Introduction to μSR
(muon-spin rotation/relaxation)

Stephen J. Blundell

Clarendon Laboratory, Department of Physics, University Of Oxford, UK

(see S.J. Blundell, Contemp. Phys. **40**, 175 (1999) - also cond-mat/0207699)

Muon training course - 2010

Lecture plan

- Setting muons in their context, which in this case means a historical context!
- Muons were originally mis-identified. An important lesson in the history of science!
  "History always repeats itself; it has to, no-one listens."
- Muons were first studied in cosmic rays; now produced in large accelerators

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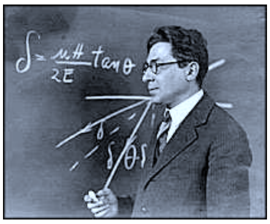
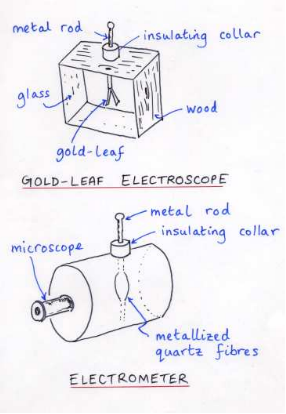
I.I. Rabi (1898-1988) - on the discovery of the muon:

"Who ordered that?"



How to detect ionising radiation

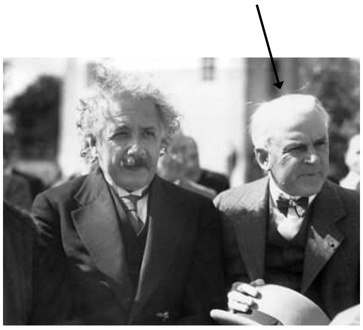


Father Theodor Wulf (Jesuit priest) 1911

Victor F. Hess (1883-1964)

Nobel prize 1936
(balloon flights 1911-1913)

Robert A. Millikan (1868-1953)



Oil drop experiment

founded Caltech

first used the term "cosmic rays"

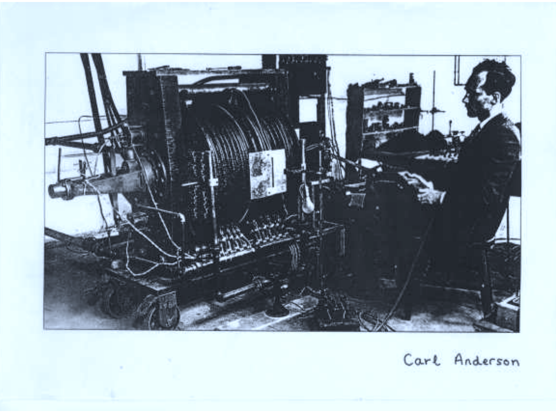
(music of the spheres)

....but to really make progress, you need.....

... a research student!

Robert Millikan
- Nobel Prize 1923

his PhD student:
Carl D. Anderson
- Nobel Prize 1936
(shared with Hess)



Carl D. Anderson
(1905-1991)

discovered positron in 1931

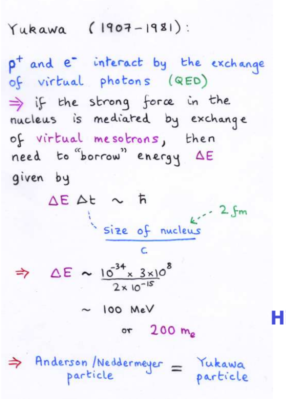
and in 1936
with Seth Neddermeyer
discovered a particle
called

the **MESOTRON**

mass ~ 200 m_e

It is a dangerous thing...

…when experiments agree with theory



Yukawa (1907–1981):

p^+ and e^- interact by the exchange of virtual photons (QED)

⇒ if the strong force in the nucleus is mediated by exchange of virtual mesotrons, then need to "borrow" energy ΔE given by

$$\Delta E \, \Delta t \sim \hbar$$

Δt ⇢ $\frac{\text{size of nucleus}}{c}$ ⇠ 2 fm

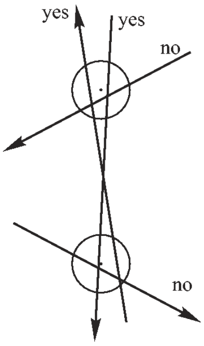
$$\Rightarrow \Delta E \sim \frac{10^{-34} \times 3\times10^{8}}{2\times10^{-15}}$$

