Probing internal magnetic field features of the II-IV-V2:Mn DMS via MuSR

An in depth study exploring fundamental properties and characteristic of local magnetic features in II-IV-V2:Mn chalcopyrite DMS systems

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Support:
Provided by: US DoE

Experimental Facility:
EMU Beamline at ISIS
(Rutherford Appleton Labs, Didcot, UK)

LF-μSR

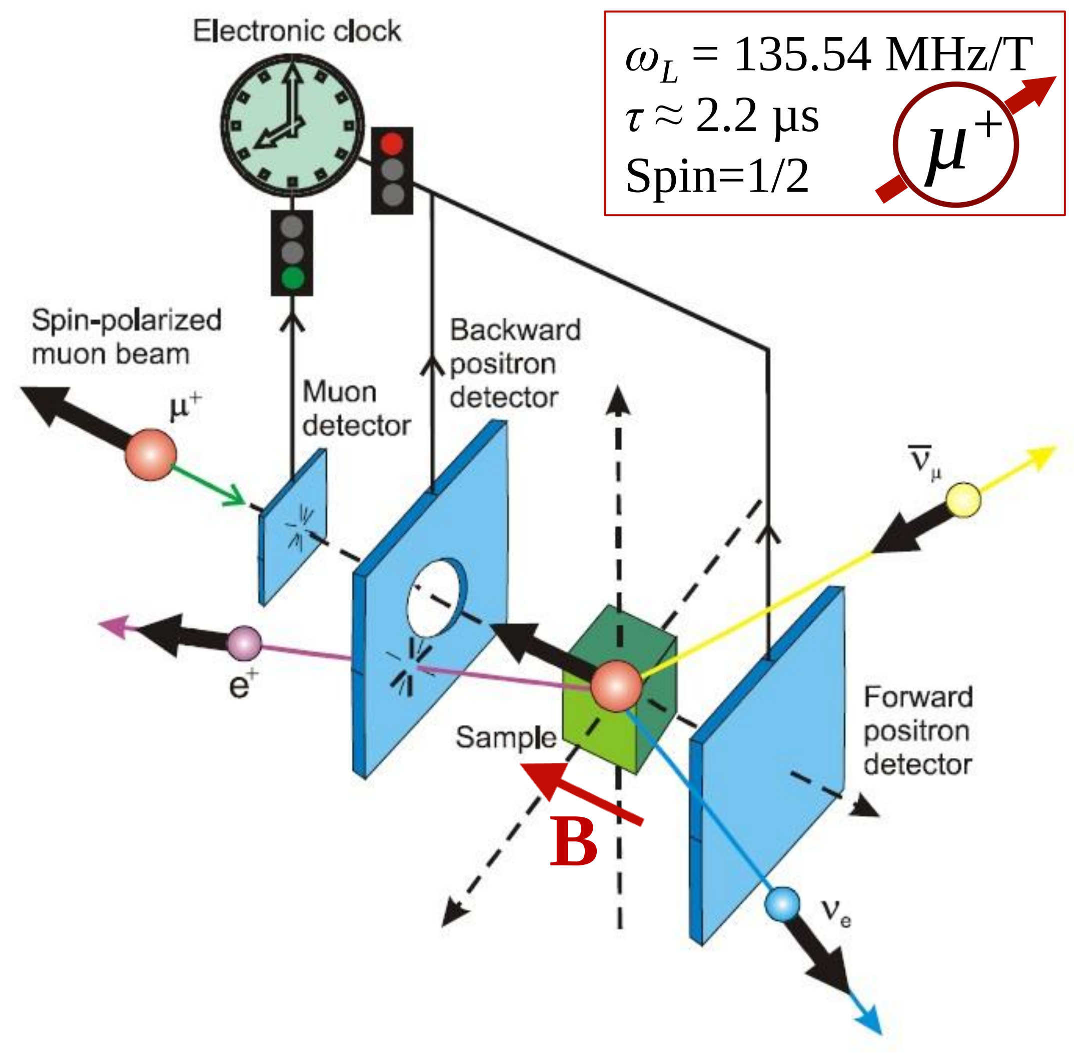
μ^+= Local probe

Implant 100% spin polarized muons

B applied || to initial spin direction

Spin evolves in local environment

Evolution of polarization tracked



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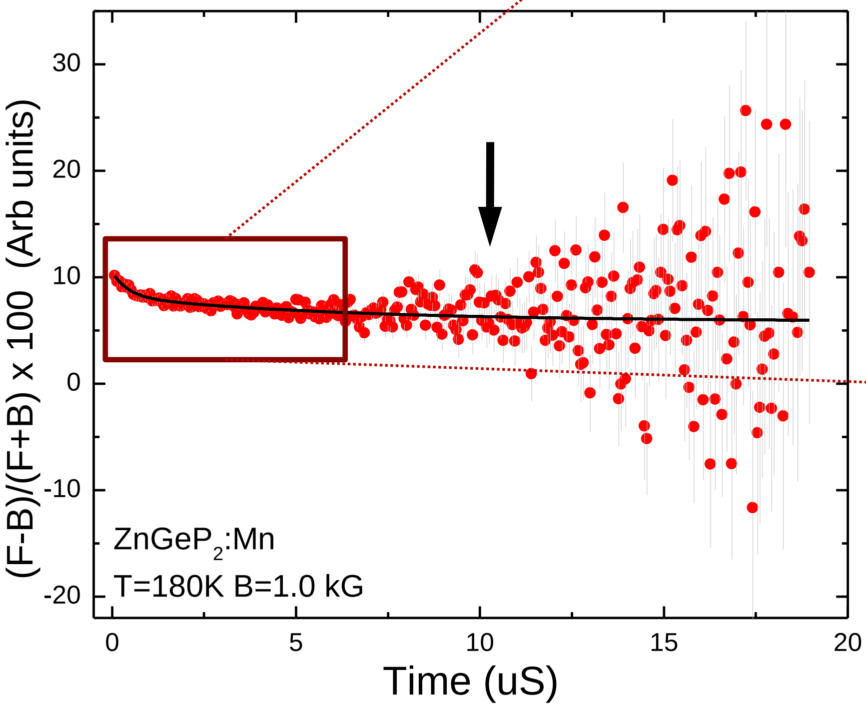
P.W. Mengyan, et al. APS (2012)

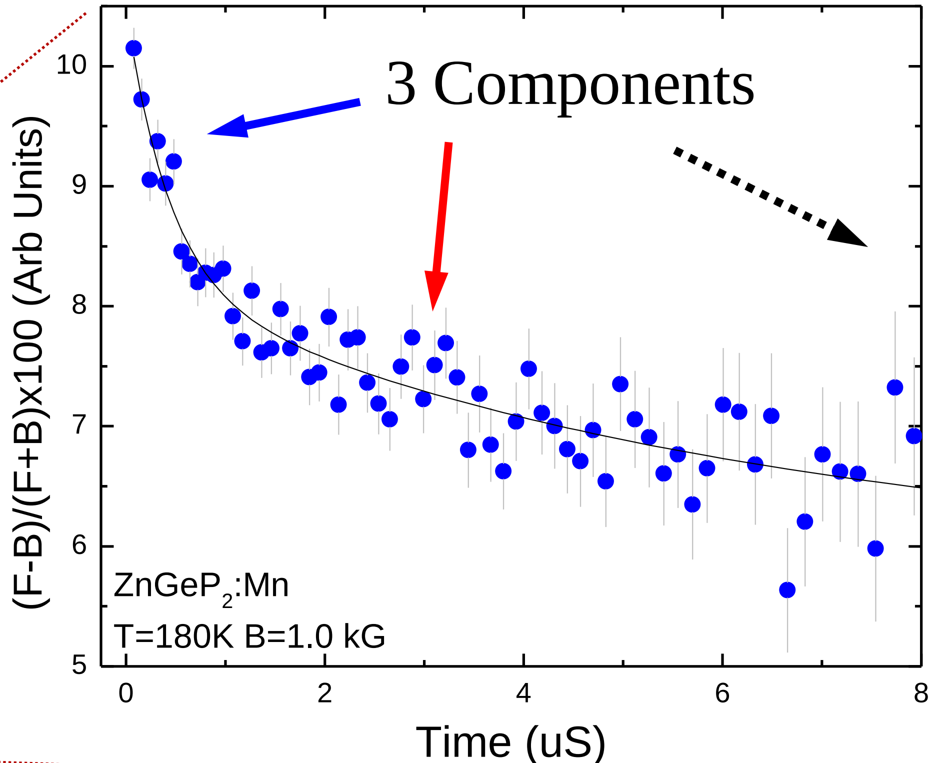
LF-μSR on ZnGeP2:Mn: T=180 with B_{LF}=1.0 kG

