Study of Novel Superconducting and Magnetic Materials using Muon Spin Rotation Technique

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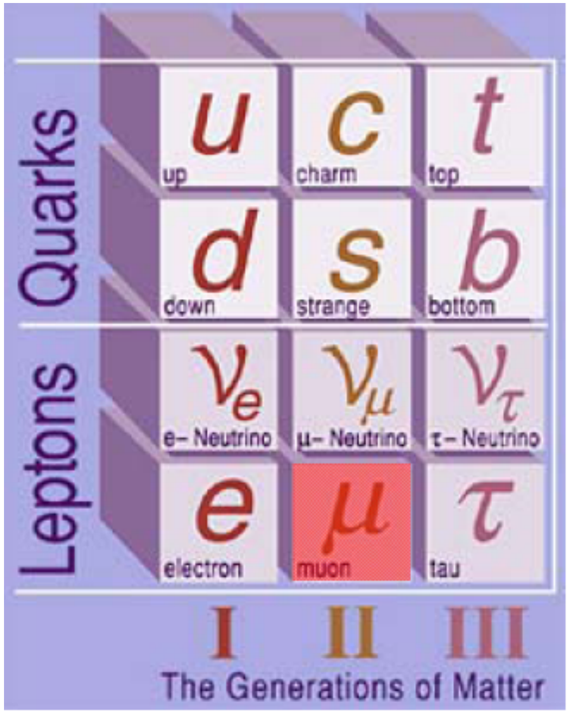
4 May 2010

What are muons ?

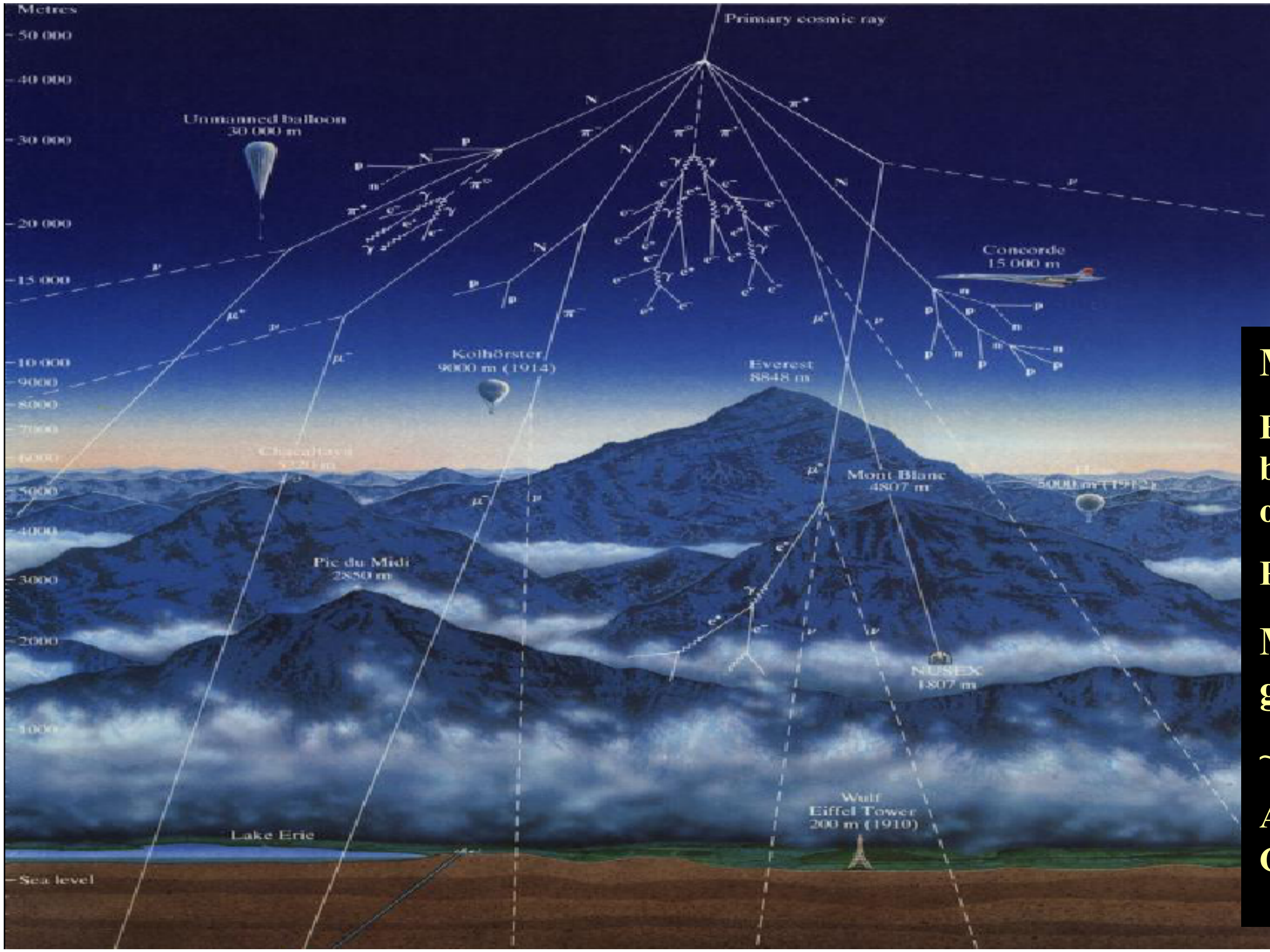
Elementary Particles



Familiar Particles and Muons

	charge	spin	mass	moment	$\gamma\ /\ 2\pi$ (kHz G^{-1})	lifetime (μs)
e	$\pm e$	$1/2$	m_e $= 0.51$ MeV	$657\ \mu_p$	2800	∞
μ	$\pm e$	$1/2$	$207\ m_e$ $= 105.7$ MeV	$3.18\ \mu_p$	13.5	2.19
p	$\pm e$	$1/2$	$1836\ m_e$ $= 938$ MeV	μ_p	4.26	∞

A positive muon behaves like an unstable light isotope of hydrogen



Muon:

Elementary particle but not constituent of ordinary matter

Present in cosmic rays

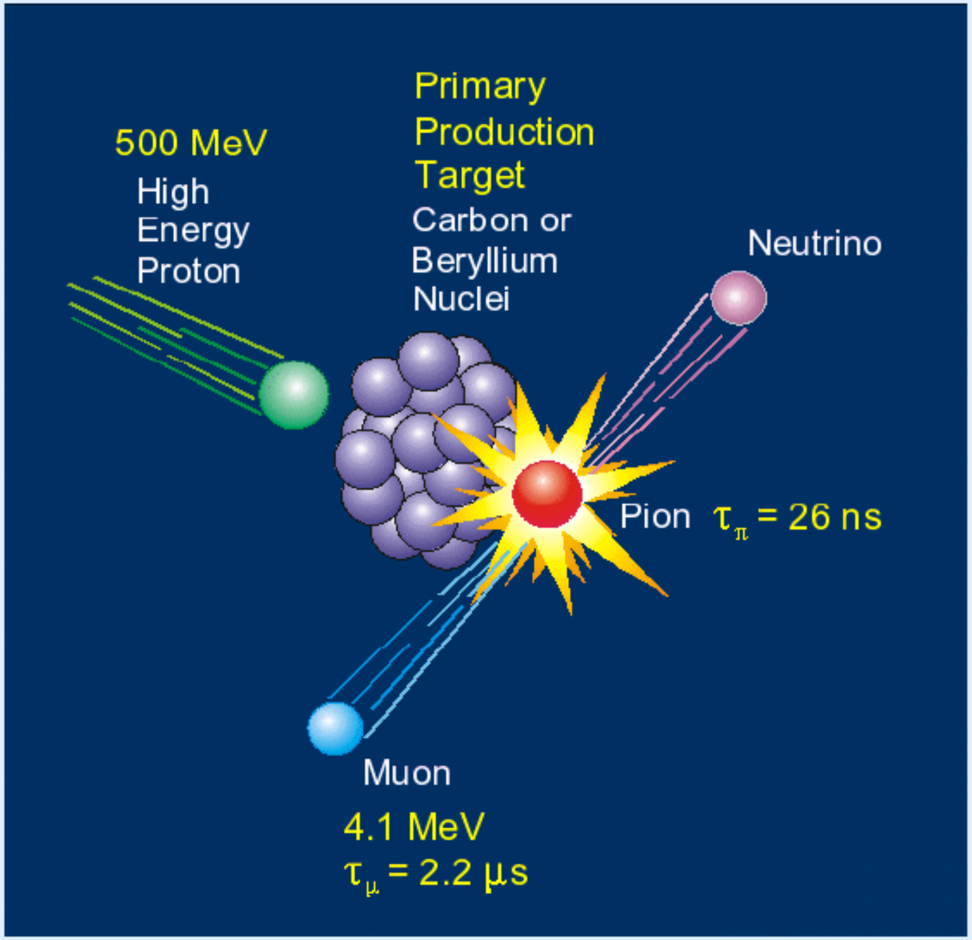
Muon flux at ground:

