231$ 2DXY

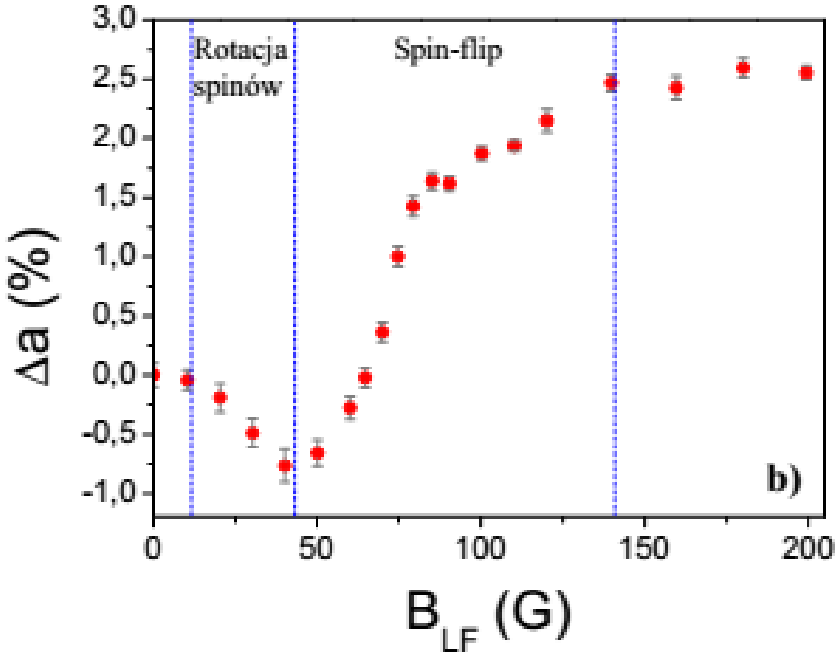
Cu4W4 LF

Obserwacja reorientacji spinów pod wpływem zewnętrznego pola magnetycznego
T = 14 K, $B_{LF} \in (0 , 200)$ G

$$a_{st}(B_{LF}) = A_1 A_{osc}\left(\frac{B_{LF}}{B_1}\right) + A_2 A_{osc}\left(\frac{B_{LF}}{B_2}\right)$$

