3rd Neutron Muon SCHOOL

2018 Nov 21

Muon Spin Rotation/Relaxation/Resonance (μSR)

Wataru HIGEMOTO[1,2,3]

higemoto.wataru@jaea.go.jp

1,Japan Atomic Energy Agency, Advanced Science Research Center
2,J-PARC Center
3,Department of Physics, Tokyo Institute of Technology

Contents

What is muon?

Material research by using positive muon

Property of Muon

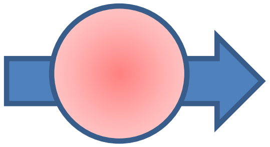
Elementary particle Lapton same family with electron $\pi^+ \longrightarrow \mu^+ + \nu_\mu$

Charge: -e (μ^-), +e(μ^+) ⇔Neutron

Mass: m_μ= 105.658 MeV/c^2

=207 m_e Heavy Positron (Electron)

= 1/9 m_p Light Proton



Spin : s= ½

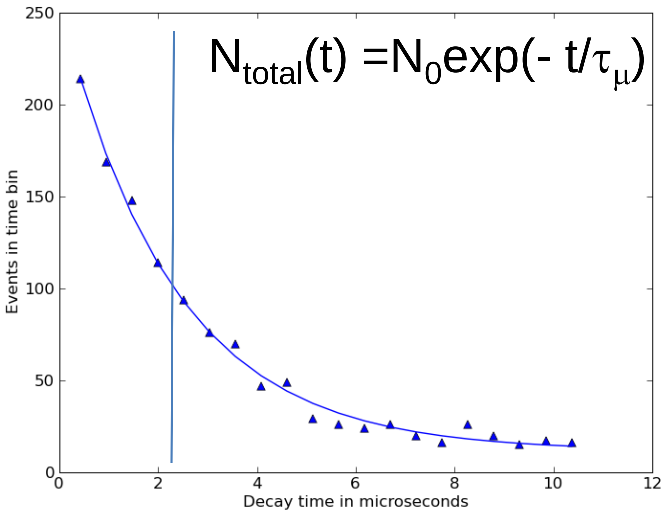
Magnetic moment: $\mu_\mu = 3.18\ \mu_p$

Gyromagnetic ratio: γ_μ=2πx13.55kHz/G

Rotate 35degree in 10 μs under 1G

Mean Life time: τ_μ= 2.19714 μs

$$\mu^+ \longrightarrow e^+ + \nu_e + \overline{\nu_\mu}$$



Cosmic-ray muon

Very High energy,

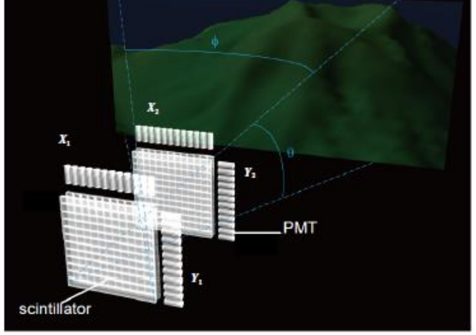
Low flux,

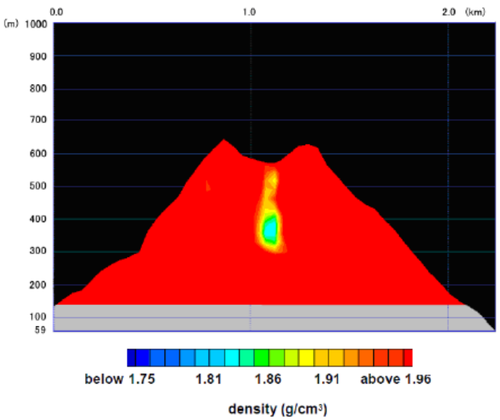
Highly energy distribution

→ Difficult to investigate a material

Taking Several weeks/one data

Huge amount of sample





Tanaka et al.,
Earth Planets Space, ***62*, *119–129*, *2010***

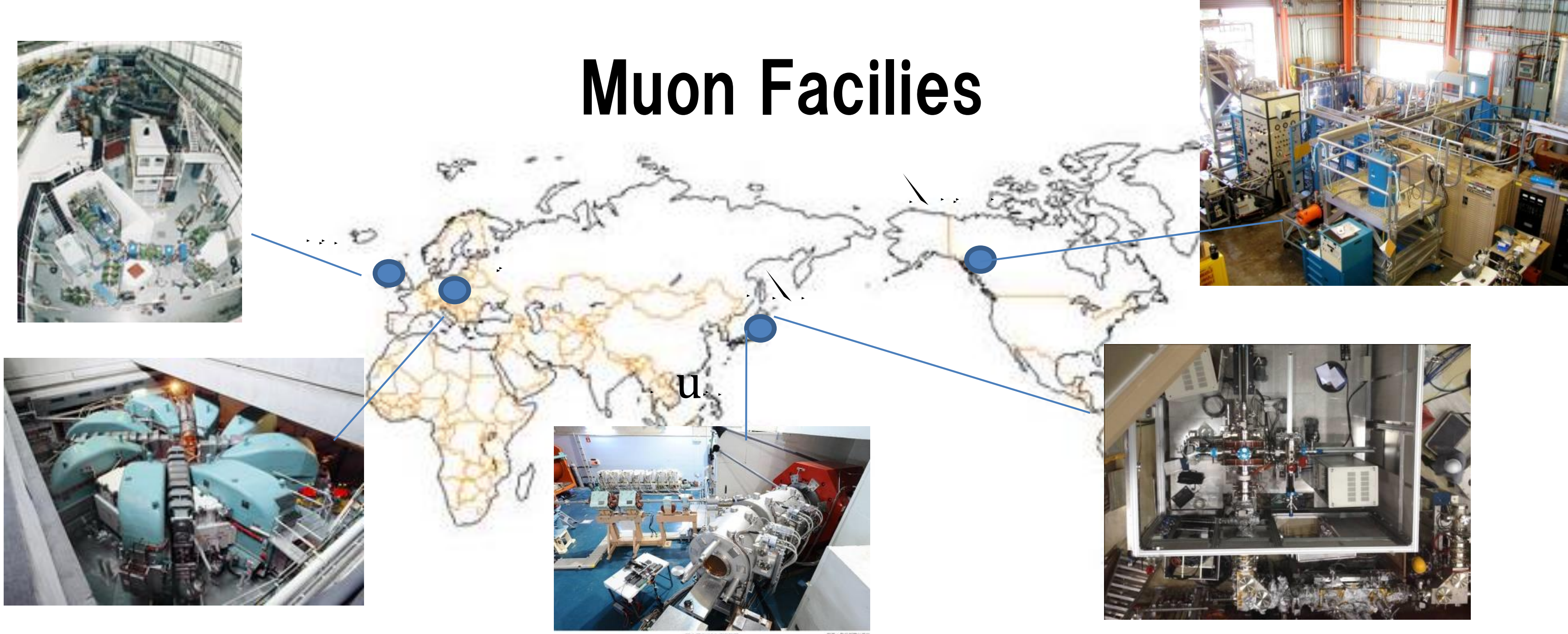
Usually μSR measurement use 10^6-10^9 muons/1data to obtain enough accuracy

→Accelerator is definitely required (ex J-PARC 10^7muons/s)

μSR (Muon Spin Rotation/Relaxation/Resonance)

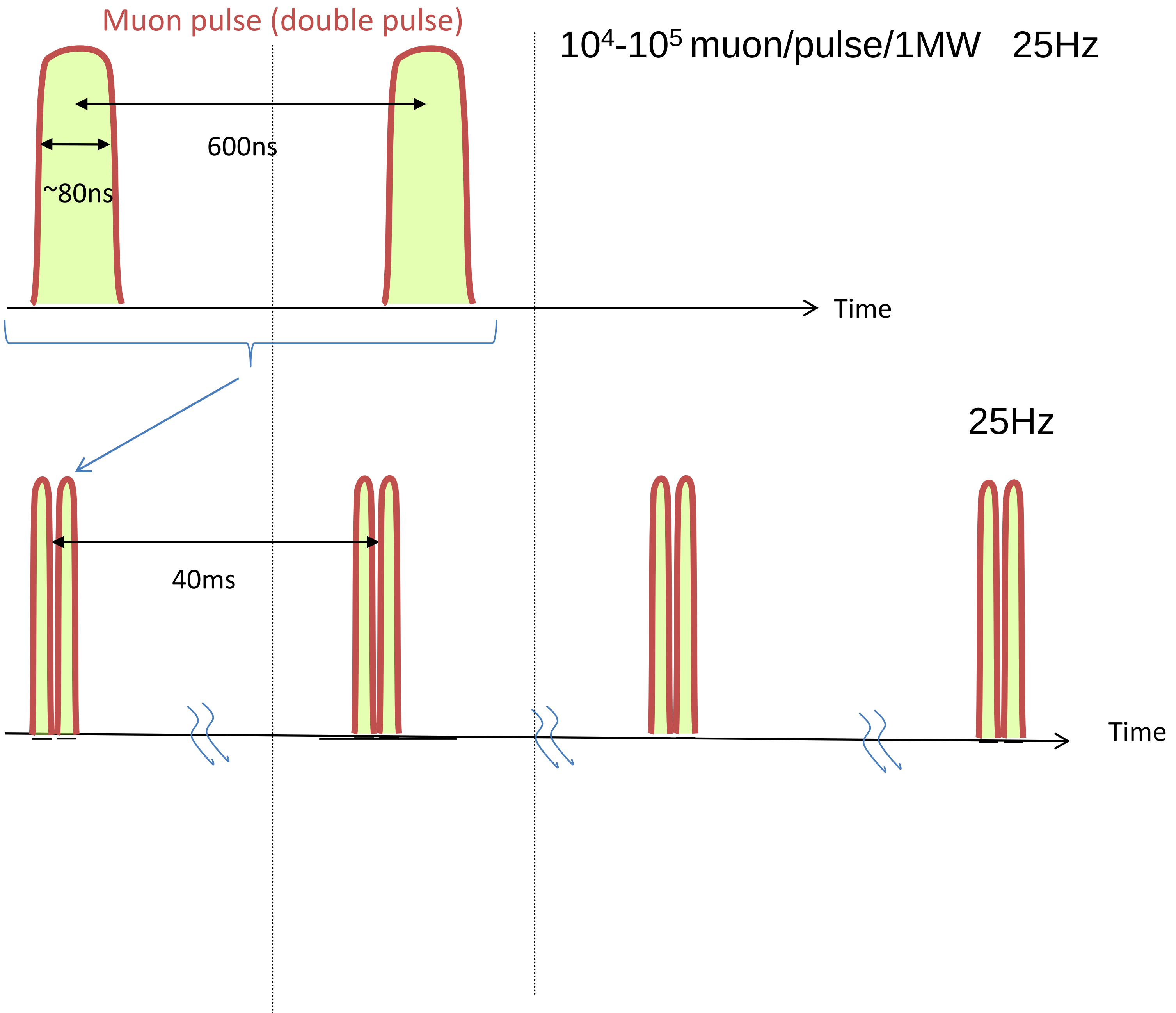
Microscopic measurement ⇔ Bulk measurement (Resistivity, Specific heat etc)

Muon Facilies



	Place	Beam structure	Proton beam energy (MeV)	Proton beam current (μA)	Maximu Muon intensity
TRIUMF	Canada	Continuous	500	150	10^5
RAL (UK, RIKEN)	UK	Pulse	800	300	$2x10^5$
PSI	Switzerland	Continuous	590	2200	10^8
J-PARC	Japan (Tokai)	Pulse	3000	333	10^8
MuSIC	Japan (Osaka)	Continuous	400	1	10^8

Muon Beam at J-PARC



DC(Cyclotron MuSIC) and Pulse(Synchrotron J-PARC)

Pulse

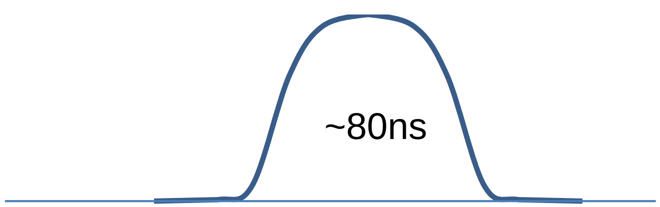
Really high intensity muon is obtained.

Synchronized to pulse (Laser, photo, E-field, B-field,,,)

Muon Pulse width 80ns

Rotation time at 0.1T 70ns/1turn

→ High frequency rotation averaged out



10^4-10^5 muon/pulse/1MW   25Hz

Continuous beam

time resolution → sub-ps order

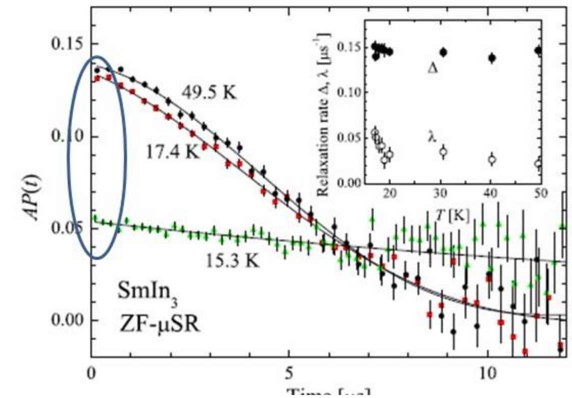
Fast muon spin depolarization

High frequency(field) muon spin rotation are observable.

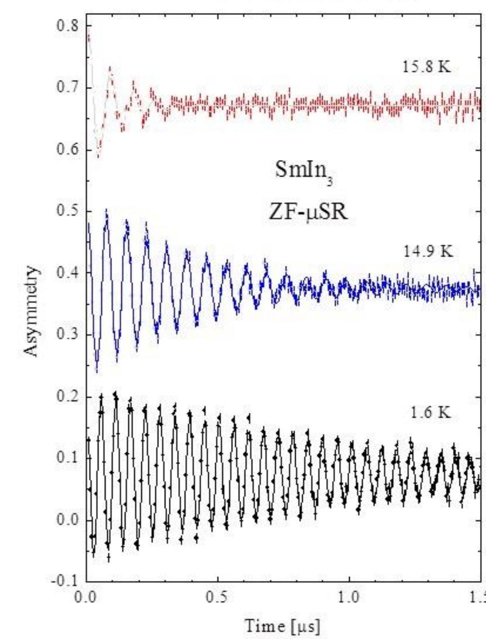
Intensity is limited <10^5/s

Complementary

Pulse muon (J-PARC)



DC muon (PSI)



T.U.Ito, W.Higemoto et al.,
J. Phys. Soc. Jpn. 80 (2011) 033710

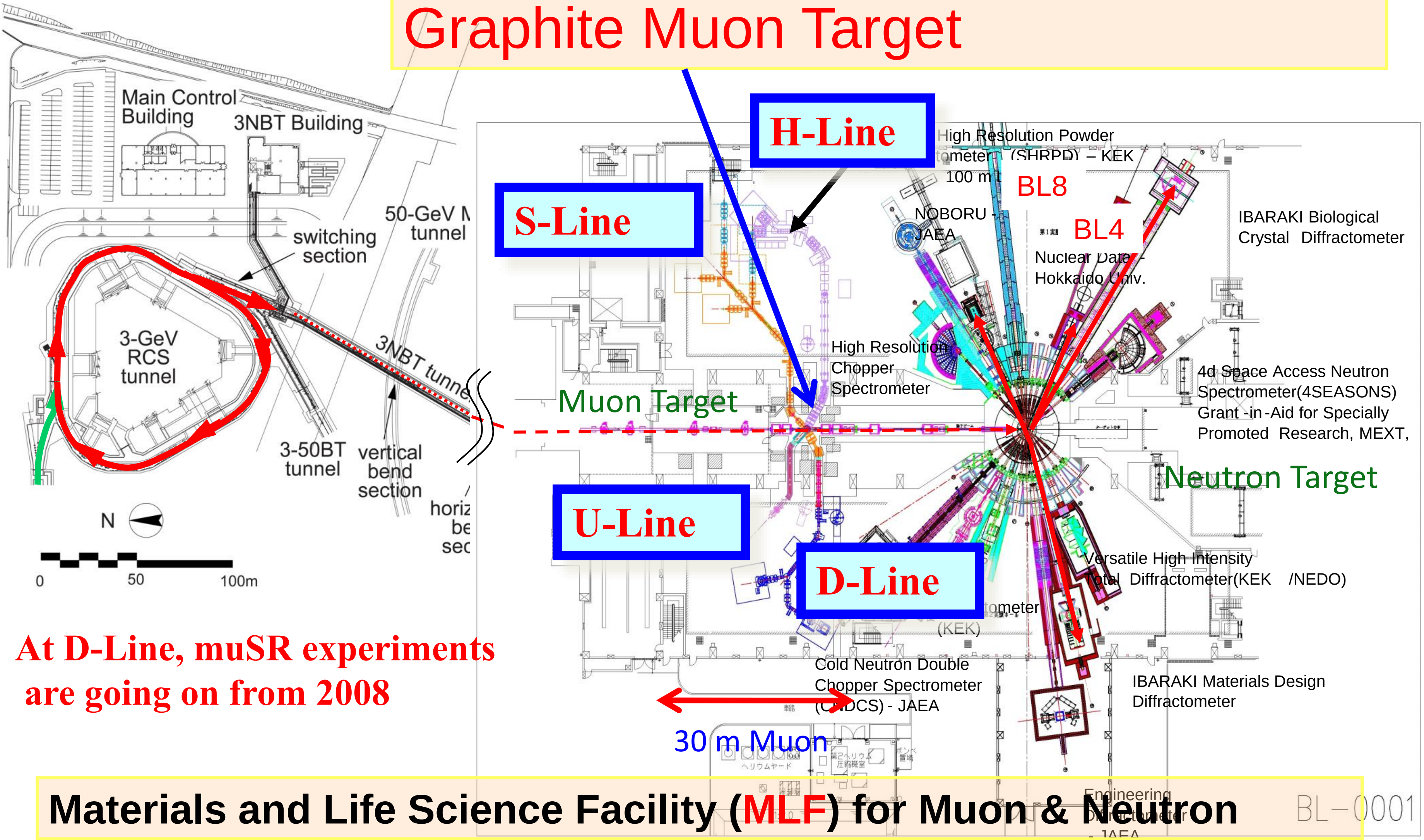
J-PARC(Tokai）


J-PARC 施設
(KEK/JAEA共同)
リニアック
ニュートリノビーム
3 GeVシンクロトロン
メインリング
物質・生命科学実験施設
原子核・素粒子実験施設
(ハドロン実験施設)

Proton Beam Transport from 3GeV RCS to MLF

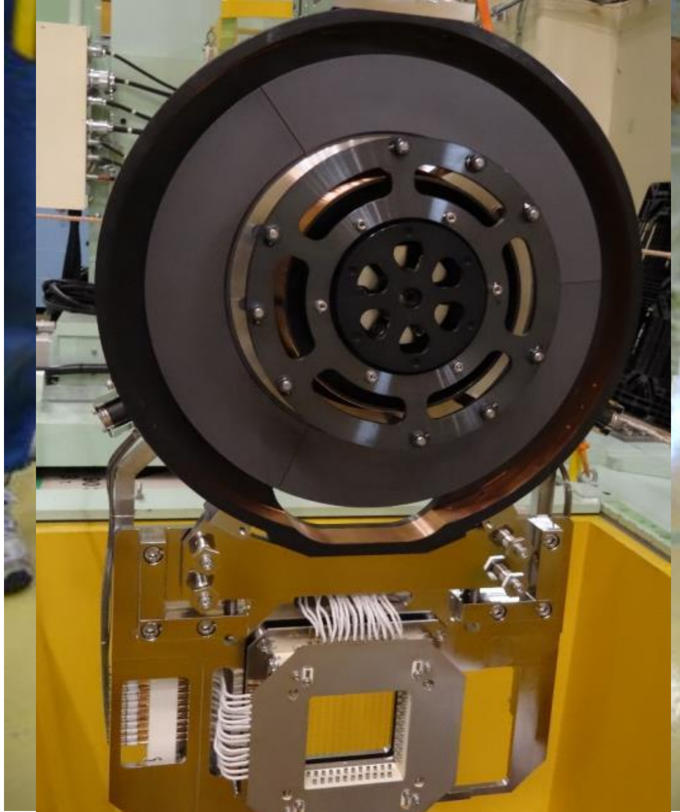
On the way, towards neutron source

Graphite Muon Target



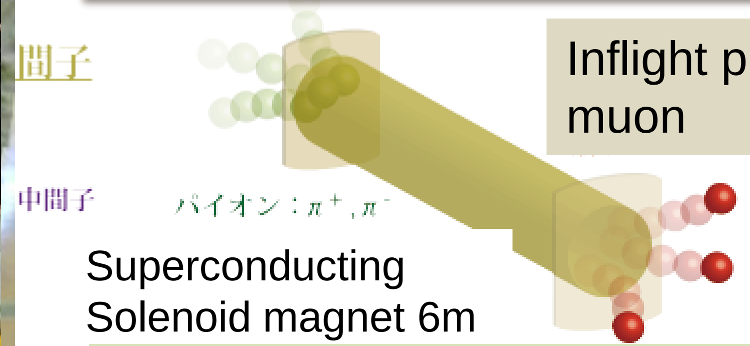
At D-Line, muSR experiments are going on from 2008

Materials and Life Science Facility (MLF) for Muon & Neutron



ミュオンビーム

Decay (Fast) Muon (3-50 MeV)

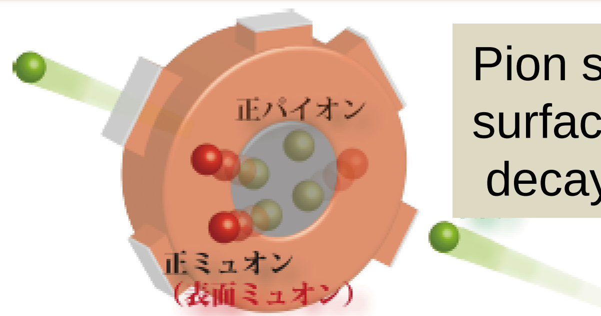


Inflight pion decay to muon

Superconducting Solenoid magnet 6m

Both μ+ and μ- is obtained

Surface (Slow) Muon (4MeV)



Pion stopping at surface of target decay to muon

Low energy μ+ is obtained
Stopping range is less than 1mm
Most of μSR is using 4MeV muon