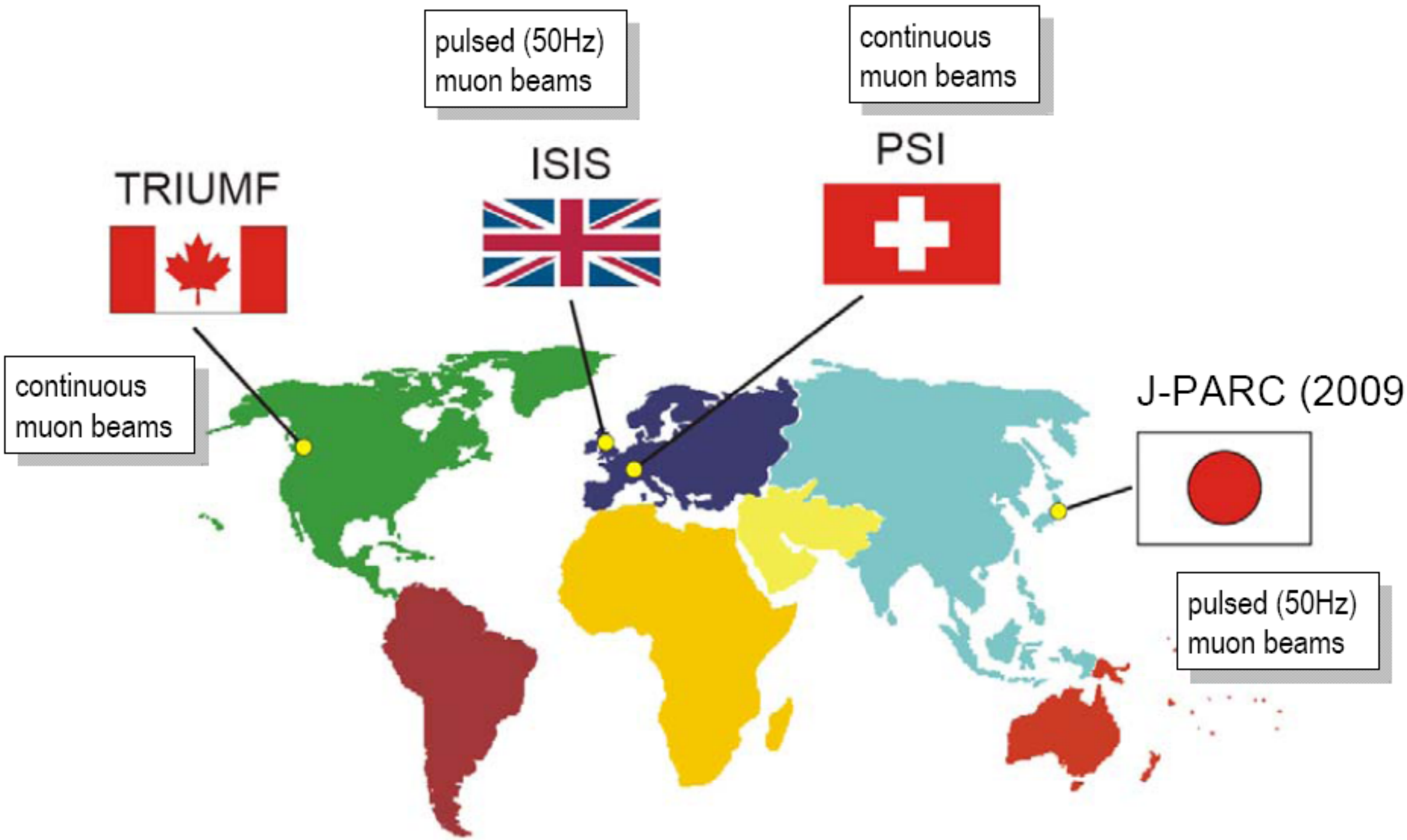
~1 Muon/Min/cm2

Average energy ~ 2 GeV

Muons Production

From Proton Accelerators:





From "µSR brochure" by J.E Sonier, Simon-Fraser-Univ., Canada, 2002. http://musr.org/intro/musr/muSRBrochure.pdf

Muons Production

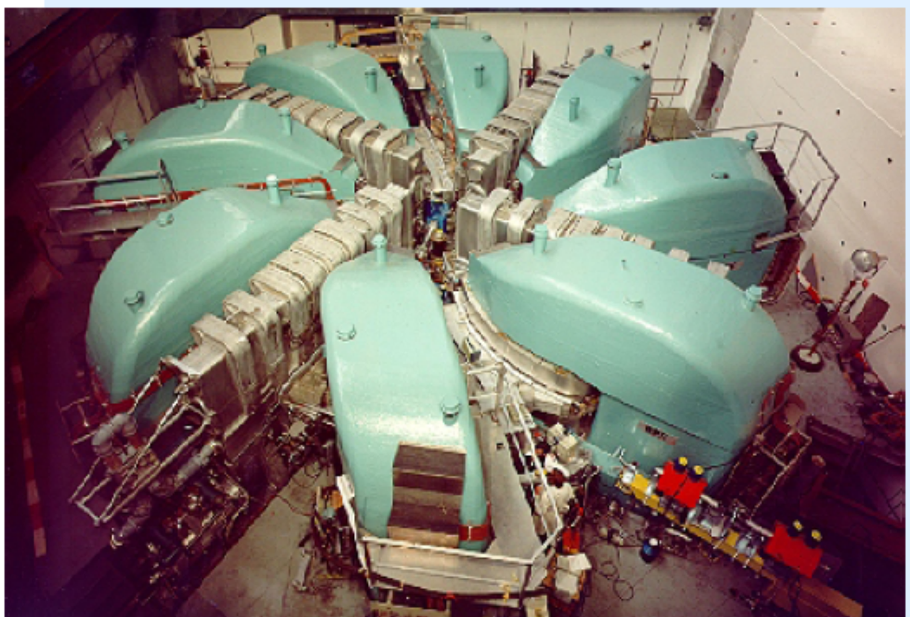
From Proton Accelerators:

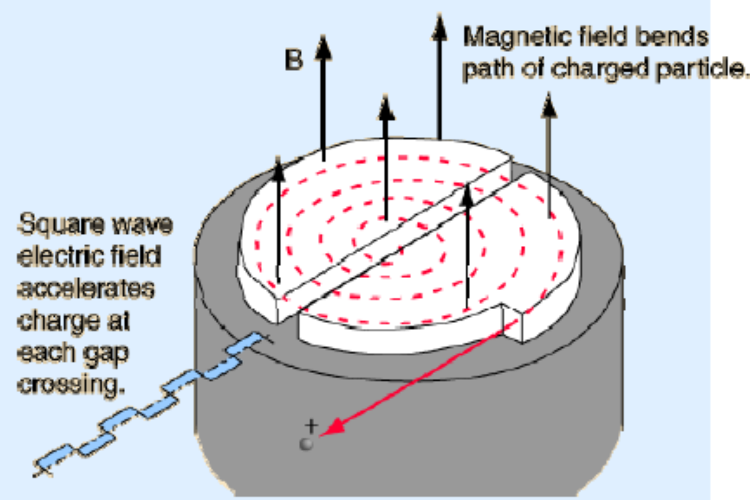
At Paul Scherrer Institute:

2 mA proton beam

10^{16} protons / sec with an extraction energy of ~590 MeV

(➡ 1.2 MW power on $5x5mm^2$, $50kW/mm^2$)





Why are muons interesting for solid-state physicists ?

Why use muons?

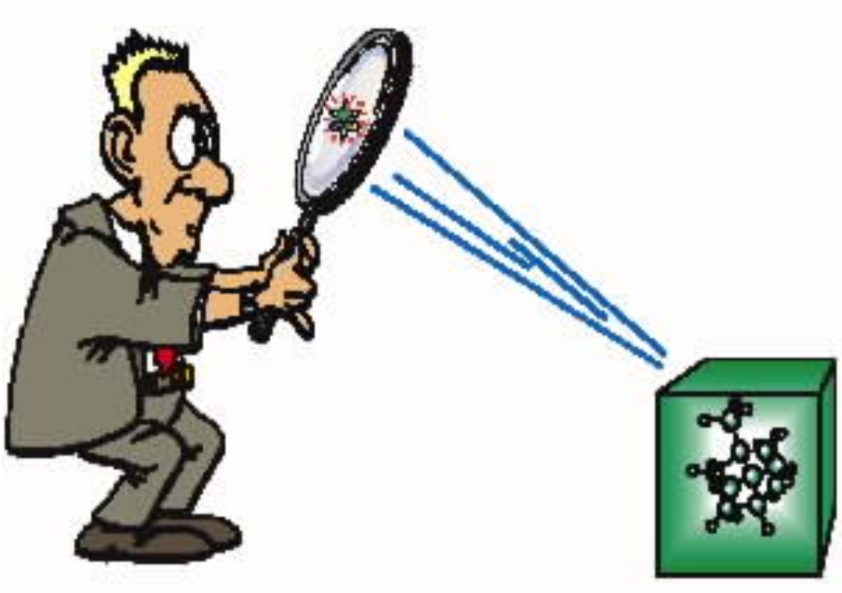
Use their spin (magnetic moment) as a magnetic probe

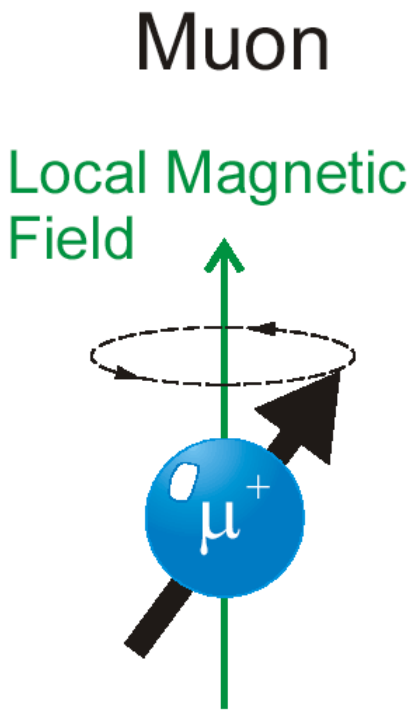
- Sensitive and accurate magnetometer
- Measures internal field and their variations
  (distribution in space, fluctuation in time)
- Applications in superconductivity, magnetism, conducting polymers...

Exploit the analogy with protons

- Diffusion in metals
- A model for hydrogen in semiconductors and dielectrics
- Muonium chemistry – isotope effects
- A spin label for organic radicals – molecular dynamics

Exploit the timescale...



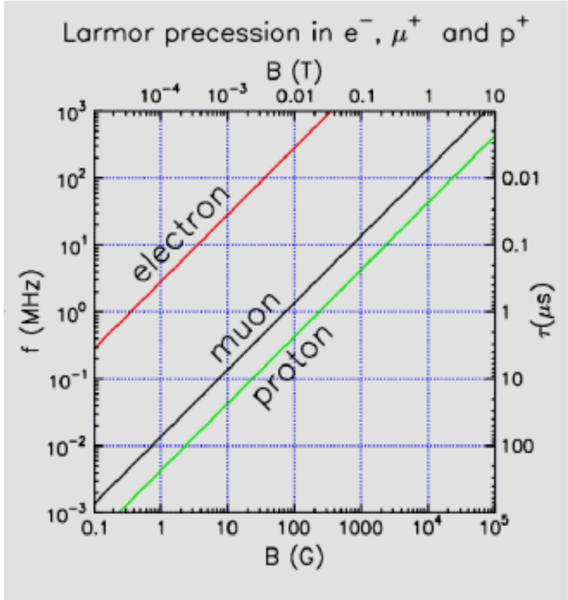


μSR is used to study properties
of materials at a microscopic level

Muon precession

- beam of spin polarized muons μ^+ with polarization $\boldsymbol{P}_\mu(0)$
- μ^+ precesses around the local field with Larmor frequency ω_μ

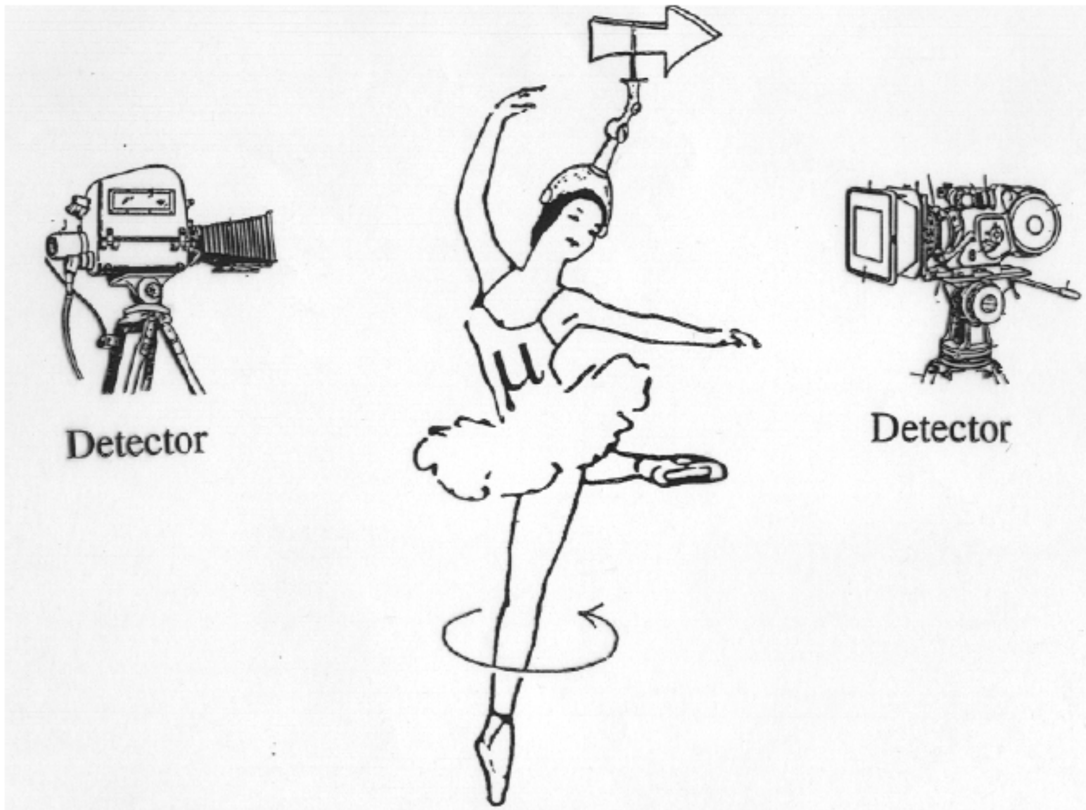
local magnetic field



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

gyromagnetic ratio
γ_μ= 135.5 MHz/T

How to detect the muon spin?



