(NOT "$\mu^s SR$"!)

$\mu^- SR$ IN NUCLEI WITH SPIN

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HUH? WUZZAT?

μSR — muon spin rotation / relaxation / resonance

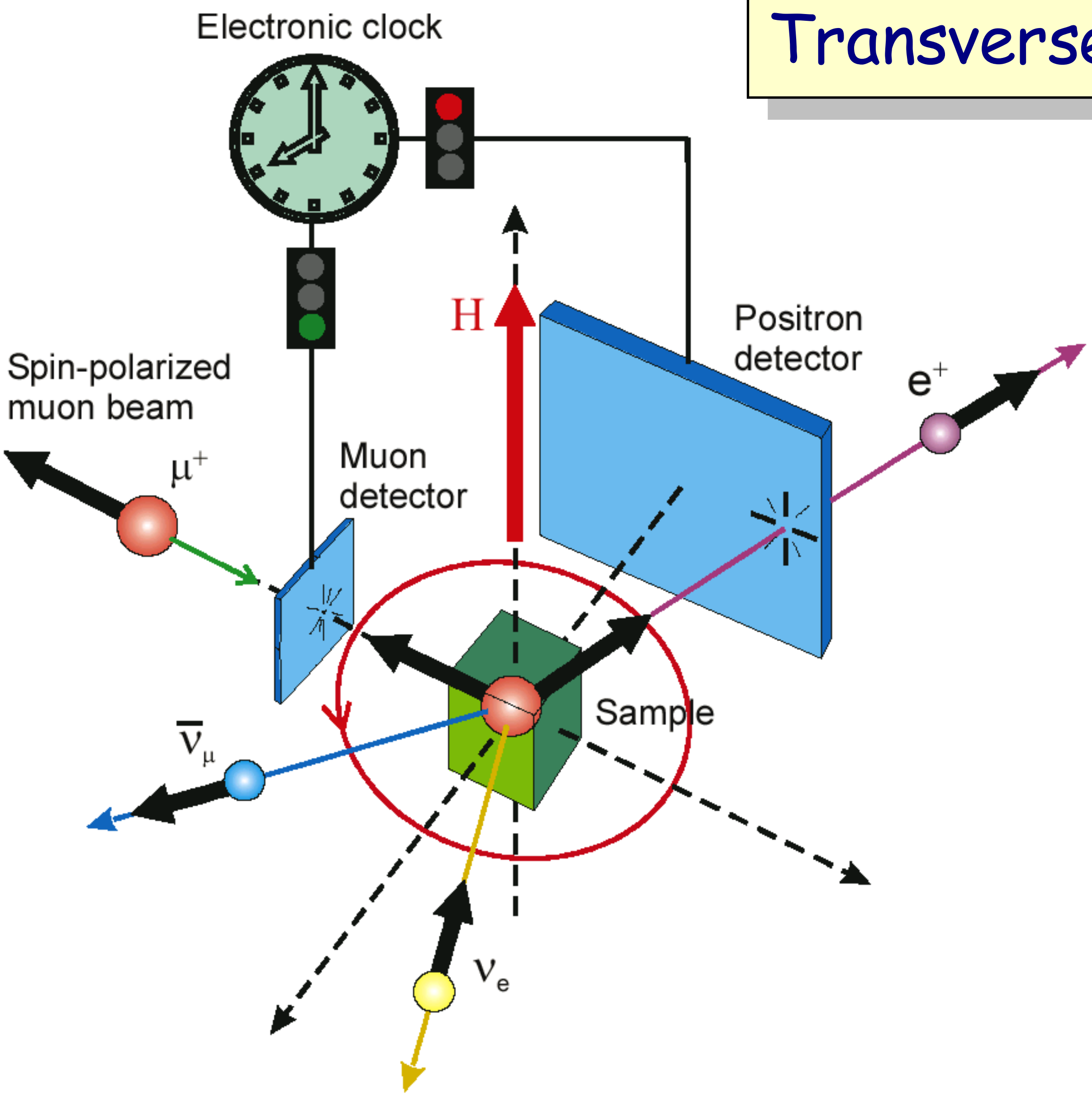
m u o n — s p i n

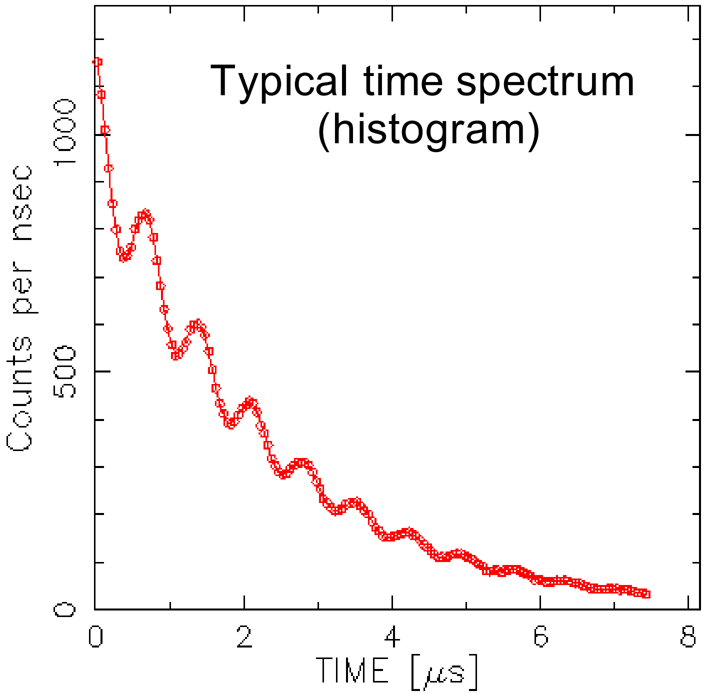
Applied*
Elementary
Particle
Physics

*(to basic research in
Materials Science
and Chemistry)

