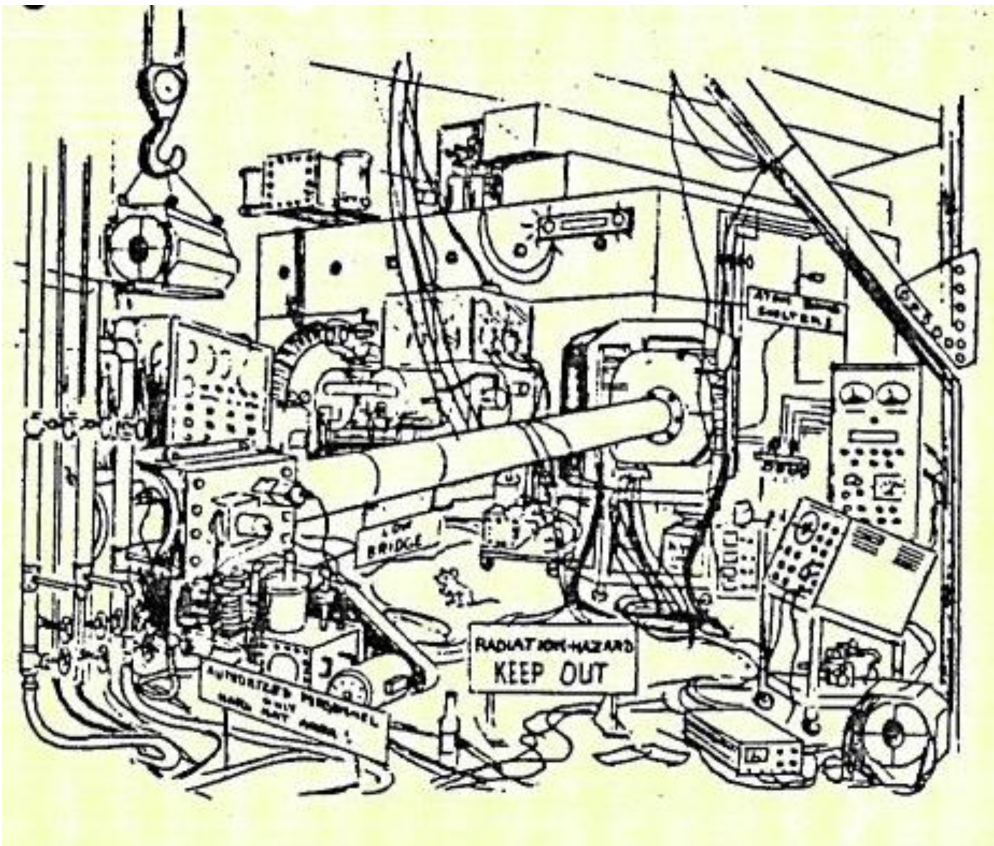
Anything protons do, muons do better – a short history of μSR



THE CYCLOTRON AS SEEN BY THE VISITOR

Steve Cox
ISIS (retired…)

Anything protons do, muons do better – a short history of μSR

Coulomb
1780!

1890	1900	1910	1920	1930

radioactivity
electrometers

cosmic rays

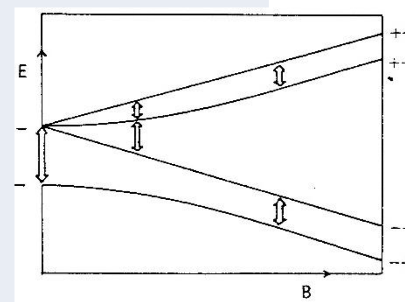
cloud chambers

nuclear atom…

electron 1897

proton 1919

1931 Breit-Rabi



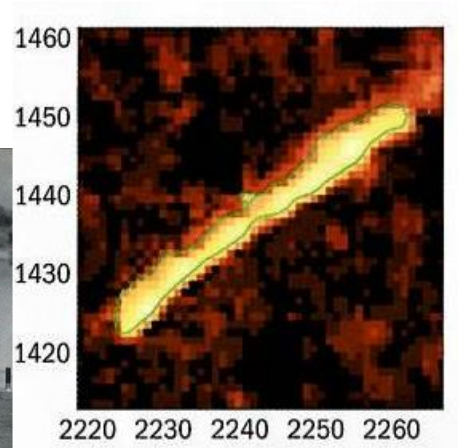
Dirac's antimatter 1928

positron 1932

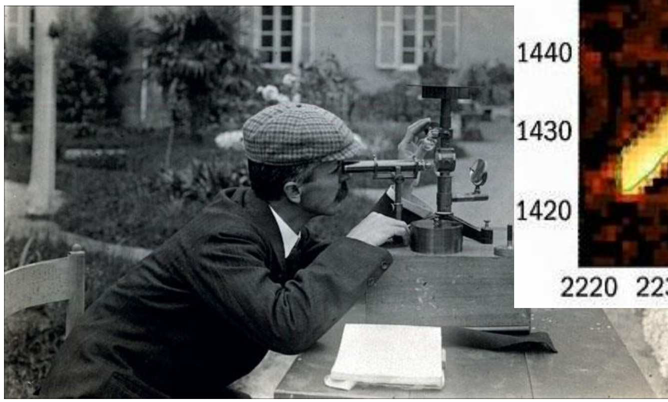
neutron 1932

Electron spin,
1921, 25

Born-Oppenheimer
1927

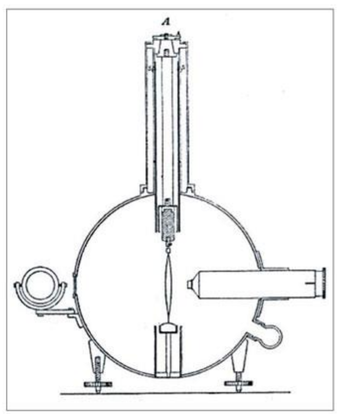


Phone app! (2015?)



Domenico Pacini 1910
underground, underwater, up mountains…

Viktor Hess 1912
5 km altitude!



Father Theodor Wulf 1911
up the Eiffel Tower…

Timeline for particle physics

1890	1900	1910
radioactivity electrometers	cosmic rays	
electron 1897		proton
		Dira

Carl Anderson (left) and Seth Neddermeyer, who presented the first evidence for the muon in 1937

positron 1932

neutron 1932

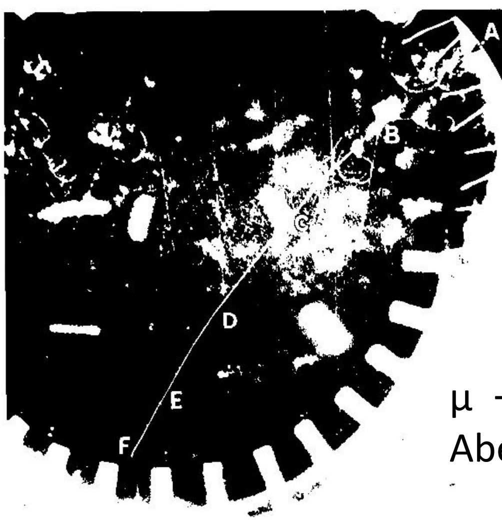
Kunze's forgotten track 1933

Yukawa's prediction 1935

the mesotron! 1936-1938

1938–40 $m_\mu \sim 220\ m_e$

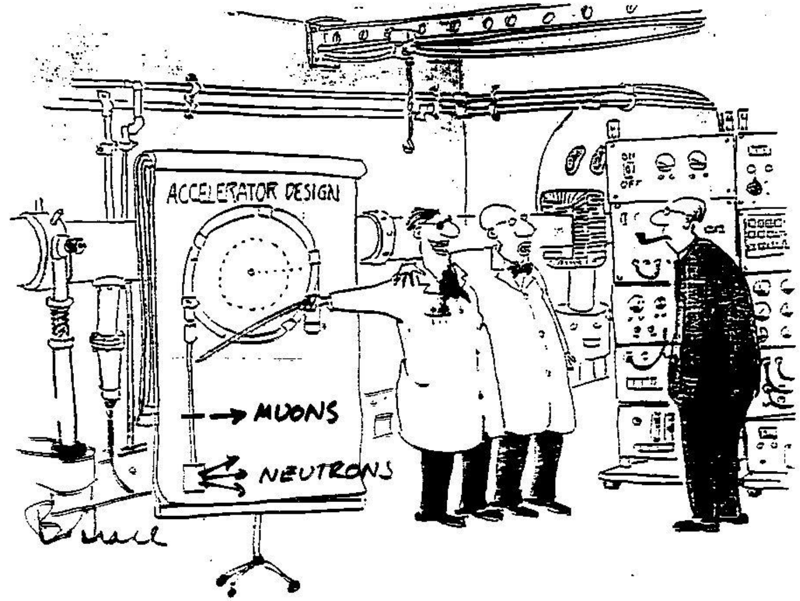
II Rabi:
"Who ordered that?"



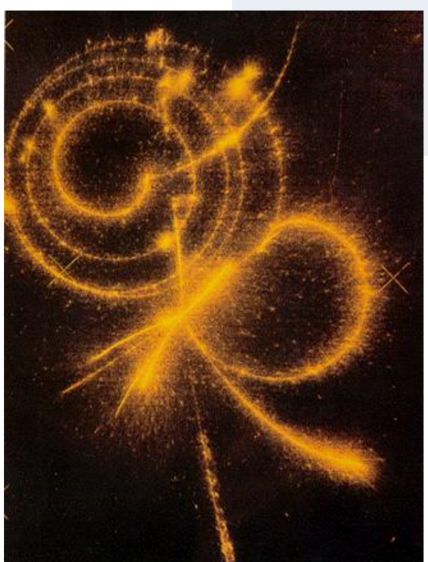
$\mu \rightarrow e$ decay
Aberystwyth, 1940

π → μ → e

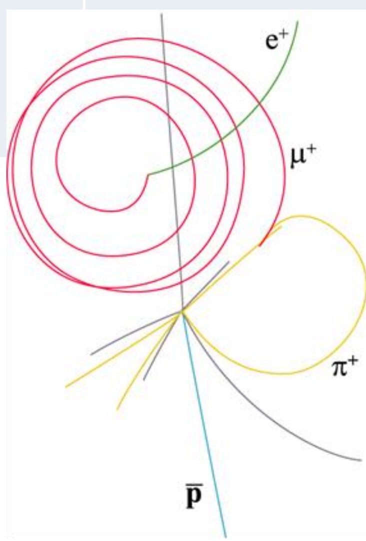
1940	1950
…cosmic rays… nuclear emulsions	accelerator sources 1948 artificial pions at Berkeley cyclotron
“Vatican” μ^+, μ^- expts 1945-47 pi-meson, pion 1947	



“You push the first switch down, and the protons go round and round, oh-oh-oh-ohhh-oh-oh, and they come out here.”



