Introduction to μSR

From parity violation to modern techniques

Graeme Luke   August 20, 2025

McMaster University

Parity Violation

Prediction & Observation

PHYSICAL REVIEW VOLUME 104, NUMBER 1 OCTOBER 1, 1956

Question of Parity Conservation in Weak Interactions*

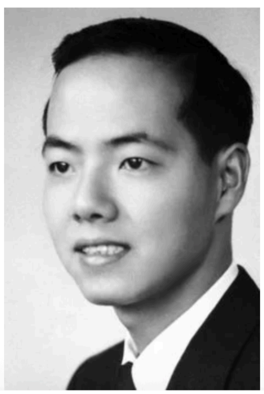
T. D. Lee, *Columbia University, New York, New York*

AND

C. N. Yang,† *Brookhaven National Laboratory, Upton, New York*

(Received June 22, 1956)

The question of parity conservation in β decays and in hyperon and meson decays is examined. Possible experiments are suggested which might test parity conservation in these interactions.



Experimental Test of Parity Conservation in Beta Decay*

C. S. Wu, *Columbia University, New York, New York*

AND

E. Ambler, R. W. Hayward, D. D. Hoppes, and R. P. Hudson, *National Bureau of Standards, Washington, D. C.*

(Received January 15, 1957)

[4] Their arguments are as follows: From the He^6 recoil experiment and from Eq. (A-4) of reference 1 one concludes that $(|C_A|^2+|C_A'|^2)/(|C_T|^2+|C_T'|^2)\lesssim\frac{1}{3}$. Hence, by comparing Eq. (16) of reference 3 [see also Eq. (A-6) of reference 1], one concludes that the present large asymmetry is possible only if both conservation of parity and invariance under charge conjugation are violated.

Observations of the Failure of Conservation of Parity and Charge Conjugation in Meson Decays: the Magnetic Moment of the Free Muon*

Richard L. Garwin,† Leon M. Lederman, and Marcel Weinrich

Physics Department, Nevis Cyclotron Laboratories, Columbia University, Irvington-on-Hudson, New York, New York

(Received January 15, 1957)

Lee and Yang[1–3] have proposed that the long held space-time principles of invariance under charge conjugation, time reversal, and space reflection (parity) are violated by the "weak" interactions responsible for decay of nuclei, mesons, and strange particles. Their hypothesis, born out of the $\tau-\theta$ puzzle,[4] was accompanied by the suggestion that confirmation should be sought (among other places) in the study of the successive reactions

$$\pi^+\rightarrow\mu^++\nu, \qquad (1)$$

$$\mu^+\rightarrow e^++2\nu. \qquad (2)$$

They have pointed out that parity nonconservation implies a polarization of the spin of the muon emitted from stopped pions in (1) along the direction of motion and that furthermore, the angular distribution of electrons in (2) should serve as an analyzer for the muon polarization. They also point out that the longitudinal polarization of the muons offers a natural way of determining the magnetic moment.[5] Confirmation of this proposal in the form of preliminary results on β decay of oriented nuclei by Wu *et al.* reached us before this experiment was begun.[6]

By stopping, in carbon, the μ^+ beam formed by forward decay in flight of π^+ mesons inside the cyclotron, we have performed the meson experiment, which establishes the following facts:

I. A large asymmetry is found for the electrons in (2), establishing that our μ^+ beam is strongly polarized.

II. The angular distribution of the electrons is given by $1+a\cos\theta$, where θ is measured from the velocity vector of the incident μ's. We find $a=-\frac{1}{3}$ with an estimated error of 10%.

III. In reactions (1) and (2), parity is not conserved.

IV. By a theorem of Lee, Oehme, and Yang,[2] the observed asymmetry proves that invariance under charge conjugation is violated.

V. The g value (ratio of magnetic moment to spin) for the (free) μ^+ particle is found to be $+2.00\pm0.10$.

VI. The measured g value and the angular distribution in (2) lead to the very strong probability that the spin of the μ^+ is $\frac{1}{2}$.[7]

VII. The energy dependence of the observed asymmetry is not strong.

VIII. Negative muons stopped in carbon show an asymmetry (also leaked backwards) of $a\sim-1/20$, i.e., about 15% of that for μ^+.

IX. The magnetic moment of the μ^-, bound in carbon, is found to be negative and agrees within limited accuracy with that of the μ^+.[8]

X. Large asymmetries are found for the e^+ from polarized μ^+ beams stopped in polyethylene and calcium. Nuclear emulsion (as a target in Fig. 1) yields an asymmetry of about half that observed in carbon.

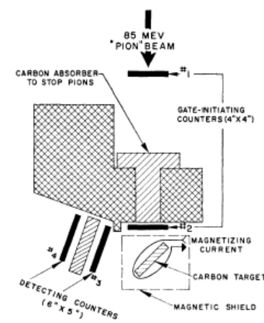


Fig. 1. Experimental arrangement. The magnetizing coil was close wound directly on the carbon to provide a uniform vertical field of 79 gauss per ampere.

The experimental arrangement is shown in Fig. 1. The meson beam is extracted from the Nevis cyclotron in the conventional manner, undergoing about 120° of magnetic deflection in the cyclotron fringing field and about −30° of deflection and mild focusing upon emerging from the 8-ft shielding wall. The positive beam contains about 10% of muons which originate principally in the vicinity of the cyclotron target by pion decay-in-flight. Eight inches of carbon are used in the entrance telescope to separate the muons, the mean range of the "85-"Mev pions being ~5 in. of carbon. This arrangement brings a maximum number of muons to rest in the carbon target. The stopping of a muon is signalled by a fast 1–2 coincidence count. The subsequent beta decay of the muon is detected by the electron telescope 3–4 which normally requires a particle of range >8 g/cm²(~25-Mev electrons) to register. This arrangement has been used to measure the lifetimes of μ^+ and μ^- mesons in a vast number of elements.[9] Counting rates are normally ~20 electrons/

Richard Garwin

1928-2025

- Student of Fermi (1949).
- First muon spin rotation experiment (1957).
- Designer of first hydrogen bomb.
- National Medal of Science
- National Academy of Sciences, Medicine, Engineering.
- Presidential Medal of Freedom.
- AAAS Award for Scientific Freedom and Responsibility.
- U.S. President’s Science Advisory Committee, JASON.
- “The most influential scientist you never heard of.”

Pion Production

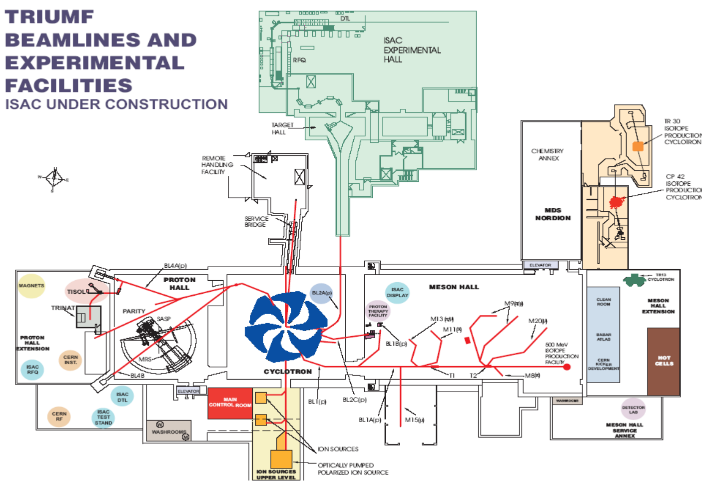
- Bombard nucleons with other nucleons of sufficient K.E. to give C of M energy greater than 140MeV/c².
- Typically, lab frame single pion production threshold roughly 280 MeV.
- Pion production cross-section rises roughly linearly with energy to roughly 1000 MeV.
- At higher energies, pion produced in pairs (>1GeV).

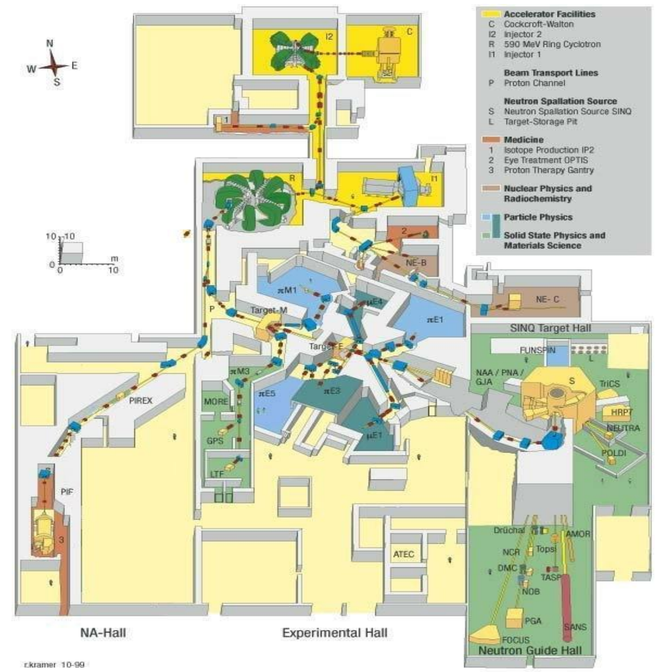
$$\begin{aligned} p + p &\rightarrow p + n + \pi^+ \\ &\rightarrow p + p + \pi^0 \end{aligned}$$

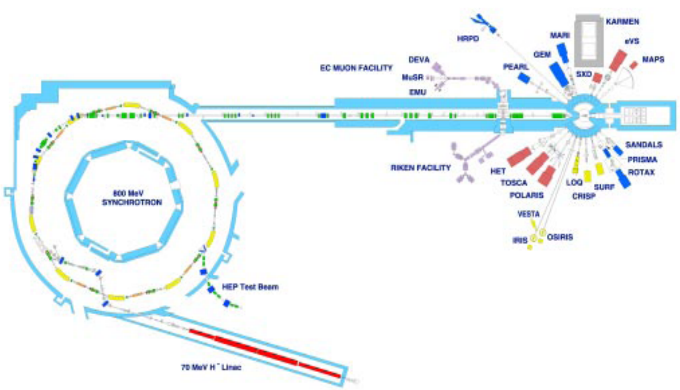
$$\begin{aligned} p + n &\rightarrow p + n + \pi^0 \\ &\rightarrow p + p + \pi^- \\ &\rightarrow n + n + \pi^+ \end{aligned}$$