$$\sim 100 \text{ MeV}$$

or $200\ m_e$

⇒ Anderson / Neddermeyer particle = Yukawa particle

Hideo Yukawa (1907-1981)
Nobel prize 1949

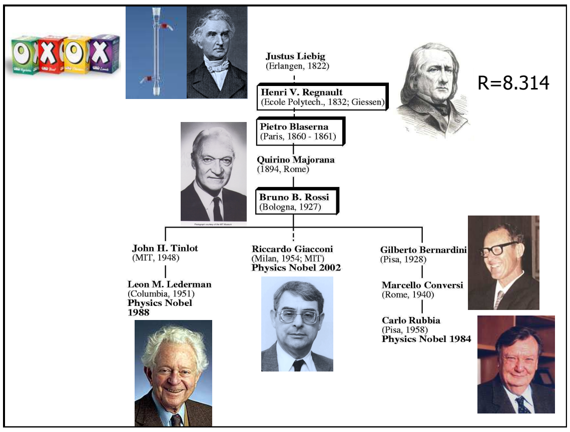


Bruno Rossi

lifetime of "mesotron"= 2.15(7) microseconds (1942)

Marcello Conversi

(1917-1988)



R=8.314

Justus Liebig
(Erlangen, 1822)

Henri V. Regnault
(Ecole Polytech., 1832; Giessen)

Pietro Blaserna
(Paris, 1860 - 1861)

Quirino Majorana
(1894, Rome)

Bruno B. Rossi
(Bologna, 1927)

John H. Tinlot
(MIT, 1948)

Leon M. Lederman
(Columbia, 1951)
Physics Nobel 1988

Riccardo Giacconi
(Milan, 1954; MIT)
Physics Nobel 2002

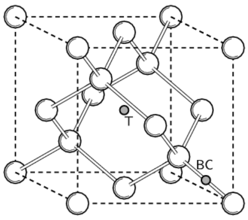
Gilberto Bernardini
(Pisa, 1928)

Marcello Conversi
(Rome, 1940)

Carlo Rubbia
(Pisa, 1958)
Physics Nobel 1984

Muons STOP in a sample

- they do not diffract, or reflect



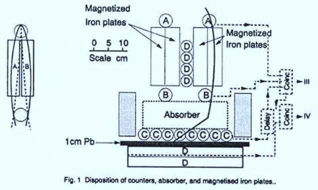
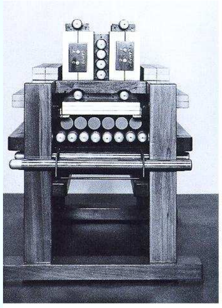


Fig. 1 Disposition of counters, absorber, and magnetised iron plates..
All counters "D" are connected in parallel.

Table 1. Results of measurements on β-decay rates for positive and negative mesons.

Sign	Absorber	III	IV	Hours	M/100 hours
(a) +	5 cm Fe	213	106	155.00'	67± 6.5
(b) -	5 cm Fe	172	158	206.00'	3
(c) -	none	71	69	107.45'	-1
(d) +	4 cm C	170	101	179.20'	36± 4.5
(e) -	4 cm C+5 cm Fe	218	146	243.00'	27± 3.5
(f) +	6.2 cm Fe	128	120	240.00'	0

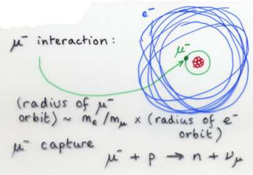


Conversi, Pancini, Piccioni experiments (1947)

Results of the experiment to implant cosmic ray muons in matter and measure their lifetime:

μ^+ in anything	2 μs
μ^- in C	2 μs
μ^- in Pb	0.07 μs

hence, <u>mesotrons (muons) are not interacting strongly enough to be Yukawa's particle!</u>



μ^- interaction:

(radius of μ^- orbit) ~ m_e/m_μ x (radius of e^- orbit)

μ^- capture $\mu^- + p \rightarrow n + \nu_\mu$

Reason for μ^- interaction: μ^- capture $\mu^- + p > n + \nu_\mu$

(radius of μ^- orbit is ~ (m_e/m_μ) x radius of e^- orbit)
so the μ^- occupies an orbit close to the nucleus, and sees the full +Ze charge on nucleus)

Cecil Powell (1903-1969)