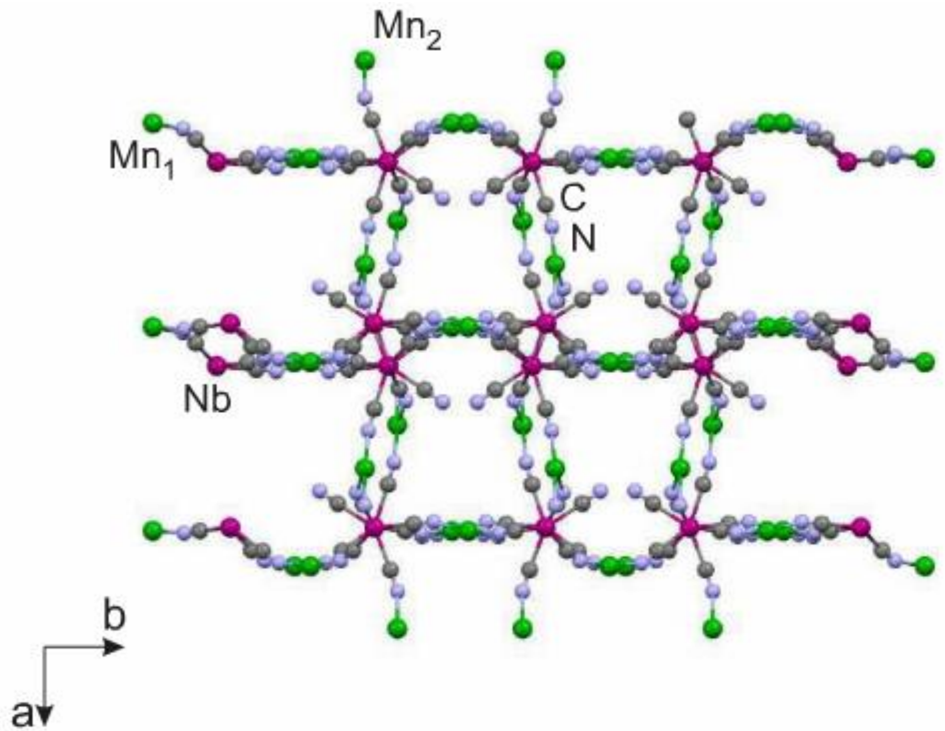
$$\Delta a = a_{osc} - a_{st}$$

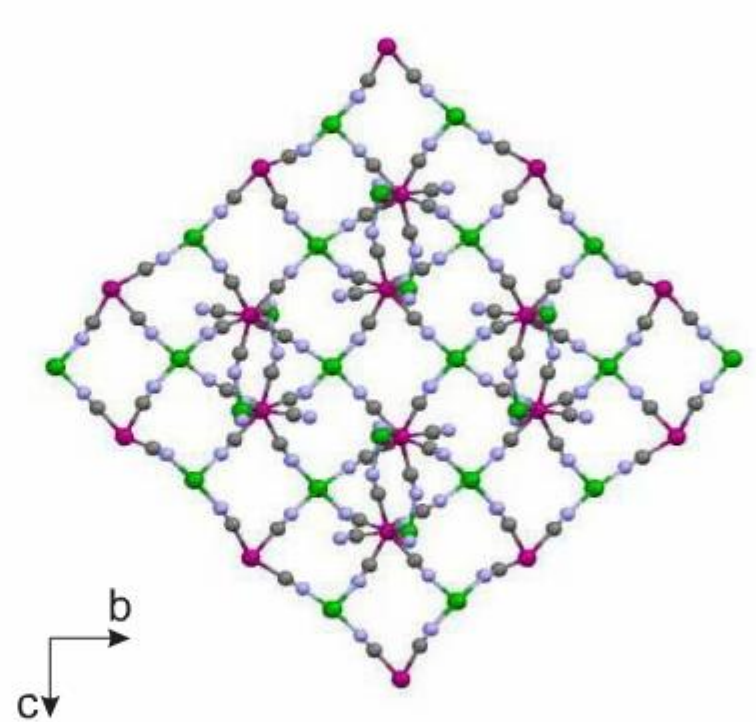




Pierwsza obserwacja przejścia metamagnetycznego metodą μSR

$\{[Mn^{II}(pirydazyna)(H_2O)_2][Mn^{II}(H_2O)_2][Nb^{IV}(CN)_8]\cdot 2H_2O\}_n$





$[Nb(CN)_8]^{4-}$

$[Mn(pydz)(H_2O)]^{2+}$

$[Mn(H_2O)]^{2+}$

- Mn^{V} (S=5/2)
- Nb^{IV} (S=1/2)