CERN picture library

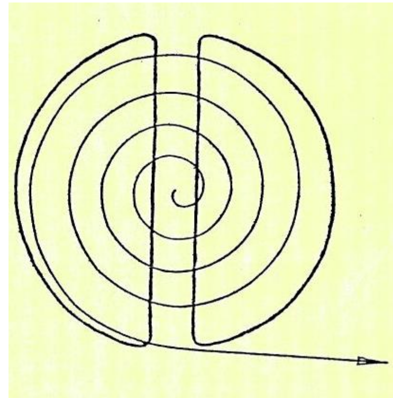


Artificial muons

1950s

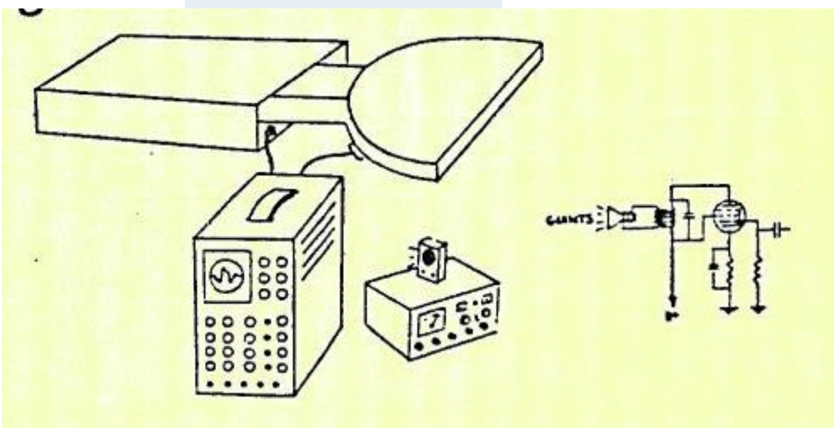
Campus accelerators,
decay beams, low rates

1948 Berkeley Cy
1950 Columbia
1951 Chicago
1954 Berkeley PS

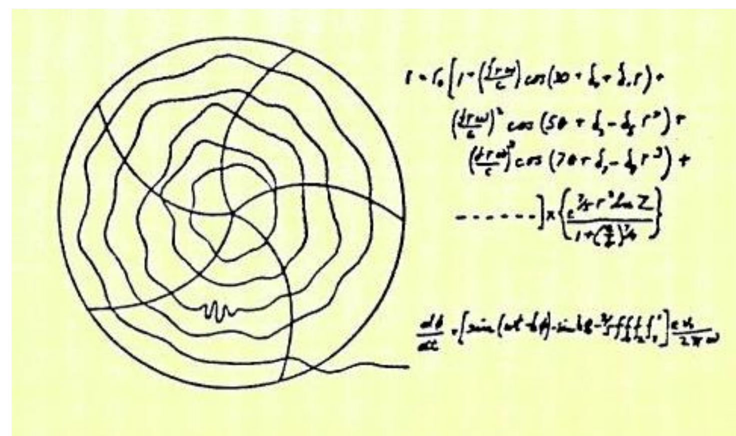


THE CYCLOTRON AS SEEN BY THE INVENTOR

$p \rightarrow \pi \rightarrow \mu \rightarrow e$



THE CYCLOTRON AS SEEN BY THE ELECTRICAL ENGINEER



THE CYCLOTRON AS SEEN BY THE THEORETICAL PHYSICIST

1966 Cartoons (from “The Physics Teacher” 1986)

π → μ → e and the origins of μSR

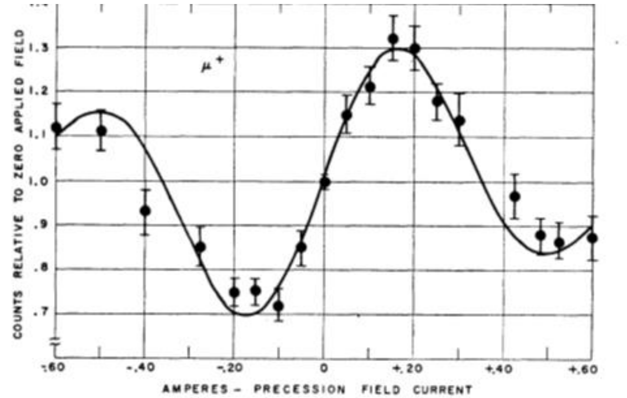


Fig. 2. Variation of gated 3–4 counting rate with magnetizing urrent. The solid curve is computed from an assumed electron ngular distribution $1-\frac{1}{3}\cos\theta$, with counter and gate-width esolution folded in.

1950s

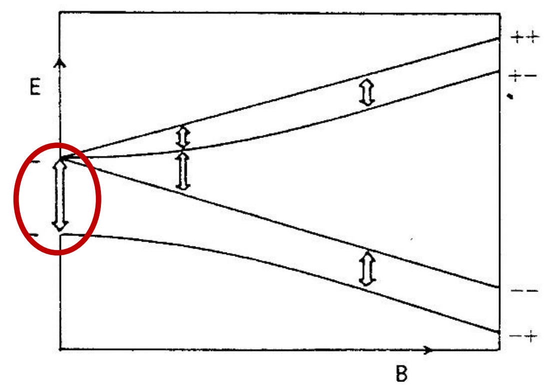
rator sources

single-particle detectors

Pauli:
"I do not think that God is left-handed….
…the experiment will give a symmetrical result."

1956
parity violation mooted

1957
confirmed by
– Wu et al (^{60}Co)
– Garwin, Lederman & Weinrich
– Friedman &Telegdi



π → μ → e and the origins of μSR

20 counts per min,
20 mins per point!

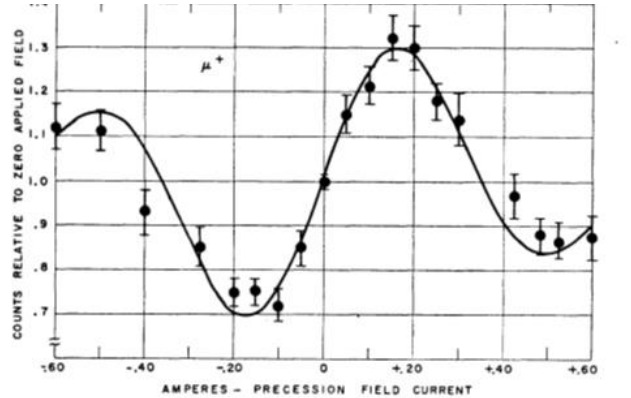


FIG. 2. Variation of gated 3–4 counting rate with magnetizing current. The solid curve is computed from an assumed electron angular distribution $1-\frac{1}{3}\cos\theta$, with counter and gate-width resolution folded in.

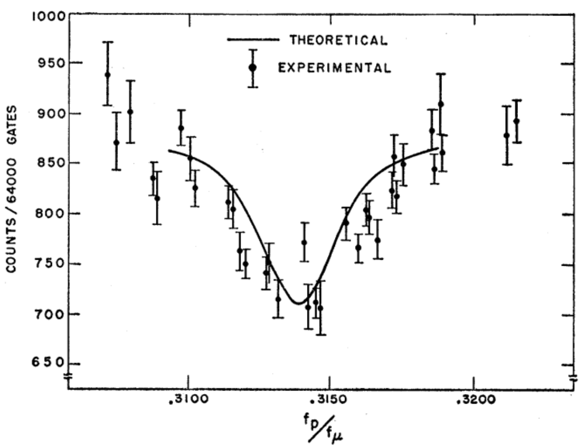


FIG. 5. Theoretical line shape and composite of the experimental points.

1950s

rator sources

single-particle detectors

1956
parity violation mooted

1957
confirmed by
- Wu et al (^{60}Co)
- Garwin, Lederman & Weinrich
- Friedman &Telegdi

"…will become a powerful tool for exploring magnetic fields in … interatomic regions."

1958 Swanson's
(Chicago) survey
and precession signals

Coffin, Garwin et al's
RF resonance (g = 2.005…)

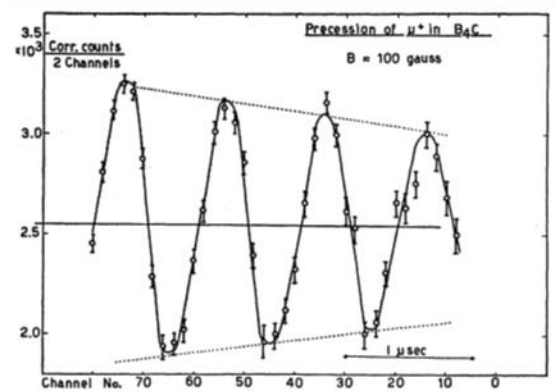


FIG. 7. Muon precession in boron carbide after decay and background correction.

Timeline for magnetic resonance, nuclear probes

1969 moon landing!

1940s	1950s	1960s	1970s

1905 Langevin
Brillouin
Curie's law

1966 Kubo-Toyabe...

1980s MRI

1920s electron spin, nuclear moments, atomic spectra, HFIs

radiation chemistry

PAC, Mossbauer etc

1978 muoniated organic radicals

Leiden spin-temperature expts
spin-lattice relaxation...

NQR?...

1952 organic free radicals

radar research

(Zavoisky, λ = 25 m!...) 1944 ESR

1945 NMR

1949 Knight shifts

1950 chemical shifts

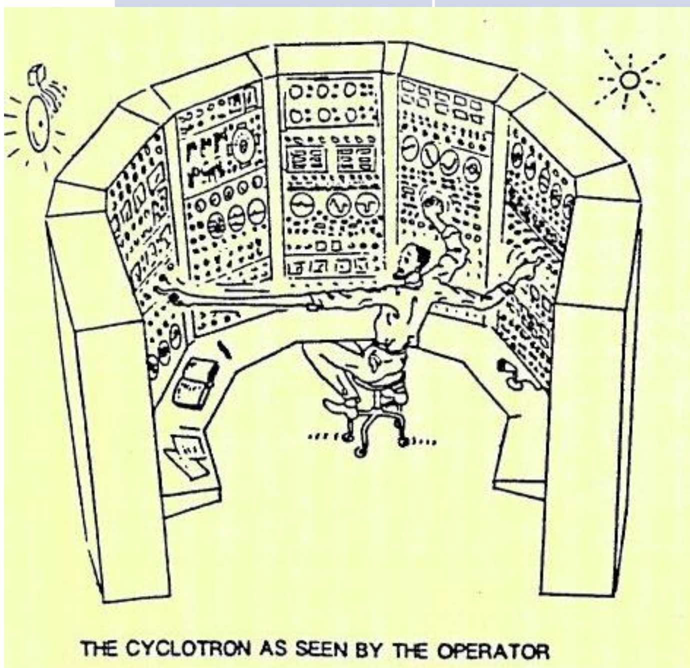
1957 origins of μSR

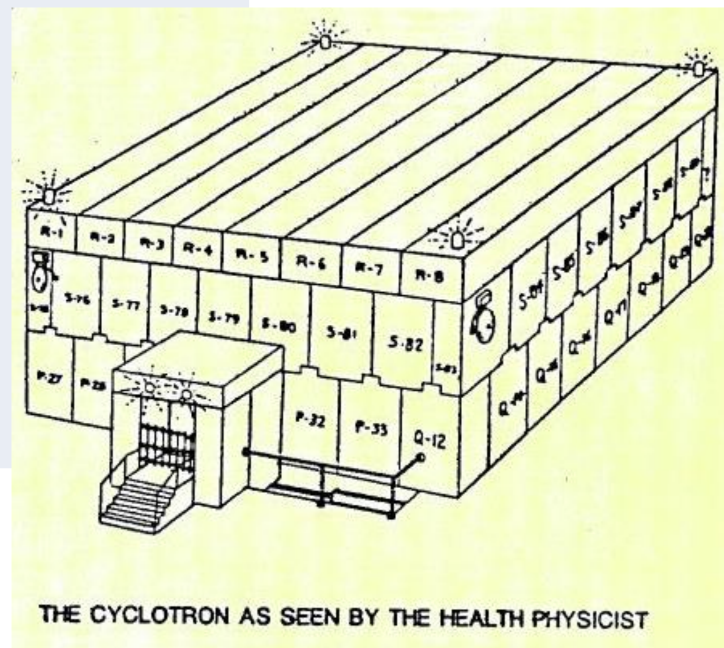
	NMR	ESR	μSR
Polarization at 300K	10^{-5}	10^{-3}	~1
Spins needed	10^{17}	10^{10}	~10^{6}
Time resolution	1 μs	10 ns	~1 ns (CW) ~50 ns (pulsed)

Bigger and better accelerators…

1969 moon landing!

1950s	1960s	1970s
Campus accelerators, decay beams, low rates	*1960s poor beams… but a flood of new particles…*	Meson factory era, decay beams, higher rates
1948 Berkeley Cy 1950 Columbia 1951 Chicago 1954 Berkeley PS	1958 Dubna 1966 SREL 1968 Gatchina	1972 LAMPF 1974 SIN 1975 TRIUMF 1976 CERN μSR


THE CYCLOTRON AS SEEN BY THE OPERATOR


THE CYCLOTRON AS SEEN BY THE HEALTH PHYSICIST

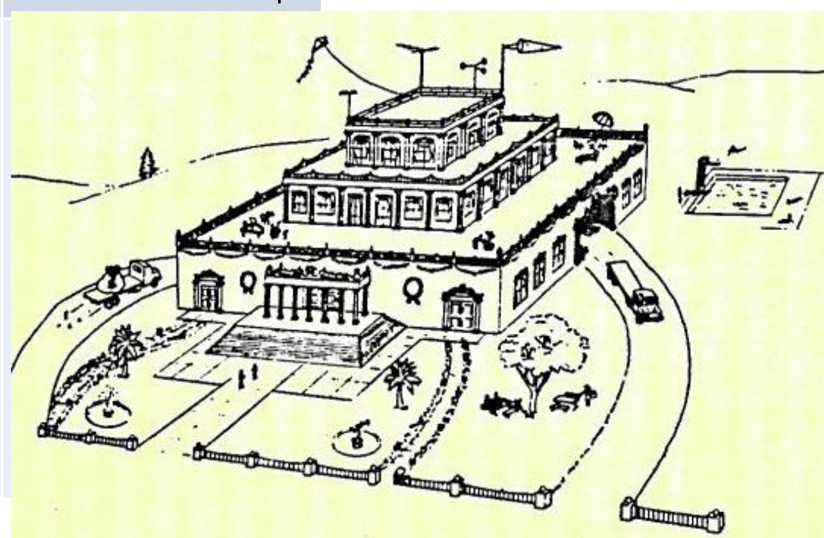
…Meson Factory Era

1969 moon landing!

