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Spin fluctuations and their effect on superconductivity in Titanium-Vanadium alloys

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Outline

- Introduction
- Superconductivity
- μSR
- Spin fluctuations in TiV alloys
- Outlook

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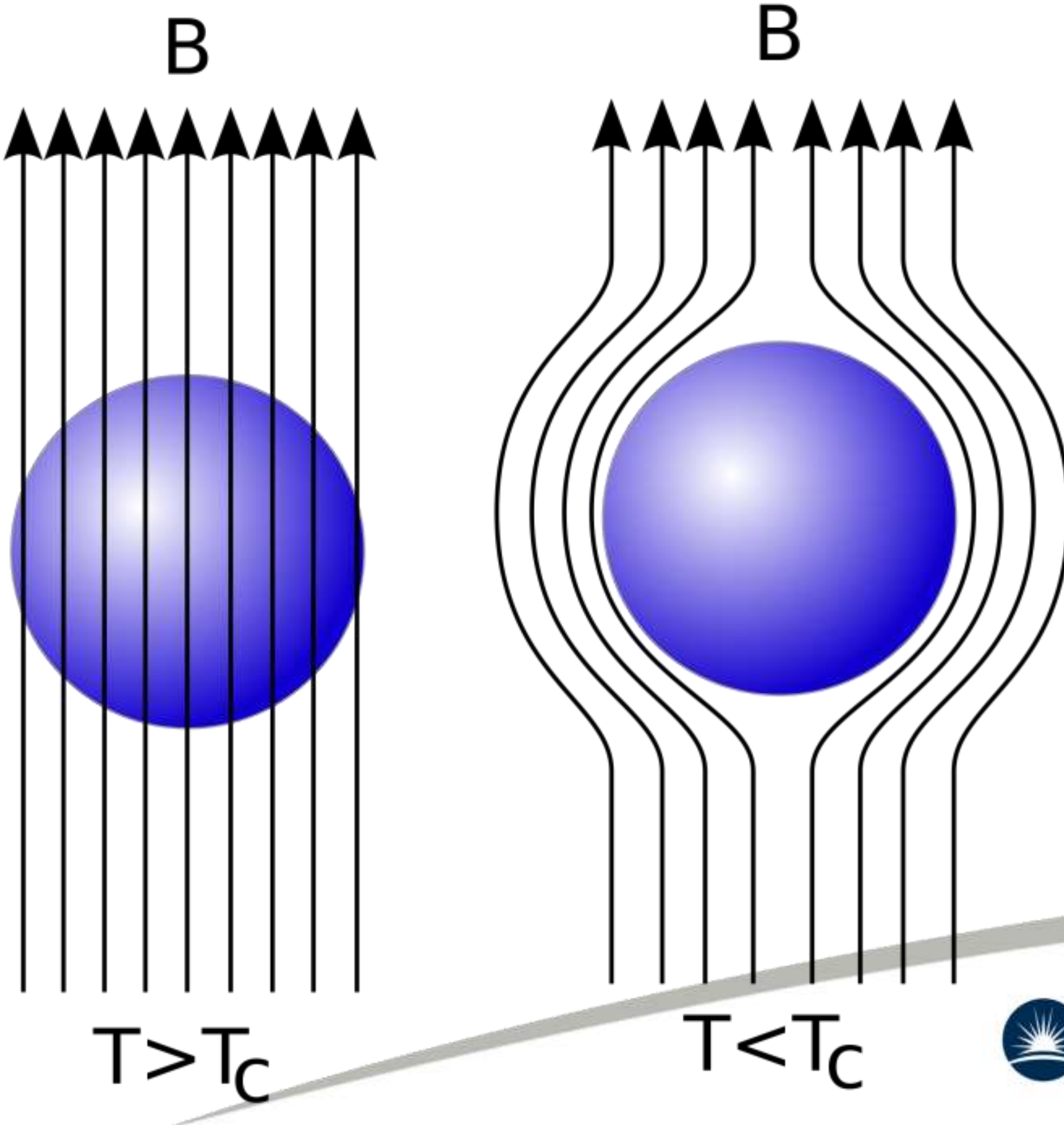
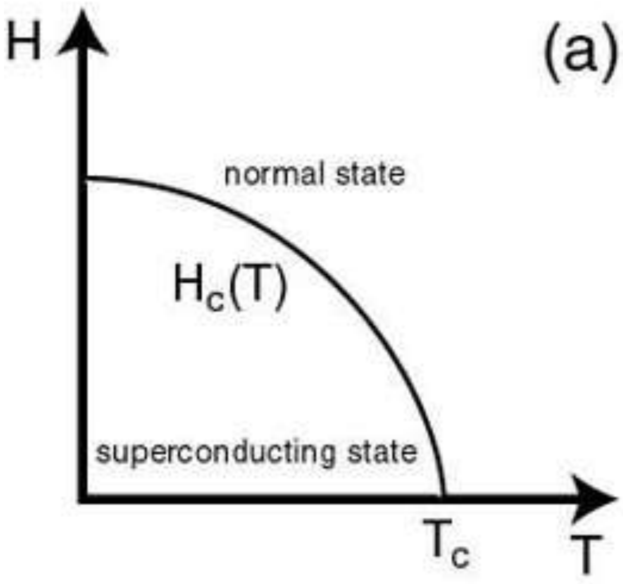
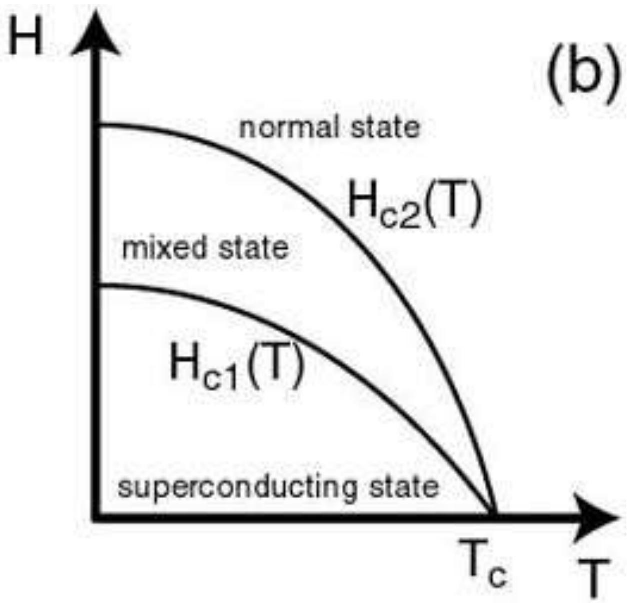

B
B
$T>T_C$
$T<T_C$

- Type I
  - Meissner state: $H < H_C$
  - Normal state: $H > H_C$
- Type II
  - Meissner state: $H < H_{C1}$
  - Mixed state: $H_{C1} < H < H_{C2}$
  - Normal State: $H > H_C$





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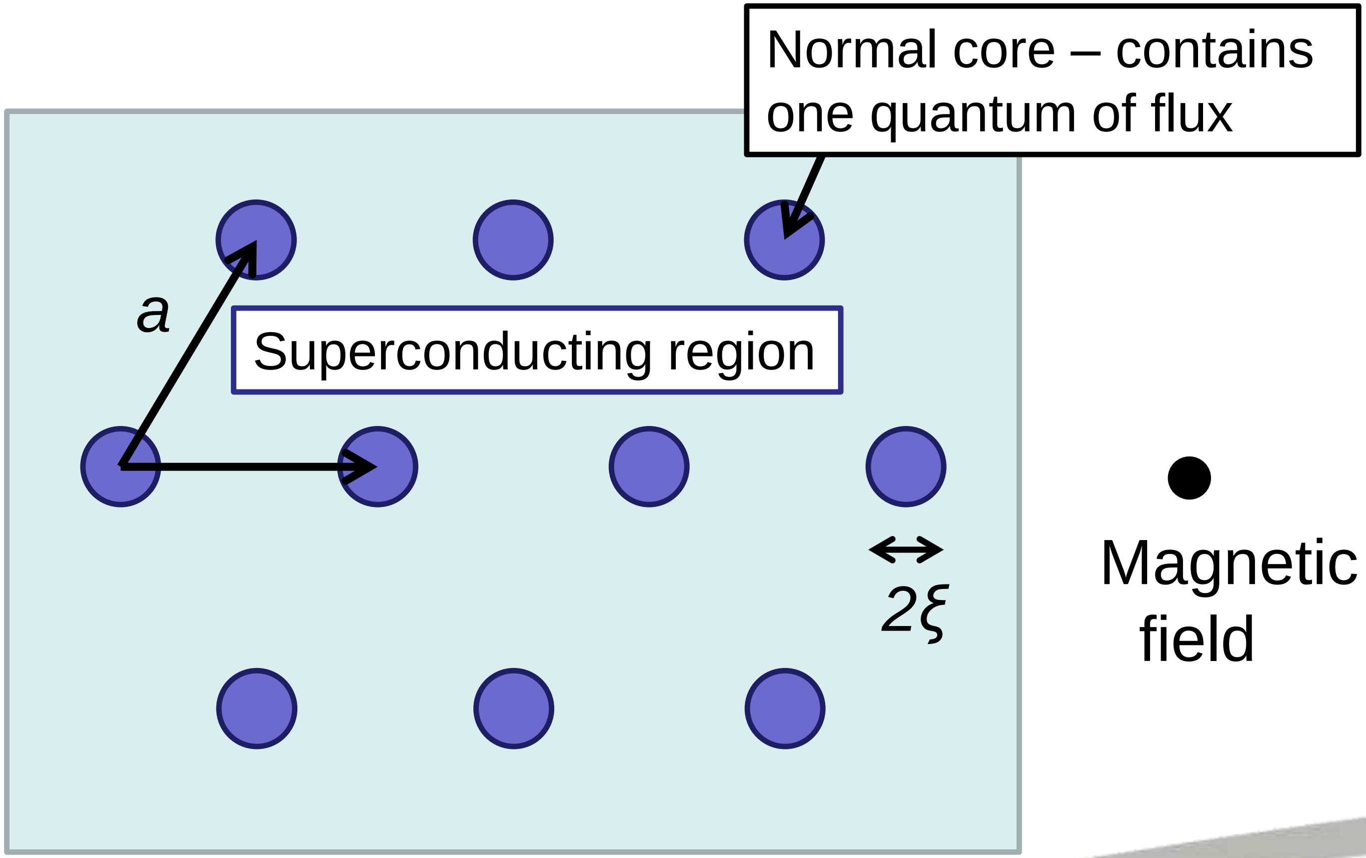
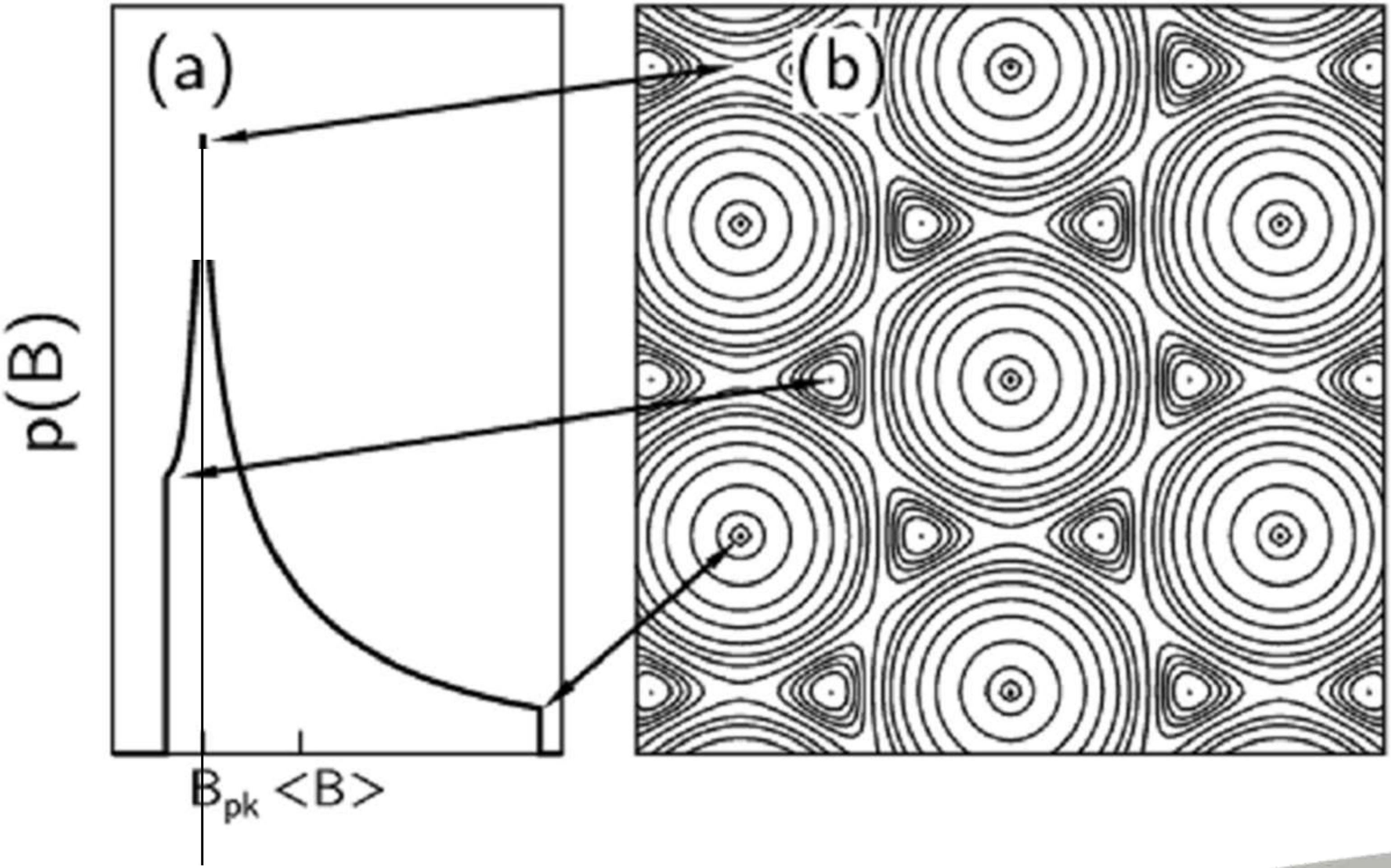
The vortex lattice