ISIS-RAL

ARGUS,

m ≈ 0.8 g; polikrystaliczna

ZF

LF 0-3900 G

TF 20 G

T 4,5 -100 K

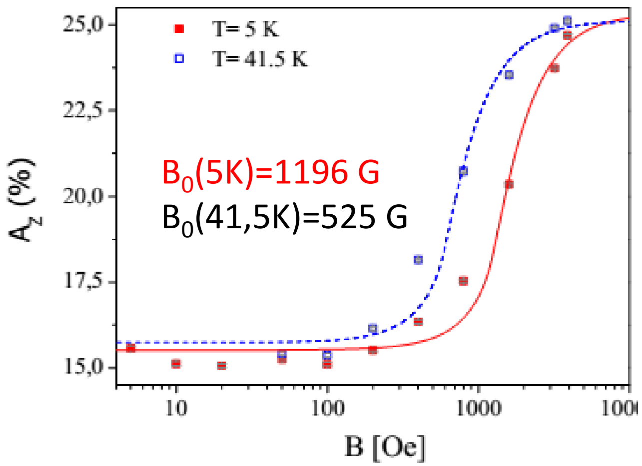
SμS-PSI

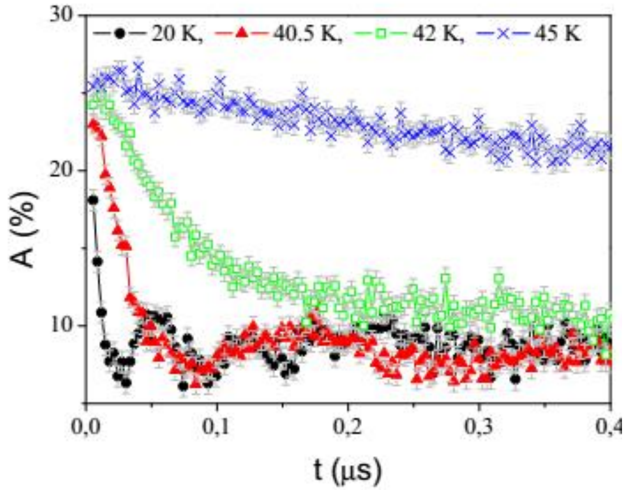
GPS,

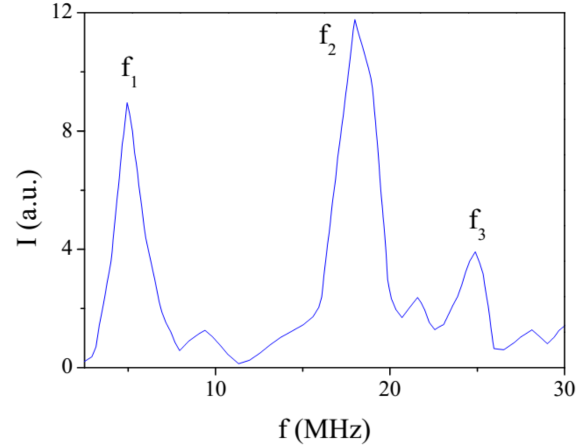
ZF 4.5-70 K

Mn2Nb LF, ZF (ISIS, PSI)

ZF T<Tc

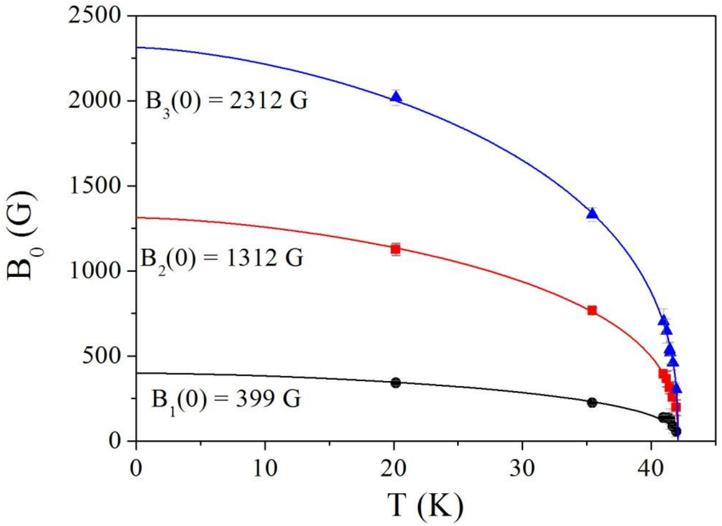






$$A_Z(b) = \frac{3}{4} - \frac{1}{4b^2} + \frac{(b^2-1)^2}{8b^3} log\left|\frac{b+1}{b-1}\right|$$

$$A_{osc}(b) = 1 - A_Z(b), \quad b = \frac{B_{ext}}{B_0}$$



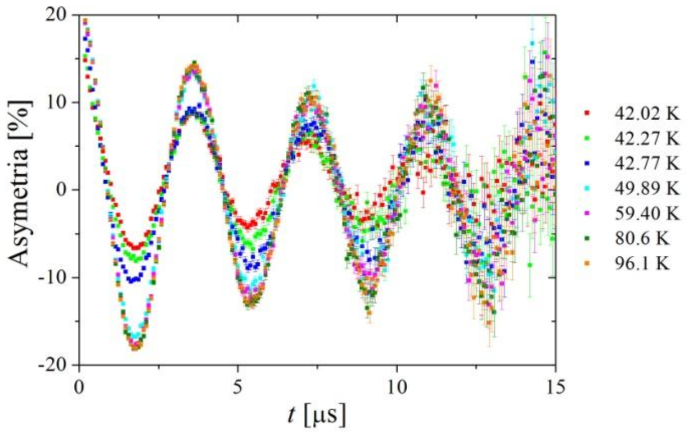
$$B_i(t) = B_i(0)\left[1 - \left(\frac{T}{T_C}\right)\right]^{\beta}$$

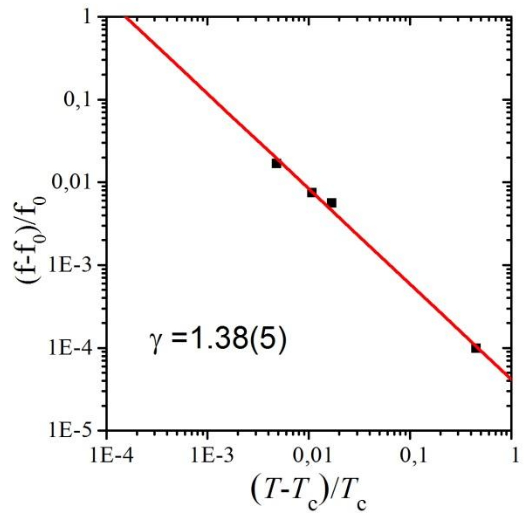
T_C = 42.08(3) K

β = 0.38(1)