1950s	1960s	1970s
Campus accelerators, decay beams, low rates	*1960s poor beams… but a flood of new particles…*	Meson factory era, decay beams, higher rates
1948 Berkeley Cy 1950 Columbia 1951 Chicago 1954 Berkeley PS 1958 Dubna	1966 SREL 1968 Gatchina	1972 LAMPF 1974 SIN 1975 TRIUMF 1976 CERN μSR

Big Science versus Little Science…

THE CYCLOTRON AS SEEN BY THE LABORATORY DIRECTOR



THE CYCLOTRON AS SEEN BY THE GOVERNMENTAL FUNDING AGENCY

1966 Cartoons (from “The Physics Teacher” 1986)

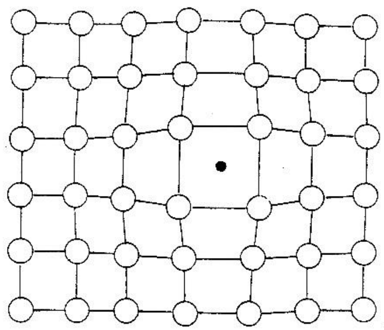
Birth of μSR

1969 moon landing!

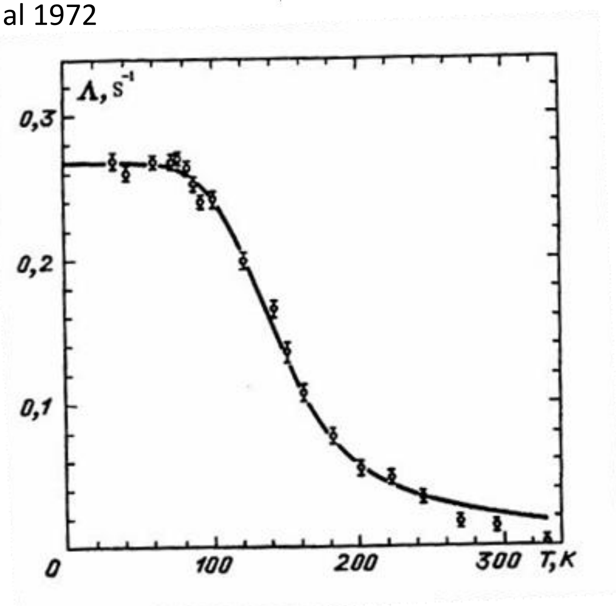
1950s	1960s	1970s
Campus accelerators, decay beams, low rates	*1960s poor beams… but a flood of new particles…*	Meson factory era, decay beams, higher rates
1948 Berkeley Cy 1950 Columbia 1951 Chicago 1954 Berkeley PS 1958 Dubna	1966 SREL 1968 Gatchina	1972 LAMPF 1974 SIN 1975 TRIUMF 1976 CERN μSR
1958 Swanson 1st precession signals asymmetries in various materials	Exploratory studies muons in metals, semiconductors, magnetic mtls, muonium in gases, liquids..	… and objections! 1972 μSR acronym (Berkeley group) 1978 first μSR conference (Switzerland)

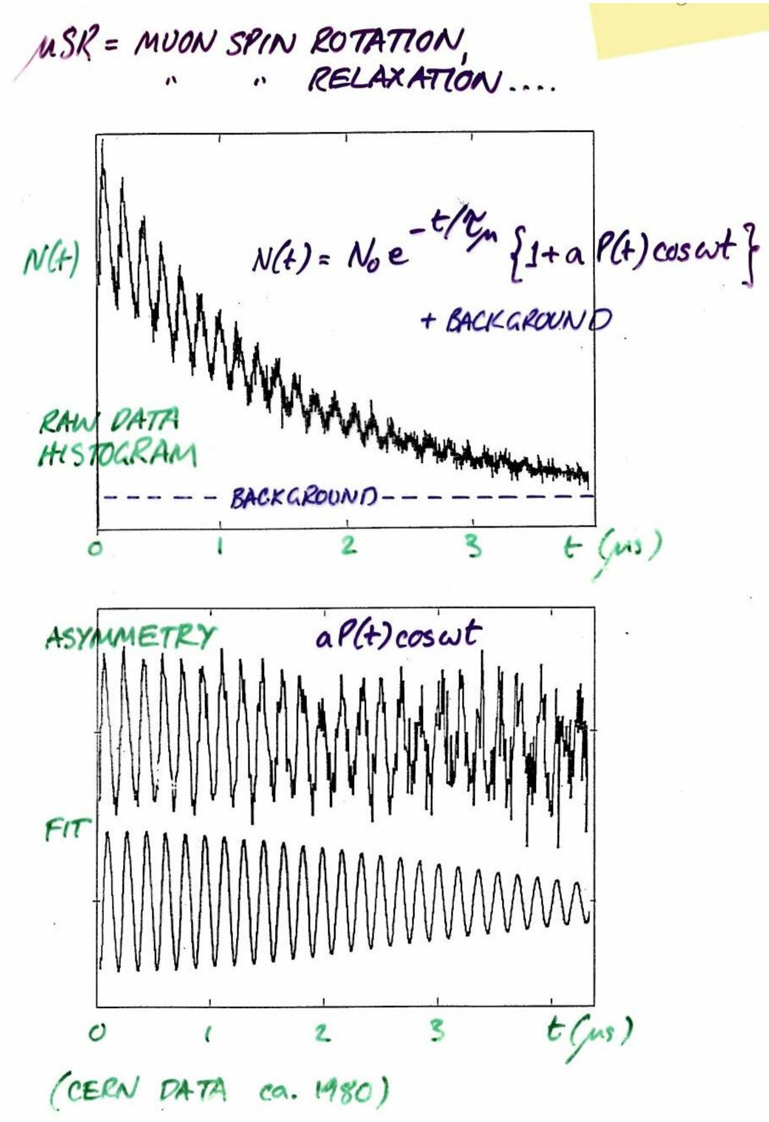
graphite	1
diamond	0.2
Si	1*
SiO_2	0.1
Mg	1
MgO	0.4
Al	0.9
Benzene	0.2
S	0.06

Hydrogen in metals
…and interstitial muons

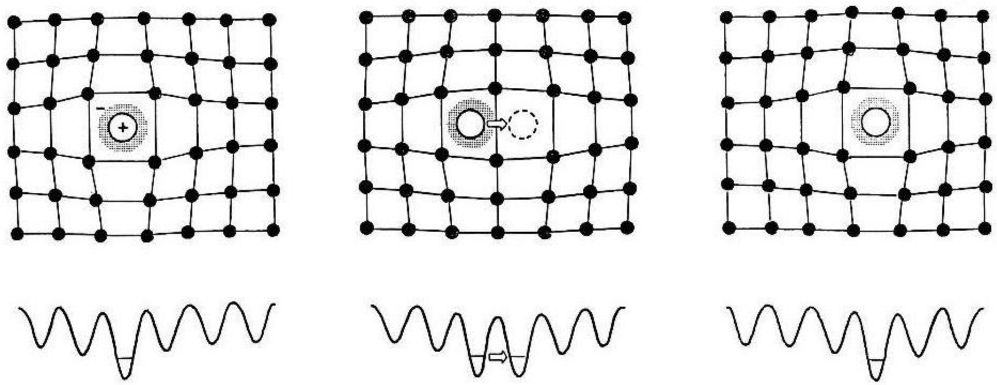


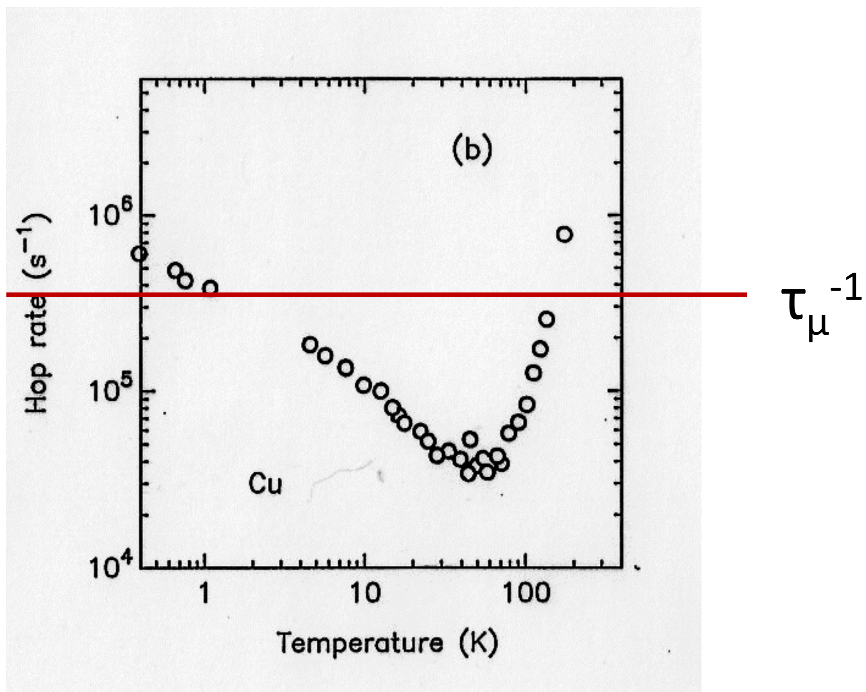
Cu
Gurevich et al 1972
(Dubna?)



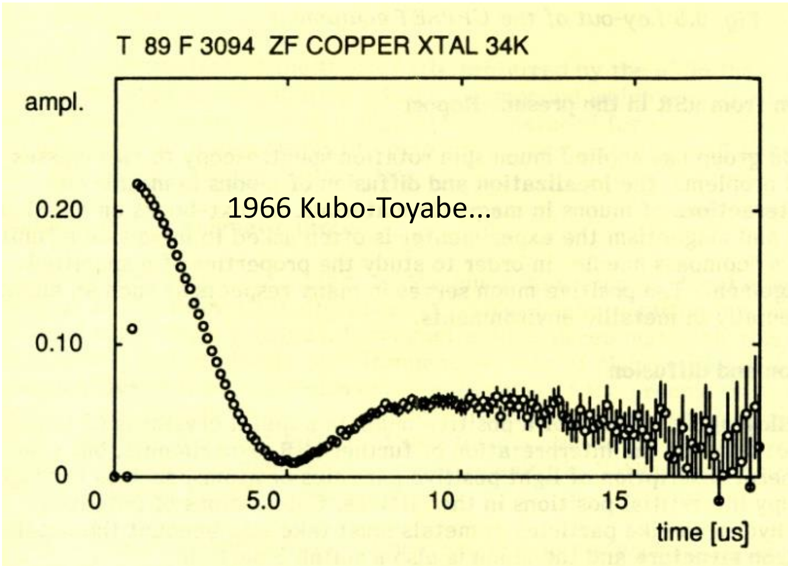


Quantum Diffusion
Phonon-assisted tunnelling





Zero-field μSR

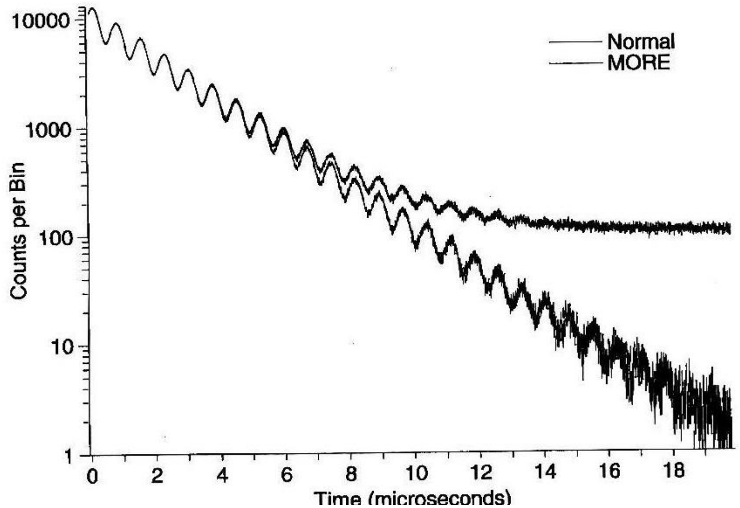


Uppsala group
At ISIS (1989)