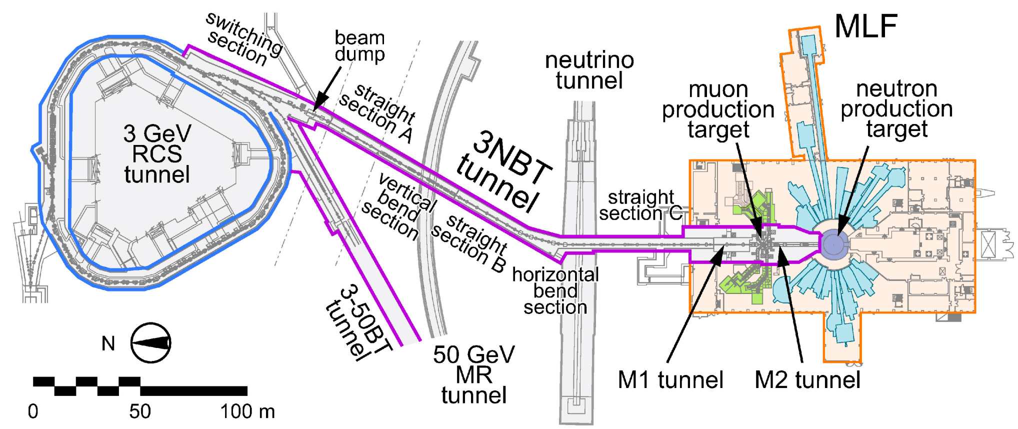
$$p + p \rightarrow d + \pi^+$$

Accelerators





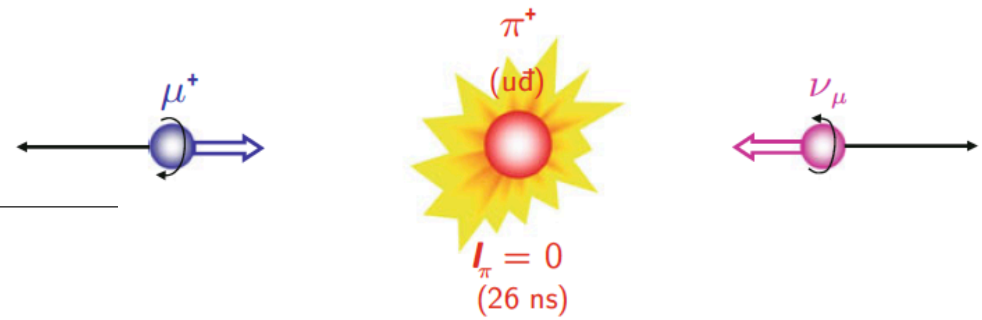





HEEDE
WLL 56 TON (2x28 Ton)

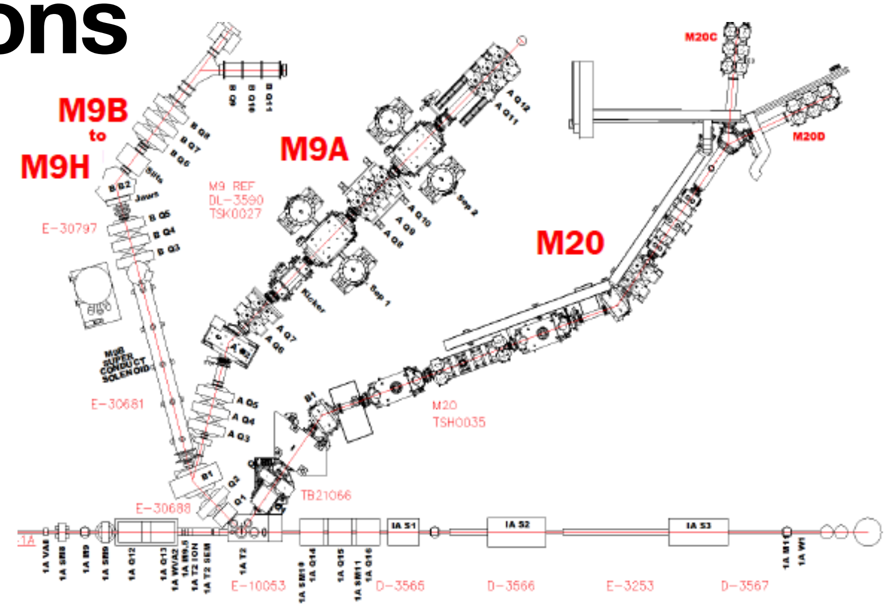
Pion Decay

Parity violation

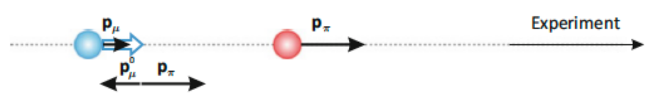


- π has I=0
- Conservation of momentum, υ and μ travel 180° to each other.
- only left-handed neutrinos.
- muon spin antiparallel to momentum.
- In π rest frame, mono-energetic muon 4.1 MeV, p=29.7877 MeV/c.

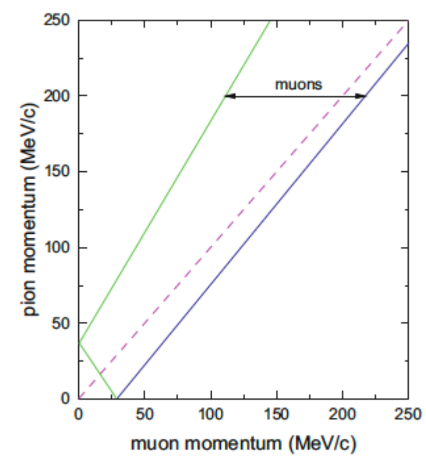
Surface vs. Decay Muons



- Surface beam mono-energetic (4.1 MeV).
  - small beam spot (high luminosity).
- Only positive surface muons.
- Higher energy muons from pions that decay in flight
  - Negative muons
  - high pressure experiments

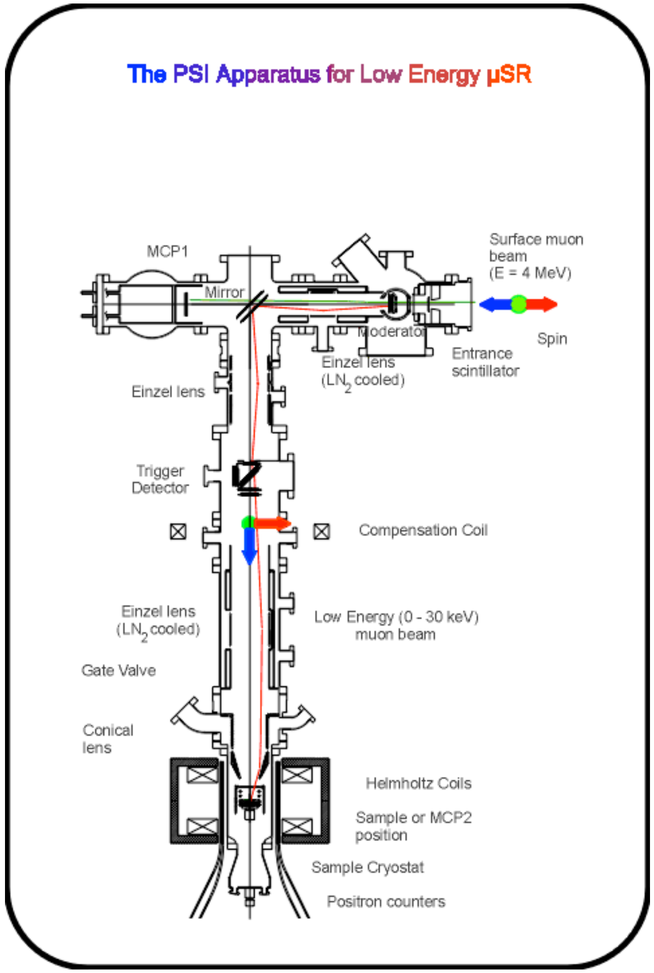


“Backward muons”

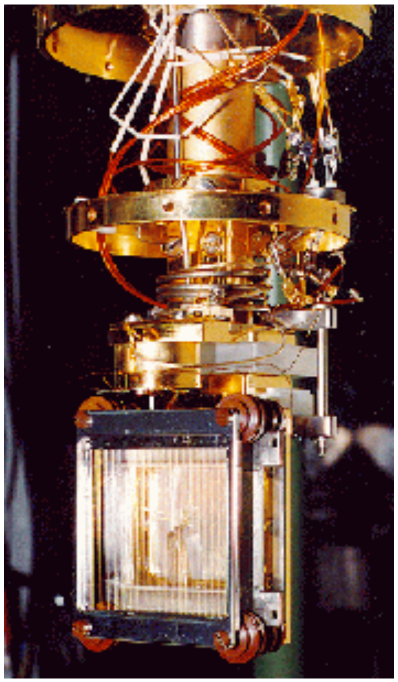


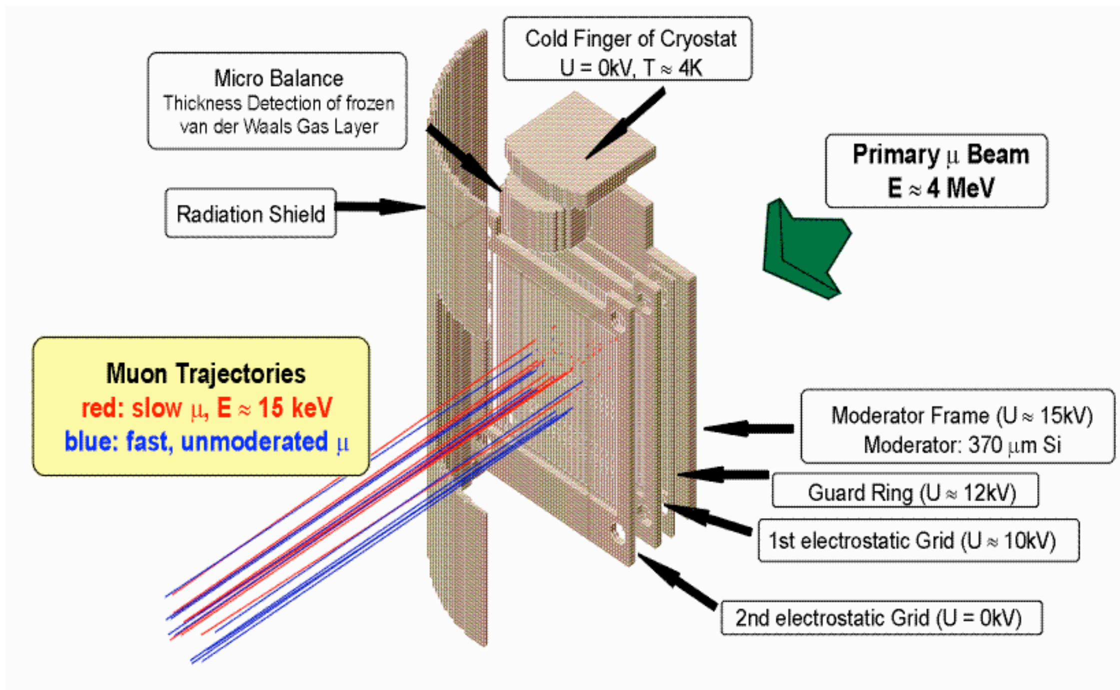
Low Energy Muons

- Conventional surface muons have stopping range of 140 mg/ cm^2
- Thin film samples/ surfaces require reduced depth penetration.