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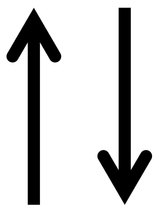
Microscopic mechanism behind superconductivity

- Cooper pair of electrons: conventionally a spin singlet state
  - **No net angular momentum**



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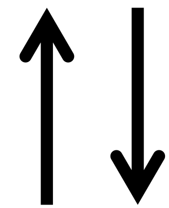
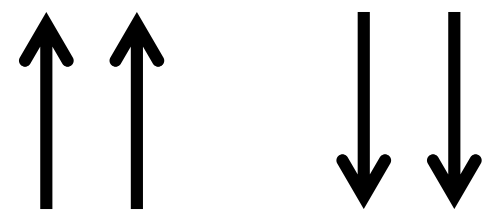


- Unconventional pairing: spin triplet
  - **Net angular momentum**
  - Time-reversal symmetry broken



μSR is sensitive enough to detect the low fields (~0.1 G) caused by triplet pairing in the superconducting state

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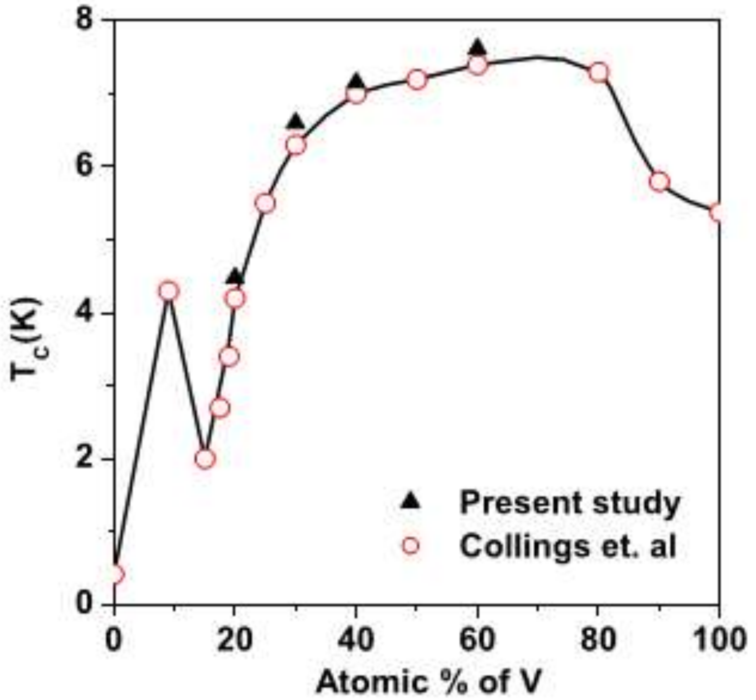
Unusual superconductivity in TiV

- T_C of TiV alloys much lower than predicted
- Hints of spin fluctuations in the presence of superconducting state
- Can we see them directly?
  - Yes, with muons
- How are they tied to the superconductivity?
  - …not really sure



Matin *et al.*, Eur. Phys. J. B, **87** 131 (2014)

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Fundamentals: the positive muon

- Microscopic particle
  - Local probe
- Spin ½
  - Sensitive to magnetism
- $\tau_{1/2}$ = 2.2 μs
  - Independent of material

μ^+

μSR provides a picture of a the local magnetic environment that may be missed by susceptibility measurements

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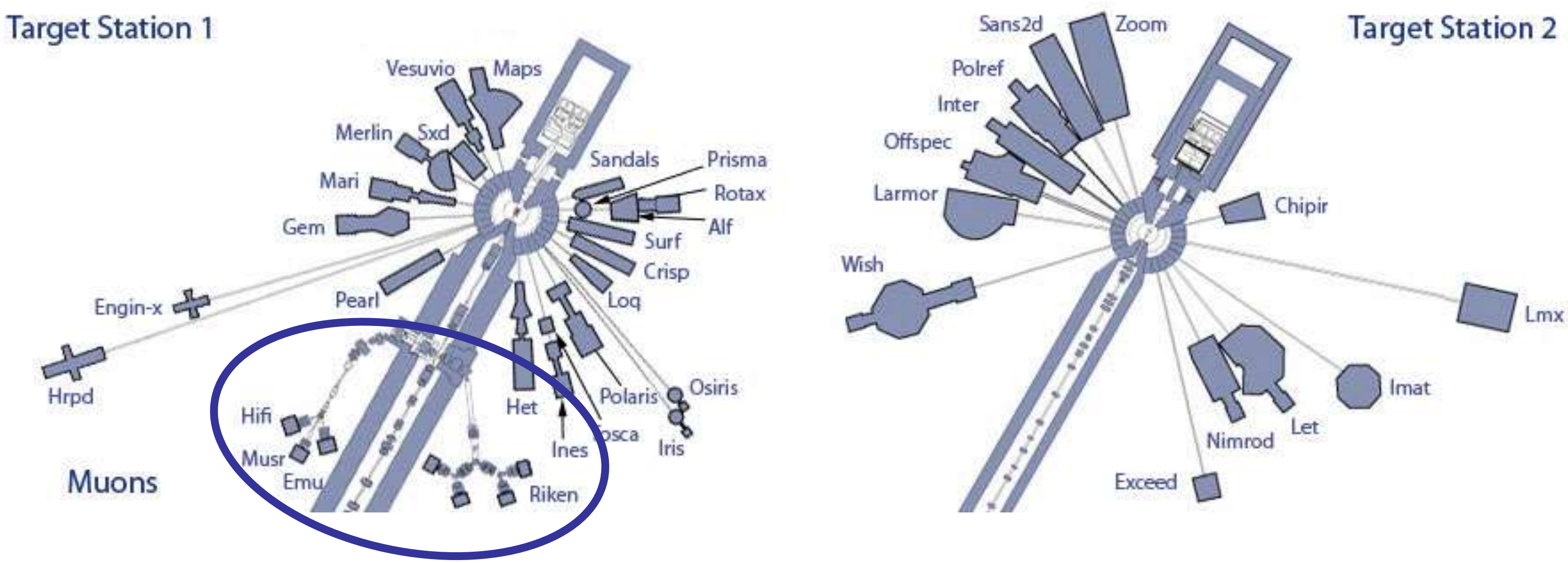
The Muon Source at ISIS