π is generated by

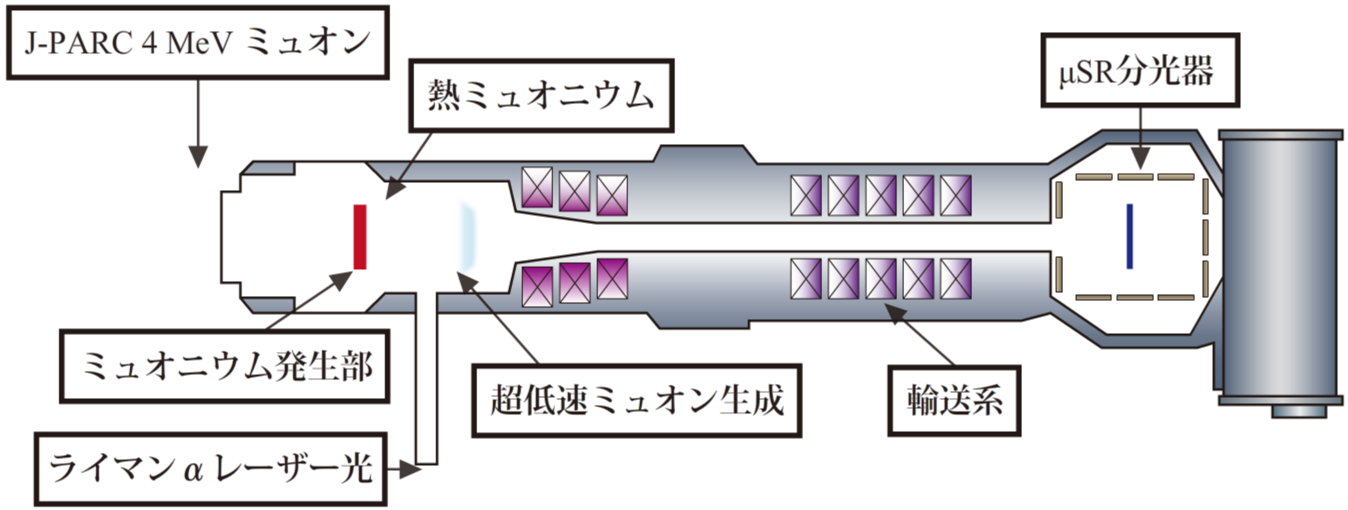
$$p + p \rightarrow p + n + \pi^+$$
$$p + n \rightarrow p + p + \pi^-$$
$$p + n \rightarrow n + n + \pi^+$$
$$n + n \rightarrow p + n + \pi^-$$
$$p + p \rightarrow p + p + \pi^+ + \pi^-$$

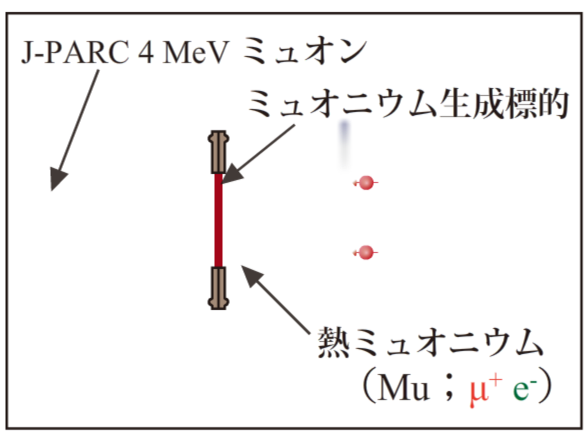
10 - 40 mbarn

閾値エネルギー 280 MeV

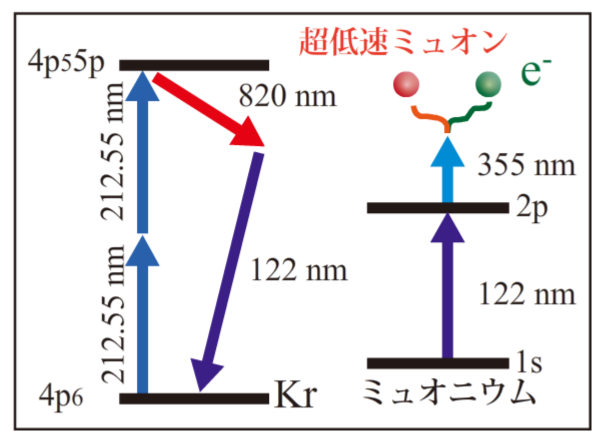
Generation of Ultra slow muon at J-PARC

J−PARC





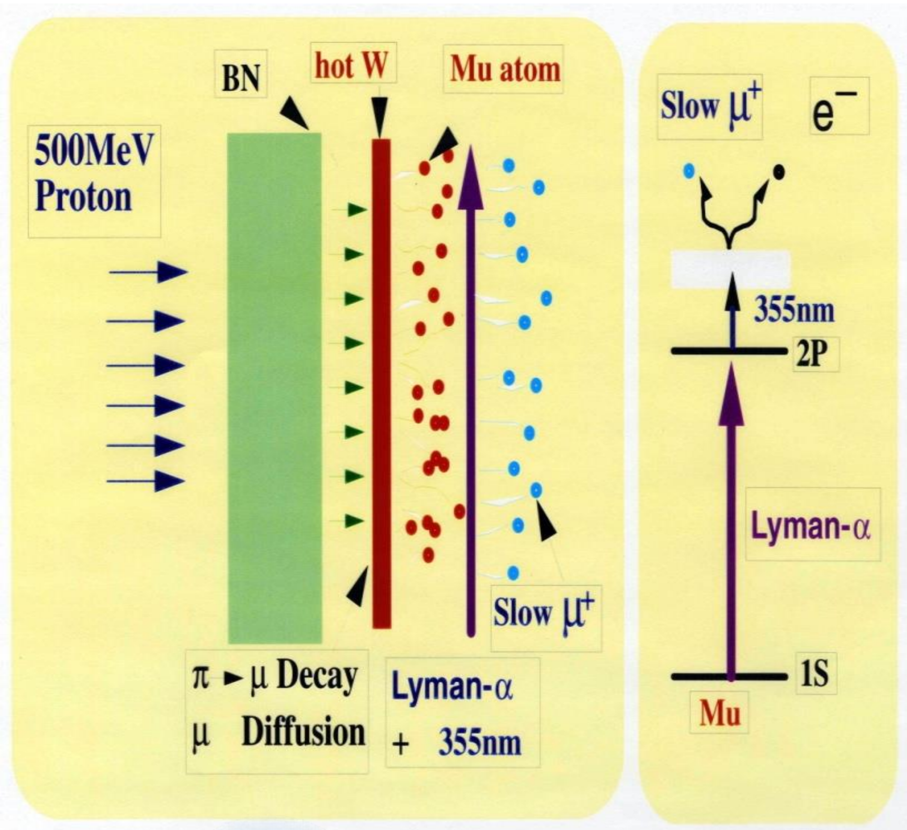
ミュオニウム発生部

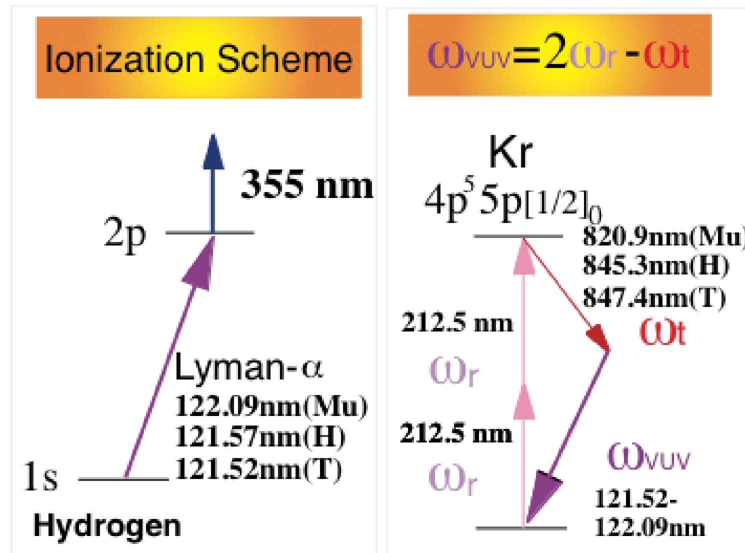


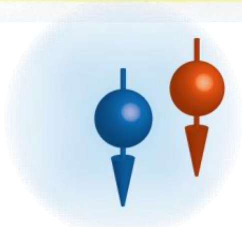
ライマンαレーザー光生成、並びに
ミュオニウムの共鳴イオン化解離法の原理

Pulse muon
and
Pulse laser

Cooling its
Energy
7 order



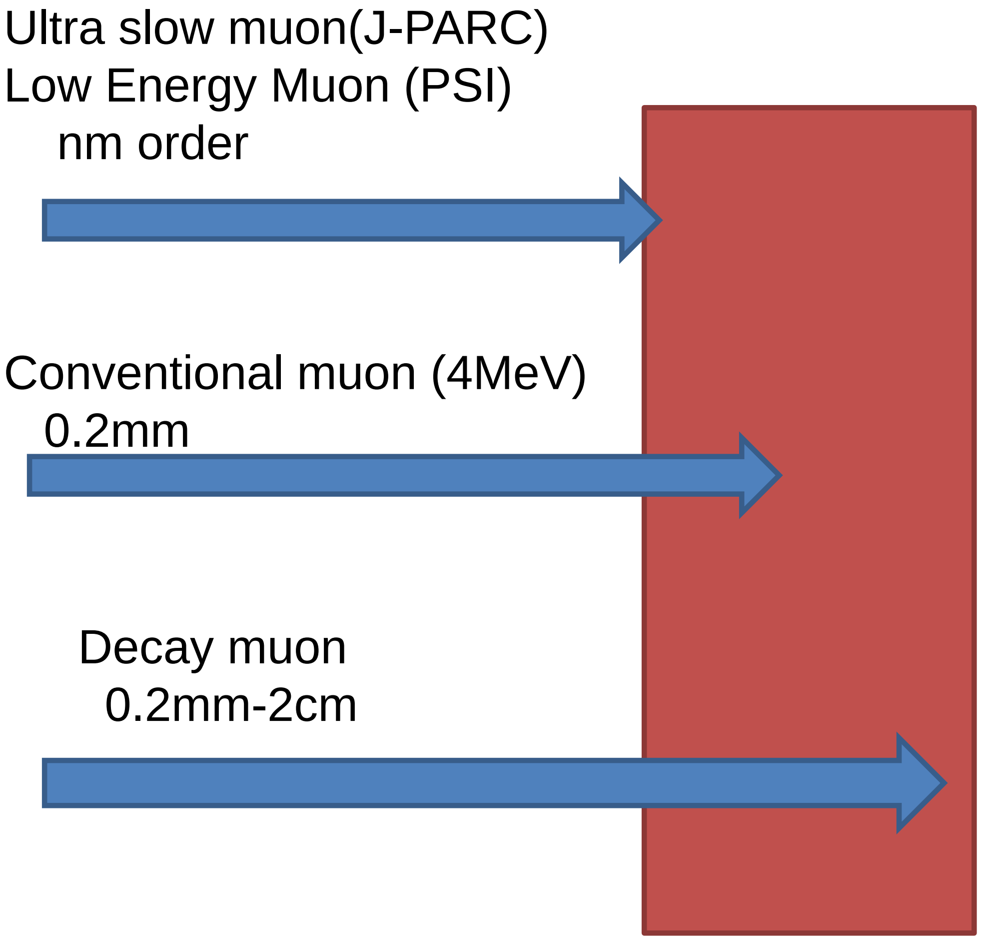




熱エネルギーミュオニウム

μ^+

Implantation Depth

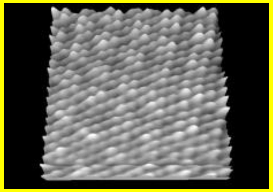


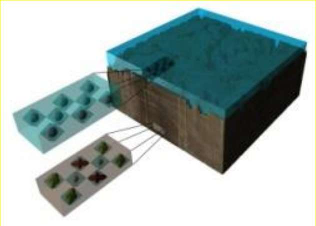
Ultra slow muon research

Ultra slow muon

0.2-200nm

Continuous research from surface to bulk





Surfacestate
Thin film
Buttery
Spintronics
Surface Science

Interface device

Micro beam mSR（Domain, Grain)
micro sample Actinide, DNA ）

Muon obtained by Ordinary technique

Slow muon
0.2mm

Bullk properties of materials

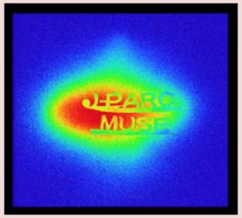
Superconductor

Hydrogen state in semiconductor

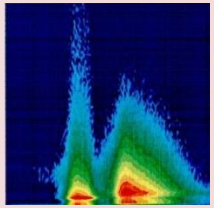
Magnetic materials、
Superconductor、
Hydrogen state
Chemical reactions

High energy muon
0.02-2cm

Bulk and



Muon radiography



Muon catalysis fusion

Elemental analysis

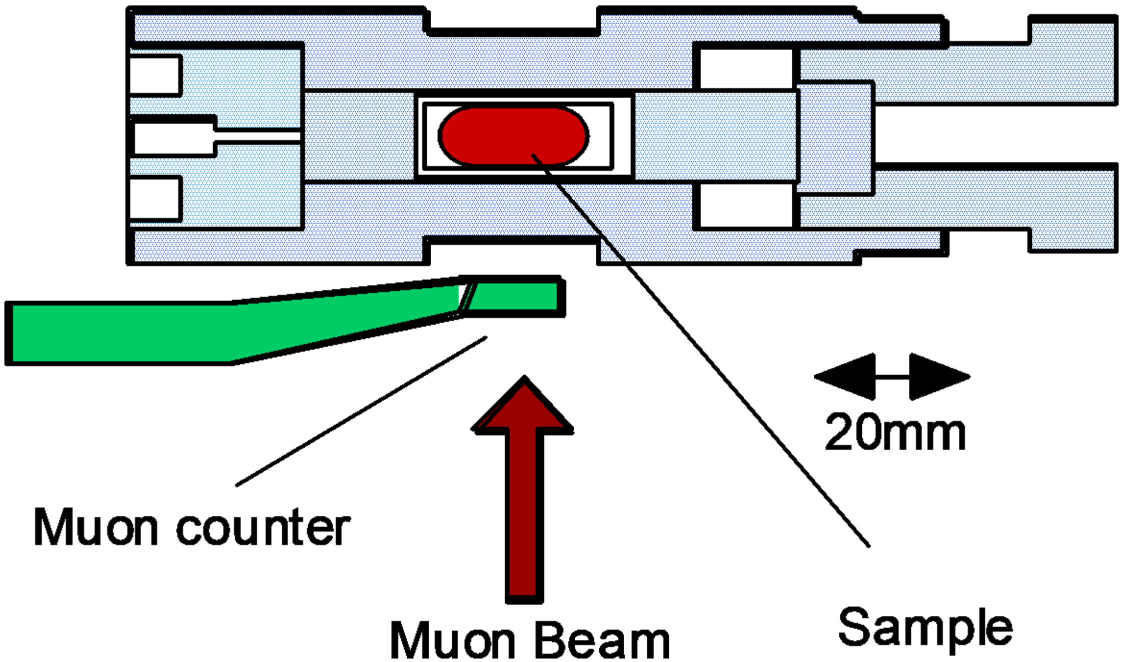
Positive and negative muon
High pressure
Fundamental physics
Muonic Atom

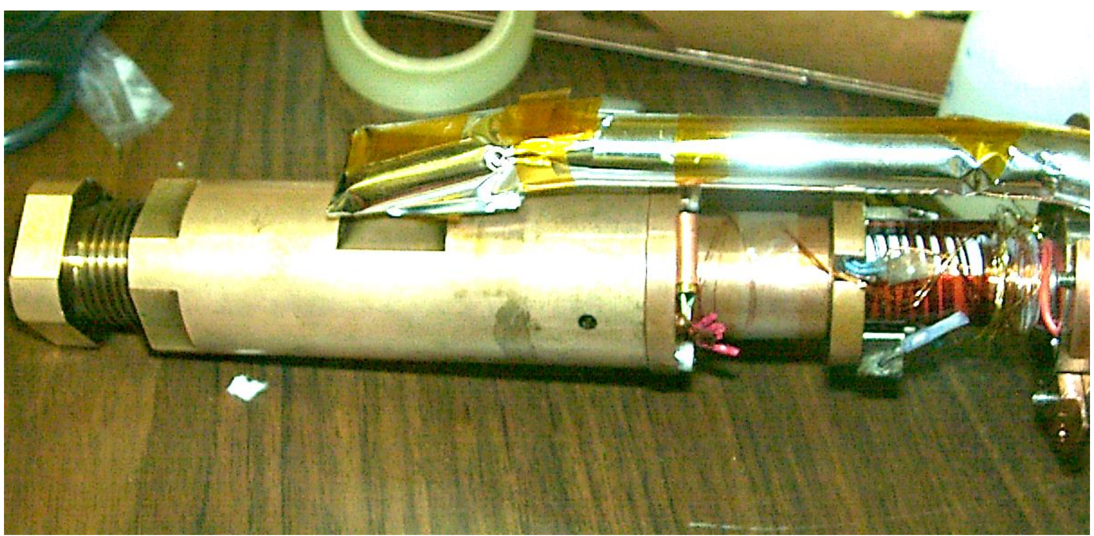
Surfacc to Bulk
USMμSR

顕微機能の付加

Bulk
通常のμSR

Our High Pressure Cell



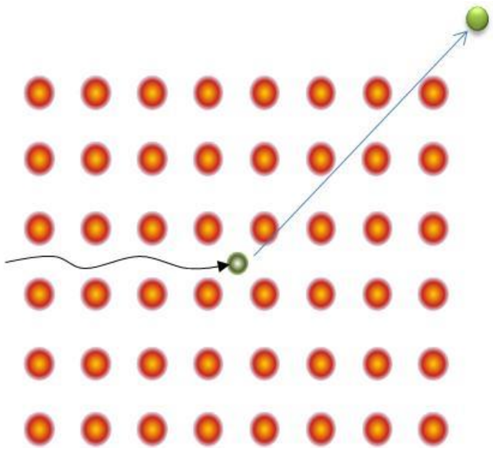


- O-1GPa (at LT)
- Cu-Be or MP35N
- Pressure Medium
  Flourinate
  Daphne 7373

Material Research
by using positive muon

Muon,Neutron and Positron in a matter

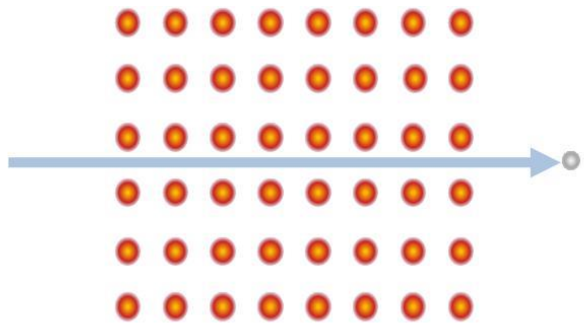
Muon



Interstitial site
chemical bond,
Muonium formation,

Detection → Positron
(Muon decay positron)
(High energy)

Neutron, Photon

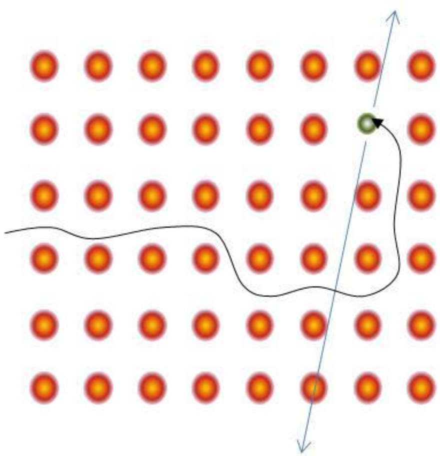


Penetrate whole crystal
(Average)

Diffraction

Detection
→Neutron（Photon) itself

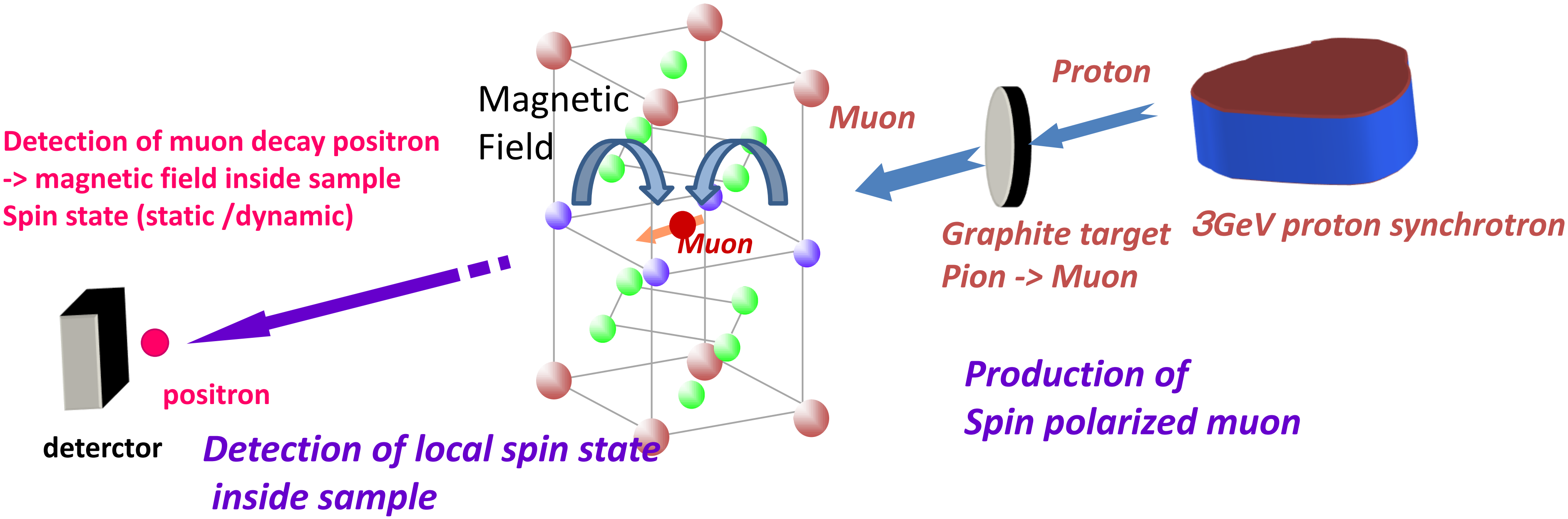
Positron

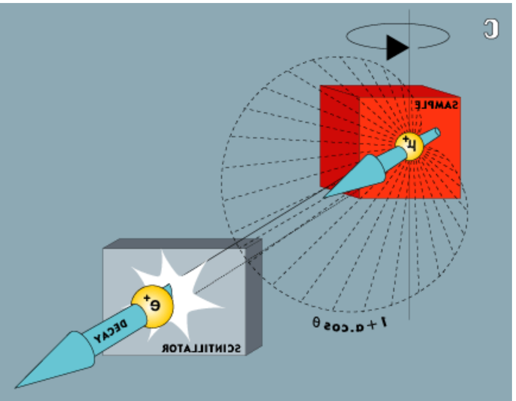


Selectively stop at **defect**

Detection→ photon
(pair annihilation γ-ray)

Muon spin rotation/relaxation (μSR) technique





Observation of local magnetic field with high sensitivity

↓

Detection of spin related phenomena inside sample.