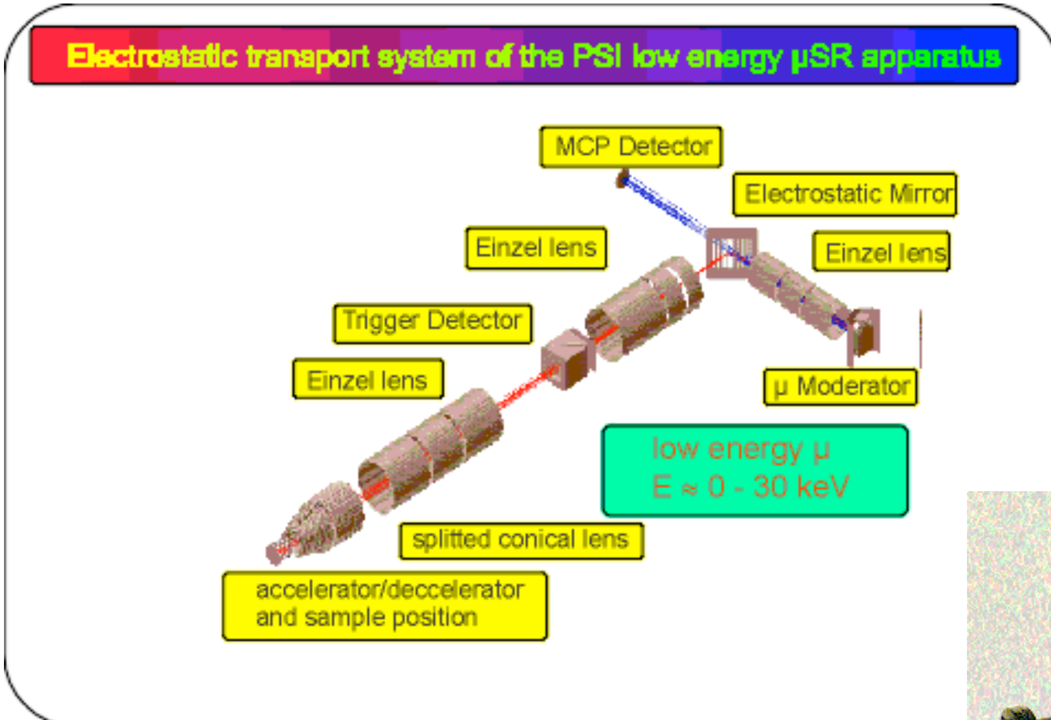


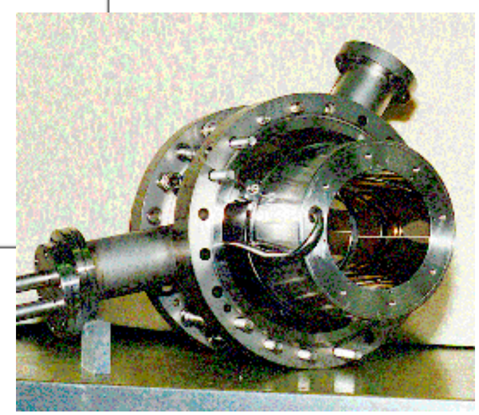
Muon Moderation



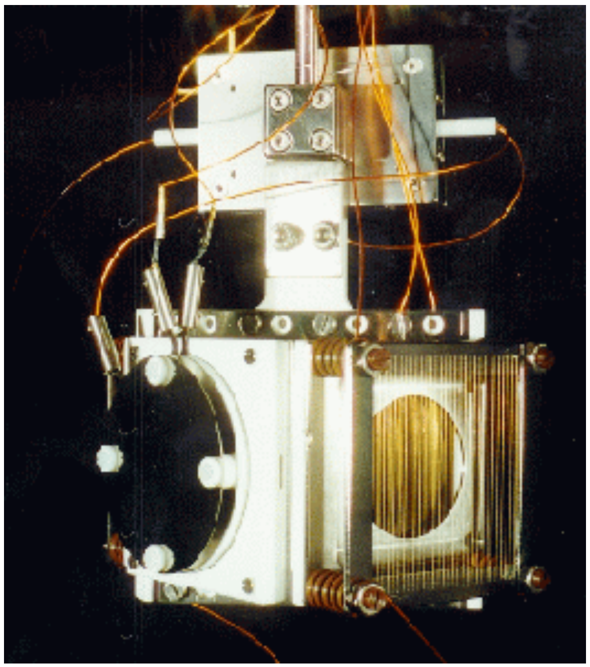


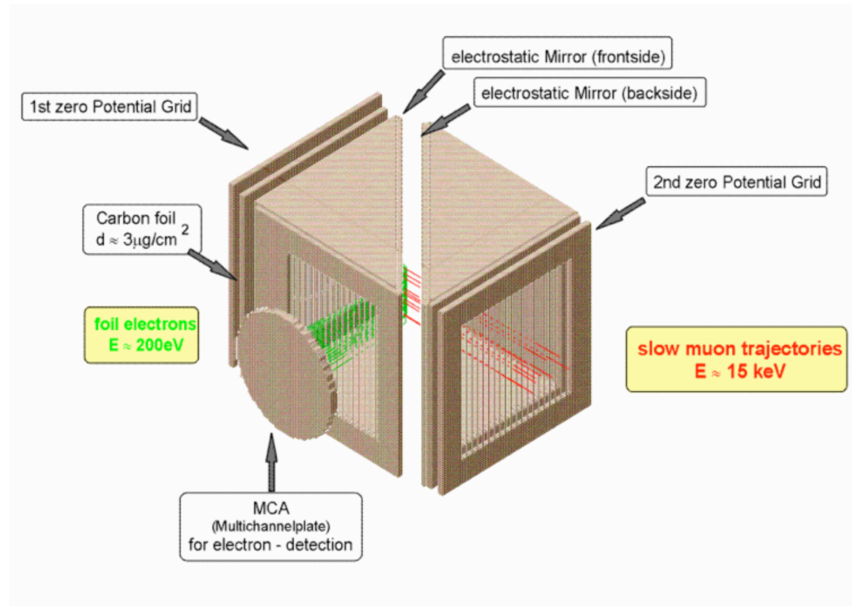
Low Energy Transport



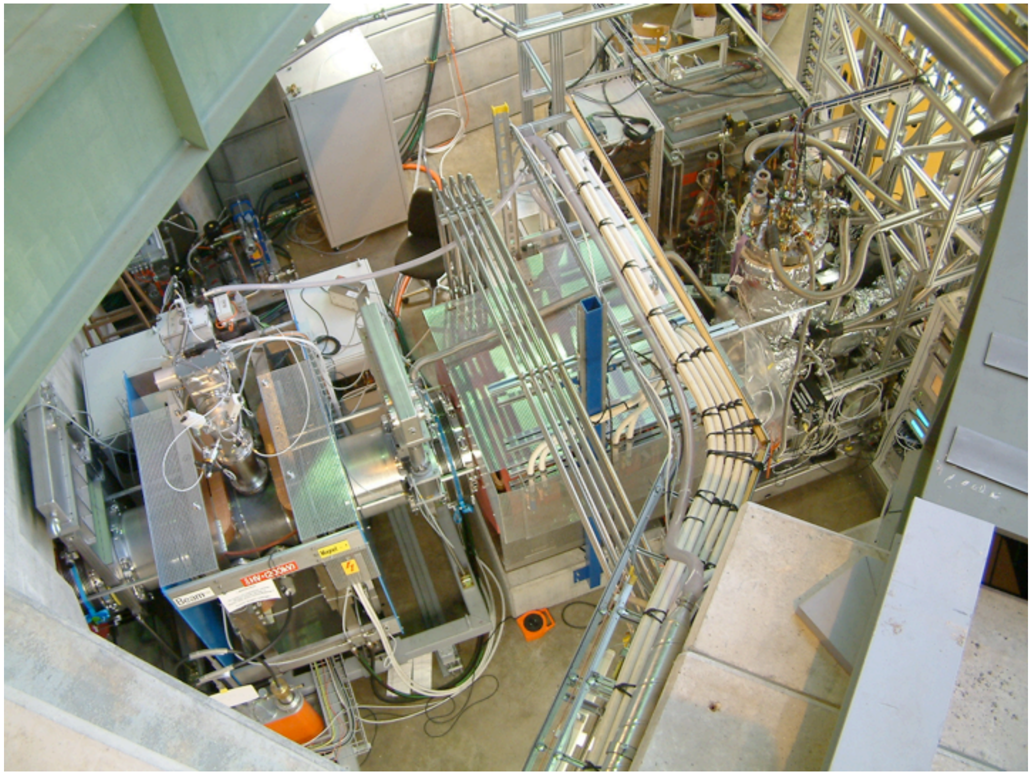


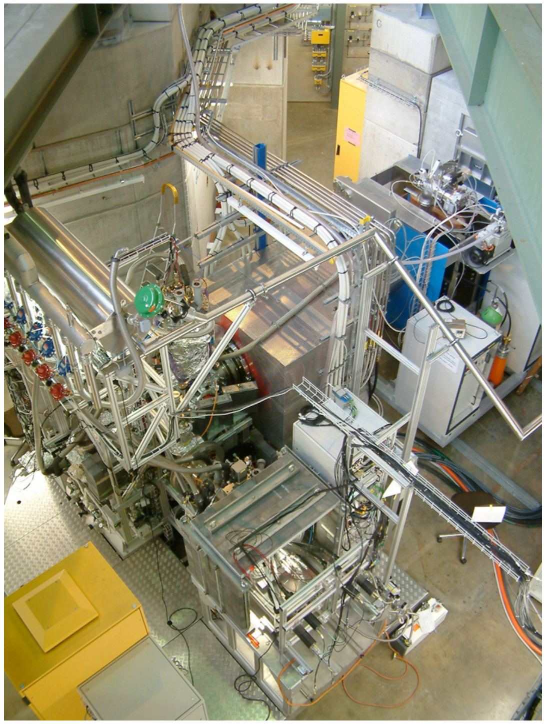
Muon Trigger





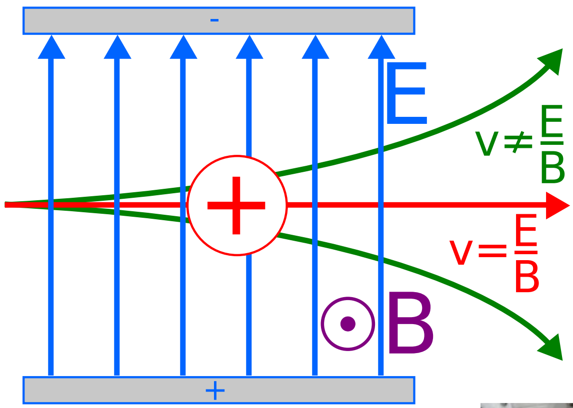
Low Energy uSR- PSI



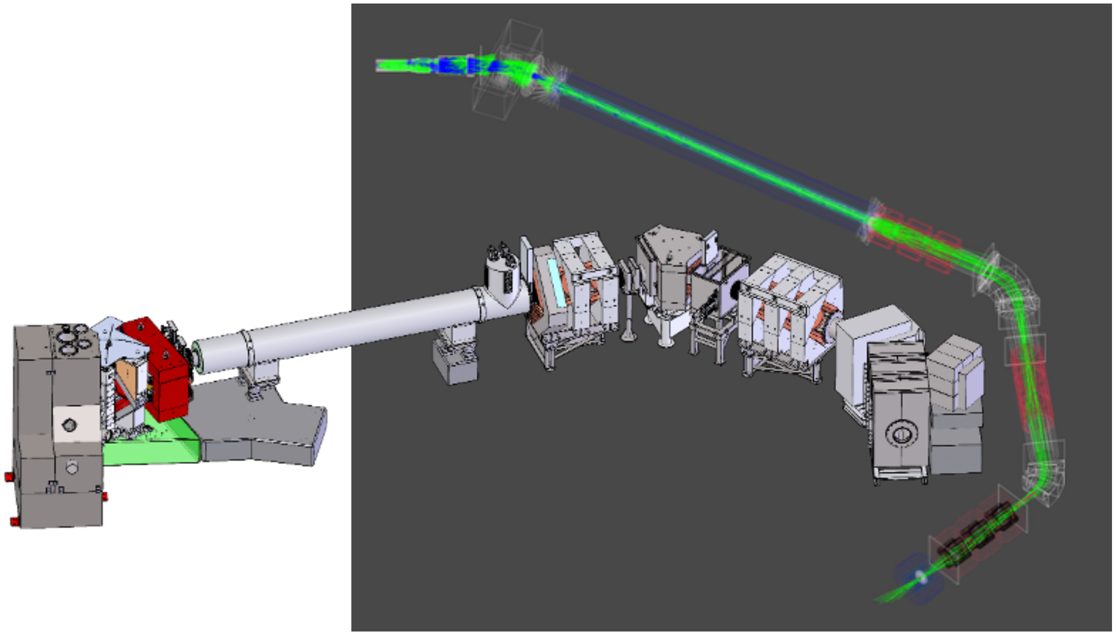


Initial Muon Spin Polarization

Surface vs. Decay muons



Wien filter, acts as spin rotator. Typically ±400 kV for 90 degree rotation.



