Introduction to μSR (muon-spin rotation/relaxation)

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

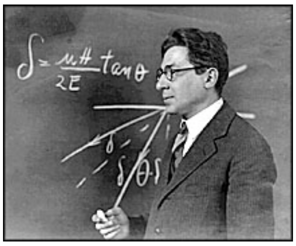
Muon training course - 2008

Lecture plan

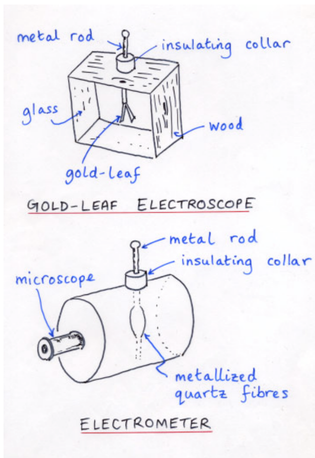
- Setting muons in their context, which in this case means a historical context!
- Muons were originally mis-identified. An important lesson in the history of science!
  "History always repeats itself; it has to, no-one listens."
- Muons were first studied in cosmic rays; now produced in large accelerators

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

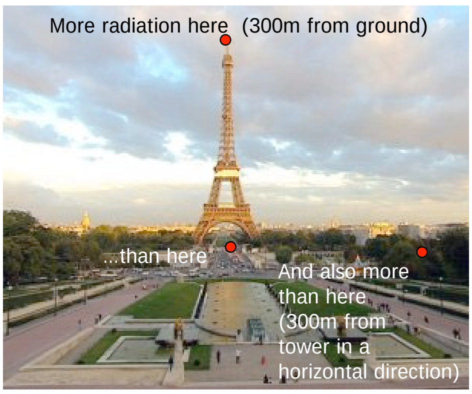
"Who ordered that?"



How to detect ionising radiation

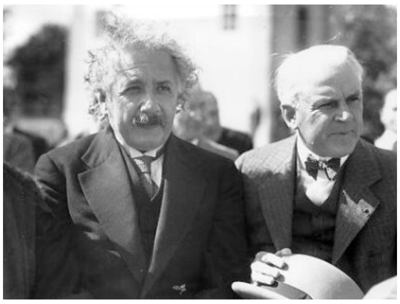


Father Theodor Wulf (Jesuit priest) 1911

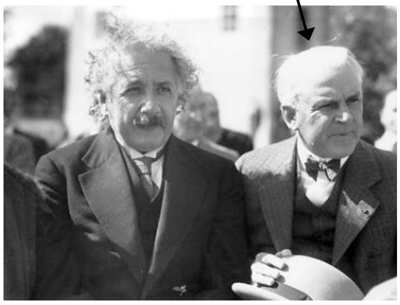


Victor F. Hess (1883-1964)

Nobel prize 1936
(balloon flights 1911-1913)



Robert A. Millikan (1868-1953)



Oil drop experiment

founded Caltech

first used the term “cosmic rays”

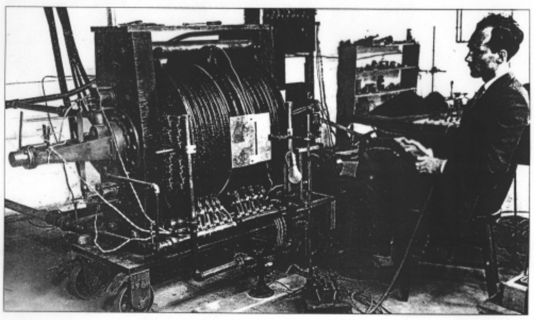
(music of the spheres)