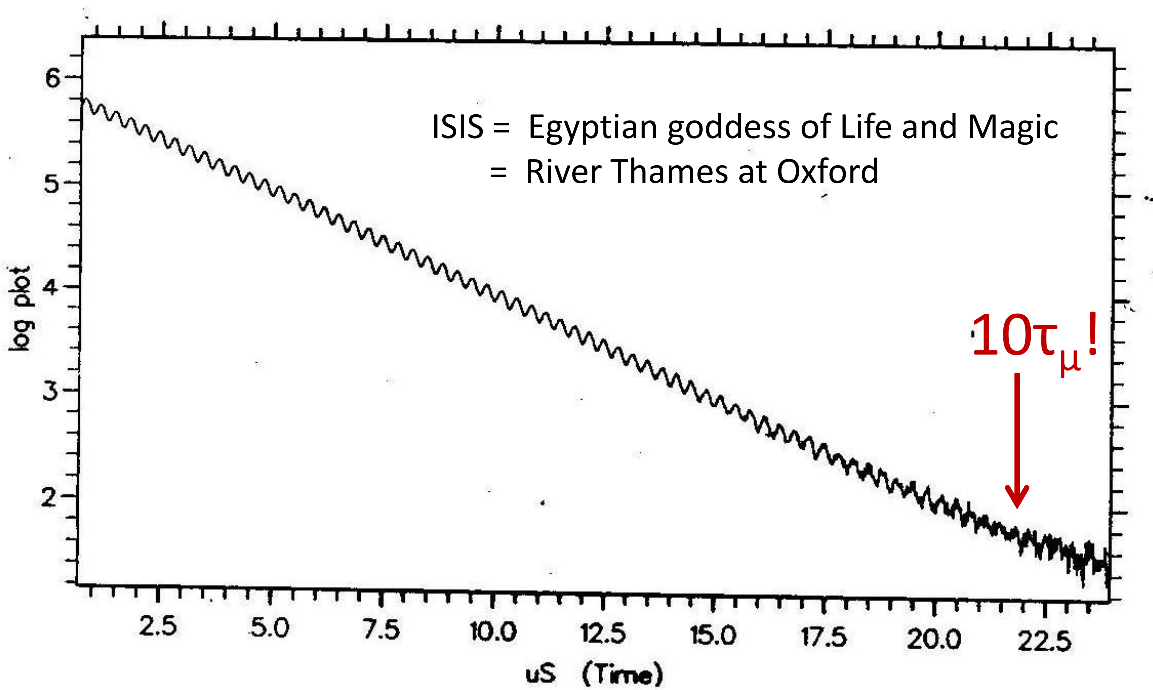
Pulsed sources: KEK-BOOM (Tokyo, 1980)
RAL SNS, ISIS muons 1987
RIKEN-RAL (1994?))

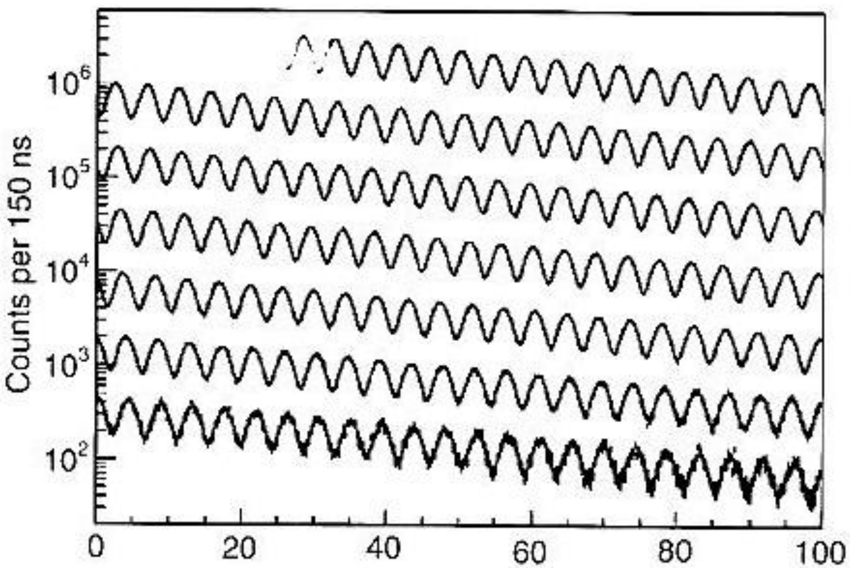
"Difficult metals" at ISIS: Pt, Pb, W, Ag ...Pd...

Metal hydrides. Batteries. Hydrogen storage...



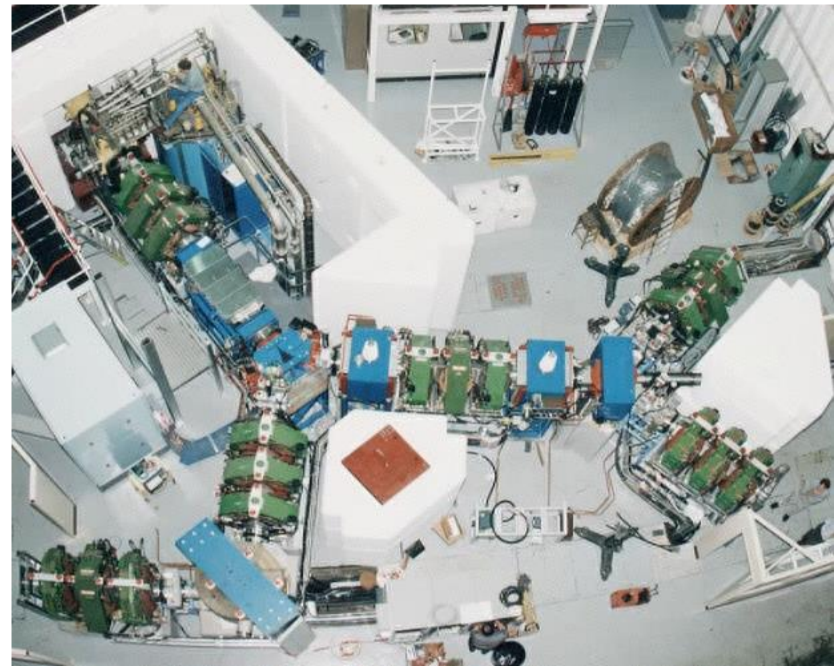
Swiss Institute for Nuclear Research (SIN)
→ Paul Scherrer Institute (PSI)…





μs!

g-2 = 0.002

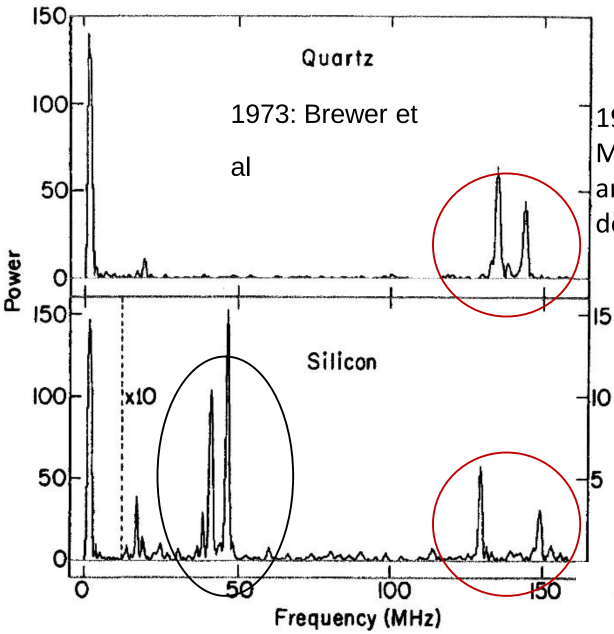


(RIKEN-RAL beams)

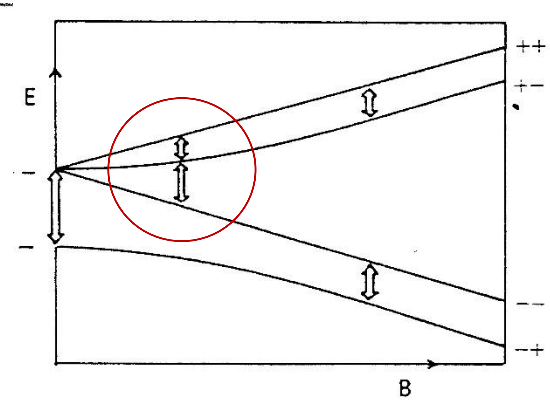
Muonium in semiconductors story

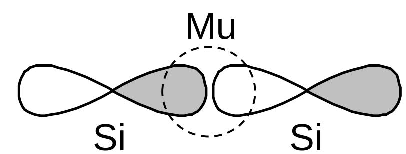
1950s	1960s	1970s	1980s
1958 P=1 in Si	1960 Muonium fractions in Si and Ge (Feher et al, doping and quenching)	1973 Berkeley Mu, Mu* Signals in Si	Mu, Mu* in diamond
	1970 HFC In Si (Andrianov)	1978 HF tensor and <111> symmetry for Mu* in Si (Zurich, Konstanz)	Bond-centre model (1986)

1973: Brewer et al

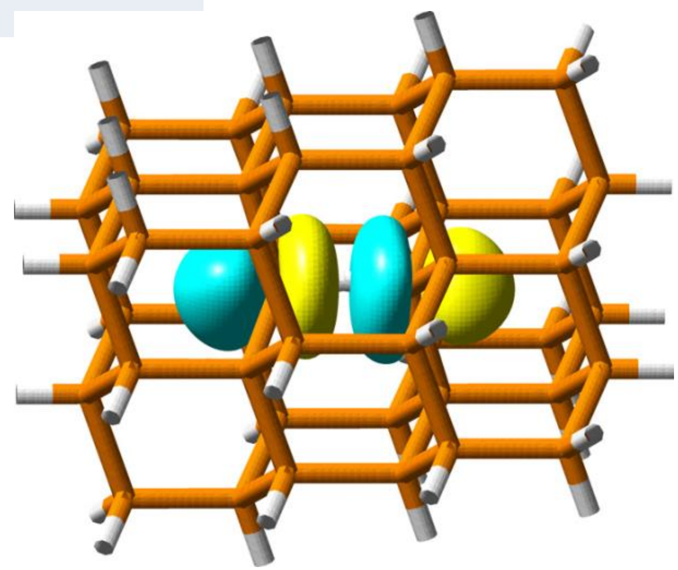


Mu*
"anomalous muonium"



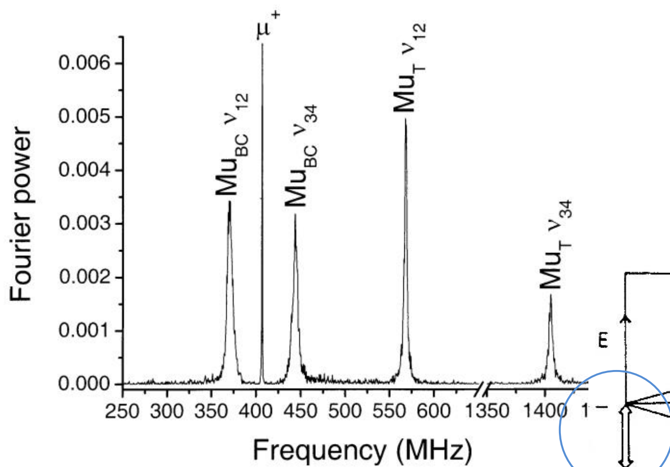


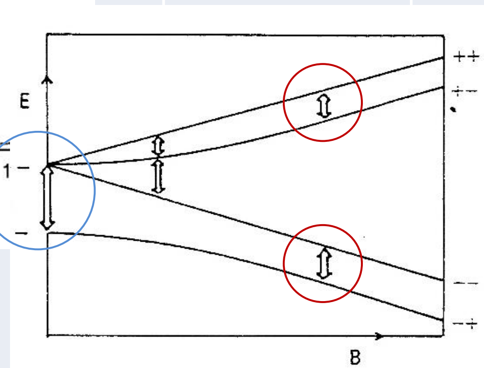
(Inferred from hf parameters – predates successful computation!)

