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All in a spin – An introduction to muon spectroscopy

Adrian Hillier
ISIS Muon Group

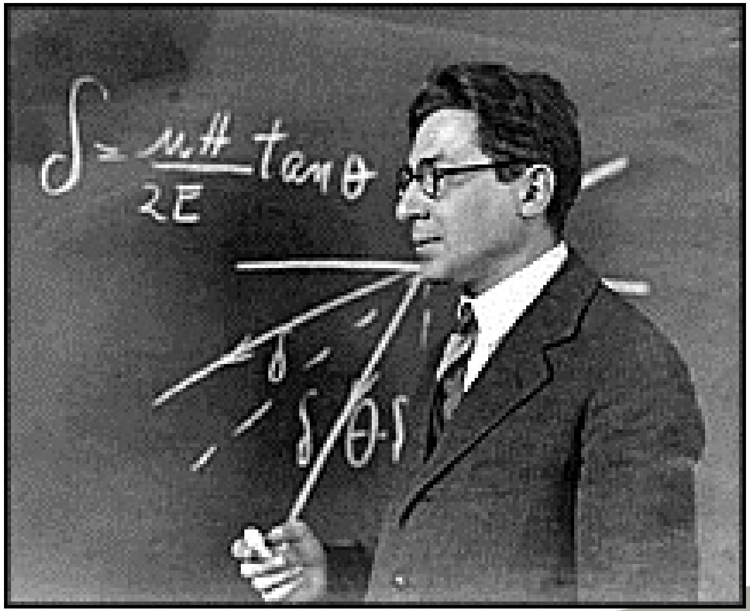
Plan

1. An Introduction to Muons
2. The μSR technique
3. The ISIS μSR Facility
4. Condensed matter studies with muons
5. Muons elsewhere in the world

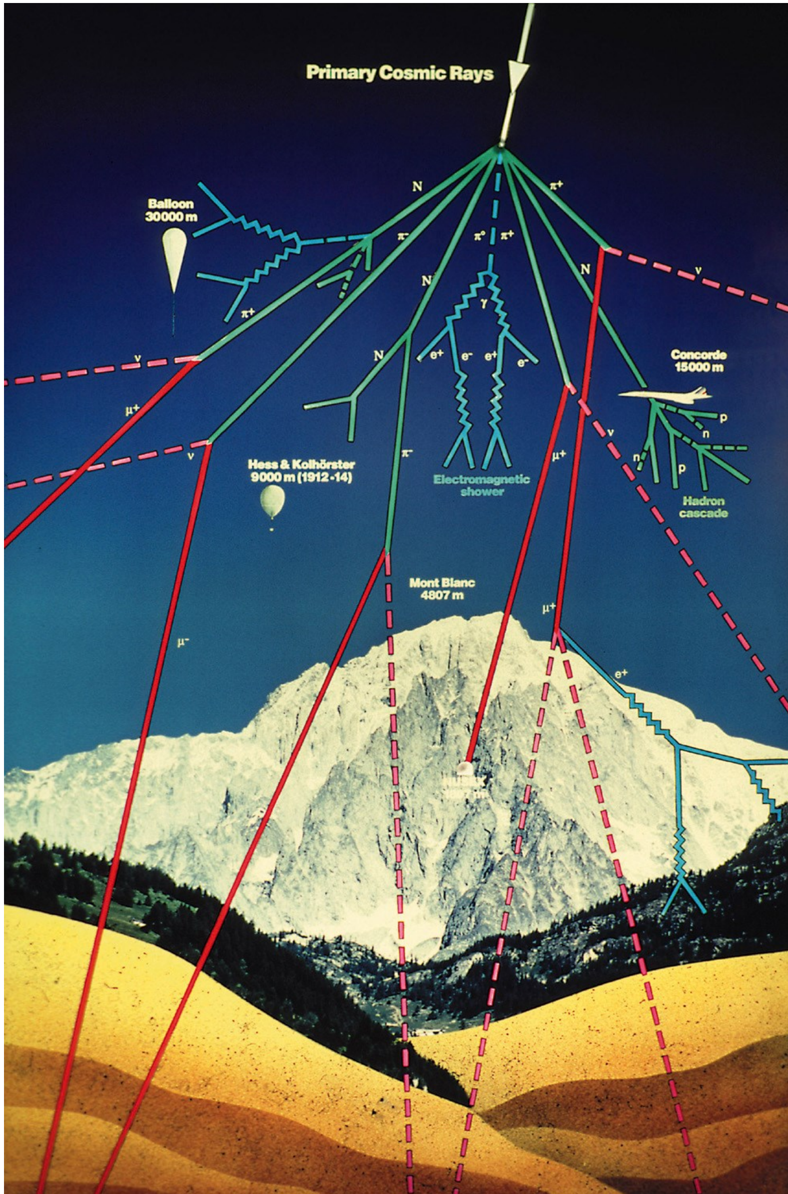
1. An Introduction to Muons

‘Who ordered that?!’

I.I. Rabi, Physics Nobel prize winner, 1944



Discovery of the muon

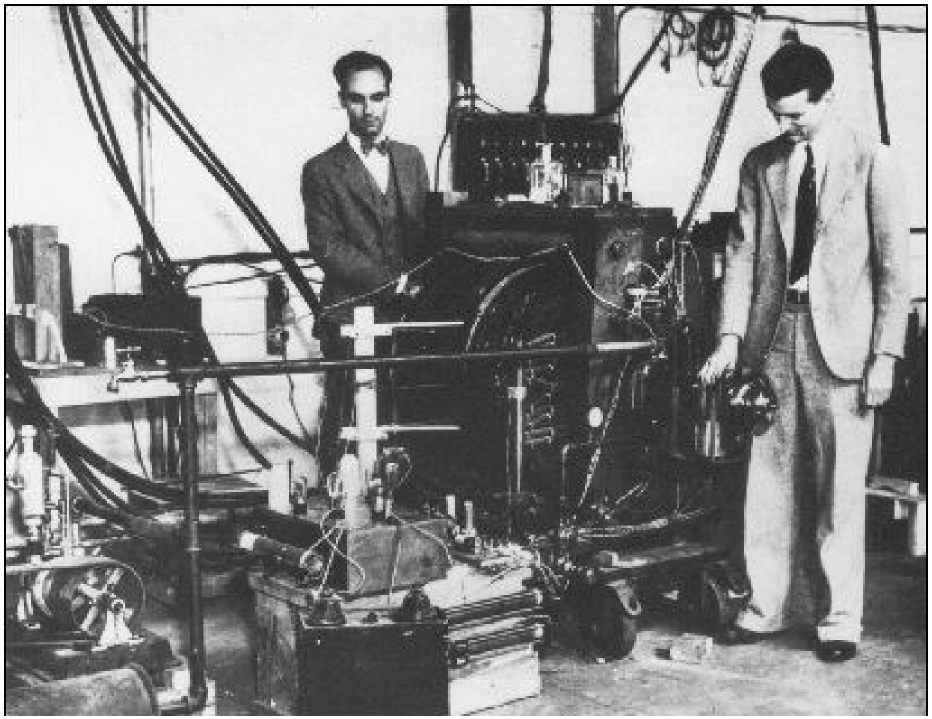


Cosmic rays

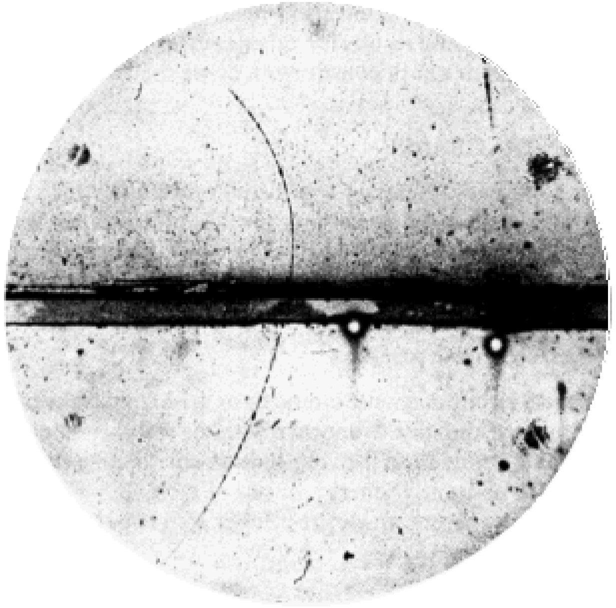
- Discovered 1912 – Victor Hess (Nobel Prize 1936)
- 87% protons, 12% He, 1% heavier nuclei

Discovery of the muon

Carl Anderson – Caltech
1936 Nobel prize for discovery of positron



Carl Anderson and Seth Neddermeyer with cloud chamber
courtesy Caltech Archives



1937, with Seth Neddermeyer – charged particle 200 x electron mass – the **muon**

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Discovery of the muon

Physics at the farm: discovery of the muon.

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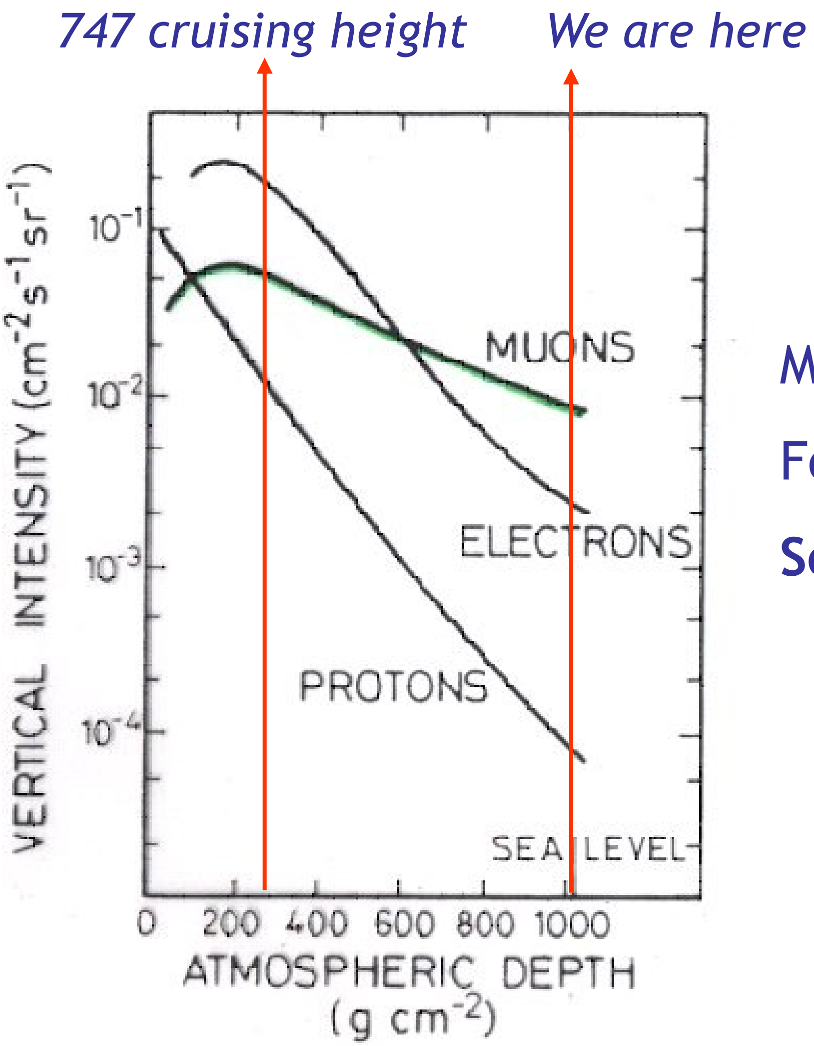
Muons in cosmic rays



Muons – average energy 4 GeV.

For muons E>1 GeV, flux is 1 cm^{-2} min^{-2}

So – we get hit by ~1 muon s^{-1}!

Muon properties

Muons:

- fundamental, charged particles
- heavy electrons
- spin 1/2
- magnetic moment 3.2 x m_p
- mass 0.11 x m_p

- produced from pion decays
- lifetime 2.2 μs
- decay into a positron (+ 2xν)

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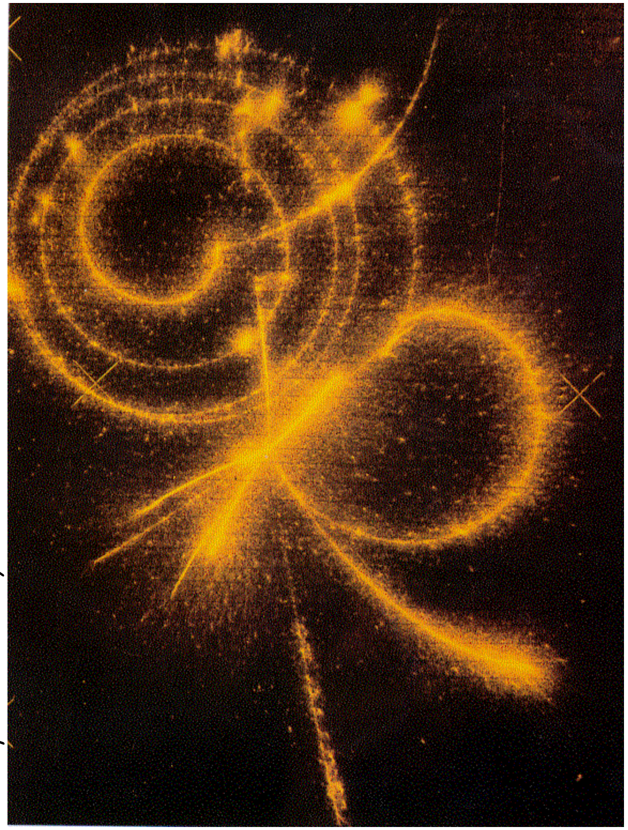
The life of a muon

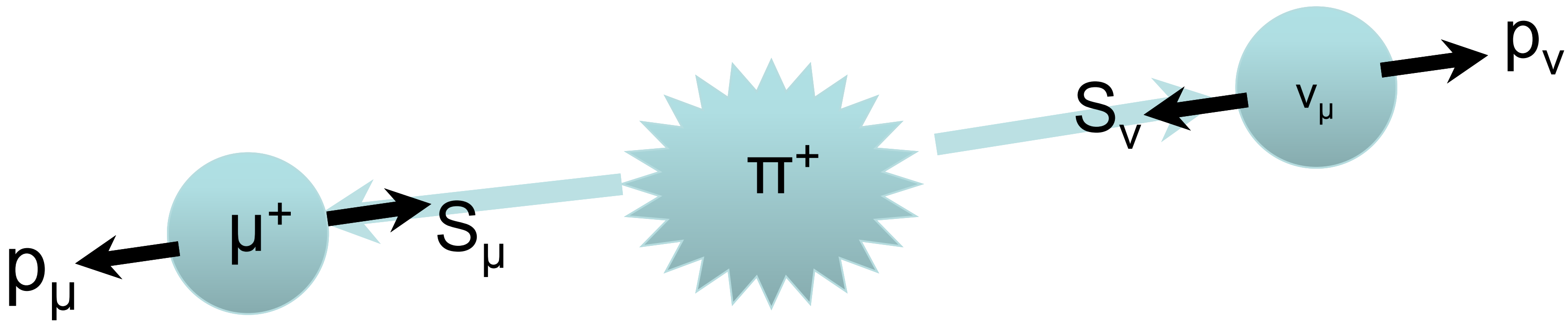


CERN picture library

2. The μSR technique

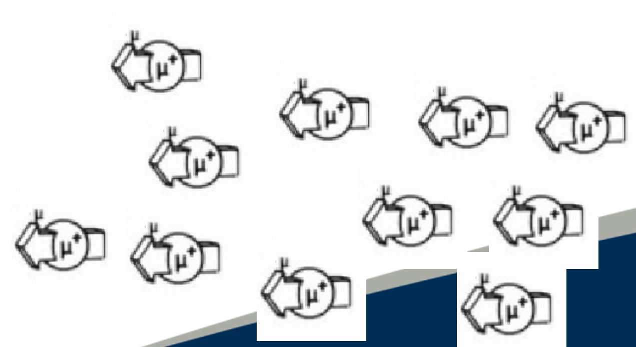
Muon birth

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



π^+ at rest, l=0

Result: a fully spin-polarised muon beam



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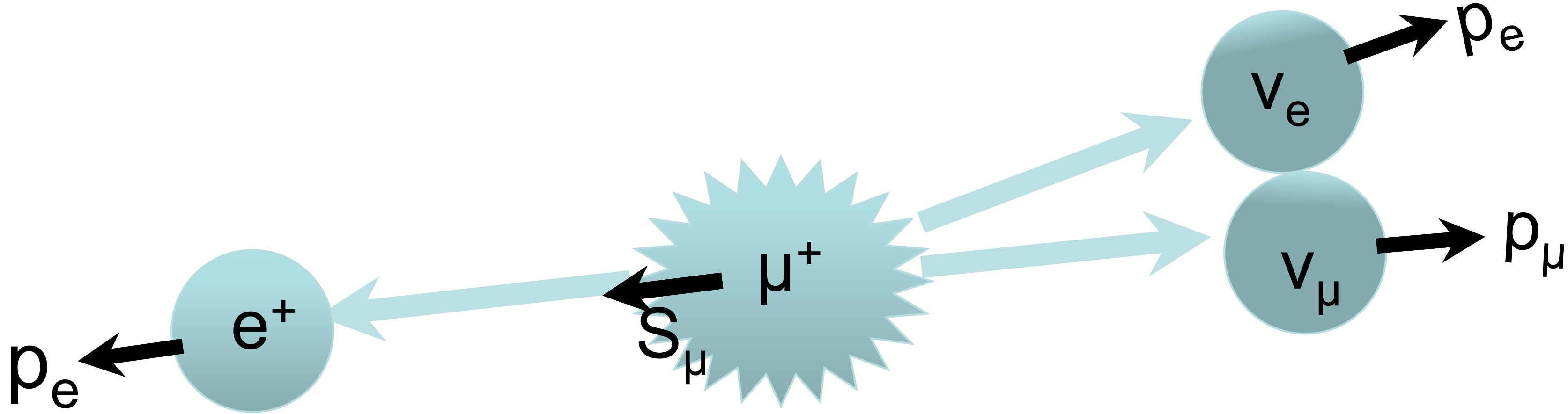
Muon death

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



Positrons emitted preferentially in muon spin direction

Muon death

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

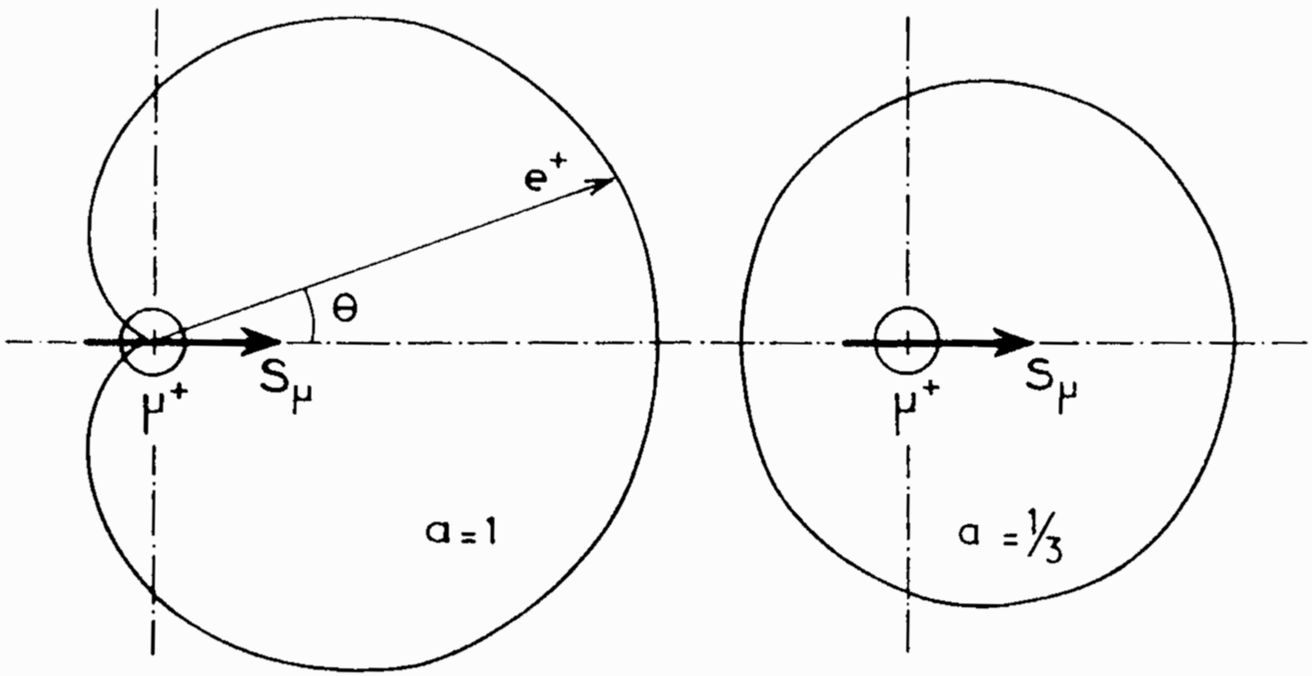


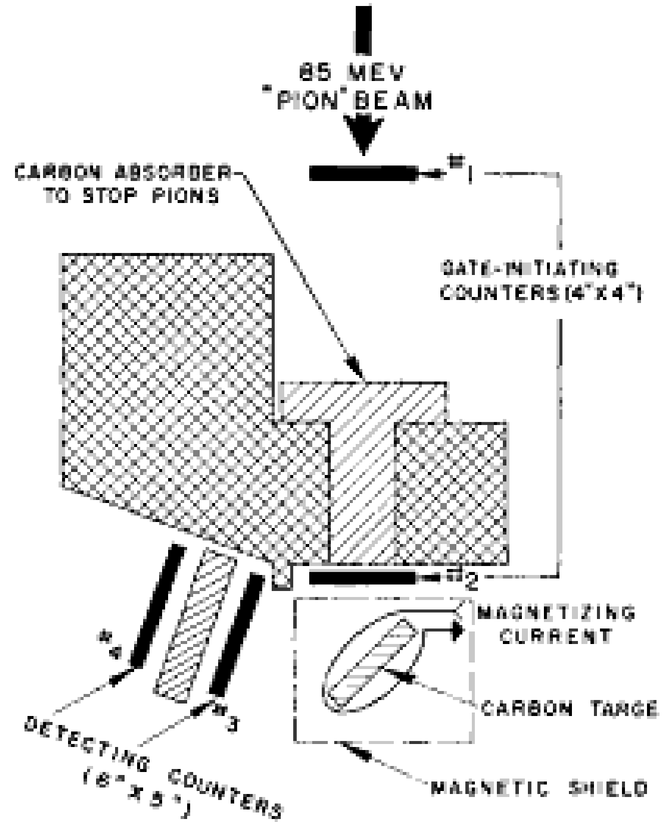
Fig. 1 Angular distribution of positrons for asymmetry parameters 1 and $\frac{1}{3}$

Muon death

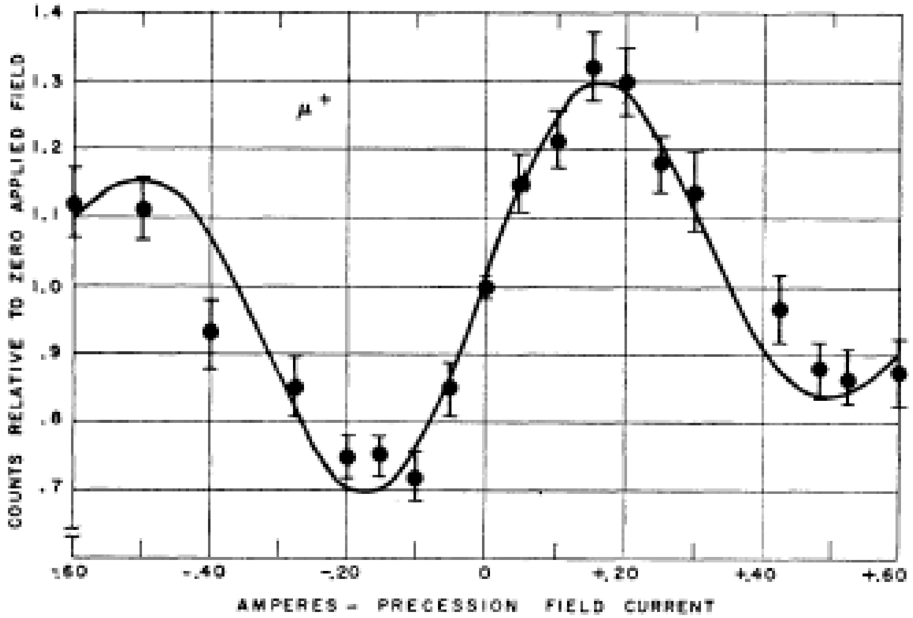
Observations of the Failure of Conservation of Parity and Charge Conjugation in Meson Decays: the Magnetic Moment of the Free Muon*

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

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



Muon death



'It seems possible that polarised positive and negative muons will become a powerful tool for exploring magnetic fields in nuclei, atoms and interatomic regions'.