Measuring P(t): Muon Decay $\mu^+ \rightarrow e^+ + \bar{\nu}_\mu + \nu_e$

- Muon decay violates parity conservation

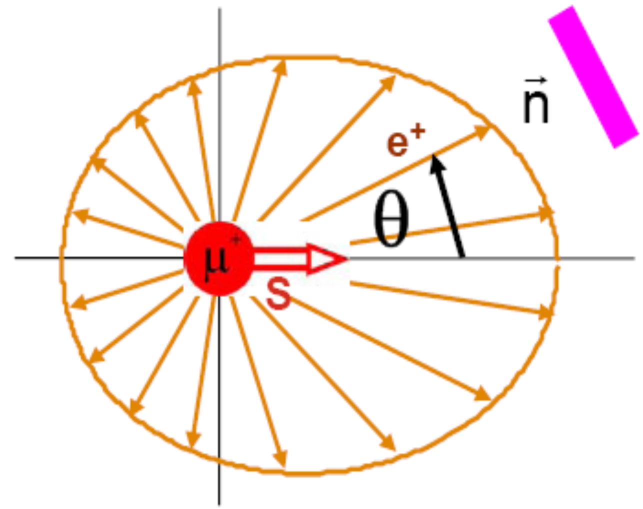
→ asymmetric decay

- Positrons preferentially emitted along muon spin (along polarization vector of an ensemble of muons)

$$\frac{dN_{e^+}(\theta)}{d\Omega} \propto (1+\frac{1}{3}P\cos\theta) = (1+\frac{1}{3}\vec{P}\cdot\vec{n})$$

$\vec{n}$: direction of observation (detector position)

For $P=1$:



$$\frac{dN_{e^+}(\theta)}{d\Omega} \propto (1+\frac{1}{3}P\cos\theta)$$

θ : angle between spin and positron direction

- Measuring positrons allows to observe time evolution of the polarization P(t) of the muon ensemble
- Positron intensity as a function of time after implantation:

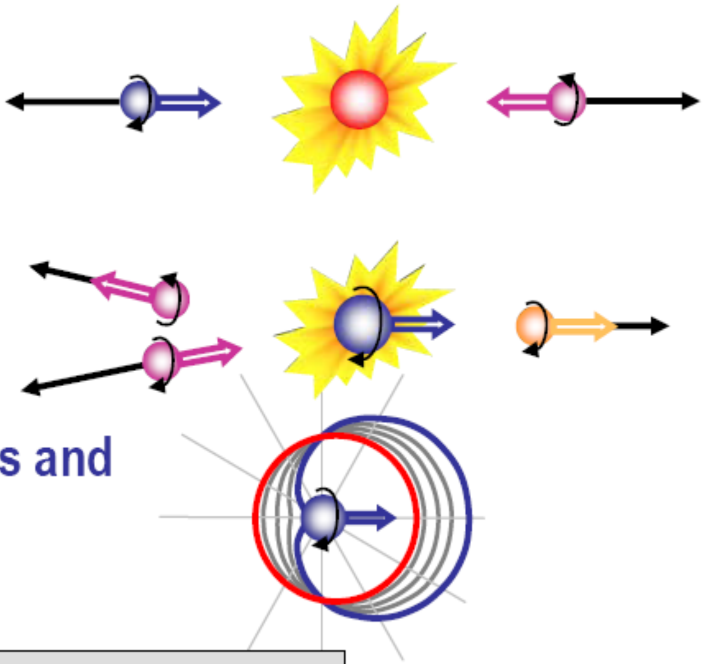
$$N_{e^+}(t) = N_0\left[1+AP(t)\right]\, e^{-\frac{t}{\tau_\mu}} \qquad P(t) = \vec{P}(t)\cdot\vec{n}$$

- A: Maximum observable asymmetry

  theoretically: A=1/3

  practically it depends on setup (average over solid angle, absorption in materials): A = 0.25- 0.30
- AP(t) is termed asymmetry (A(t))

1. Take a bunch of polarized muons (at least 10^6)
2. Implant them into your sample
3. Wait an average time of 2.2 μs
4. Measure the exact time of the emitted positrons and their spatial direction



Distribution and time evolution of the internal magnetic fields inside your sample

THE
PHYSICAL REVIEW
A journal of experimental and theoretical physics established by E. L. Nichols in 1893

SECOND SERIES, VOL. 105, NO. 4 FEBRUARY 15, 1957

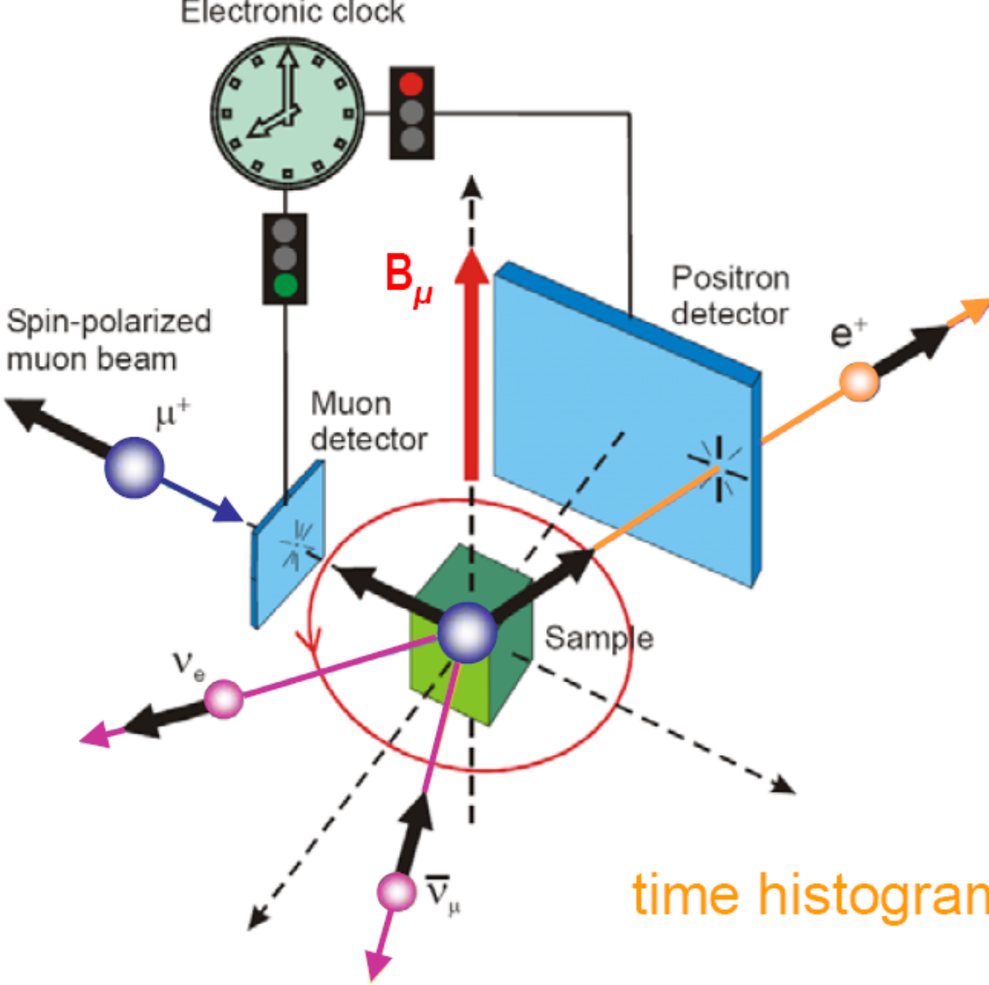
Observations of the Failure of Conservation of Parity and Charge Conjugation in Meson Decays: the Magnetic Moment of the Free Muon*