Visit **http://musr.org**

Transverse Field (TF) $\mu^+ SR$





Brewer's List of *μSR* Acronyms

Transverse Field

Longitudinal Field

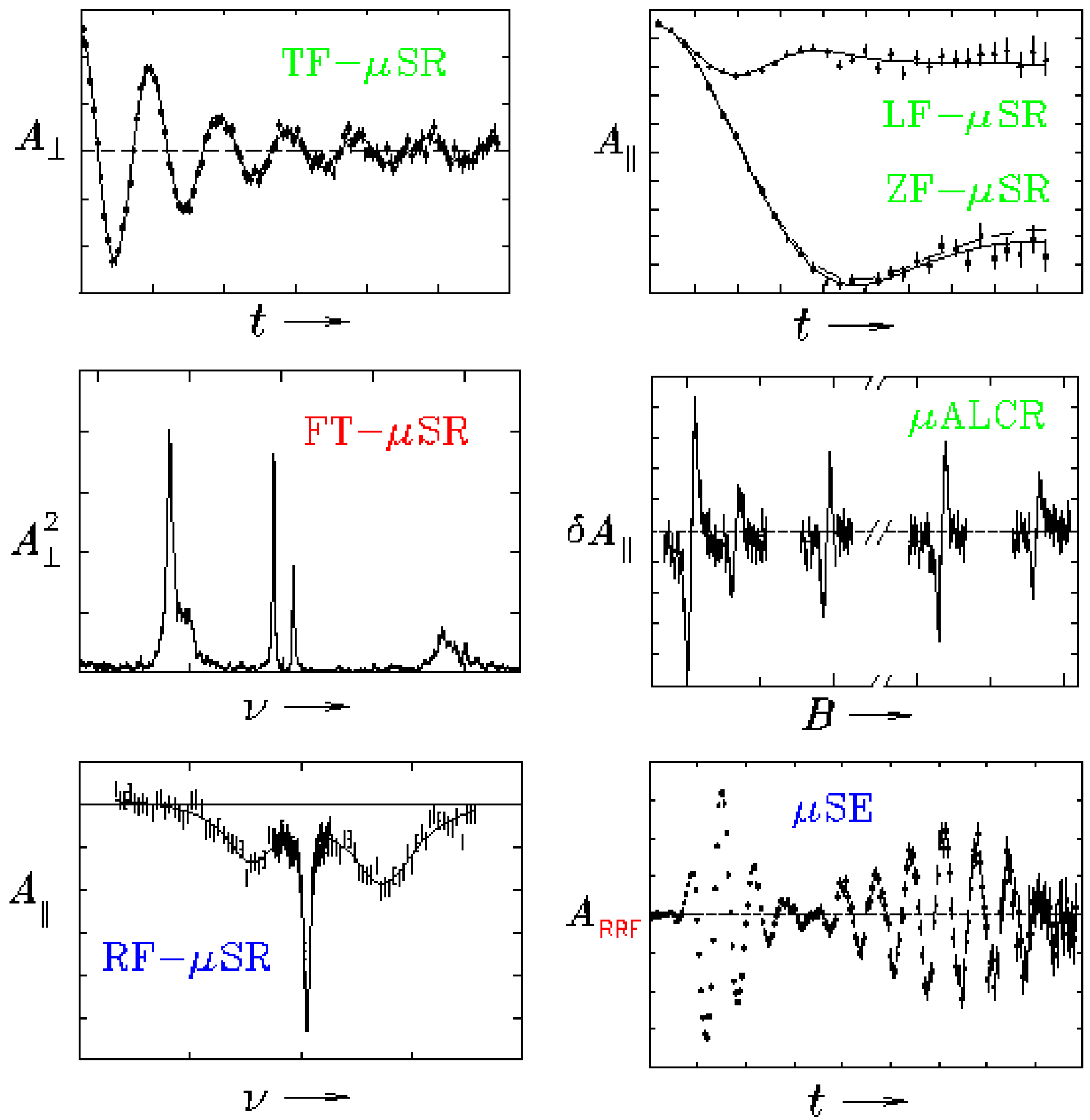
Zero Field

Fourier Transform μSR