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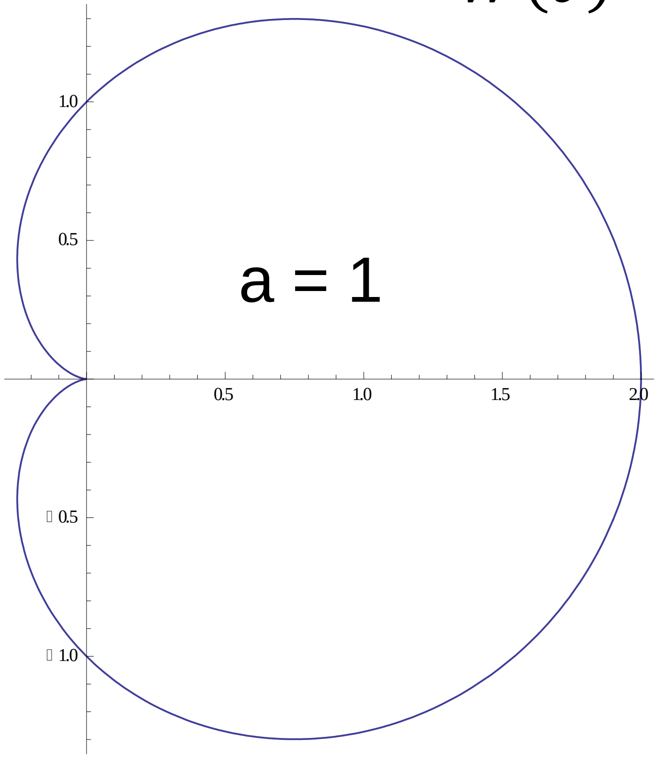
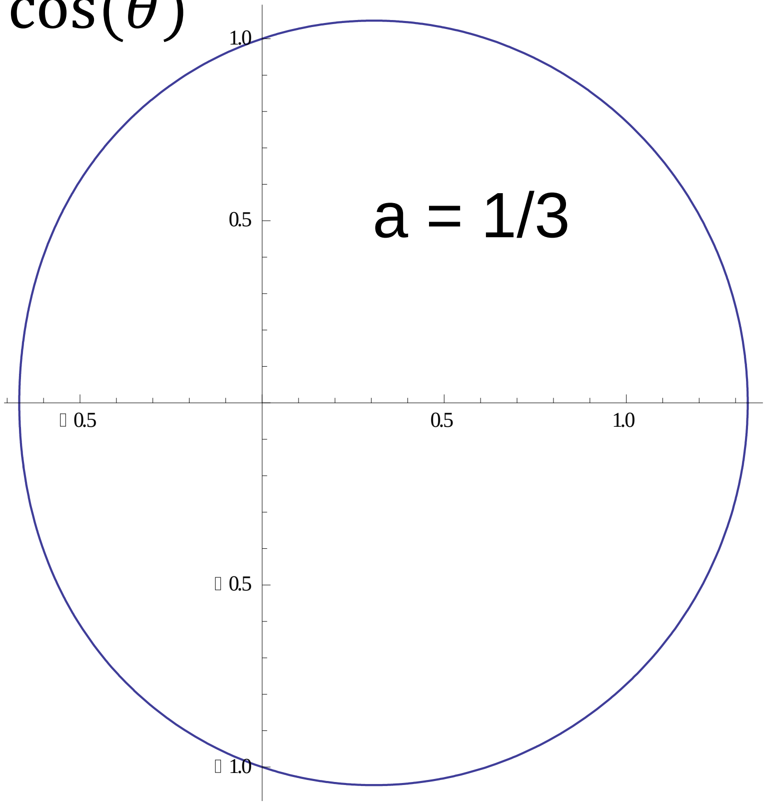
$$W(\theta) = 1 + a.\cos(\theta)$$



Highest energy positrons



Average over all positron energies

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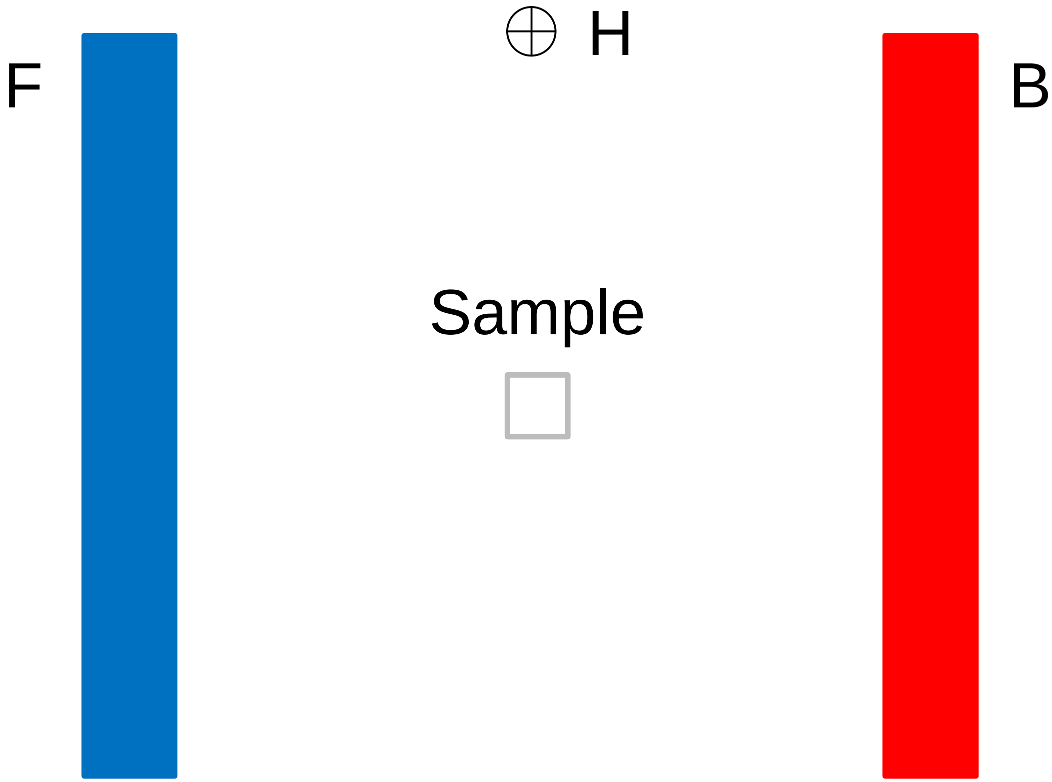

MuSR instrument at ISIS

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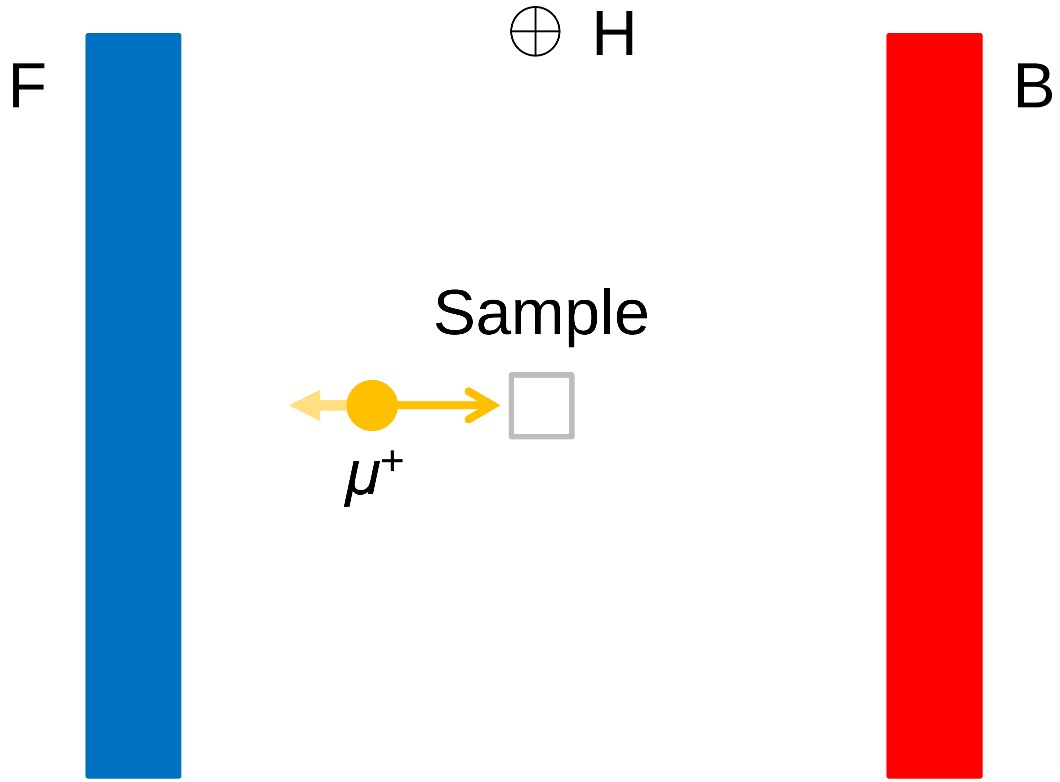
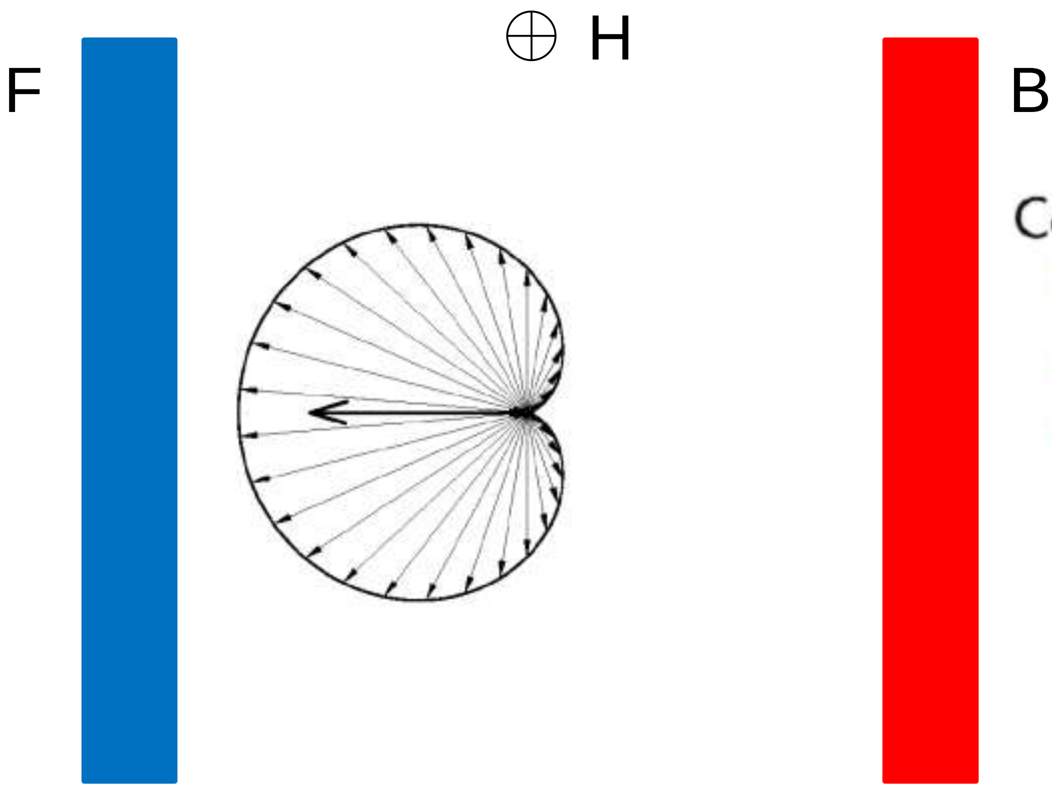
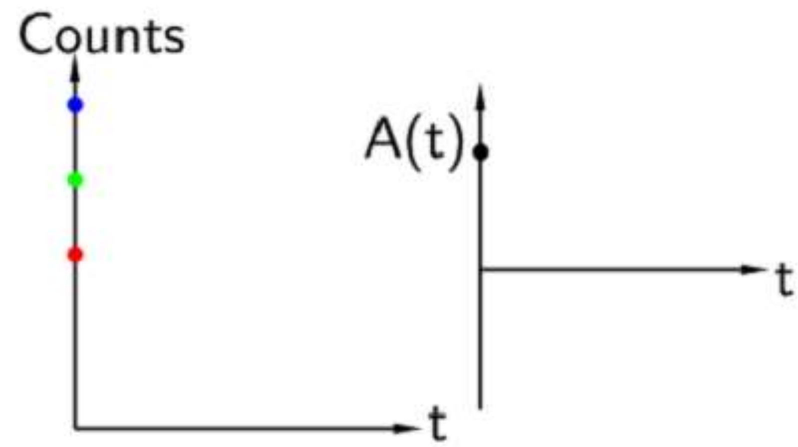