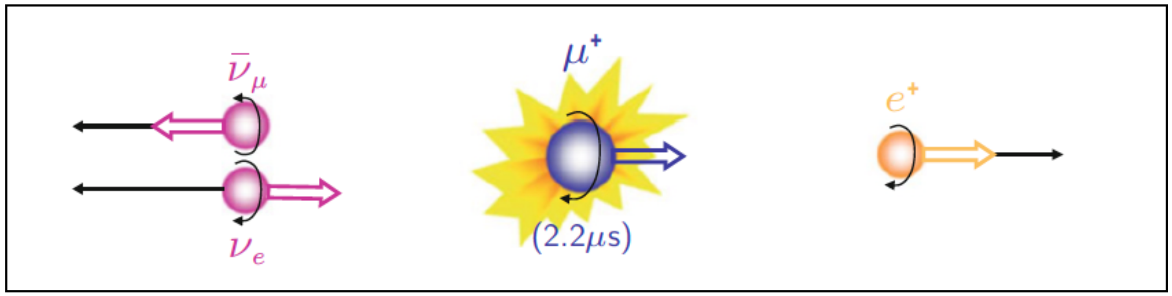
Off-axis tuning of decay beam can deliver transverse field polarization. TRIUMF M9H

Muon Decay

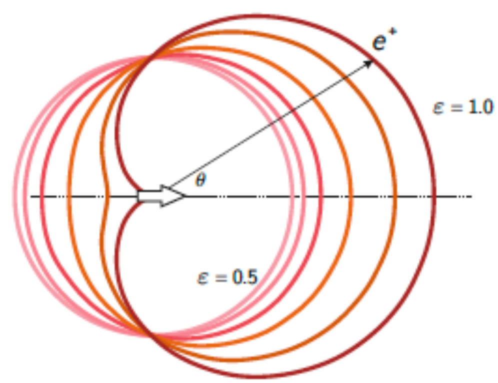
Weak interaction: parity violation

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

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



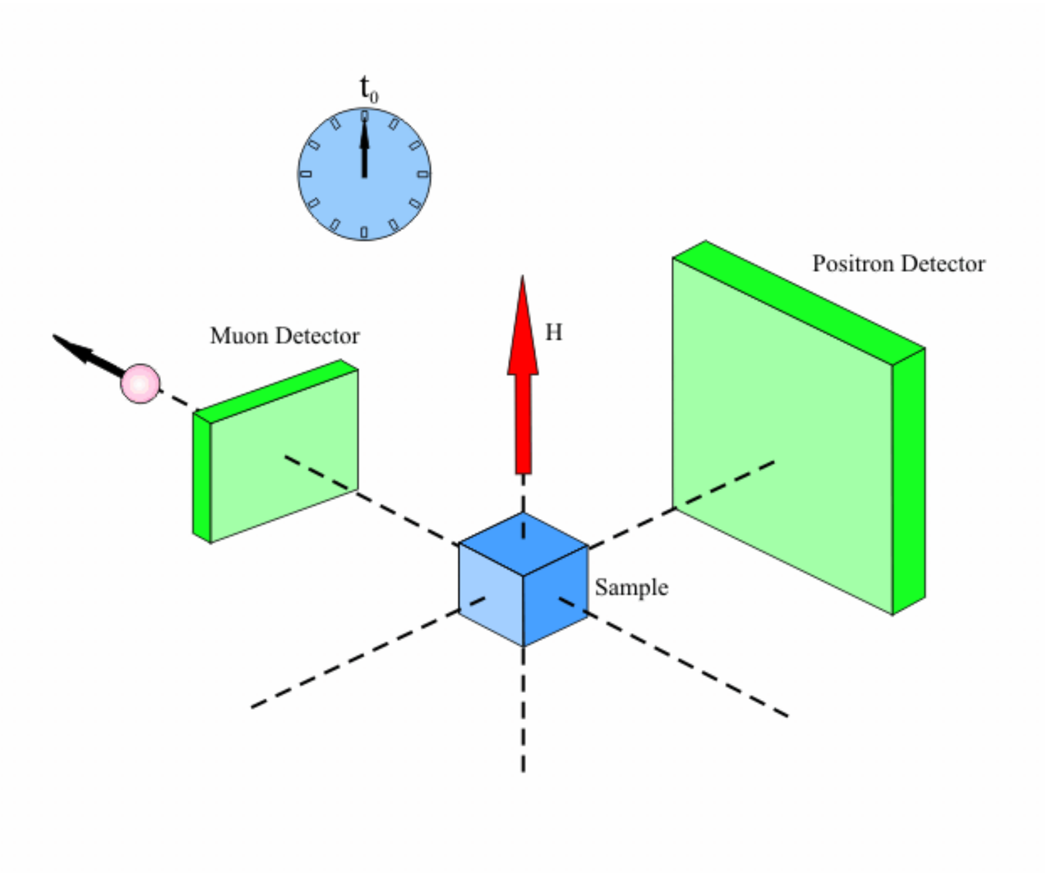
Max E_{e+}= 52.83 MeV.

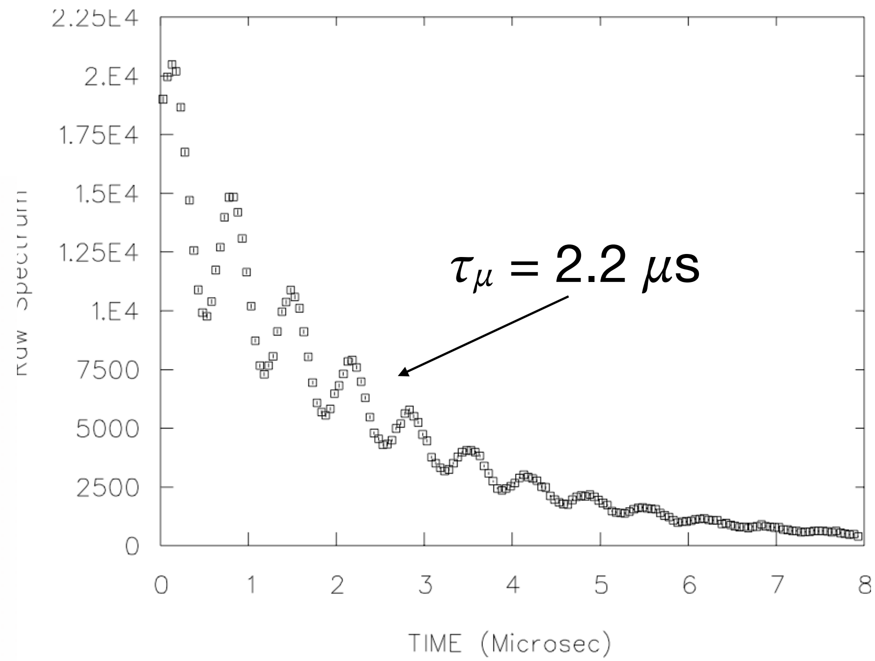


<a>=1/3

μSR Technique

Continuous (dc) beam



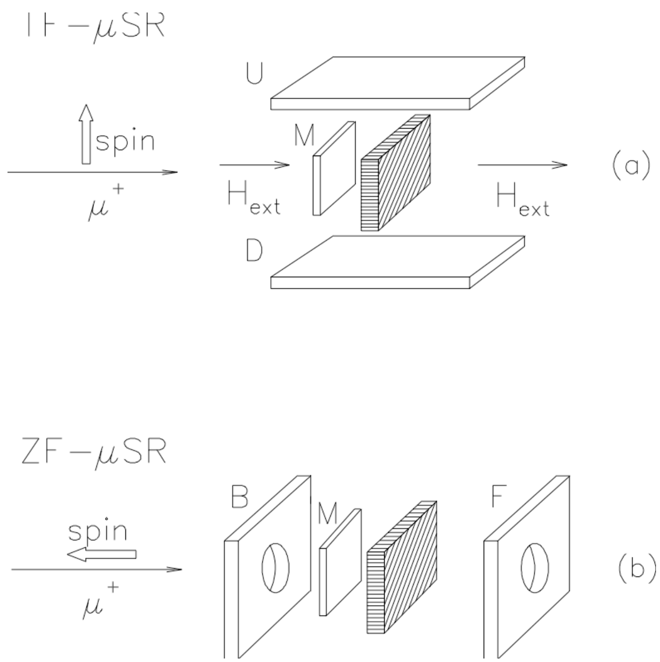


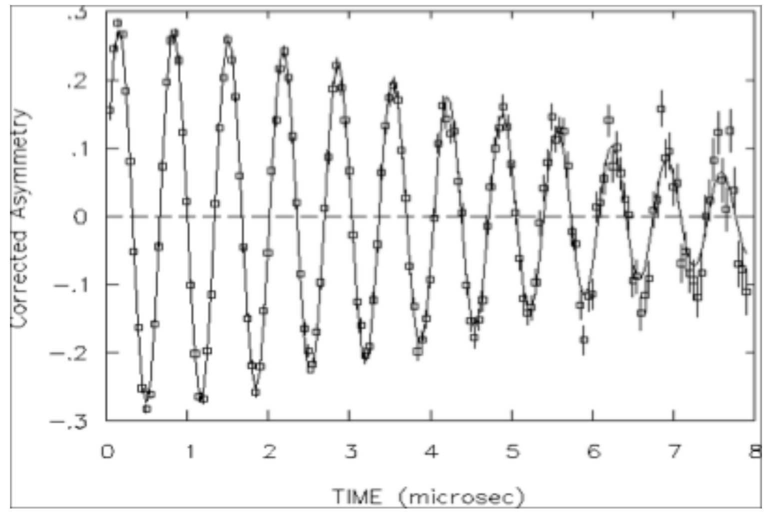
$$N(t) = N_0\left(B + e^{-t/\tau_\mu}\left[1 + A_0\mathcal{P}(t)\right]\right)$$

Experimental Geometry

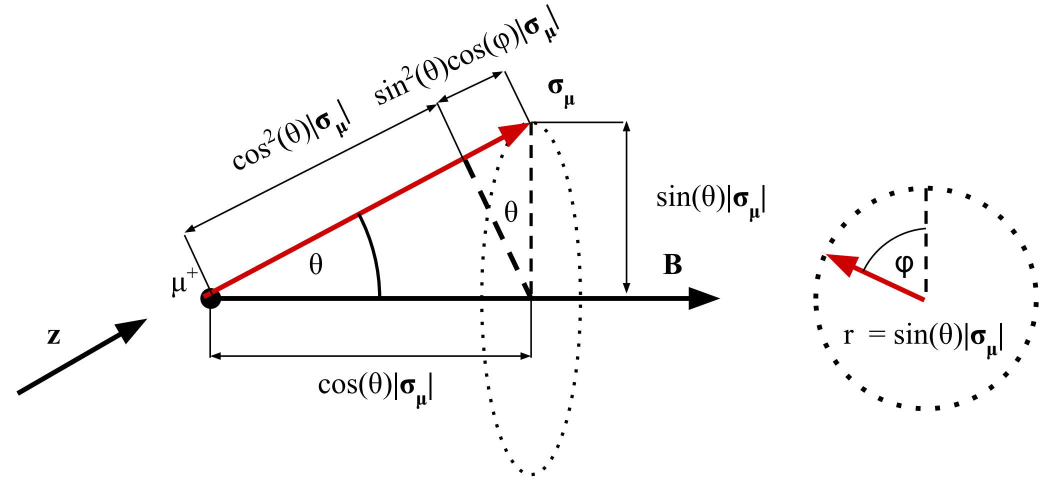
$$A(t) = \frac{N_A(t) - \alpha N_B(t)}{N_A(t) + \alpha N_B(t)}$$