Mn2Nb ZF, TF (ISIS, PSI)

TF T>T_C





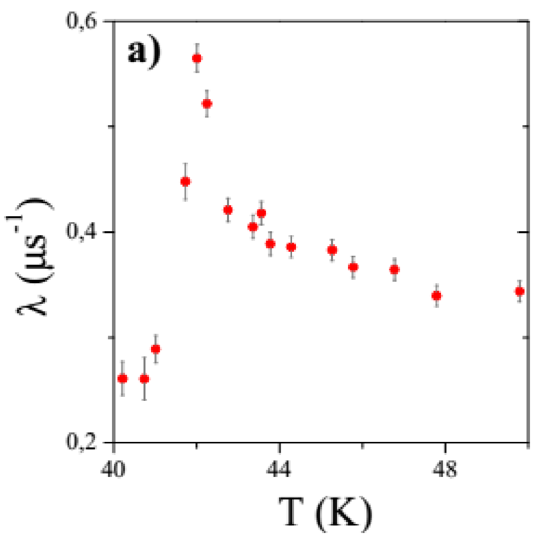
$$\frac{f-f_0}{f_0} \sim \chi(T) \sim \left(\frac{T}{T_C}-1\right)^{-\gamma}$$

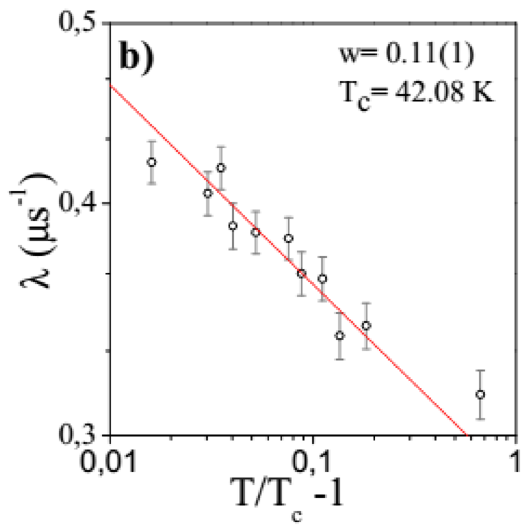
$$f_0 = \frac{\gamma_\mu B_0}{2\pi};\ B_{ind} \sim \chi B_0$$

$$B_{loc} = B_0 + B_{ind}$$

$\gamma = 1.38(5)$

ZF T>T_c



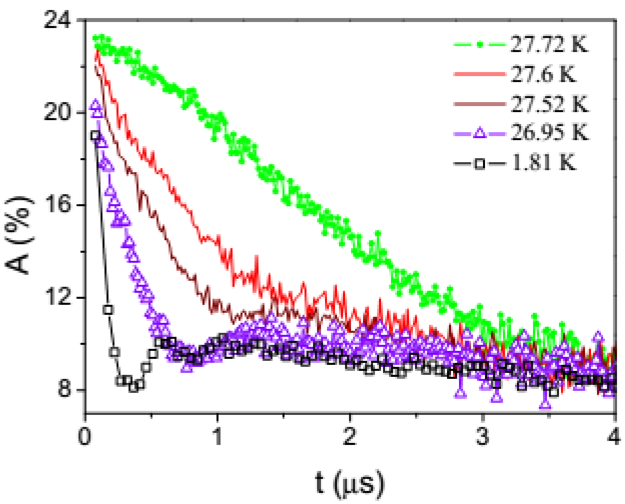


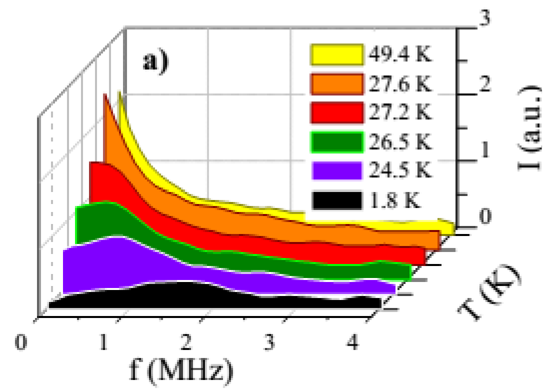
$$\tau \sim \left(\frac{T}{T_C}-1\right)^{-w}$$