Asymmetry: 'corrected' average of counts

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

Data: Shown





Faster: 1 → 25+ us^{-1}

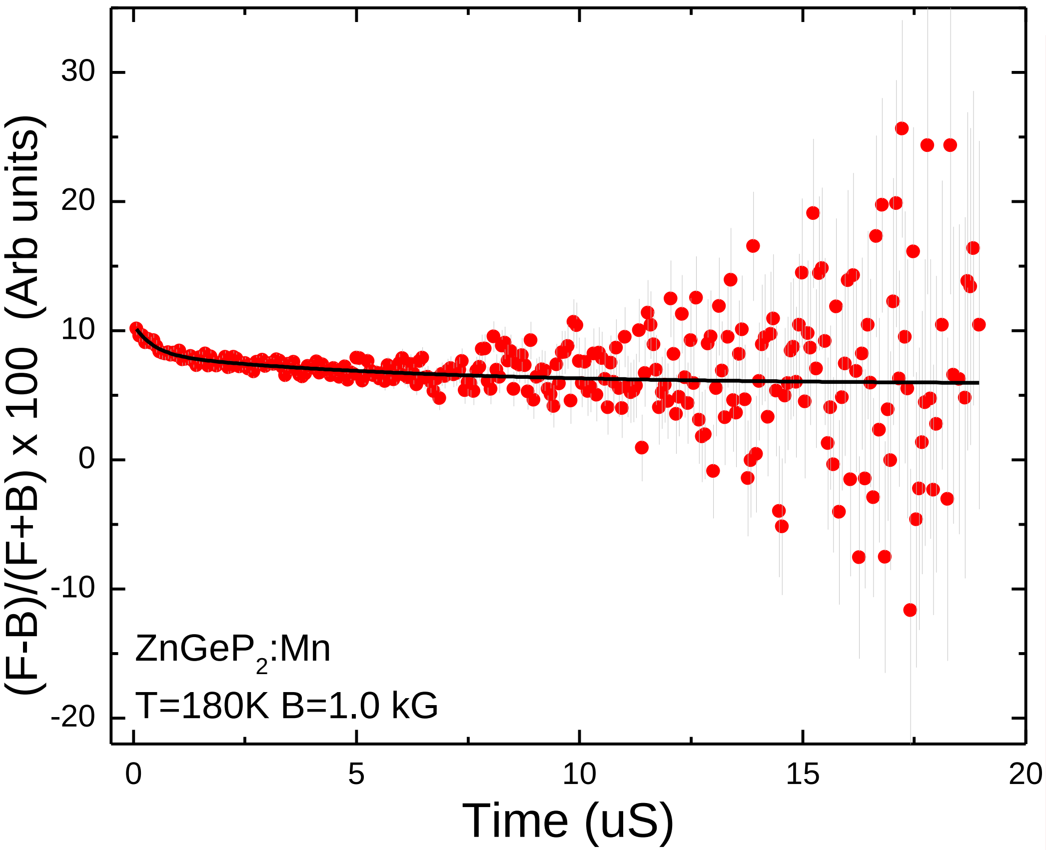
Slower: ~0.01 → 1.0 us^{-1}

Non-Rlx: $\lambda < 0.01$ us^{-1}

P.W. Mengyan, et al., Unpublished data, *ISIS*, Dec 2012

P.W. Mengyan, et al. APS (2012)

Polarization Function



$$P(t) = A_1 e^{-t/T_1} + A_2 e^{-t/T_2} + A_3$$

Fit Parameters: A_i, T_j

$$\frac{1}{T_j} = \frac{2\Delta_i^2}{\nu_j}$$

For dilute alloys:

$$\rho(\Delta_i) = \sqrt{\frac{2}{\pi}} \frac{a}{\Delta_i^2} \exp\left(\frac{-a^2}{2\Delta_i^2}\right)$$

$$\Delta = \gamma_\mu \mathrm{B}_i$$

$$P_z^L(t) = \int_0^\infty P_z^G(t)\rho(\Delta)d\Delta = \cdots$$

ie: A. Schenk, *Muon Spin Rotation Spectroscopy: Principles and Applications in Solid State Physics* (Adam Hilger Ltd, Bristol, 1985).

P.W. Mengyan, et al. APS (2012)

B-Field at Mu+ Site

Localized magnetic density contributing to $\mathbf{B}_{loc}$ via:

1) classical dipole interaction
2) RKKY [metals] or via hyperfine field [insulators]

ν

$$\mathbf{B}_{loc} = \langle\mathbf{B}_{loc}\rangle + \delta\mathbf{B}_{loc}$$
$$= \mathbf{B}_{ext} + \mathbf{B}_{dip} + \mathbf{B}_{hyp} + \mathbf{B}_{fermi} + \delta\mathbf{B}_{loc}$$

$\mathbf{B}_{ext}$ = Applied External Field

$$\mathbf{B}_{dip} = \frac{\mu_0}{4\pi}\sum_{i=1}^{N}\left(-g_i\mu_B\right)\left[-\frac{\mathbf{J}_i}{r_i^3} + \frac{3(\mathbf{J}_i\cdot\mathbf{r}_i)\mathbf{r}_i}{r_i^5}\right] + \frac{\mu_0}{4\pi}\sum_{i=1}^{N}\left(-\gamma_i\hbar\right)\left[-\frac{\mathbf{I}_i}{r_i^3} + \frac{3(\mathbf{I}_i\cdot\mathbf{r}_i)\mathbf{r}_i}{r_i^5}\right]$$

= dipolar field -- sum of contributions from localized magnetic moments over whole crystal

$\mathbf{B}_{hyp}$ = field from HF interaction; $\mathbf{B}_{hyp} = \frac{\mu_0}{4\pi}\sum_{i=1}^{N'}\frac{(-g_i\mu_B)H_{\mathbf{r}_i}}{v_c}\mathbf{J}_i$

short range magnetic interaction between μ^+ and local magnetic moments near μ^+ site

$\mathbf{B}_{Fermi}$ = Fermi magnetic field operators, i.e.:

Fermi contact interaction [magnetic interaction of μ^+ & e^- spins for *s* & *p* e^- metals]

RKKY – indirect exchange between μ^+ and unpaired e^- via conduction e^- [*d* & *f* materials]

Transferred hyperfine field [μ^+ & e^- wavefunction overlap in insulators]

ie: A. Schenk, *Muon Spin Rotation Spectroscopy: Principles and Applications [...]* (Adam Hilger Ltd, Bristol, 1985).