1947 - discovered the pion

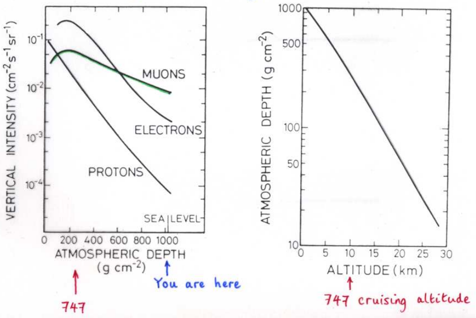
Bristol University

Nobel Prize 1950

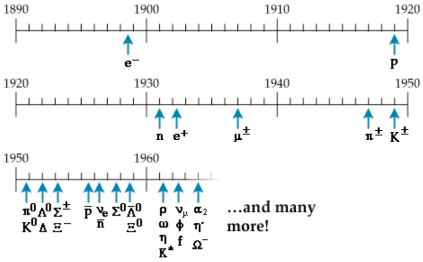
pion mass 139.6 MeV
muon mass 105.7 MeV

Cosmic rays [mostly muons!]

Muons at ground level – average energy 4 GeV
For E > 1 GeV get ~vertically 1 muon cm^{-2} min^{-1}



And particle physics has kept on rolling….



Particle properties

	charge	spin	mass	moment	γ / 2π (MHz T^{-1})	lifetime (μs)
e	$\pm$e	1/2	m_e = 0.51 MeV	657 μ_p	28x10^3	∞
μ	$\pm$e	1/2	207 m_e = 105.7 MeV	3.18 μ_p	135.5	2.19
p	$\pm$e	1/2	1836 m_e = 938 MeV	μ_p	42.6	∞

* Muon beams have 100% spin polarization.
* Samples do not have to be deuterated.

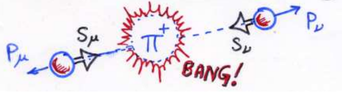
STEP 1:

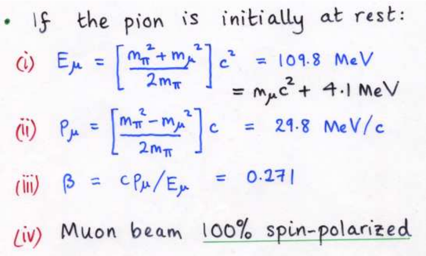
Production of muons

- Pions produced by $p + p \rightarrow \pi^+ + p + n$
- Pion decays in 26 ns

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

- This is a TWO-BODY decay





- If the pion is initially at rest:

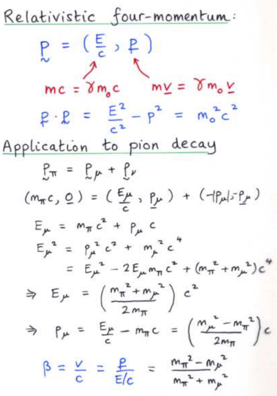
(i) $E_\mu = \left[\frac{m_\pi^2 + m_\mu^2}{2m_\pi}\right] c^2 = 109.8$ MeV $= m_\mu c^2 + 4.1$ MeV

(ii) $p_\mu = \left[\frac{m_\pi^2 - m_\mu^2}{2m_\pi}\right] c = 29.8$ MeV/c

(iii) $\beta = cp_\mu / E_\mu = 0.271$

(iv) Muon beam 100% spin-polarized

Derivation:



Relativistic four-momentum:

$$\underset{\sim}{p} = \left(\frac{E}{c}, \underline{p}\right)$$

$$mc = \gamma m_0 c \qquad m\underline{v} = \gamma m_0 \underline{v}$$

$$\underset{\sim}{p} \cdot \underset{\sim}{p} = \frac{E^2}{c^2} - p^2 = m_0^2 c^2$$

Application to pion decay

$$\underset{\sim}{p}_\pi = \underset{\sim}{p}_\mu + \underset{\sim}{p}_\nu$$

$$(m_\pi c, \underline{0}) = \left(\frac{E_\mu}{c}, \underline{p}_\mu\right) + (-|p_\mu|, -\underline{p}_\mu)$$