TF-μSR : ZF/LF-μSR





ZF-μSR



$\sigma_Z = \cos^2\theta + \sin^2\theta \cos(\gamma_\mu|H|t)$

$\cos^2\theta$: average time-independent polarization along z

$\sin^2\theta$: precessing signal

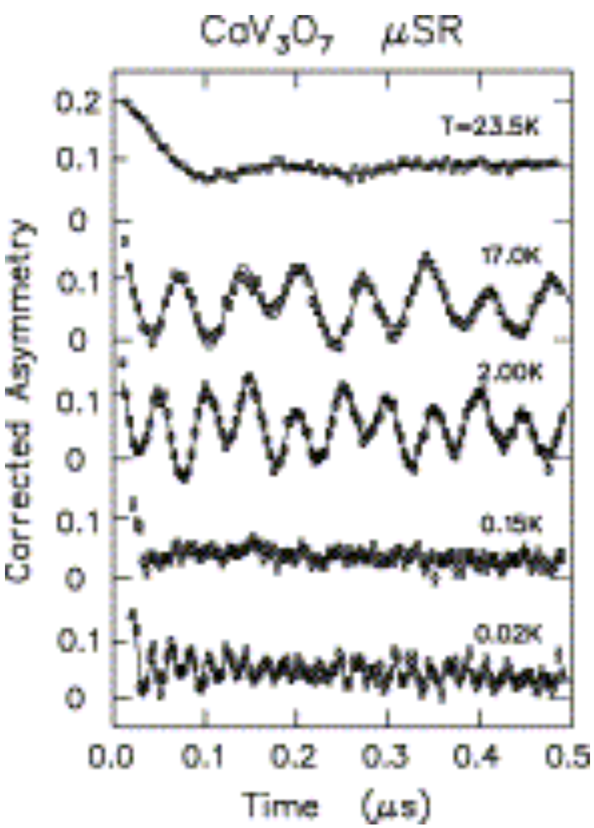
frequency: $\gamma_\mu|H|$ indep. of θ.

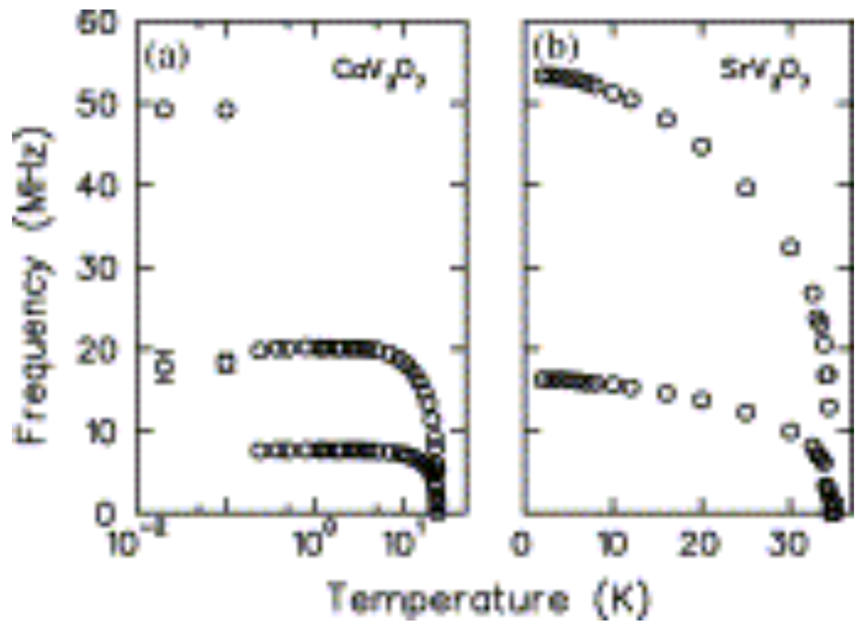
$$G_Z(t) = \int P(\vec{H})\sigma_Z d\vec{H}$$

•For isotropic polycrystal/powder/ceramic with well-defined local field:

$G_Z(t) = 1/3 + 2/3\cos(\gamma_\mu|H|t)$

•Measuring $\omega_\mu = \gamma_\mu|H|$ vs. T gives order parameter

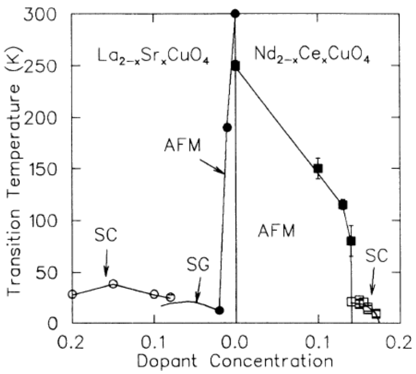


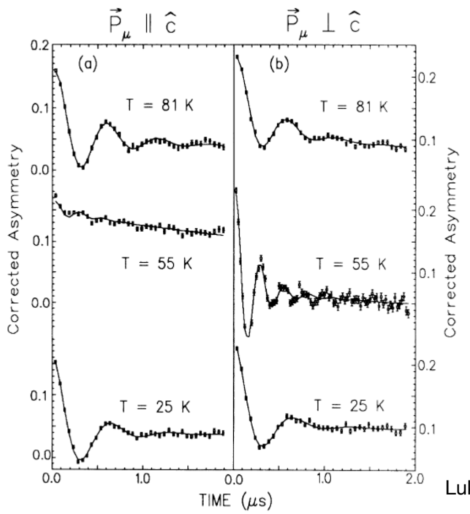


Fudamoto *et al.*, Physica B 329-333, 717 (2003)

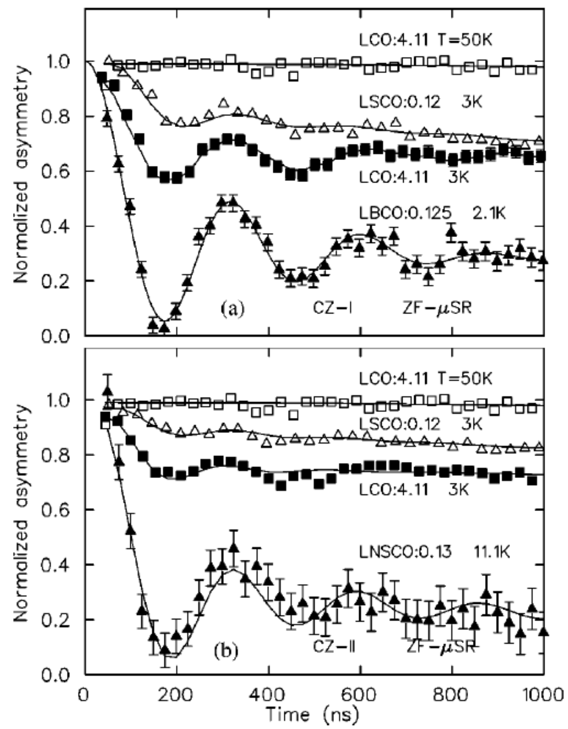
ZF-μSR

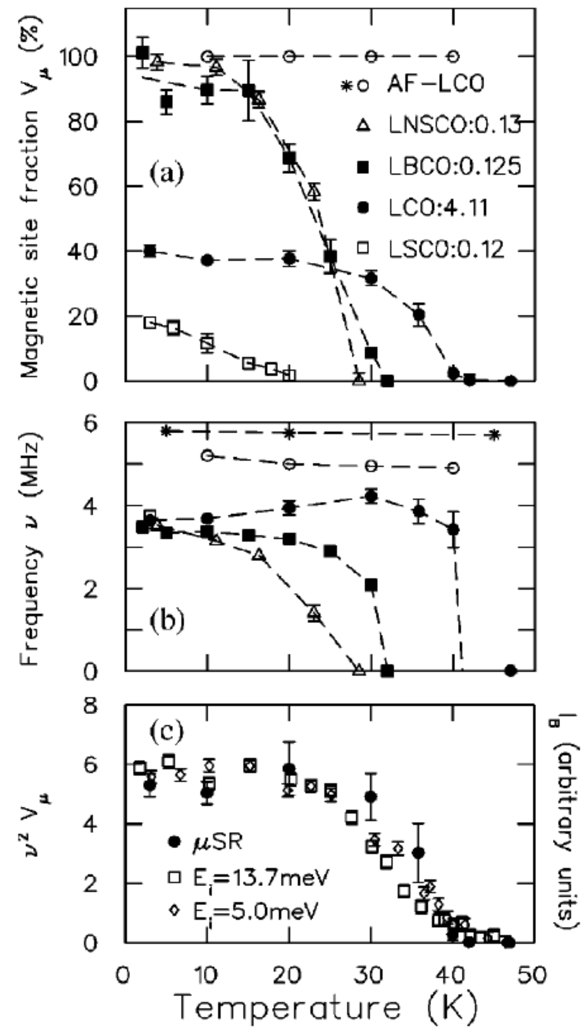
Magnetic Order





Luke *et al.*, PRB **42**, 07981 (1990)



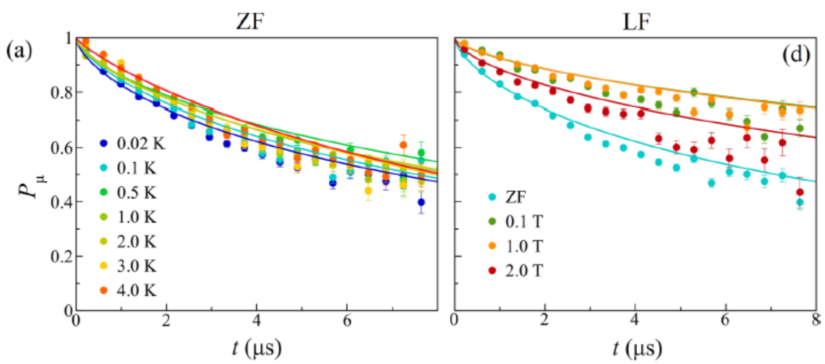


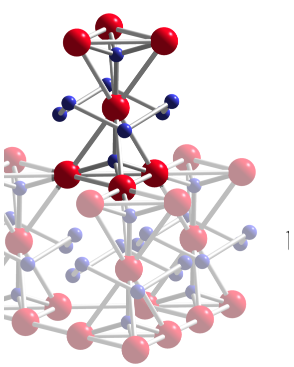
Savici *et al.*, PRB **66**, 014524 (2002)