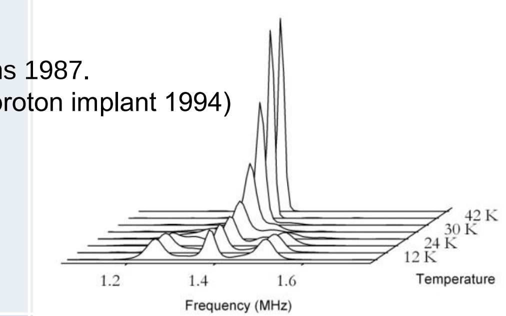


Muonium in semiconductors story

1950s	1960s	1970	1980s	1990s	2000s
	and urves)	1973 Mu, Mu* in Si	ZF heartbeat signal 1981 Spin rotators and high TFs Mu, Mu* in GaAs, GaP	Deep donor and acceptor levels	Very high TFs Electrical activity
			1986 Bond-centre model AA9! (Russians 1987. Danes' proton implant 1994)		Shallow donors!
Hydrogen in semiconductors	"none"	"maybe, but not important"	"what's all this Mu stuff?"	"might be useful"	PANIC…

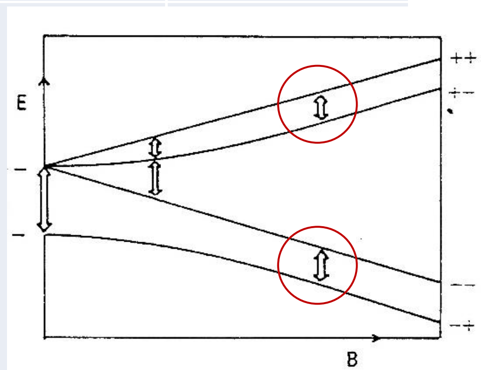




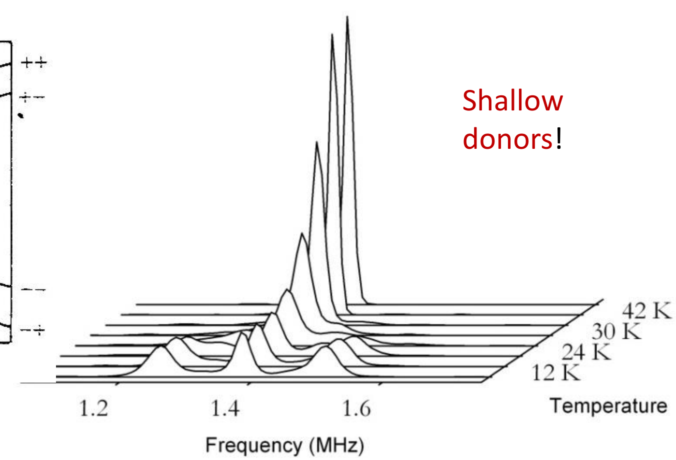


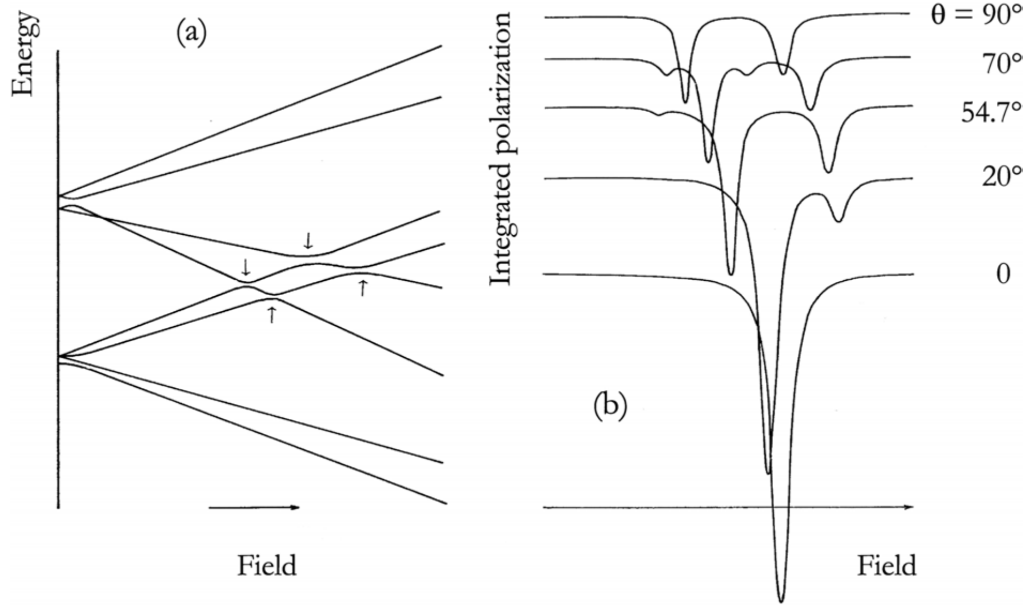
Muonium in semiconductors story

1950s	1960s	1970	1980s	1990s	2000s
(1958 bad result in Si!)	Mu fraction and quenching curves In Si, Ge (US)	1973 Mu, Mu* in Si	ZF heartbeat signal 1981 Hi TFs	Very high TFs Deep donor and acceptor levels	Oxide muonics…
Hydrogen in semiconductors	“none”	“maybe, but not important”	“what’s all this Mu stuff?”	“might be useful”	PANIC…



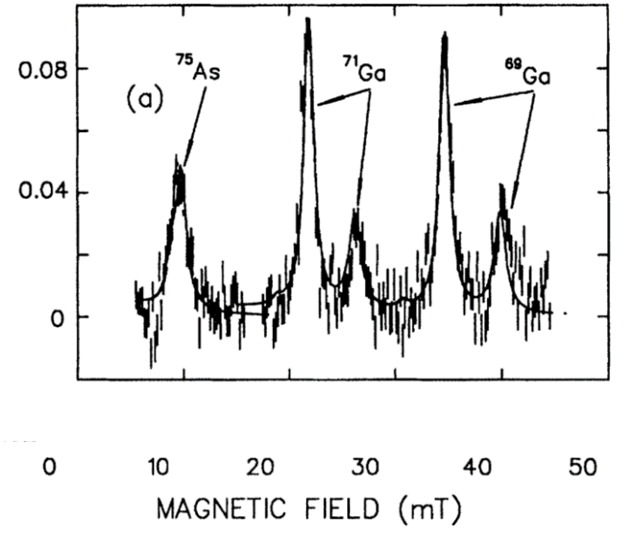
Electrical activity

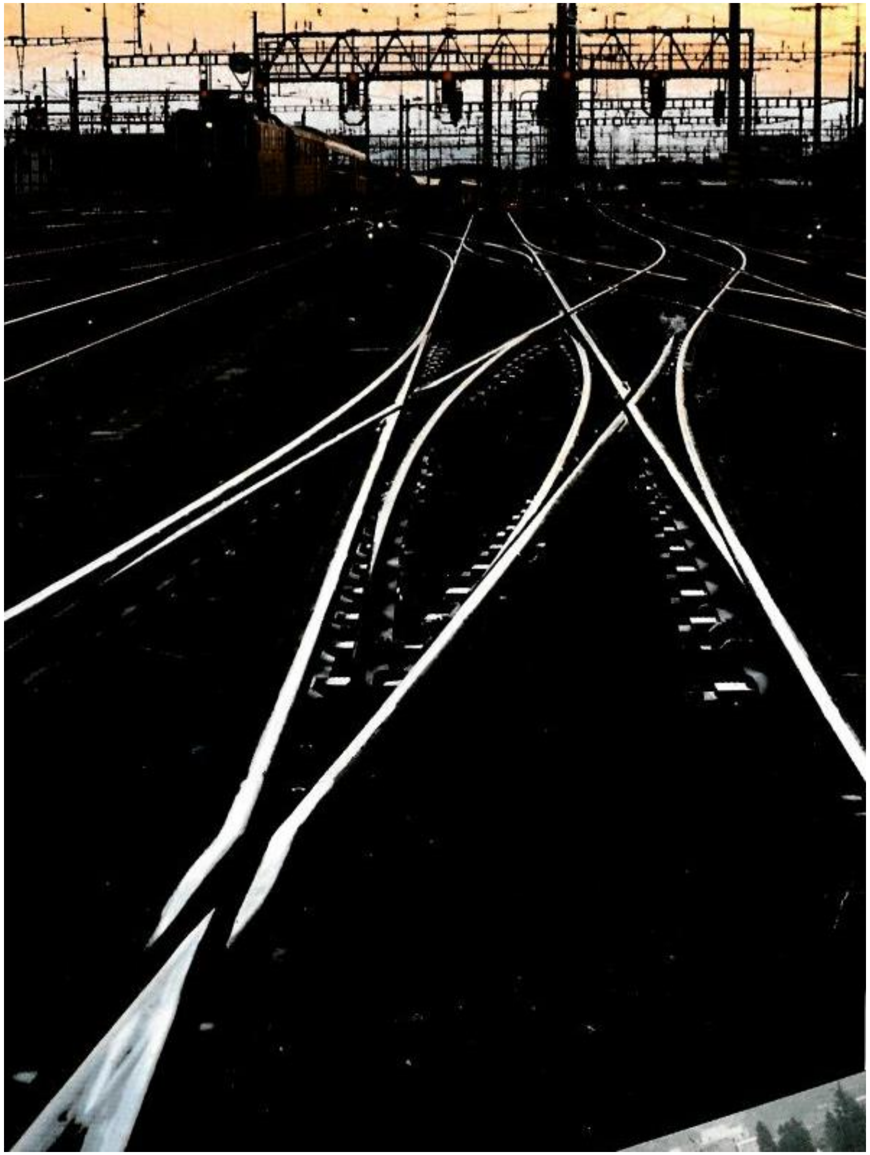




Quadrupole level-crossing resonance

Mu$^-$ in n-type GaAs
(LAMPF, 1995)





Muonium Chemistry

1950s	1960s	1970s	1980s

radiation chemistry

1952 stable free radical ESR

1958 transient free radical ESR

1957, ‘58 Muonium concept

1959 muonium in N_2O

1960 muonium in Ar

1967, ‘69 muonium in quartz, ice

1971 HMuO in gypsum!

1976 Don’s muonium reaction with Br_2/Ar

1978 muoniated organic radicals

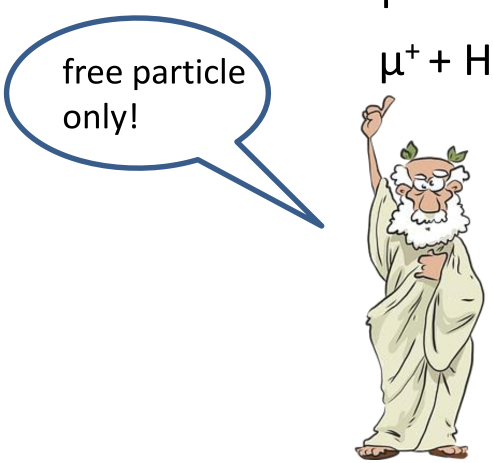
1978 muonium in H_2O

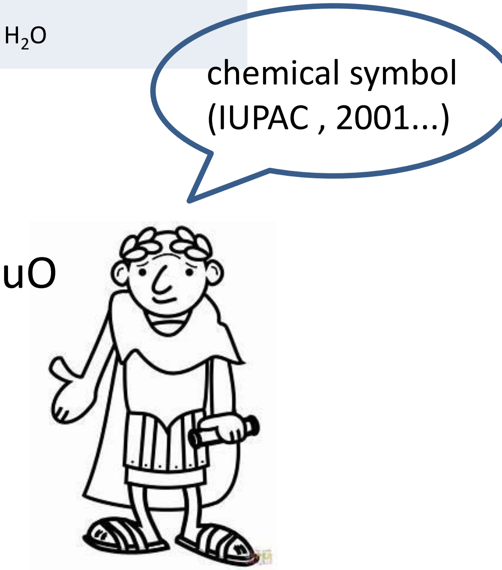
Nomenclature

$$\mu^+ + e^- \rightarrow Mu$$

$$\mu^+ + H_2O \rightarrow H_2MuO^+$$

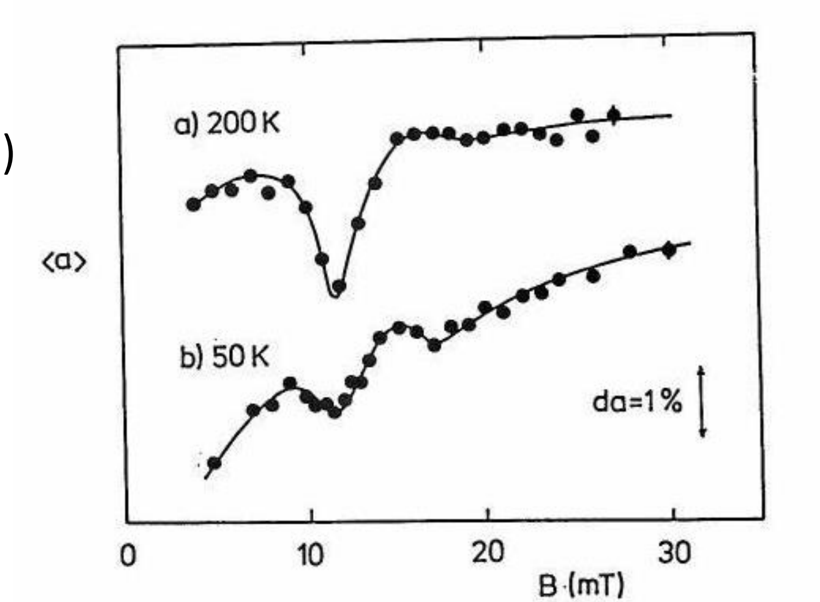
$$H_2MuO^+ + H_2O \rightarrow H_3O^+ + HMuO$$