Garwin et al., Phys Rev 1957

The muon technique was born!

μSR . . . muon spin rotation, relaxation and resonance – or just muon spin research

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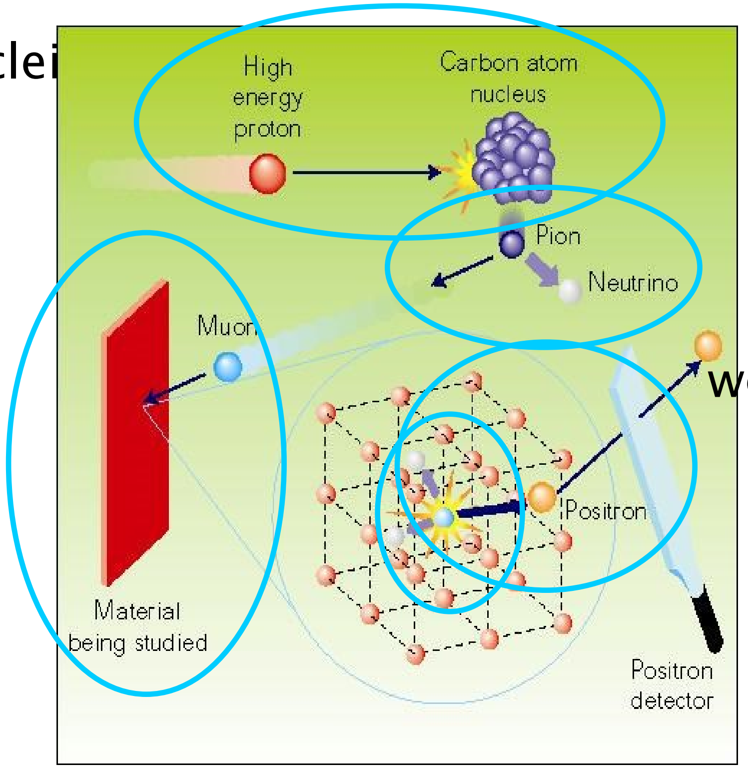
The μSR technique

High energy protons (800 MeV at ISIS) collide with carbon nuclei producing pions



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

4 MeV muons are 100% spin polarised

Decay, lifetime 2.2μs

$\mu^+ \rightarrow e^+ + \nu_e + \nu_\mu$

we detect decay positrons

Implantation, (stopped in ~1mm water)

Muons interact with local magnetic environment

The positrons are preferentially emitted in muon spin direction

Monitor the positron distribution to infer the muons' polarisation after implantation. Learn about the muons' local environment or the muon behaviour itself.

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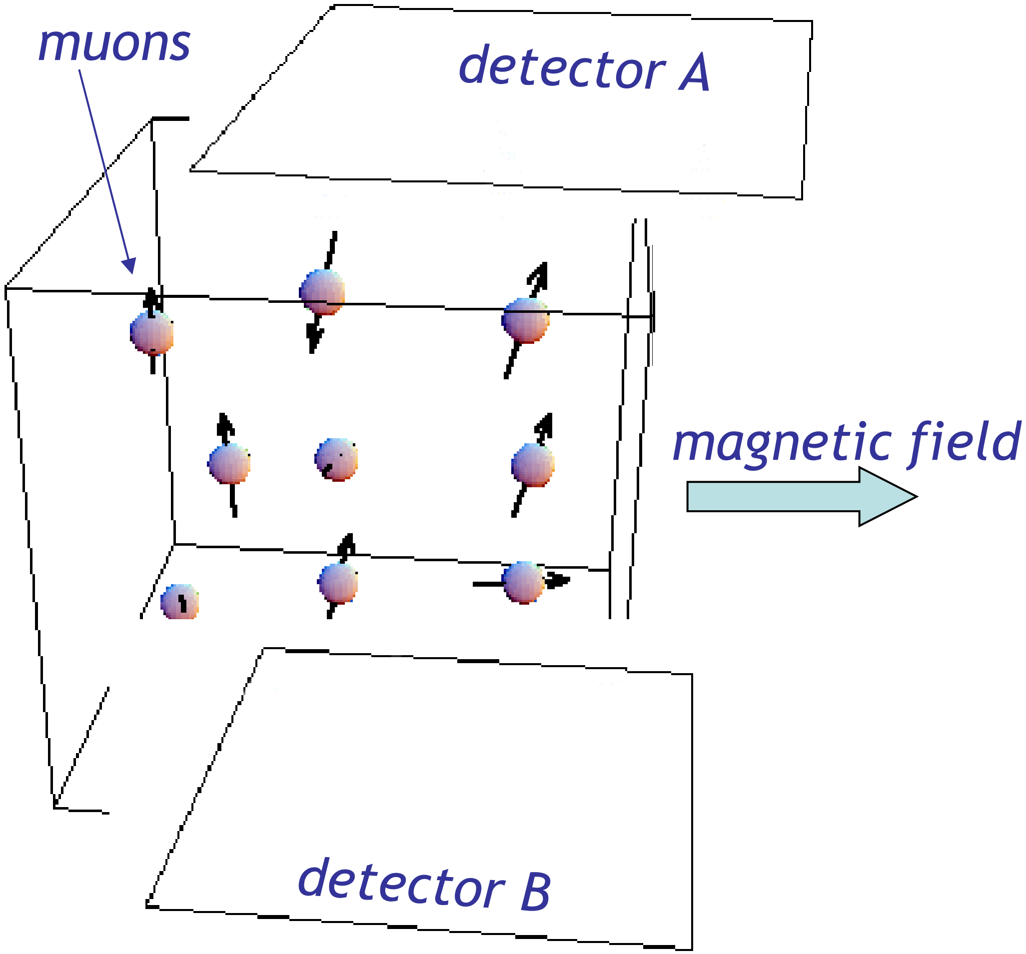
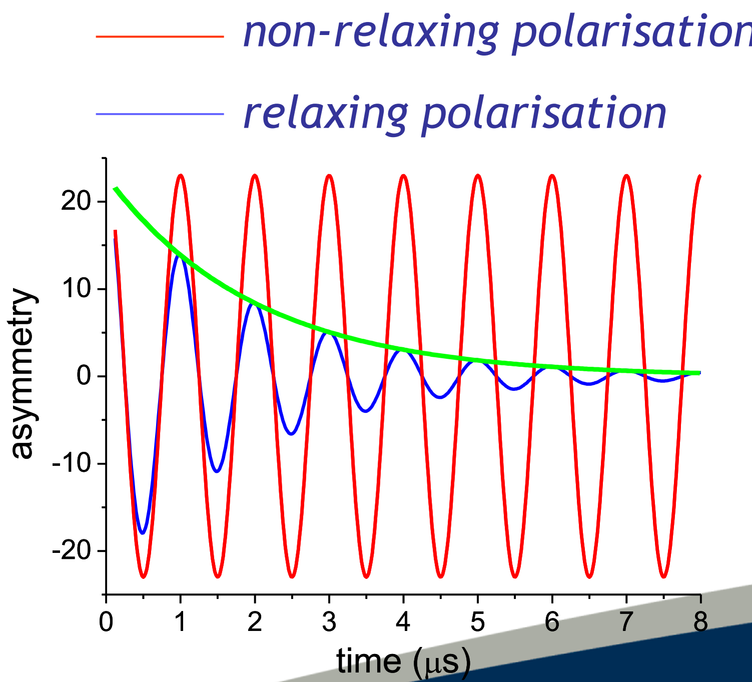
The μSR technique



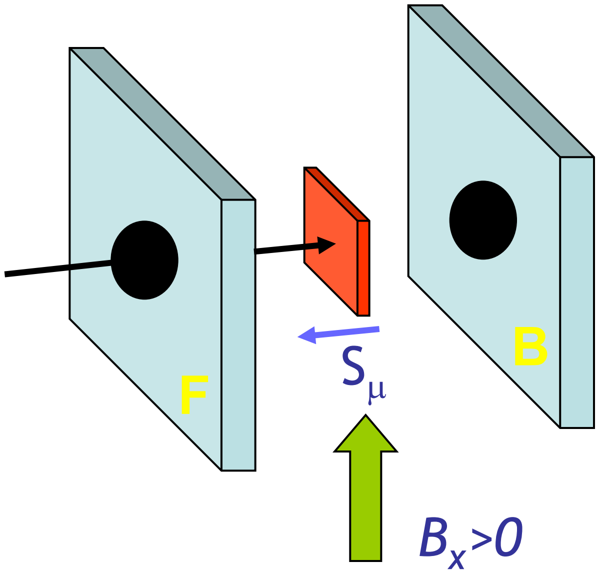
'asymmetry' =

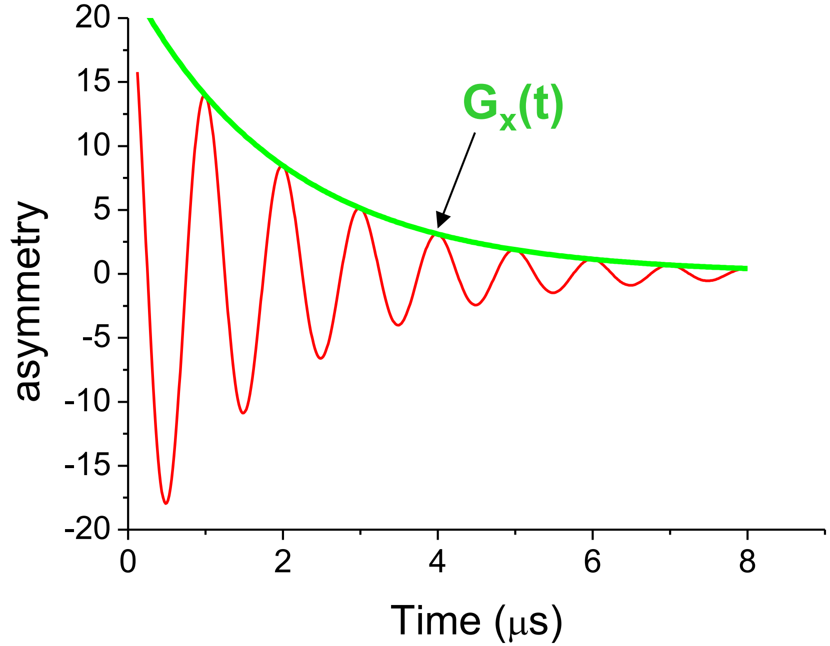
$$\frac{N_A(t) - N_B(t)}{N_A(t) + N_B(t)}$$



The μSR technique

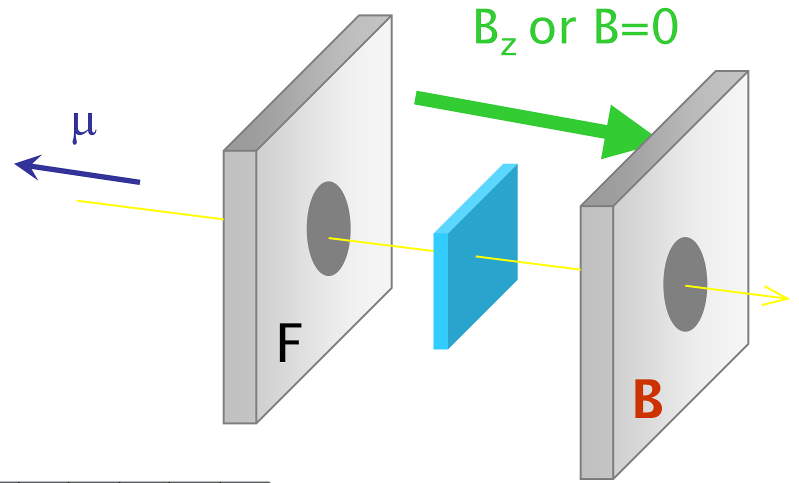
'Transverse' field

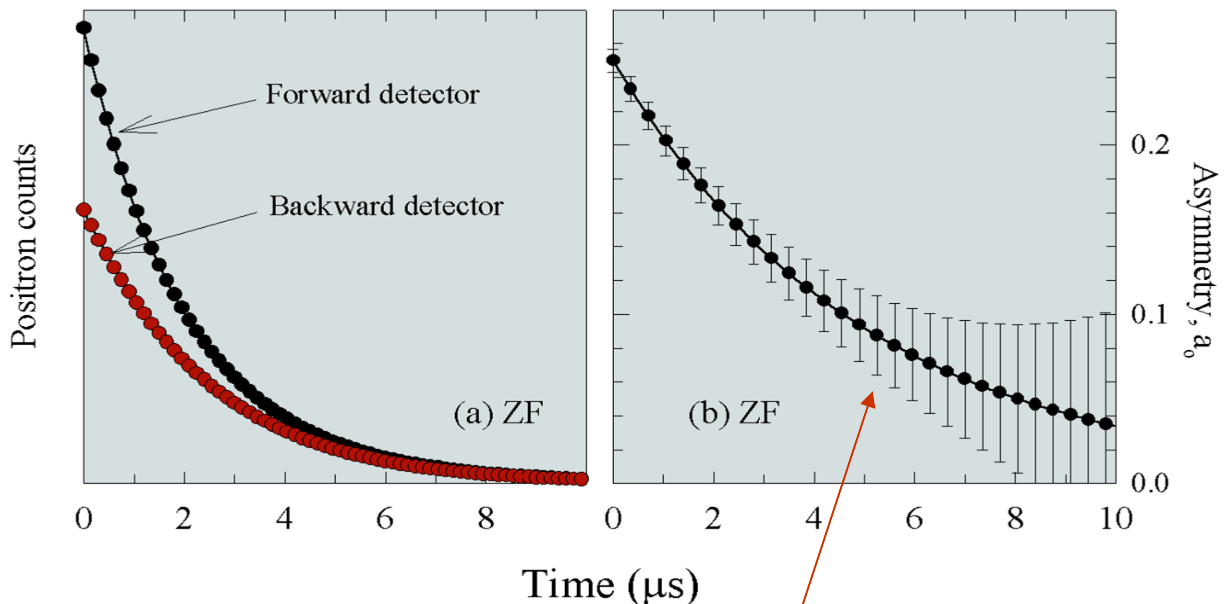




$$\text{asymmetry} = \frac{N_F(t) - N_B(t)}{N_F(t) + N_B(t)} = a_0 G_x(t) \cos(\omega t)$$

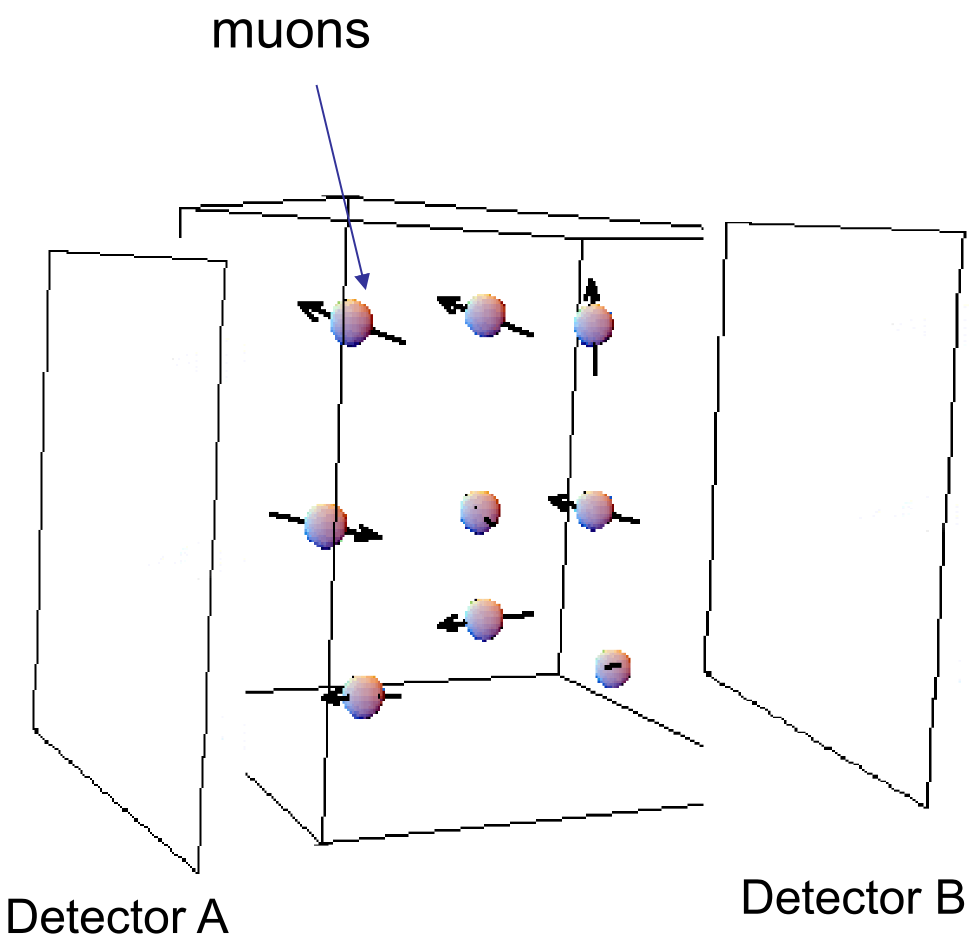
The μSR technique

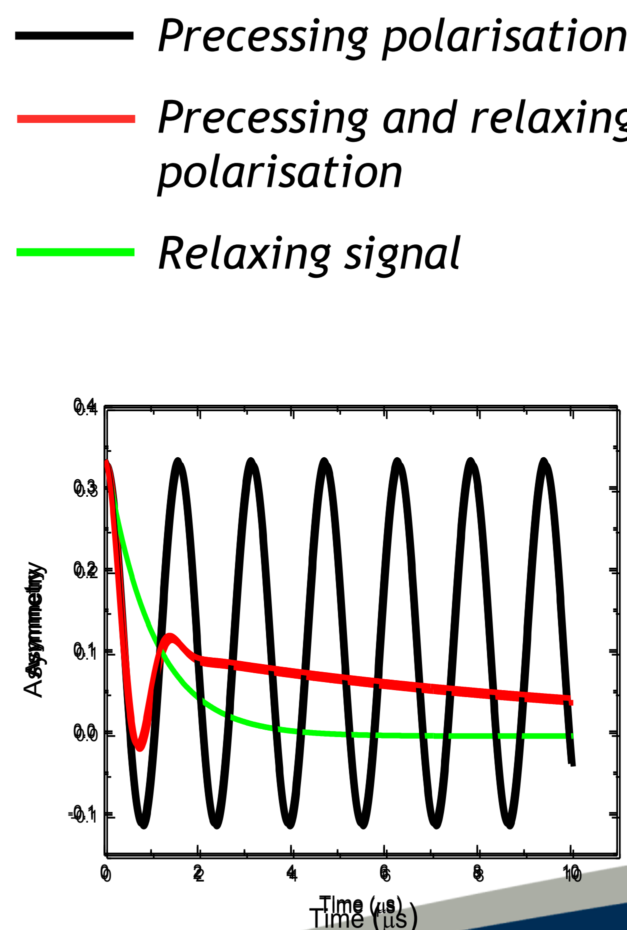




$$R_z(t) = \frac{F(t) - B(t)}{F(t) + B(t)} = a_o G_z(t)$$

The μSR technique

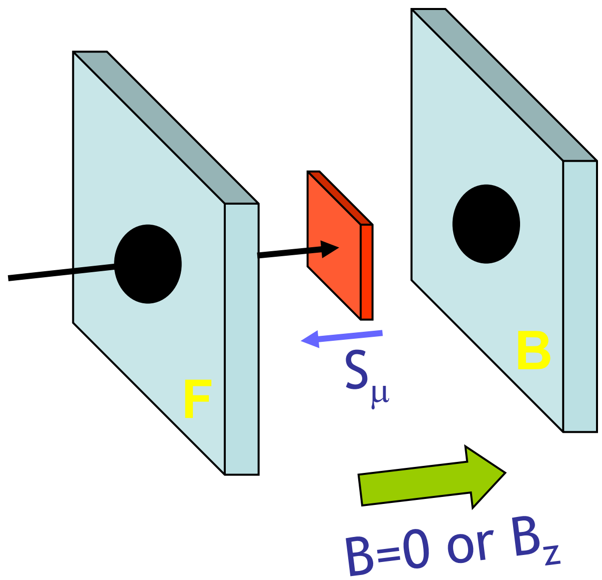


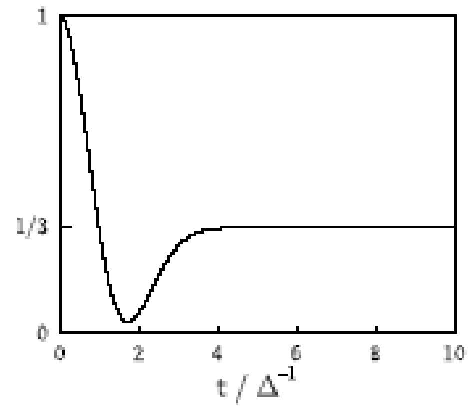


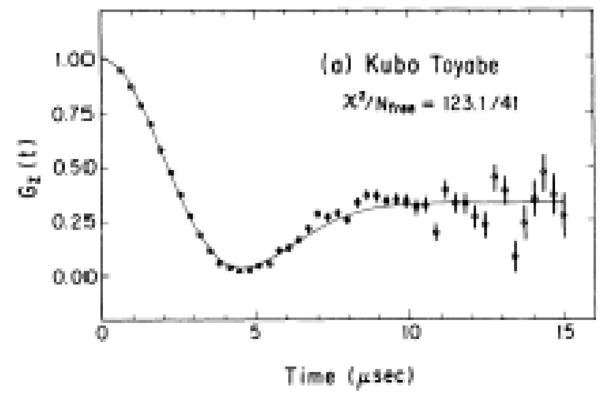
The μSR technique

Zero or ‘longitudinal’ field

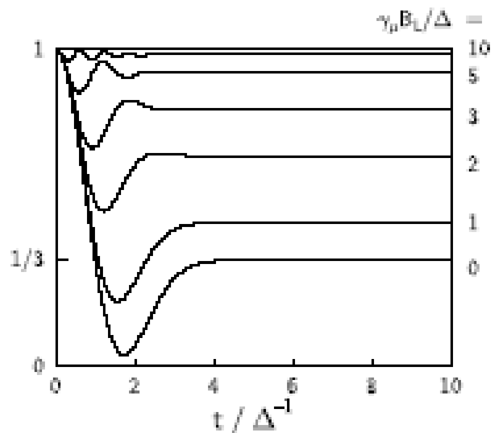
$$\text{asymmetry} = \frac{N_F(t) - N_B(t)}{N_F(t) + N_B(t)} = a_0 G_z(t)$$