After muon pulse implanted start clock and begin counting



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



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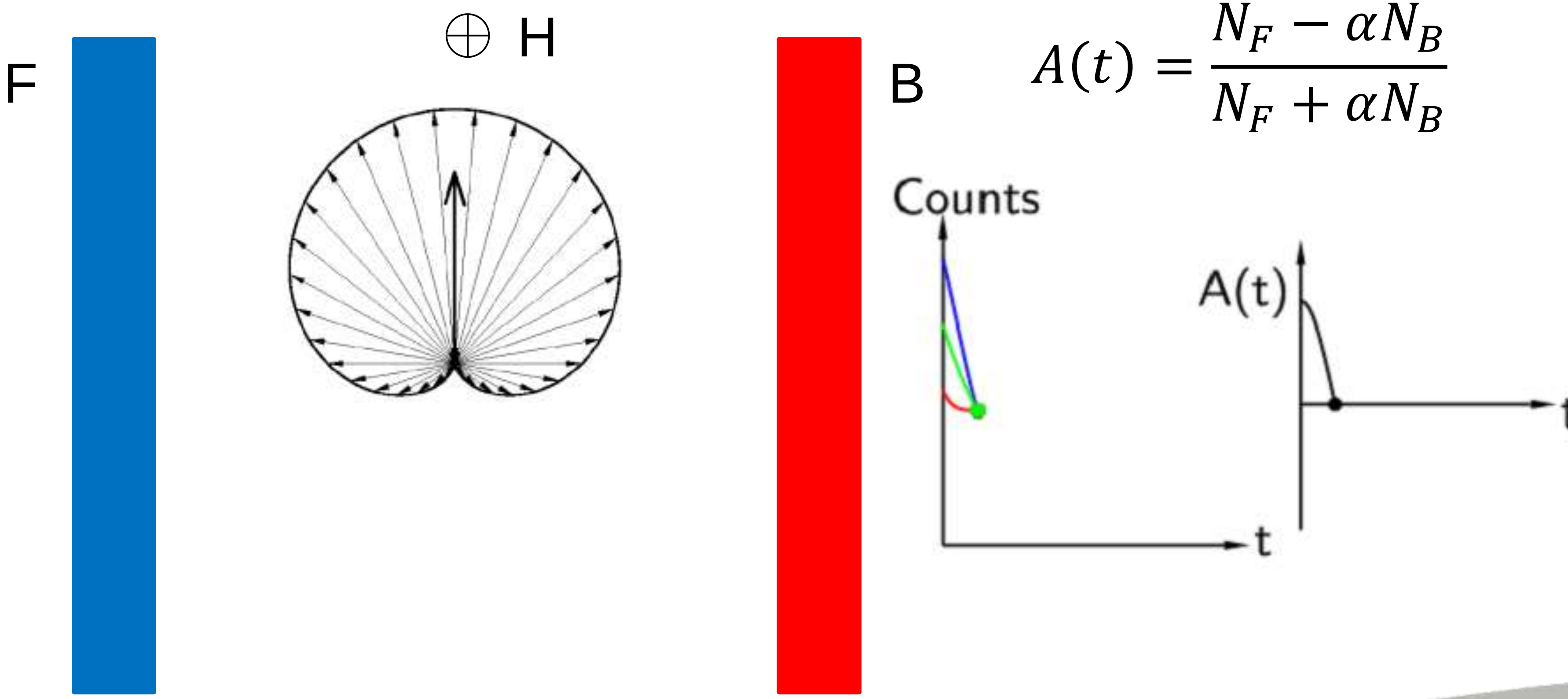

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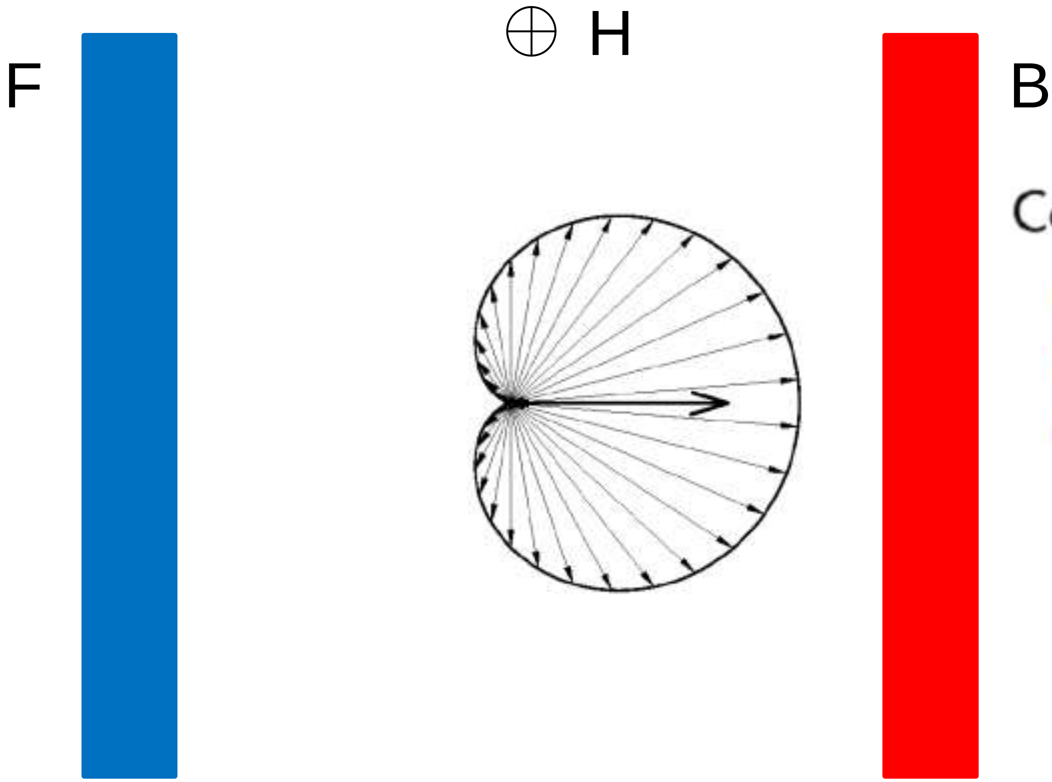

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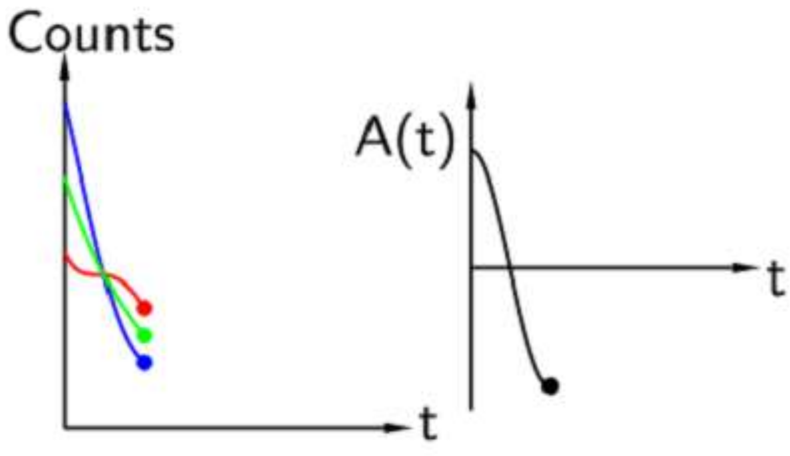

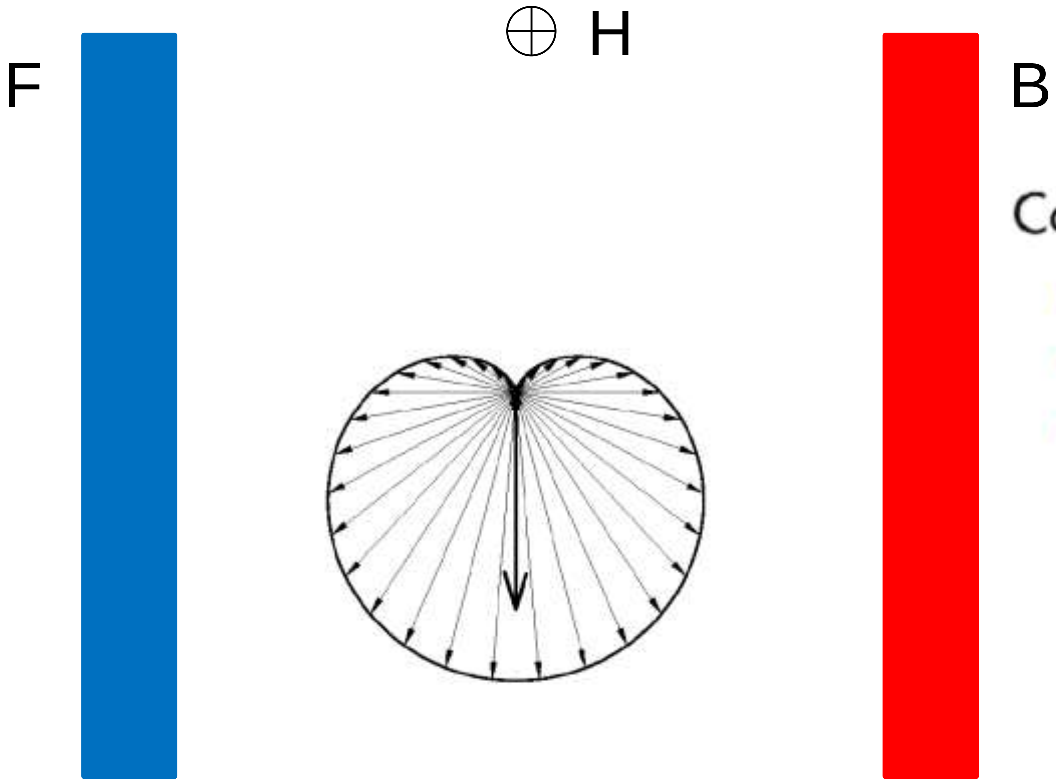

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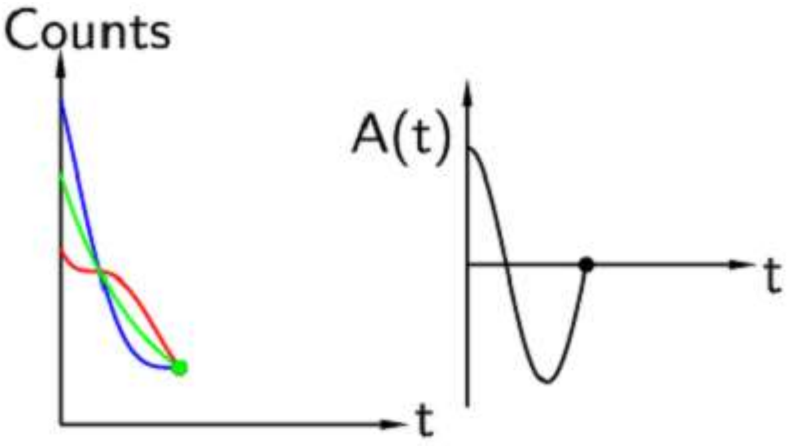