Diamagnetic fraction in ice

^{17}O QLCR (ISIS, 1990)



$\mu^+ + e^- \rightarrow Mu$

$\mu^+ + H_2O \rightarrow H_2MuO^+$

$H_2MuO^+ + H_2O \rightarrow H_3O^+ + HMuO$

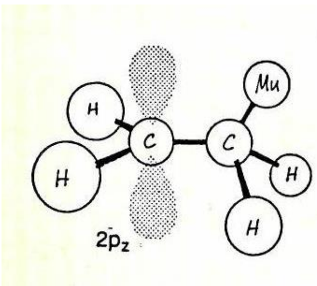
free particle only!

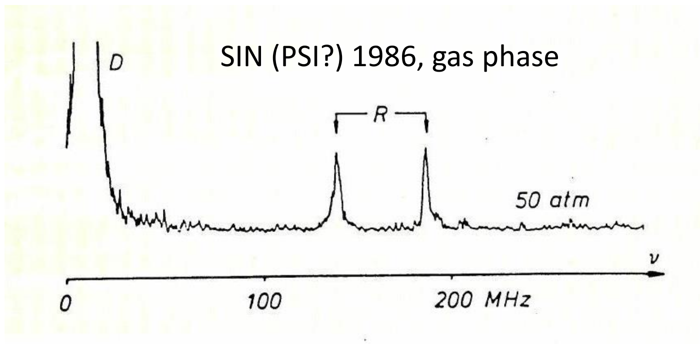
chemical symbol (IUPAC , 2001...)

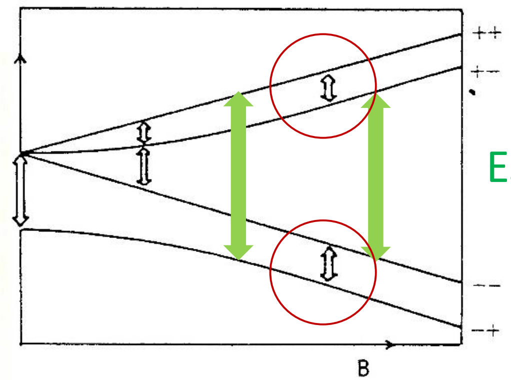
not F-μ-F
but $(FMuF)^-$!

Muoniated organic radicals

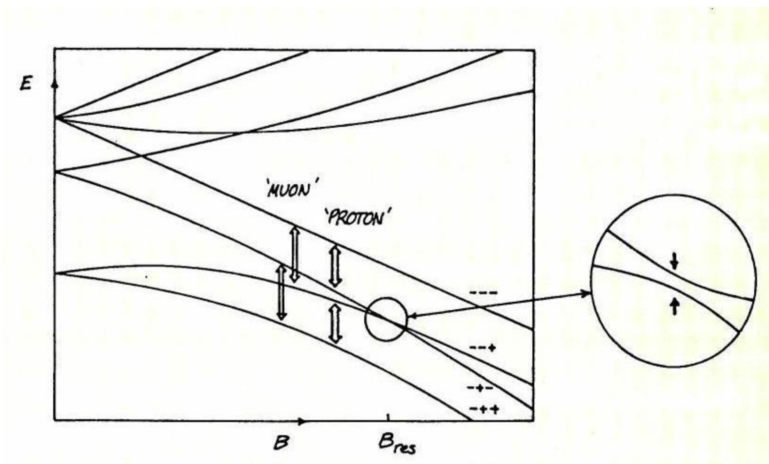
e.g. ethyl $CH_2{=}CH_2 + \dot{Mu} \rightarrow \dot{C}H_2{-}CH_2Mu$



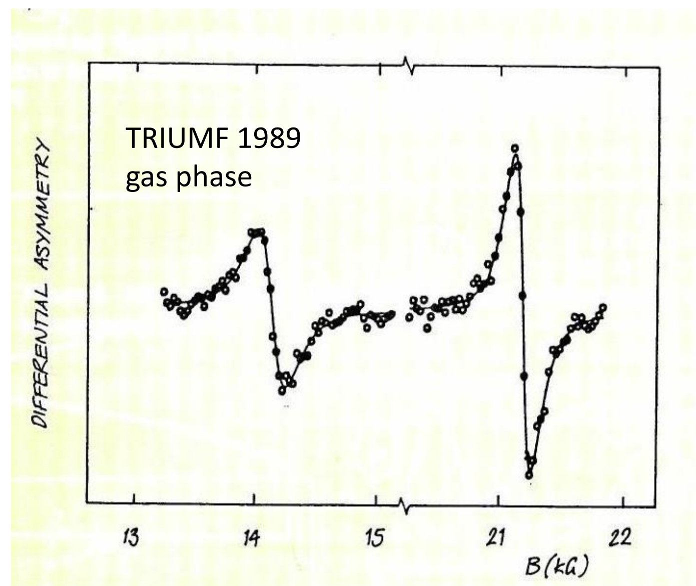




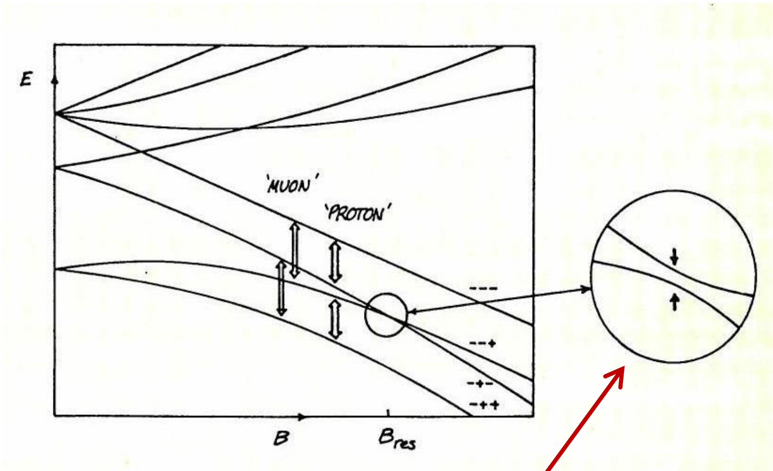
ESR



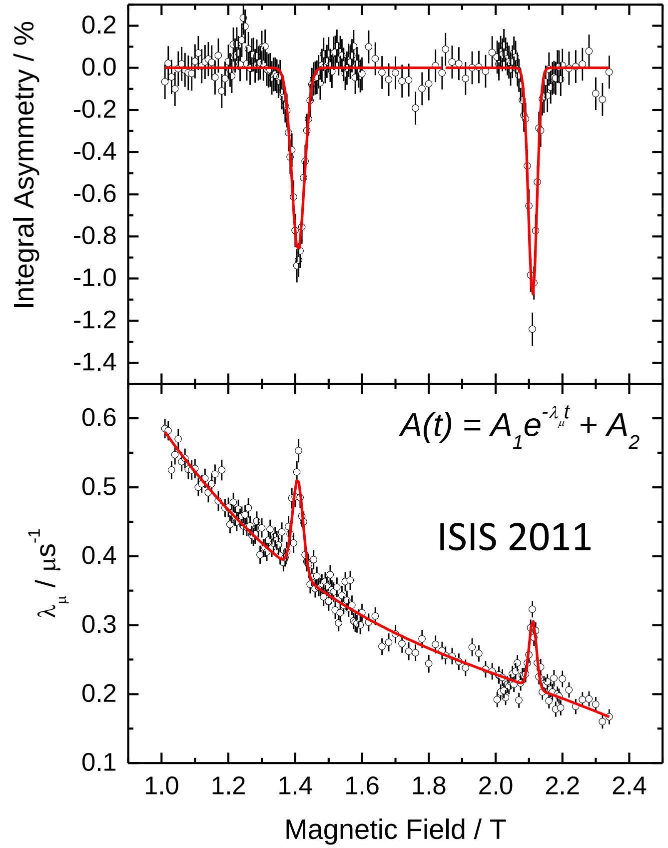
Hyperfine LCR



Level crossing, or…



"Avoided level crossing"
…to be pedantic



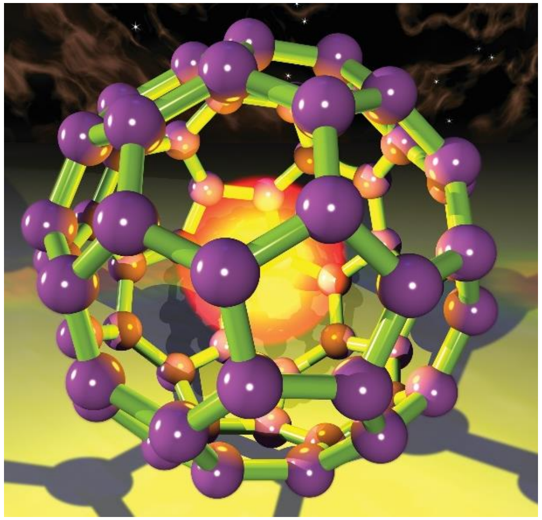
Isotope effects in reaction kinetics and mol structure:

T : D : H : Mu = 3 : 2: 1: 1/9

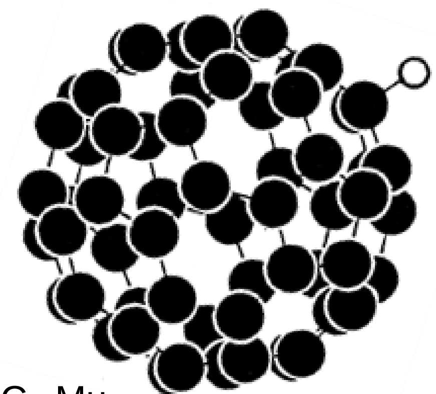
A spin label for organic radicals – molecular dynamics