Avoided Level Crossing Resonance

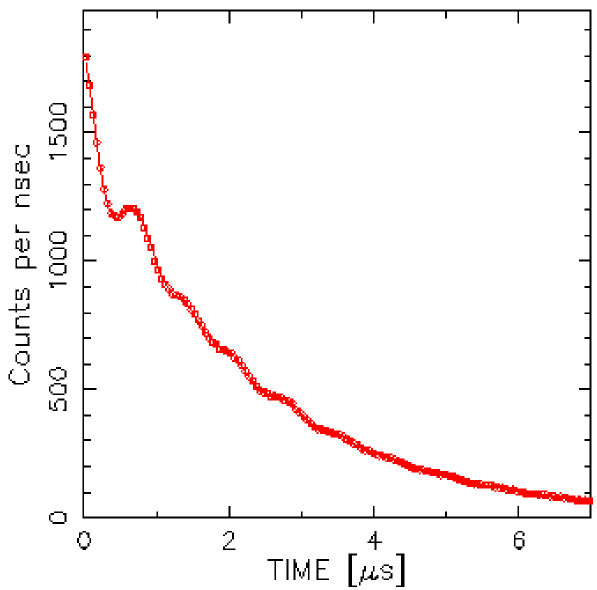
Muon Spin Resonance

Muon Spin Echo



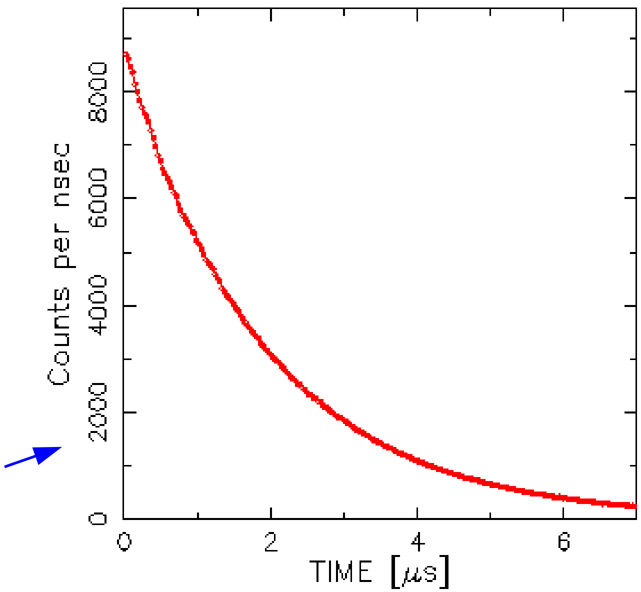
μ^+SR *vs.* μ^-SR

Typical time spectrum (histogram)