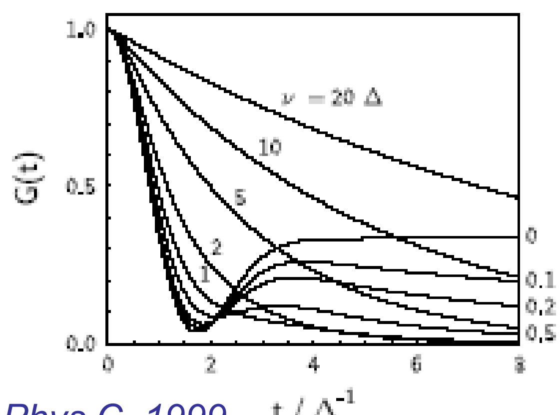






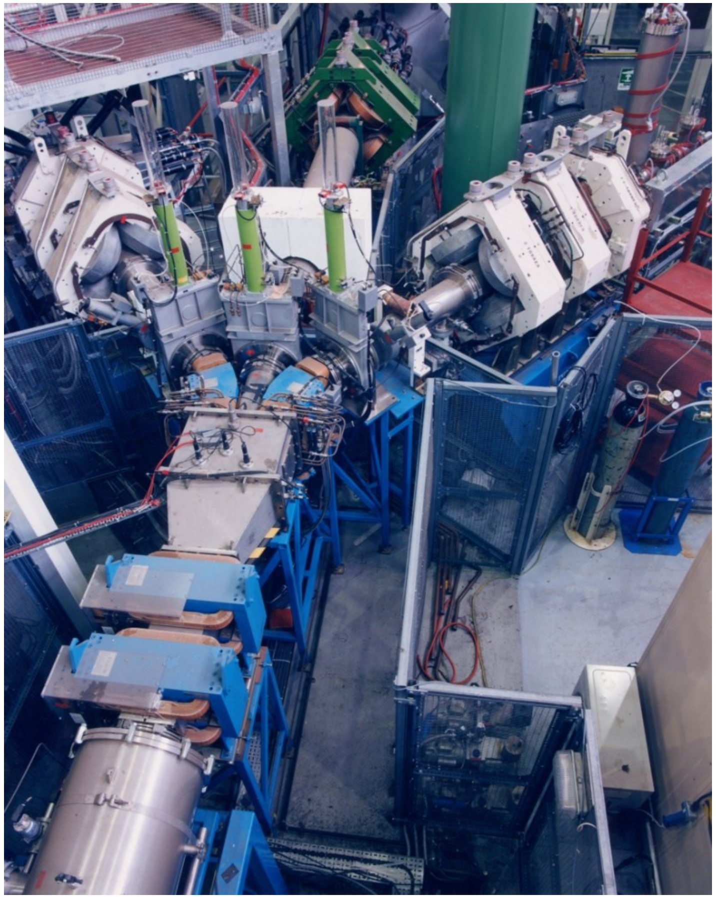
Kadono et al., PRB 1989





Blundell, J. Phys C, 1999

3. The ISIS Muon Facility



The ISIS Facility

The Rutherford Appleton Laboratory

Science & Technology Facilities Council ISIS

The ISIS Facility

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Spallation neutron source

800 MeV proton beam

Neutrons produced for 25 instruments

7 muon experimental areas

2000 users/yr

~800 experiments/yr

~500 publications/yr

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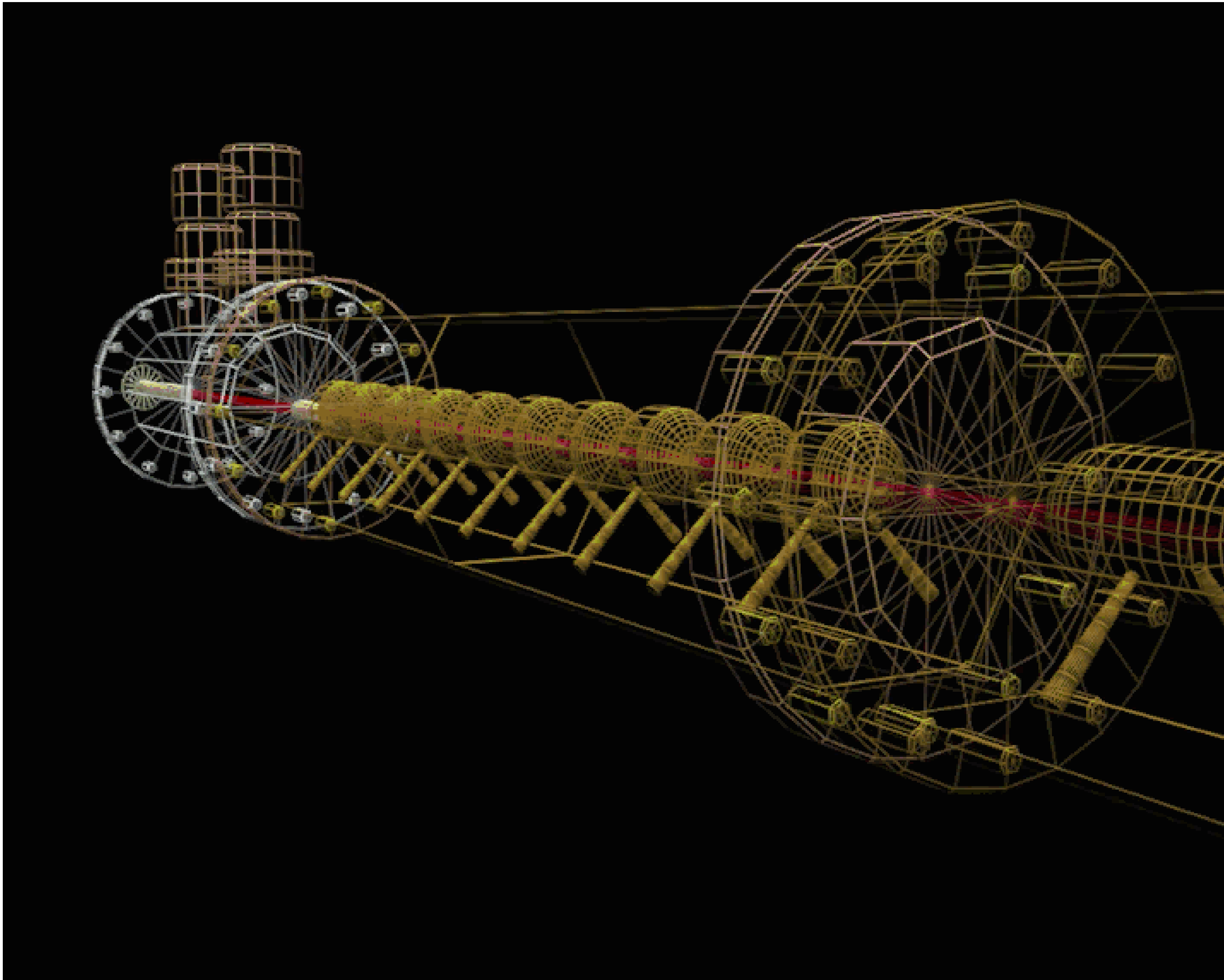
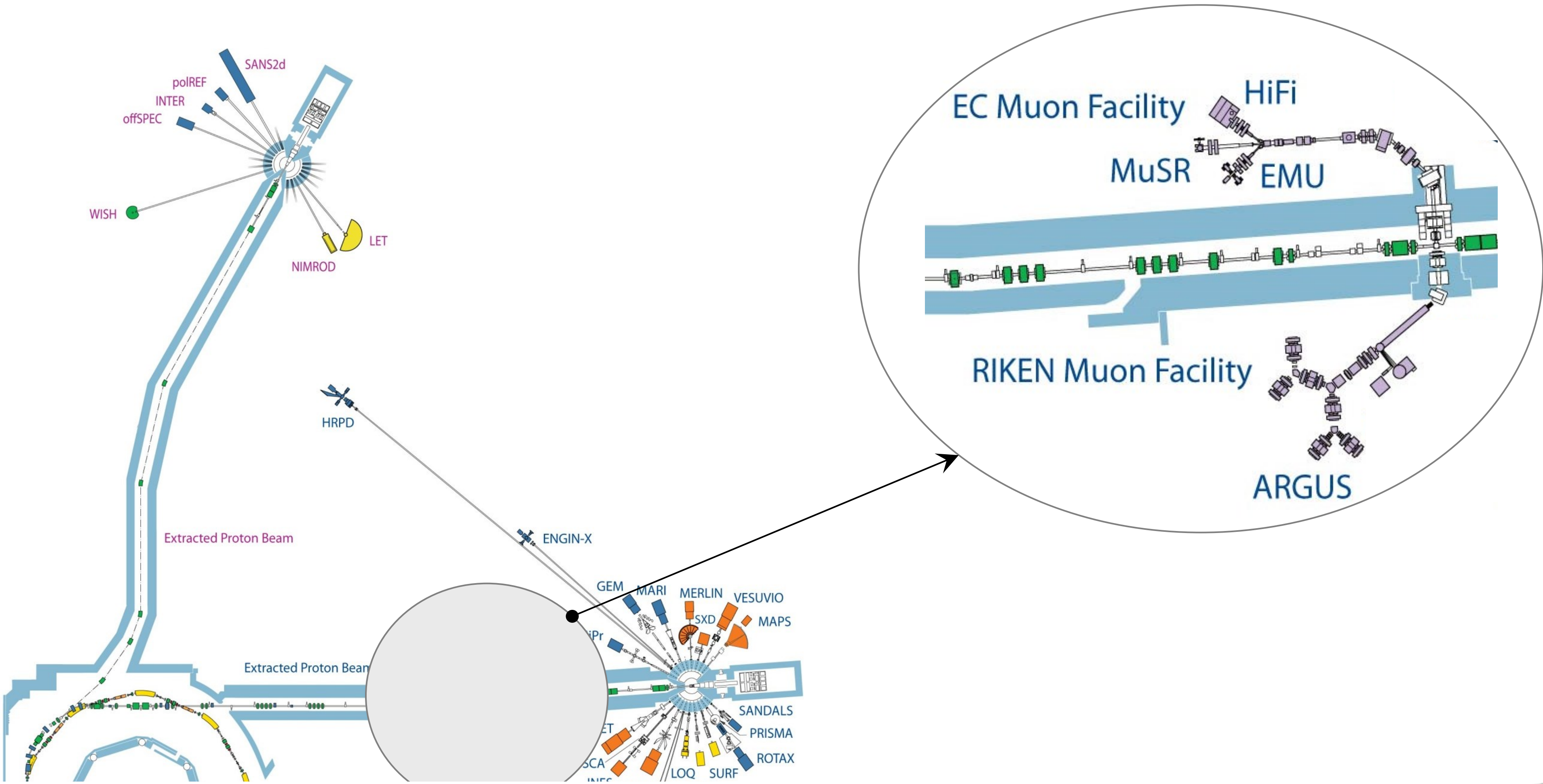
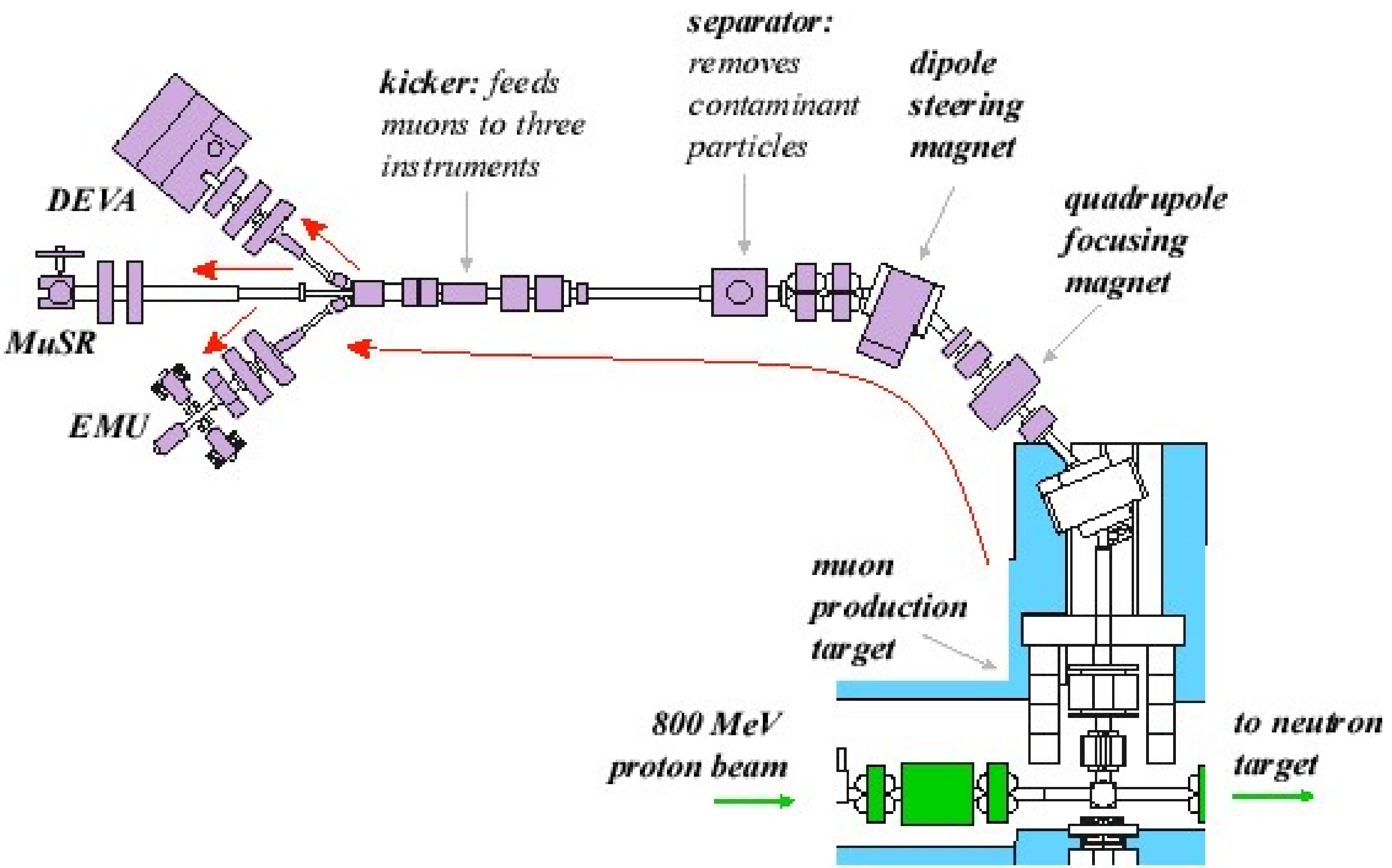


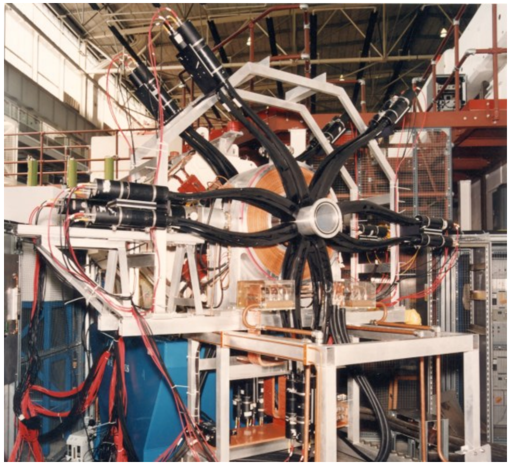
Muons at ISIS



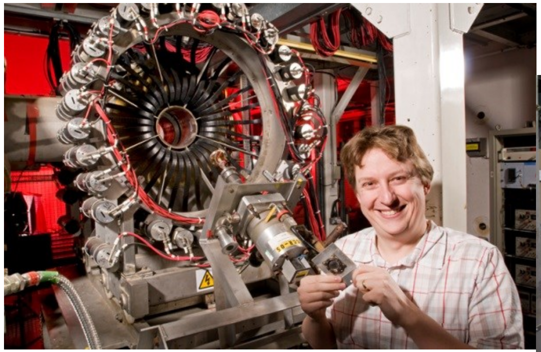
Muons at ISIS



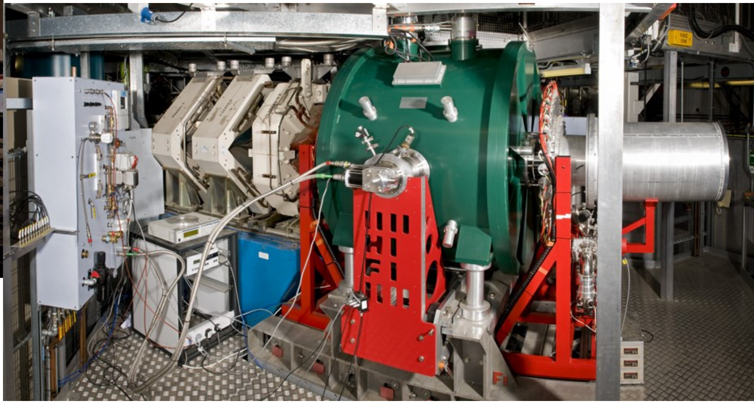
Muons at ISIS



EMU

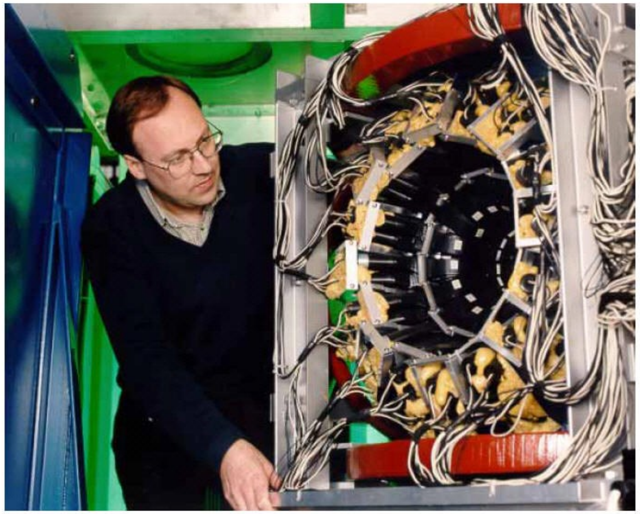


MuSR



HiFi

ARGUS



- Fields: 0G – 5 T
- Temperatures:
  30 mK – 1500 K
- Pressure:
  up to 6.4kbar
- + and - muons

- Gas/liquid samples
- Pulsed stimuli,
  e.g. light, E/B-fields, RF

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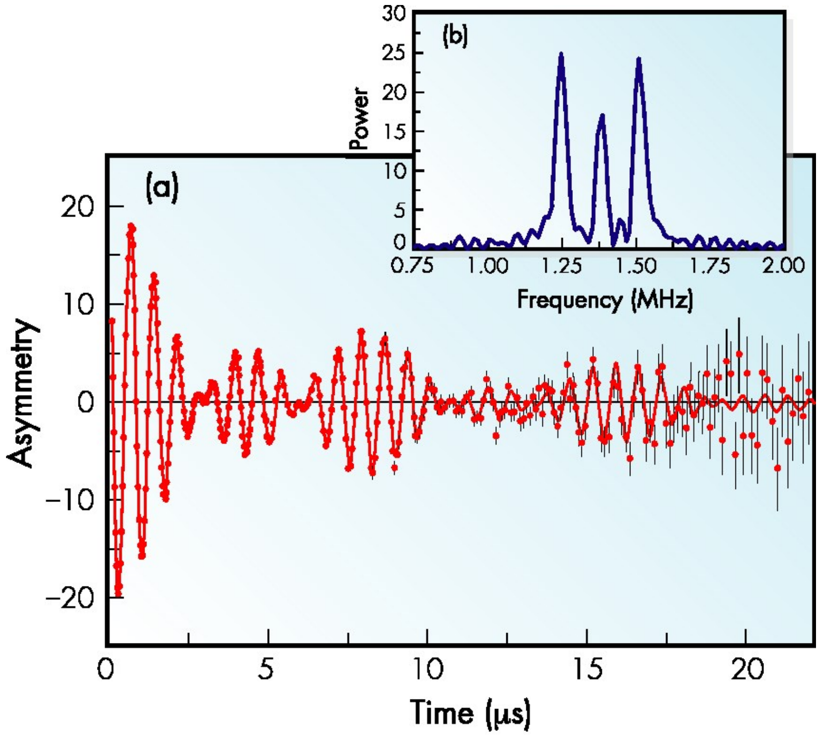
4. Science with muons



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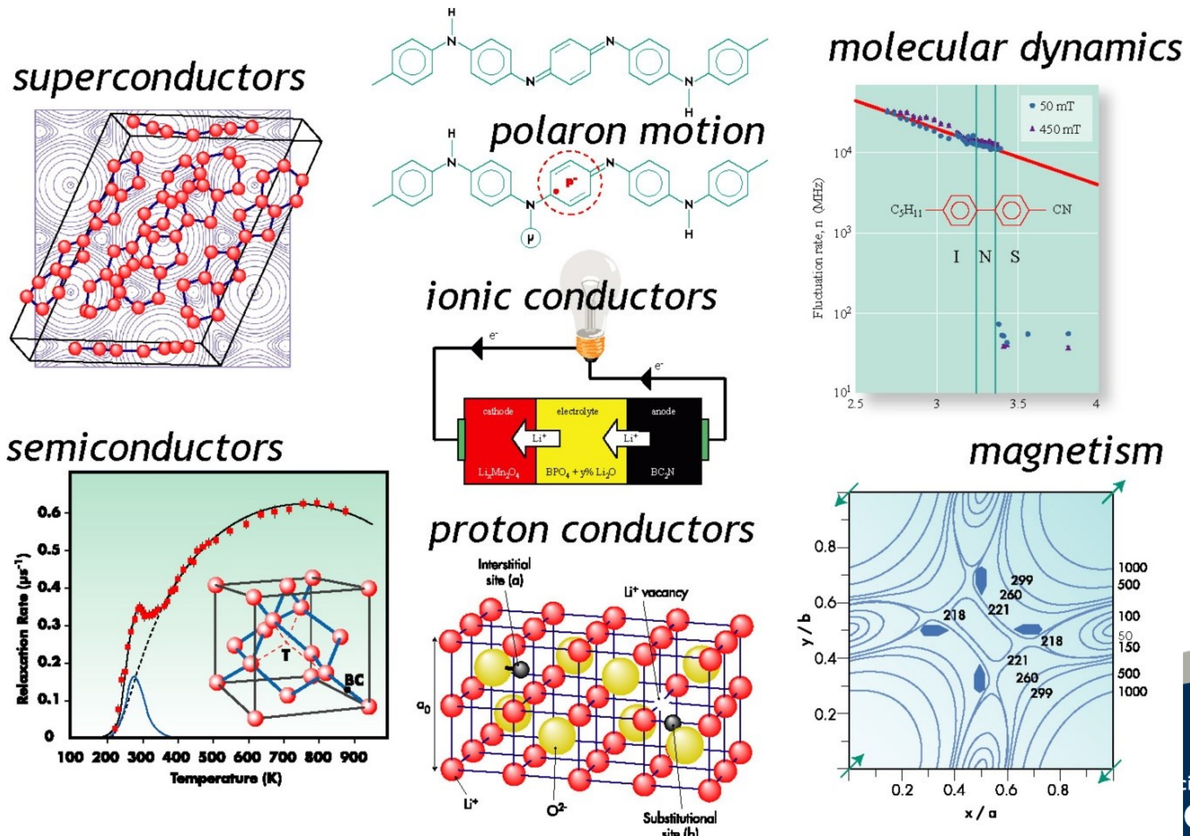
Muon science areas

- Muons as passive probes in superconductivity, magnetism, molecular dynamics, charge transport.

- Muons as active probes: proton analogues in semiconductors, proton conductors, light particle diffusion, etc.



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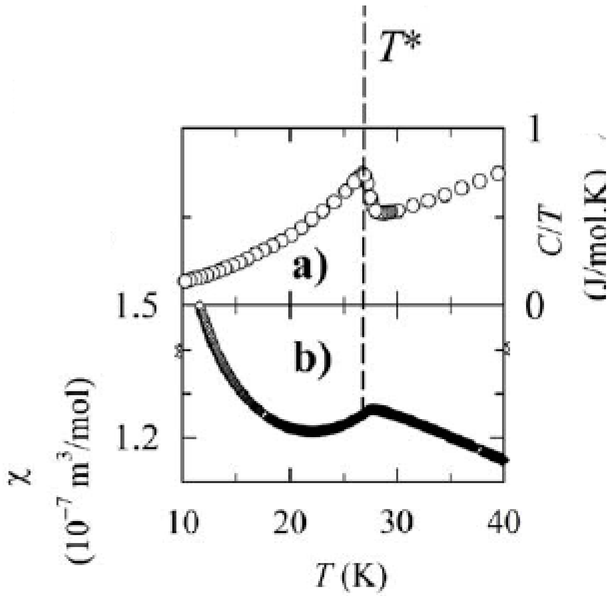
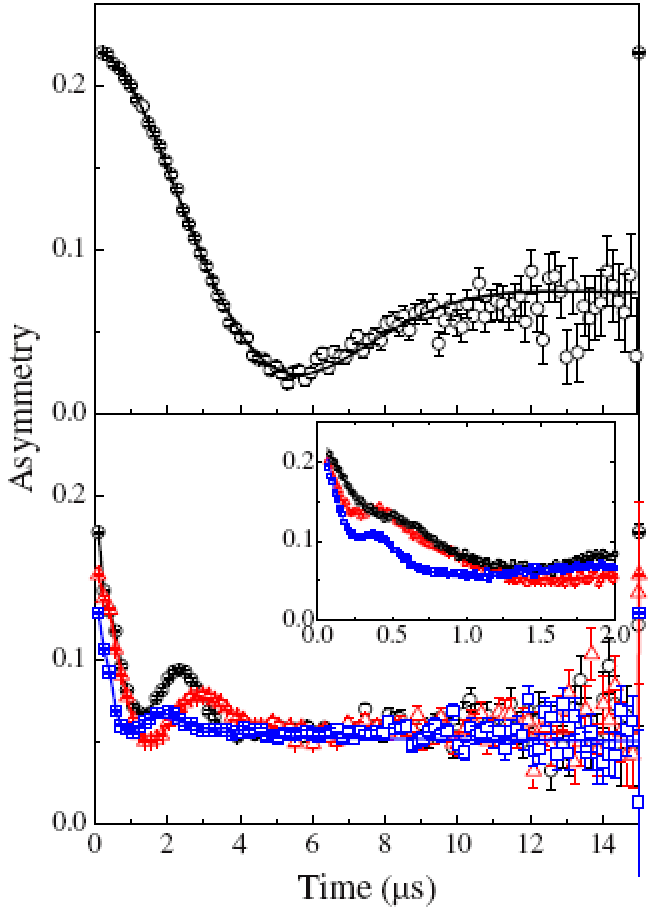
$CeRu_2Al_{10}$





Khalyavin, Hillier *et al* Phy. Rev. B 82 100405R (2010)