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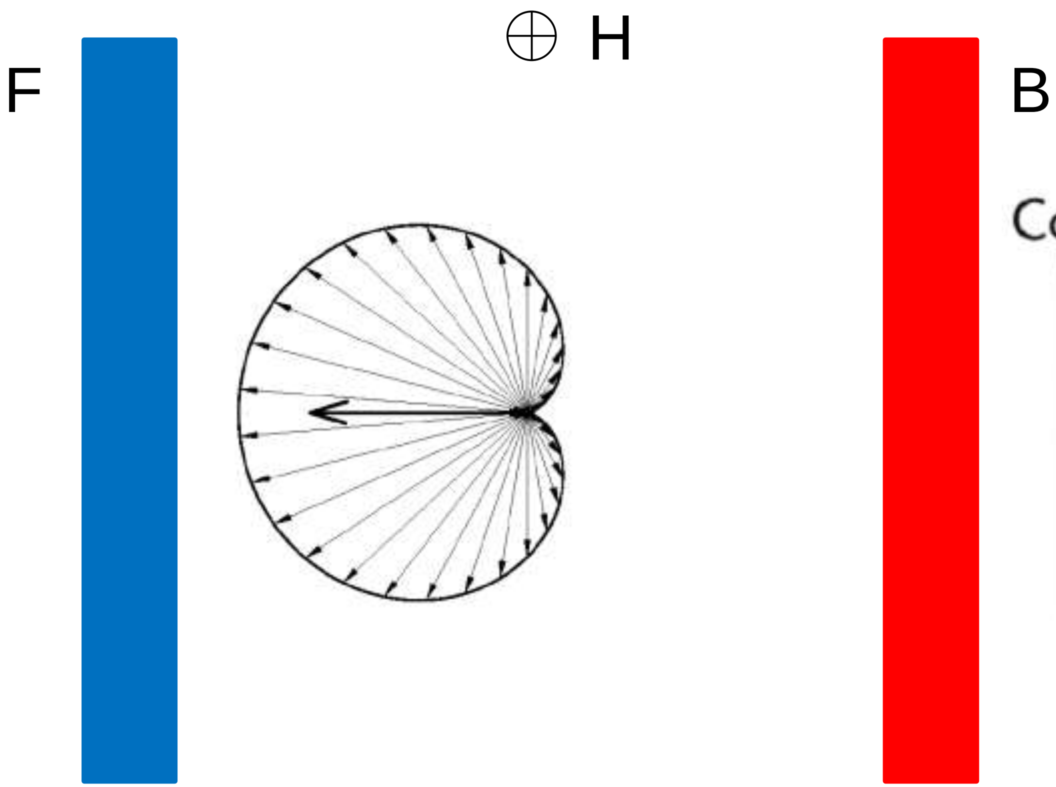

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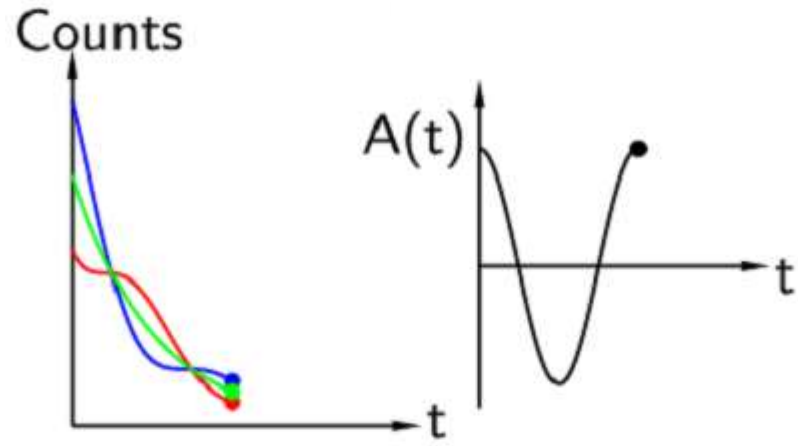

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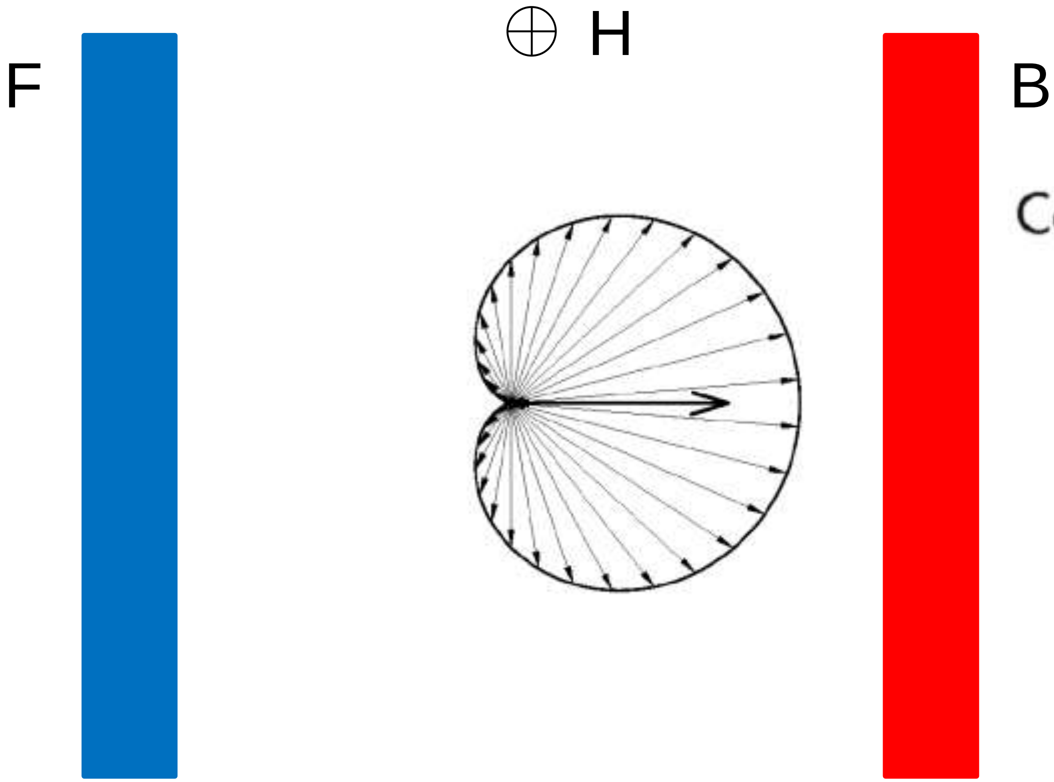

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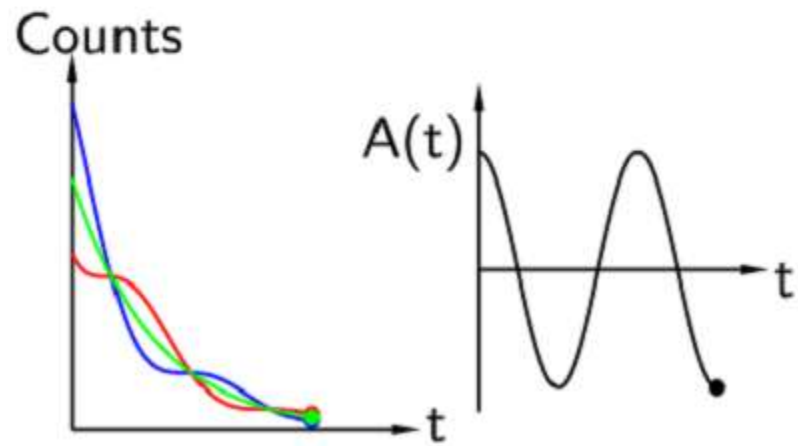
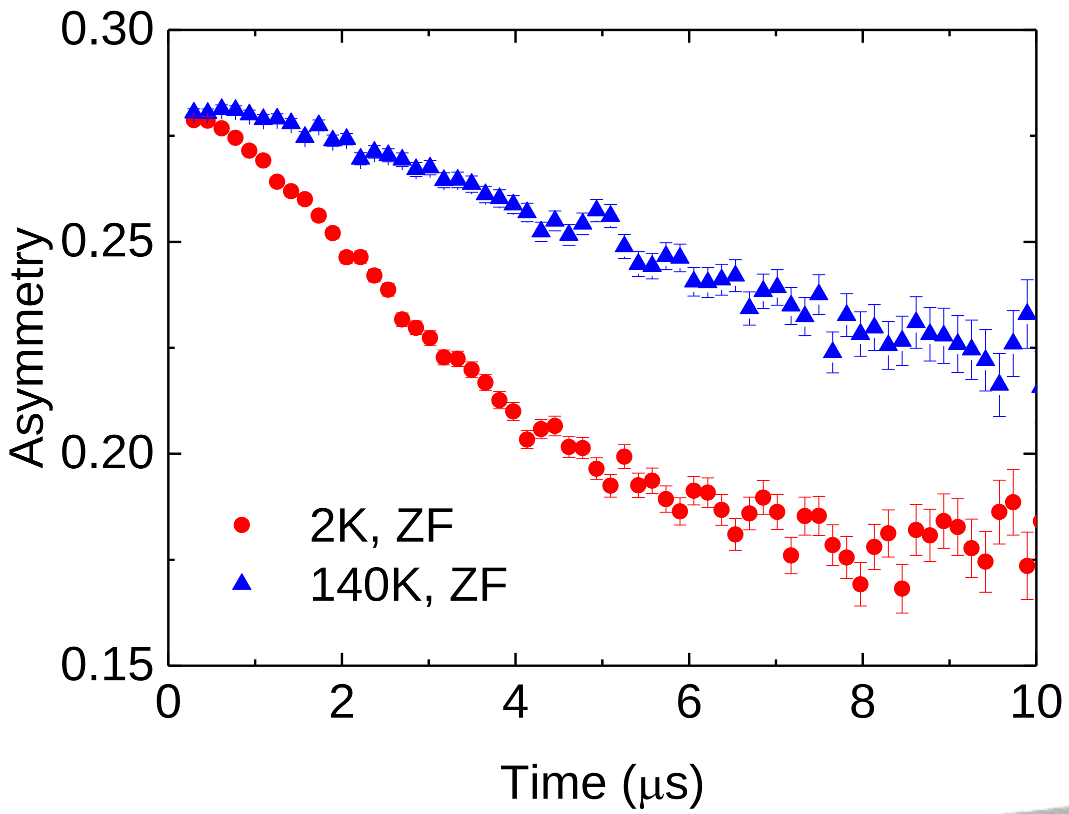