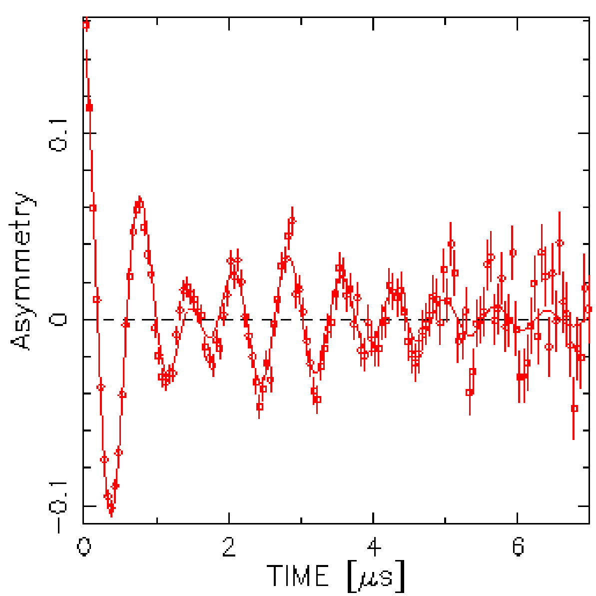


Single lifetime
τ_μ = 2.197 μs

Multiple lifetimes
(some very short!)