....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 Anderson

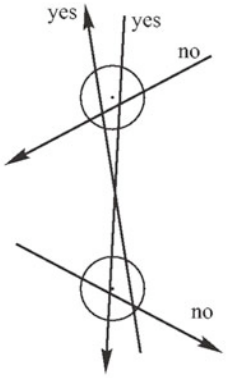
Carl D. Anderson
(1905-1991)

discovered positron in 1931

and in 1936
with Seth Neddermeyer
discovered a particle
called

the **MESOTRON**

mass ~ 200 m_e



Bruno Rossi

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

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

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

$$\Delta t = \frac{\text{size of nucleus}}{c} \qquad \text{size of nucleus} \approx 2\,\text{fm}$$

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

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

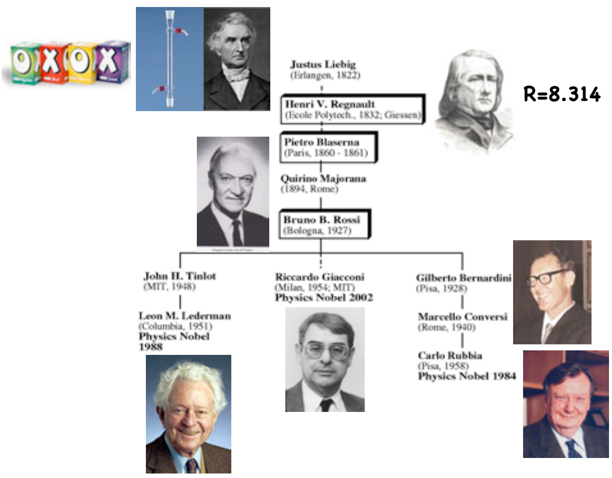
or $200\, m_e$

⇒ Anderson/Neddermeyer particle = Yukawa particle

Hideo Yukawa (1907-1981)
Nobel prize 1949

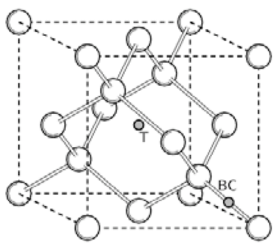
Marcello Conversi

(1917-1988)



R=8.314

Muons STOP in a sample
- they do not diffract, or reflect



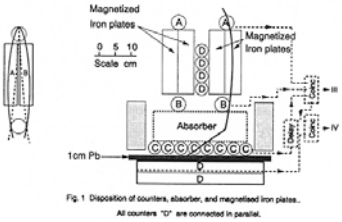


Fig. 1 Disposition of counters, absorber, and magnetised iron plates.. All counters "D" are connected in parallel.

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, mesotrons (muons) are not interacting strongly enough to be Yukawa's particle!

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

The method appeared so simple that "even a theoretician might be able to do it." (Heitler to Powell, 1937)

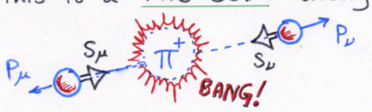
STEP 1:

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:

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

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

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

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

4 MeV μ^+ $v \sim c/4$

Sample

ionization of atoms, electron scattering (10^{-10}s)

↓

2-3 keV

↓

muonium formation – successive e^- capture & loss (10^{-12}s)

↓

200 eV $v \sim 0.002c$

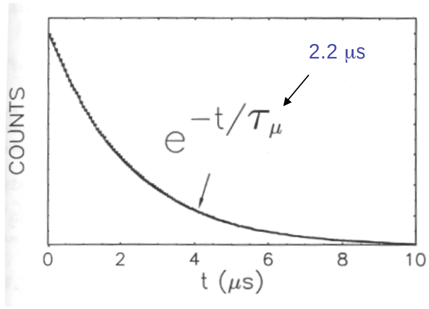
↓

inelastic collisions between muonium and host atoms (10^{-12}s)

↓

few eV

STEP 3: decay



Muon decay

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

  e^+: POSITRON
- This is a THREE-BODY decay

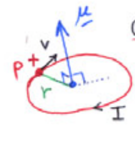
Spin-precession frequencies

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

magnetic moment (μ), angular momentum (J), gyromagnetic ratio (γ)