$$E_\mu = m_\pi c^2 + p_\mu c$$

$$E_\mu^2 = p_\mu^2 c^2 + m_\mu^2 c^4$$

$$= E_\mu^2 - 2E_\mu m_\pi c^2 + (m_\pi^2 + m_\mu^2) c^4$$

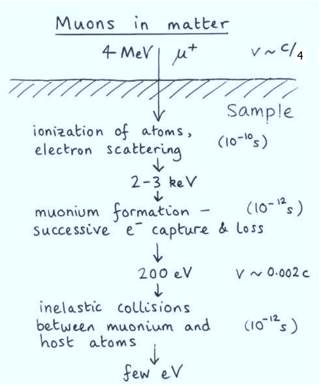
$$\Rightarrow E_\mu = \left(\frac{m_\pi^2 + m_\mu^2}{2m_\pi}\right) c^2$$

$$\Rightarrow p_\mu = \frac{E_\mu}{c} - m_\pi c = \left(\frac{m_\mu^2 - m_\pi^2}{2m_\pi}\right) c$$

$$\beta = \frac{v}{c} = \frac{p}{E/c} = \frac{m_\pi^2 - m_\mu^2}{m_\pi^2 + m_\mu^2}$$

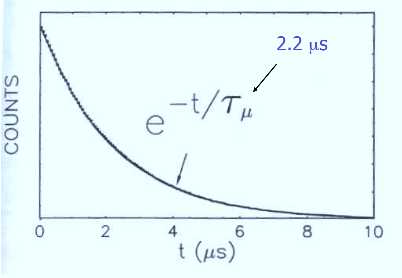
STEP 2:

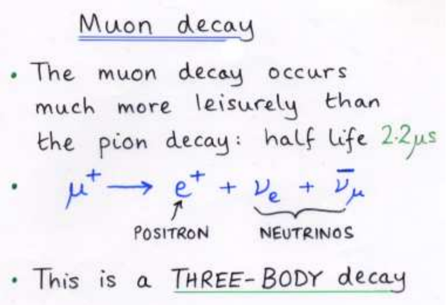
implantation



Muons in matter

STEP 3: decay

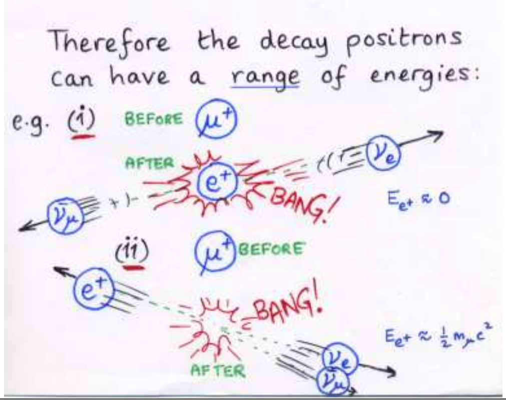




Muon decay

- The muon decay occurs much more leisurely than the pion decay: half life 2.2μs
- $\mu^+ \longrightarrow e^+ + \underbrace{\nu_e + \bar{\nu}_\mu}_{\text{NEUTRINOS}}$

- This is a THREE-BODY decay



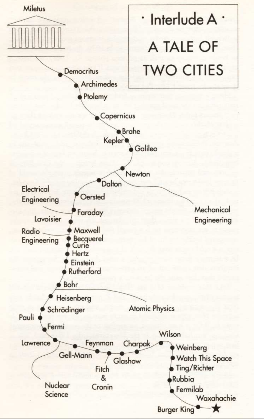
Therefore the decay positrons can have a range of energies:

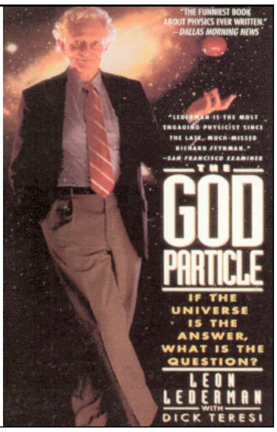
e.g. (i)

(ii)

Richard L. Garwin

Leon Lederman





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)

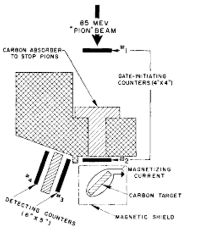
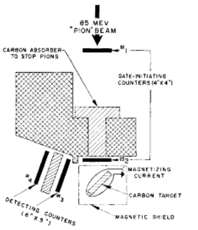


FIG. 1. Experimental arrangement. The magnetizing coil was close wound directly on the carbon to provide a uniform vertical field of 79 gauss per ampere.