ZF/LF-μSR

Absence of magnetism QSL candidates

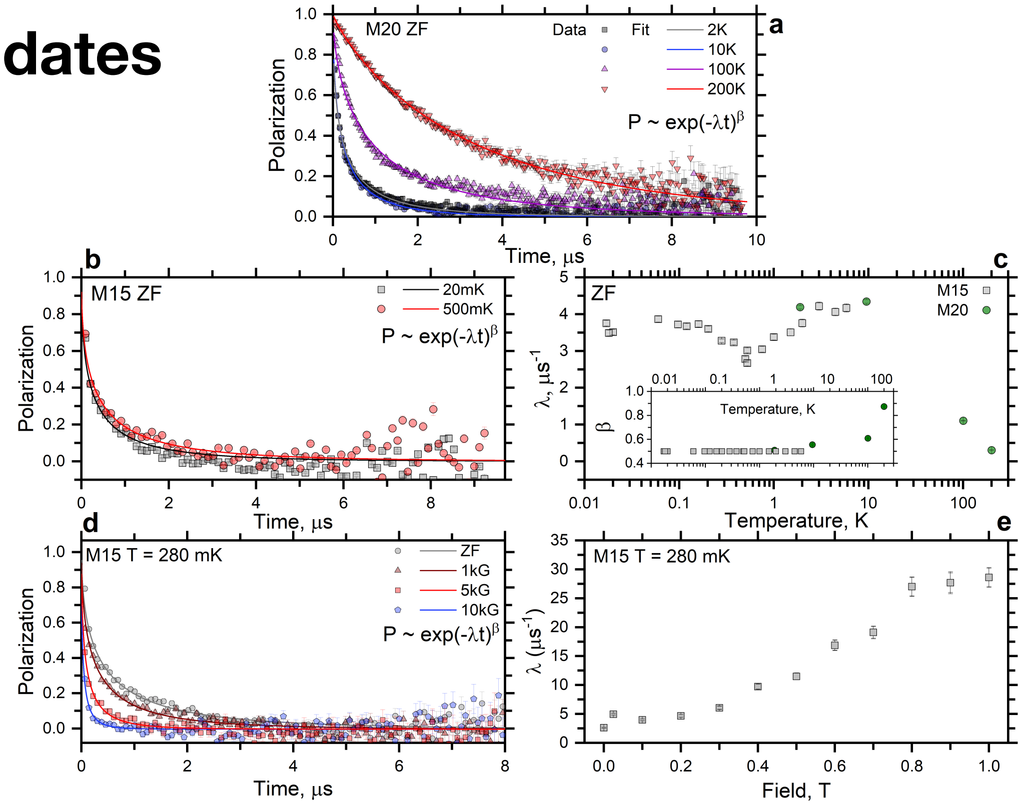
Ce$_2$Zr$_2$O$_7$





Beare *et al*., PRB **108**, 174411 (2023).

Yb$_2$Be$_2$GeO$_7$



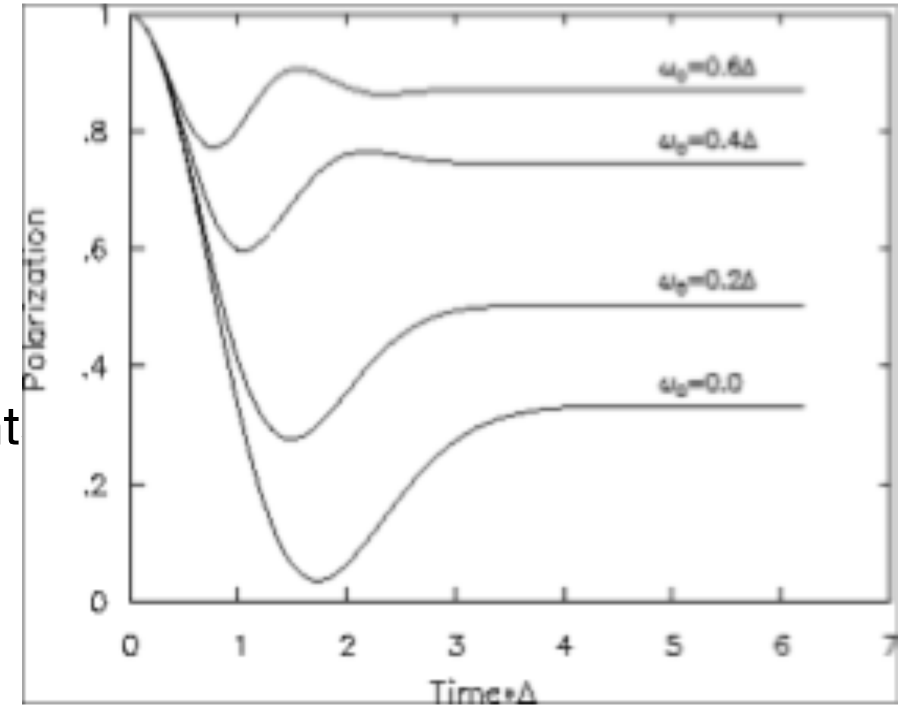
Pula *et al*., PRB **110**, 014412 (2024).

ZF/LF-µSR

Field Distributions

Kubo Toyabe Theory for random moments.

Approximate field distribution for dense moment as Gaussian



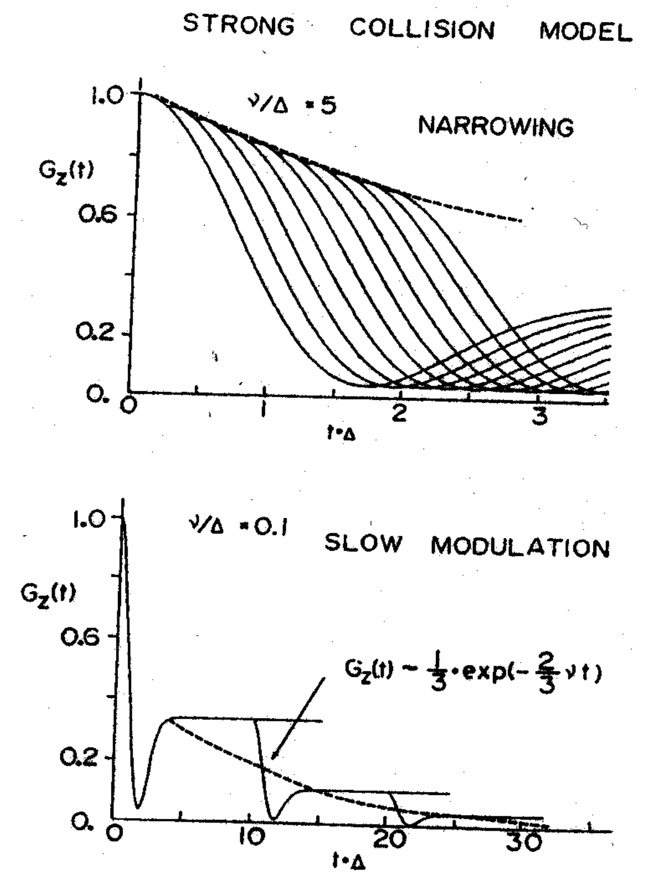
$$
\begin{aligned}
P(H_i) &= \frac{\gamma_\mu}{2\pi\Delta} \exp\left[\frac{-\gamma_\mu^2 H_i^2}{2\Delta^2}\right] \quad i = x, y, z \\
\frac{\Delta^2}{\gamma_\mu^2} &= \langle H_x^2 \rangle = \langle H_y^2 \rangle = \langle H_z^2 \rangle \\
G_z(t) &= \int\int\int \left[\frac{H_z^2}{H^2} + \left(\frac{H_x^2 + H_y^2}{H^2}\right) \cos\left(\gamma_\mu H t\right)\right] P(H_x) P(H_y) P(H_z) dH_x dH_y dH_z \\
&= \frac{1}{3} + \frac{2}{3}\left(1 - \Delta^2 t^2\right) \exp\left[-\frac{1}{2}\Delta^2 t^2\right]
\end{aligned}
$$

Dynamics

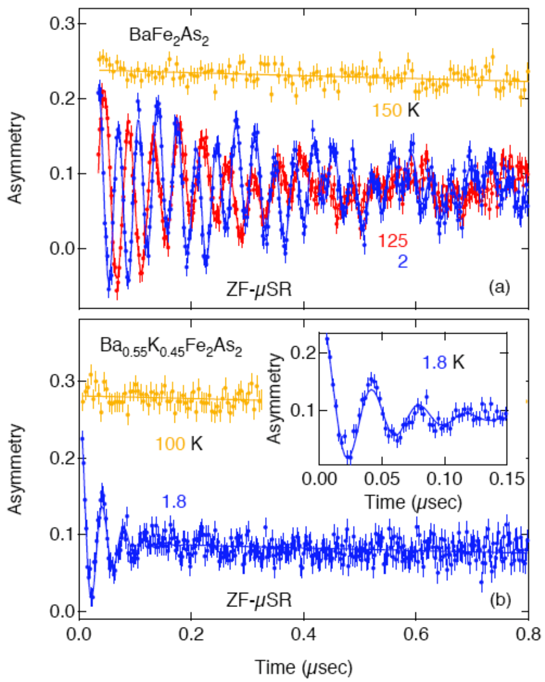
Strong collision model

- If fields not constant in time: Strong Collision Model
  - Model fluctuations by assuming local field jumps instantaneously at time t. exp(-vt) is probability of no jump.
  - Field after collision chosen randomly from static distribution, otherwise uncorrelated with original.

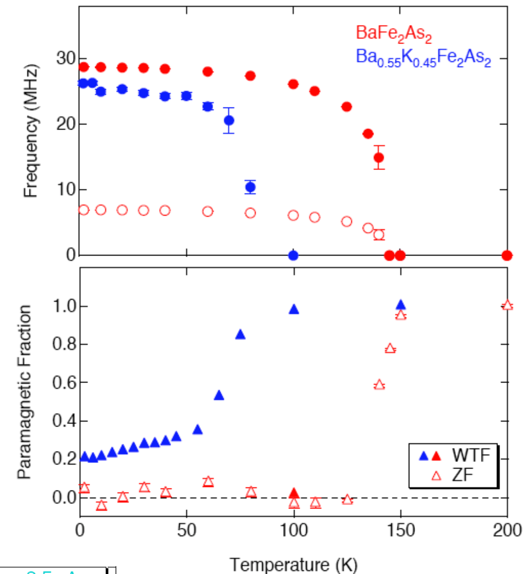
$$G_z(t,\nu) = e^{-\nu t}[g_z(t) + \nu \int_0^t g_z(t_1) g_z(t-t_1) dt_1 + \nu^2 \int_0^t \int_0^{t_2} g_z(t_1) g_z(t_2 - t_1) g_z(t - t_2) dt_1 dt_2 + ...]$$



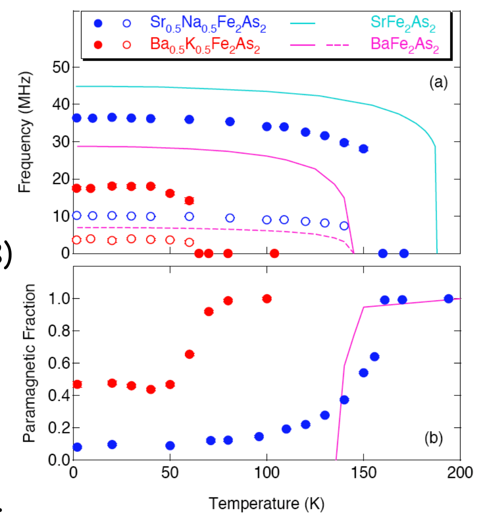
WTF- Wipeout



Aczel et al., Phys. Rev. B **78**, 214503 (2008)