Zero-field studies of $Ti_{55}V_{45}$

- Exponential term in relaxation function is evidence for the presence of spin fluctuations



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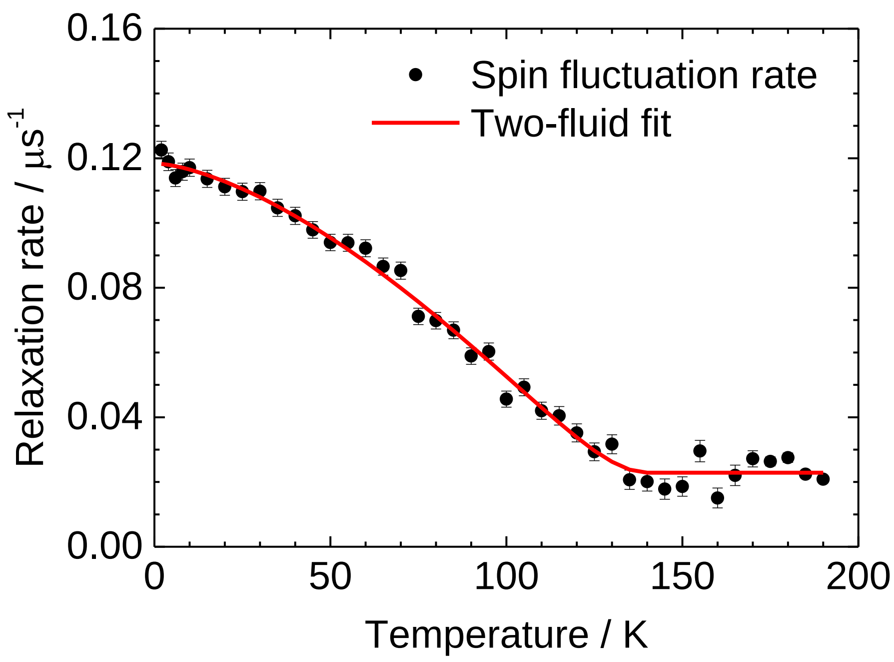
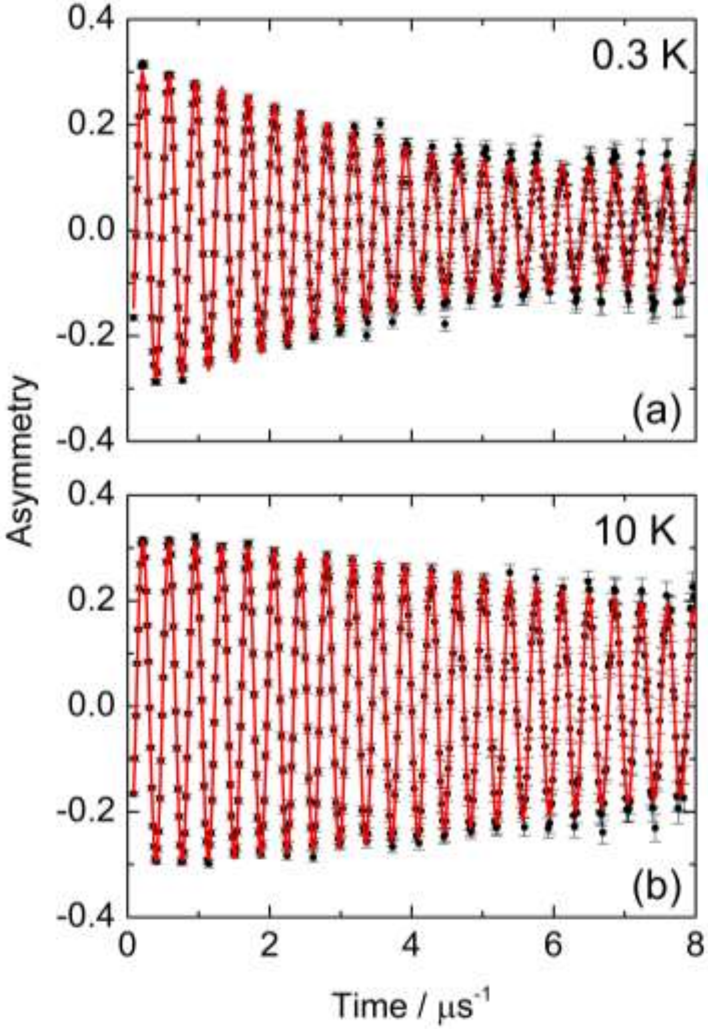
- Spin fluctuations appear to have an onset temperature of ~140 K

$$\Lambda(T) = \Lambda_0\left(1-\left[\frac{T}{T_{sf}}\right]^N\right)+\Lambda_{BG}$$

$N = 1.54\pm0.09 \approx 3/2$



Superconducting state in $Ti_{55}V_{45}$



- Below T_C: characteristic depolarization rate caused by the vortex lattice
- Above T_C: small residual depolarization rate from randomly oriented nuclear spins

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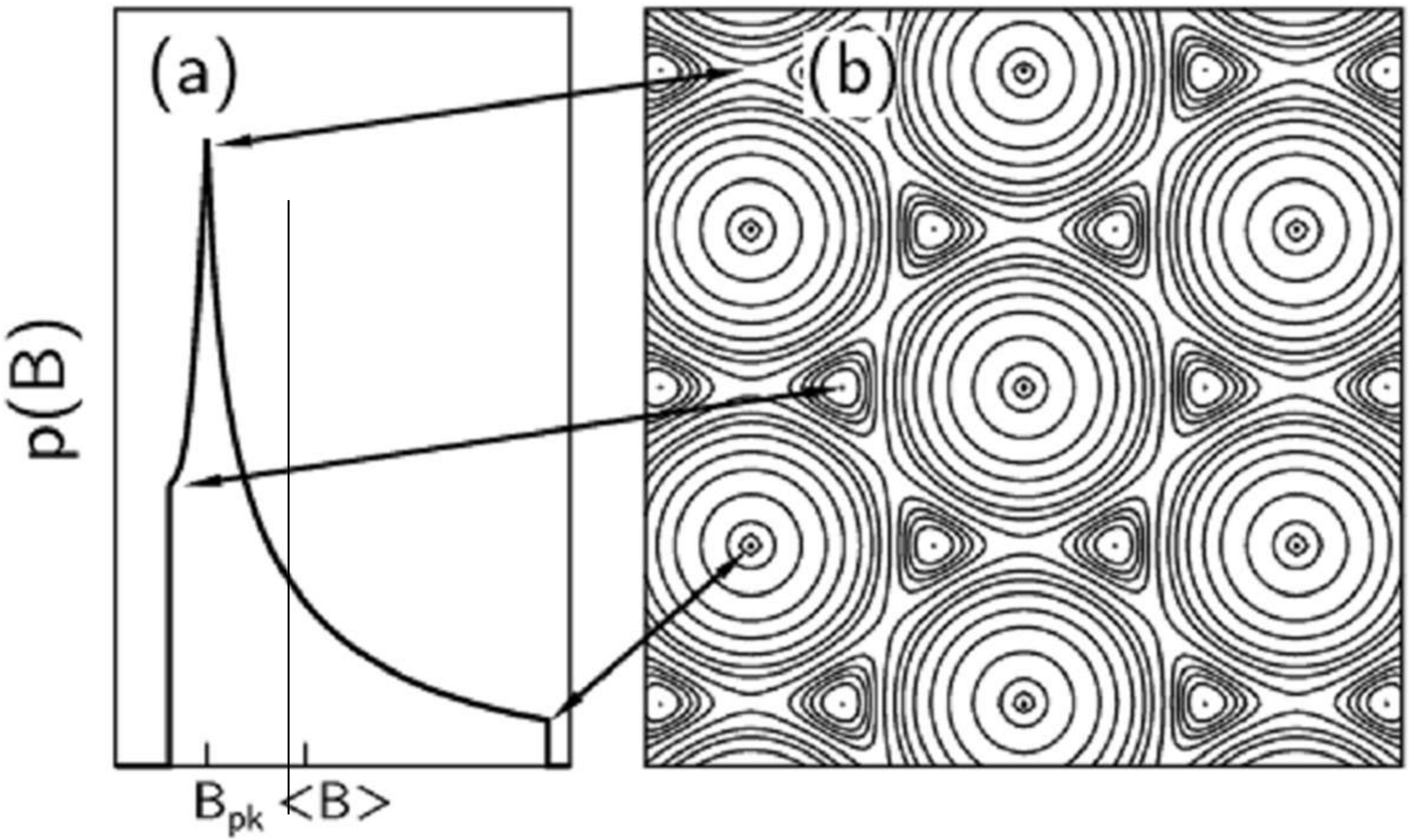

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- Magnetic field distribution of the lattice leads to depolarization of the muon ensemble