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

g-value (g), nuclear magneton (μ_N)



Classically:

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

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

$\frac{e}{2m_p}$: γ

Nuclear magneton

$$\mu_N = e\hbar/2m_p = 5.05 \times 10^{-27}\ \mathrm{J\,T^{-1}}$$

Bohr magneton

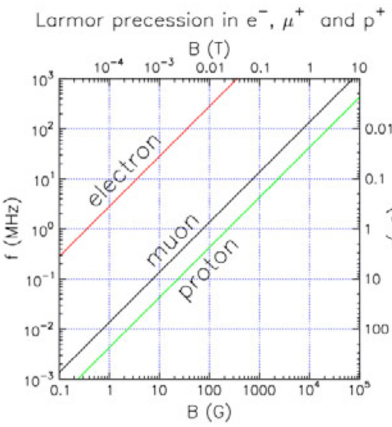
$$\mu_B = e\hbar/2m_e = 9.27 \times 10^{-24}\ \mathrm{J\,T^{-1}}$$

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

$$\omega_e = \gamma_e B_e$$

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

$$\omega_p = \gamma_p B_p$$



In the presence of magnetic order, muons sense the internal magnetic field in a material, measured at the muon stopping site.

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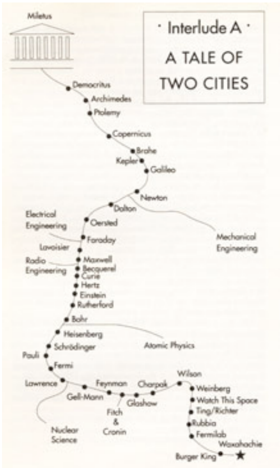
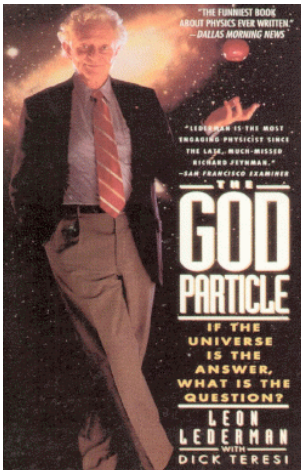
The muon spin precession frequency, $\omega_\mu=2\pi\nu_\mu$, is given by

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

This allows us to follow the temperature dependence of the magnetic order.

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)

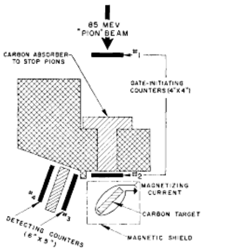
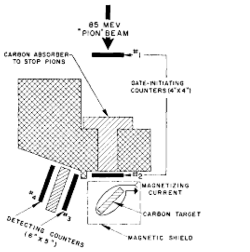


Fig. 1. Experimental arrangement. The magnetizing coil was close wound directly on the carbon to provide a uniform vertical field of 79 gauss per ampere.

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



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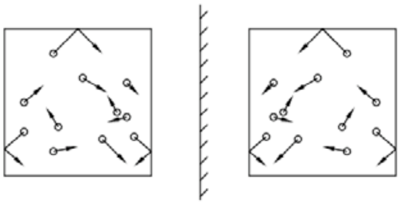
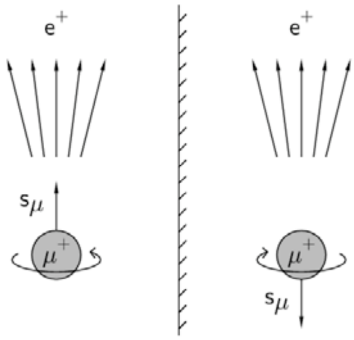
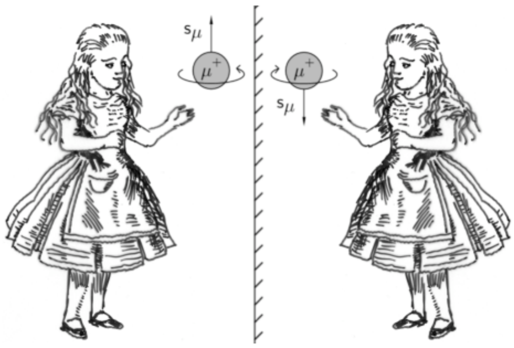
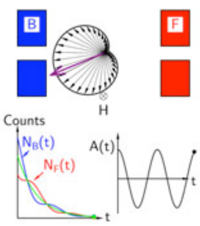