P.W. Mengyan, et al. APS (2012)

Practical Material: II–IV–V_2:Mn

$ZnGeP_2$:Mn

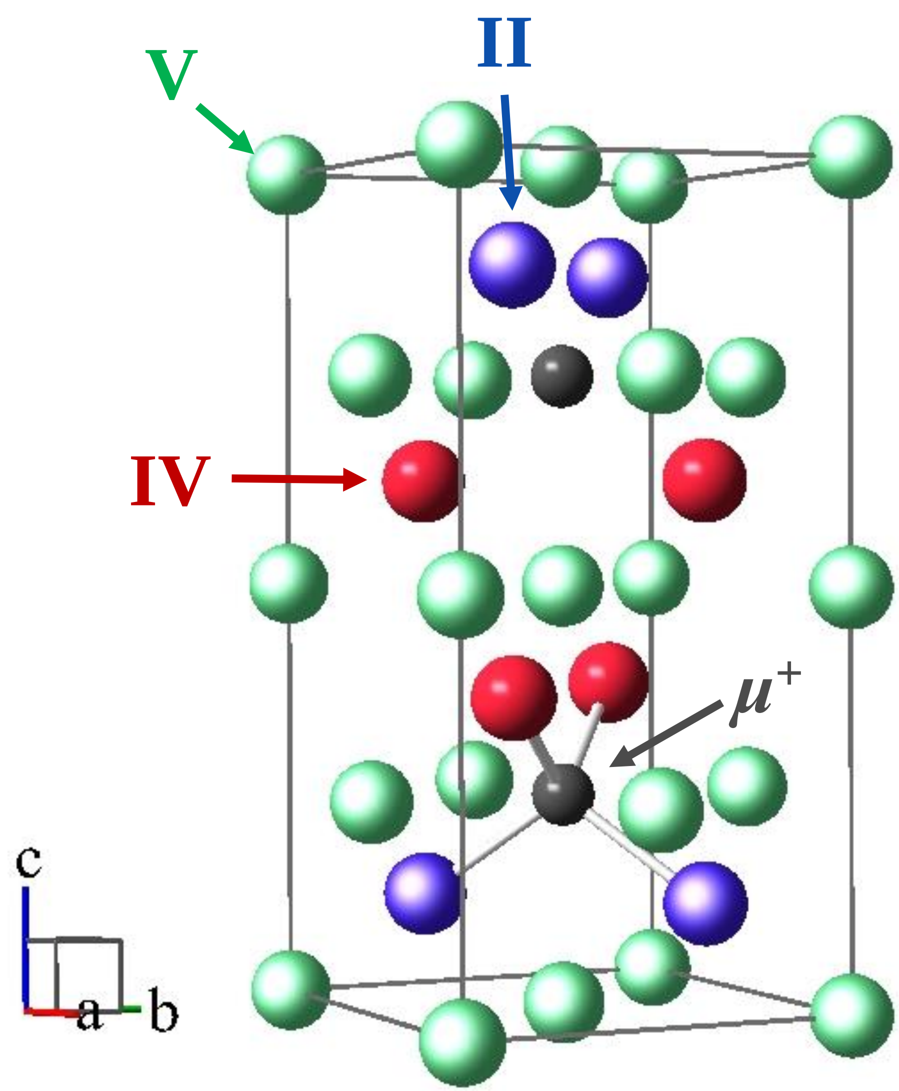
- $E_g \approx 2.0$ eV & FM order above RT (T_c = 310K to 350K)
  →Prime choice for *spin*-based devices

$CdGeAs_2$:Mn

- $E_g \approx .67$ eV & FM order above RT (T_c=355K)

Mn^{2+} Substitution:

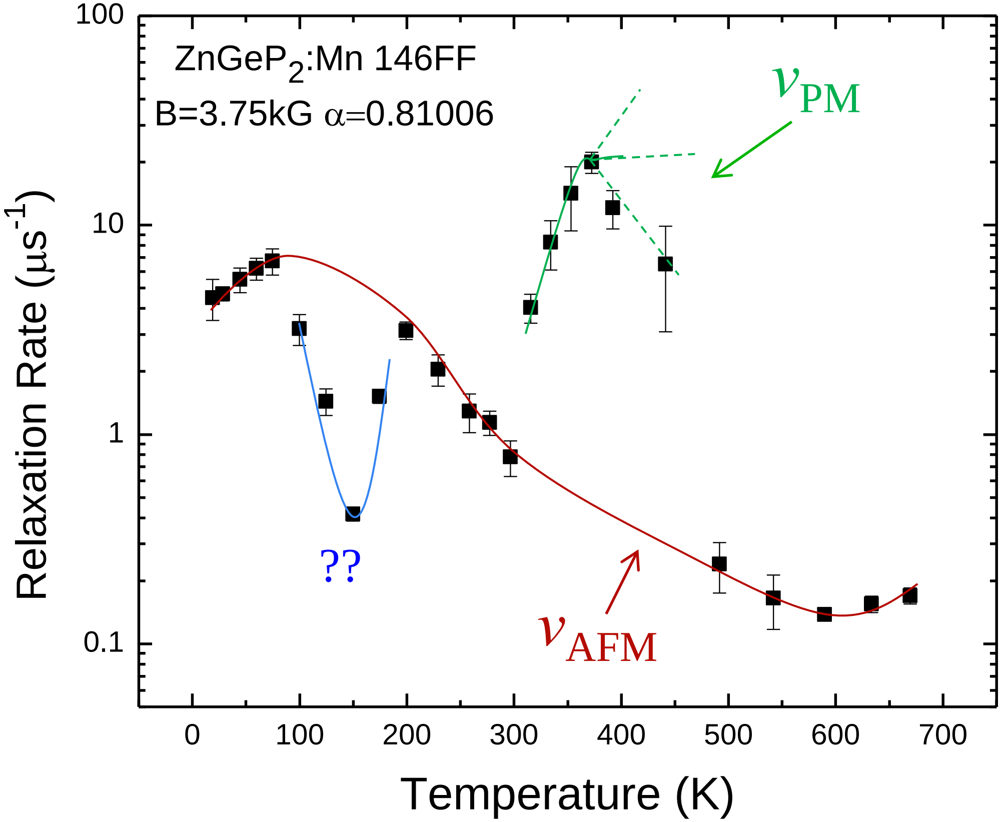
- Isovalent – Group-II
- Double Acceptor – Group-IV
- Light conc. of Mn^{2+} on IV
  Heavy conc. of Mn^{2+} on II
  →AFM if Mn only on II
  → With Mn sub on IV sites, provides extra carriers, mix results in FM order



P.W. Mengyan, et al. APS (2012)