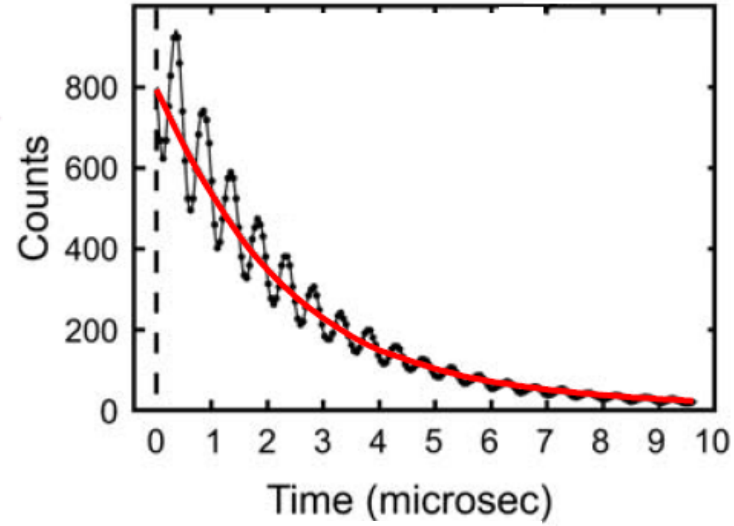
RICHARD L. GARWIN,† LEON M. LEDERMAN, AND MARCEL WEINRICH

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

(Received January 15, 1957)

It seems possible that polarized positive [...] muons will become a powerful tool for exploring magnetic fields in [...] interatomic regions.