Fullerenes

C_{60} available, 1990

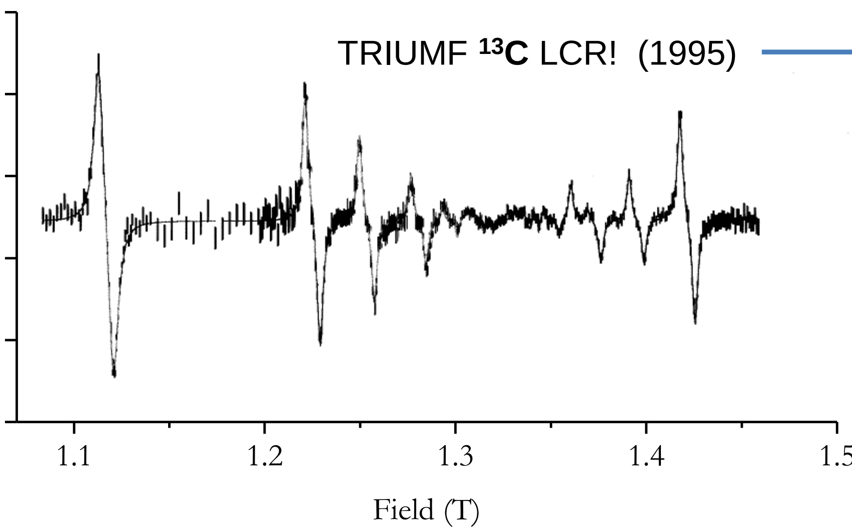


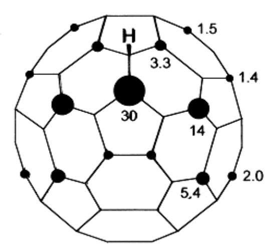
Trapped atom: Mu@C_{60}



External addition: C_{60}Mu

TRIUMF ^{13}**C** LCR! (1995) → Spin density distribution

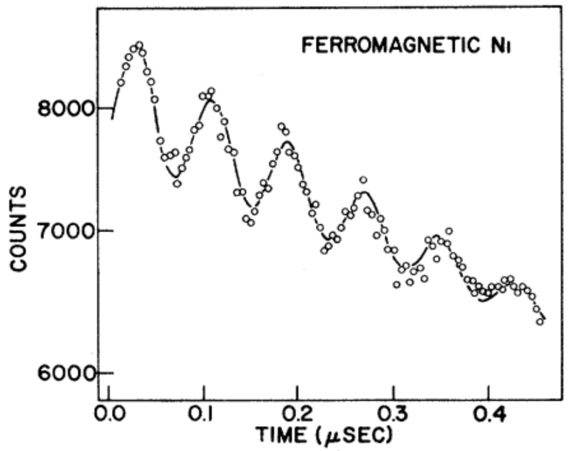


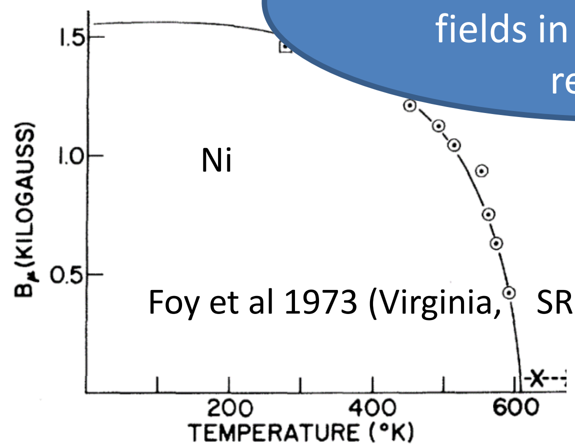


Muons probing magnetism

First used to measure internal fields in the ferromagnets Ni, F, Co, Gd and antiferro Cr plus a lot of REs.

"…will become a powerful tool for exploring magnetic fields in … interatomic regions."

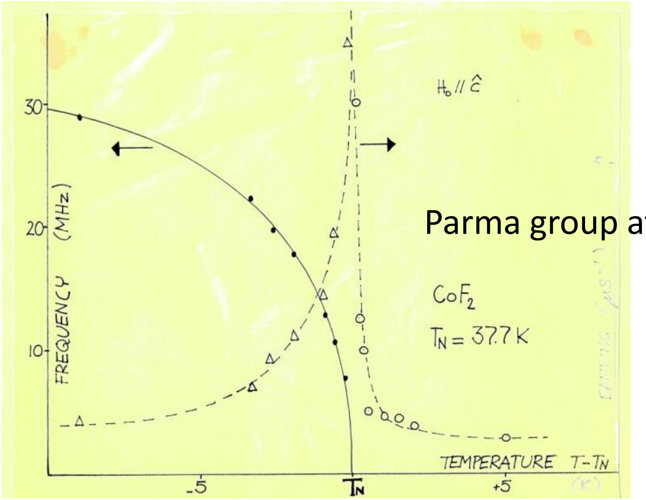




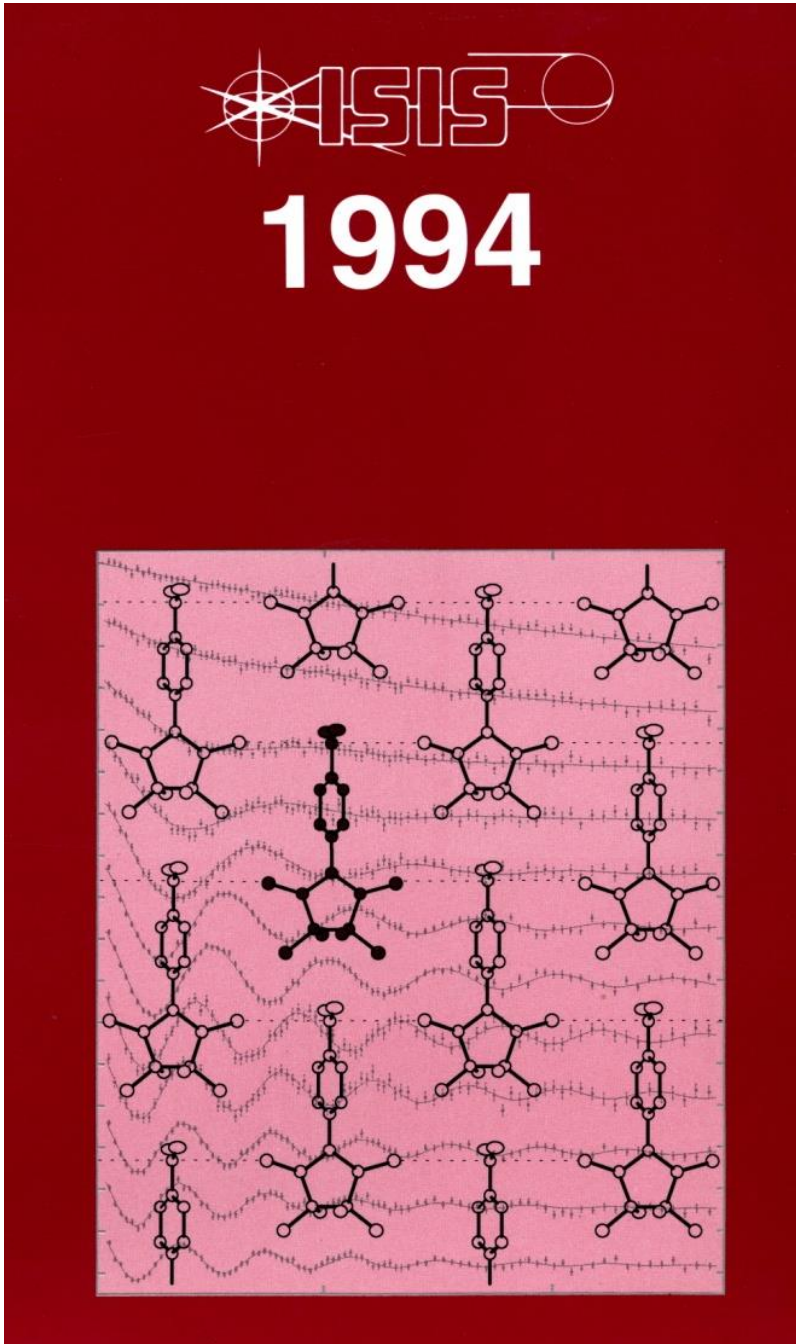
Ni

Foy et al 1973 (Virginia, SREL)

1976 Fe2O3, CuMn, AuFe.. 1978 First μSR conference!



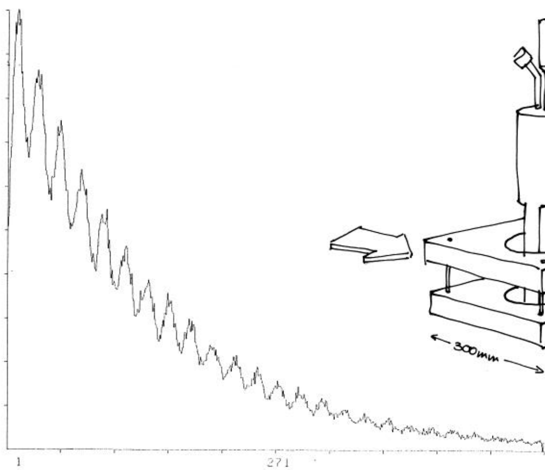
Parma group at CERN 1984

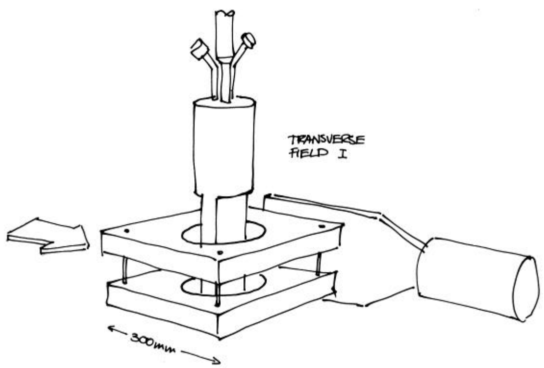


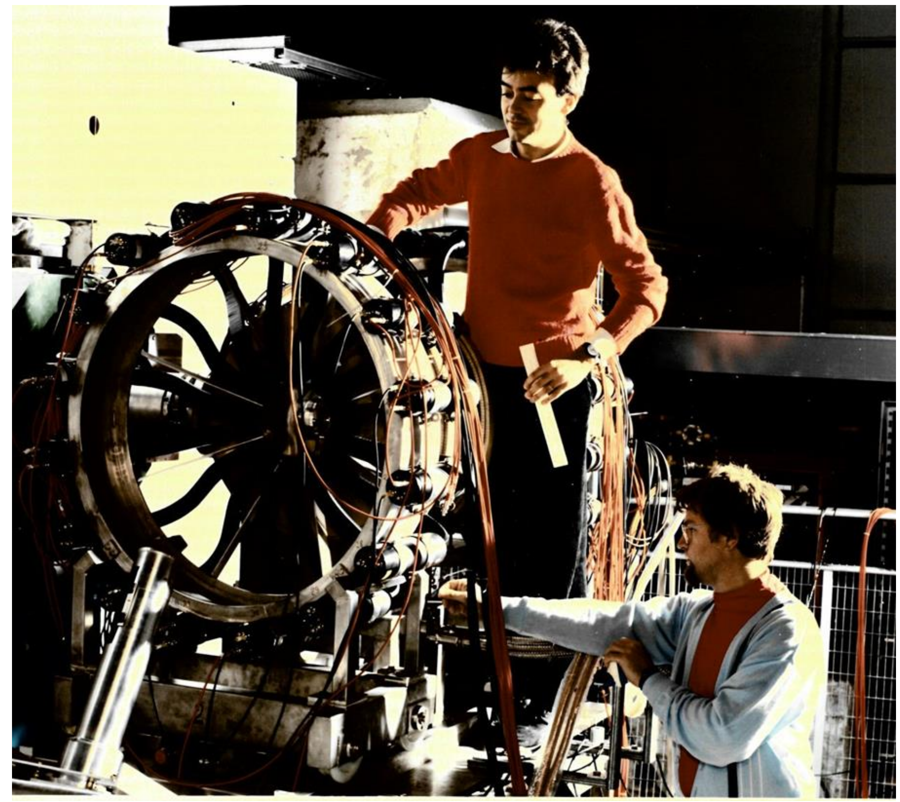
Oxford group:
organic ferromagnets

μSR at the Rutherford Appleton Lab: the ISIS muon and neutron facility

First neutrons 1984, first muons 1987
A pulsed source, like KEK (1980)

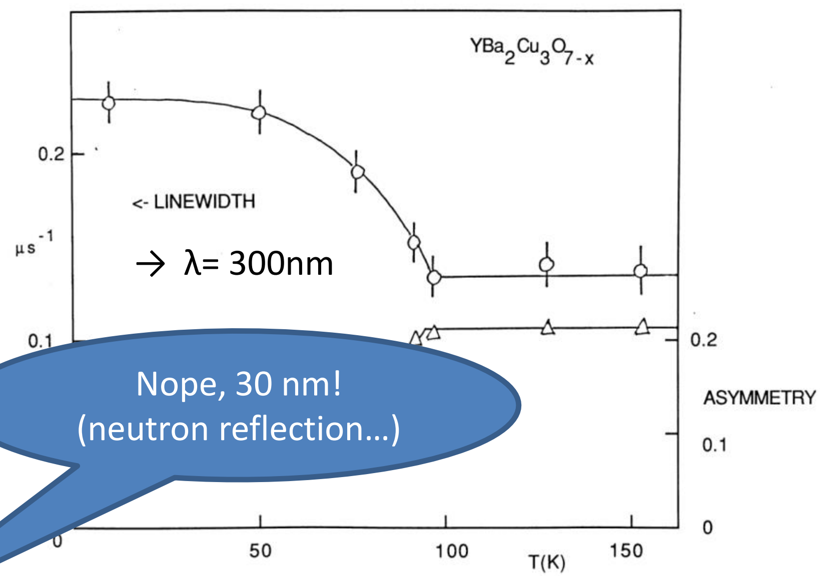






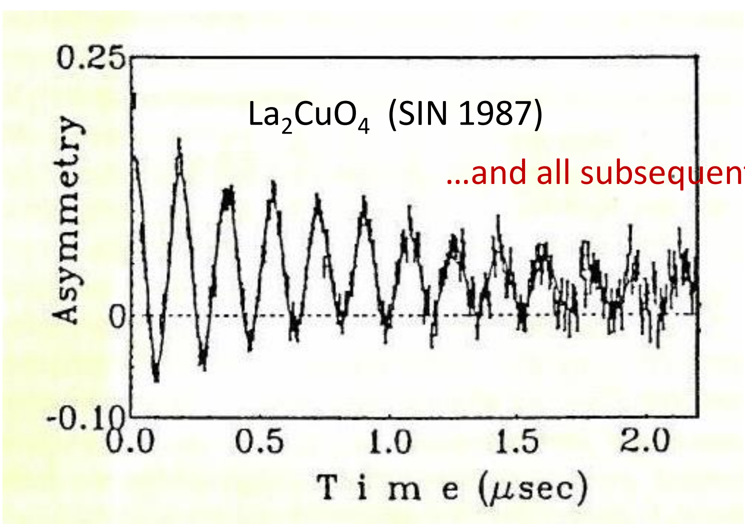
1987: Hi T_cs!