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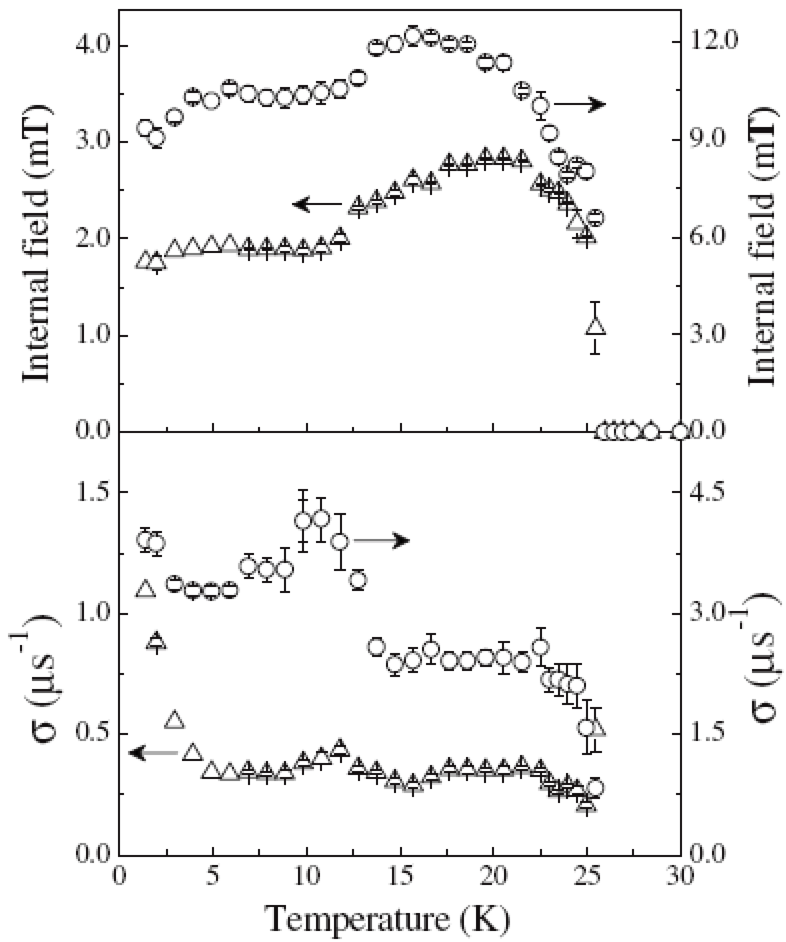
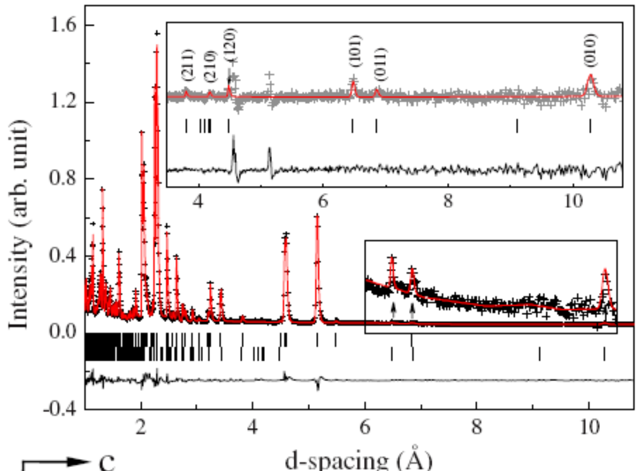
Magnetism

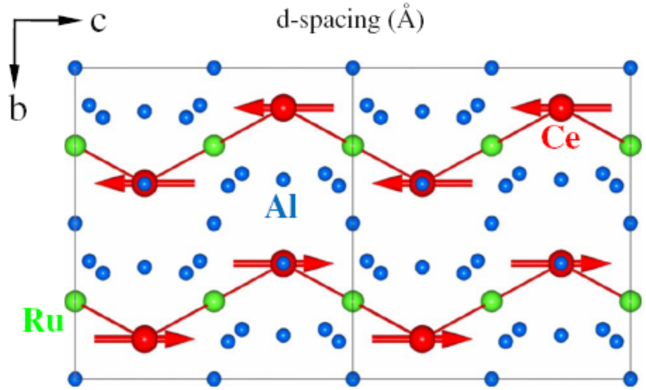
$CeRu_2Al_{10}$

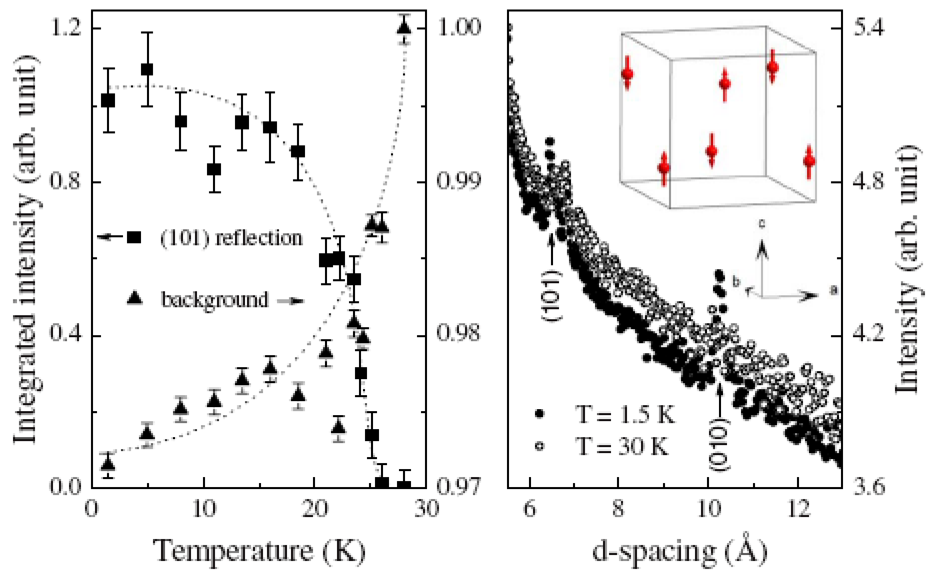


Khalyavin, Hillier *et al* Phy. Rev. B 82 100405R (2010)

$CeRu_2Al_{10}$



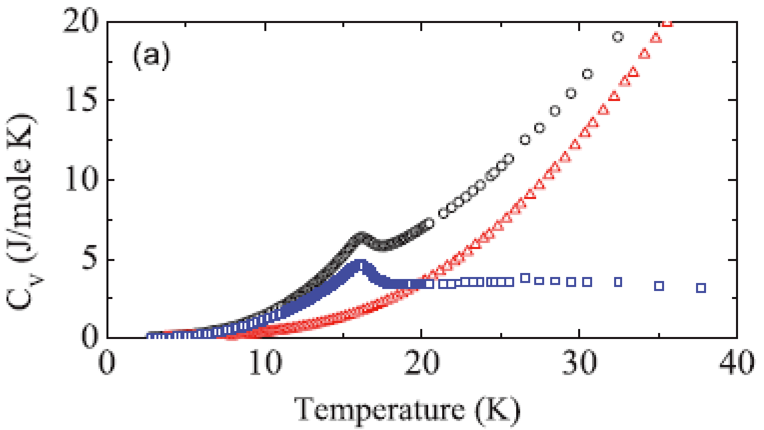


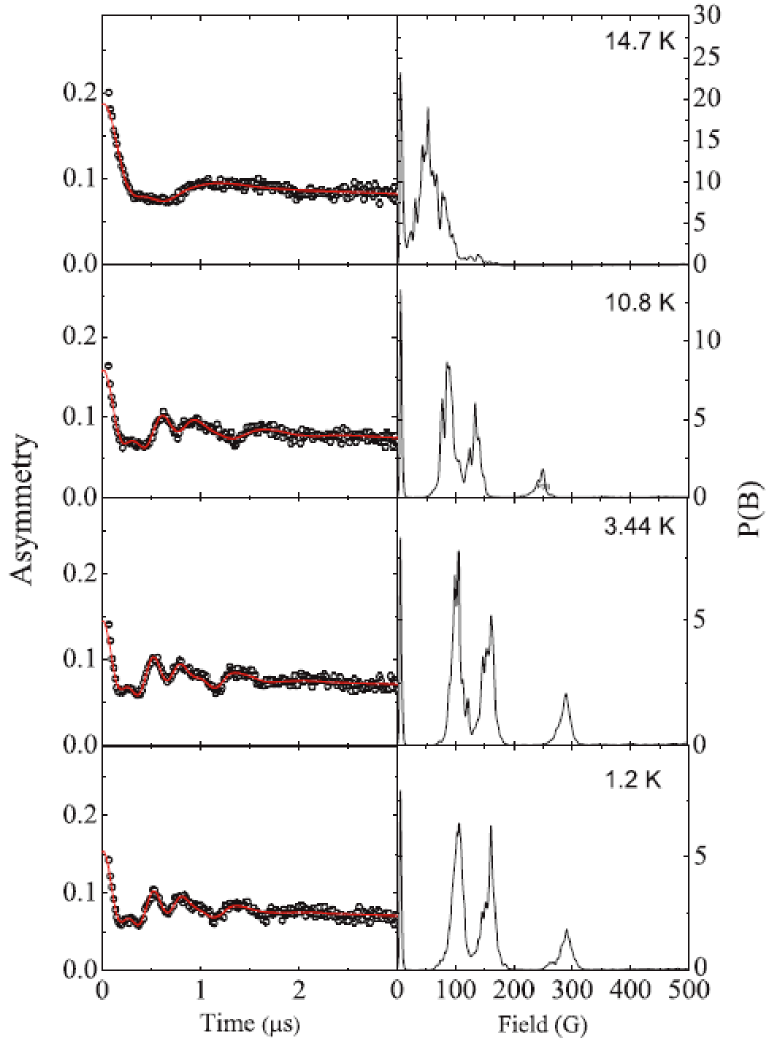


Khalyavin, Hillier *et al* Phy. Rev. B 82 100405R (2010)

Magnetism

Sr_3ZnRhO_6





Hillier *et al* Phys. Rev. B 83 24414 (2011)

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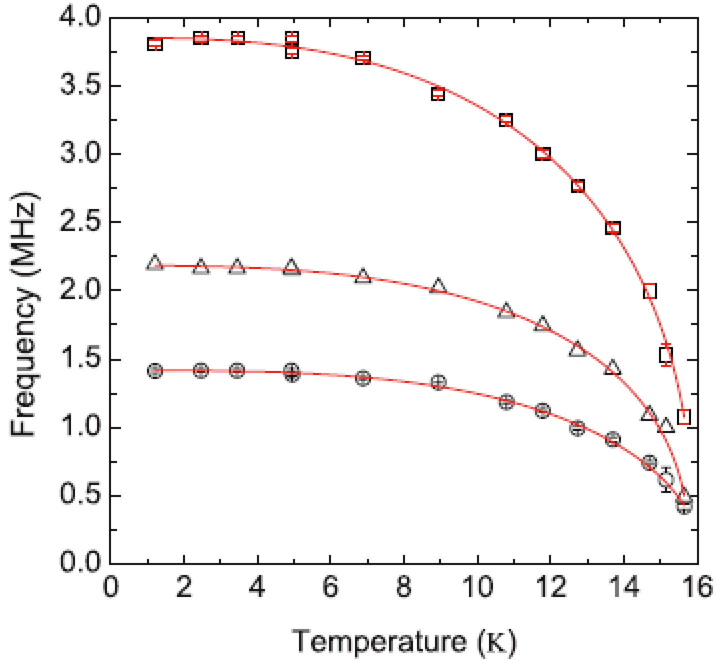
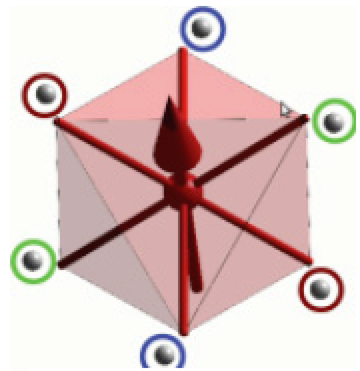
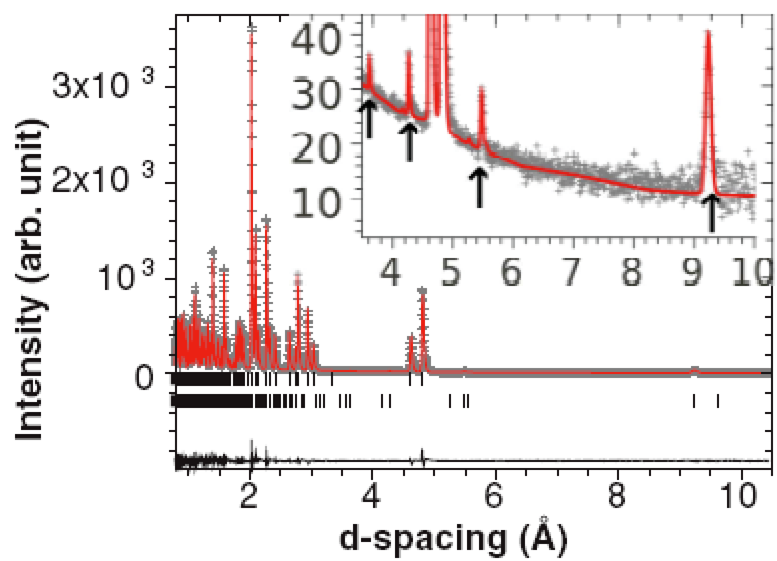
Magnetism

Sr_3ZnRhO_6





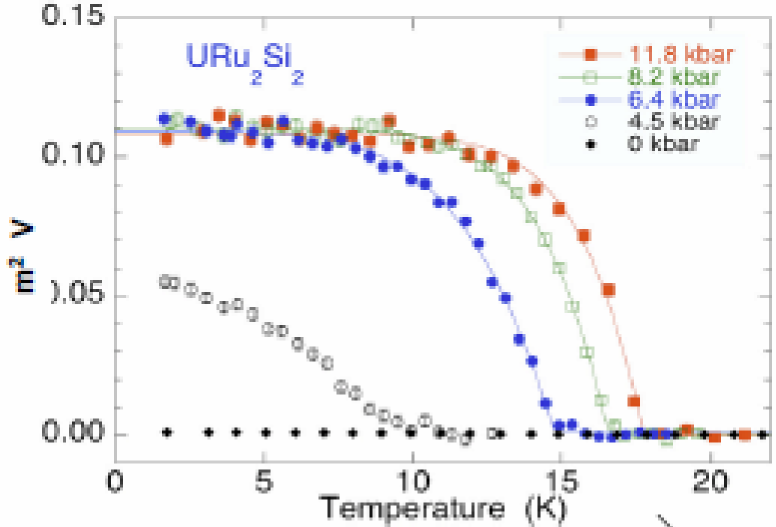


Hillier *et al* Phys. Rev. B 83 24414 (2011)

Example URu_2Si_2

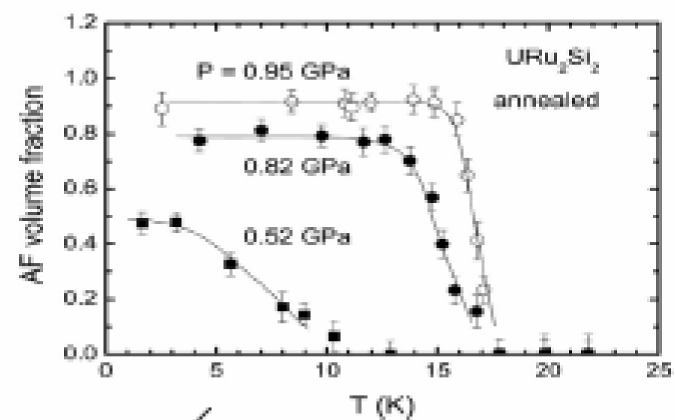
Neutron scattering:

F. Bourdarot et al., condmat/0312206



Muon Spin Rotation:

A. Amato et al., J. Phys.: Condens. Matter 16 (2004) S4403

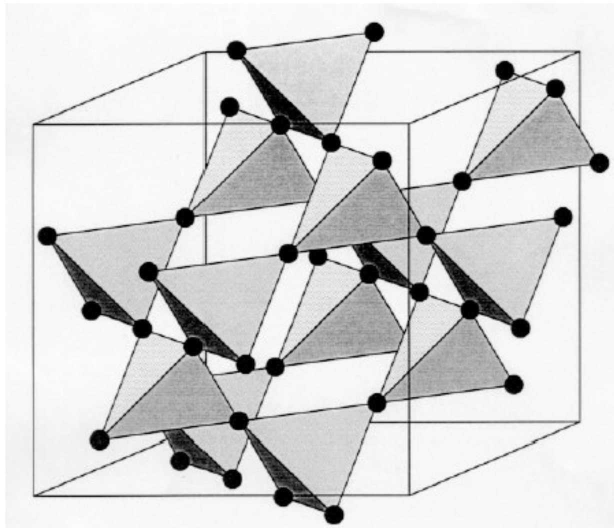


Phase separation in magnetic and non magnetic volumes

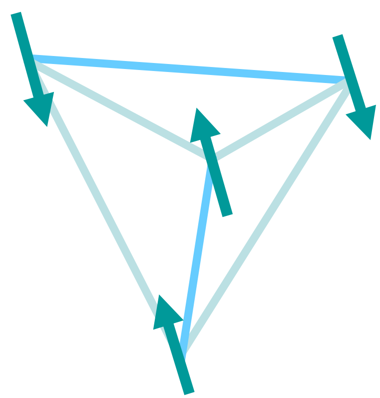
Only the combination of neutron and muon data allows the correct interpretation of the data

Frustrated magnetism

Geometrical frustration: anti-ferromagnetism, spins cannot all be satisfied



Pyrochlore compounds: Corner-sharing tetrahedra lead to geometrical frustration

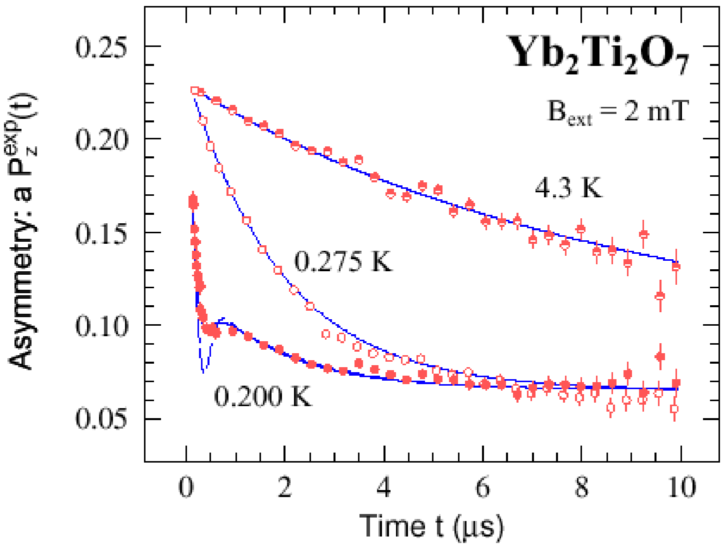


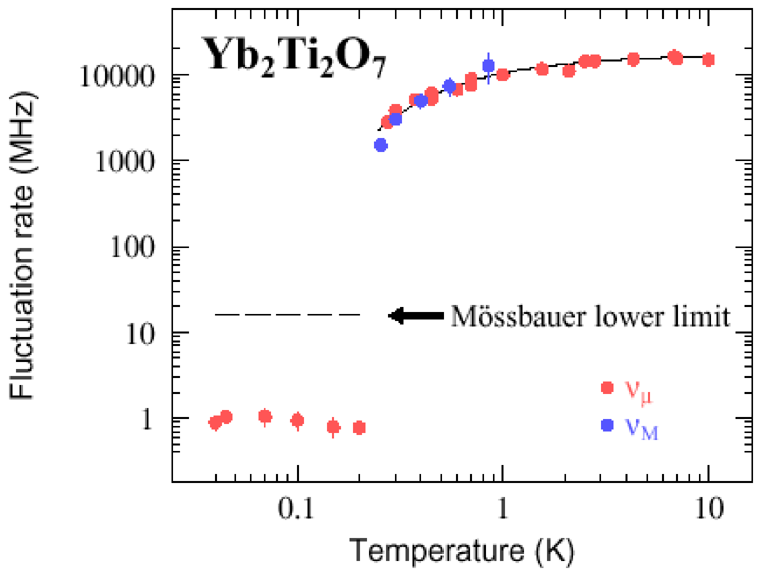
The μSR technique

- is highly sensitive to local fields,
- is able to characterise the timescale of local field fluctuations,
- is well suited to the investigation of compounds which do not display long-range magnetic correlations,
- requires no application of external fields.

Frustrated magnetism

First order transition in the spin dynamics of geometrically frustrated $\mathbf{Yb_2Ti_2O_7}$
J Hodges et al, PRL 88 (2002) 077204





- First order transition at 0.24 K is not to long (or short) range order, but is a change in the Yb^{3+} fluctuation rate.
- Neutron diffraction, Mossbauer and μSR used

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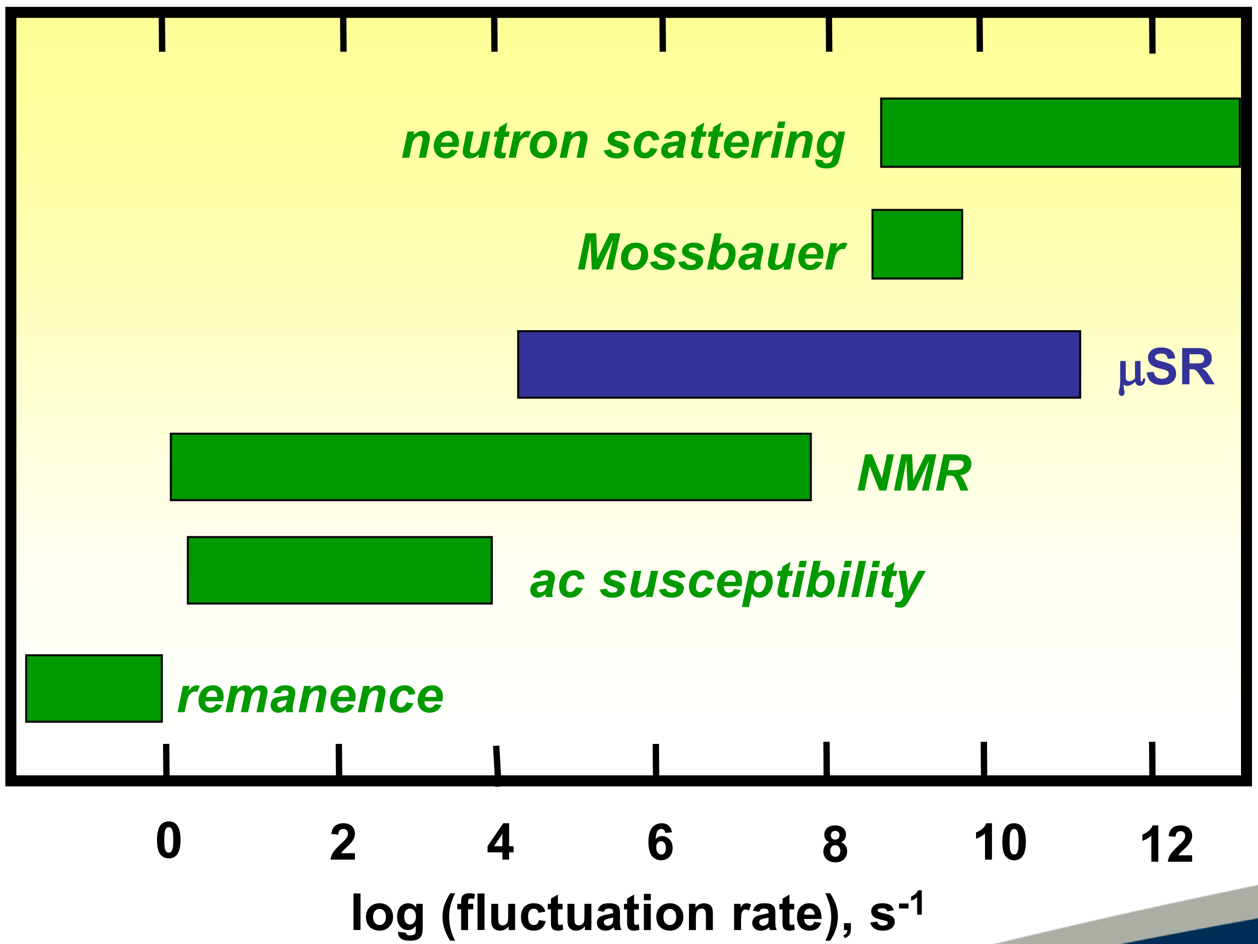
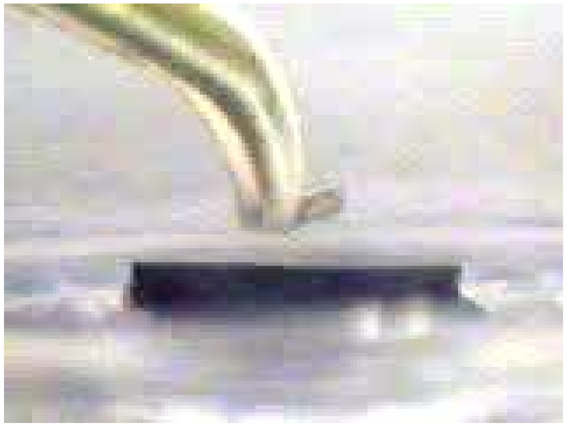
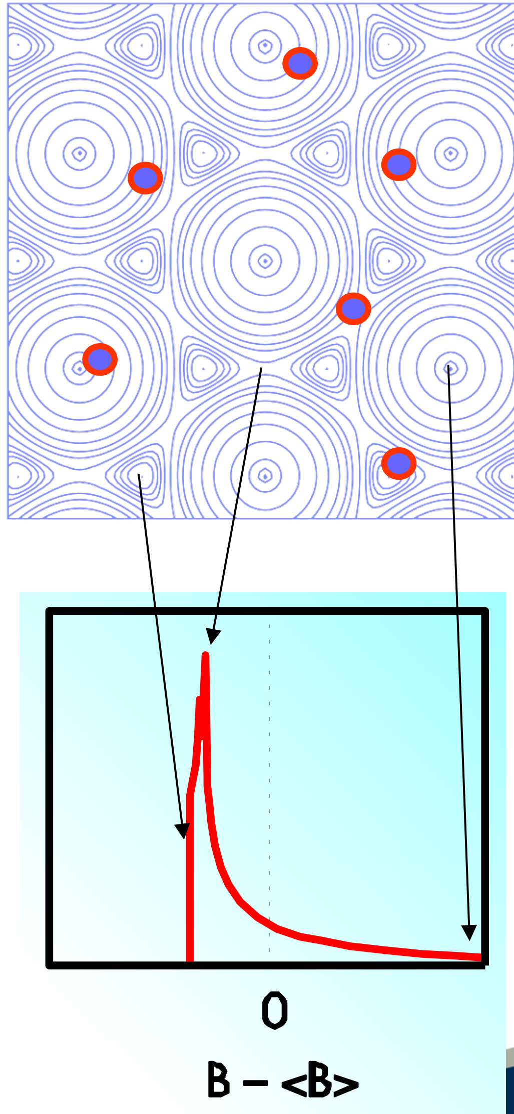
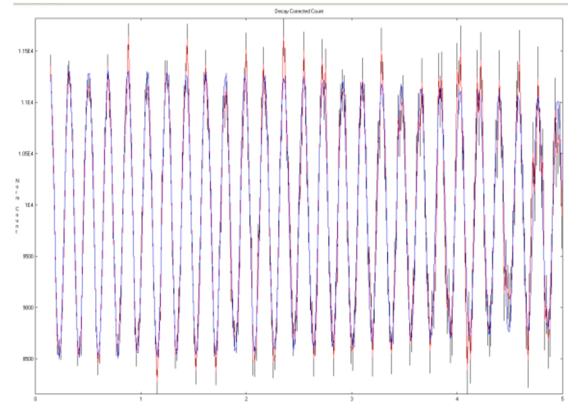
Complementary