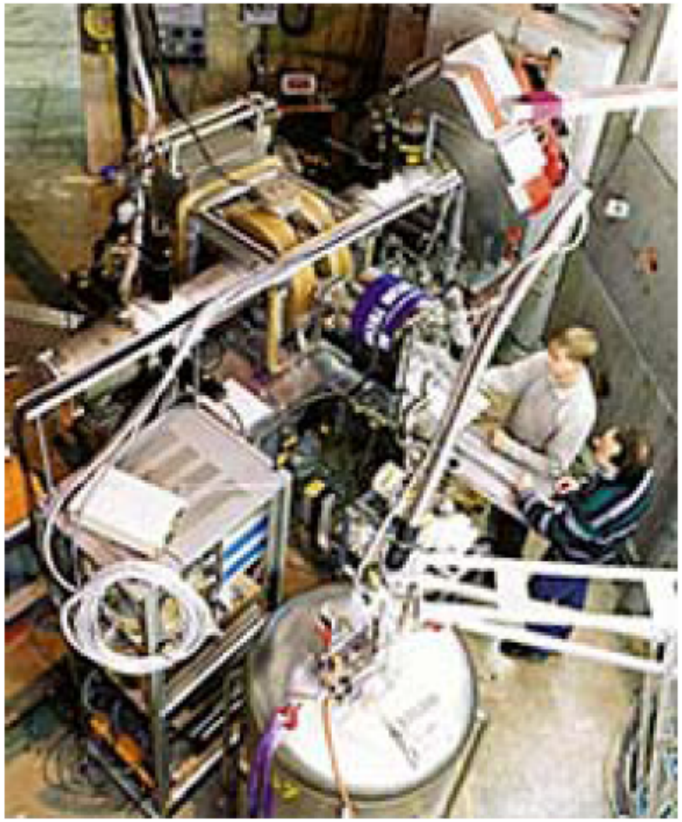


time histogram

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

$\mathbf{B}_\mu$ internal or external field

Real spectrometers



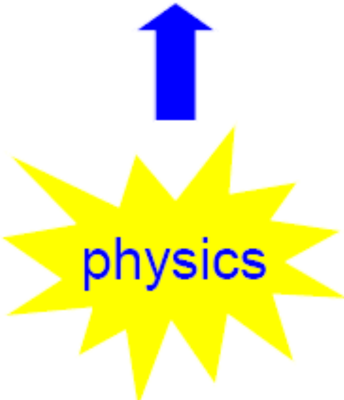
GPS at PSI

LAMPF at Triumf

Example ferromagnet

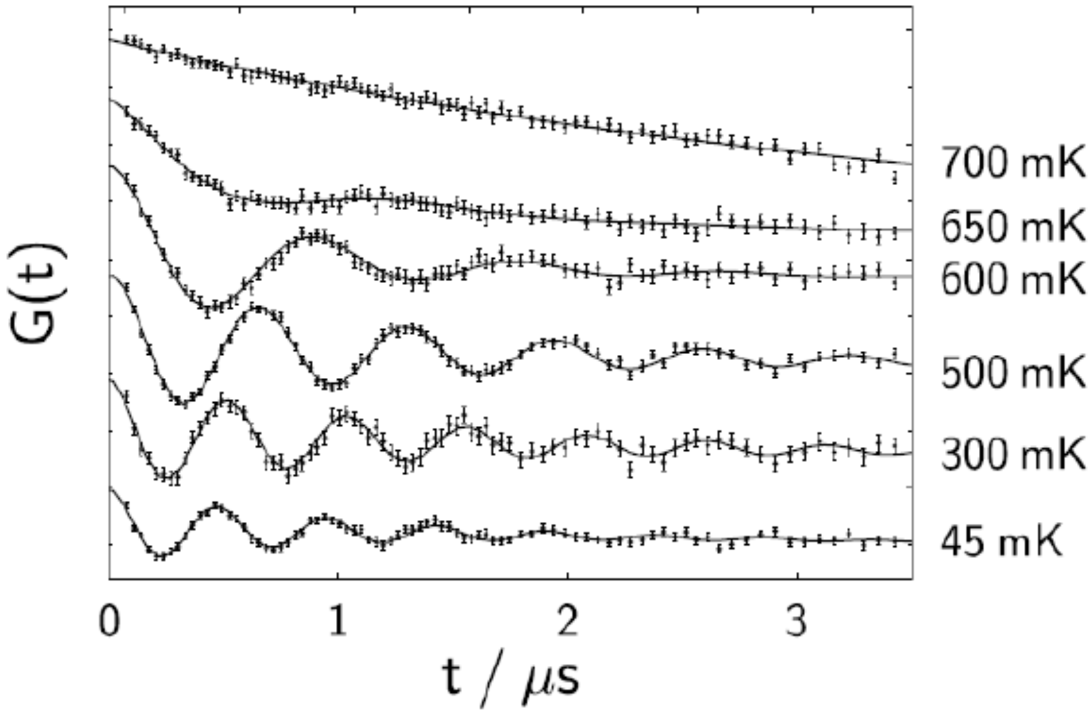
- μ^+ depolarization function $G(t)$

$$\boxed{G(t) \sim e^{-\frac{1}{2}\sigma^2 t^2} \cos(\omega t)}$$



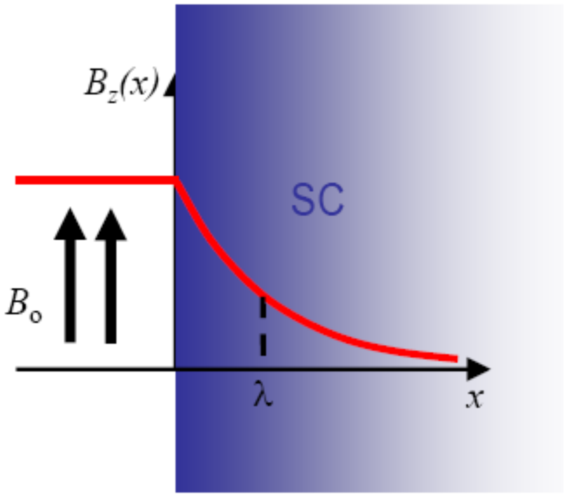
zero-field muon precession in an organic ferromagnet
(Blundell et al., 1995)

Curie temperature
T_C=0.7 K

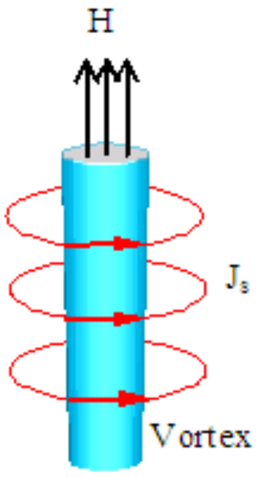


Measuring Properties of Type II Superconductors

$H < H_{c1}$: Meissner state

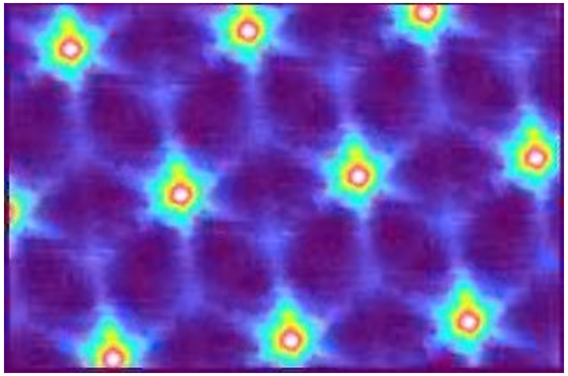


$H_{c1} < H < H_{c2}$: Vortex state



One Vortex

Abrikosov Vortex Lattice



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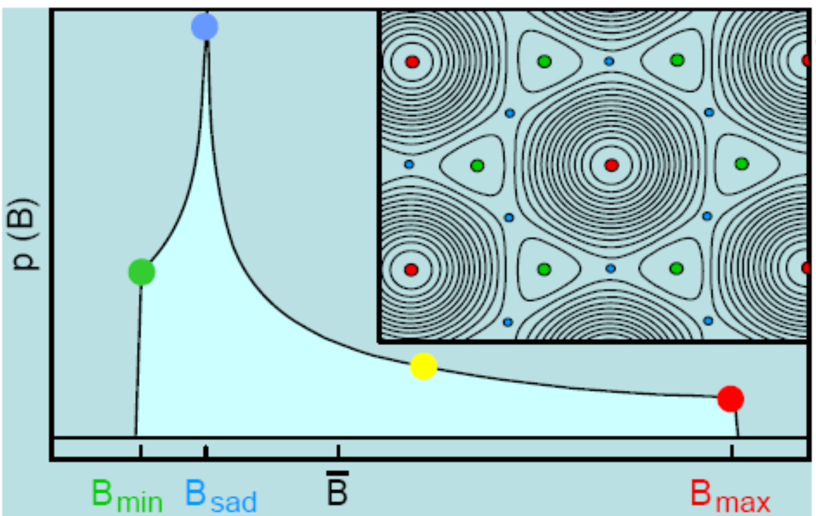
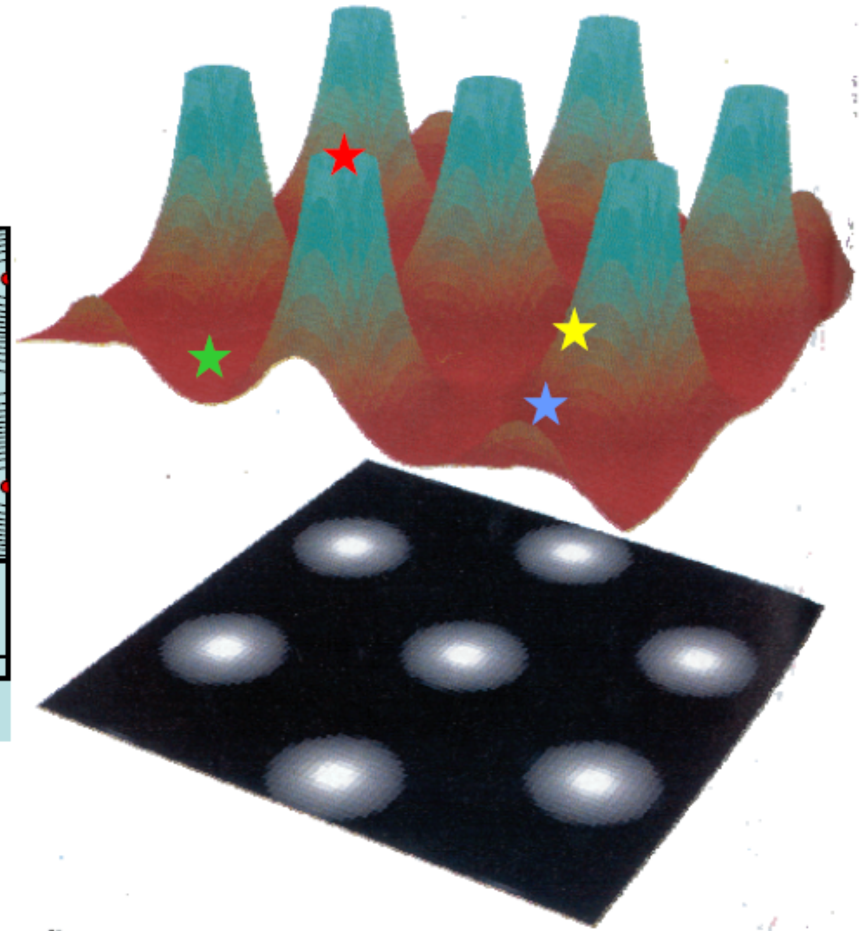
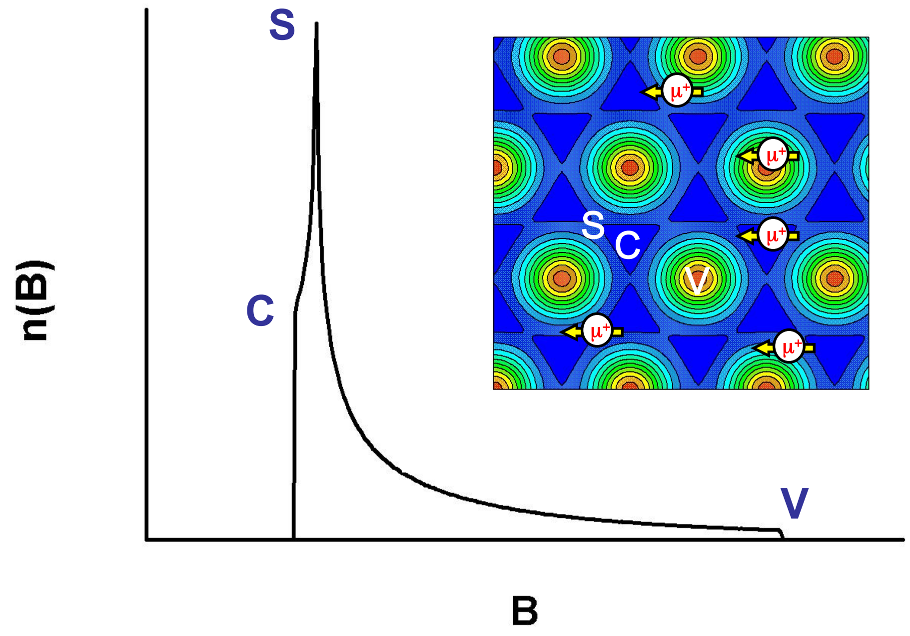
Muons and Field Distribution in Type II S.C.