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

Decay of oscillations → σ

Magnetic penetration depth → λ

Superconducting carrier density → n_s

Effective mass → m^*

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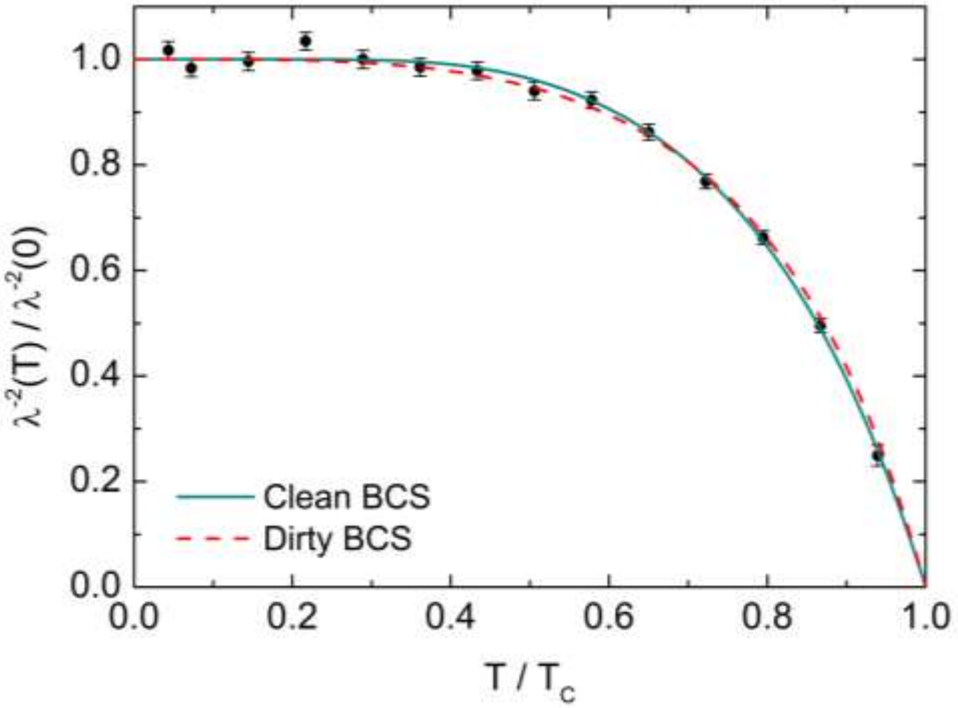
- Isotropic energy gap of 2.1±0.2 meV
- Expected:

$$\frac{2\Delta_{BCS}}{k_B T_C} = 3.528$$

- For TiV

$$\frac{2\Delta_{TiV}}{k_B T_C} = 7.2 \pm 0.4$$



$\lambda = 536 \pm 2$ nm

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- Predicted $T_{C,pr}$ = 13.7 K (using the McMillan formula)
  - $T_{C,pr} = \frac{\theta_D}{1.45} \exp\left\{-1.04 \frac{1+\lambda}{\lambda - \mu^* - 0.62\lambda\mu^*}\right\}$

$$\frac{2\Delta_{TiV}}{k_B T_{C,pr}} = 3.56$$

- Much closer to BCS value

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  - $T_{C,pr} = \frac{\theta_D}{1.45} \exp\left\{-1.04 \frac{1+\lambda}{\lambda - \mu^* - 0.62\lambda\mu^*}\right\}$

$$\frac{2\Delta_{TiV}}{k_B T_{C,pr}} = 3.56 \qquad \frac{2\Delta_{BCS}}{k_B T_C} = 3.528$$

- Much closer to BCS value

Conclusions

- Spin fluctuations coexist with superconductivity, and have an onset temperature of ~140 K
- Temperature dependence of the penetration depth fits an s-wave BCS model
- Magnitude of energy gap is too large for measured T_C

- Are spin fluctuations unconventionally pairing the Cooper pairs? Or are they suppressing the conventional singlet superconductivity?

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Outlook

- Single crystals + SANS study
  - Koss, 1976
- Stoichiometry variation study with μSR

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Thanks for listening.

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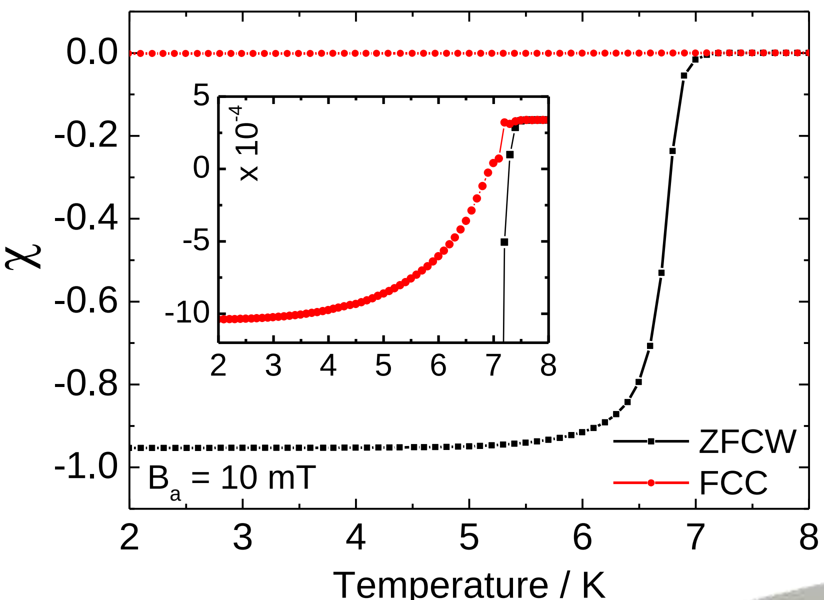
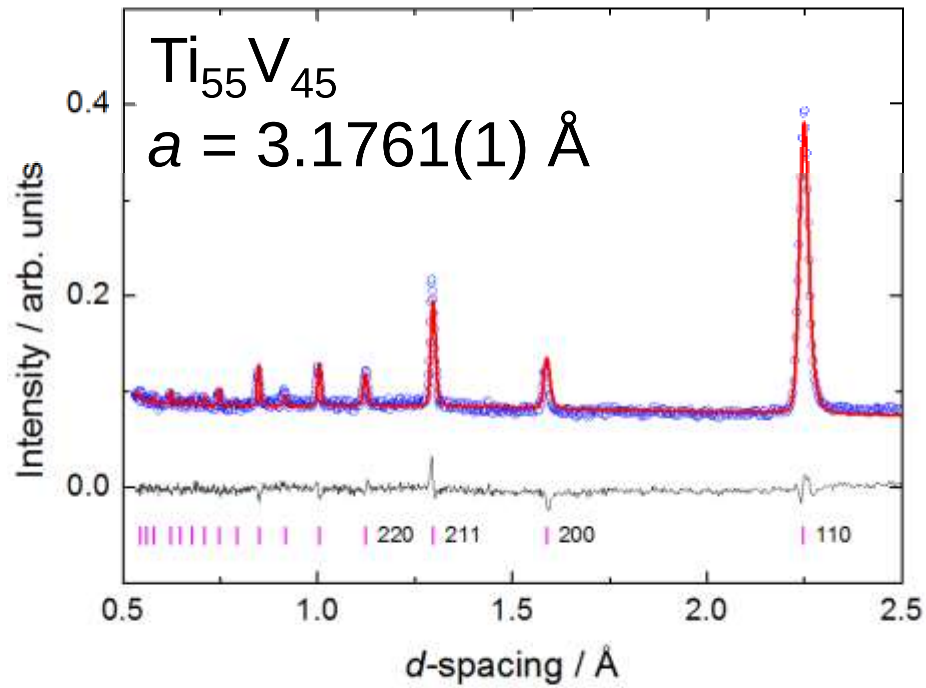
Growth & characterization

- GSAS: refined to single *bcc* phase with expected *Im-3m* spacegroup





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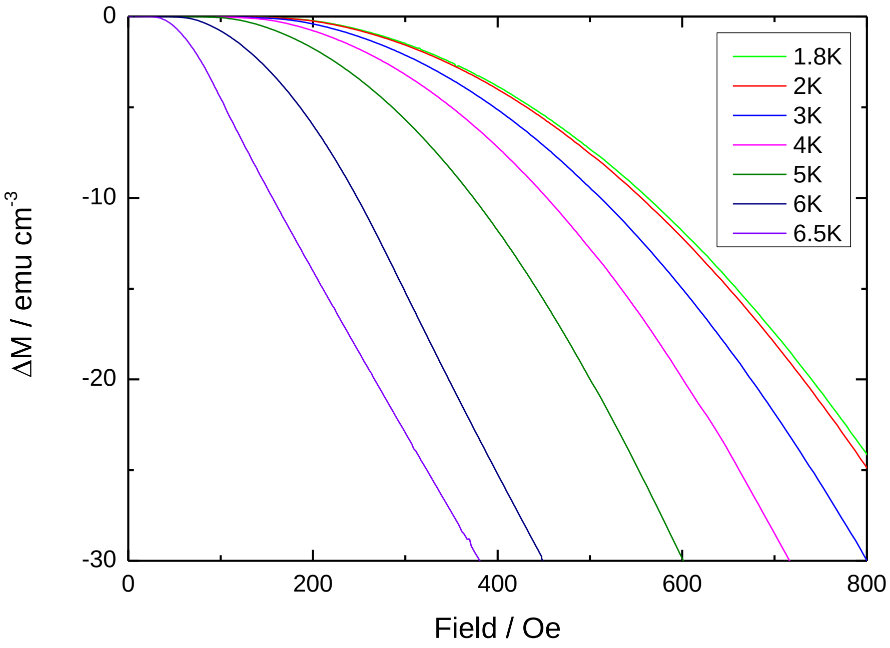
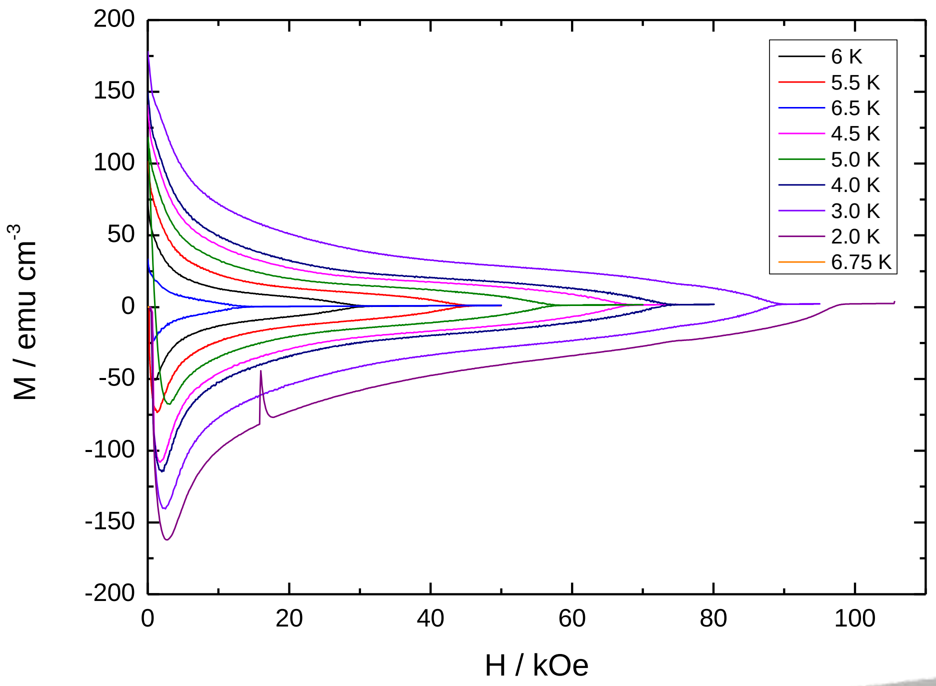
Growth & characterization