Superconductors

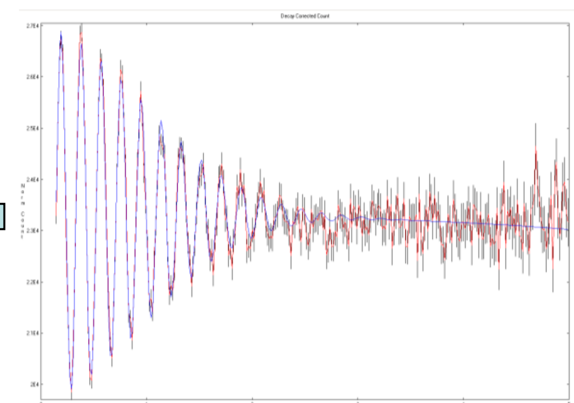






Above T_c

Below T_c



- Interplay of superconductivity and magnetism;
- flux lattice studies;
- measurement of fundamental superconducting parameters

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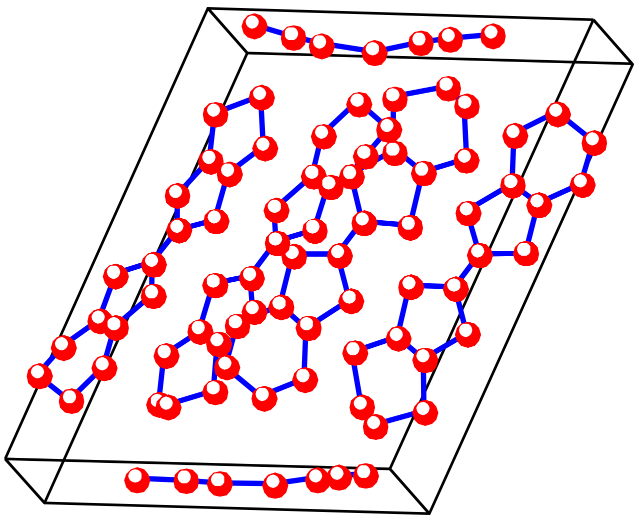
Superconductors

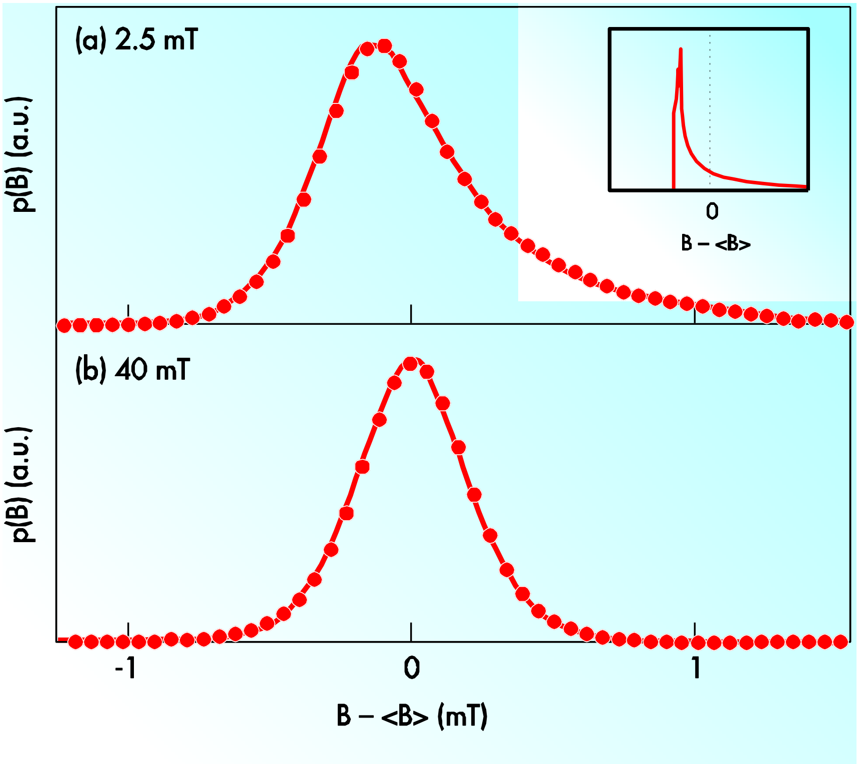
Investigation of Vortex Behavior in the Organic Superconductor κ-(BEDT-TTF)$_2$Cu(SCN)$_2$ Using Muon Spin Rotation

Lee et al, PRL 1997



T_c = 10.4 K

Highly anisotropic



Measurements at 1.8K

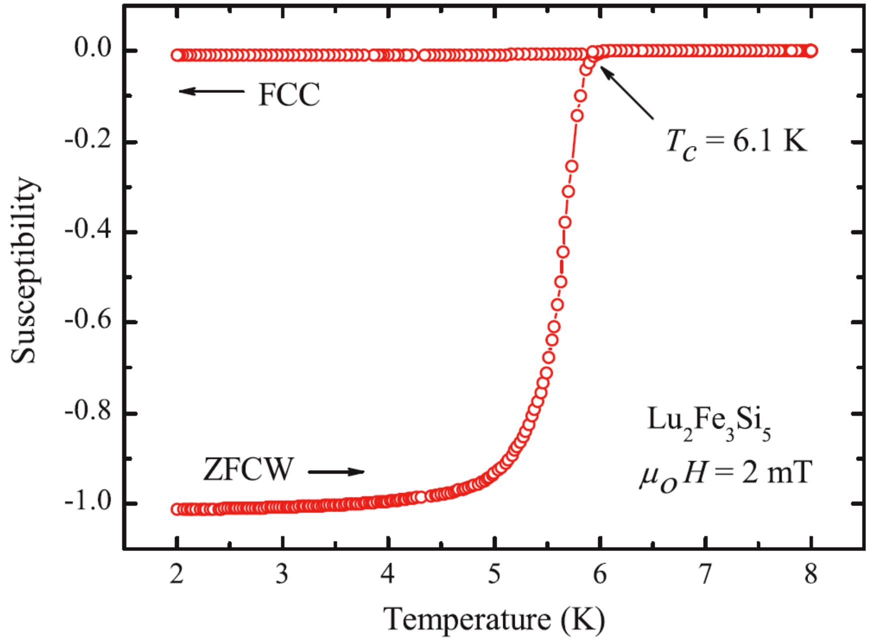
Breakdown of 3D order with B and T

Science & Technology Facilities Council

ISIS

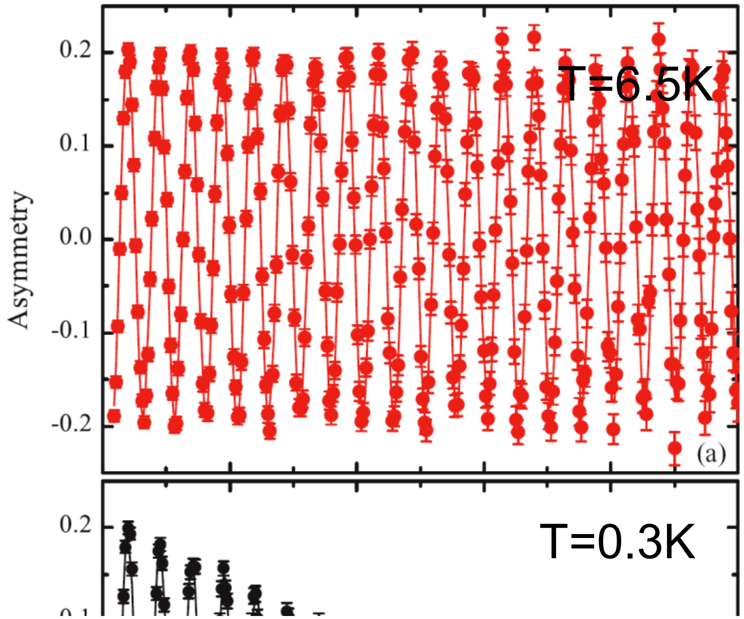
Superconductors

$Lu_2Fe_3Si_5$



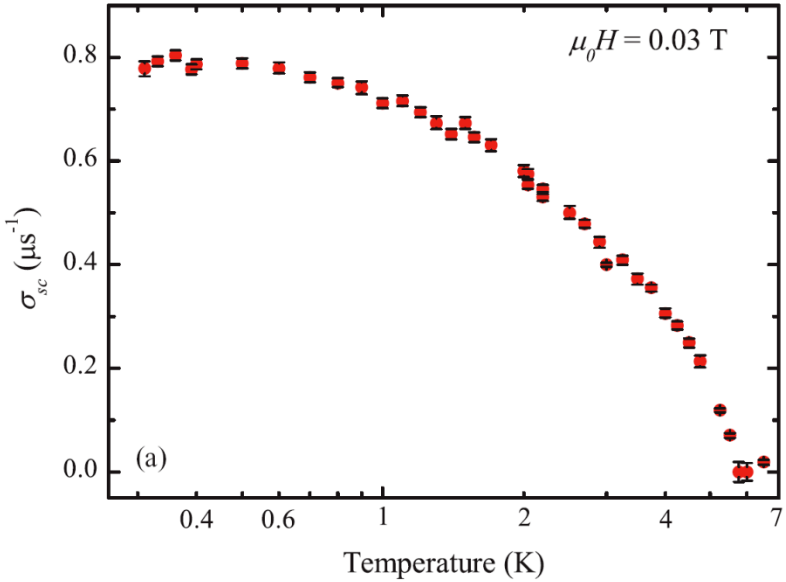
Biswas et al Phys. Rev. B, 83 54517 (2011)

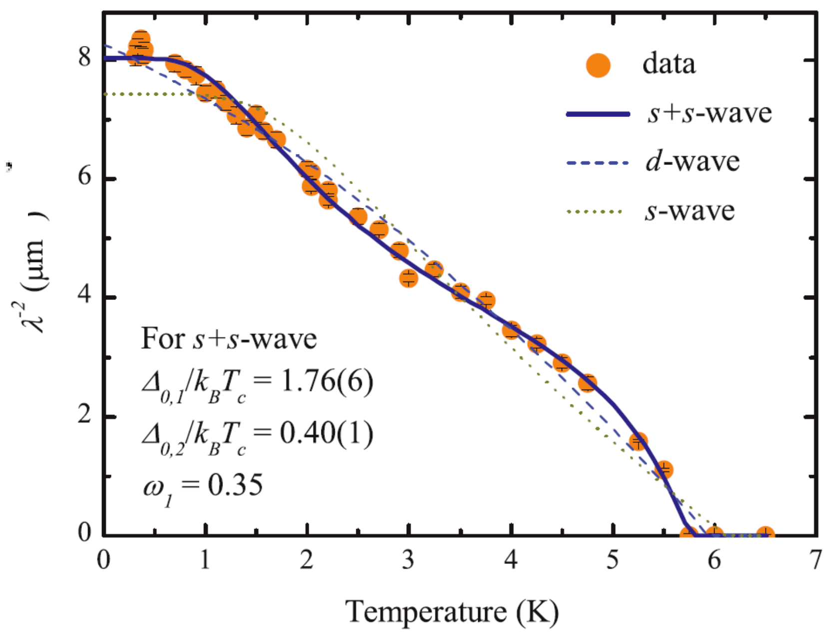
Superconductors



$$\frac{\lambda^{-2}(T,\Delta_{0,i})}{\lambda^{-2}(0,\Delta_{0,i})} = 1 + \frac{1}{\pi}\int_0^{2\pi}\int_{\Delta(T,\varphi)}^{\infty}\left(\frac{\partial f}{\partial E}\right)\frac{E\,dE\,d\varphi}{\sqrt{E^2-\Delta_i(T,\varphi)^2}},$$

$$\frac{\lambda^{-2}(T)}{\lambda^{-2}(0)} = \omega_1\frac{\lambda^{-2}(T,\Delta_{0,1})}{\lambda^{-2}(0,\Delta_{0,1})} + \omega_2\frac{\lambda^{-2}(T,\Delta_{0,2})}{\lambda^{-2}(0,\Delta_{0,2})},$$



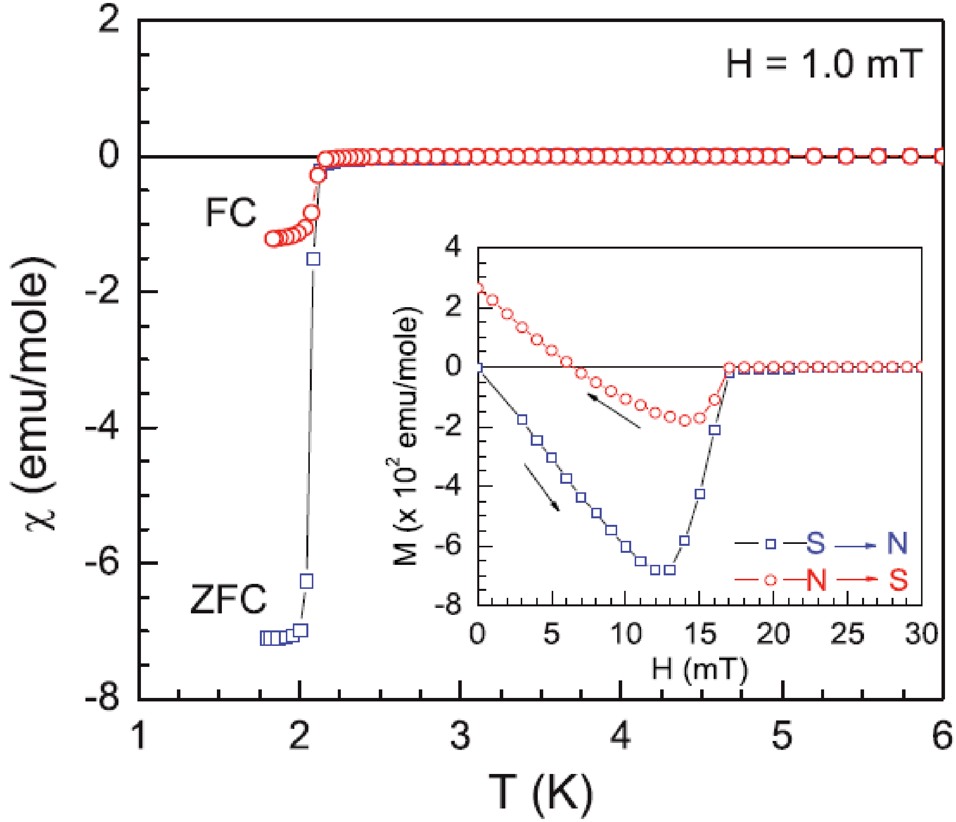


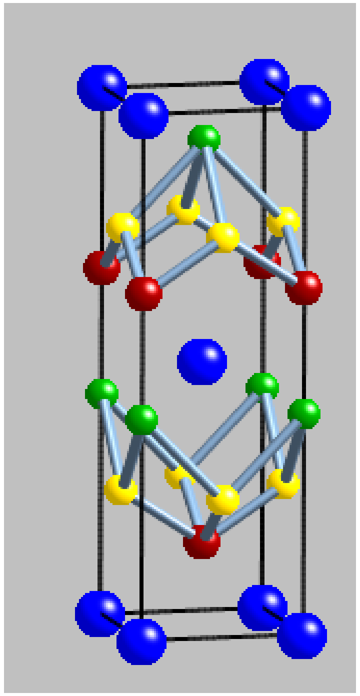
Biswas et al Phys. Rev. B, 83 54517 (2011)

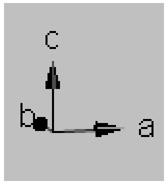
Council

Superconductors

$LaRhSi_3$







Anard, Hillier *et al* Phys. Rev. B 83 64522 (2011)

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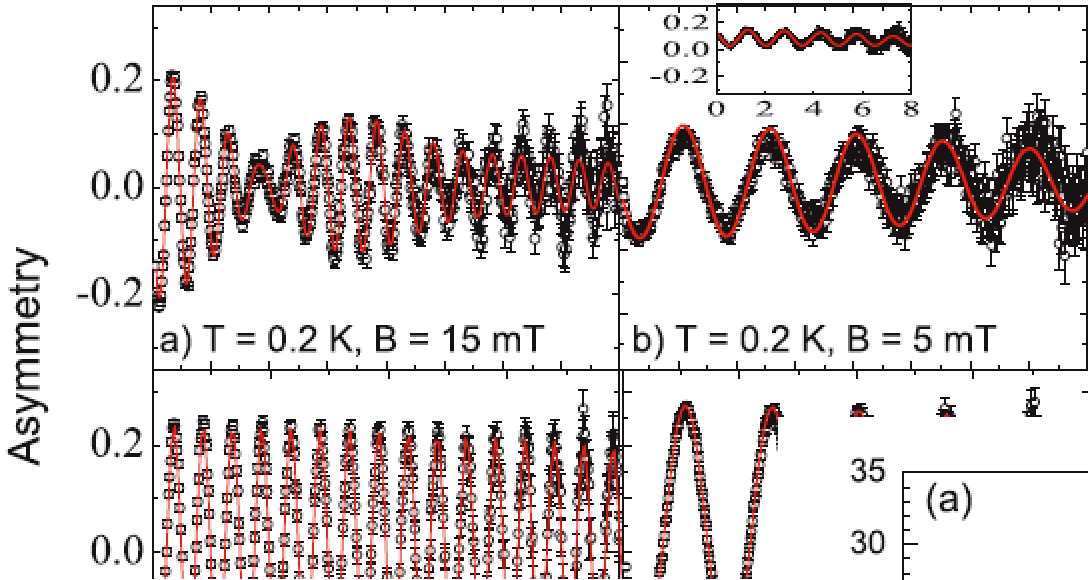
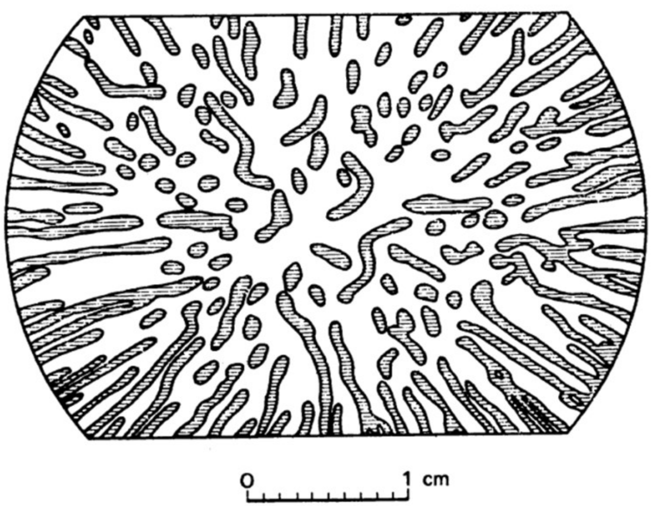
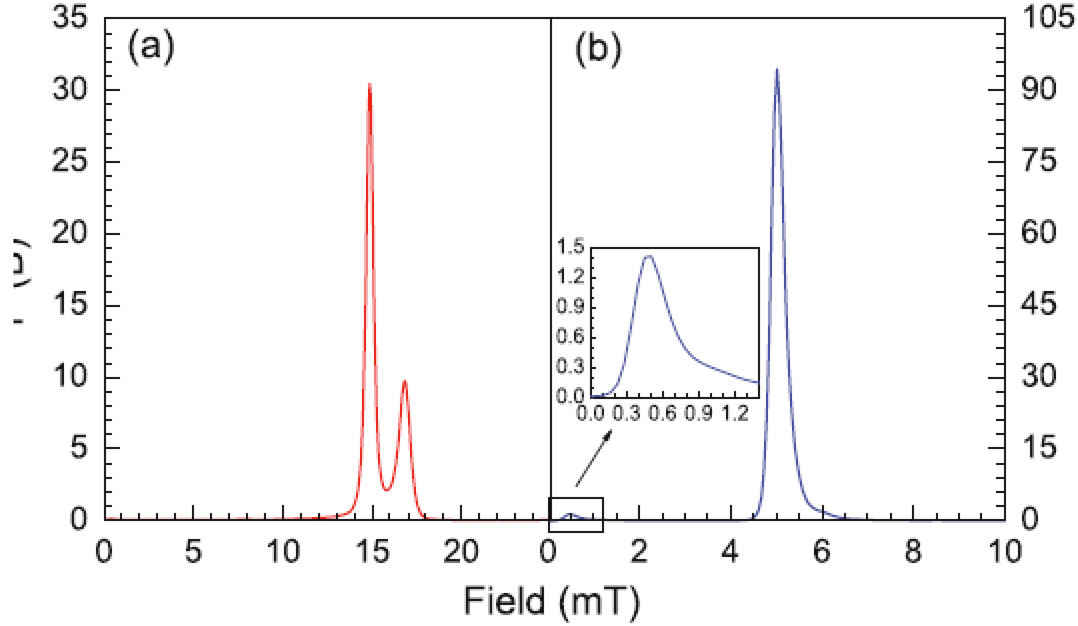
Superconductors







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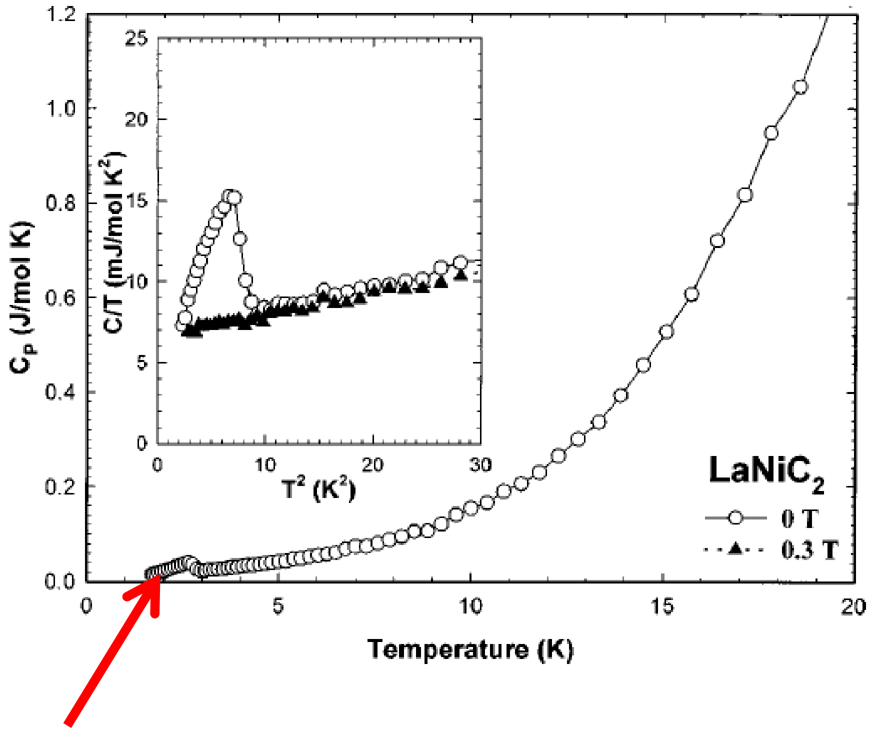
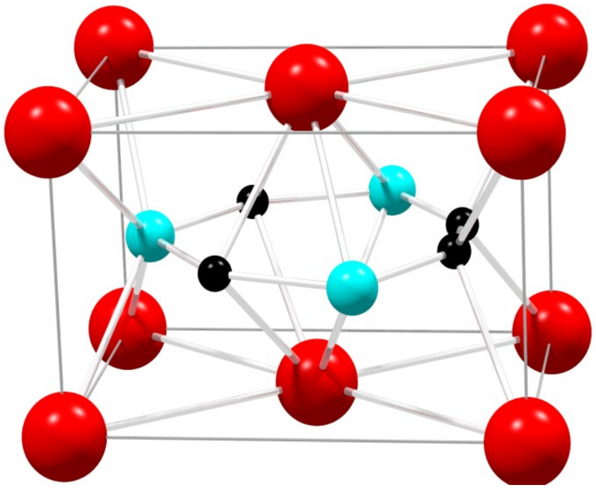
Superconductors

$LaNiC_2$

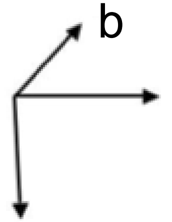


T_c=2.7 K

$\Delta C/\gamma T_C$=1.26 c.f. (BCS: 1.43)



Orthorhombic Amm2 C_{2v}



a=3.96 Å
b=4.58 Å
c=6.20 Å

Note no inversion centre.