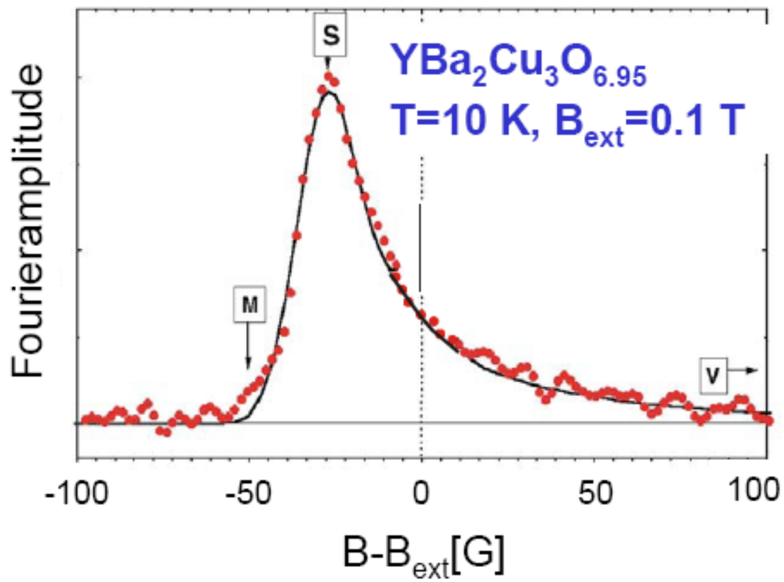
*Bishop et al., Scientific American **48** (1993)*

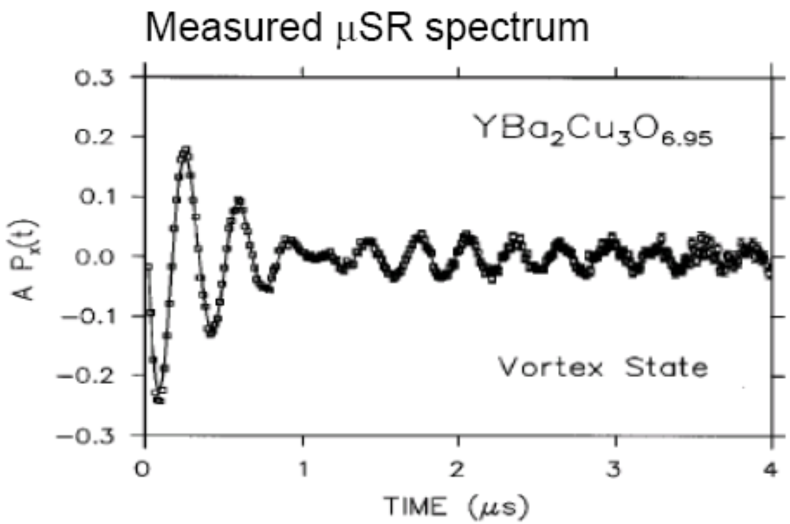


Theory

On the left is a theoretical magnetic field distribution for a hexagonal vortex lattice in a type-II superconductor.

Also shown is a contour plot of the spatial distribution of the internal field *B*(*r*).





Spintronics

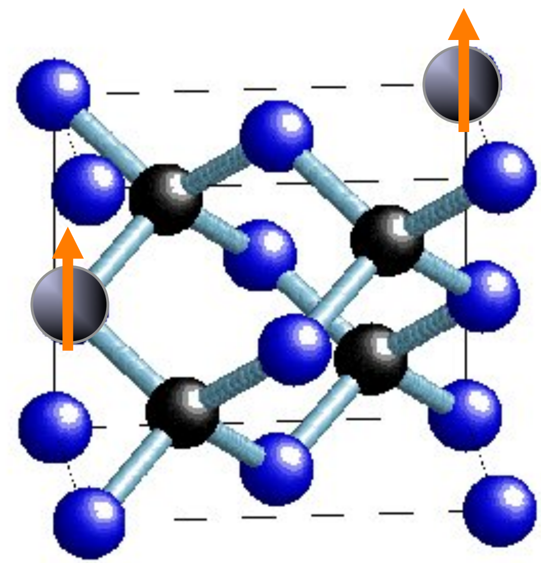
• **Conventional electronics: charge of electron used to achieve functionalities – *e.g.,* diodes, transistors, electro-optic devices (detectors and lasers….)**

• **Spintronics: manipulate electron spin (or resulting magnetism) to achieve new/improved functionalities -- spin transistors, memories, higher speed, lower power, tunable detectors and lasers, bits (Q-bits) for quantum computing….**

Need for Ferromagnetic Semiconductors

(Ga,Mn)As

H. Ohno et al. (1996): ferromagnetism in GaAs thin films doped ~5% with Mn



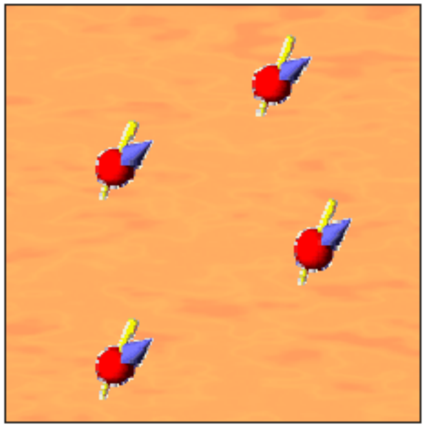
Growth by low temperature MBE to beat equilibrium solubility limit

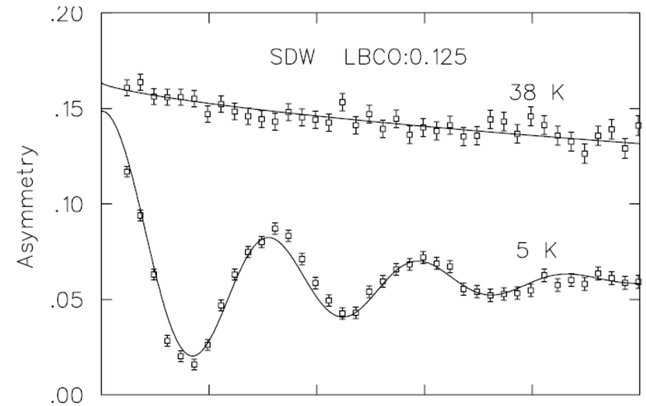
Max. T_C=172K

(so far...)