"How we violated parity in a weekend .. and discovered God"



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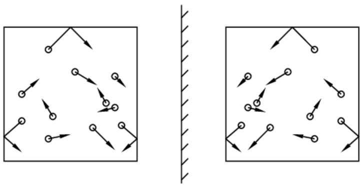
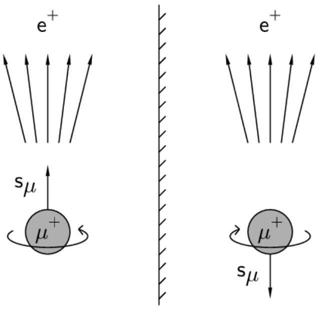
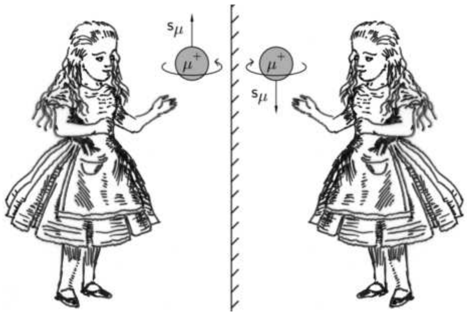




"I cannot believe God is a weak left-hander"

Wolfgang Pauli
(1900–1958)



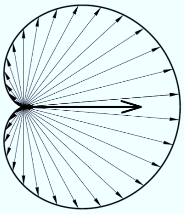
Muon decay

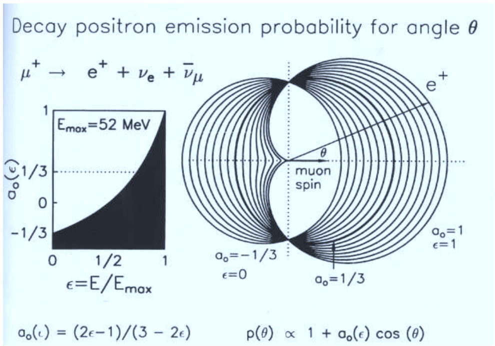
Muon decays into a positron:

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

MUON POSITRON NEUTRINOS

Positron decay is asymmetric with respect to the initial muon-spin polarization because of parity violation (weak interaction)

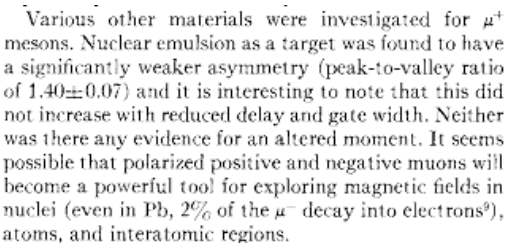




Decay positron emission probability for angle θ

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

$a_0(\epsilon) = (2\epsilon-1)/(3-2\epsilon)$ $p(\theta) \propto 1 + a_0(\epsilon)\cos(\theta)$



Various other materials were investigated for μ^+ mesons. Nuclear emulsion as a target was found to have a significantly weaker asymmetry (peak-to-valley ratio of 1.40±0.07) and it is interesting to note that this did not increase with reduced delay and gate width. Neither was there any evidence for an altered moment. It seems possible that polarized positive and negative muons will become a powerful tool for exploring magnetic fields in nuclei (even in Pb, 2% of the μ^- decay into electrons[9]), atoms, and interatomic regions.

Garwin, Lederman and Weinrich, Physical Review, 1957

Spin-precession frequencies

magnetic moment

$$\boxed{\underline{\mu} = \gamma\, \underline{J}}$$

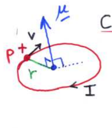
angular momentum

gyromagnetic ratio

g-value

$$\gamma = \frac{g\mu_N}{\hbar}$$

nuclear magneton



Classically:

$$I = e\frac{v}{2\pi r}$$

$$\Rightarrow \mu = \frac{I}{\pi r^2} = \boxed{\frac{e}{2m_p}}\, \overset{m_p v r}{J}$$

γ

Nuclear magneton

$\mu_N = e\hbar/2m_p = 5.05\times10^{-27}\ JT^{-1}$

Bohr magneton

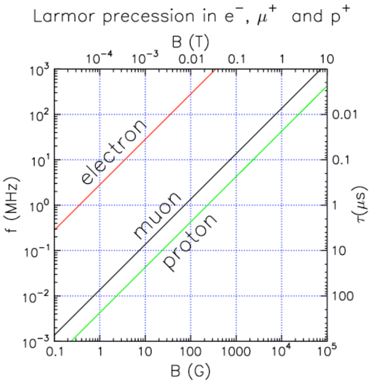
$\mu_B = e\hbar/2m_e = 9.27\times10^{-24}\ JT^{-1}$

	g	$J/\hbar$	μ	$\gamma/2\pi$
PROTON	5.5883	1/2	$2.793\mu_N$	42.8 $MHz\,T^{-1}$
ELECTRON	2.00	1/2	$-\mu_B$	28.1 $GHz\,T^{-1}$
MUON	2.00	1/2	$8.9\mu_N$	136 $MHz\,T^{-1}$