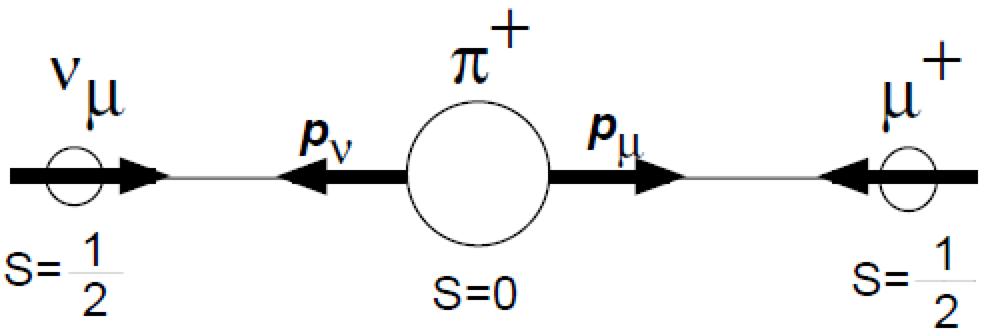
Two imoprtant principal

- 100% Spin Polarized muon

- Muon decay positron is preferencially emitted to muon spin direction

Generation of Spin Polarized muon

$$\pi^+ \longrightarrow \mu^+ + \nu_\mu$$



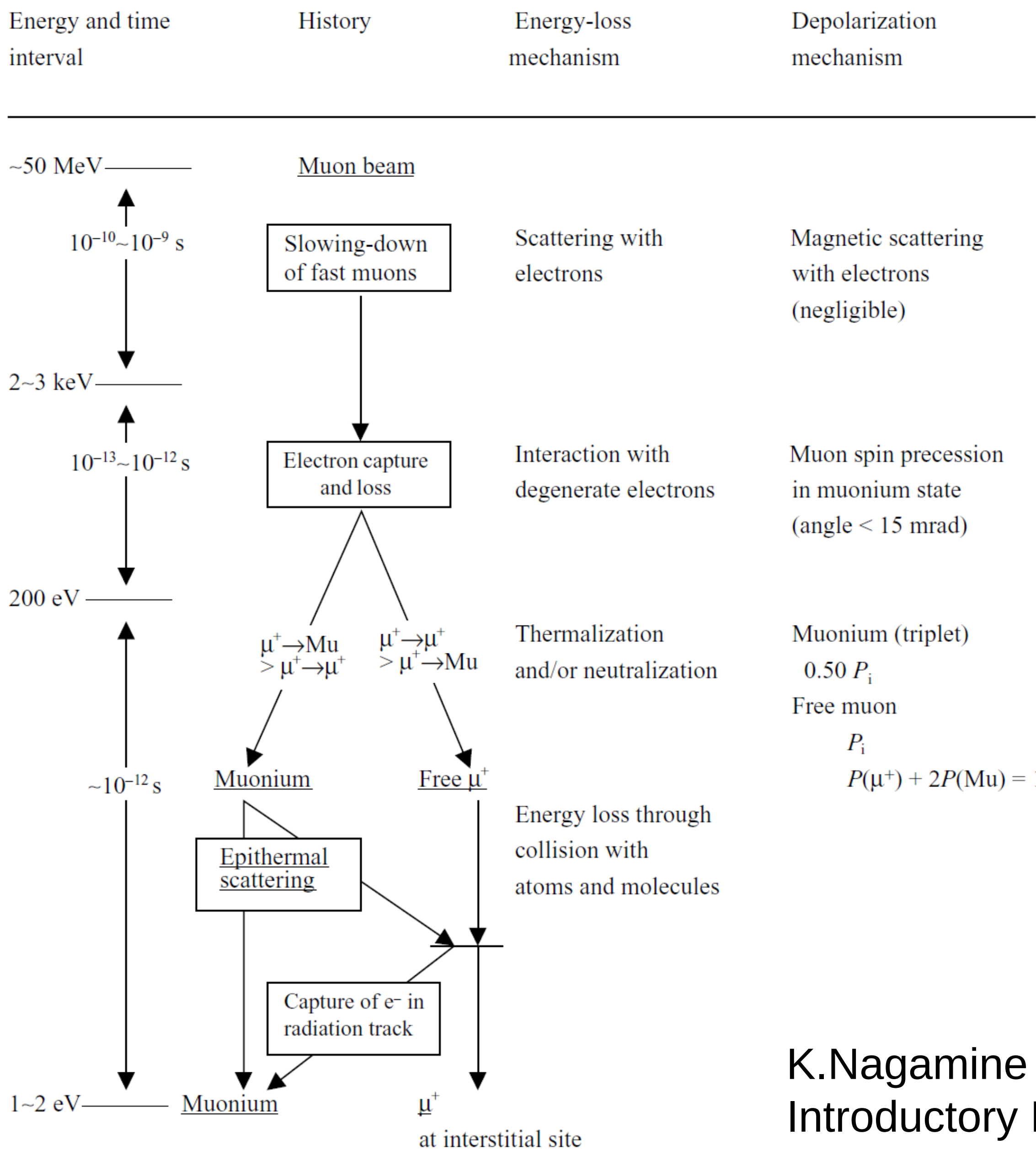
Neutrino Helicity −1

Spin direction -> opposite direction with flight direction

−> opposite direction with flight direction

<u>**100% Spin polarized muon**</u>

Positive muon



K.Nagamine
Introductory Muon Science

Muon in Material

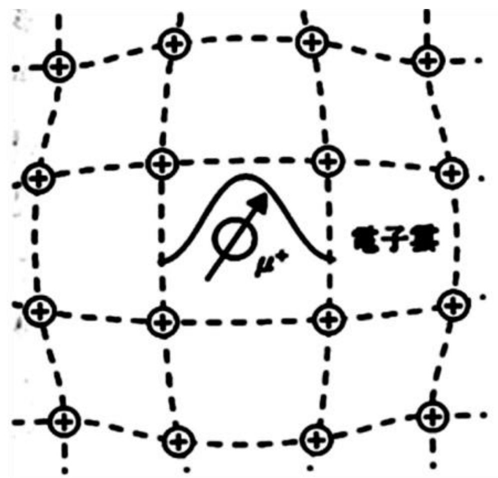
- ·Spin 1/2　　cahrge +-1
- ·mass : 1/9 mp　　: 200 me
- ·Unstable : Lifetime 2.2μsec
- ·Gyromagnetic ratio: 2πx135.5 (MHz/T)

μ^+

Metal

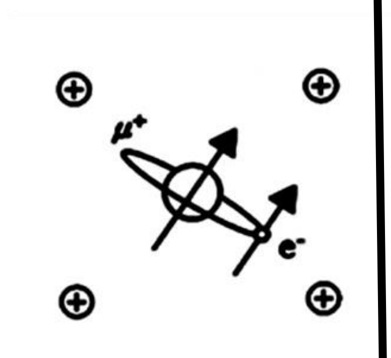
Light Proton

100% Polarized muon

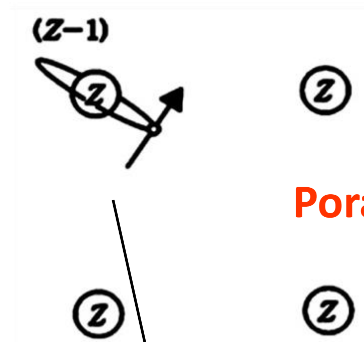


Insulator, semiconductor

"Muonium" Just similar with Hydrogen



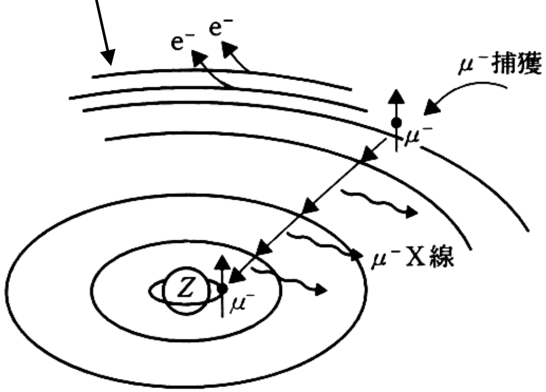
μ^-



Poralization 16%

(Z-1)impurity NMR

Heavy electron



Larmore precession of muon spin

$$\boldsymbol{\mu} = \gamma_\mu \boldsymbol{J} = \gamma_\mu \hbar \boldsymbol{I}$$

$$\gamma_\mu = 2\pi \times 135.54 \quad [\mathrm{MHz/T}]$$

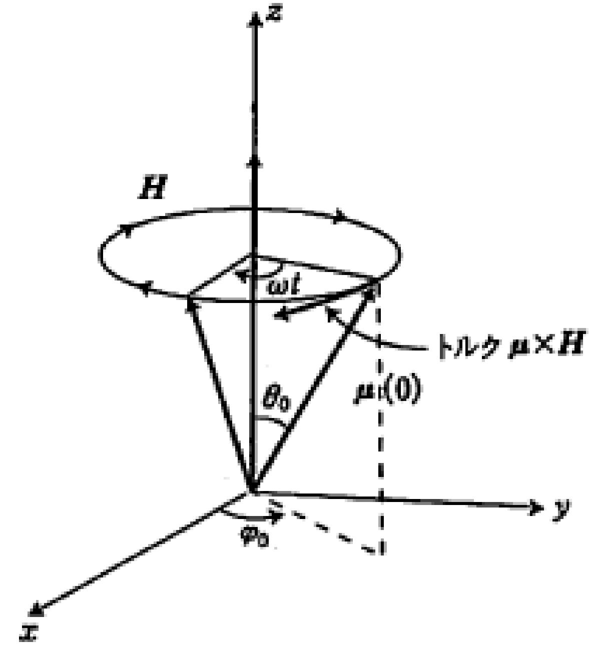
$$\frac{\mathrm{d}\boldsymbol{J}}{\mathrm{d}t} = \boldsymbol{\mu} \times \boldsymbol{H}$$

$$\frac{\mathrm{d}\boldsymbol{\mu}}{\mathrm{d}t} = \gamma_\mu \boldsymbol{\mu} \times \boldsymbol{H}$$

$$\boldsymbol{\mu}(0) = (\mu \sin\theta_0 \cos\phi_0,\ \mu \sin\theta_0 \sin\phi_0,\ \mu \cos\theta_0)$$

$$\boldsymbol{\mu}_x(t) = (\mu \sin\theta_0 \cos(\phi_0 - \omega_\mu t),\ \mu \sin\theta_0 \sin(\phi_0 - \omega_\mu t),\ \mu \cos\theta_0)$$

$$\omega_\mu = \gamma_\mu H_0$$



Muon Decay

Mean life time 2.2μs

$$\mu^+ \longrightarrow e^+ + \nu_e + \overline{\nu_\mu}$$

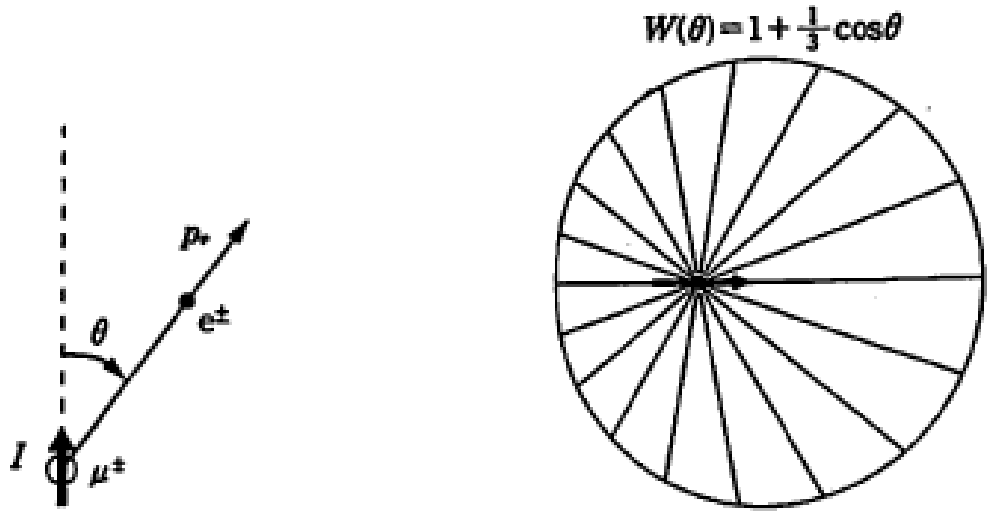
$$E_{max}^{kin} = \frac{1}{2} m_\mu c^2 \left[1 + \left(\frac{m_e}{m_\mu}\right)^2\right] - m_e c^2 = 52.32 \text{ [MeV]}$$

$$W^\pm(\theta, \varepsilon)\, d(\cos\theta)\, d\varepsilon = \frac{1}{2} \frac{1}{\tau_\mu} (3 - 2\varepsilon) \left(1 \pm \frac{2\varepsilon - 1}{3 - 2\varepsilon} \cos\theta\right) \varepsilon^2 d(\cos\theta)\, d\varepsilon$$

$$\varepsilon = \frac{E}{E_{max}},$$

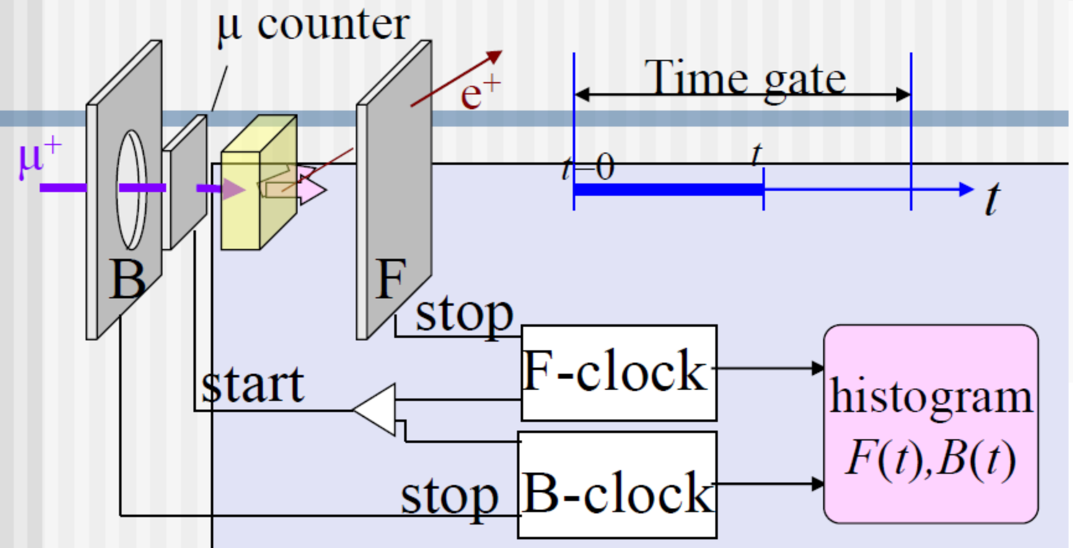
$$W^\pm(\theta) = 1 \pm A(\varepsilon) \cos\theta$$

$$A(\varepsilon) = \frac{2\varepsilon - 1}{3 - 2\varepsilon}$$

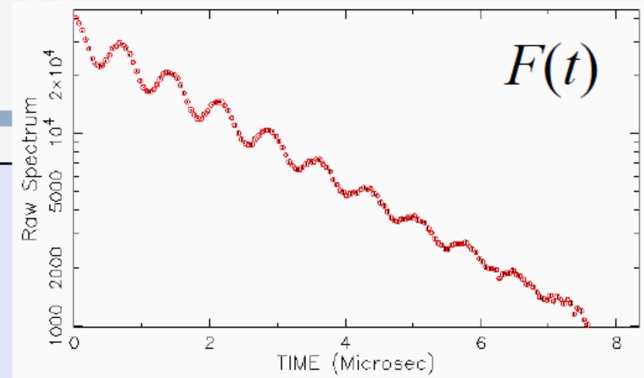


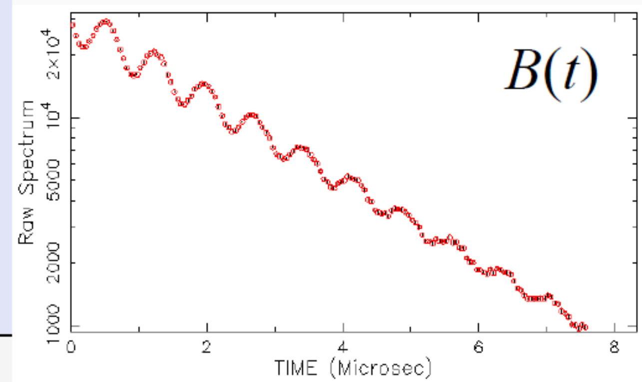
Spatial distribution of positrons from the decay of a polarized muon （average)

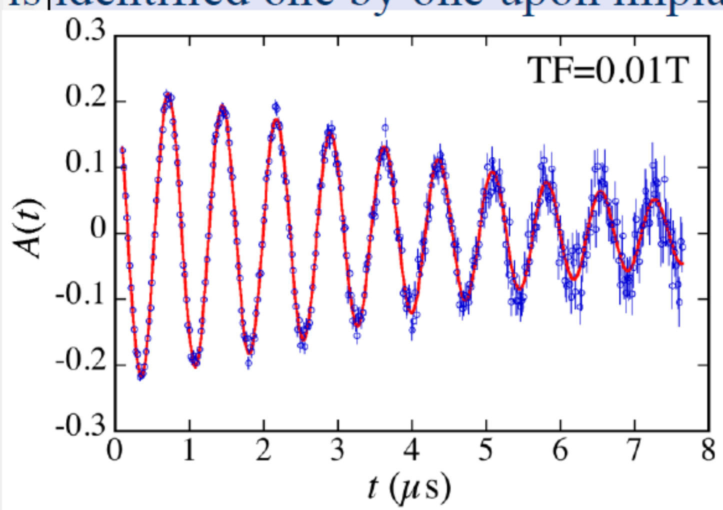
μSR experiment using continuous (dc) muon beam



...Muon is identified one by one upon implantation.



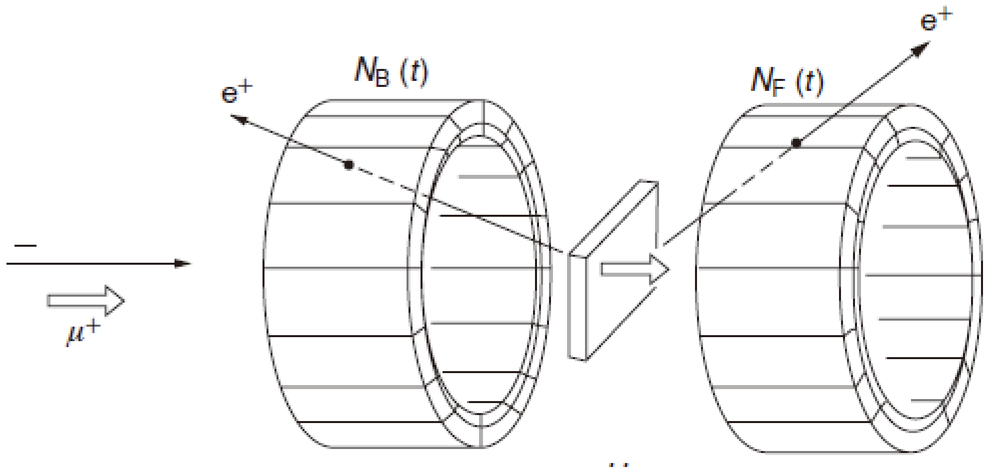


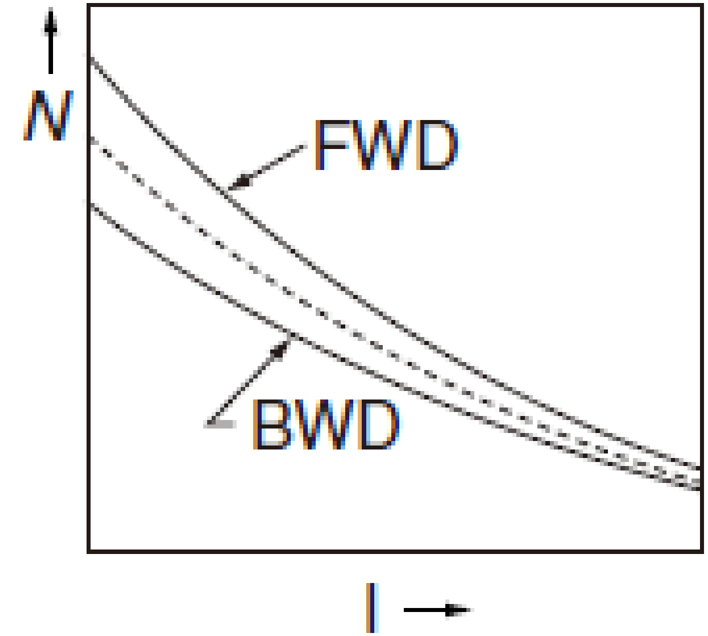


$$A(t) = \frac{F(t) - \alpha B(t)}{F(t) + \alpha B(t)}$$

[TRIUMF(Canada), PSI(Switzerland)]

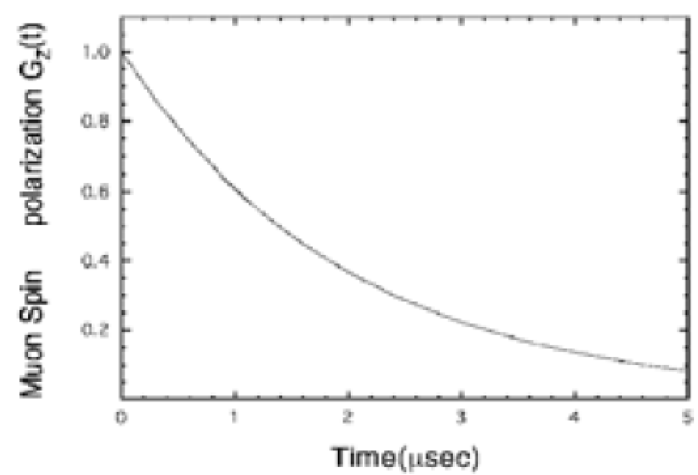
$$N(\theta, t) = N_0 \exp\left(-\frac{t}{\tau_\mu}\right) \times (1 + A \cdot P(t) \cos\theta)$$