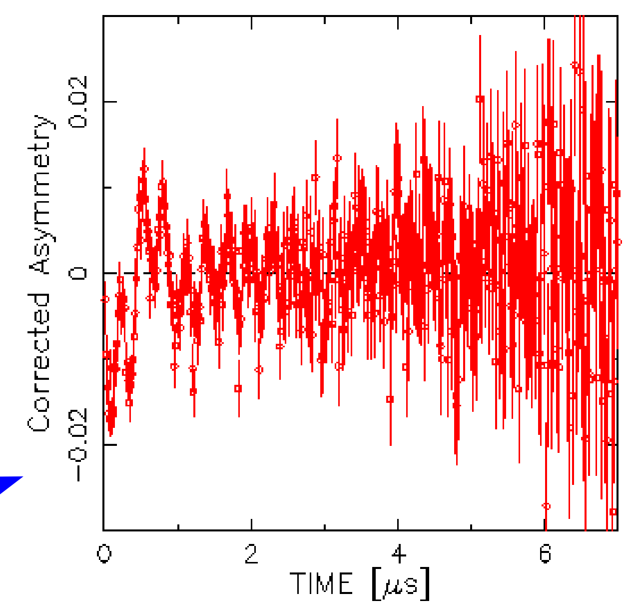


Asymmetry spectrum

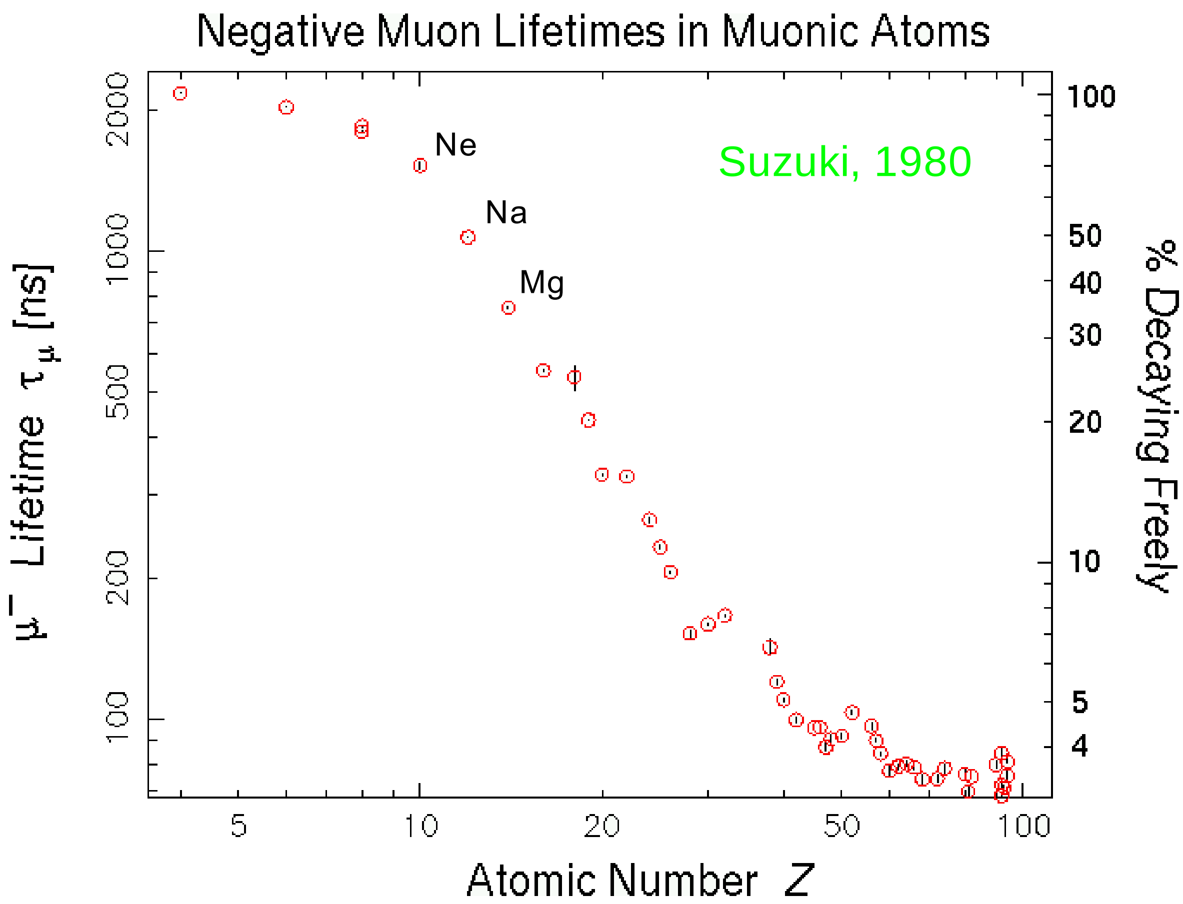


Large amplitudes

Small amplitudes



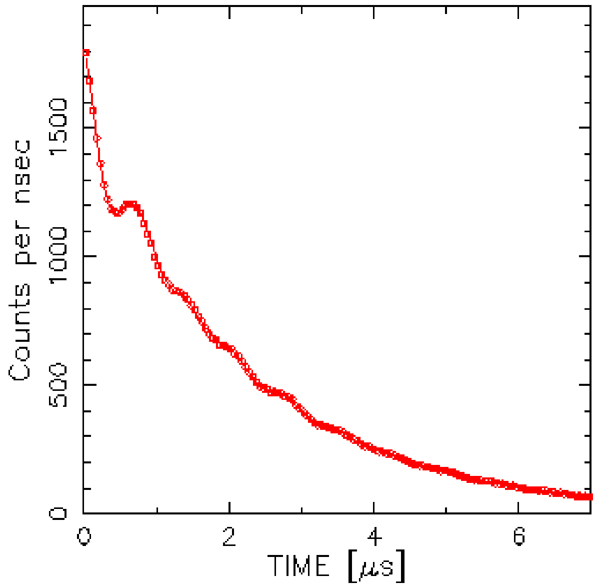
Nuclear μ^- Capture



$\mu^- p \rightarrow n\, \nu_\mu$ in a nucleus:

Rate exceeds that of $\mu^- \rightarrow e^-\, \nu_\mu \nu_e$ for $Z \geq 11$.