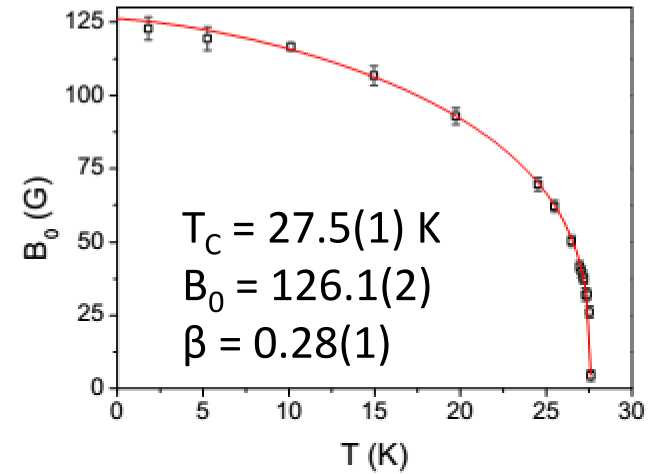
$w = 1.117(8)$

Cu3Mo3 ZF (ISIS)

ZF T<Tc



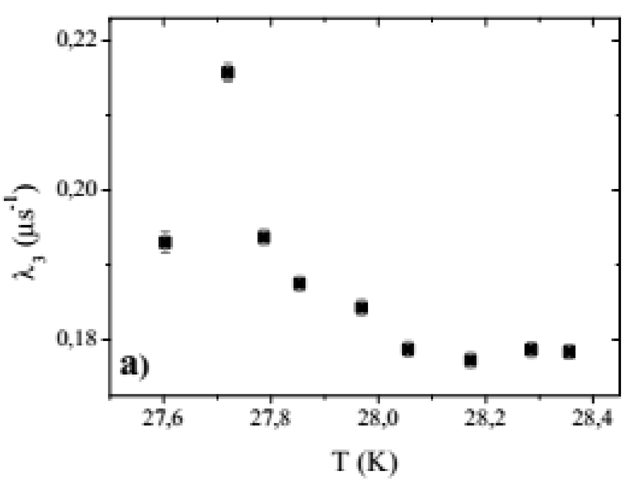


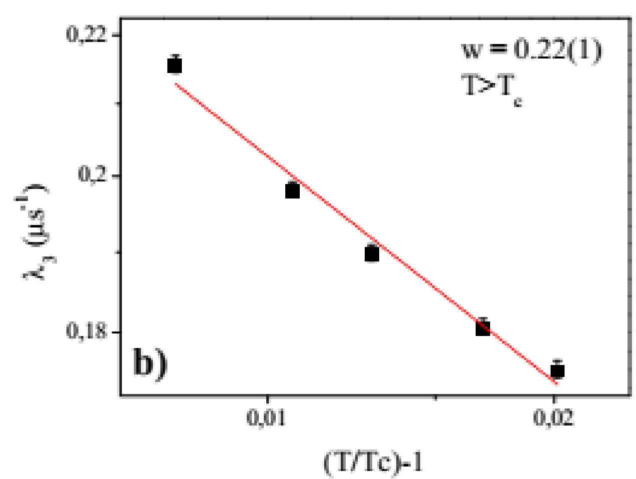


$$B_i(t) = B_i(0)\left[1 - \left(\frac{T}{T_C}\right)\right]^{\beta}$$

$$A(t) = A_1 \cos(\omega t + \phi) e^{-\lambda t}$$

ZF T>Tc

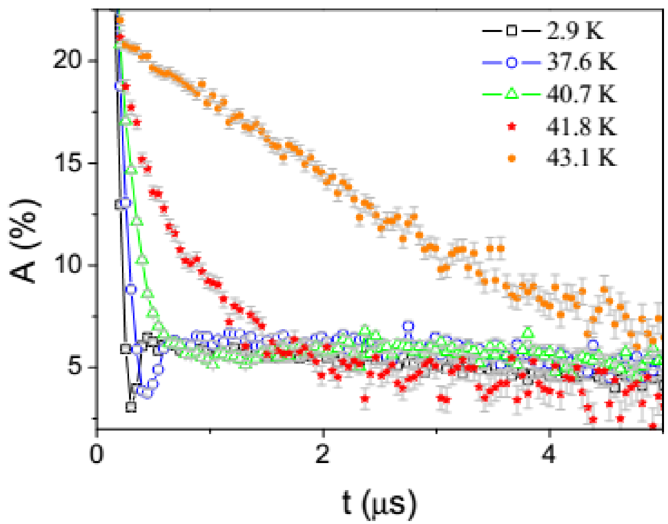


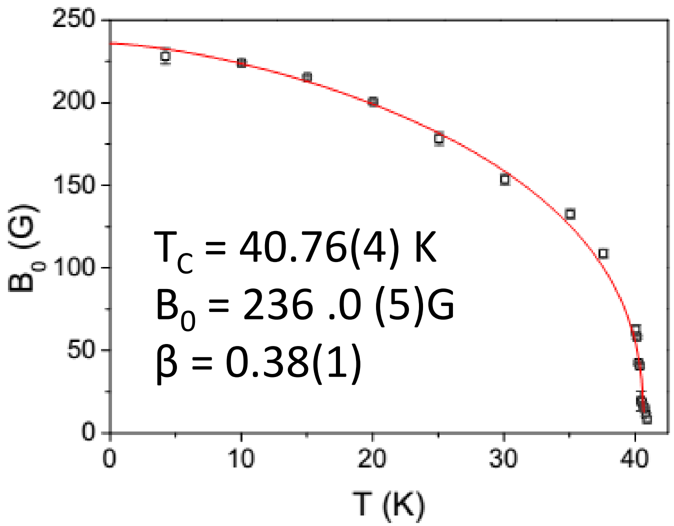


$$A(t) = A_{rel}\, e^{-\lambda_3 t}$$

Cu3W2 ZF, TF (ISIS)