C.f. $CePt_3Si$ (1), Li_2Pt_3B & Li_2Pd_3B (2), ...

(1) Bauer et al. PRL'04 (2) Yuan et al. PRL'06

V. K. Pecharsky, L. L. Miller, and Zy, Physical Review B **58**, 497 (1998)
W. H. Lee *et al.*, Physica C **266**, 138 (1996)

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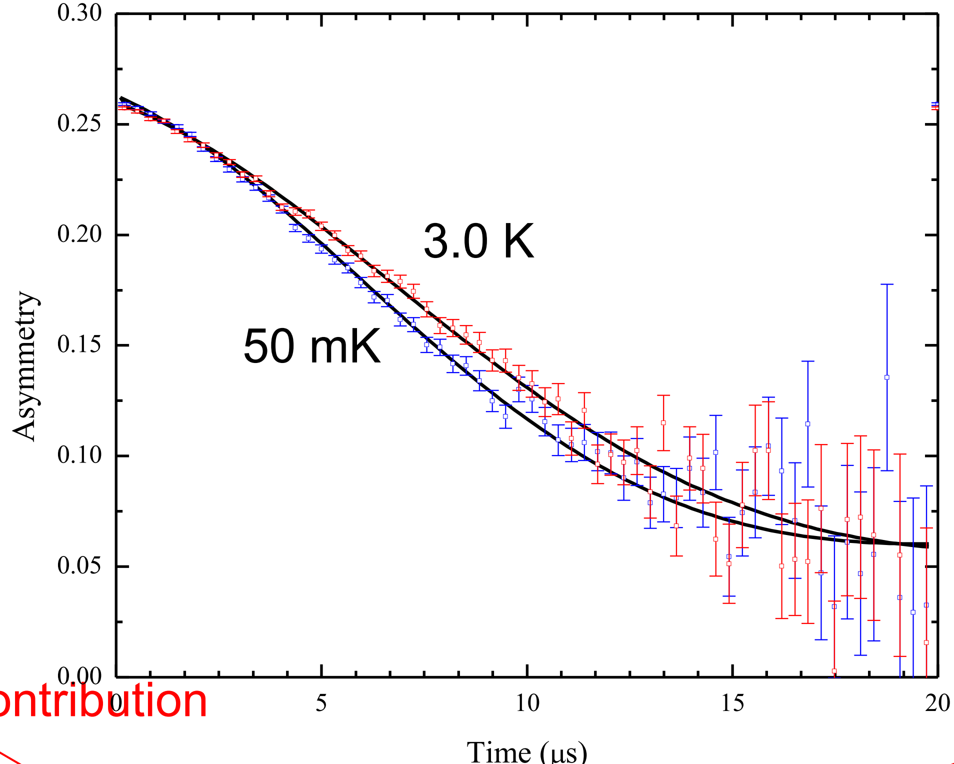
Superconductors

ZFμSR on $LaNiC_2$



Nuclear contribution

Electronic contribution

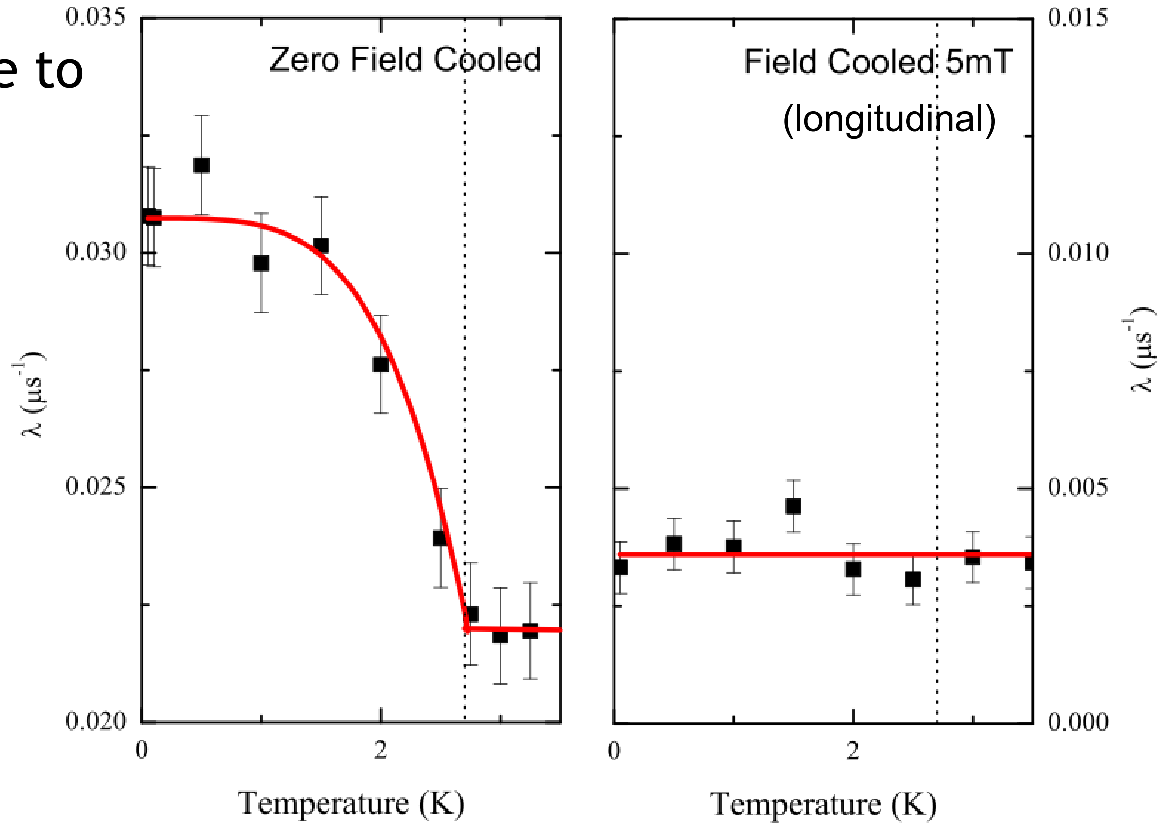
$$G_z(t) = A_0\left(\frac{1}{3}+\frac{2}{3}\left(1-\sigma^2 t^2\right)\exp\left(-\frac{\sigma^2 t^2}{2}\right)\right)\exp(-\lambda t) + A_{bckgrd}$$

Hillier *et al PRL* **102** 117007 (2009)

Superconductors

Relaxation due to electronic moments

Moment size
~ 0.1G
(~ 0.01μ_B)



Spontaneous, quasi-static fields appearing at T_c
⇒ superconducting state breaks time-reversal symmetry

Hillier *et al PRL* **102** 117007 (2009)

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Superconductors

$SO(3)xC_{2v}$	Gap function (unitary)	Gap function (non-unitary)
$^1A_1$	$\Delta(\mathbf{k})=1$	-
$^1A_2$	$\Delta(\mathbf{k})=k_x k_Y$	-
$^1B_1$	$\Delta(\mathbf{k})=k_X k_Z$	-
$^1B_2$	$\Delta(\mathbf{k})=k_Y k_Z$	-
$^3A_1$	$\mathbf{d}(\mathbf{k})=(0,0,1)k_Z$	$\mathbf{d}(\mathbf{k})=(1,i,0)k_Z$
$^3A_2$	$\mathbf{d}(\mathbf{k})=(0,0,1)k_X k_Y k_Z$	$\mathbf{d}(\mathbf{k})=(1,i,0)k_X k_Y k_Z$
$^3B_1$	$\mathbf{d}(\mathbf{k})=(0,0,1)k_X$	$\mathbf{d}(\mathbf{k})=(1,i,0)k_X$
$^3B_2$	$\mathbf{d}(\mathbf{k})=(0,0,1)k_Y$	$\mathbf{d}(\mathbf{k})=(1,i,0)k_Y$

breaks only U(1) x SO(3) *

Non-unitary

* C.f. Li2Pd3B & Li2Pt3B,
H. Q. Yuan et al. PRL'06

Hillier *et al PRL* **102** 117007 (2009)

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H and Semiconductors

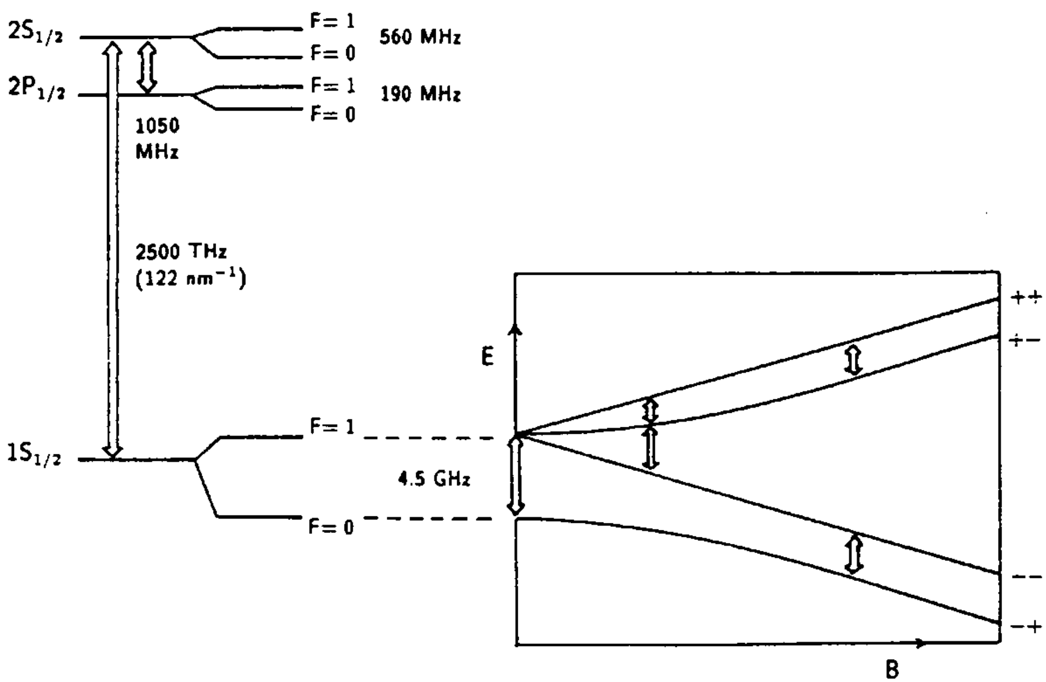
'Muonium' (Mu): light hydrogen atom

Mass: $m_{Mu}=1/9m_H$

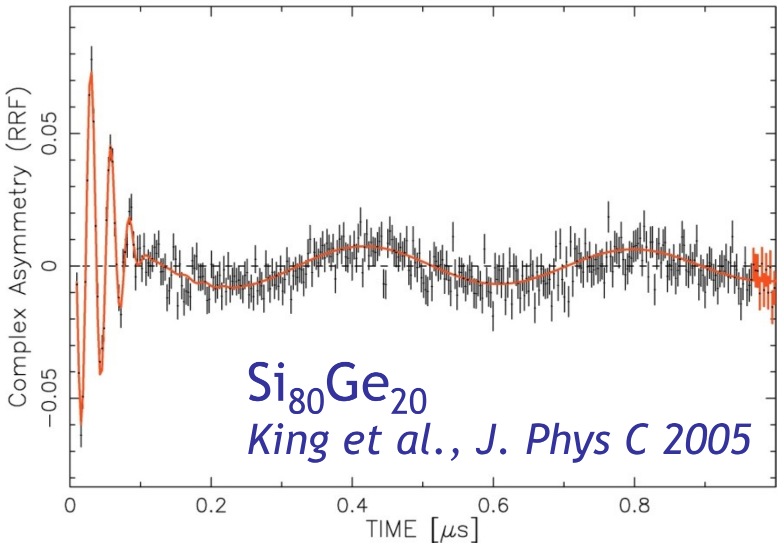
Bohr radius: $a_{Mu}=1.004a_H$

Ionisation potential: $I_{Mu}=0.996I_H$

Chemical behaviour very similar – dynamics different



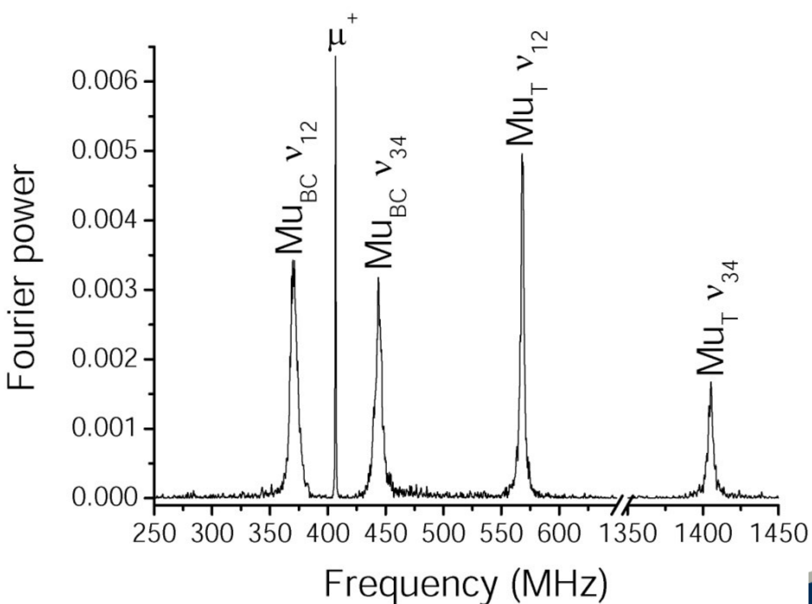
H and Semiconductors

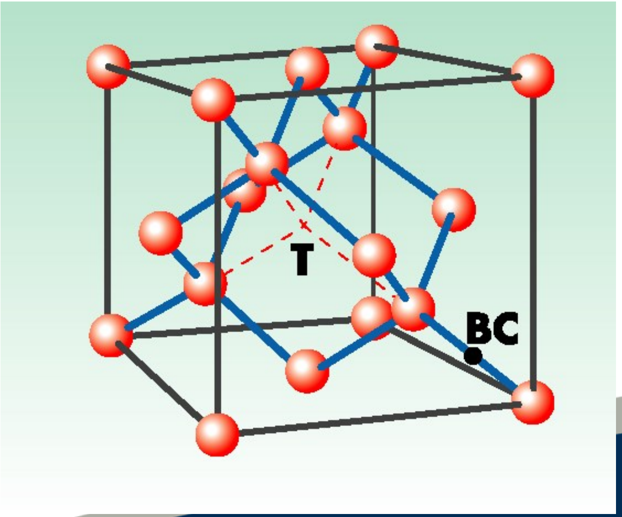


Silicon: two muon species exist at low temperatures.

Mu_T: Cage-centred, isotropic, mobile

Mu_{BC}: Bond centred, axially symmetric, immobile





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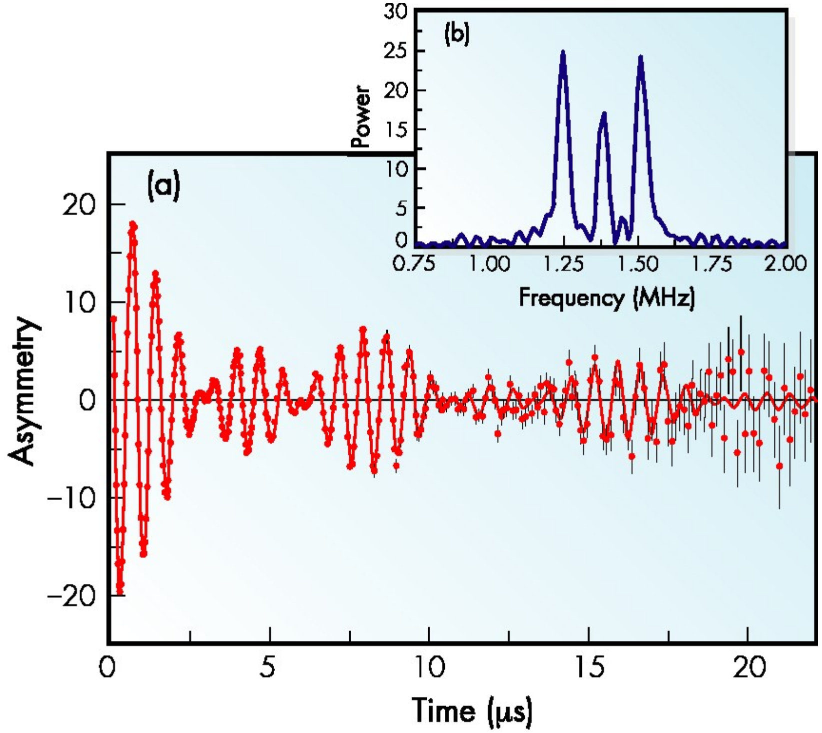
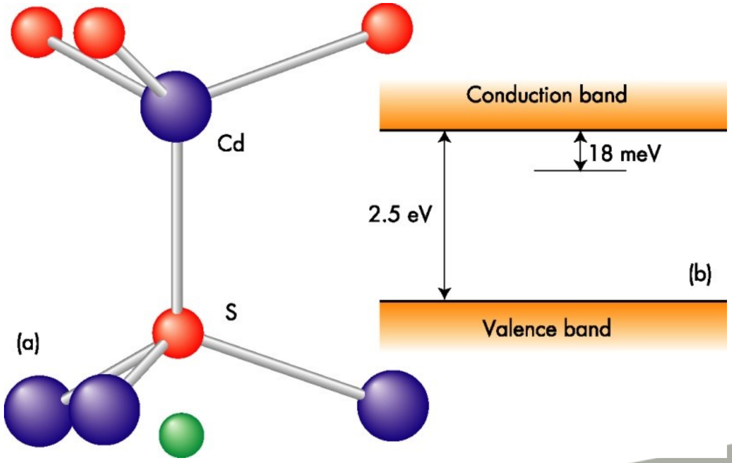
H and Semiconductors

CdS: II-VI semiconductor



- Hyperfine parameter 10^{-4} of vacuum value
- Extended wavefunction
- Ionises at 22 K
- ***Shallow donor state***

Gil et al, PRL 1999



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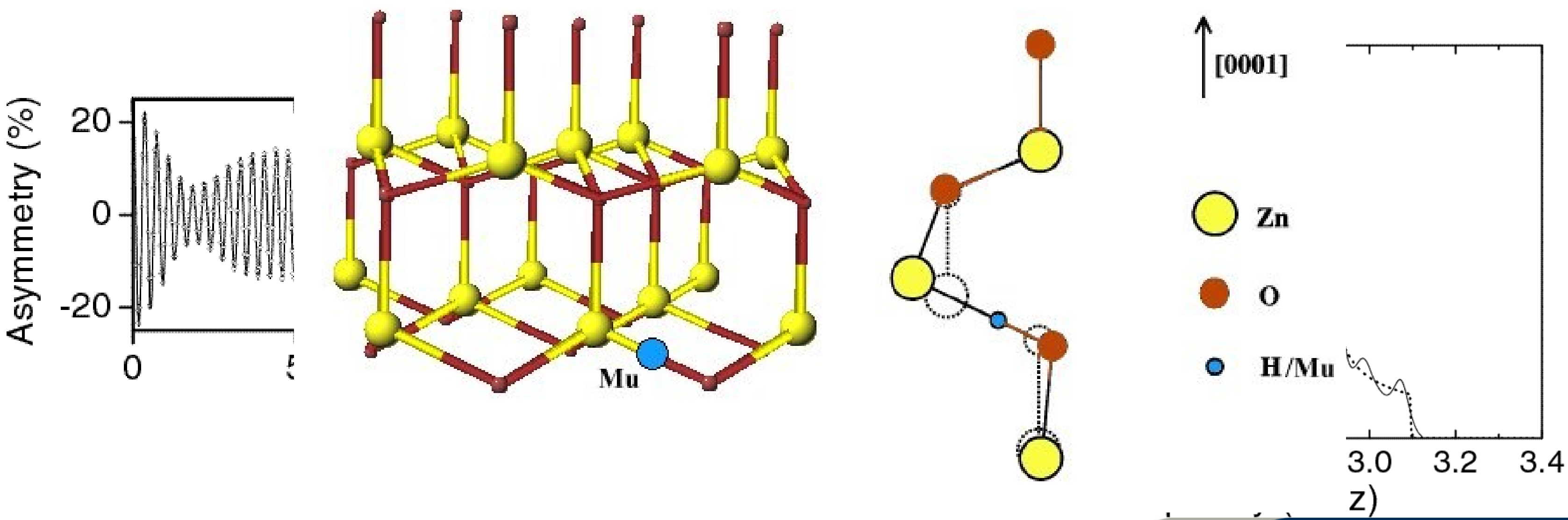
H and Semiconductors

VOLUME 86, NUMBER 12 PHYSICAL REVIEW LETTERS 19 MARCH 2001

Experimental Confirmation of the Predicted Shallow Donor Hydrogen State in Zinc Oxide

S. F. J. Cox,[1,2] E. A. Davis,[3] S. P. Cottrell,[1] P. J. C. King,[1] J. S. Lord,[1] J. M. Gil,[4] H. V. Alberto,[4] R. C. Vilão,[4] J. Piroto Duarte,[4] N. Ayres de Campos,[4] A. Weidinger,[5] R. L. Lichti,[6] and S. J. C. Irvine[7]

[1] *ISIS Facility, Rutherford Appleton Laboratory, Chilton OX11 0QX, United Kingdom*



Organic Spintronics

PHYSICAL REVIEW B **84**, 085209 (2011)

Importance of intramolecular electron spin relaxation in small molecule semiconductors

L. Schulz,[1] M. Willis,[2] L. Nuccio,[2] P. Shusharov,[2] S. Fratini,[3] F. L. Pratt,[4] W. P. Gillin,[2] T. Kreouzis,[2] M. Heeney,[5] N. Stingelin,[5] C. A. Stafford,[6] D. J. Beesley,[5] C. Bernhard,[1] J. E. Anthony,[7] I. McKenzie,[4] J. S. Lord,[4] and A. J. Drew[1,2]
[1]*Department of Physics and Fribourg Center of Nanomaterials, University of Fribourg, CH-1700 Fribourg, Switzerland*
[2]*Queen Mary University of London, Department of Physics, London, E1 4NS, United Kingdom*
[3]*Institut Néel CNRS, F-38042 Grenoble, France*
[4]*ISIS Muon Facility, Rutherford Appleton Laboratory, Didcot, OX11 0QX, United Kingdom*
[5]*Centre for Plastic Electronics, Imperial College London, London, SW7 2AZ, United Kingdom*
[6]*Department of Physics, University of Arizona, Tucson, Arizona, USA*
[7]*Department of Chemistry, U*

Small molecule semiconductors used in molecular electronic devices such as:

- Spin valves
- OLEDs
- FETs

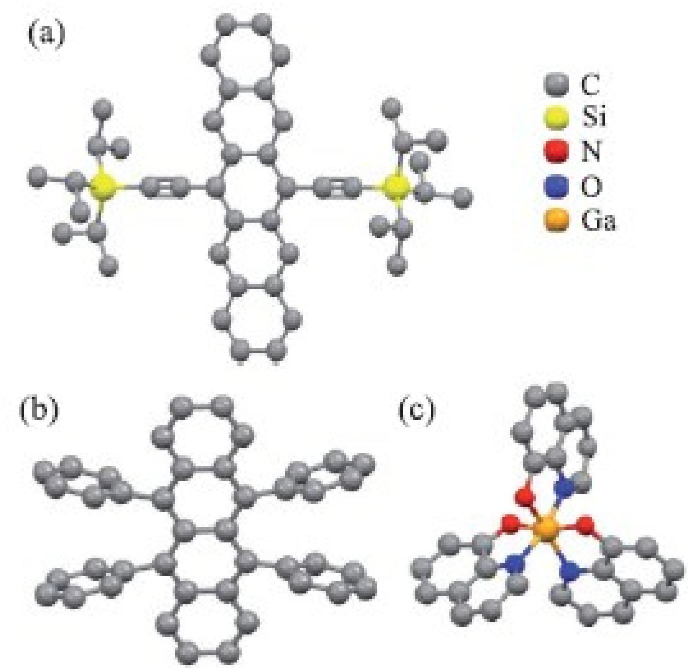
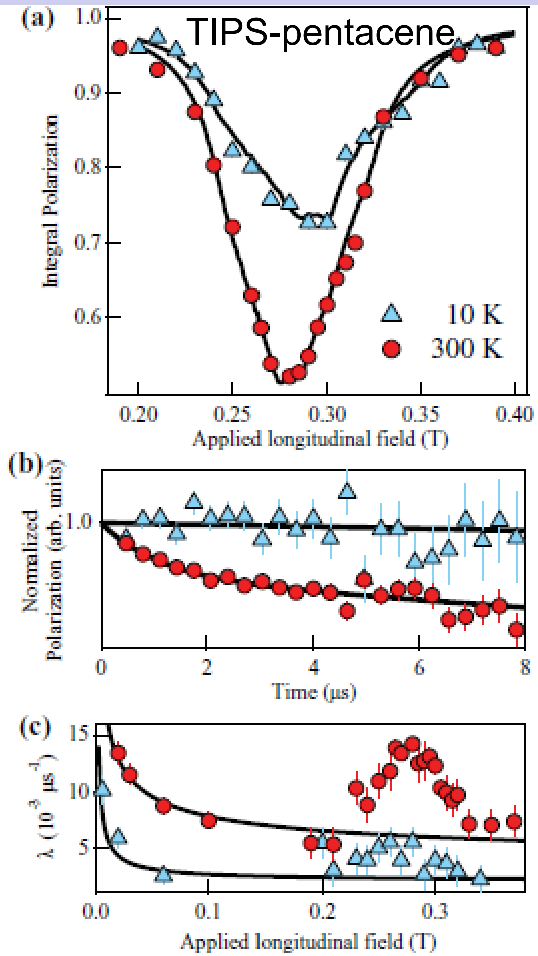


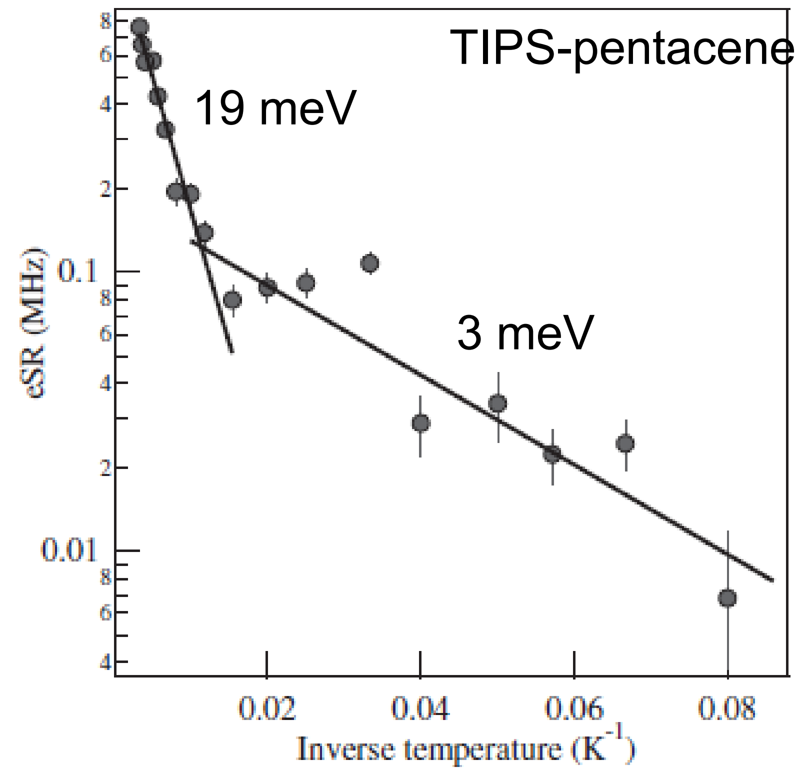
FIG. 1. (Color online) Molecular structures of (a) TIPS-pentacene, (b) rubrene, and (c) Gaq_3 (Refs. 13, 14, and 22–24). Hydrogen has been omitted for clarity.

Organic Spintronics

ALC resonance gives a sensitive measure of the electron spin relaxation (eSR)



T dependence of the eSR is governed by intramolecular vibrational modes



Vibration-modulated spin-orbit coupling emerges as the dominant spin relaxation mechanism in this type of system (rather than hyperfine interaction)

cil
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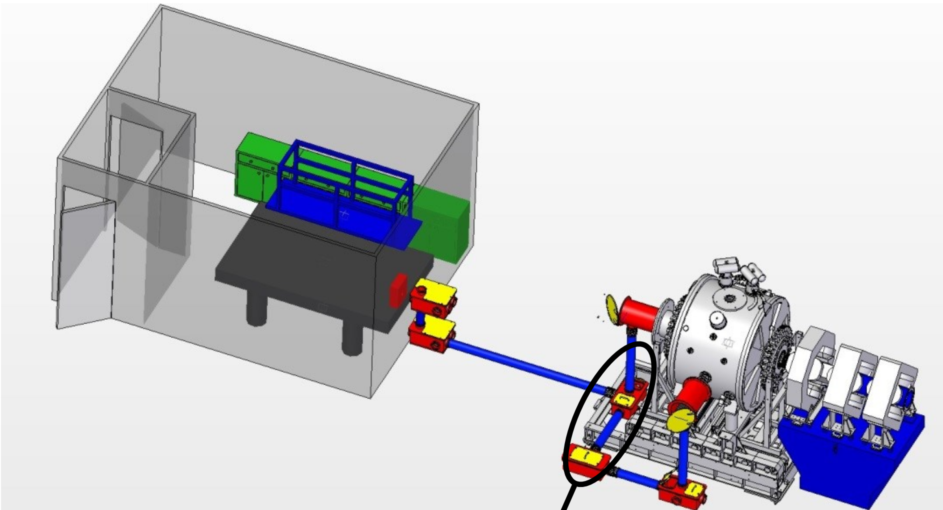
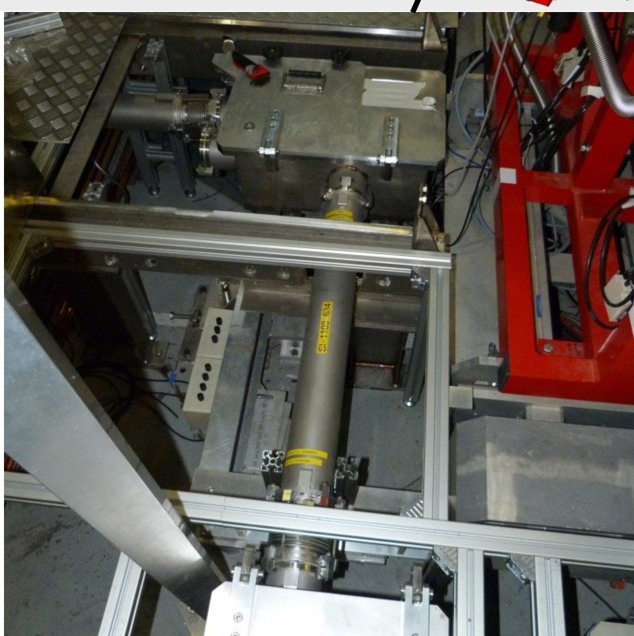
Organic Spintronics – Exciting muons





Alan Drew from QMUL has been awarded 1.5MEuros European Research Council grant to develop the HiFi muon spectrometer.

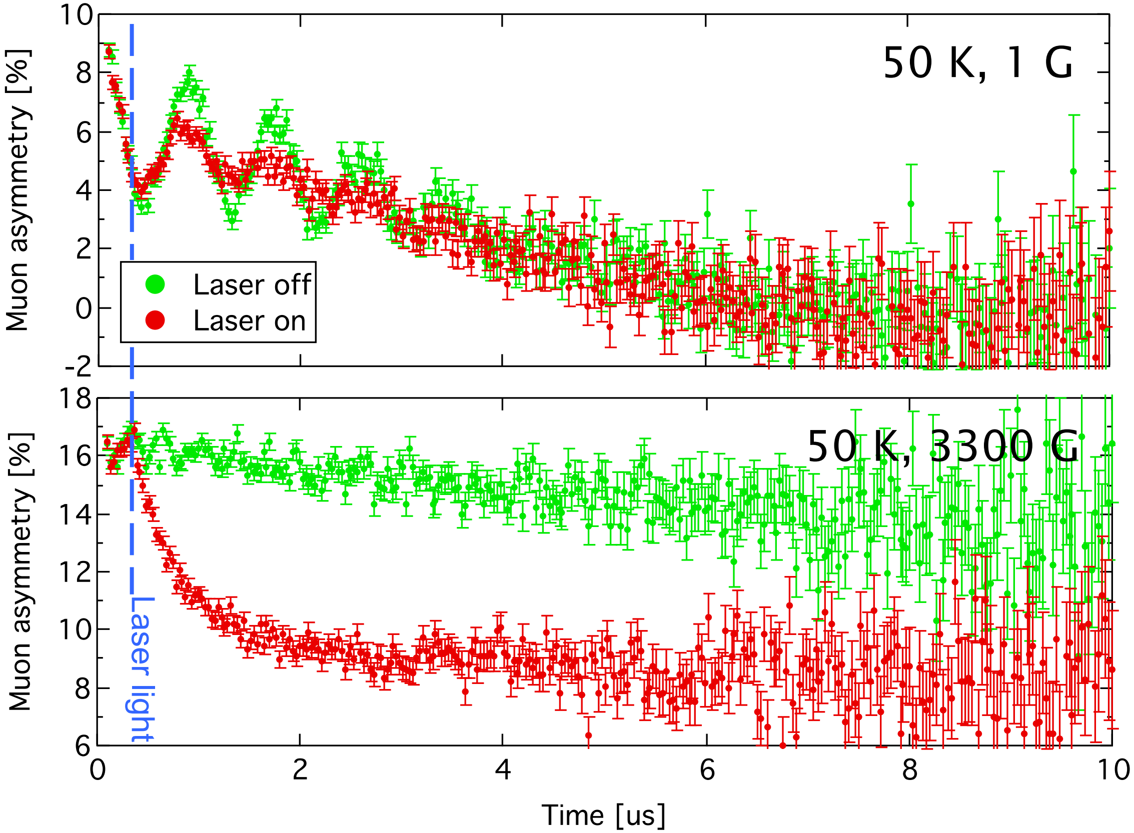
By installing a powerful laser system on to the existing HIFI instrument – the ability to perform muon experiments enhanced by a laser in magnetic fields as high as 5T is not available anywhere else.

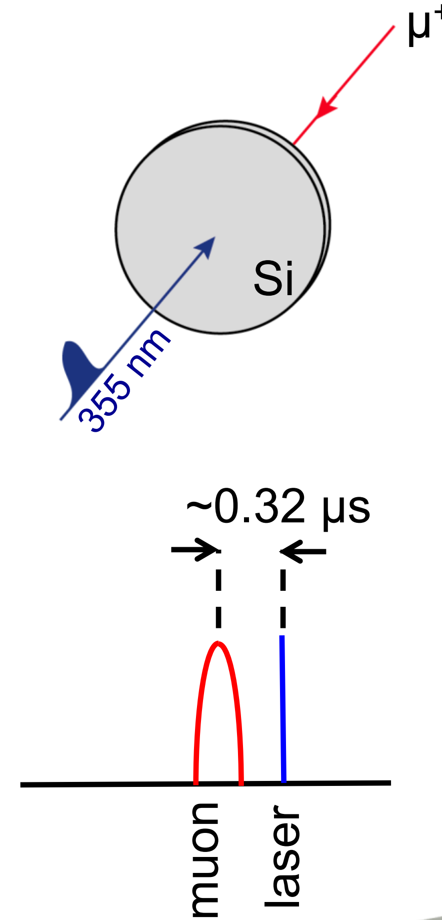
This research has potential impact in fields ranging from green energy production to biology and medicine.

Transport system installed and first beam Dec. First experiments already completed

Commissioning experiment on Silicon

n-type Si: well-studied system





- Site exchange conversion induces relaxation: $Mu_T^0 \rightarrow Mu_{BC}^0$

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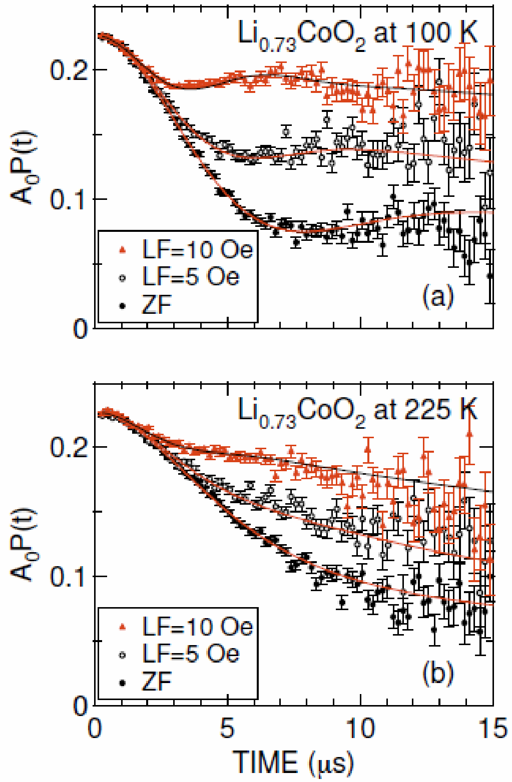
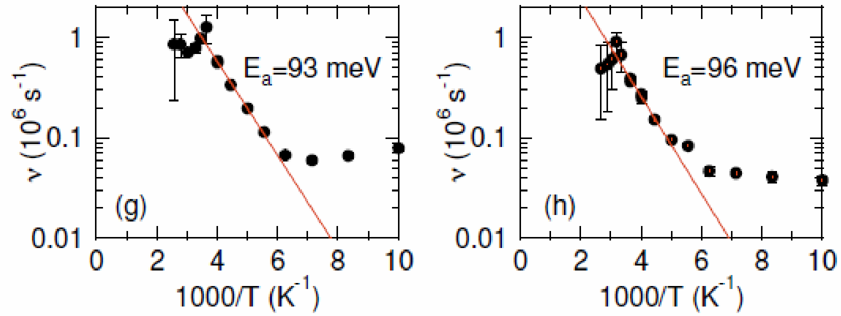
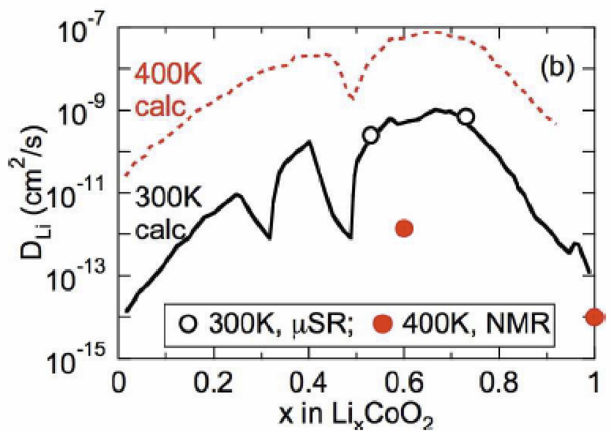
Ionic conduction





Li diffusion constant determined from the fluctuation rate

$$D_{\mathrm{Li}} = \sum_{i=1}^{n} \frac{1}{N_i} Z_{v,i} s_i^2 \nu,$$



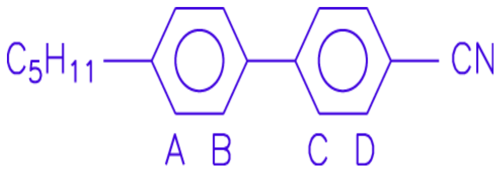
Fit to a dynamic Gaussian KT function

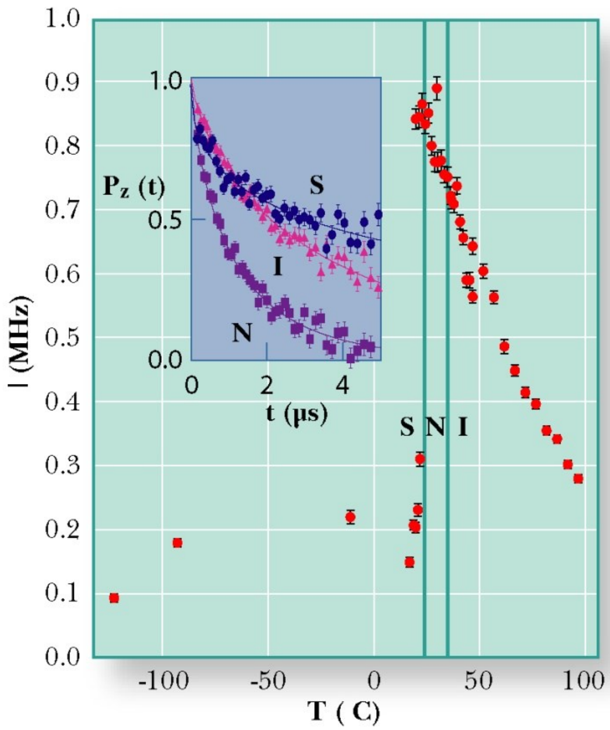
$$A_0 P_{\mathrm{LF}}(t) = A_{\mathrm{KT}} G^{\mathrm{DGKT}}(\Delta, \nu, t, H_{\mathrm{LF}}) + A_{\mathrm{BG}}$$

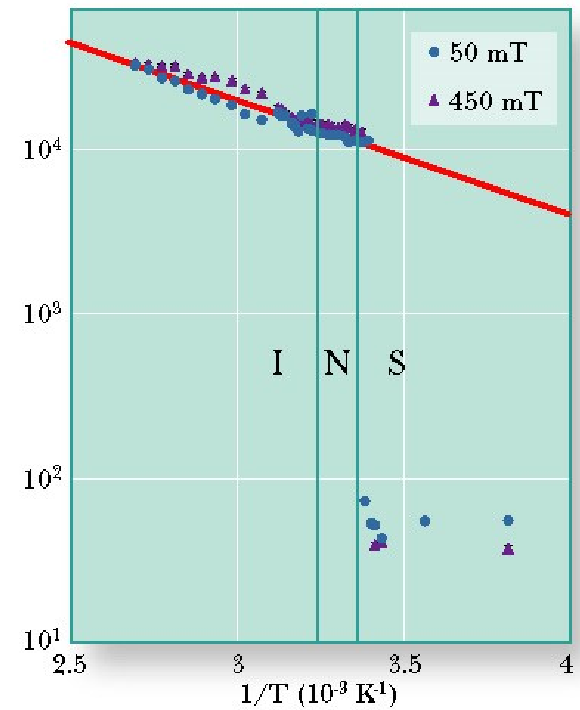
J. Sugiyama, Phys. Rev. Lett. 103, 147601 (2009)

Molecular dynamics

liquid crystal
4'-n-pentyl-4-cyanobiphenyl







- Molecular fluctuation rate extracted from muon depolarisation
- Large increase at solid-nematic phase transition.
- Motion is consistent with rotation of the whole molecule.

Molecular dynamics in a nematic liquid crystal probed by muons; BW Lovett t al, PRB 63 (2000) 054204.

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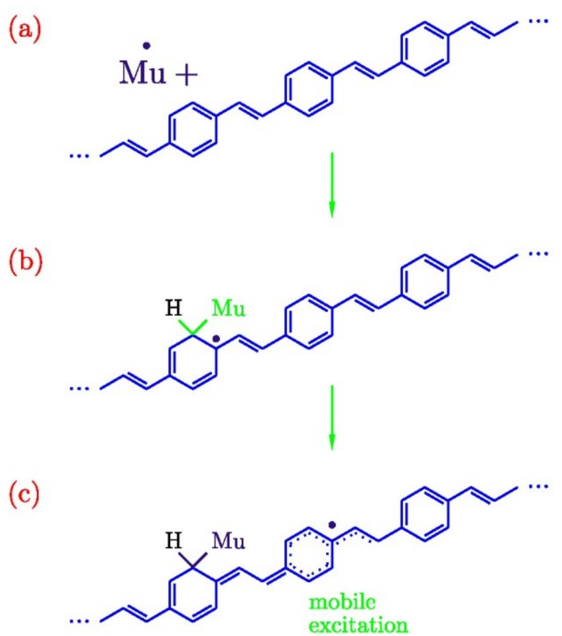
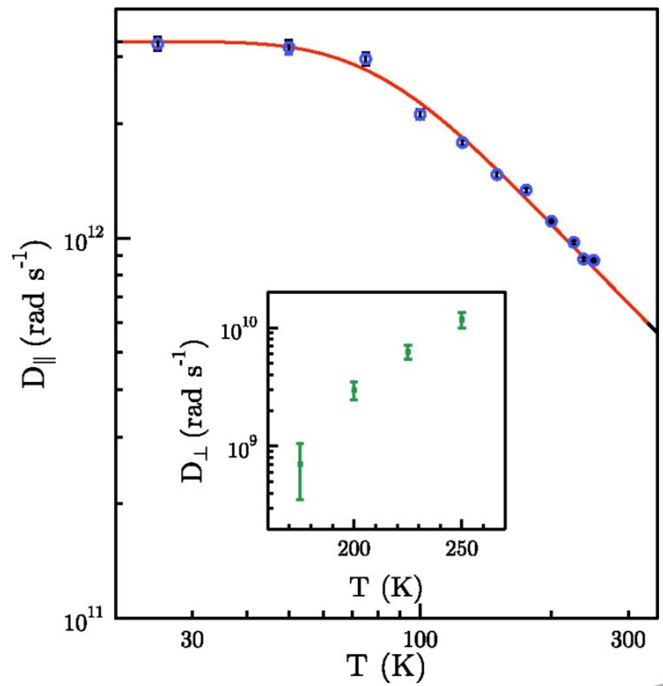
Carrier motion in polymers

Polyphenylvinylene (PPV)



• Polymer LEDs based upon PPV
• muons can study polaron motion in *undoped* polymers; they provide information on intrinsic mobility processes

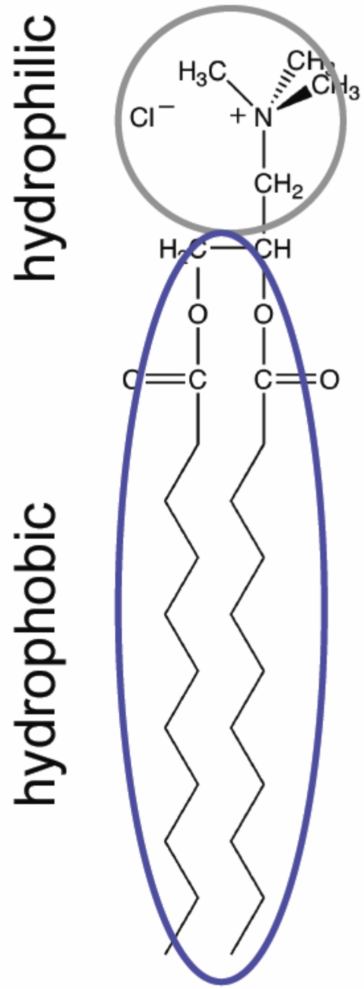


For PPV, *intrachain* diffusion is phonon-limited, metallic-style; *interchain* diffusion is thermally-assisted.

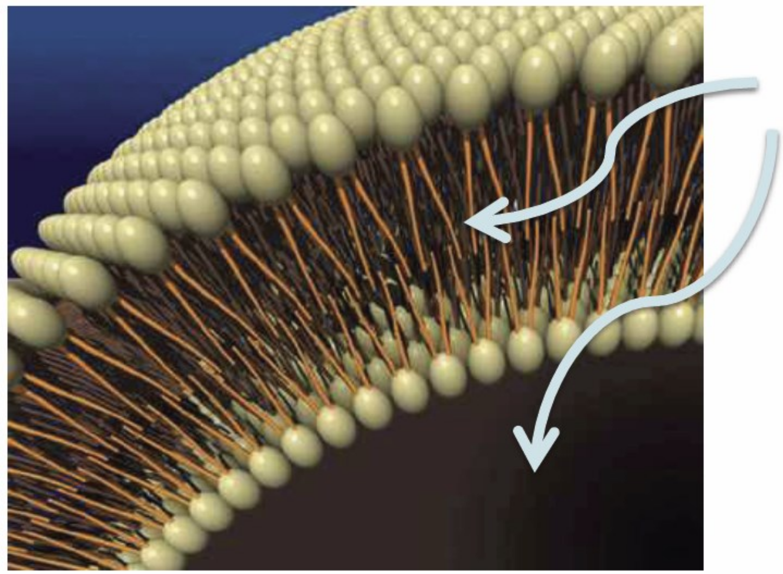
Muon-spin relaxation study of charge carrier dynamics in the conducting polymer PPV, SJ Blundell et al, Synth Met.119 (2001) 205

Partitioning of co-surfactants

Surfactant

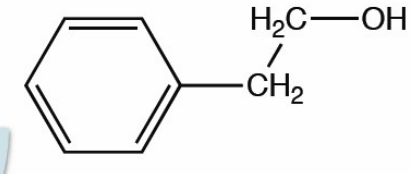


DHTAC



Surfactants can form bilayers, micelles, vesicles, etc.