μ^+SR *vs.* μ^-SR



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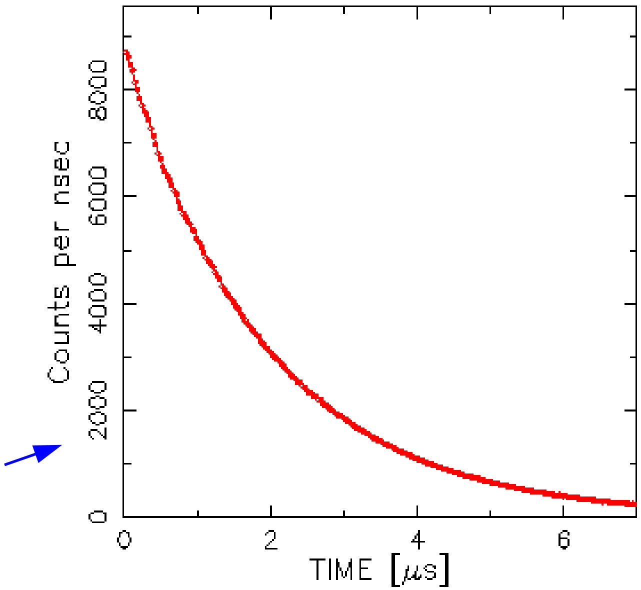

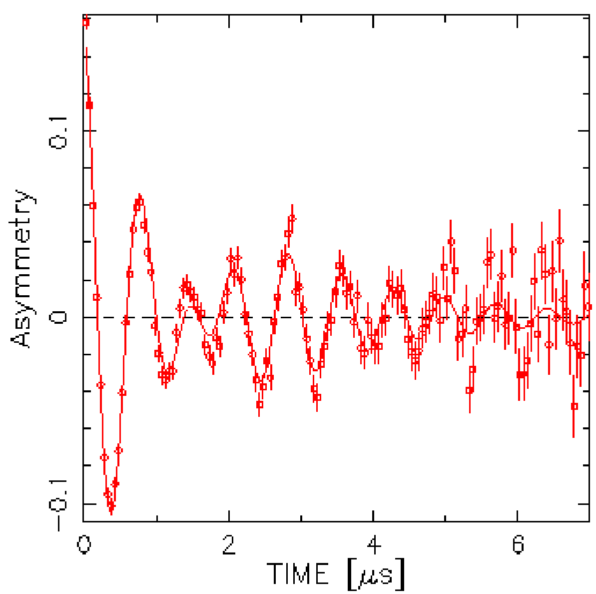

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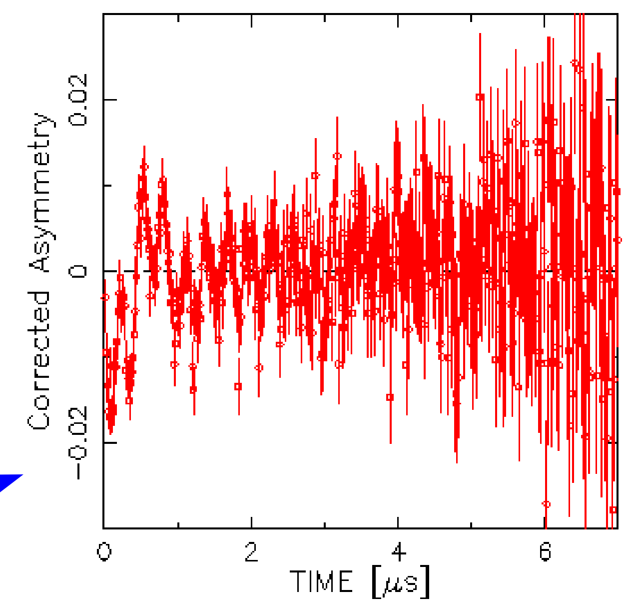
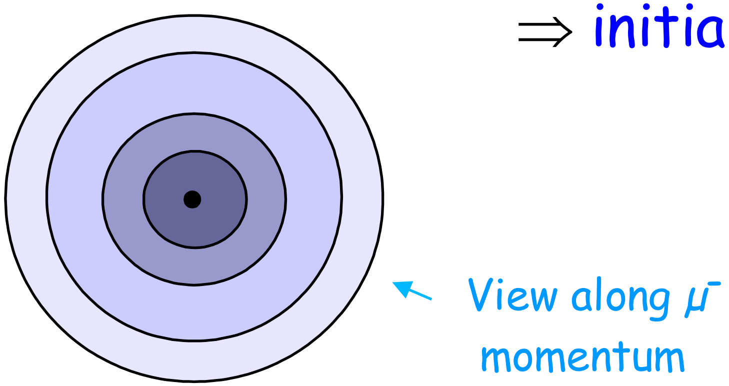