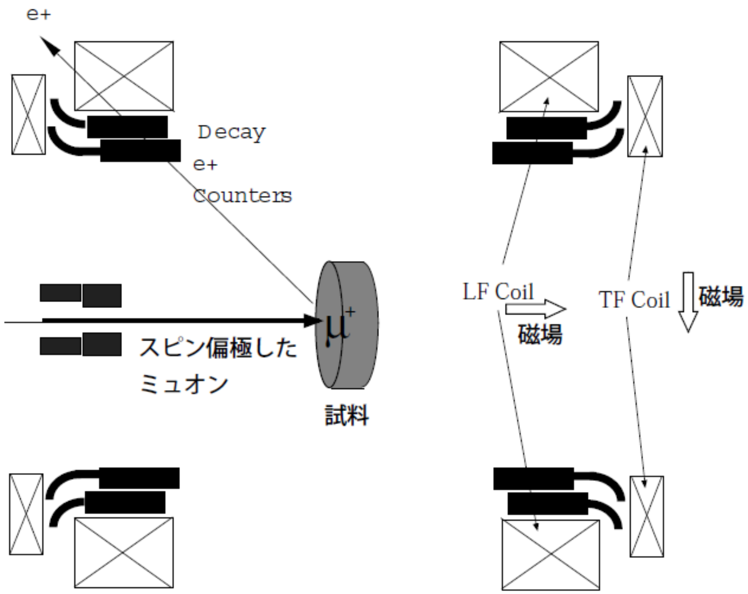


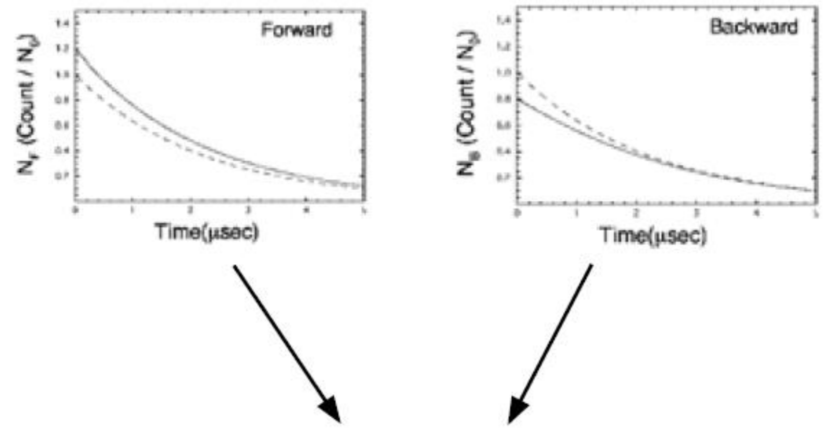
$$N_{FWD}(t) = N_{F0}\ (1 + AP(t)) \times e(-\ t/\tau_\mu)$$
$$N_{BWD}(t) = N_{B0}\ (1 - AP(t)) \times e(-\ t/\tau_\mu)$$

$$AP(t) = \frac{N_{FWD}(t) - \alpha N_{BWD}(t)}{N_{FWD}(t) + \alpha N_{BWD}(t)}$$

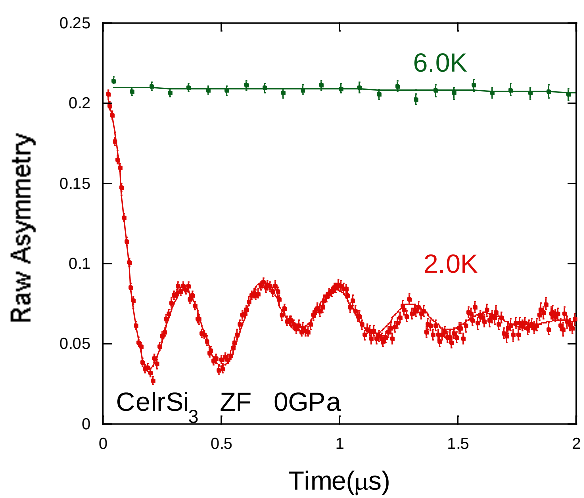


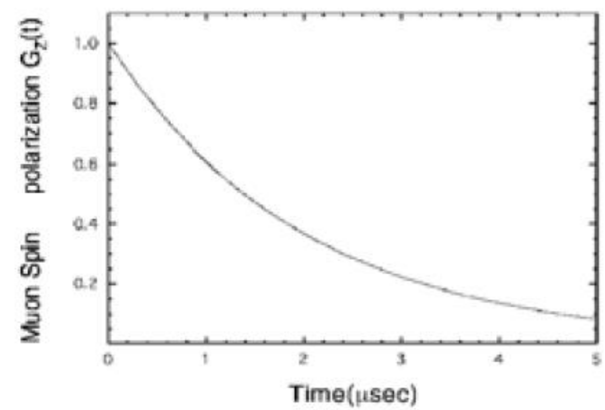
$$N(\theta, t) = N_0 \exp\left(-\frac{t}{\tau_\mu}\right) \times (1 + A \cdot P(t) \cos\theta)$$



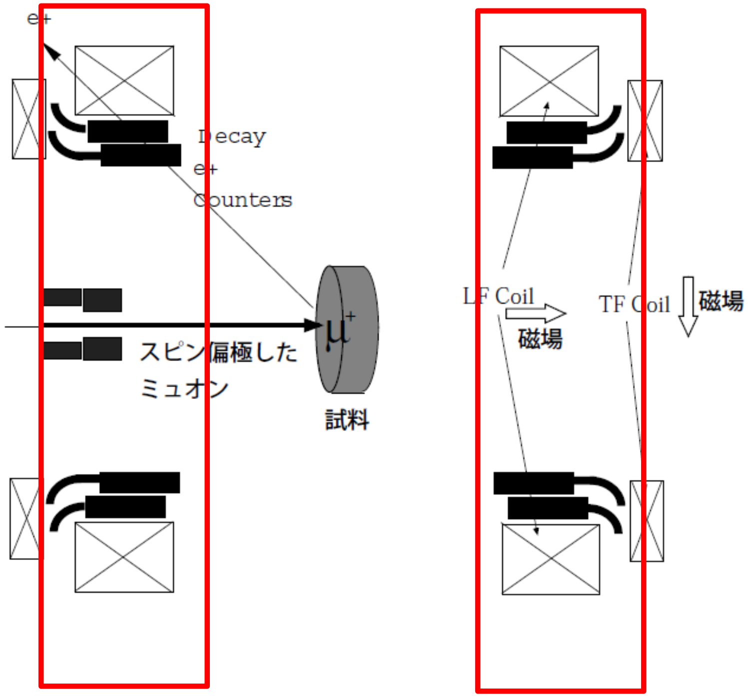


$$\frac{N_F(t) - \alpha N_B(t)}{N_F(t) + \alpha N_B(t)} = AG_Z(t)$$



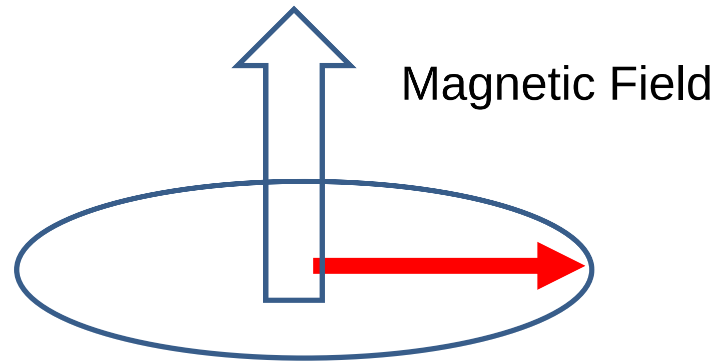


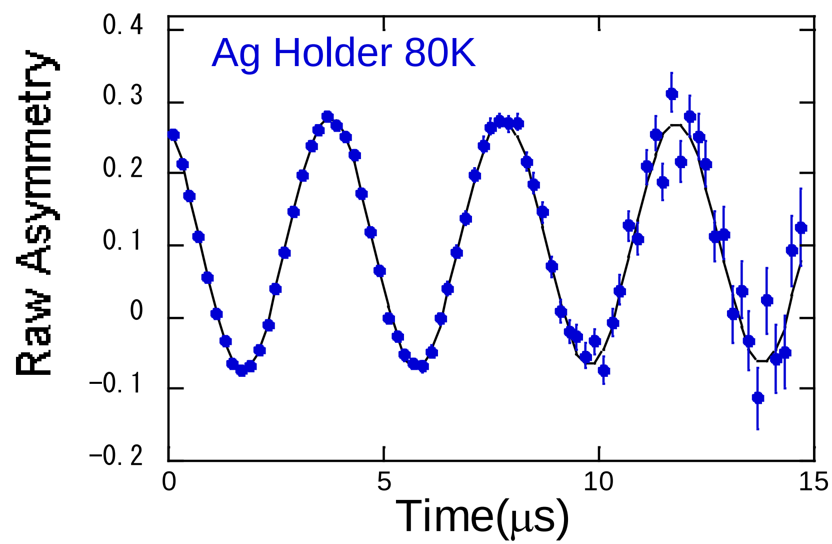
A Constant Value (~0.2)

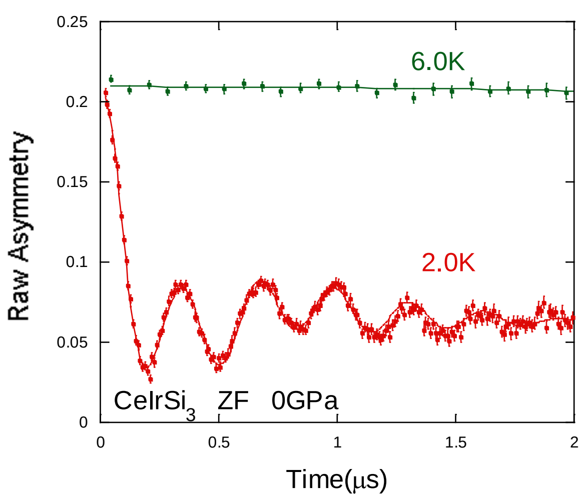


Forward
NF

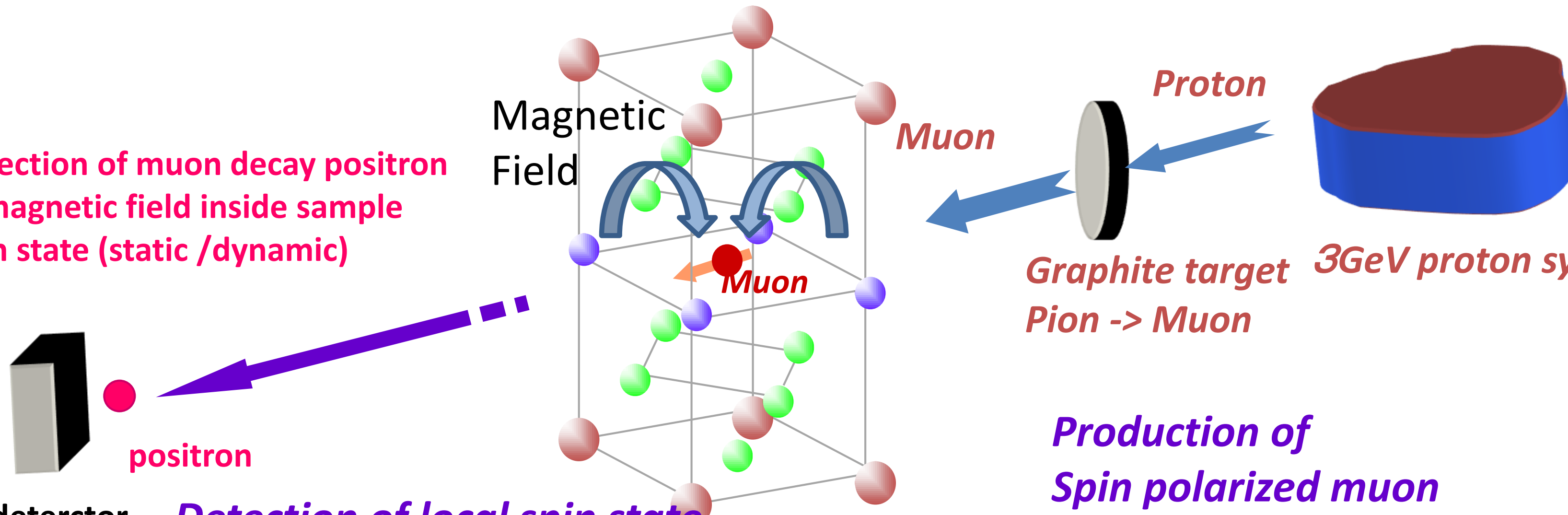
Backward
NB







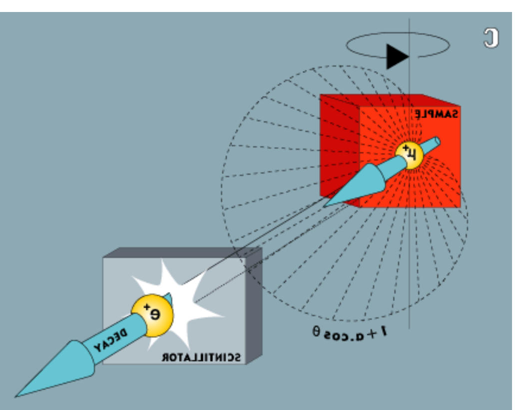
Muon spin rotation/relaxation (μSR) technique



Detection of muon decay positron
-> magnetic field inside sample
Spin state (static /dynamic)

Detection of local spin state inside sample

Production of Spin polarized muon



Observation of local magnetic field with high sensitivity

↓

Detection of spin related phenomena inside sample.

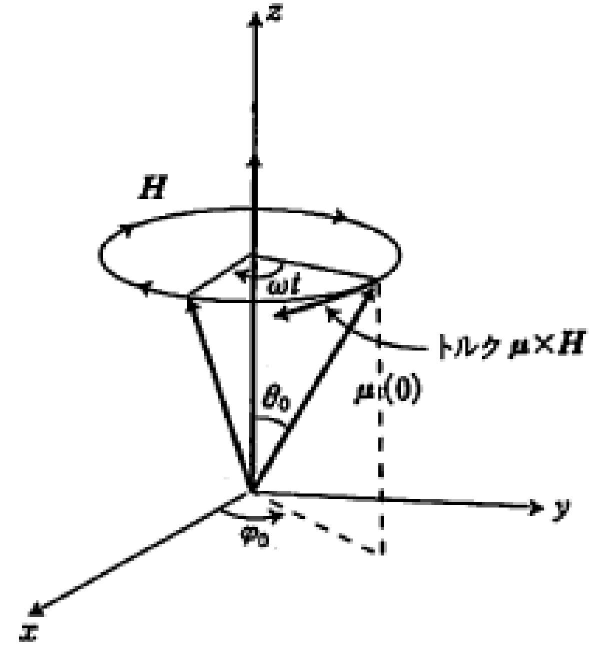
Larmor Precession by magnetic field

$$\boldsymbol{\mu} = \gamma_\mu \boldsymbol{J} = \gamma_\mu \hbar \boldsymbol{I}$$

$$\gamma_\mu = 2\pi \times 135.54 \quad [\mathrm{MHz/T}]$$

$$\frac{\mathrm{d}\boldsymbol{J}}{\mathrm{d}t} = \boldsymbol{\mu} \times \boldsymbol{H}$$

$$\frac{\mathrm{d}\boldsymbol{\mu}}{\mathrm{d}t} = \gamma_\mu \boldsymbol{\mu} \times \boldsymbol{H}$$



$$\boldsymbol{\mu}(0) = (\mu \sin\theta_0 \cos\phi_0,\ \mu \sin\theta_0 \sin\phi_0,\ \mu \cos\theta_0)$$

$$\boldsymbol{\mu}_x(t) = (\mu \sin\theta_0 \cos(\phi_0 - \omega_\mu t),\ \mu \sin\theta_0 \sin(\phi_0 - \omega_\mu t),\ \mu \cos\theta_0)$$

$$\omega_\mu = \gamma_\mu H_0$$

Spin Relaxation

t=0 muon spin 100% polarized

gradually depolarized owing to magnetic circumstance around muon

Time dependence of residual polarization

Magnetic field at muon site

Magnetic dipole-dipole interaction

nucleus、electron spin and muon spn

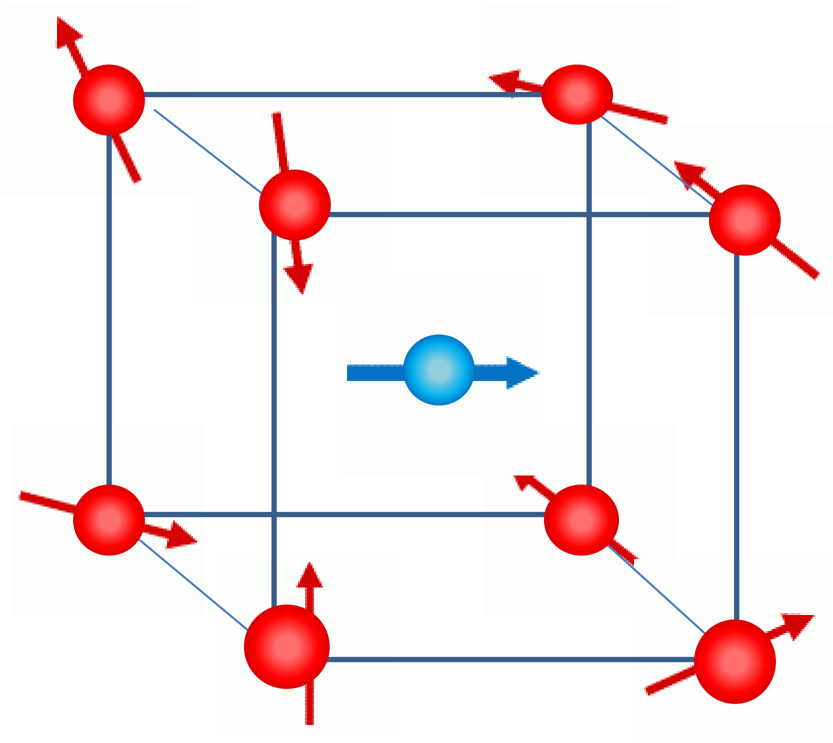
$\mathcal{H}_d = -\gamma_e \gamma_\mu \hbar^2 (\boldsymbol{S} \cdot \boldsymbol{I} / r^3 - 3(\boldsymbol{S} \cdot \underline{\mathbf{r}})(\boldsymbol{I} \cdot \boldsymbol{r}) / r^5)$

Fermi Contact

$\mathcal{H}_F = (8\pi/3)\gamma_e \gamma_\mu \hbar^2 \boldsymbol{I} \cdot \boldsymbol{S} \delta(\mathbf{r})$

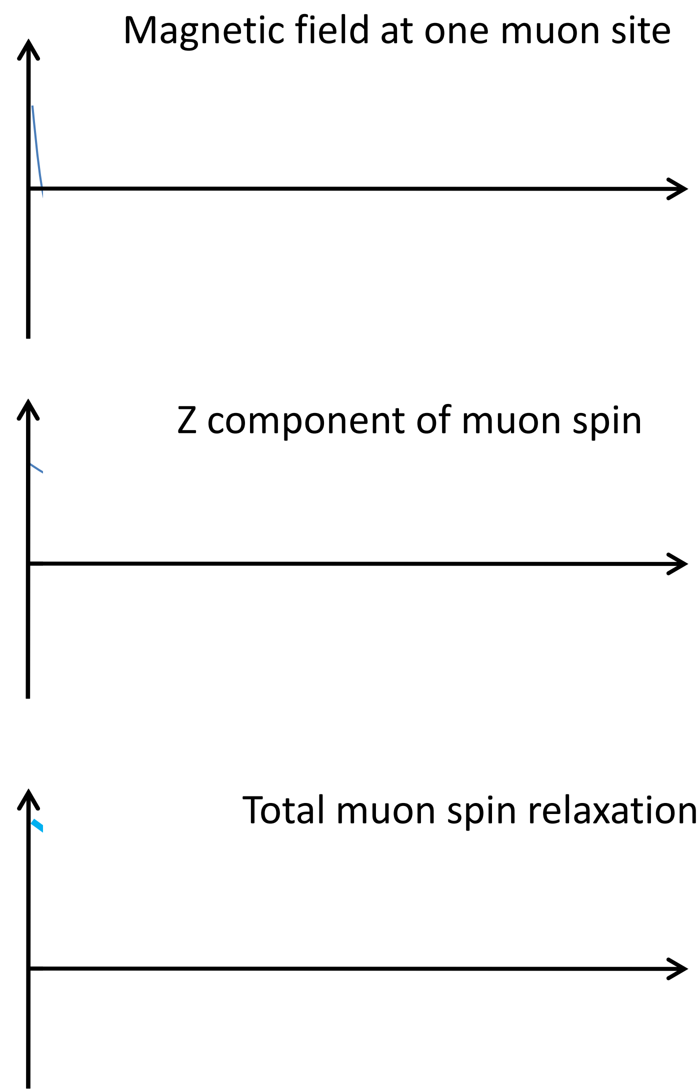
Transfer interaction due to hybridization orbital

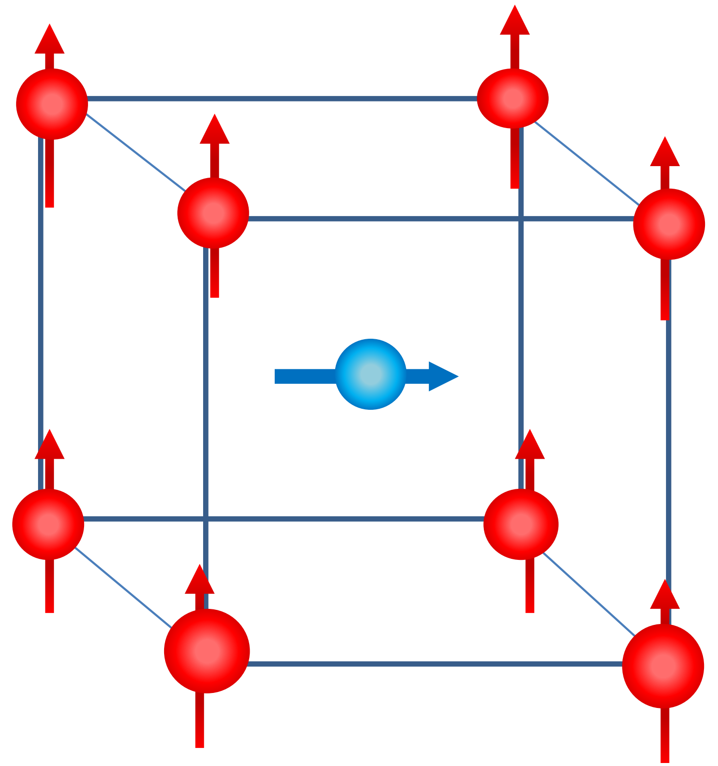
$\mathcal{H}_t = a_s \boldsymbol{I} \cdot \boldsymbol{S}$