FIRST MuSR RESULTS



→ λ= 300nm

Nope, 30 nm!
(neutron reflection…)



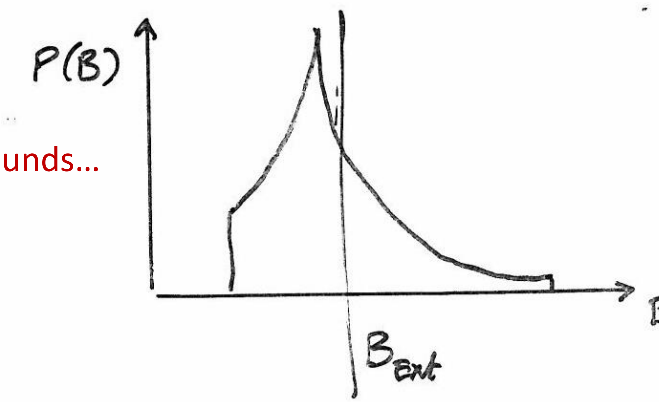
La_2CuO_4 (SIN 1987)

…and all subsequent parent compounds…

"All matter consists of whirlpools with an outer ring of large curving vortices and an inner core of small globules sucked into the centre." flux quanta

(Descartes 17th C)

"Proprietary data?
No thanks!



User Facilities Era (ISIS, CMMS, SμS…)

1980s | **1990s** | **2000s** | **2010s**

1980 Vancouver
1983 Shimoda
1986 Uppsala
1990 Oxford
1993 Maui!
1996 Nikko
1999 Les Diablerets
2002 Williamsburg
2005 Oxford again

Intermetallics, heavy fermions, critical phenomena

High Tc superconductors!

Penetration depths, AF parents, interplay/competition…

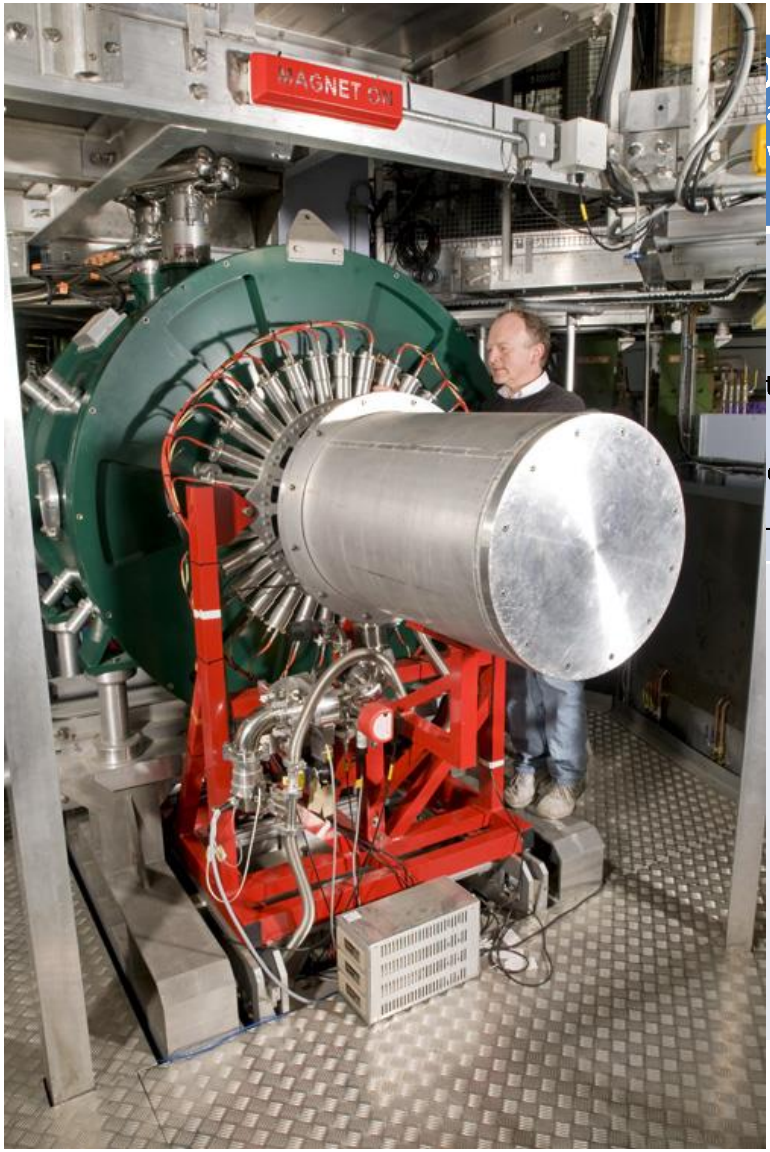
Fullerenes!

Molecular structure, dynamics, reaction kinetics, isotope effects
gas-phase radicals, solids too

ultra-slow muons

High transverse fields at
continuous sources
Longitudinal and zero field
at pulsed sources, LCR

Retirement…



0s	2010s
ablerets Williamsburg 2005 Oxford again	
terplay/competition… e effects -slow muons	

2009 HiFi commissioned

2005 Cox retires…

2006 oxide muonics

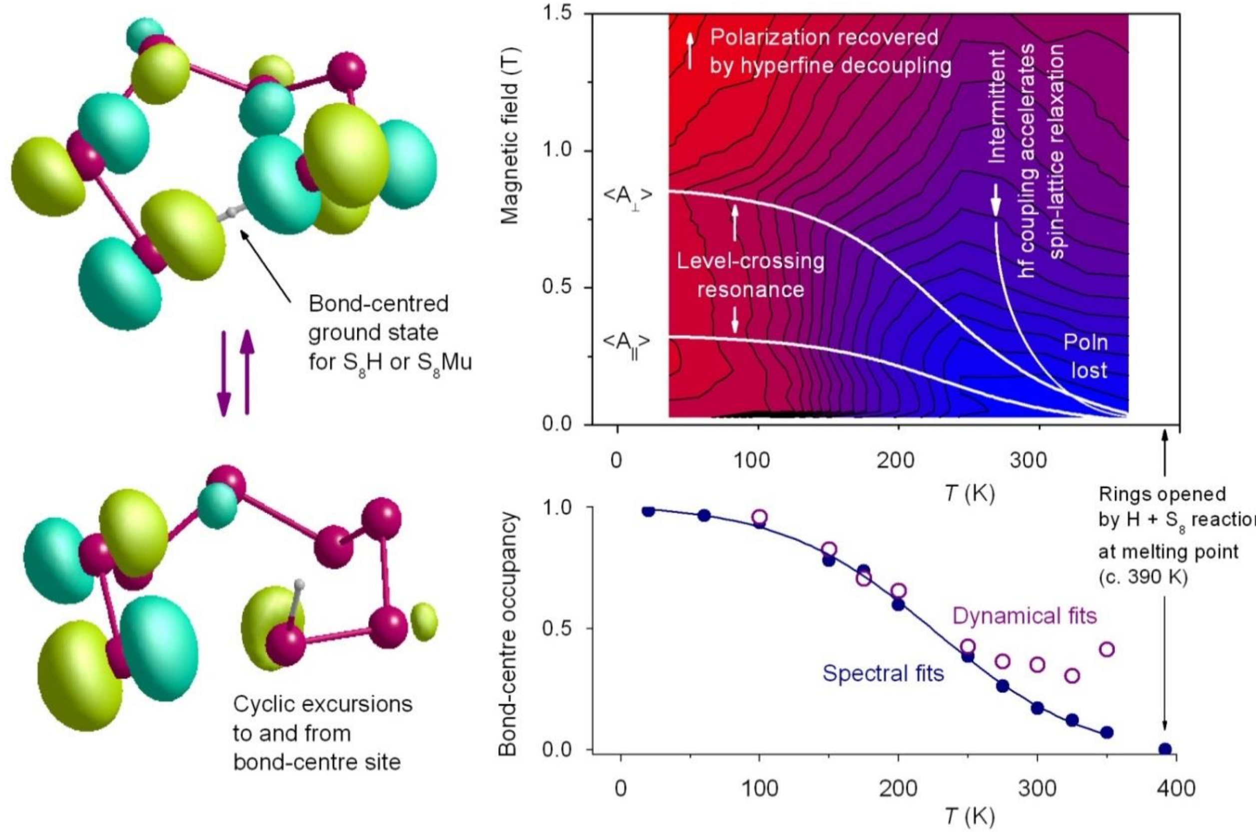
2011 sulphur revisited
after over 50 years!

μSR's oldest puzzle!

Swanson	1958
graphite	1
diamond	0.2
Si	1*
SiO_2	0.1
Mg	1
MgO	0.4
Al	0.9
Benzene	0.2
S	0.06

(zero, actually!)

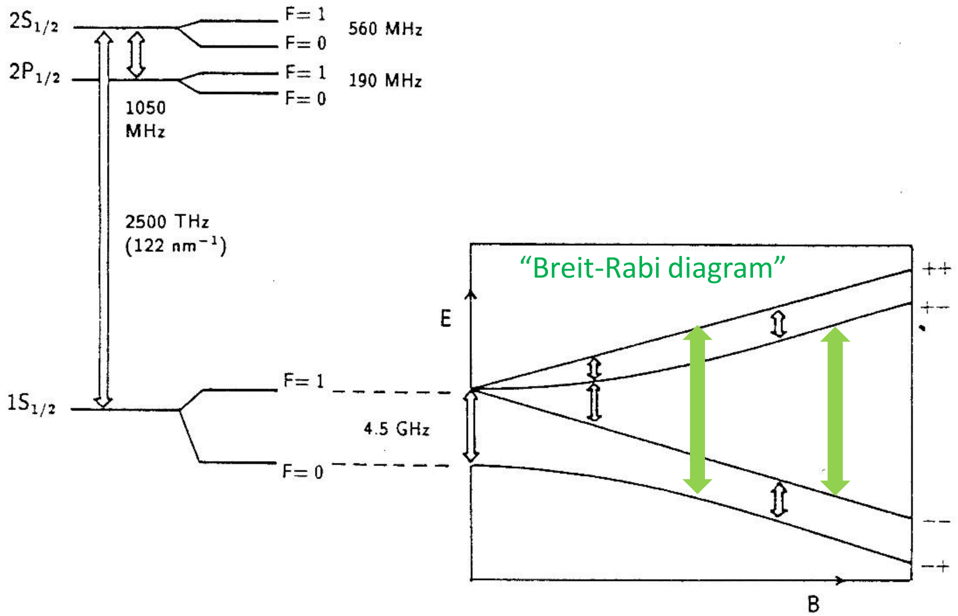
Cox, Lord, McKenzie et al (2011)



"As physicists, we know that our work has the potential to help resolve many of the world's most acute problems - whether they relate to the environment, climate change, healthcare, or supplies of food, water or energy."

(IoP President, 2019)

Muonium spectroscopy



Energy levels for vacuum-state muonium.

ESR

"Shrine of Mount Mu, save us!"
(James Joyce: Finnegan's Wake)