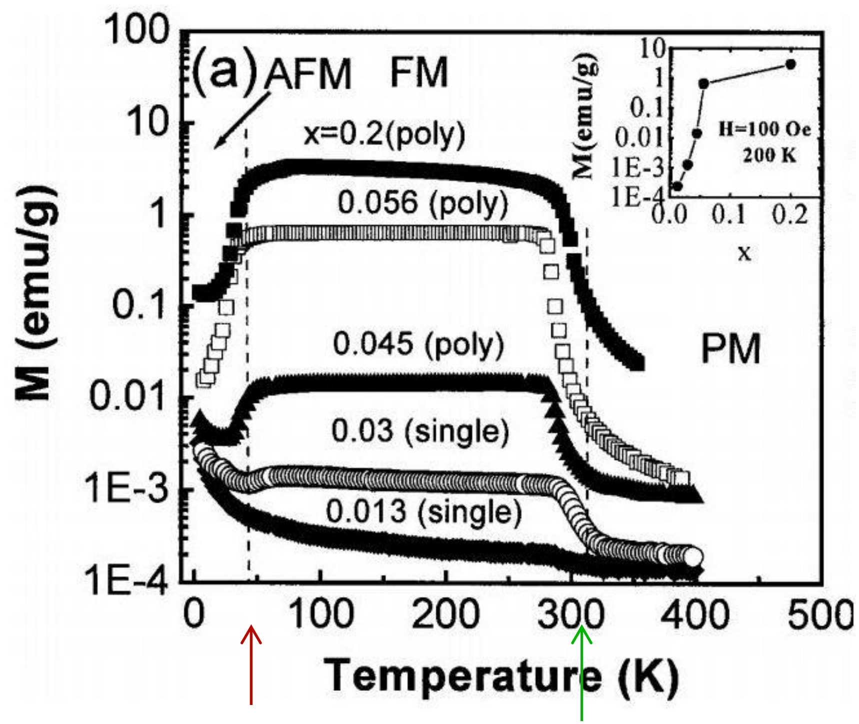
ZnGeP2:Mn – Preliminary results

High quality, single crystal, P-type samples, doping <5% Mn → Dilute regime



NOTE: Lines *only* guide for the eyes

P.W. Mengyan, et al., Unpublished data, *ISIS*, Dec 2012



S. Cho, et al., *PRL* **88** (2002) 257203

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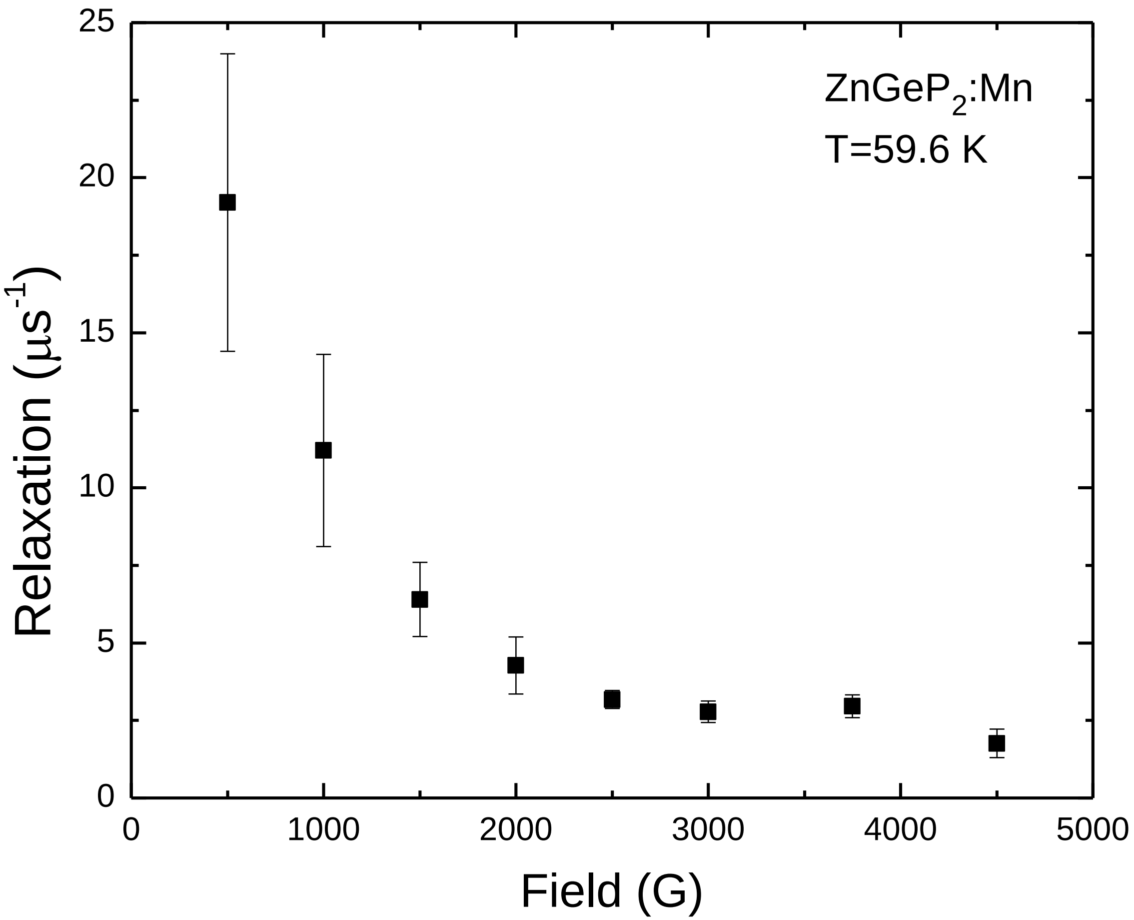

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Future Work

Additional data fitting & theoretical modeling
→ Develop model designed specifically for these DMS systems
→ Reanalyze data with new model, extract fluctuation rates, energies, etc

These measurements supplementary to additional work to characterize internal field properties and characteristics, ie:
→ distribution
→ structure
→ dynamics
→ how magnetism carried/transferred throughout DMS

Thank you

Questions, Comments, etc?

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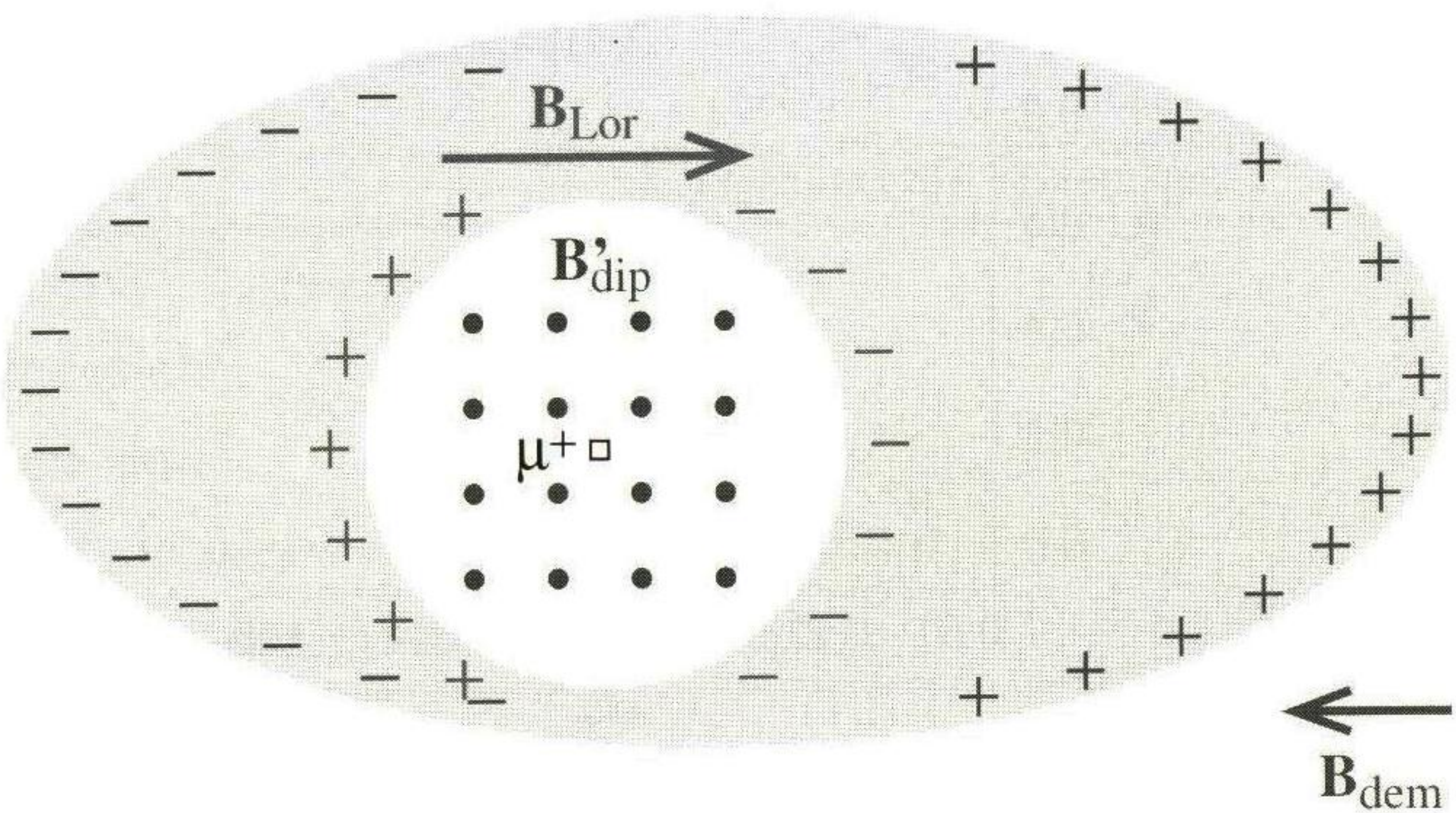

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B-Field at Mu+ Site

$$\mathbf{B}_{\text{loc}} = \mathbf{B}_{\text{ext}} + \overbrace{(\mathbf{B'}_{\text{dip}} + \mathbf{B}_{\text{Lor}} + \mathbf{B}_{\text{dem}} + \delta\mathbf{B}_{\text{dip}})}^{\mathbf{B}_{\text{dip}}} + \mathbf{B}_{\text{hyp}}$$