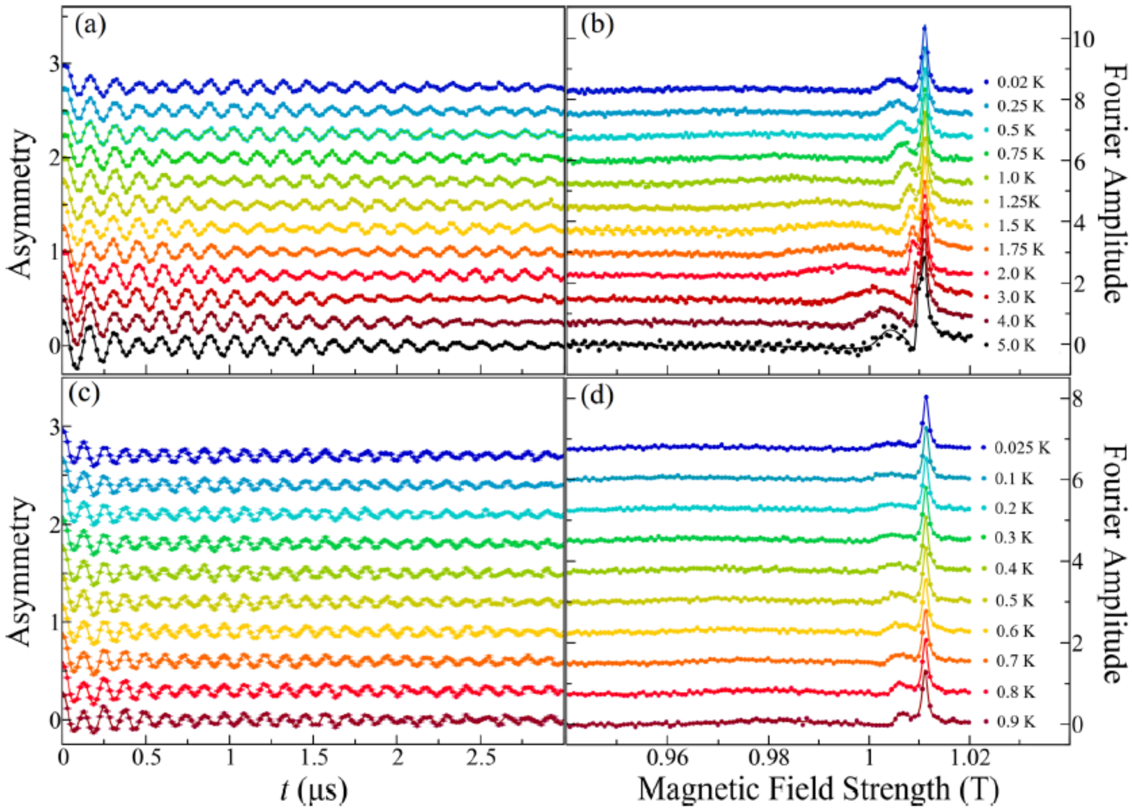
Goko et al., PRB **80**, 024508 (2009).



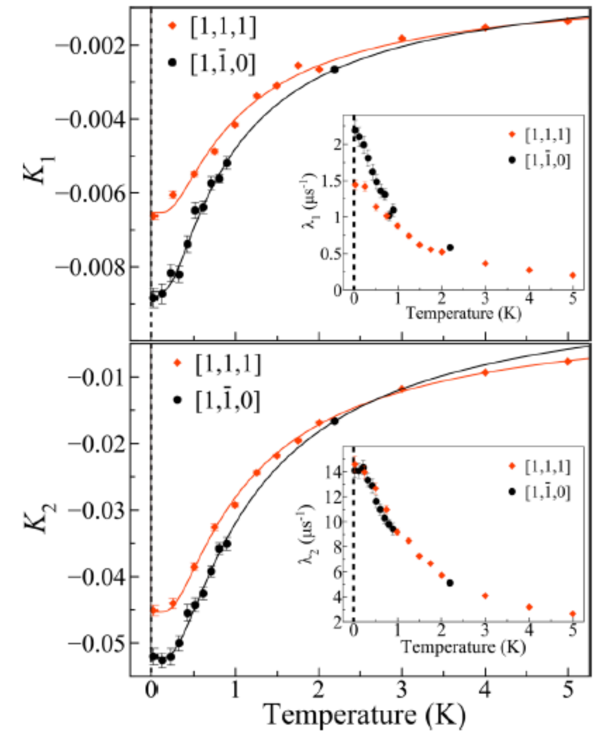
Goko et al., PRB **80**, 024508 (2009).

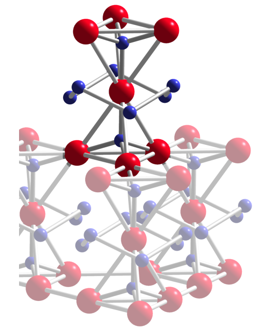
TF-µSR

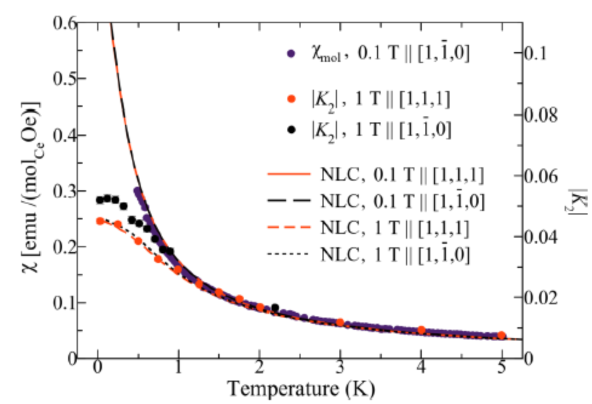
Knight shift, asymmetry, relaxation



Beare *et al.*, Phys. Rev. B **108**, 174411 (2023)

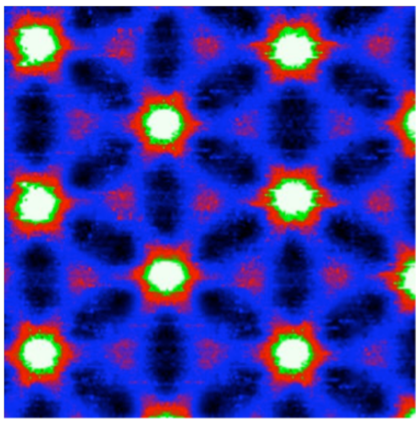


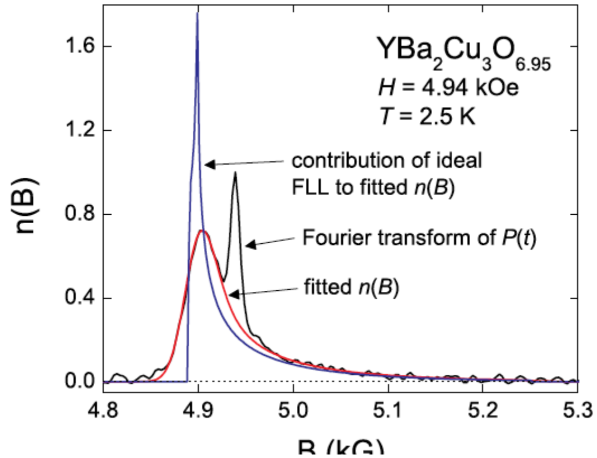


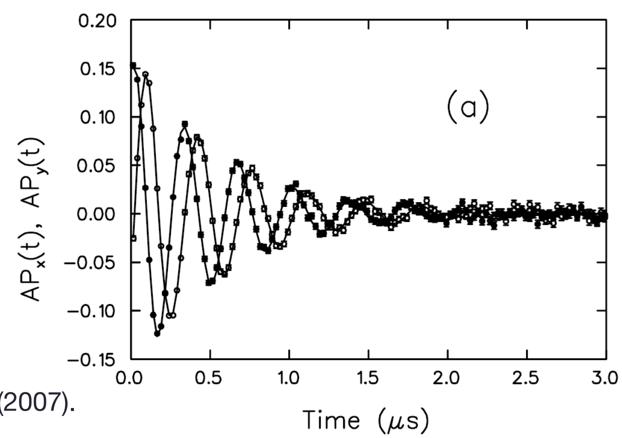


TF-μSR

Type II Superconductivity







Sonier, Rep. Prog. Phys. **70**, 1717 (2007).

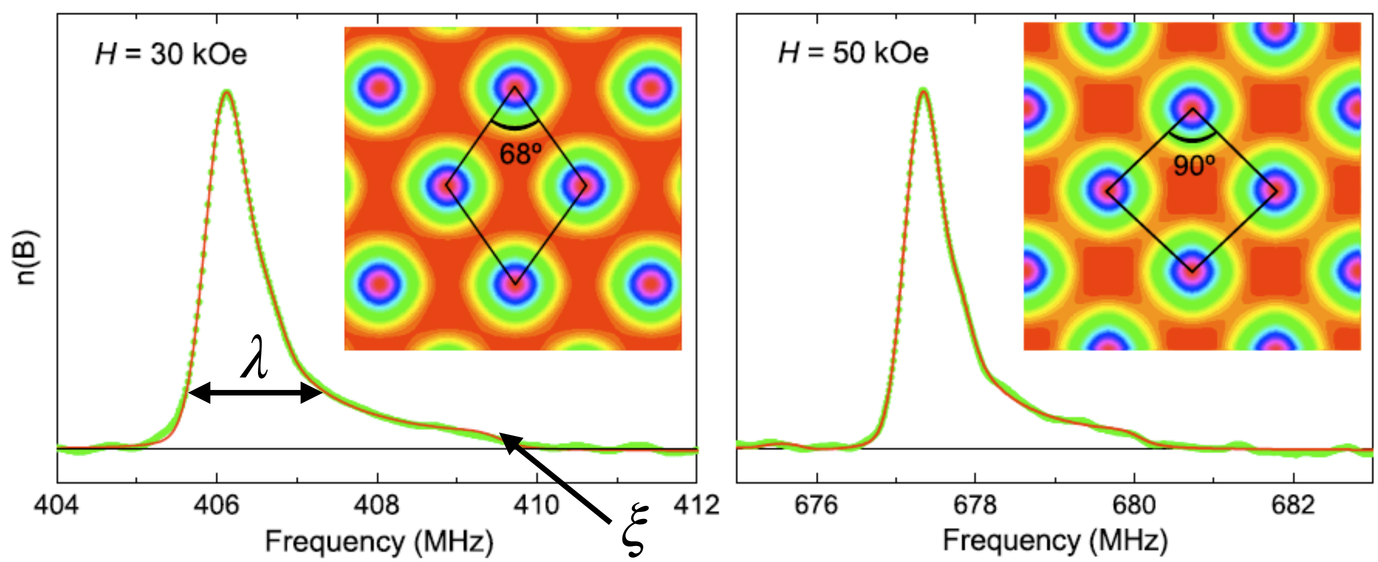
- 2 lengthscales: λ, ξ
- Disorder: broadening of line shape features (convolute with Gaussian).