$\omega_e=\gamma_e B_e$

$\omega_\mu=\gamma_\mu B_\mu$

$\omega_p=\gamma_p B_p$


Larmor precession in e^-, μ^+ and p^+

Muon production and decay

- Muons produced via pion decay:

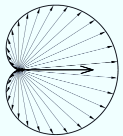
$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

PION MUON NEUTRINO

- Muons 100% spin polarized, speed~*c*/4, K.E.~4 MeV.
- Muon decays into a positron:

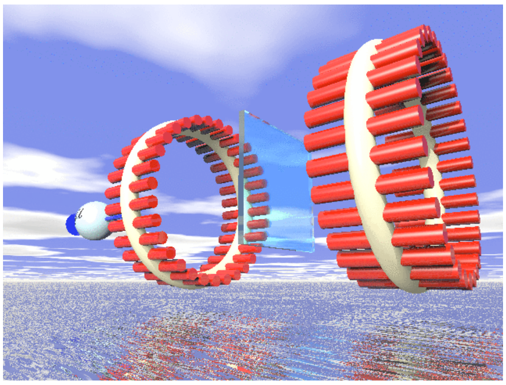
$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

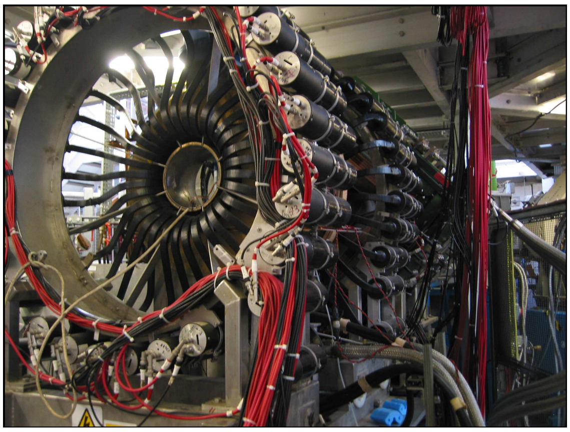
MUON POSITRON NEUTRINOS



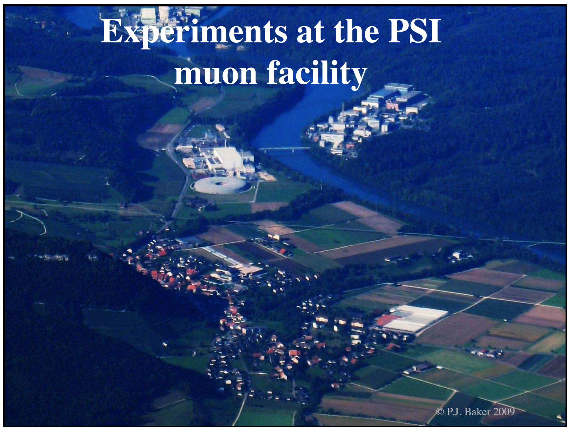
- Positron decay is asymmetric with respect to the initial muon-spin polarization because of parity violation (weak interaction)

(see S.J. Blundell, Contemp. Phys. **40**, 175 (1999))