$\mathbf{B}_{\text{ext}}$ = Applied External Field

$$\mathbf{B}_{dip} = \frac{\mu_0}{4\pi}\sum_{i=1}^{N}(-g_i\mu_B)\left[-\frac{\mathbf{J}_i}{r_i^3} + \frac{3(\mathbf{J}_i\cdot\mathbf{r}_i)\mathbf{r}_i}{r_i^5}\right] + \frac{\mu_0}{4\pi}\sum_{i=1}^{N}(-\gamma_i\hbar)\left[-\frac{\mathbf{I}_i}{r_i^3} + \frac{3(\mathbf{I}_i\cdot\mathbf{r}_i)\mathbf{r}_i}{r_i^5}\right]$$

= dipole field expressed as sum of contributions from magnetic moments over whole crystal

$\mathbf{B'}_{\text{dip}}$ = Sum of fields from within *Lorentz sphere* centered at μ^+ site
sphere taken to be large enough to allow $\mathbf{B}_{\text{dip}}$ sum to converge

$\mathbf{B}_{\text{Lor}}$ = Field from charges on surface of Lorentz sphere, ie: $\mathbf{B}_{Lor} = \frac{\mu_0}{3}\mathbf{M}_{Lor}$
$\mathbf{M}_{\text{Lor}}$ = vector sum magnetic moments inside sphere per unit volume

$\mathbf{B}_{\text{dem}}$ = Field from charges on the surface of sample, ie: $\mathbf{B}_{dem} = -\mu_0\mathbf{N}\mathbf{M}_{meas}$
$\mathbf{N}$ = Demagnetization tensor ; $\mathbf{M}_{meas}$ = Bulk magnetization of sample

$\delta\mathbf{B}_{\text{dip}}$ = Fluctuating component of dipolar field contribution

$\mathbf{B}_{\text{hyp}}$ = field from HF interaction; $\mathbf{B}_{hyp} = \frac{\mu_0}{4\pi}\sum_{i=1}^{N'}\frac{(-g_i\mu_B)H_{\mathbf{r}_i}}{\nu_c}\mathbf{J}_i$
short range magnetic interaction between μ^+ and local magnetic moments near μ^+ site

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Experimentally Accessible Analog to Hydrogen

	Muon	Proton
Mass (m_p)	0.1126 ≈ 1/9	1
Spin	½	½
Gyro. Ratio, γ (s^{-1} T^{-1})	8.51607×10^8 ≈$3.2 \times \gamma_P$	2.67520×10^8
Lifetime, τ (μs)	2.19709	Stable
	Muonium	**Hydrogen**
Red. e^- mass (m_e)	0.995187	0.999456
G. S. Radius (Å)	0.531736	0.529465
G. S. Energy (eV)	-13.5403	-13.5984

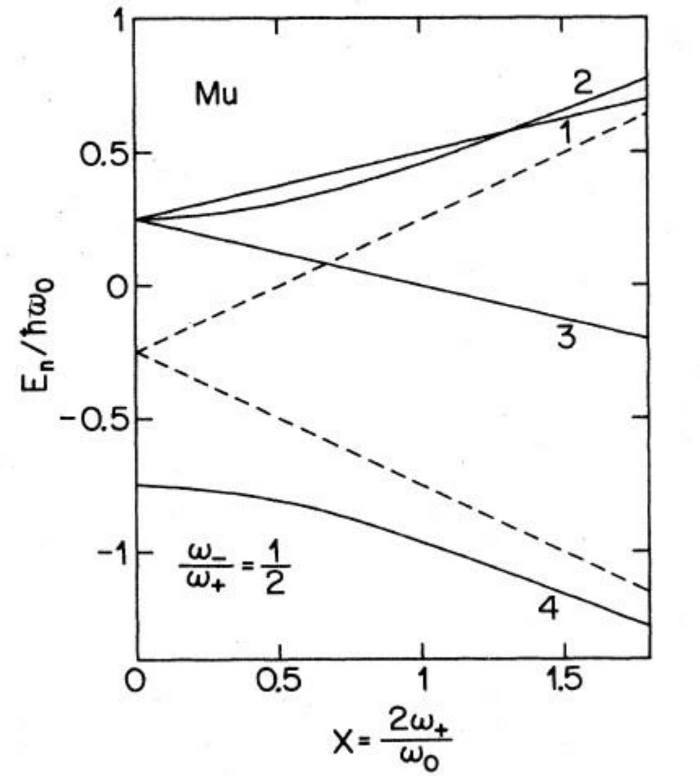
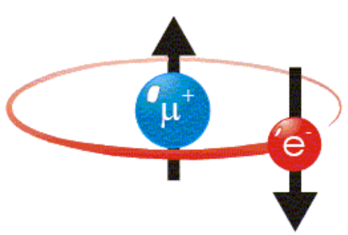


FIG. 1. The hyperfine energy-level (Breit-Rabi) diagram for isotropic 1s-Mu as a function of the dimensionless magnetic field $x = B(g_\mu \mu_\mu - g_e \mu_B)/(hA)$. A fictitious value for the quantity ω_-/ω_+ has been used for clarity; its true value is 0.9904. The dashed lines are the high-field asymptotes for levels 2 and 4.

B.D. Patterson, *Rev. Mod. Phys.*, **60**, (1988) 1

Muonium (Mu ≡ μ^+e^-)



Brewer, http://musr.ca →

P.W. Mengyan, et al. APS (2012)

Why μ^+?

	Muon	Proton
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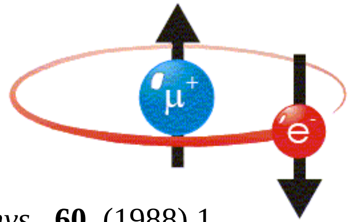

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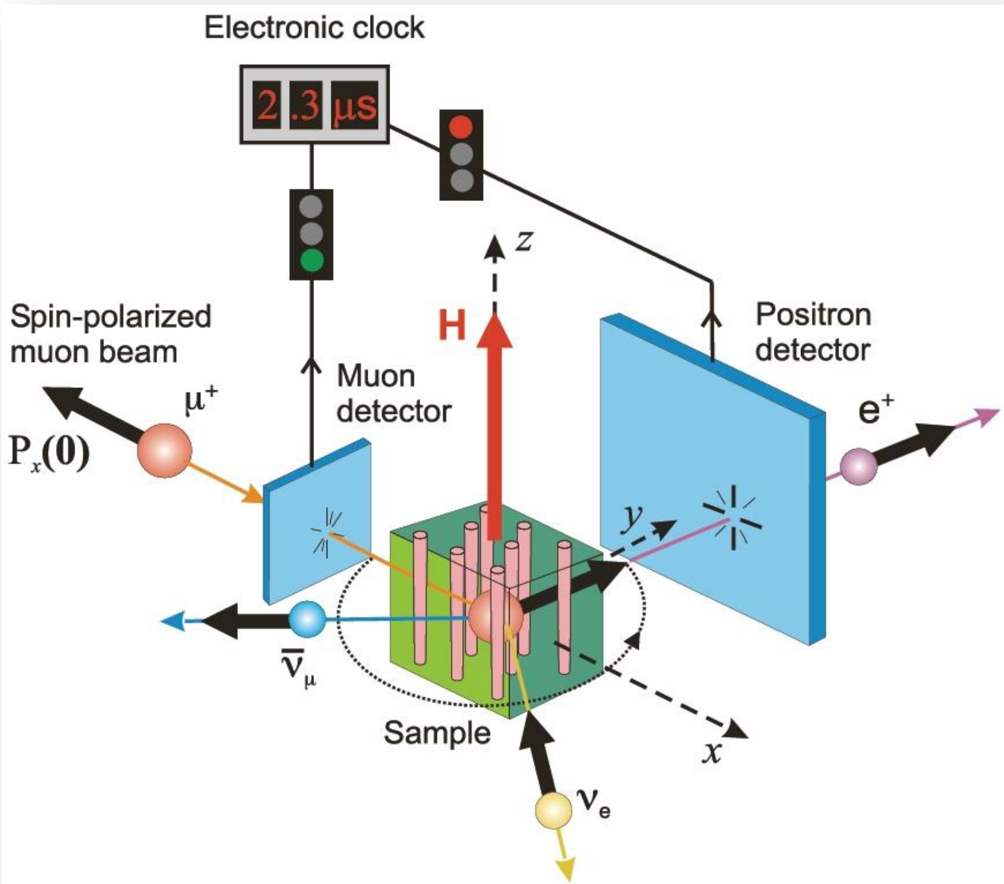
B.D. Patterson, *Rev. Mod. Phys.*, **60**, (1988) 1