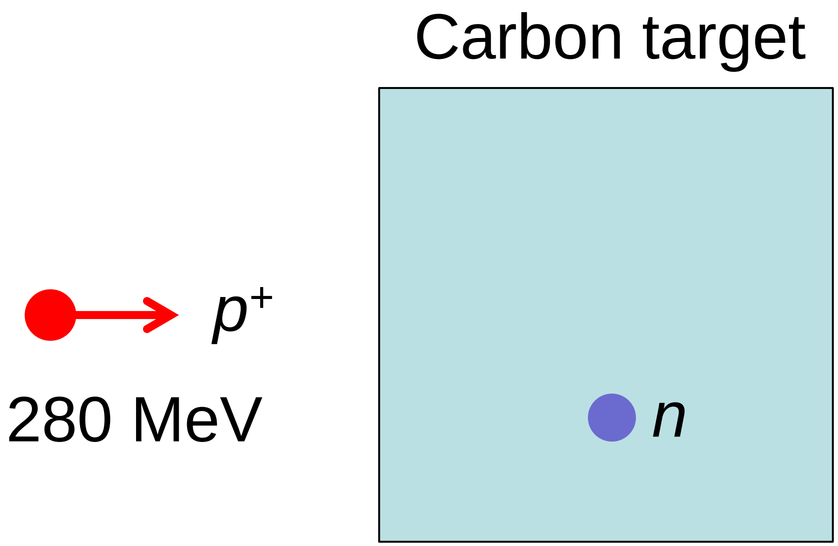




$H_{C1}(0)$= 86(2) G

$H_{C2}(0)$= 110(1) kG

Muon production



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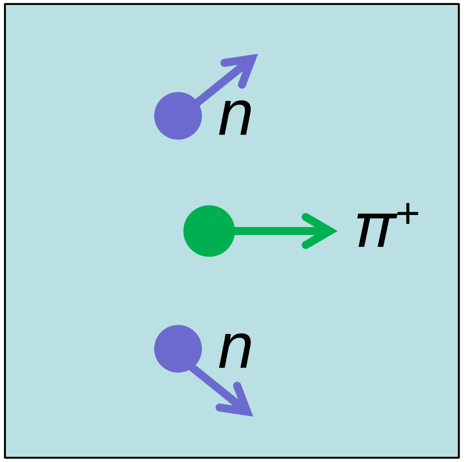
Muon production



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

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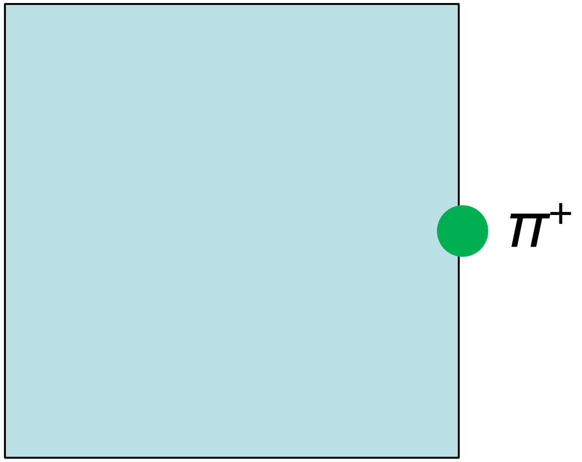
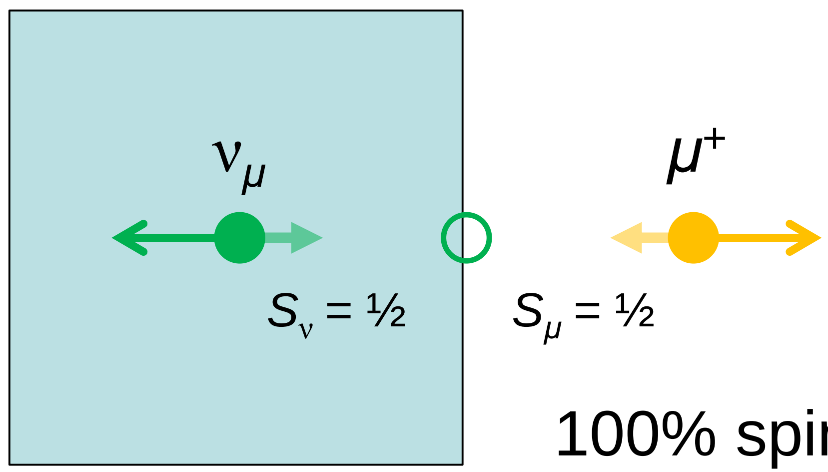
Muon production



Pions that decay at rest at the surface of the target

Muon production

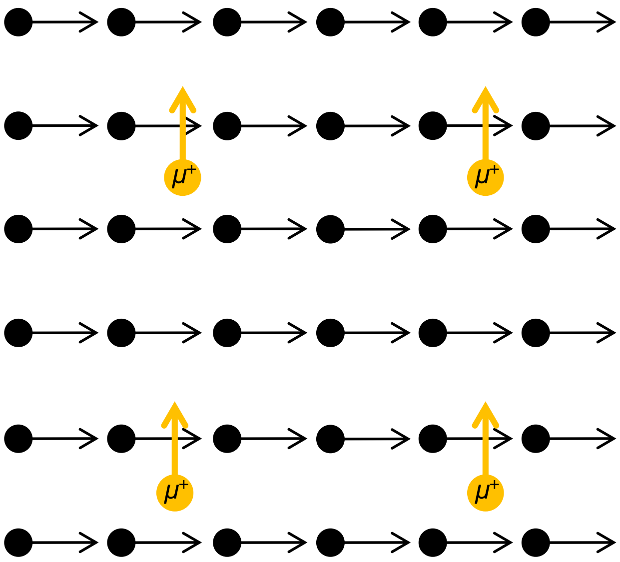


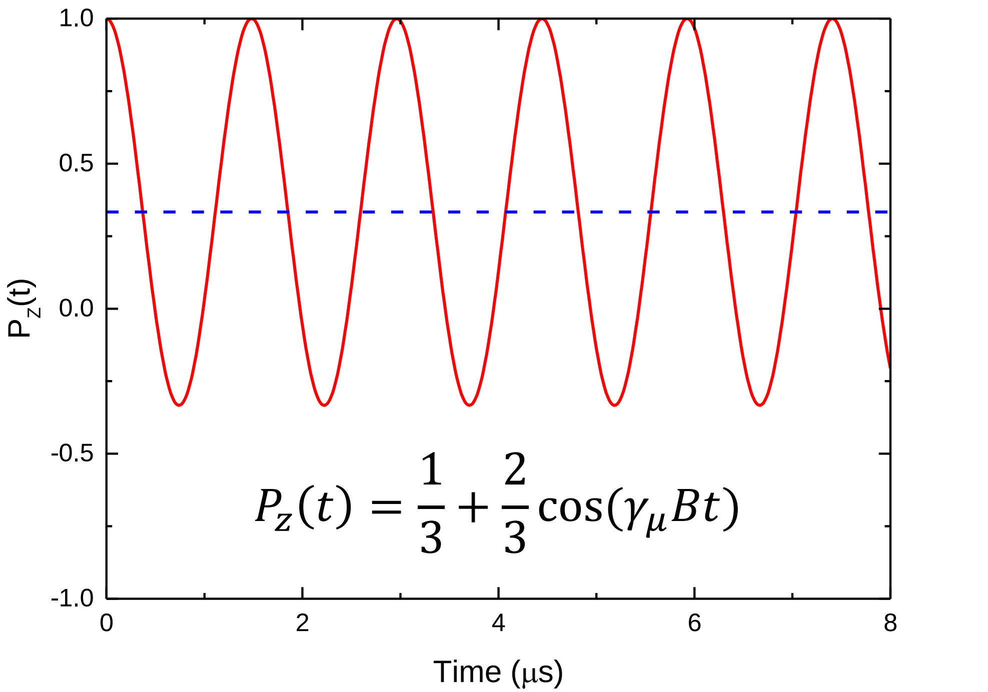
100% spin polarized muon beam thanks to parity violation

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

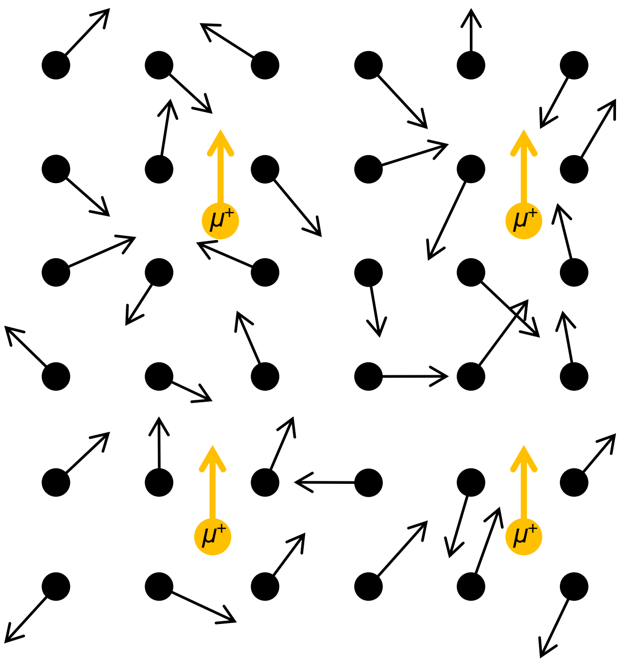
Example spectra (LF)

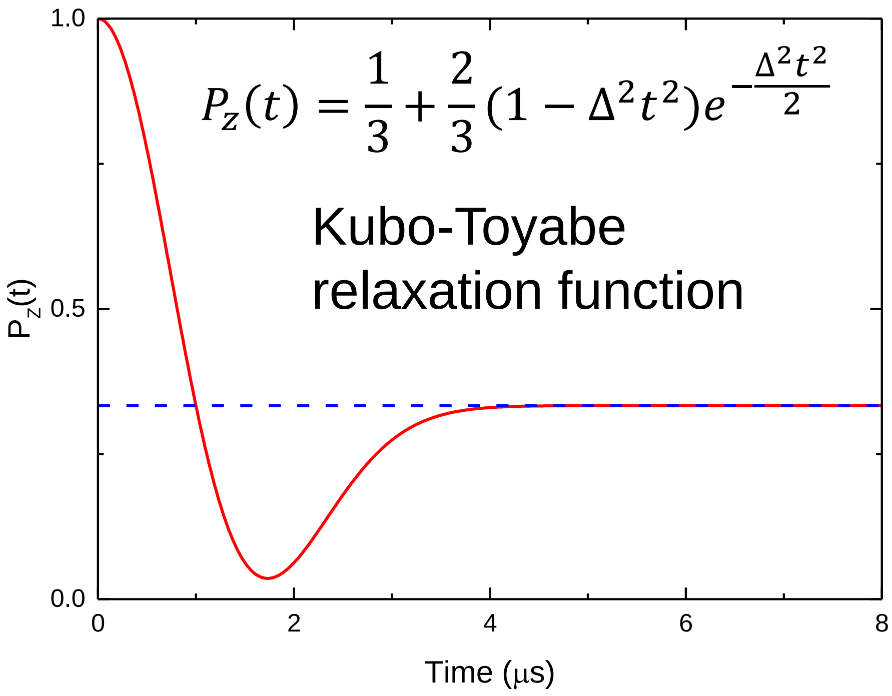
- Static order





- Static disorder





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