Atomic Capture & L•S Depolarization of μ^-

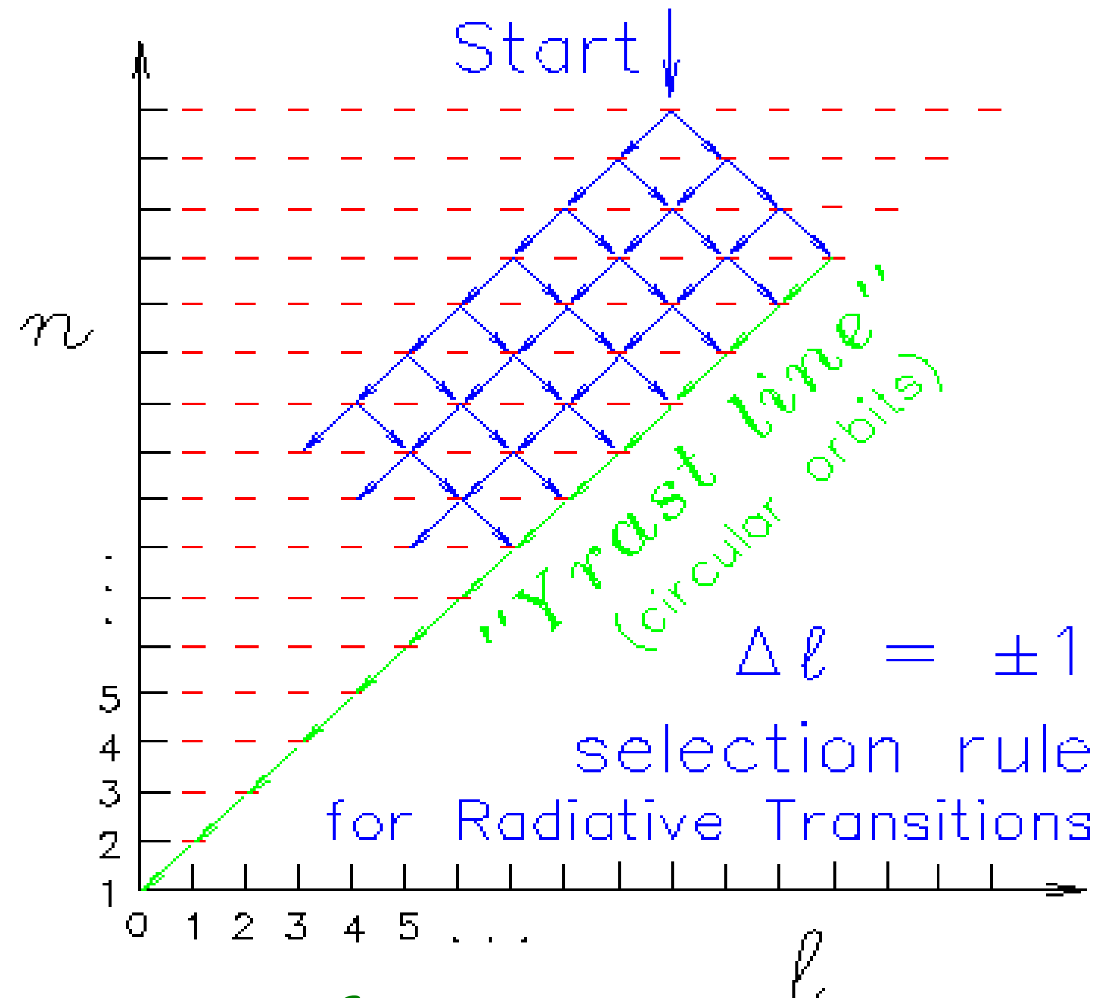
Large impact parameters are more probable
$\Rightarrow$ **initial orbits** tend to be **circular**.