Vortex Lattice Field Distribution

$$B(\boldsymbol{r}) = B_0(1 - b^4) \sum_{\boldsymbol{G}} \frac{e^{-i\boldsymbol{G}\cdot\boldsymbol{r}} F(G)}{\lambda^2 G^2}$$

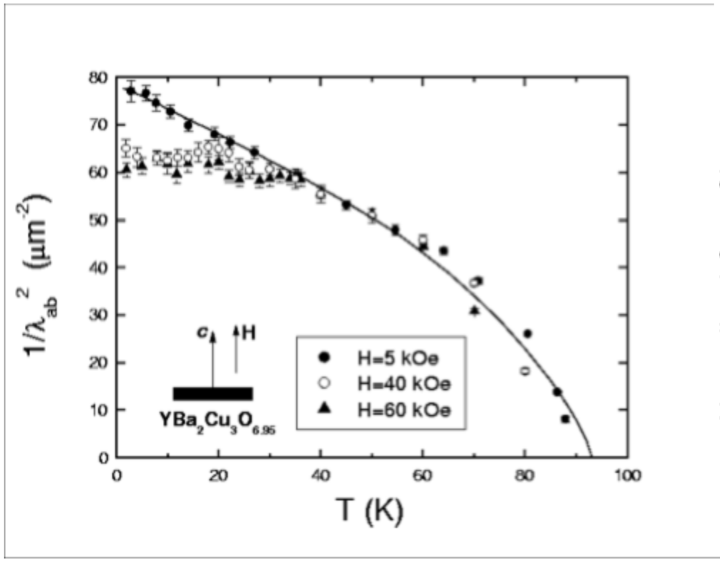
Yaouanc et al., Phys. Rev. B **55**, 11107 (1997).

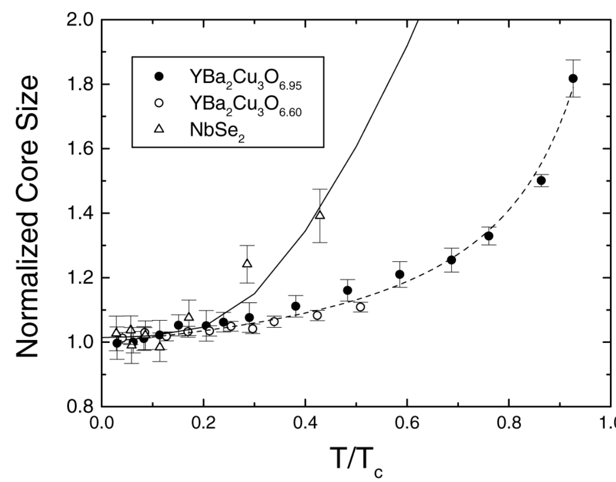
$$F(G) = uK_1(u),\ u^2 = 2\xi^2 G^2 (1 + b^4)[1 - 2b(1 - b)^2]$$



V_3Si

Superfluid density & Vortex Core Size





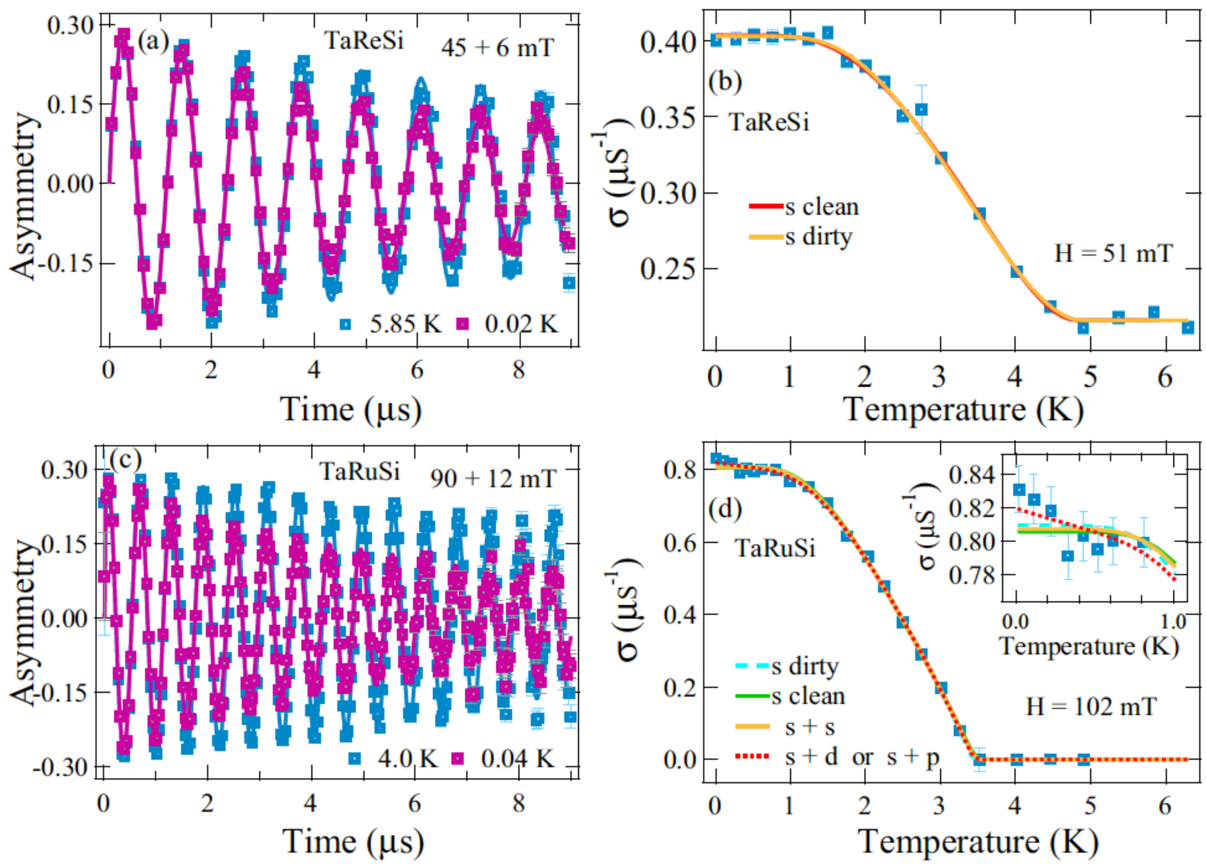
Sonier *et al.*

- Curve is ZF µ-wave result. (Hardy et al.)
- Linear T-dependence due to d-wave pairing (gap nodes)
- High field flattening due to q.p.'s at gap nodes.

- Weak dependence of ξ on T indicates absence of bound states in vortex cores.

Transverse Field μSR

Ceramics - Gaussian



Sharma *et al*., PRB **108**, 144510 (2023).

$$\sigma \propto \sqrt{<\Delta H^2>} \propto \frac{1}{\lambda^2}$$

$$\frac{1}{\lambda^2} = \frac{4\pi n_s e^2}{m^* c^2} \times \frac{1}{(1+\xi/l)}$$

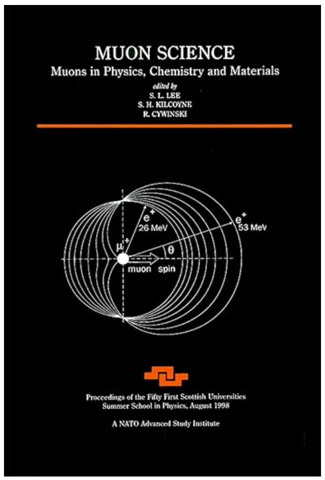
in the "clean limit" $\xi \ll l$

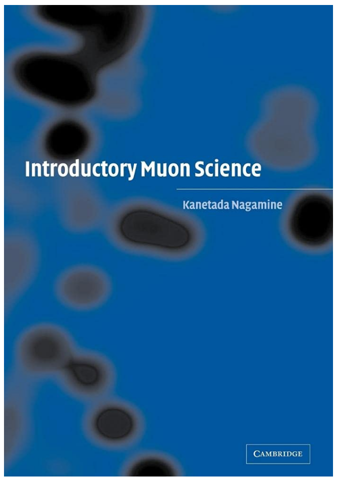
$$\sigma \propto \frac{1}{\lambda^2} \propto \frac{n_s}{m^*}$$

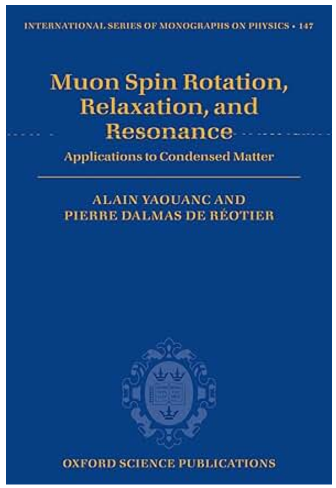
$$\sigma \sim \frac{n_s}{m^*}$$

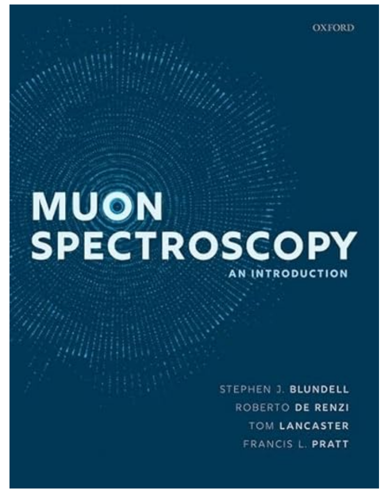
SOC

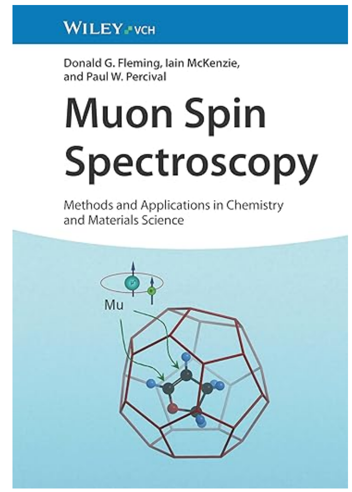
Resources

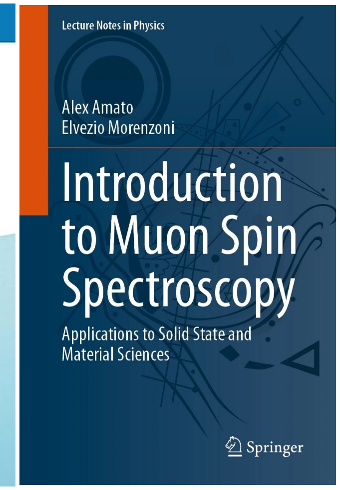

MUON SCIENCE
Muons in Physics, Chemistry and Materials
edited by
S. L. LEE
S. H. KILCOYNE
R. CYWINSKI
e+
26 MeV
e+
53 MeV
μ+
θ
muon spin
Proceedings of the Fifty First Scottish Universities
Summer School in Physics, August 1998
A NATO Advanced Study Institute


Introductory Muon Science
Kanetada Nagamine
CAMBRIDGE


INTERNATIONAL SERIES OF MONOGRAPHS ON PHYSICS • 147
Muon Spin Rotation, Relaxation, and Resonance
Applications to Condensed Matter
ALAIN YAOUANC AND
PIERRE DALMAS DE RÉOTIER
OXFORD SCIENCE PUBLICATIONS


OXFORD
MUON SPECTROSCOPY
AN INTRODUCTION
STEPHEN J. BLUNDELL
ROBERTO DE RENZI
TOM LANCASTER
FRANCIS L. PRATT


WILEY VCH
Donald G. Fleming, Iain McKenzie,
and Paul W. Percival
Muon Spin Spectroscopy
Methods and Applications in Chemistry
and Materials Science
Mu


Lecture Notes in Physics
Alex Amato
Elvezio Morenzoni
Introduction to Muon Spin Spectroscopy
Applications to Solid State and
Material Sciences
Springer