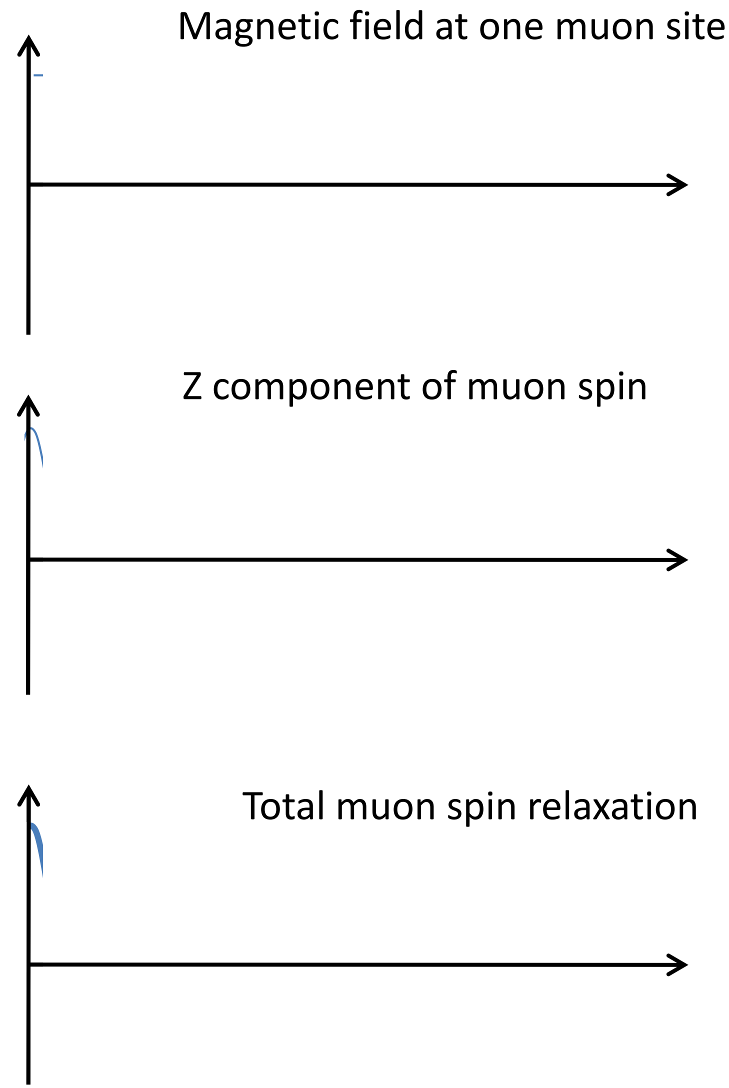


Paramagnetic state （$T >> T_C$）

Fast fluctuation







Magnetic Ordered state (T<<T_C)
All the implanted muon behave same way
(same precession frequency)

Magnetic state	Direction	distribution	dynamics
Paramagnetic electron spin nucleus spin	 Random Random	 Gaussian Gaussian	 Dynamic Static
Ferromagnetic Poly Single	 Random Specific direction	 Uniform	Static
Antiferromagnetic Poly Single	 Random Specific direction	 Uniform Uniform	Static
Spin-glass etc	Random	Lorentzian	Static
Just above Tc, TN (Critical Slowing down)	Random	Gaussian	Dynamic

Relaxation Function

$$N(\theta, t) = N_0 \exp\left(-\frac{t}{\tau_\mu}\right) \times (1 + A \cdot P(t) \cos\theta)$$

$$G_z(t) \equiv P_z(t)/P(0)$$

$$\frac{N_e(t,0) - \alpha N_e(t,\pi)}{N_e(t,0) + \alpha N_e(t,\pi)} = AP(0)\,G_z(t)$$

[1] 物質中に静的な磁場が存在するときのミュオンスピン偏極 $P(t)$

$$\frac{\langle I^i{}_x(t)\rangle}{I} = \left[\frac{1}{2}\sin 2\theta^i \cos\phi^i (1-\cos\omega^i t) + \sin\theta^i \sin\phi^i \sin\omega^i t\right]$$

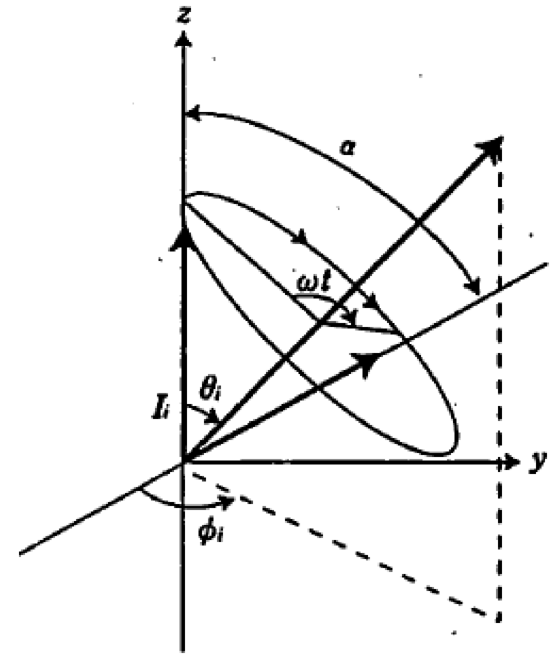
$$\frac{\langle I^i{}_y(t)\rangle}{I} = \left[\frac{1}{2}\sin 2\theta^i \sin\phi^i (1-\cos\omega^i t) + \sin\theta^i \sin\phi^i \sin\omega^i t)\right]$$

$$\frac{\langle I^i{}_z(t)\rangle}{I} = [\cos^2\theta^i + \sin^2\theta^i \cos\omega^i t]$$

$$\omega^i = \gamma_\mu B^i$$

物質中の B^i の分布$D(B^i)$

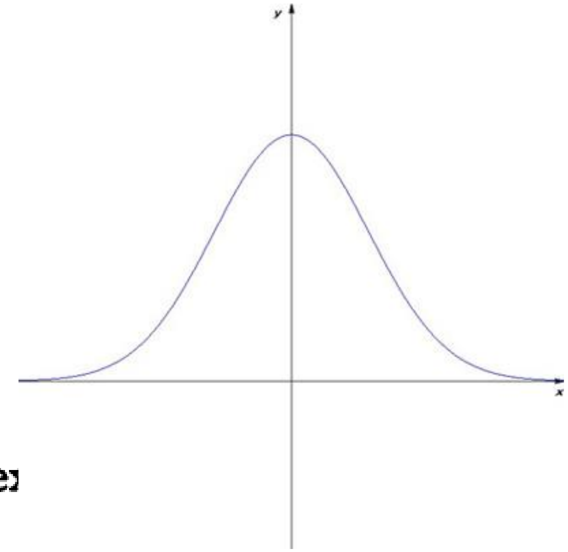
$$P_\alpha{}^{\mathrm{stat}}(t) = \frac{\overline{\langle I_\alpha\rangle}}{I} = \int \frac{\langle I_\alpha\rangle}{I} D(\boldsymbol{B})\,\mathrm{d}\boldsymbol{B} \qquad (\alpha = x, y, z)$$



Gaussian Distribution

$$p(B^i{}_a) = \frac{1}{\sqrt{2\pi}\sigma_B} \exp\left[-\frac{(B^i{}_a)^2}{2\sigma_B{}^2} \right] \qquad (a = x, y, z)$$

$$\sigma_B{}^2 = \overline{(B^i{}_x)^2} = \overline{(B^i{}_y)^2} = \overline{(B^i{}_z)^2}$$



$$P_z(t) = \frac{\overline{\langle I_z(t) \rangle}}{I} = \int_{-\infty}^{\infty} dB_x \int_{-\infty}^{\infty} dB_y \int_{-\infty}^{\infty} dB_z \, p(B_x) \, p(B_y) \, p(B_z) \frac{\langle I_z(t) \rangle}{I}$$

$$= \left(\frac{1}{\sqrt{2\pi}\sigma_B} \right)^3 \int_0^{\infty} B^2 dB \int_0^{2\pi} d\phi \int_0^{\pi} \sin\theta d\theta (\cos^2\theta + \sin^2\theta \cos\gamma_\mu B_t) \mathrm{ex}$$

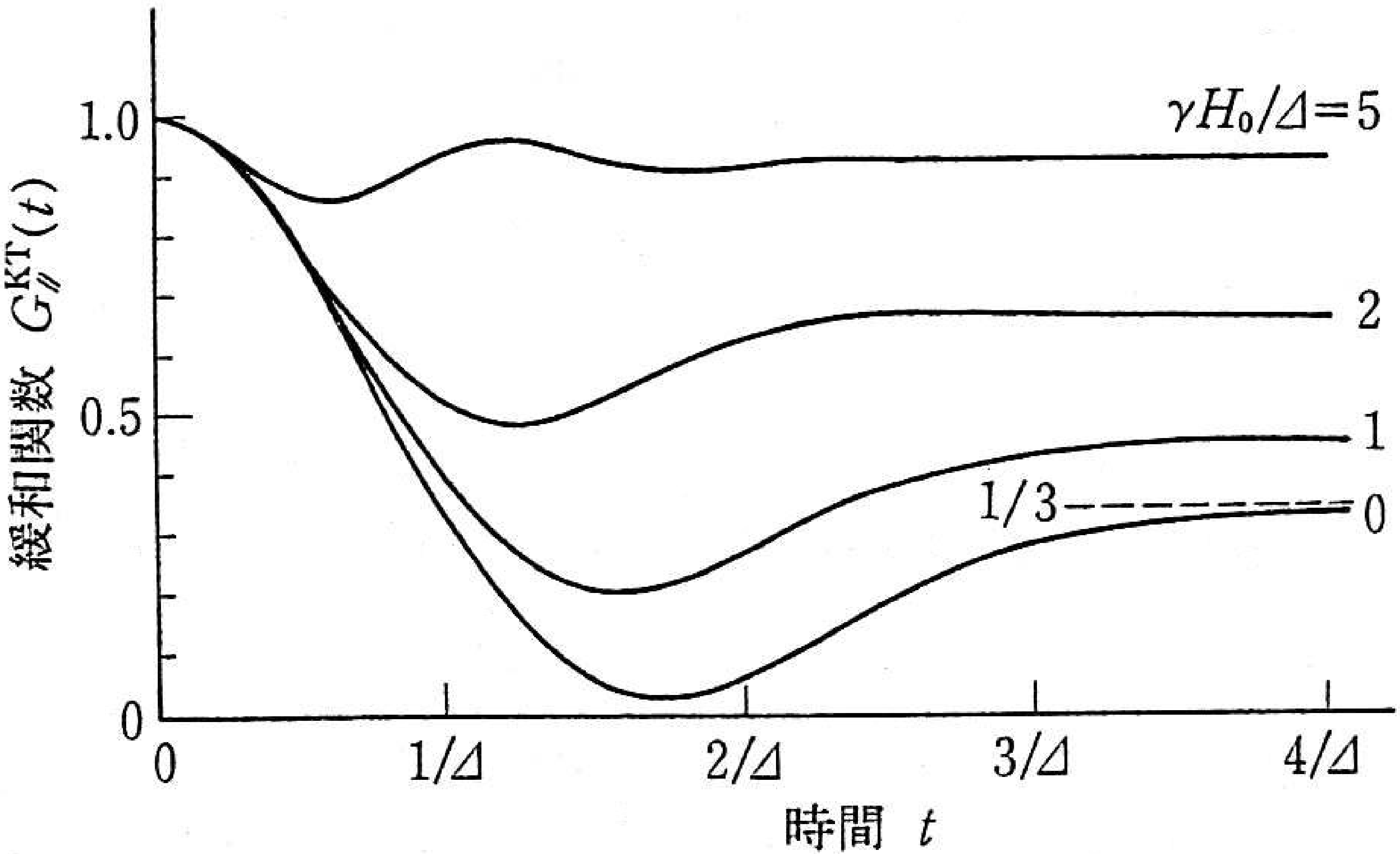
$$G_z(t) = \frac{1}{3} + \frac{2}{3} [(1 - (\gamma_\mu \sigma_B)^2 t^2] \exp\left[-\frac{1}{2} (\gamma_\mu \sigma_B)^2 t^2 \right] \equiv G_{KT}(t)$$

$p(B_z)$ を $p(B_z - B_0)$

$$G_z(t) \equiv G_z^{KT}(t, B_0) \qquad (\omega_0 = \gamma_\mu B_0)$$

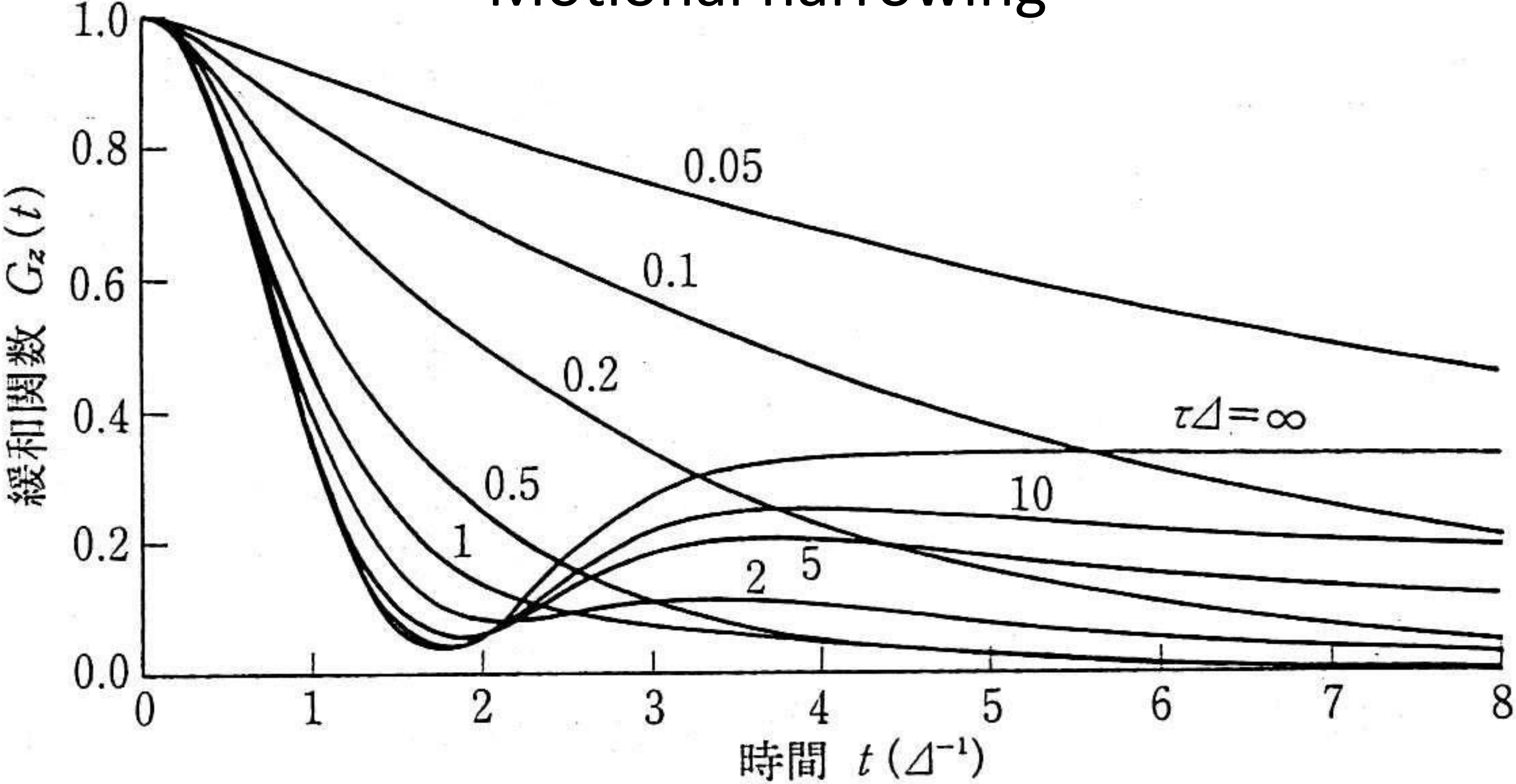
$$= 1 - \frac{2\Delta^2}{\omega_0{}^2} \left[1 - \exp\left(-\frac{1}{2} \Delta^2 t^2 \right) \cos\omega_0 t \right] + \frac{2\Delta^4}{\omega_0{}^3} \left[\int_0^t \exp\left(-\frac{1}{2} \Delta^2 \tau^2 \right) \sin\omega_0 t \, d\tau \right]$$

Kubo-Toyabe function
Gaussian distributed random direction magnetic field



Dynamic Kubo-Toyabe function
Gaussian distributed field is fluctuating (τ)

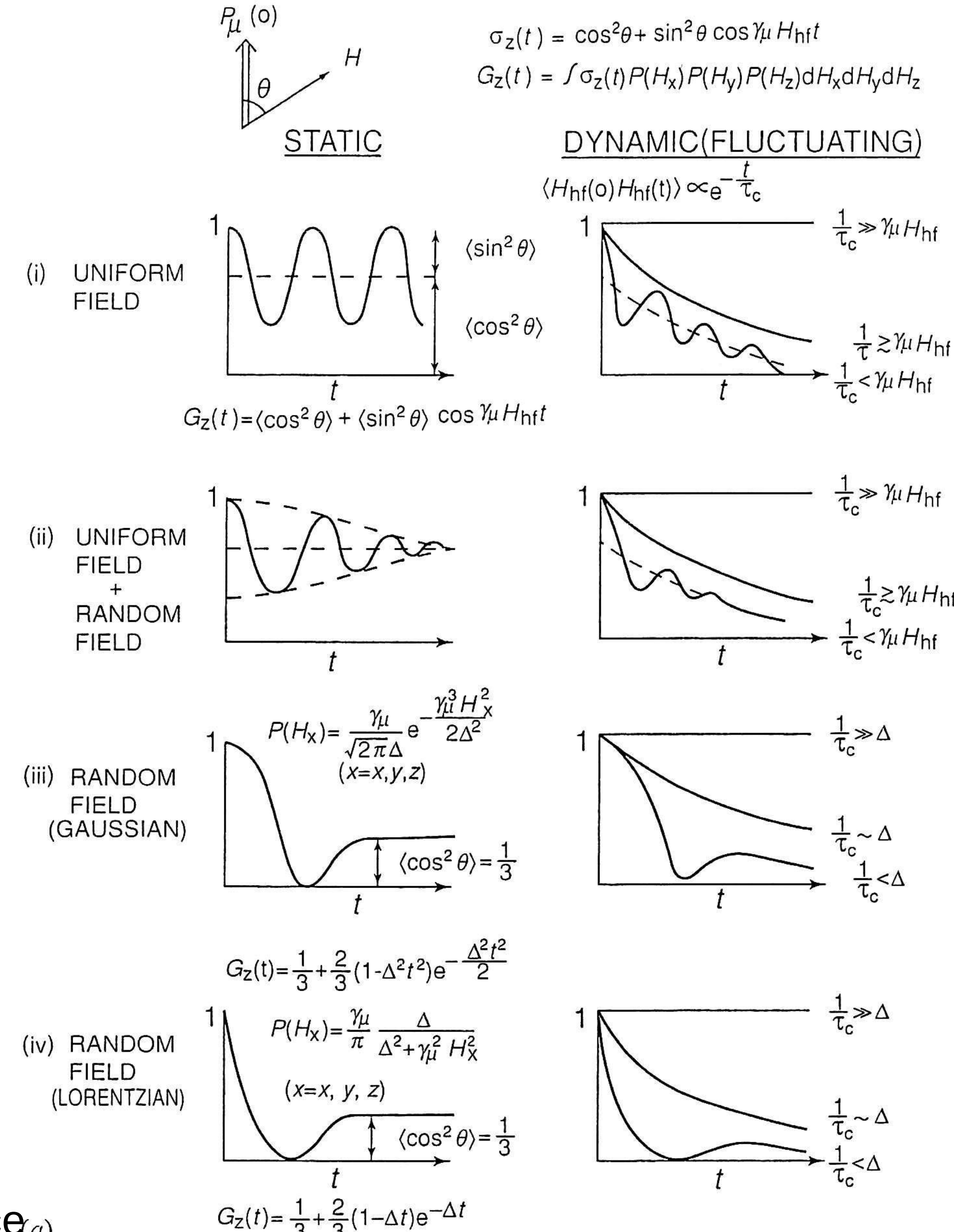
Motional narrowing



Spectra shape
Relaxation time
Magnetic field dependence

Local field
Homogenious?
Gaussian distribution?
Magnitude

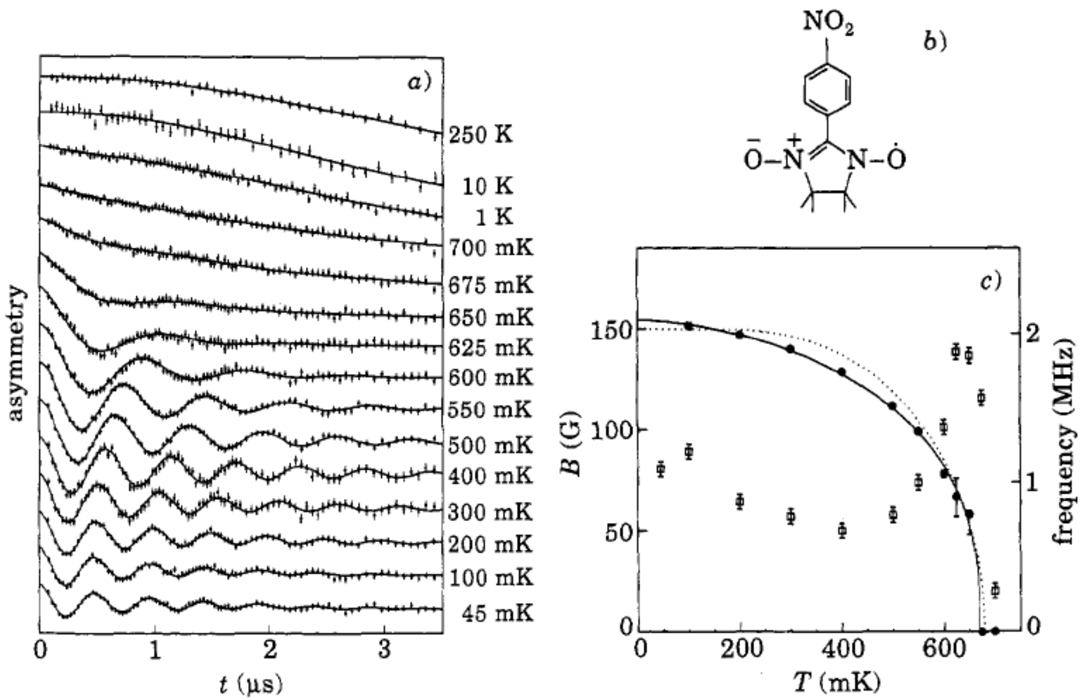
Static or dynamic
Correlation time
Volume Fraction



K.Nagamine
Introductory Muon Science

Magnetic ordered state

Very clearly and easily observed magnetic   ordered state
Size of the magnetic moment can be estimated
Temperature dependence of the order parameter