"I cannot believe God is a weak left-hander"

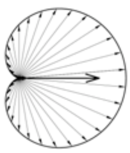
Wolfgang Pauli (1900-1958)





Muon decays into a positron:

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



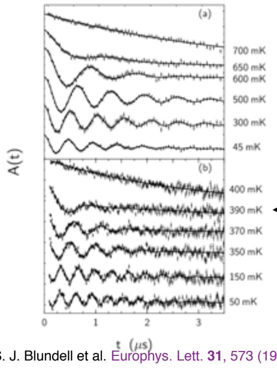
Positron decay is asymmetric with respect to the initial muon-spin polarization because of parity violation (weak interaction)

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

	charge	spin	mass	moment	$\gamma / 2\pi$ (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	∞

The lab

μSR and ordered organic ferromagnets and antiferromagnets

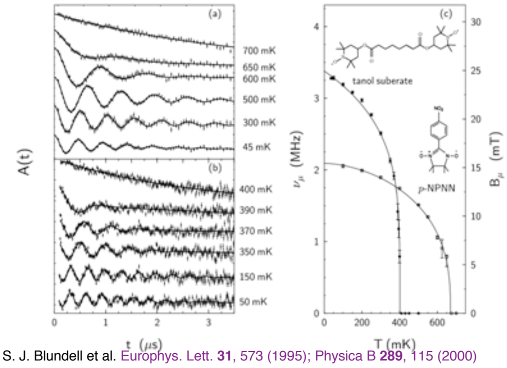


Ferromagnet

Antiferromagnet

S. J. Blundell et al. Europhys. Lett. **31**, 573 (1995); Physica B **289**, 115 (2000)

μSR and ordered organic ferromagnets and antiferromagnets



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Why muons?

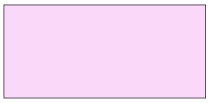
Susceptibility is a bulk measurement
measures "volume-averaged" magnetic properties.

$$\chi = \lim_{\delta H \to 0} \frac{\delta M_{\rm av}}{\delta H} \qquad M_{\rm av} = \frac{1}{V}\int_V M \, {\rm d}V$$

Muon-spin rotation is a local measurement
measures magnetic properties at a local level

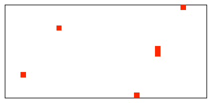
$$\omega_\mu = \frac{B_\mu}{\gamma_\mu} \qquad B_\mu \propto M \qquad p(M) \Longrightarrow p(B_\mu)$$

Uniformly weakly magnetic



or

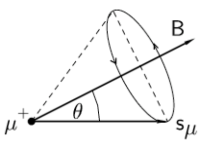
Non-magnetic, with strongly magnetic impurities



Susceptibility gives average information and therefore can give the same response for the situations sketched above (hence many false claims of room temperature organic ferromagnetism...)

μSR gives local information and therefore can distinguish between these two situations.

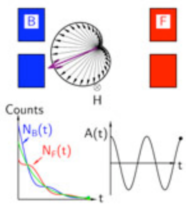
Muon spin precession

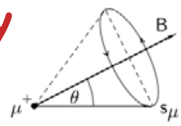


$$P_z(t) = \cos^2\theta + \sin^2\theta \cos(\gamma_\mu |B| t)$$

$|B|$ is the *modulus* of the local dipolar field

Summary





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