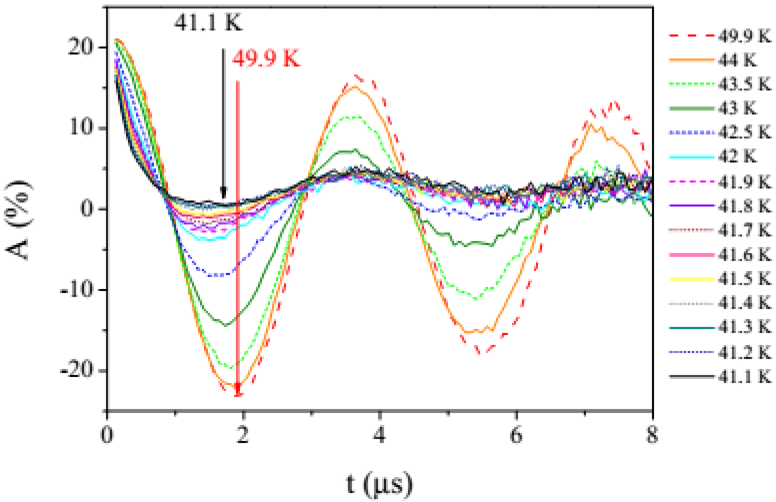
ZF T<Tc



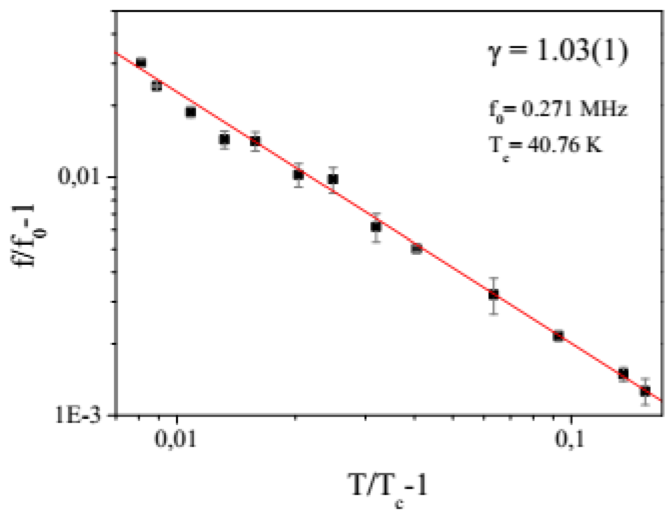


$$A(t) = A_1 \cos(\omega t + \phi) e^{-\lambda t}$$

TF T>Tc



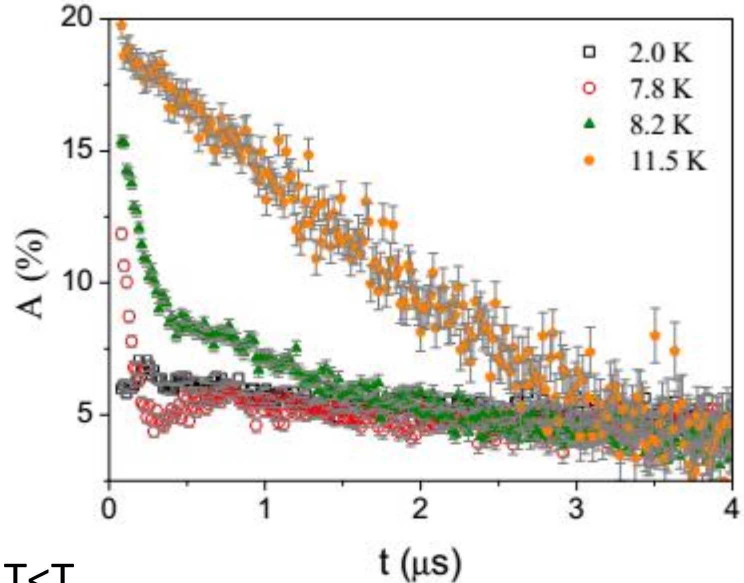
$$\frac{f - f_0}{f_0} \sim \chi(T) \sim \left(\frac{T}{T_C} - 1\right)^{-\gamma}$$