- $\mu^+ \sim p^+$
- $m_\mu \approx 1/9\ m_p$
  $m_\mu \approx 207 m_e$; **S**=1/2
- Local probe
- $Mu^0 = \mu^+ + e^-$
- Mu^0~light isotope H
  ie: Early history of H impurities

P.W. Mengyan, et al. APS (2012)

TF-μSR



Field applied ⊥ to initial spin polarization
→ μ^+ spin precession about applied field at:

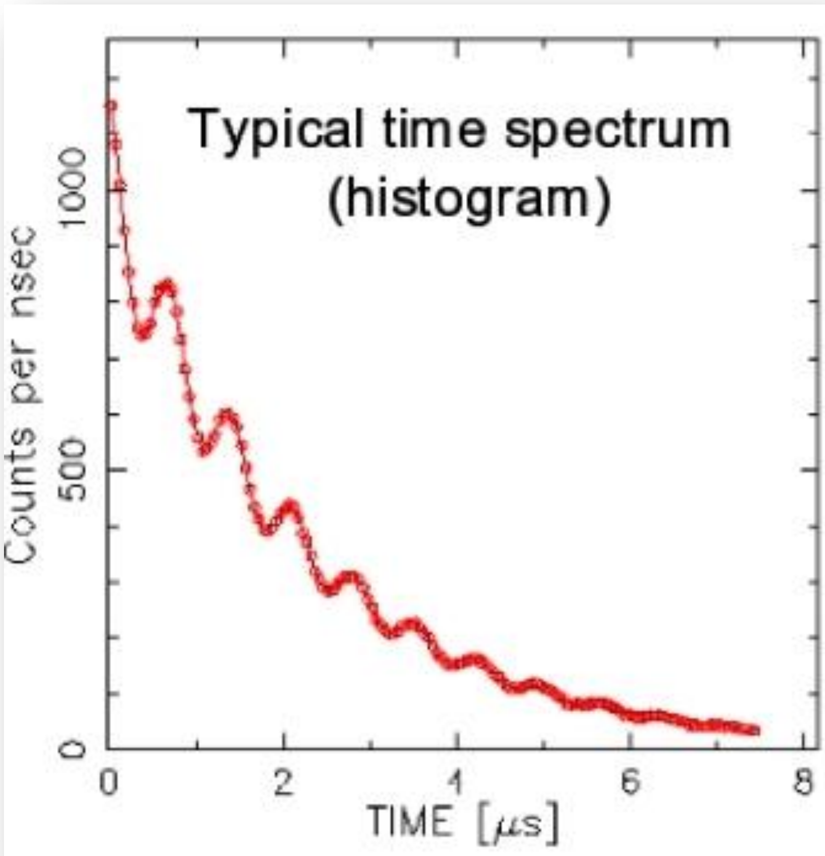
$\nu_{\mu+} = \gamma_\mu \times |\mathbf{B}|$ $|\gamma_\mu = 135.54$MHz/T

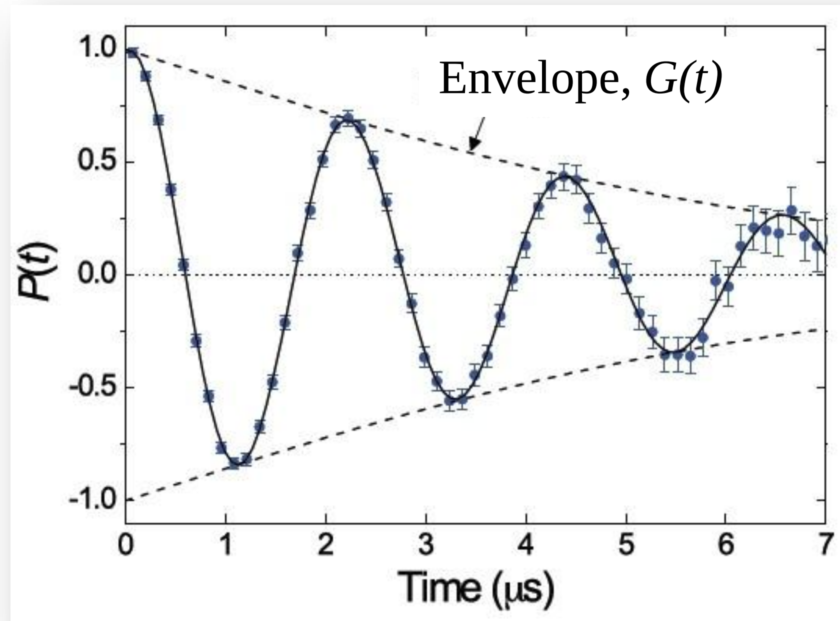
$Mu^0 = \mu^+ + e^-$
→ spin-orbit coupling
→ affects local field of μ^+
→ diff prec. Freq for:
$|\uparrow_\mu\rangle + |\uparrow_e\rangle$ & $|\uparrow_\mu\rangle + |\downarrow_e\rangle$

Brewer, http://musr.ca

B.D. Patterson, *Rev. Mod. Phys.*, **60**, (1988) 1

TF-μSR: Sample signal from relaxing μ^+





$$P(t) = G(t)\cos\left(\gamma_{\mu^+}\left|\mathbf{B}_{\mu^+}\right| + \delta\right)$$