Experiments at the ISIS muon facility



Experiments at the PSI muon facility

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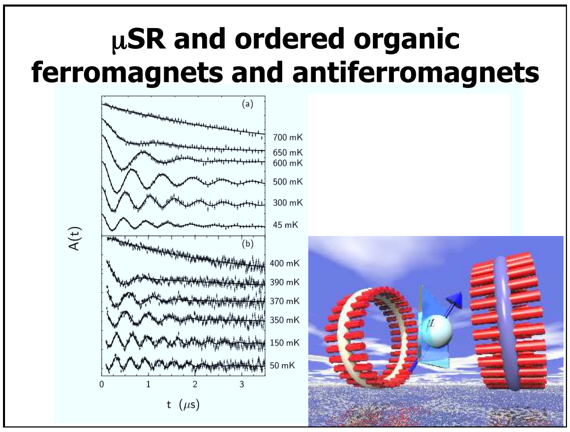
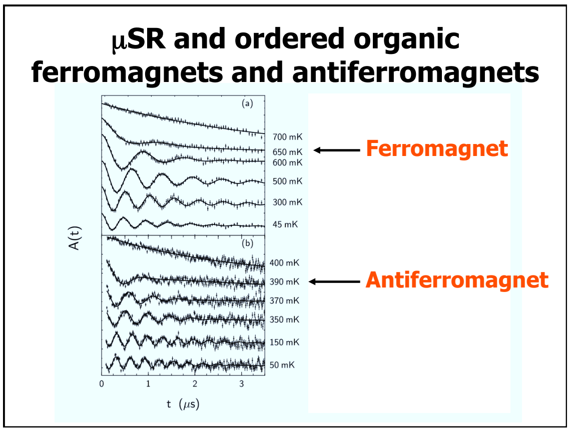


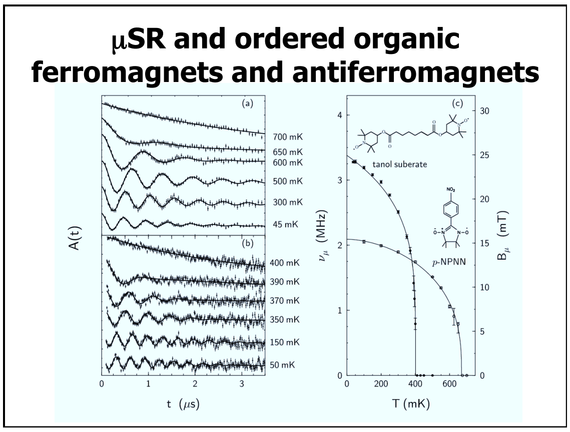
μSR and ordered organic ferromagnets and antiferromagnets



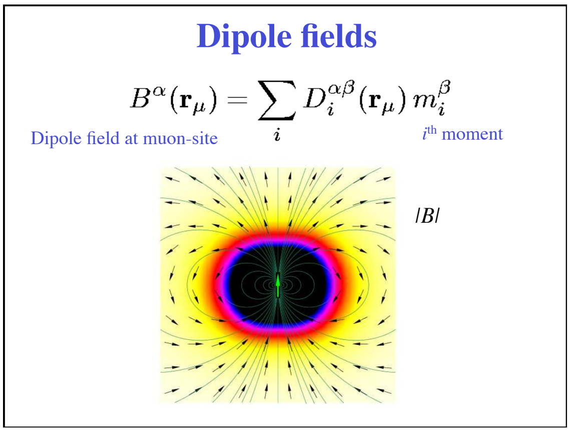
μSR and ordered organic ferromagnets and antiferromagnets

Ferromagnet

Antiferromagnet



μSR and ordered organic ferromagnets and antiferromagnets

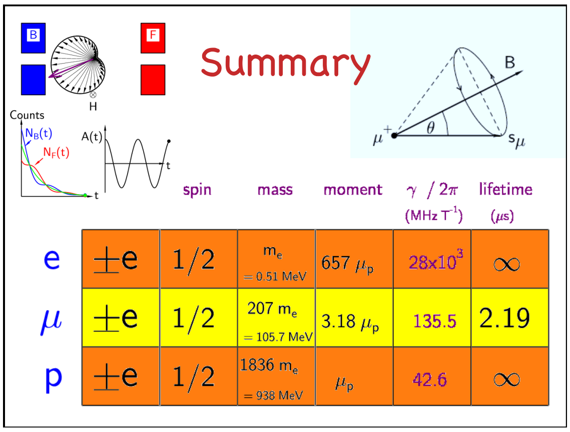


Dipole fields

$$B^\alpha(\mathbf{r}_\mu) = \sum_i D_i^{\alpha\beta}(\mathbf{r}_\mu)\, m_i^\beta$$

Dipole field at muon-site

i^{th} moment



Summary

		spin	mass	moment	$\gamma\ /\ 2\pi$ (MHz T^{-1})	lifetime (μs)
e	±e	1/2	m_e = 0.51 MeV	657 μ_p	$28\text{x}10^3$	∞
μ	±e	1/2	207 m_e = 105.7 MeV	3.18 μ_p	135.5	2.19
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