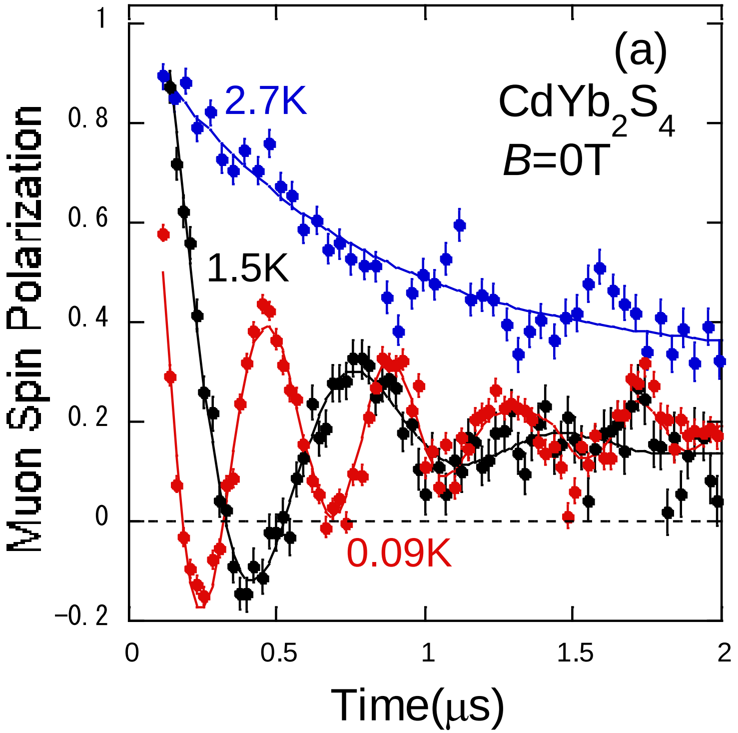


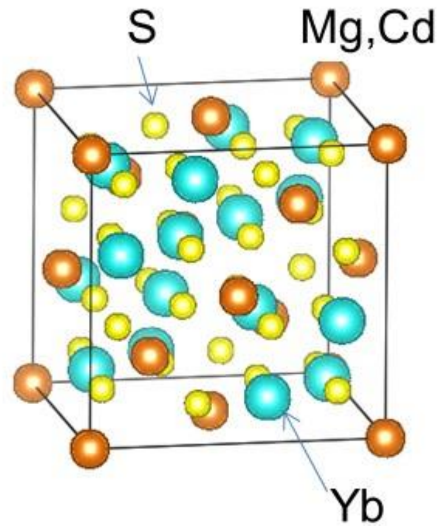
$\nu(T)=\nu(0)(1-(T/T_C)^{\alpha})^{\beta}$

$\alpha = 1.7 \pm 0.4$
$\beta=0.36 \pm 0.05$

cf
3DHisenberg 0.36
3D Ising 0.33
,,,

p-NPNN
S.Bllundel et al, EPL 1995

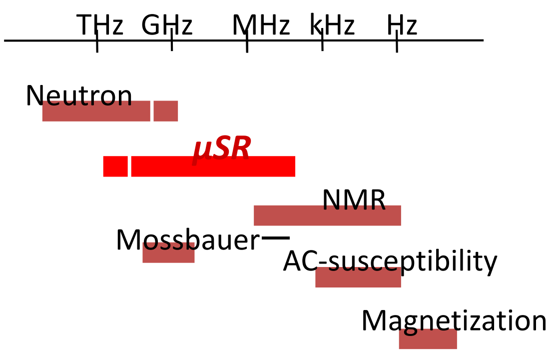




Magnetic ordering in Frustrated Material

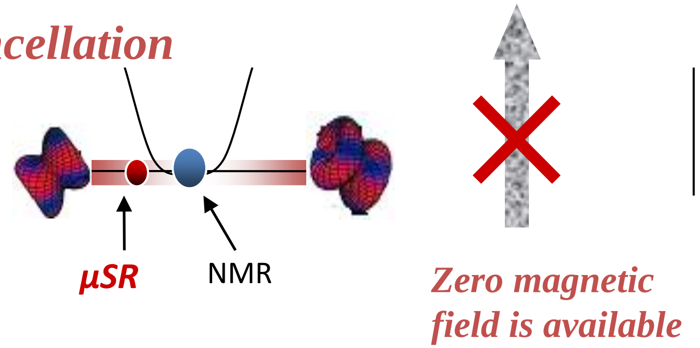
T.Higo,,,WH et al., Phys. Rev B 2017

Unique time window

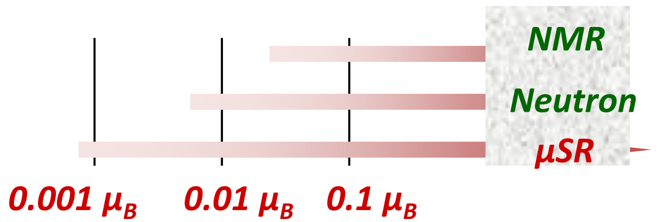


Low symmetric Interstitial position

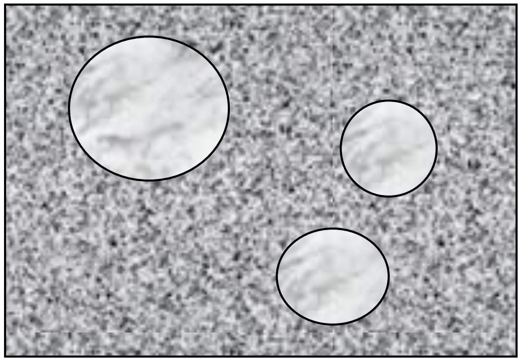
No cancellation



High sensitivity

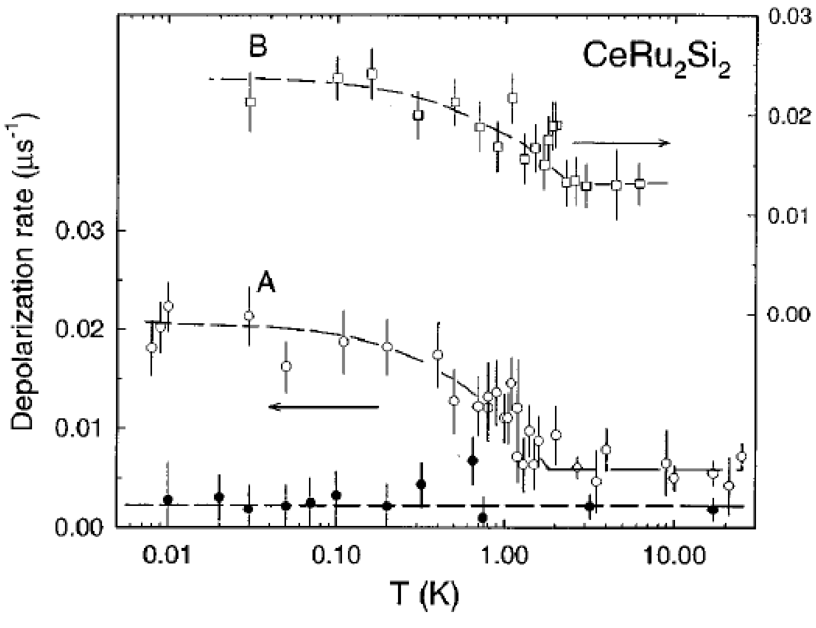


Determination of Phase separation



Applicable to any kind of materials

High sensitivity:
μSR time window 10-20 μs
$\gamma_\mu = 2\pi$x13.55kHz/G $\rightarrow$ 50 kHz detectable
B ~0.1mT
(corresponds to 0.001 μ_B or nuclear moments)



Example
Magnetic ordering in CeRu2Si2

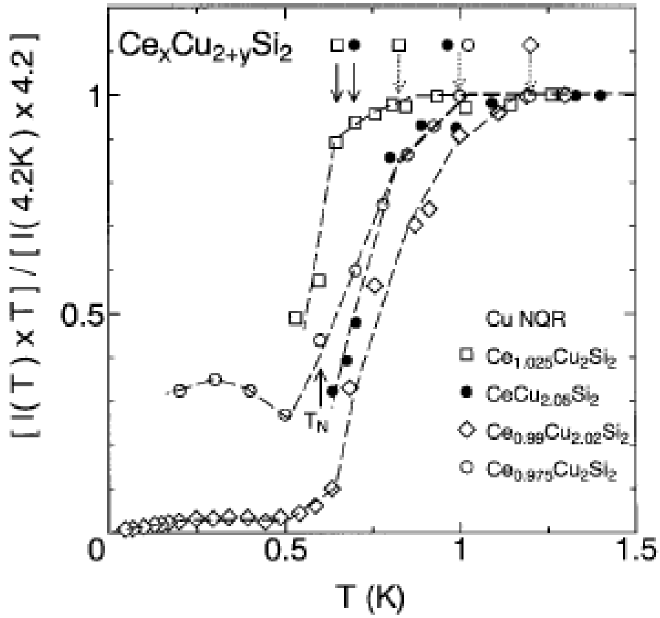
Magnetic oreder with 0.001μ_B/Ce

A. Amato, R. Feyerherm, F. N. Gygax, A. Schenck, J. Flouquet, and P. Lejay
Phys. Rev. B **50**, 619(R) (1994)

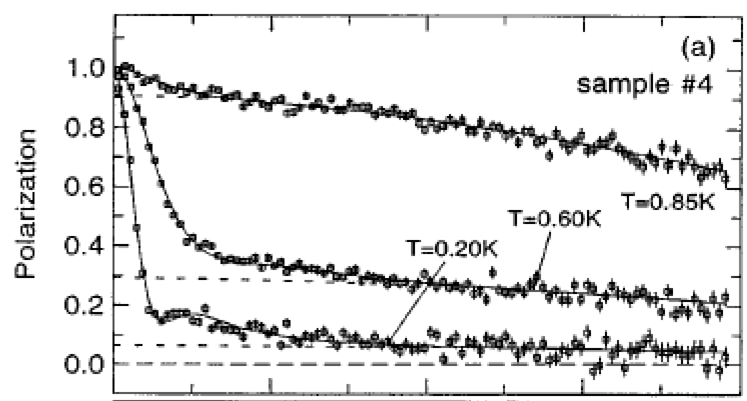
$CeCu_2Si_2$

NMR “wipe out”
Signal disappear due to
fast fluctuation

μSR Slowly(~3MHz) fluctuated
weak magnetic ordered state

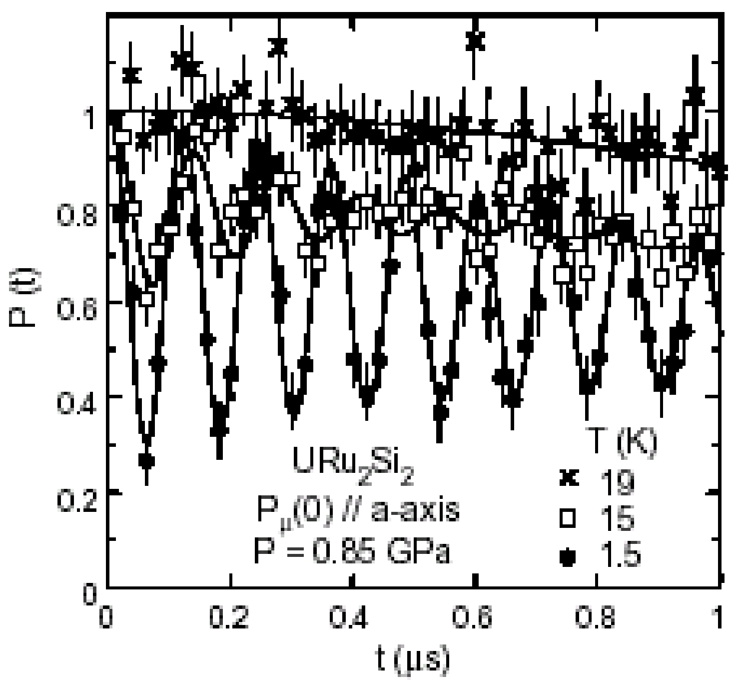


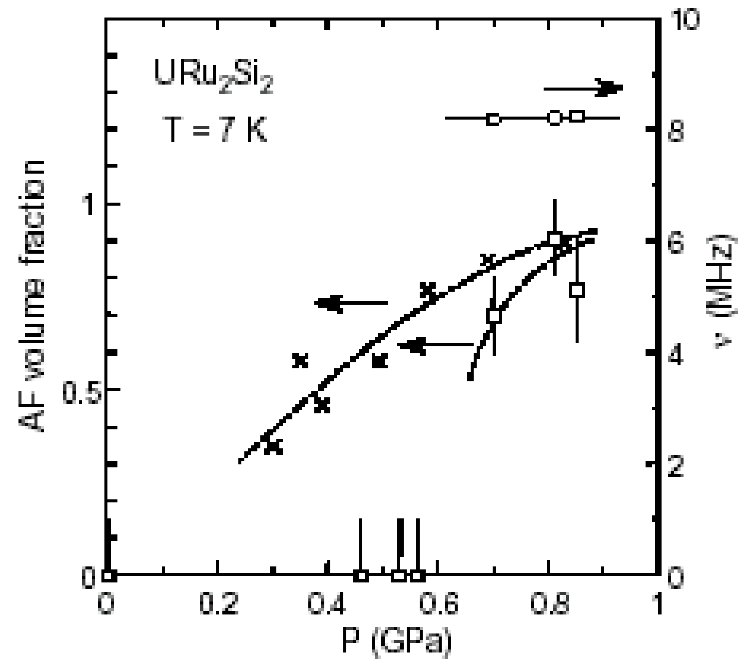
NMR Ishida et al., PRL1999



μSR Feyerhelm et al.,PRB1997

Example URu_2Si_2



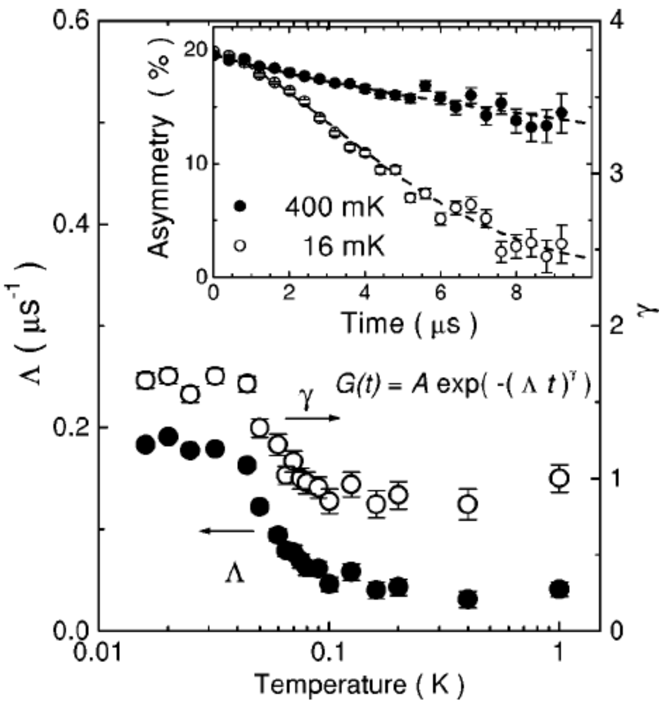


Magnetic Volume fraction can be identified.

H.Amitsuka et al. Physica B 326 (2003) 418-421

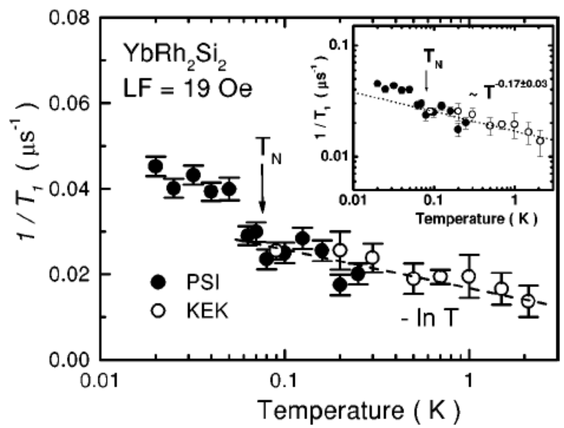
Low-temperature magnetic order and spin dynamics in $YbRh_2Si_2$

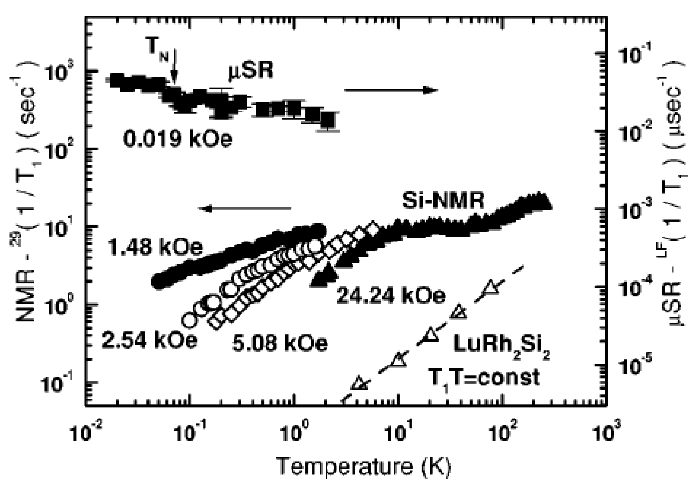
K. Ishida,[1,2,*] D. E. MacLaughlin,[1] Ben-Li Young,[1] K. Okamoto,[2] Y. Kawasaki,[2,†] Y. Kitaoka,[2] G. J. Nieuwenhuys,[3] R. H. Heffner,[4] O. O. Bernal,[5] W. Higemoto,[6] A. Koda,[6] R. Kadono,[6] O. Trovarelli,[7] C. Geibel,[7] and F. Steglich[7]
[1]Department of Physics, University of California, Riverside, California 92521-0413, USA
[2]Department of Physical Science, Graduate School of Engineering Science, Osaka University, Toyonaka, Osaka 560-8531, Japan
[3]Kamerlingh Onnes Laboratory, Leiden University, 2500 RA Leiden, The Netherlands
[4]MS K764, Los Alamos National Laboratory, Los Alamos, New Mexico 87545, USA
[5]Department of Physics and Astronomy, California State University, Los Angeles, California 90032, USA
[6]Meson Science laboratory, Institute of Materials Structure Science, High Energy Accelerator Research Organization (KEK), 1-1 Oho, Tsukuba, Ibaraki 305-0801, Japan
[7]Max-Planck Institute for Chemical Physics of Solids, D-01187 Dresden, Germany



$$\frac{^{LF}(1/T_1)}{^{29}(1/T_1)} = \left(\frac{\gamma_\mu A_\mu}{\gamma_{Si} A_{Si}}\right)^2$$

PHYSICAL REVIEW B **68**, 184401 (2003)





$1/T1 \propto$ *-ln* T
SCR (2D-AFM)

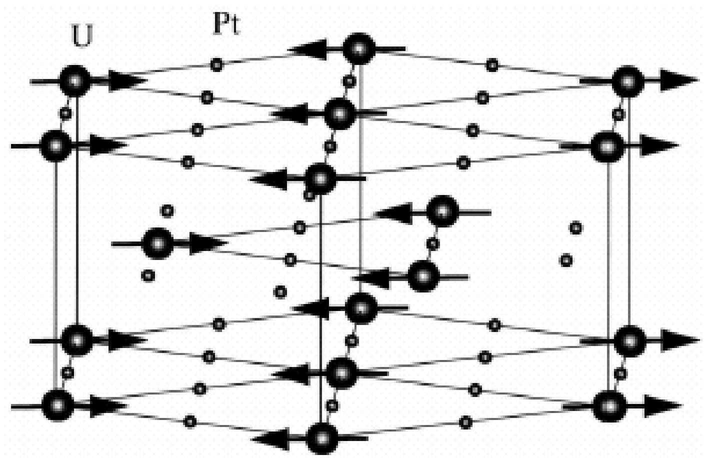
H>1.45kG
Normal Fermi Liquid
$1/TT_1$=const

Spin fluctuation near Quantum Critical Point(QCP)

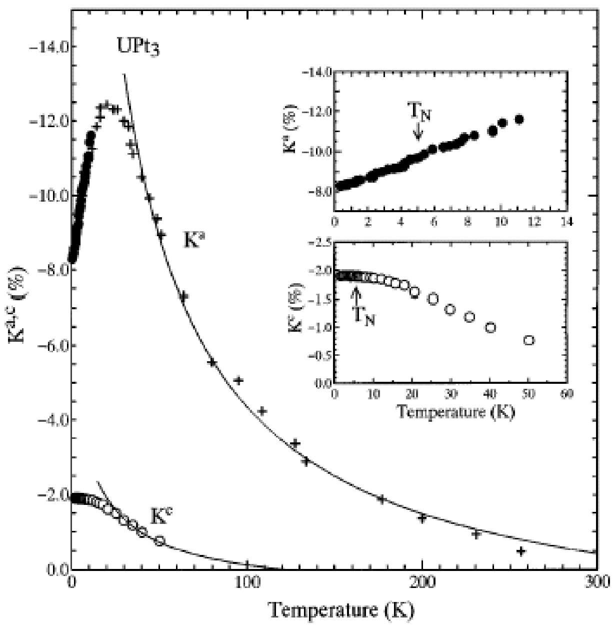
UPt3

- ***Antiferromagnetism at T_N~5K*** observed only by neutron
-
- Other technique → no detection of AF(μSR、NMR etc)