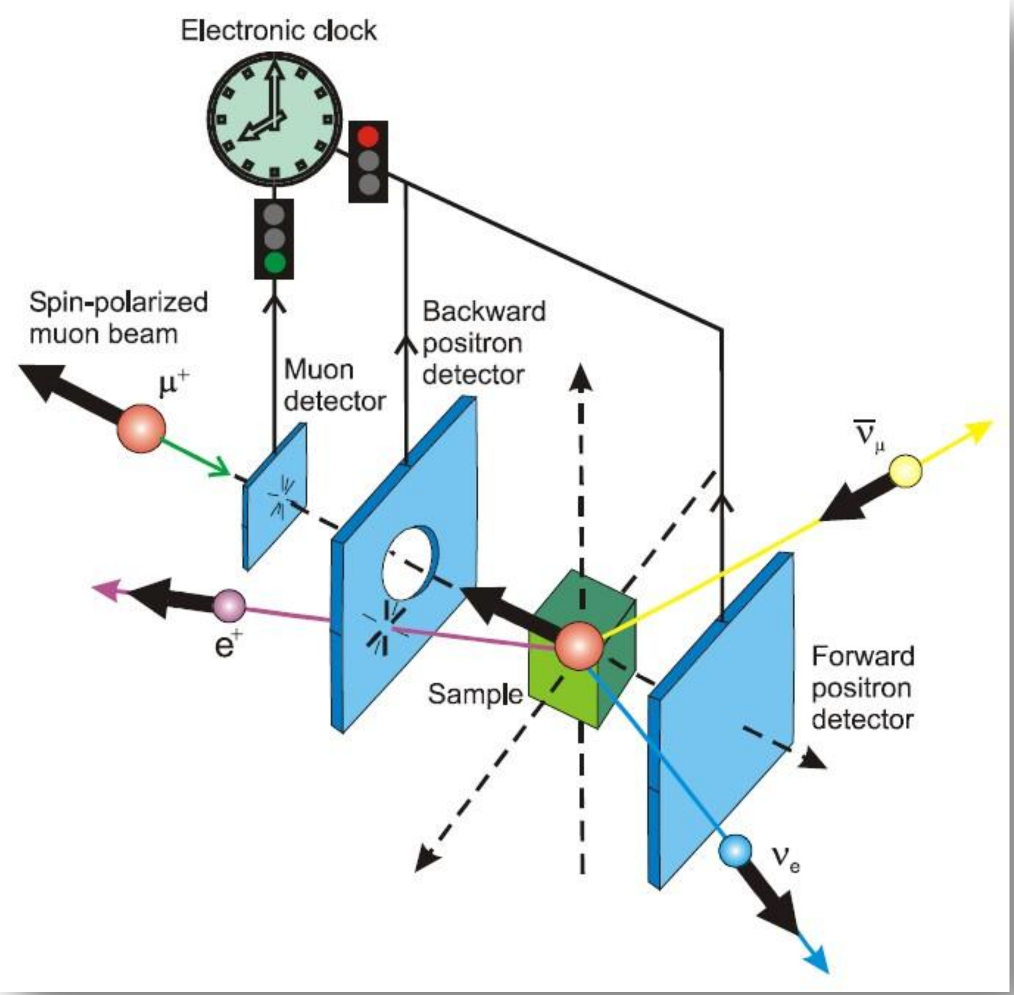
Brewer, http://musr.ca

P.W. Mengyan, *et al.* APS (2012)

LF-μSR

B applied || to μ^+ spin pol.
See time evolution of P(t)
along original direction

=> Change in Spin P(t) from:
1) local environment (nearby nuclear moments)
2) muonium motion
(e^- spin-flip w/ each site change, transferring back to μ^+ contributing to Δ P(t))



R.F. Kiefl, R. Kadono, et al., *Phys Rev Lett*, **62** (1989) 7

Brewer, http://musr.ca

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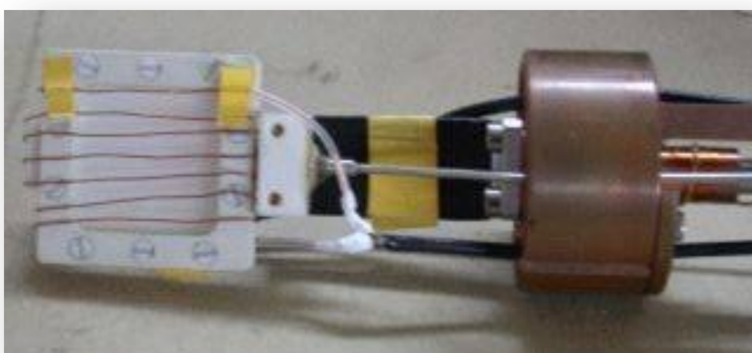
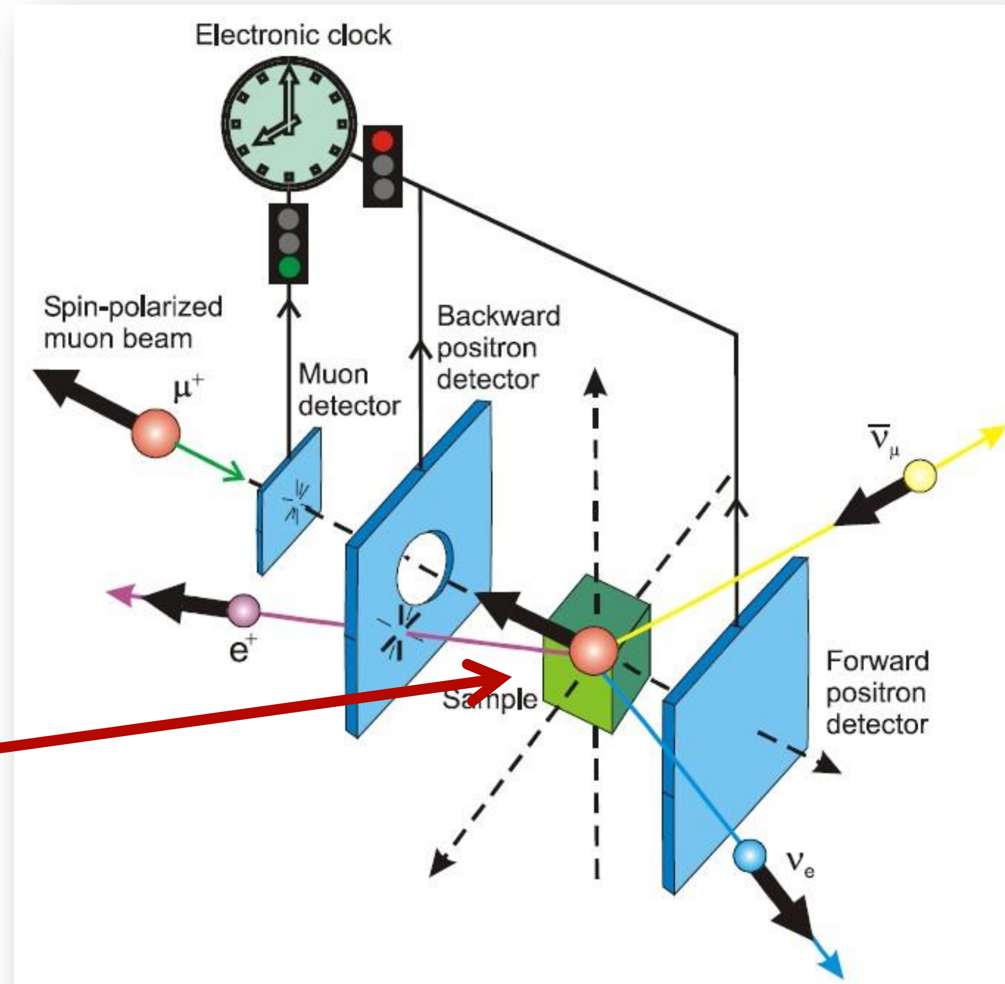
RF-μSR

Start with LF setup

Oscillating field applied to drive transitions between Zeeman level(s)



Picture: J. Lord, RF-μSR and Pulsed Techniques,
http://www.isis.stfc.ac.uk/groups/muons/muon-training-school



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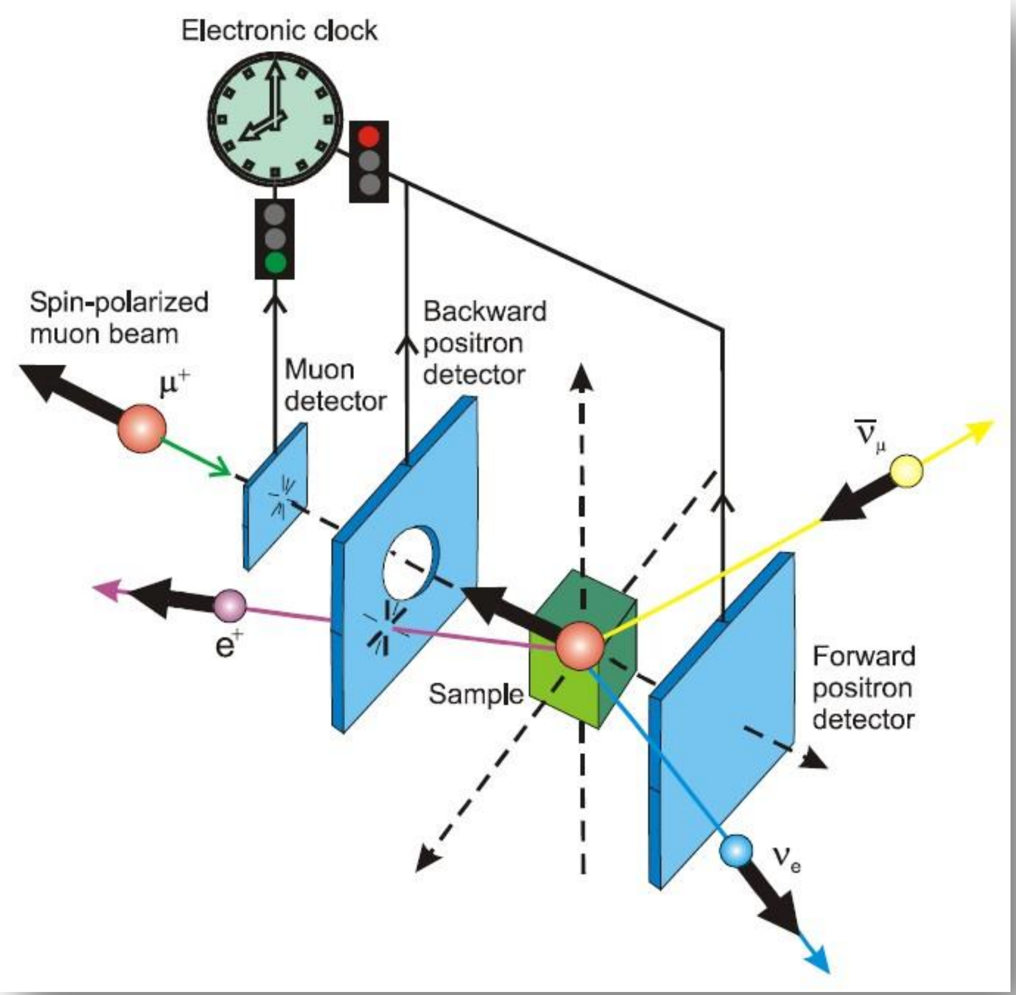
ZF-μSR