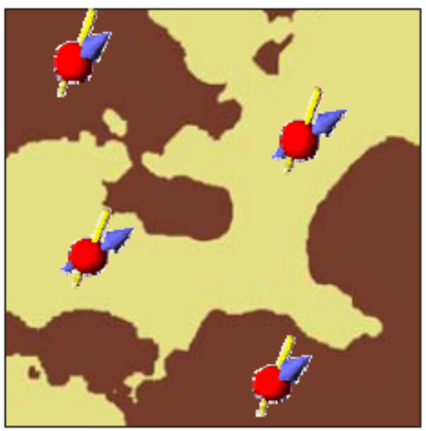
Advantage: Determination of Magnetic Volume

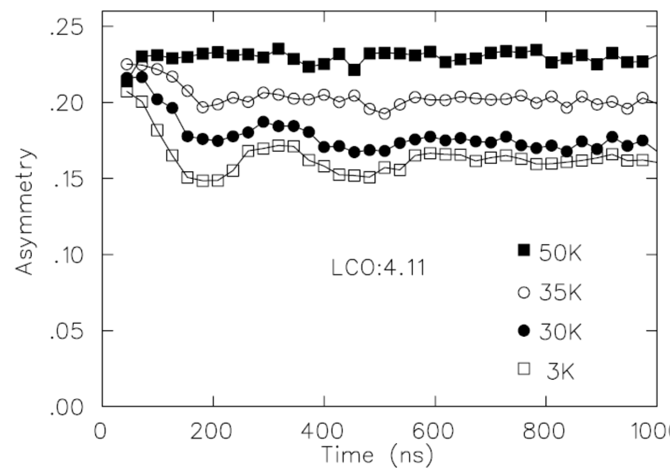
Homogeneous:

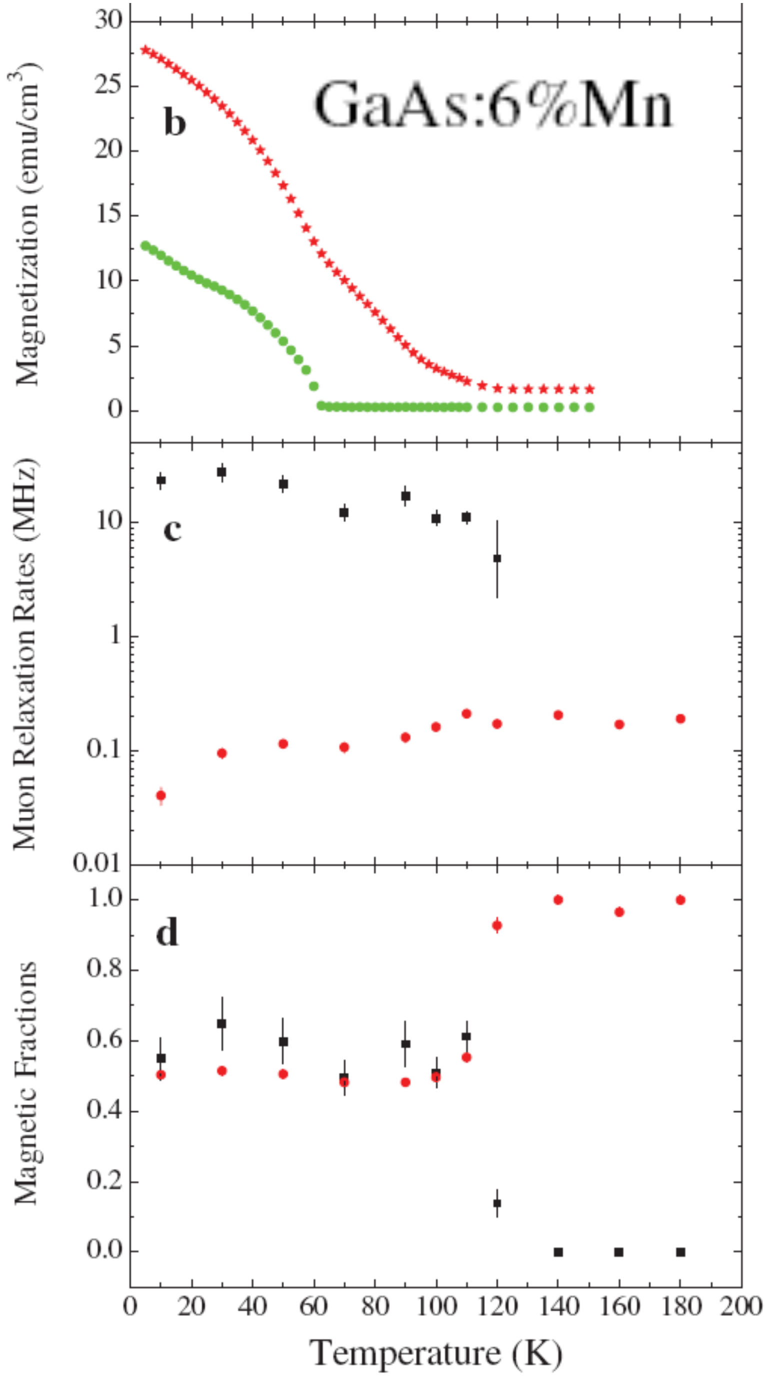


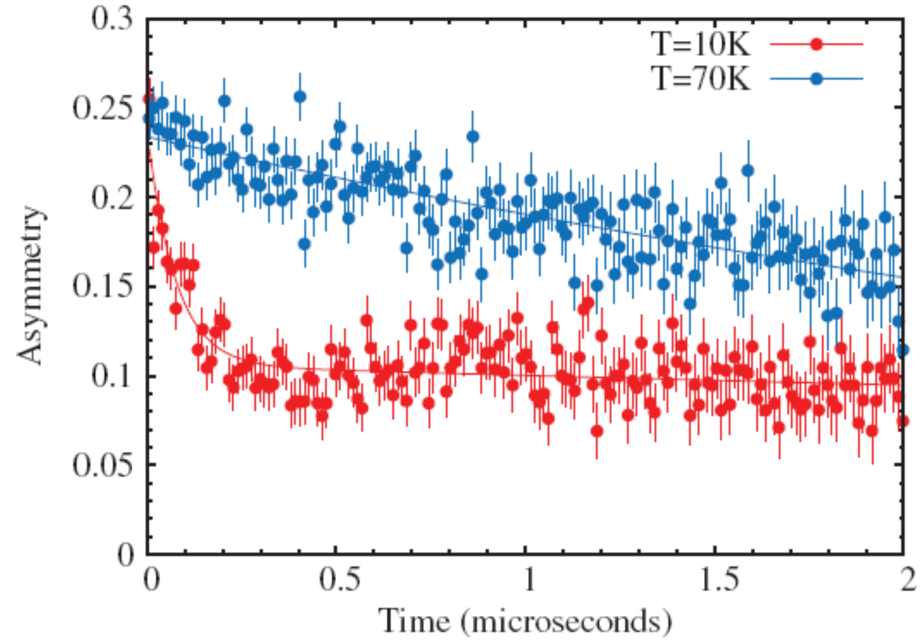


Inhomogeneous:









Storchak *et al.*, PRL 101, 027202 (2008)

To summarize:

- **Local probe**
  - Magnetic volume fraction
- **μSR frequency**
  - Magnetic order parameter ($10^{-3} – 10^{-4}$ μ_B)
  - Temperature dependence
- **μSR relaxation rate**
  - Homogeneity of magnetism
- **Magnetic fluctuations**
  - Time window: $10^5 – 10^9$ Hz

- **Field distribution of vortex lattice**
  - Penetration depth
  - Coherence length
  - Vortex dynamics
- **Absolute determination of penetration depth $\lambda(0)$**
- **Temperature dependency of**
  - Penetration depth $\lambda \propto \langle\Delta B^2\rangle^2 \propto \sigma^2$
  - Superfluid density $n_s/m^* \propto \langle\Delta B^2\rangle \propto \sigma$

The End