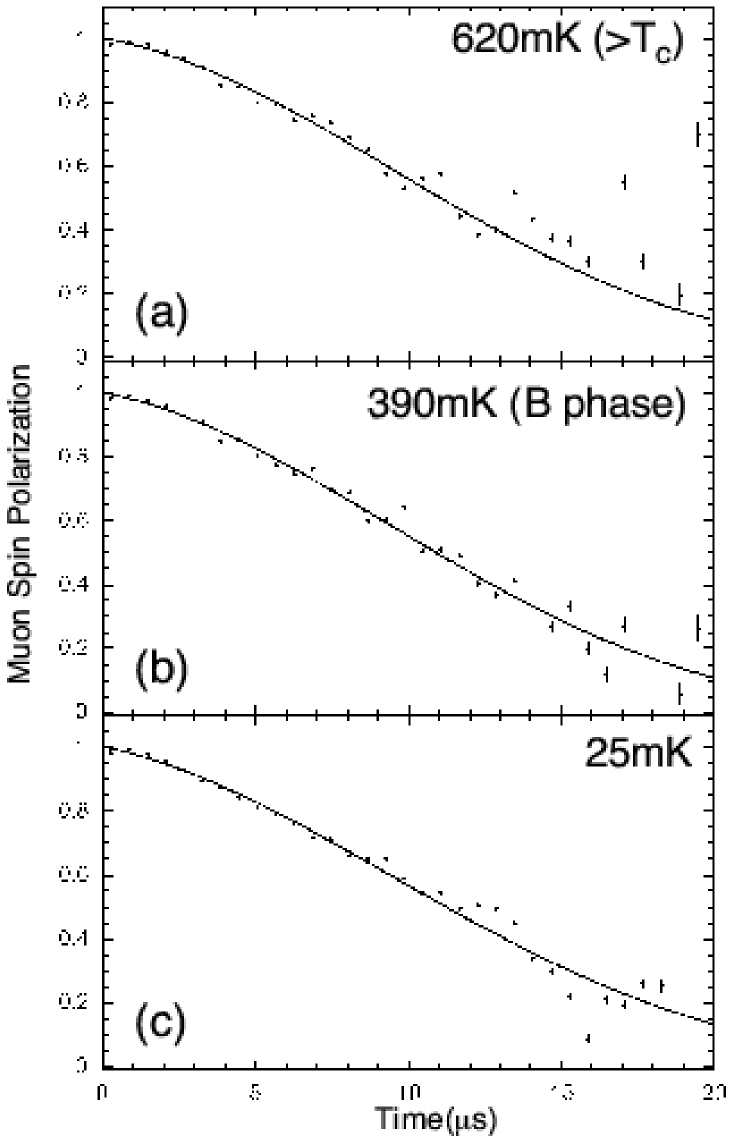
？

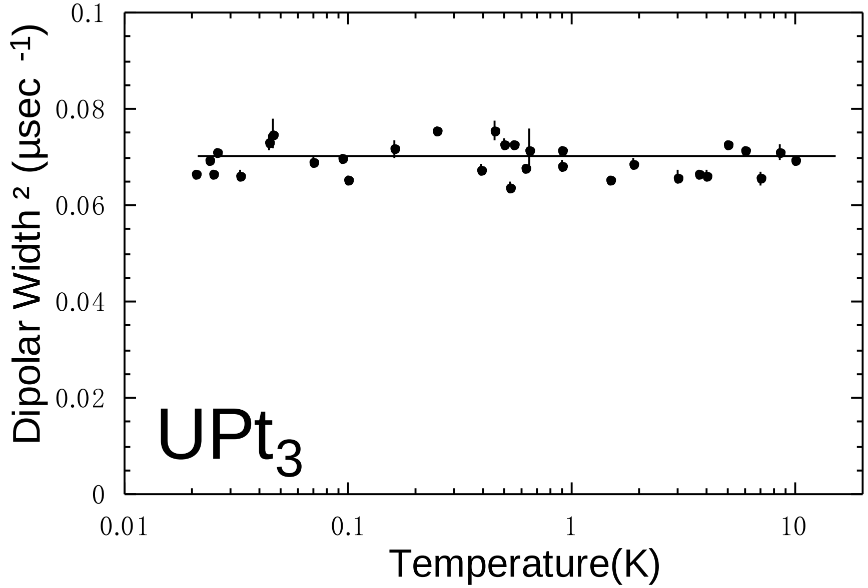


Y.Koike et al., JPSJ 1998



H.Tou et al., PRL1996

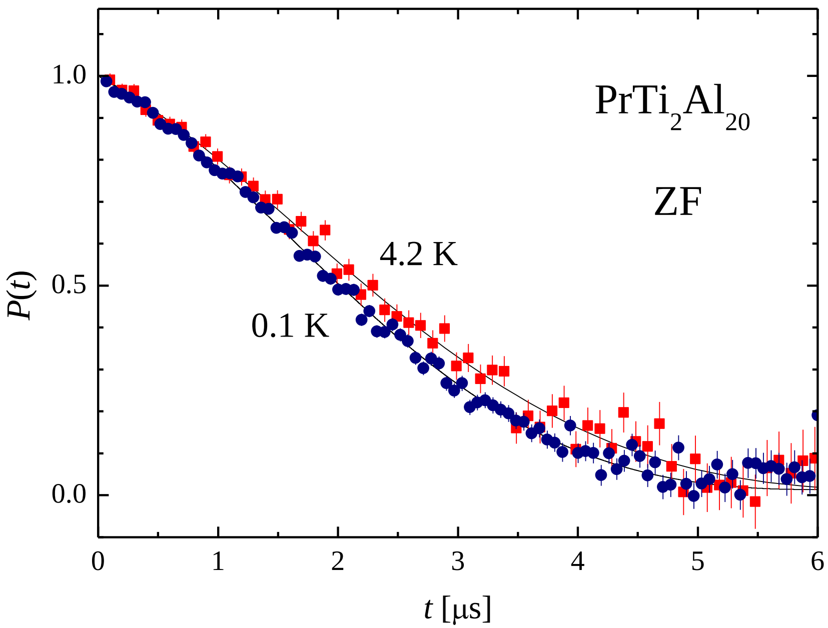


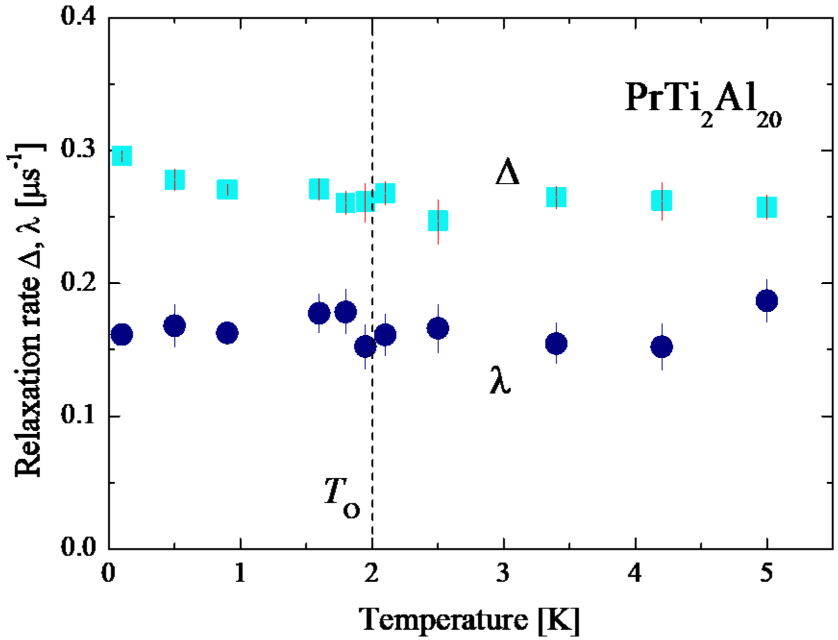


Only nuclear dipolar field was seen!

W.Higemoto et al., Physica B 2000

$PrTi_2Al_{20}$: ZF-μSR





Relaxation function: $G_{KT}(t;\Delta)*\exp(-\lambda t)$

Dynamical relaxation

Gaussian Kubo-Toyabe relaxation due to an ^{27}Al nuclear dipolar field (static)

No significant change when passing through T_Q=2 K.

⇒Nonmagnetic order parameter

(consistent with the quadrupole ordering scenario)

T.U.Ito, WH et al., J. Phys. Soc. Jpn. 80(2011) 113703.

Magnetism studied by using muon

Easily identify ordered state or
absence of magnetic order.

Single crystalline specimen is not required

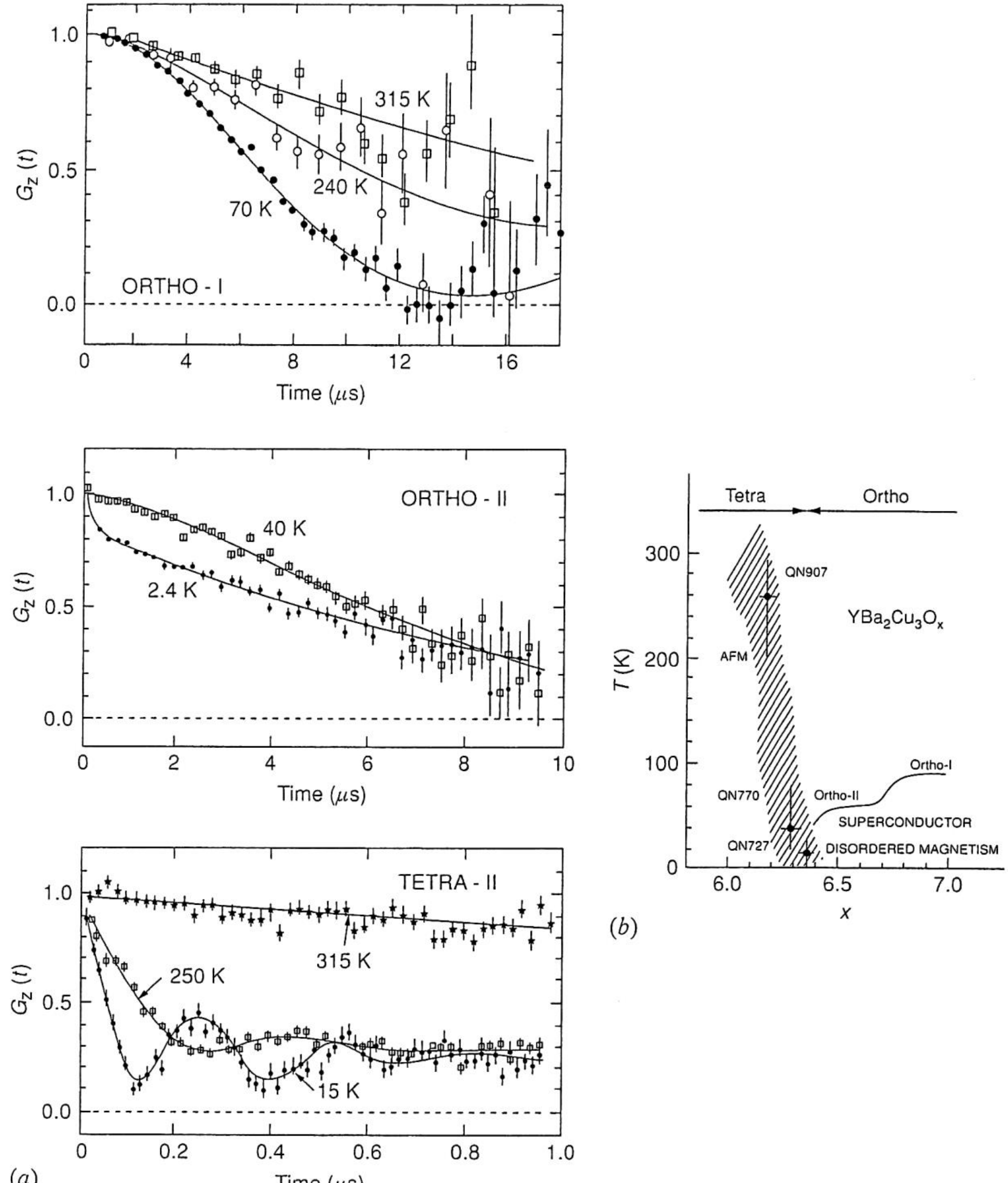
Temperature dependence of the relaxation rate or
Muon spin precession frequency.
Critical behavior

Magnetic Volume fraction

Magnetic structure is difficult to determine.

Superconductivity

Magnetism in High-Tc Superconductor



N.Nishida et al.
Jpn. J. Appl. Phys., 26, L1856–L1858 (1987)

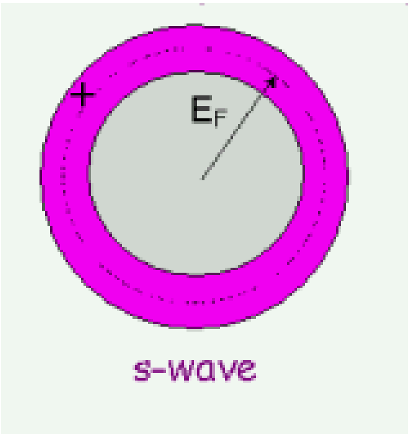
Electron Paring in Superconductor

Conventional SC —> BCS theory

isotropic pairing（s-wave）

isotropic Gap

Phonon mediated attracted interaction



High Tc Cuprate or heavy fermion systems etc,

non- s-wave superconductivity is appeared

due to strong electron correlation!

Pairing function depend on many properties,

Pairing Interaction(Phonon, Magnetic, others)

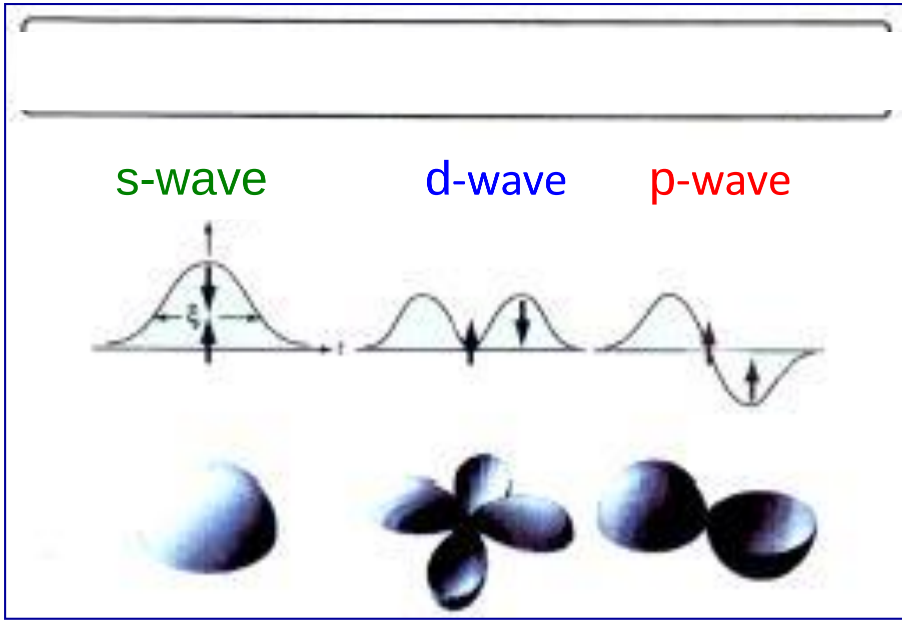
Crystal structure、

Fermi surface

etc COMPLEX

Paring symmetry is

important to know mechanism of SC!



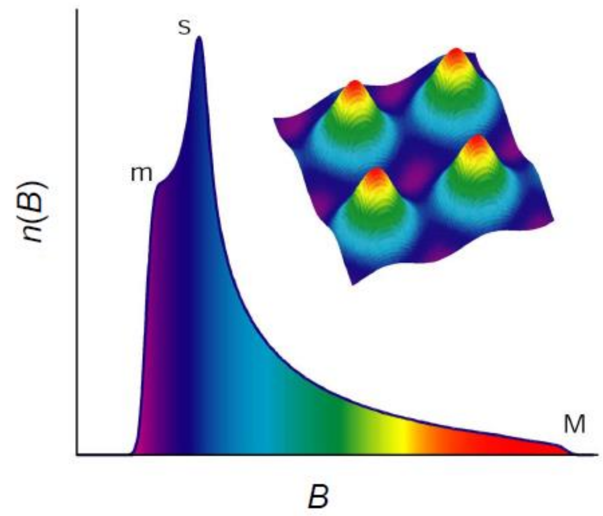
μSR Study on Superconductor
What we can know from μSR?

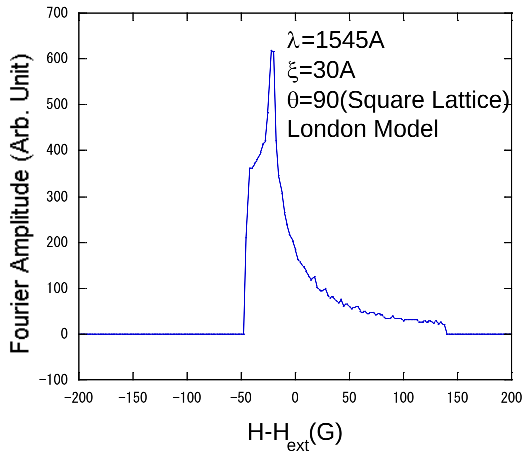
- ***Penetration Depth***
  - ***Temperature and Field Dependence***
  - ***→ SC Gap structure***
- ***Coexistence or Interplay with Magnetism***

- ***Pairing Symmetry of Cooper Pair***
  - ***Time Reversal Symmetry Broken or not***
    - ***Orbital and/or Spin***
    - ***only μSR can be detected !***

  - ***Knight Shift (μSR and NMR)***
    - ***Spin (Singlet or Triplet)***

etc.





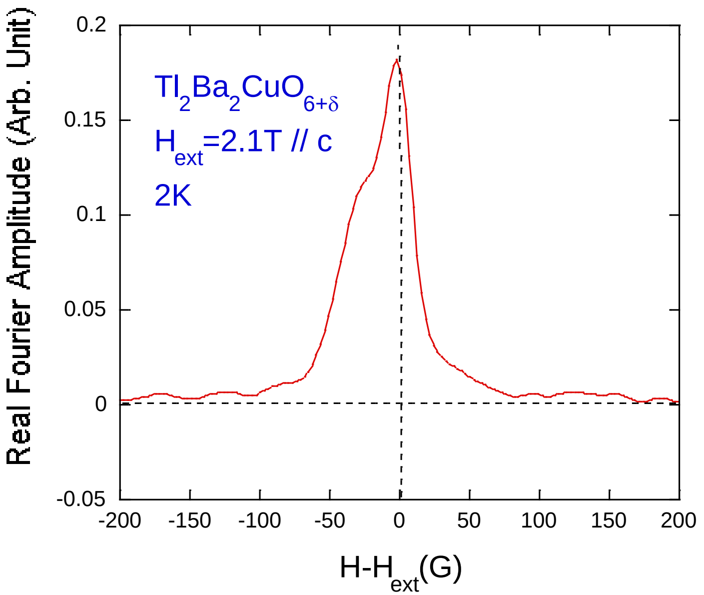
GL-model of spatial field profile:

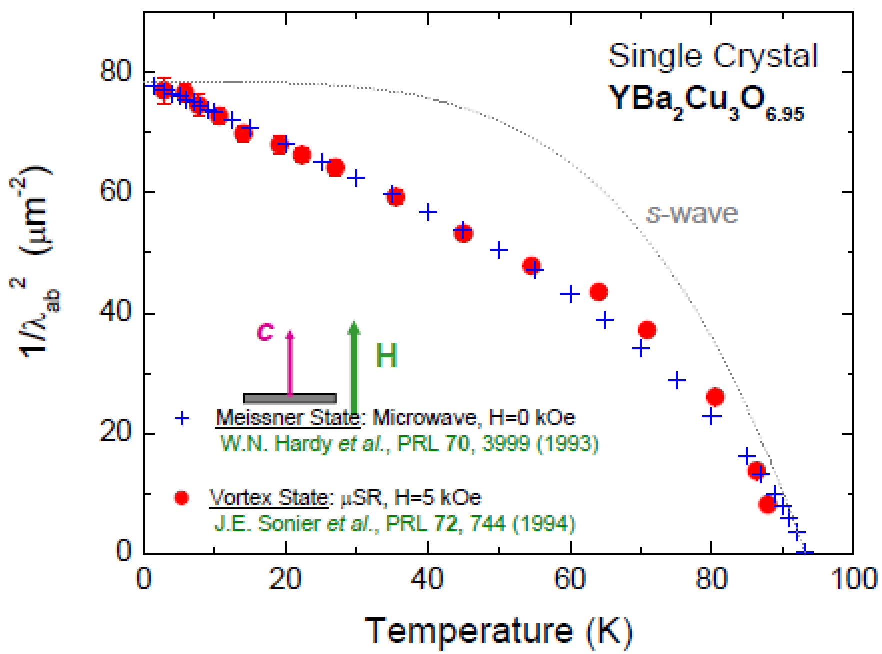
$$B(\vec{r}) = B_0(1-b^4)\sum_{\vec{G}} \frac{uK_1(u)e^{-i\vec{G}\cdot\vec{r}}}{\lambda_{ab}{}^2 G^2}$$

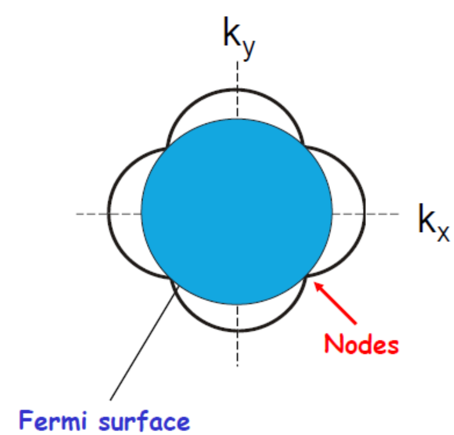
$$b = \frac{B}{B_{c2}} \qquad u^2 = 2\xi_{ab} G^2 (1+b^4)[1-2b(1-b)^2]$$

$\lambda_{ab} \equiv$ effective penetration depth

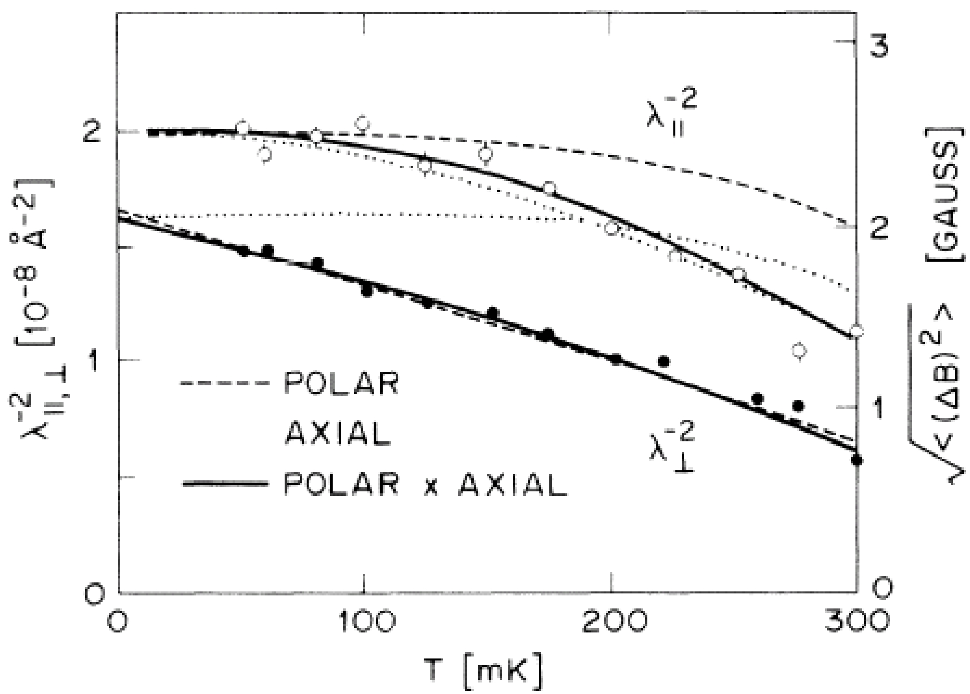
$\xi_{ab} \equiv$ effective vortex core size



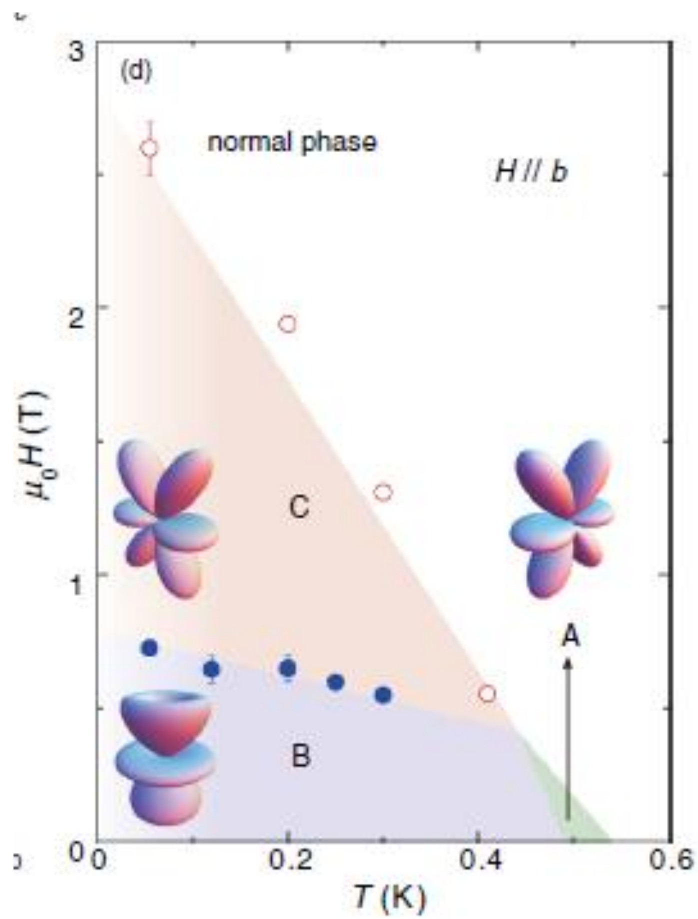

Single Crystal
YBa2Cu3O6.95
s-wave
c
H
Meissner State: Microwave, H=0 kOe
W.N. Hardy et al., PRL 70, 3999 (1993)
Vortex State: µSR, H=5 kOe
J.E. Sonier et al., PRL 72, 744 (1994)
1/λab2 (µm-2)
Temperature (K)


ky
kx
Nodes
Fermi surface

Temperature Dependence of Penetration Depth
Example UPt3



C. Broholm et al. Phys. Rev. Lett. **65**, 2062 (1990).



Y.Machida et al., Phys. Rev. Let. 108, 157002 (2012).