Brewer, http://musr.ca

No net B applied
See time evolution of P(t)
in natural environment

=> Change in Spin P(t)
from:
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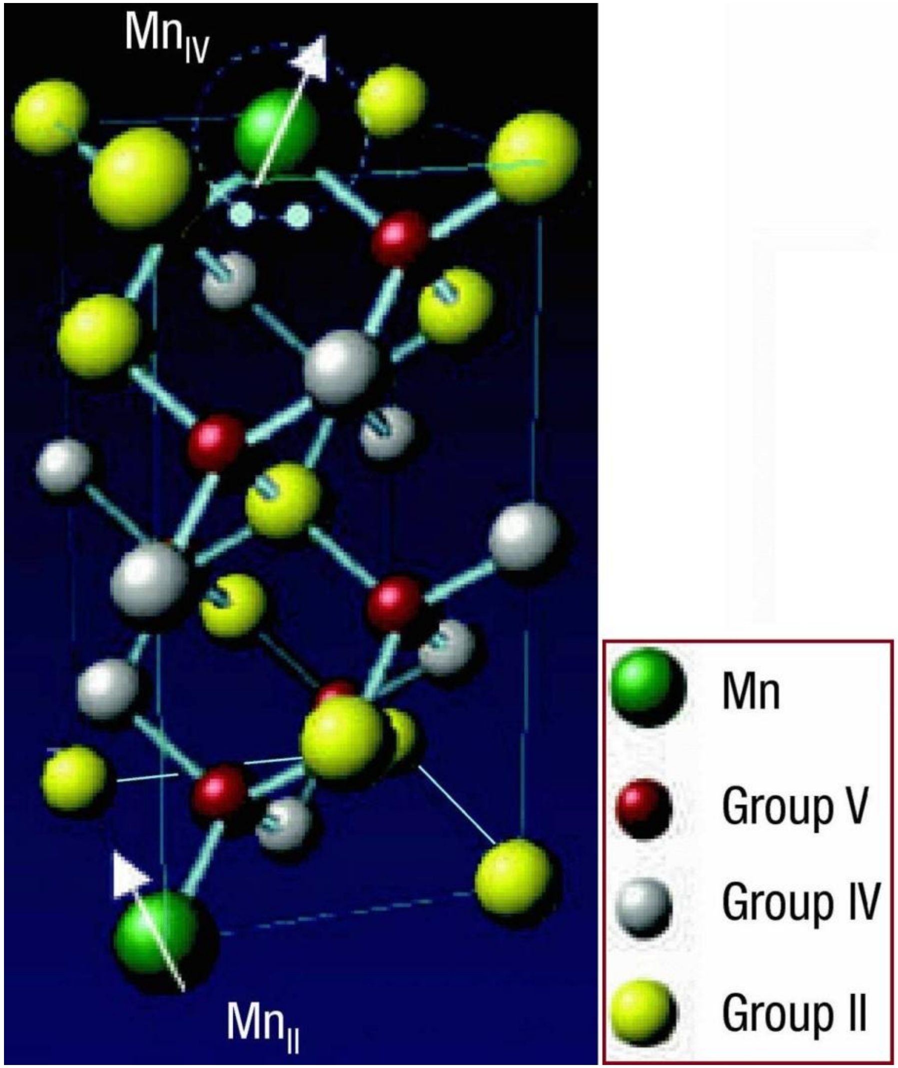

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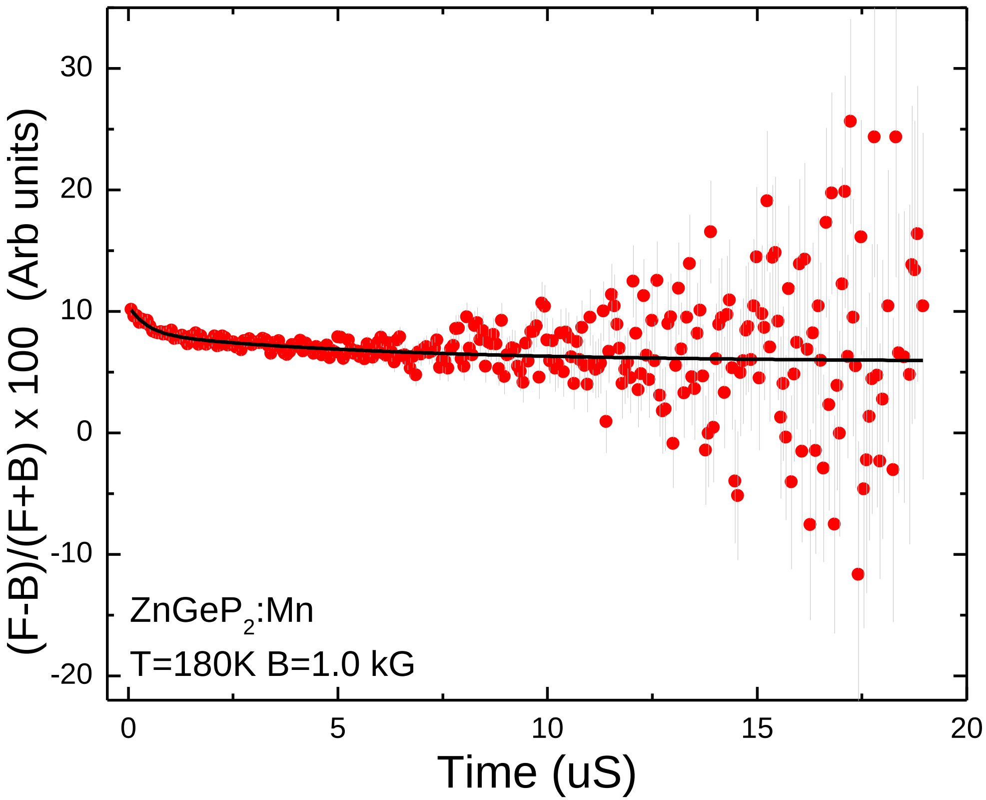
Polarization Function



$$P_z^G(t) = e^{-t/T_1} + e^{-t/T_2} + C$$

$$P_z(t) \approx e^{\left(\frac{-t}{T_1}\right)^{\beta}} \Bigg| \frac{1}{T_1} = \frac{2\Delta_i^2}{\nu}$$

$$\rho(\Delta_i) = \sqrt{\frac{2}{\pi}} \frac{a}{\Delta_i^2} \exp\left(\frac{-a^2}{2\Delta_i^2}\right) \Bigg| \Delta_i = \gamma_\mu \mathrm{B}_i$$

$$P_z^L(t) = \int_0^\infty P_z^G(t)\rho(\Delta)d\Delta = \cdots = \exp\left[-\left(\frac{4a^2 t}{\nu}\right)^{1/2}\right]$$

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