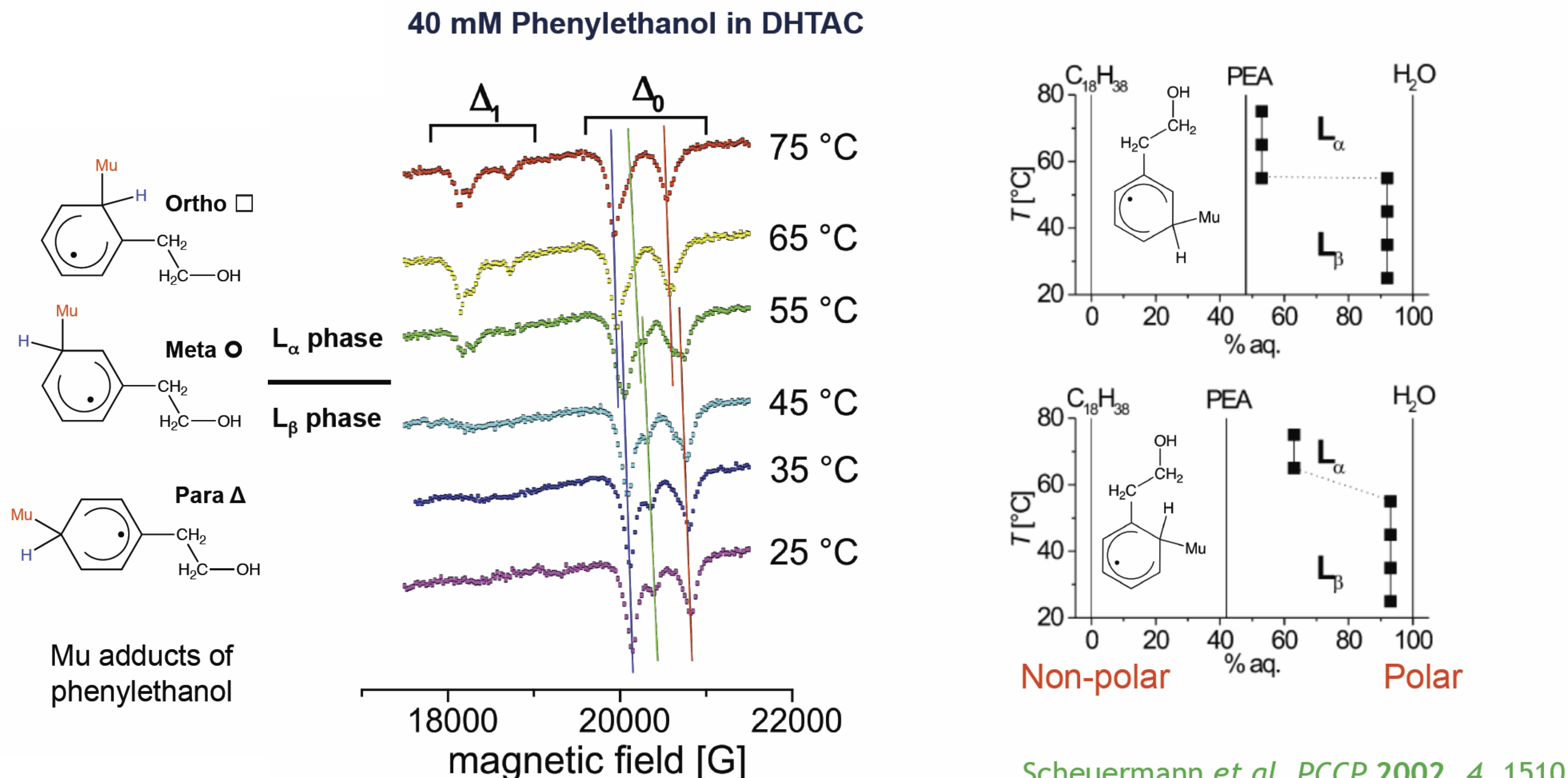
Co-surfactant



2-phenylethanol

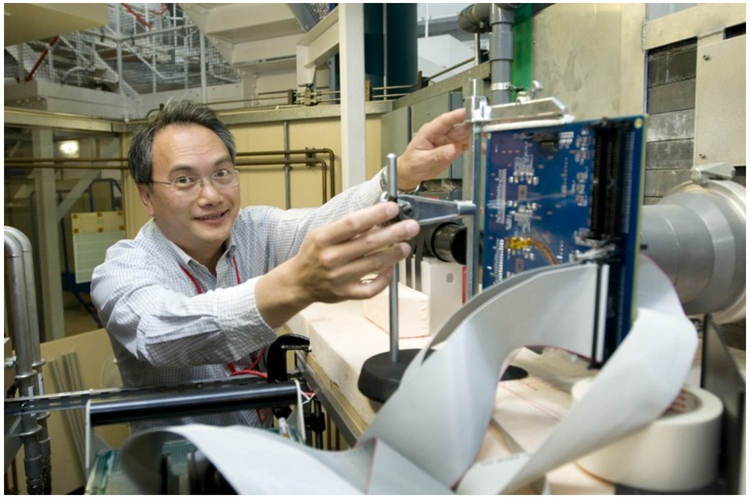
- Fragrances
- Food additives.
- Drug delivery

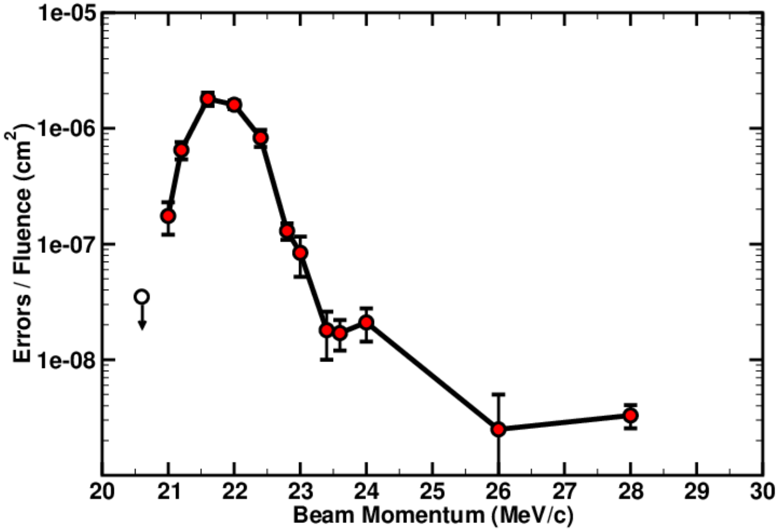
Partitioning of co-surfactants



Scheuermann *et al*. *PCCP* **2002**, *4*, 1510

Muon Electronics Irradiation





- Researchers at Vanderbilt University used RIKEN-RAL facility to investigate effects of muons on state-of-the-art microelectronic memories
- Collaborators from industry including Marvell Semiconductors, Cisco Systems, and Texas Instruments
- Muon-induced data errors clearly observed in multiple devices
- Results will support investigation into error rates of commercial electronics
- Recently tested electronics for CERN

Bias dependence of muon-induced single event upsets in 28 nm static random access memories
Sierawski, B.D. ; et al Reliability Physics Symposium, 2014 IEEE International
DOI: 10.1109/IRPS.2014.6860585 (2014) p 2B.2.1 - 2B.2.5

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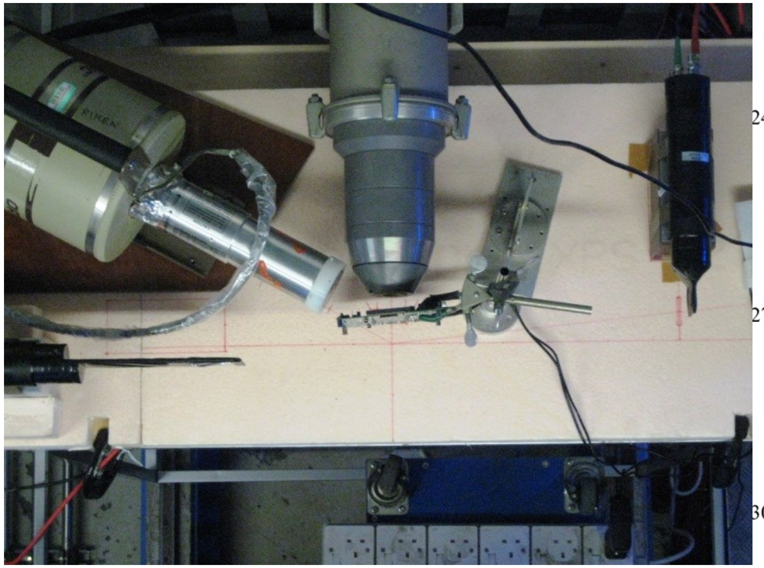
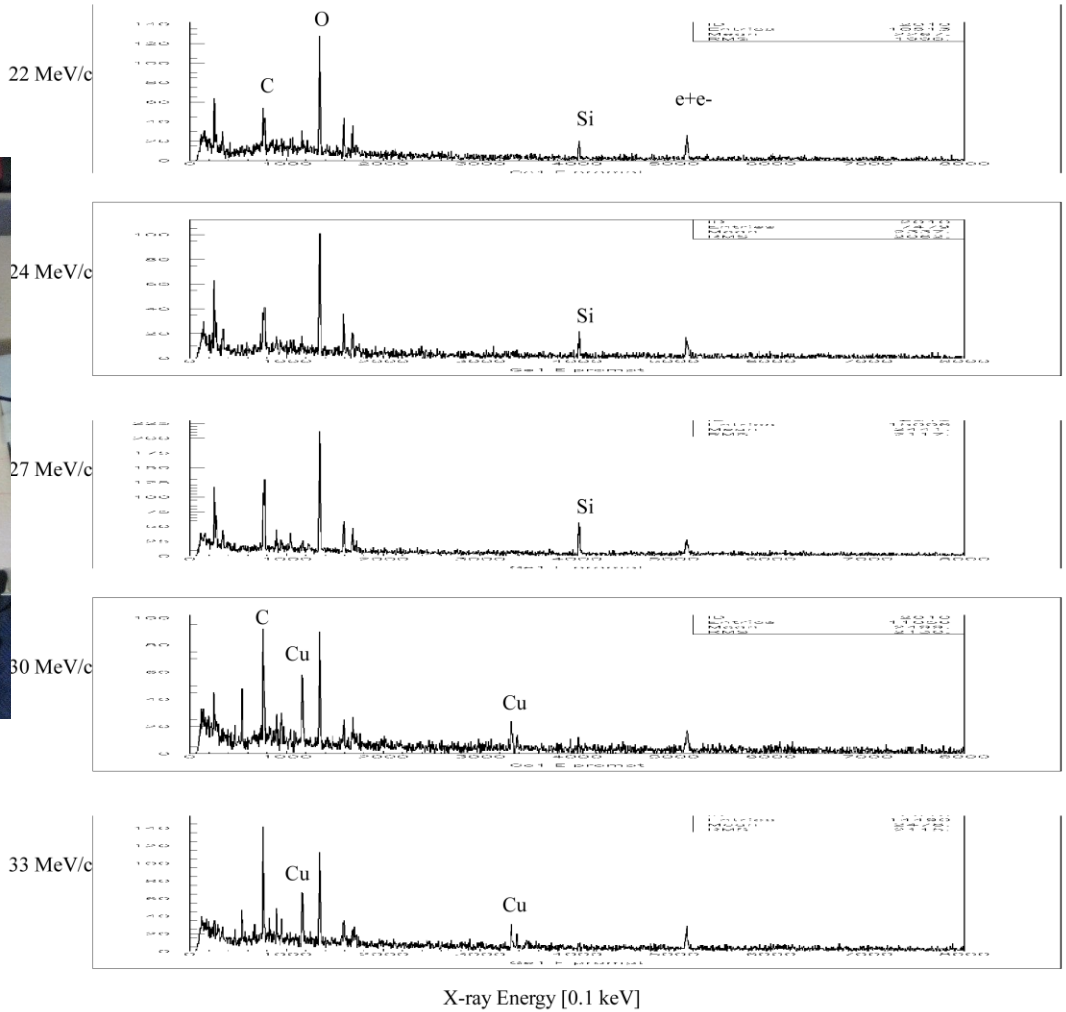
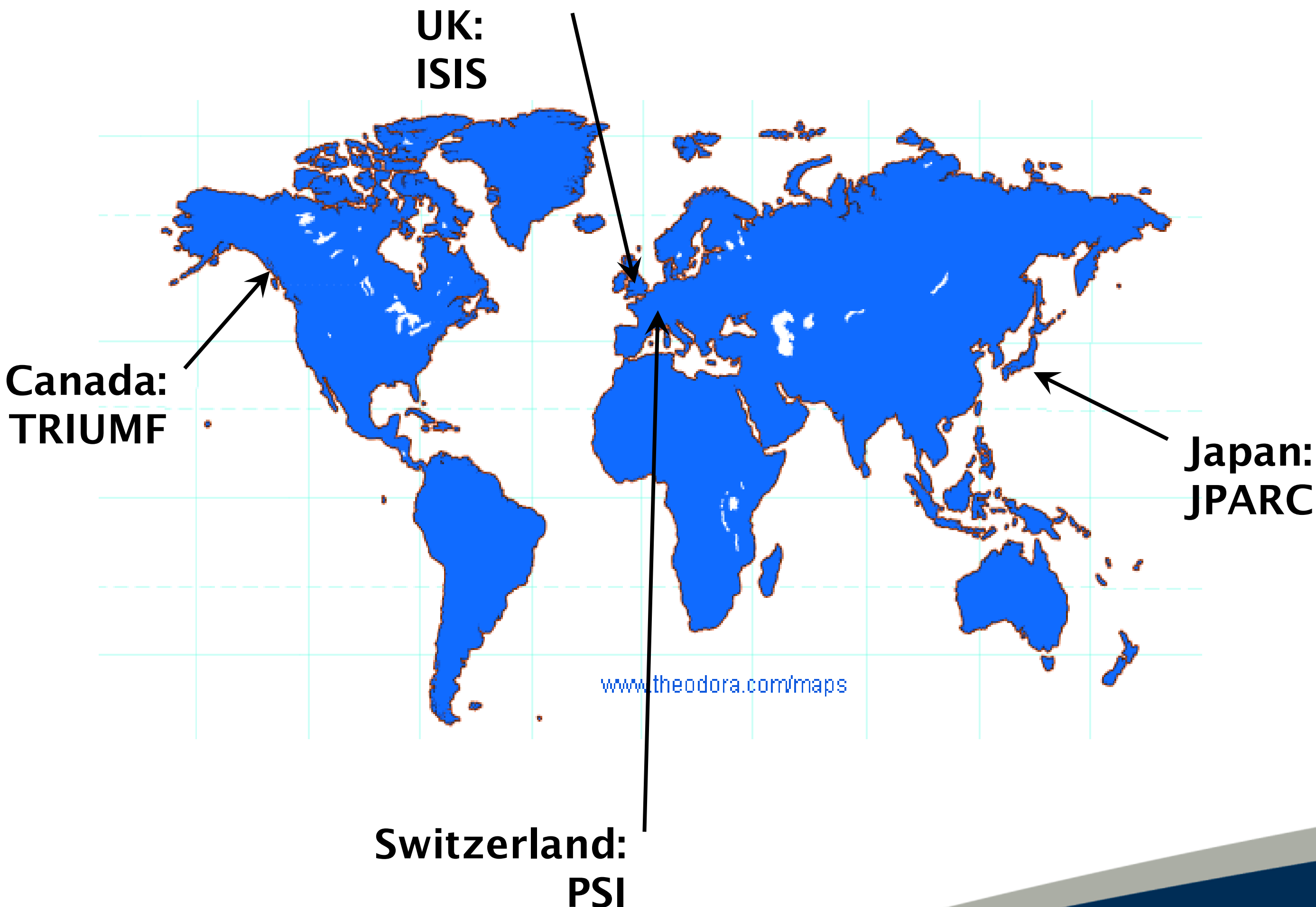
Muon Electronics Irradiation (2)

We can use negative muons finding the active component



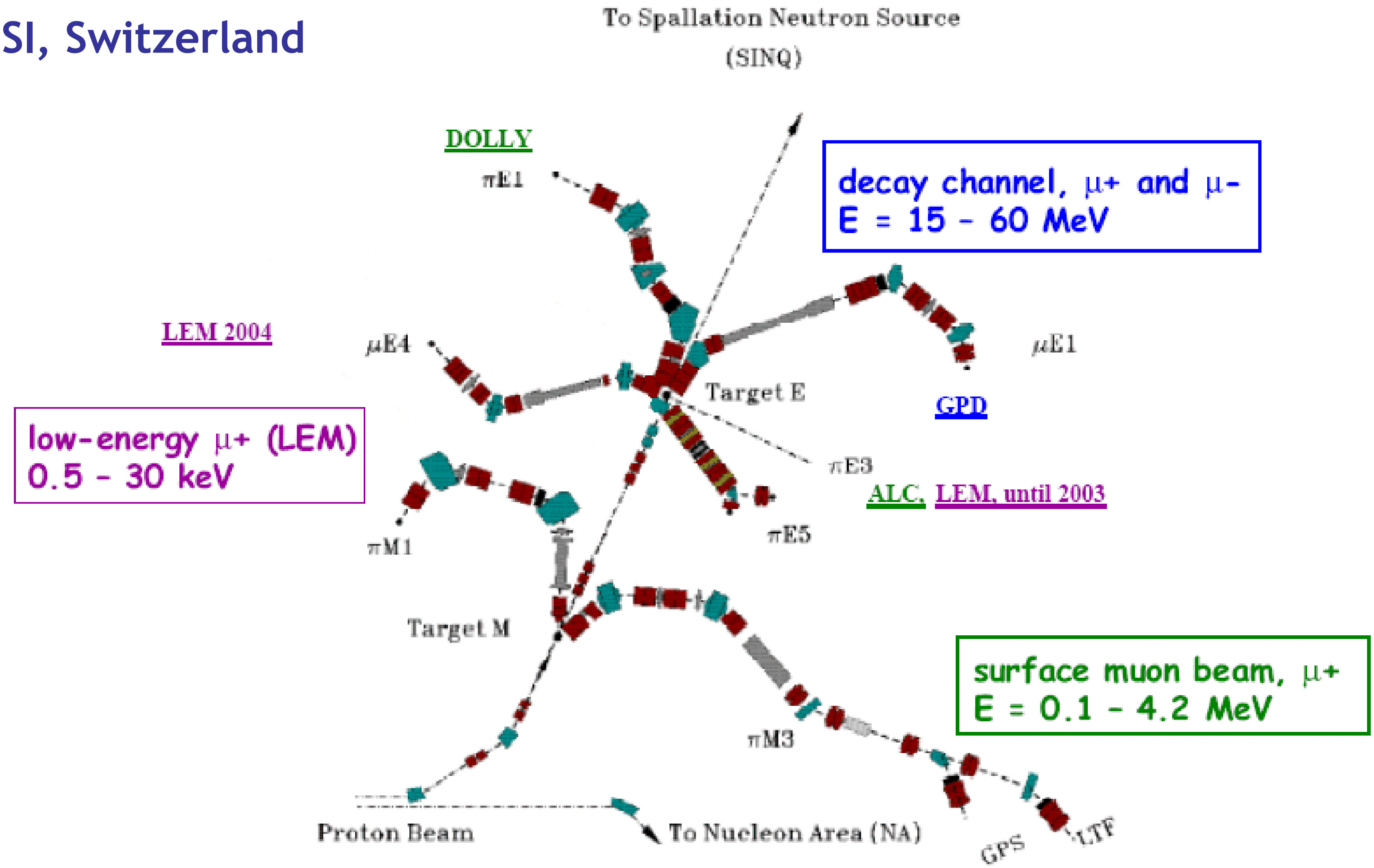


μSR facilities



μSR facilities

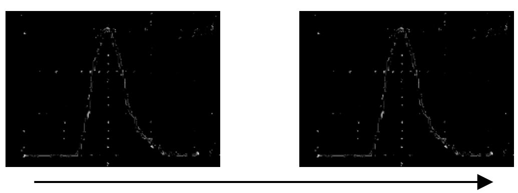
PSI, Switzerland



μSR facilities

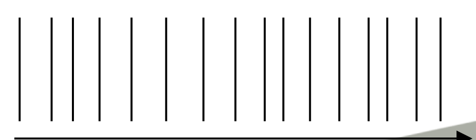
Pulsed (e.g. ISIS, J-PARC)

- Bursts of muons, ~50 Hz
- Low intrinsic background
- Weak relaxations, slow precession
- No fundamental rate limit
- Big detector arrays
- *Pulsed environments*



Continuous (e.g. PSI, TRIUMF)

- Single muons
- Higher intrinsic background
- Fast relaxations, rapid precession
- Data rates limited
- Small, compact detector arrays
- *PSI: low energy muons for surface studies, + pressure*



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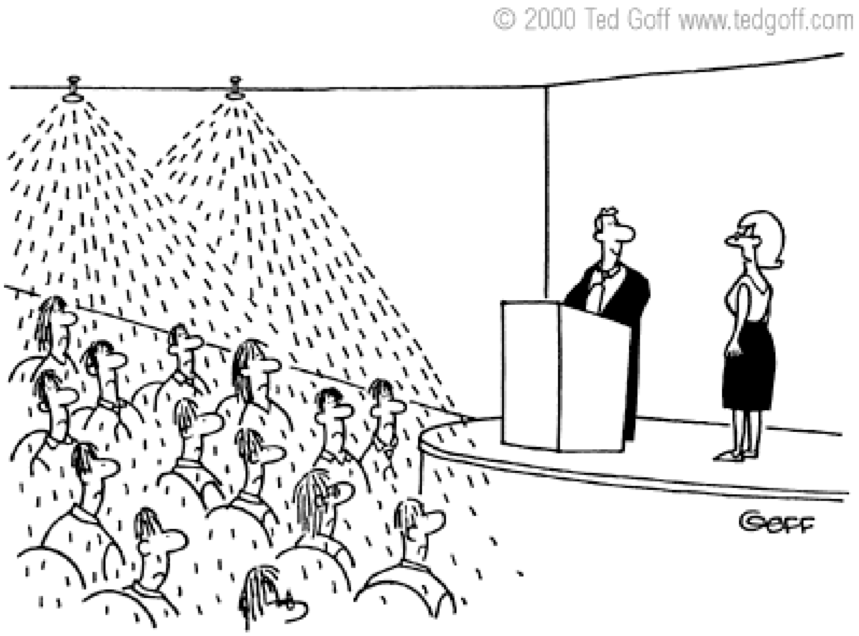
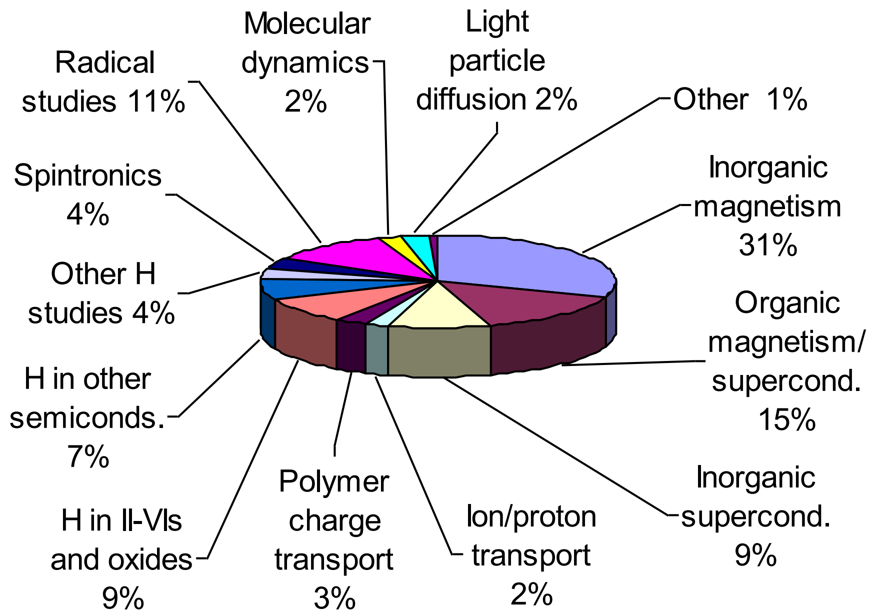
6. Summary



"You're not allowed to use the sprinkler system to keep your audience awake."

MUONS:

- Versatile probes of magnetic, superconducting, molecular systems
- Analogues of protons/hydrogen in semiconductors
- Complementary to other techniques ISIS / PSI / J-PARC all have n and μ facilities
- Around 60 groups from 20 countries using ISIS muons
- Further details:



www.isis.stfc.ac.uk/groups/muons/

Science & Technology Facilities Council ISIS