Purpose of present study

Determination of Symmetry of Cooper Pair

Superconducting State

(***Angular momentum L***)

x

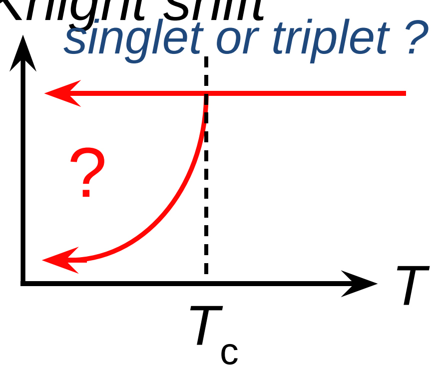
(***Total Spin S (singlet or triplet)***)

x

(***Time Reversal Symmetry***)

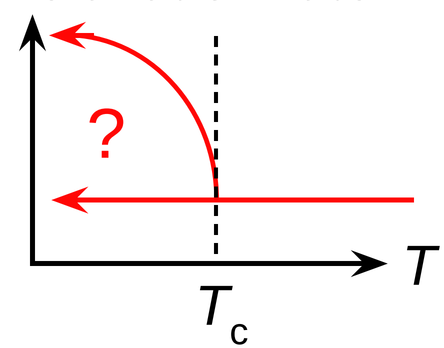
TF-μSR

Knight shift



ZF-μSR

Relaxation rate

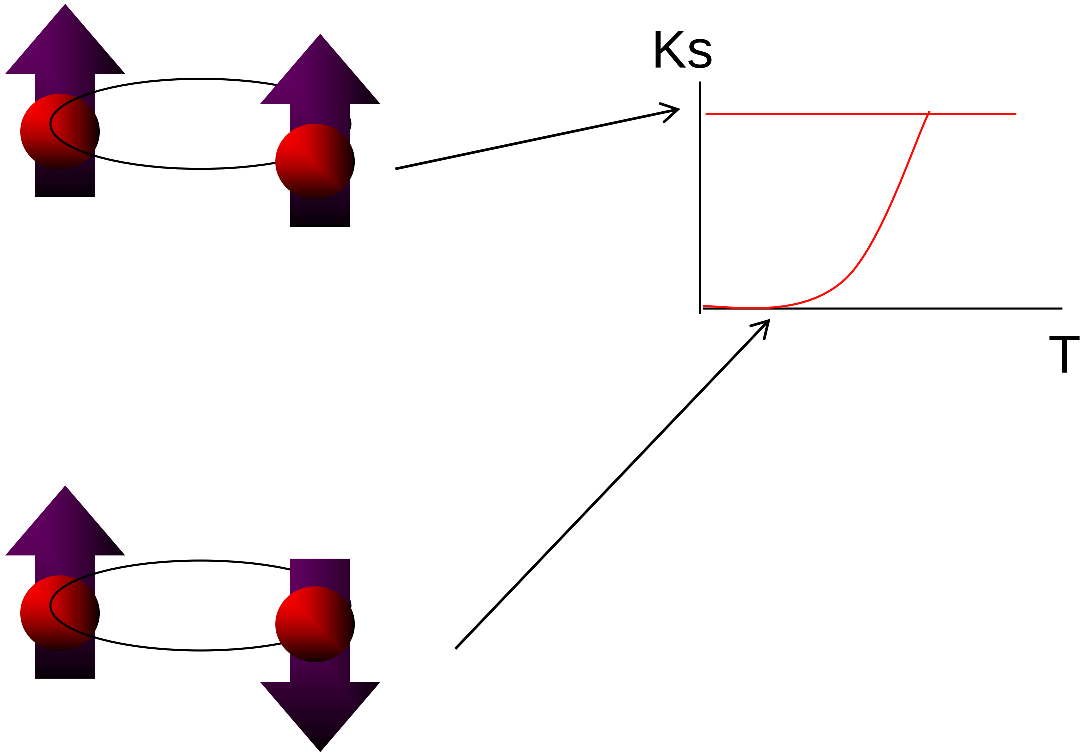


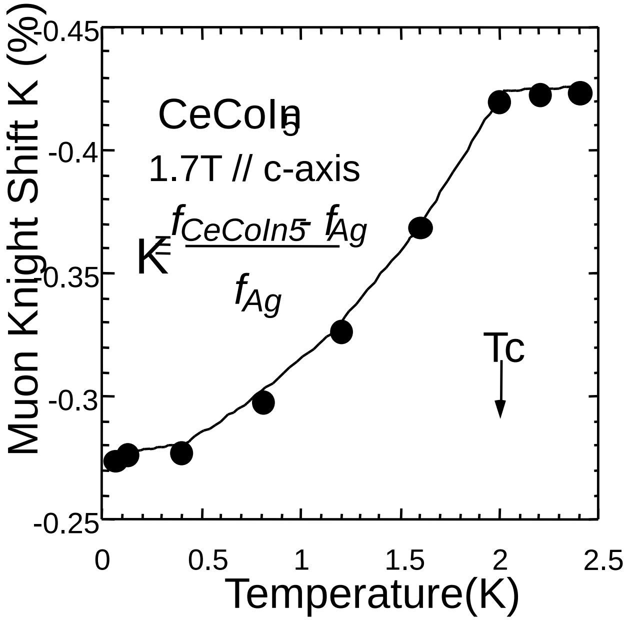
2 examples
PrOs4Sb12
Sr2RuO4

Knight shift $Ks = Ahf\chi s = -4\mu B \int Ns(E)(df/d\varepsilon)dE$

Spin triplet superconductor
rare case!

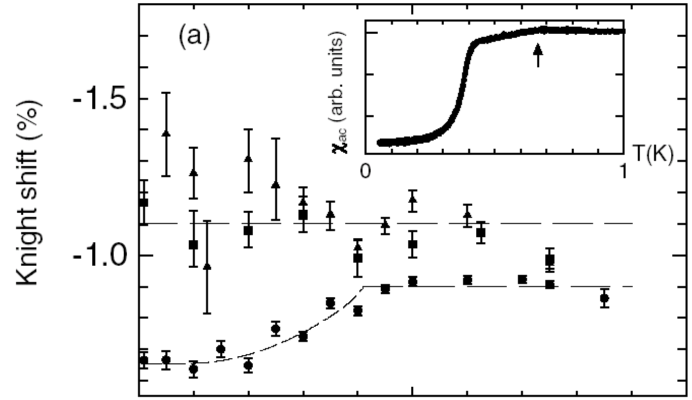
Spin singlet superconductor
BCS, d-wave etc





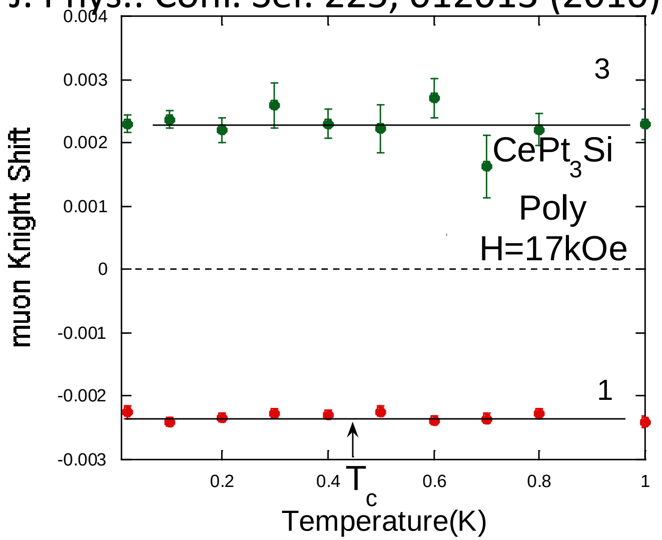
CeCoIn$_5$ Higemoto et al

J. Phys.: Conf. Ser. 225, 012013 (2010)



CeCu$_{1.99}$Si$_{2.02}$ Koda et al.

Journal of the Physical Society of Japan, 71,1427-1430(2002).



CePt3Si Higemoto et al

mSR studies of Knight shift on HFSC

muon spin ½ advantage against NMR

invariant

CePt3Si, PrOs4Sb12 etc

reduction

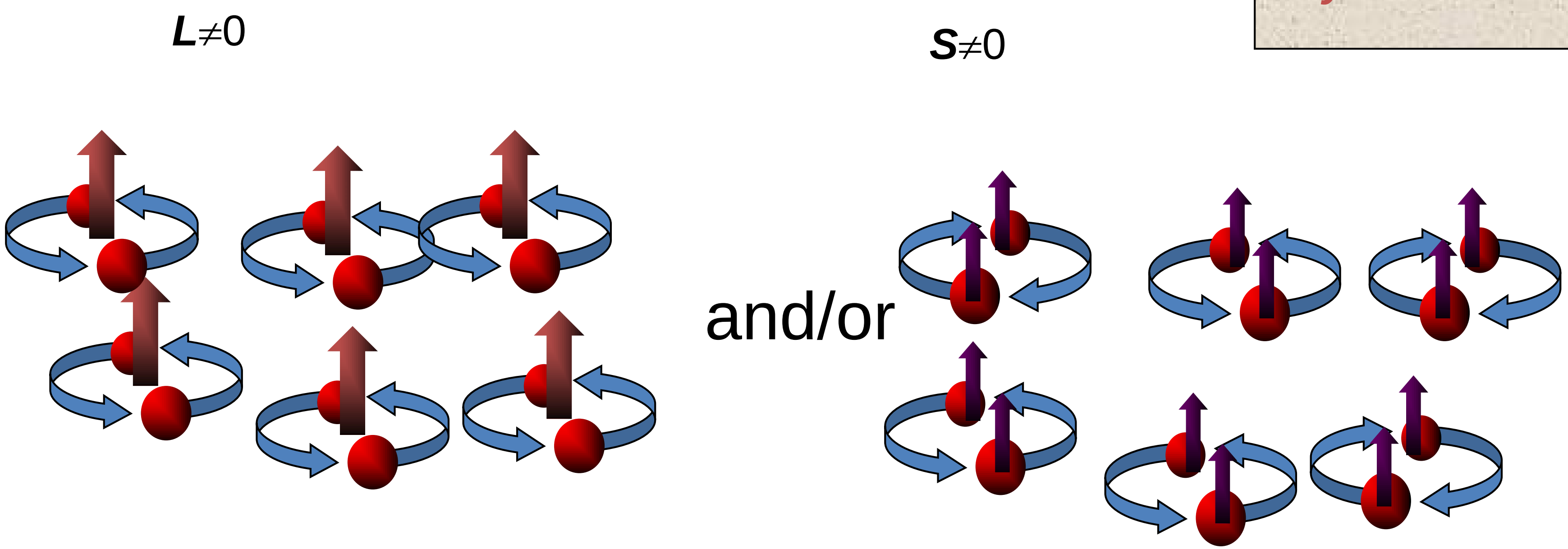
CeCoIn5, CeCu2Si2, etc

Time Reversal Symmetry Breaking Superconductivity

"Alignment" of Cooper Pair
Total Spin S≠0 and/or Total Angular Momentum L≠0
(⇔Conventional BCS Superconductor S=L=0)

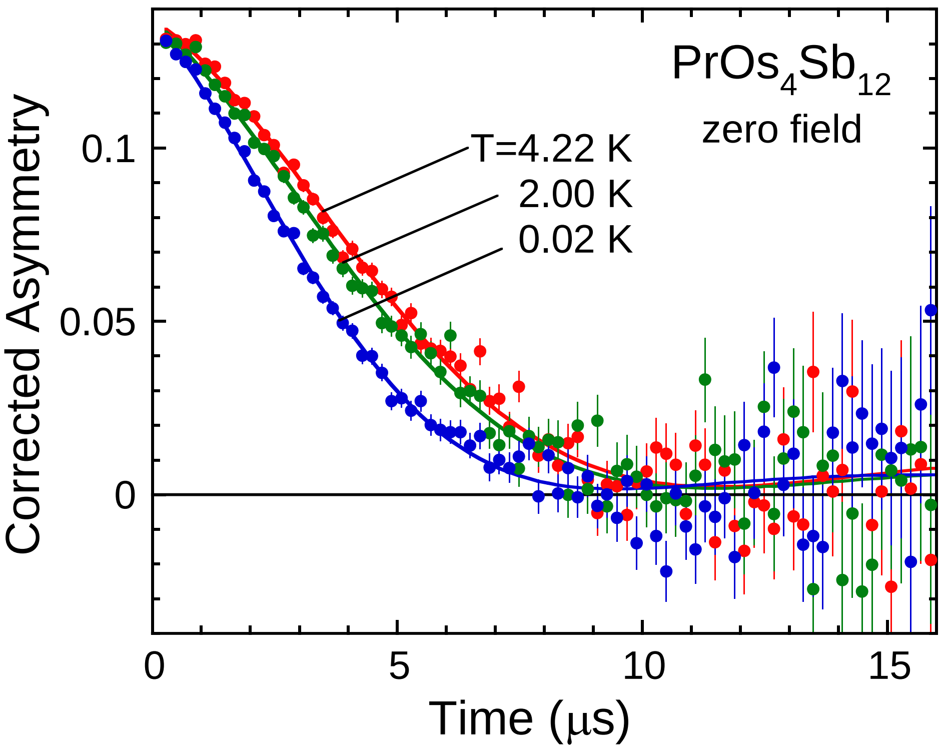
→

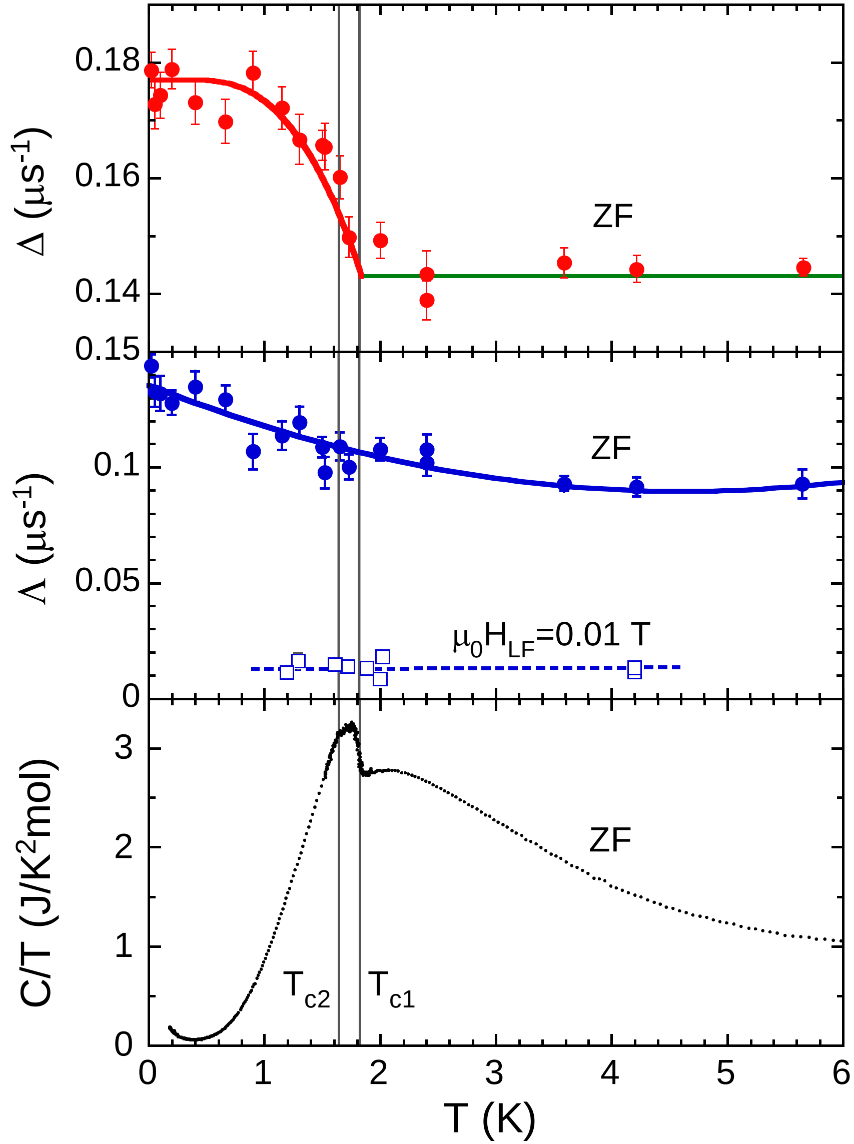
Local Field!!
Directory
Detected
by muon



Very weak local field appears
Bulk measurement → cancelled our due to domain structure
Highly sensitive probe , Muon, can detect this field!
Very rare! Only 2 examples are confirmed.

Time Reversal Symmetry Breaking SC





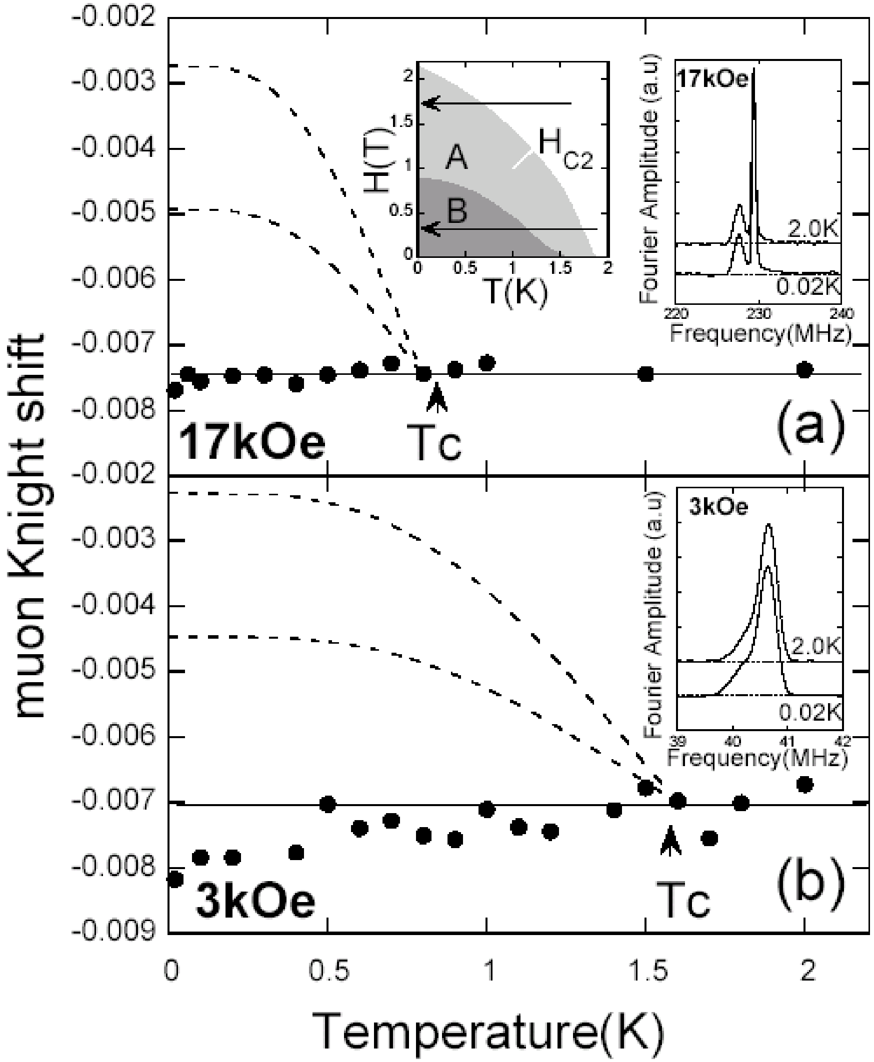
$P\mu = \exp(-\Lambda t) \bullet Gz^{KT}(\Delta, t)$ where

$\Delta = (\Delta SC^2 + \Delta n^2)^{1/2}$

Δ significant increase in the SC state

$\Delta SC(T=0) \rightarrow \sim$ **1.2 G**

*Y.Aoki, WH et al., PRL **91** (2003) 067003*



$$K^{qp} = \frac{A_{hf}}{N_A \mu_B} \frac{\gamma_{el} g_J^2 J_{eff}^2 \mu_B^2}{\pi^2 k_B^2} R.$$

Muon Knight Shift measurements

Knight shift independent on temperature
above and below Tc

Suggestion of Spin triplet SC

Consistent with NMR

W.Higemoto et al.,
PRB75 020510-1-4 (2007).

μSR Study on Superconductor

What we can know from μSR?

·Penetration Depth

Temperature and Field Dependence

→ SC Gap structure

·Coexistence or Interplay with Magnetism

·Pairing Symmetry of Cooper Pair

· Time Reversal Symmetry Broken or not

Orbital and/or Spin

only μSR can be detected !

·Knight Shift (μSR and NMR)

Spin (Singlet or Triplet)

etc.

SUMMARY: Research with muon

From basic science to industrial application

Basic Science		Applications
Materials science Superconductivity Magnetism Quantum diffusion Hydrogen related phenomena **Chemistry** Hydrogen related chemical reaction **Particle Physics** g-2 Super symmetry Rare decay	**Muon catalyzed fusion** Energy problems **Biology** Protein, DNA Electronic state **Beam development** Beam cooling	**Non destructive analysis** Element analysis inside sample **Industrial applications** Hydrogen energy Semiconductors Battery