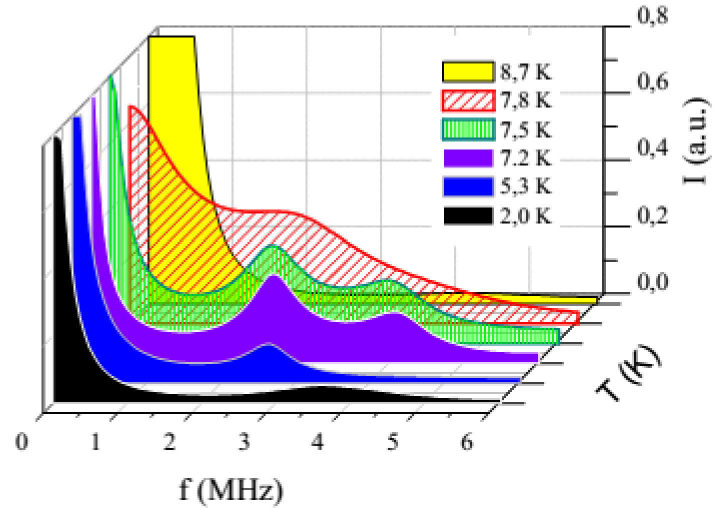


$$f_0 = \frac{\gamma_\mu B_0}{2\pi}; \; B_{ind} \sim \chi B_0$$

$$B_{loc} = B_0 + B_{ind}$$

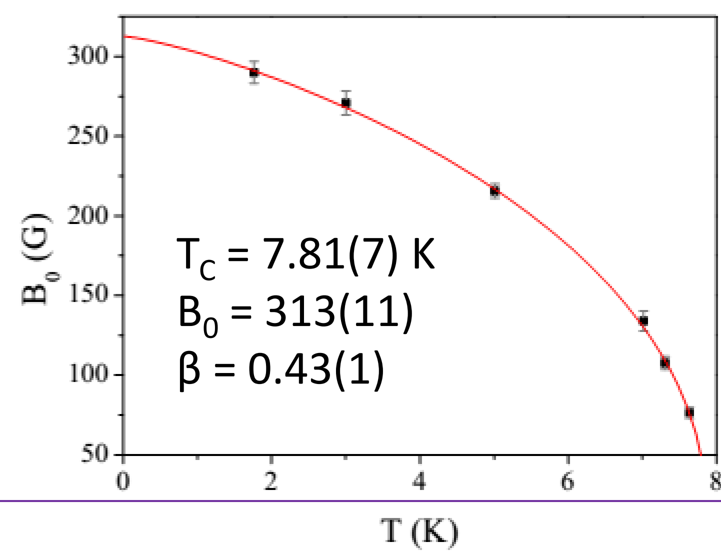
Fe2Nb ZF





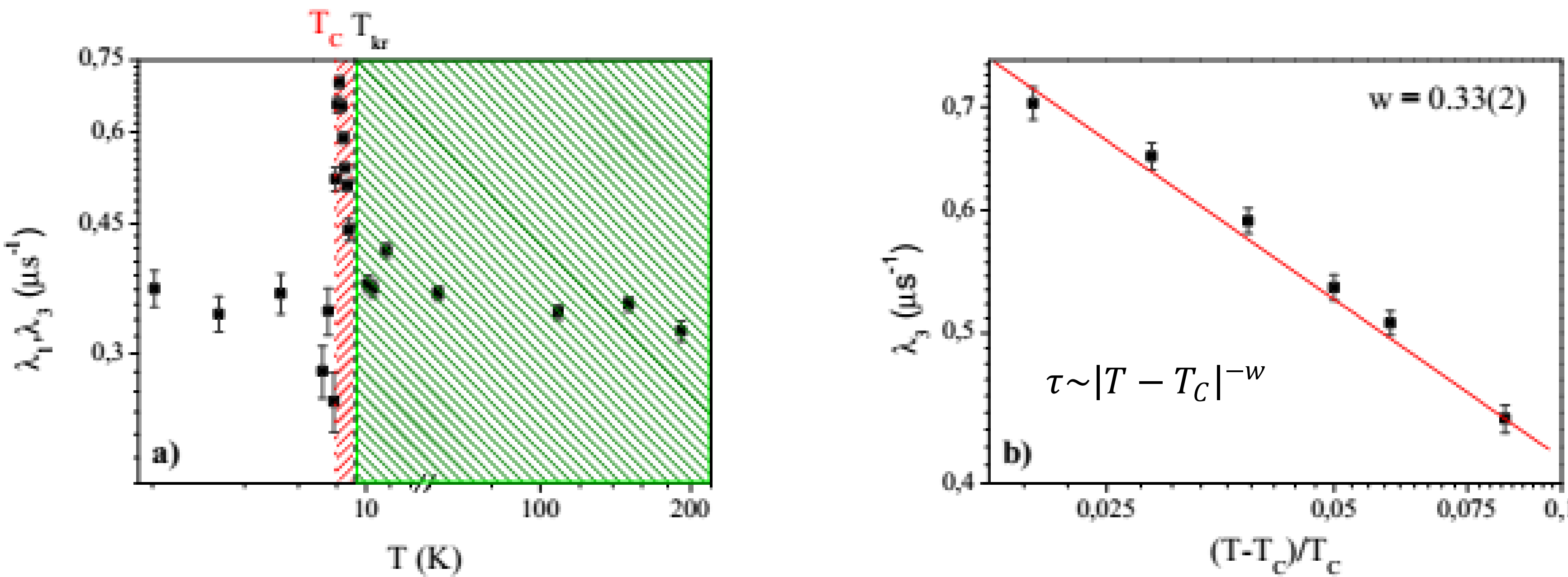
$T<T_C$

$$A(t) = A_{rel}\left(\frac{1}{3}exp(-\lambda_1 t) + \frac{2}{3}exp(-\lambda_2 t)\cos(\gamma_\mu Bt + \phi)\right)$$



T>T_C

$A(t) = A_{rel}\, exp(-\lambda_3 t)$ $\lambda_3 \sim (\Delta B_{loc})^2 \tau$



Rysunek 8.27: a) Tempa relaksacji spinu mionów poniżej (λ_1) i powyżej (λ_3) temperatury porządkowania momoentów magnetycznych (T_c) dla próbki Fe2Nb. Widoczne są dwa obszary wartości λ_3 wiązane odpowiednio ze słabą ($T_c < T < T_{kr}$) lub silną ($T > T_{kr}$) dynamiką momentów magnetycznych; b) Zależność λ_3 od temperatury zredukowanej w skali podwójnie logarytmicznej. Na podstawie dopasowania reprezentowanego na wykresie linią ciągła wyznaczono wartość wykładnika $w = 0.33(2)$.

Poniżej T_C istnieje faza o ferrimagnetycznym, dalekozasięgowym uporządkowaniu spinów

Substancja	T_C (K)	B_0 (G)	β	γ	w	Model
Cu4W4	33.16	121 61.7	0.237	-	-	2D XY BKT
Cu7W4	39.86	294	0.373	-	-	3D HSB
Mn2Nb	42.08	399 1312 2312	0.38	1.38	0.11	3D HSB
Cu3Mo3	27.5	293.5	0.28	-	0.22	3D Chiral/NK
Cu3W2	40.76	236	0.38	1.03	-	3D HSB/2D NK/MF ?
Fe2Nb	7.81	313	0.43	-	0.33	3D HSB AF

1. Wykonano 8 eksperymentów mionowych przy źródłach (ISIS, SμS), łącząc pomiary ZF, LF, TF, dla 6 magnetyków molekularnych.
2. Wyznaczono temperatury krytyczne
3. Zbadano temperaturowe zależności wewnętrznych pól magnetycznych.
4. Wyznaczono wartości parametrów krytycznych β, γ, w
5. Cu4W4 – potwierdzenie przejścia BKT (2D XY) oraz pierwsza obserwacja przejścia metamagnetycznego metodą μSR

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Dziękuję za uwagę