Primitive Atomic Physics:

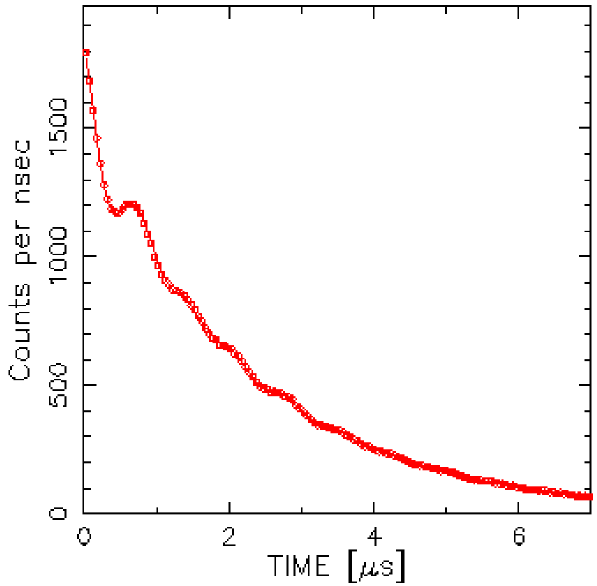
$$r_n = \frac{a_o}{Z}\left(\frac{m_e}{m}\right) n^2$$

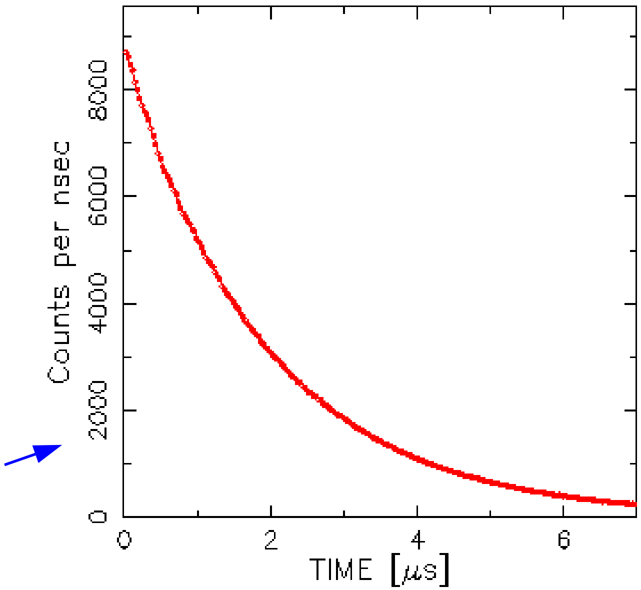
$$E_n = -\frac{13.6\ \text{eV}}{n^2}\, Z^2 \left(\frac{m}{m_e}\right)$$



L•S couplings **depolarize** μ^- **spin** **unless** **fast** Auger!

μ^+SR *vs.* μ^-SR





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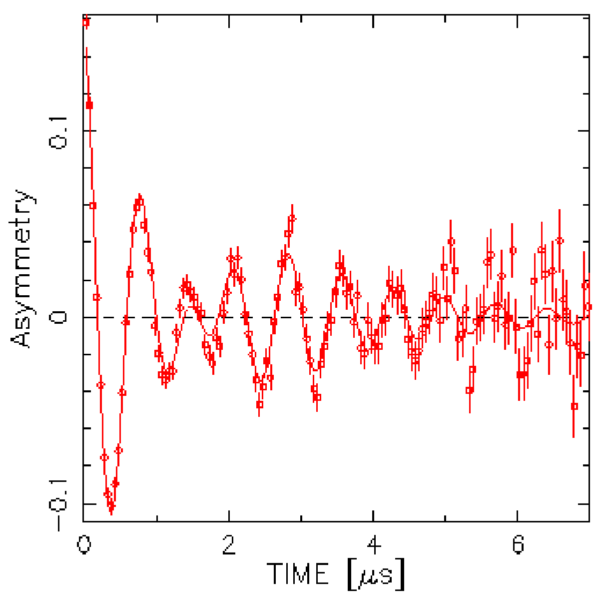

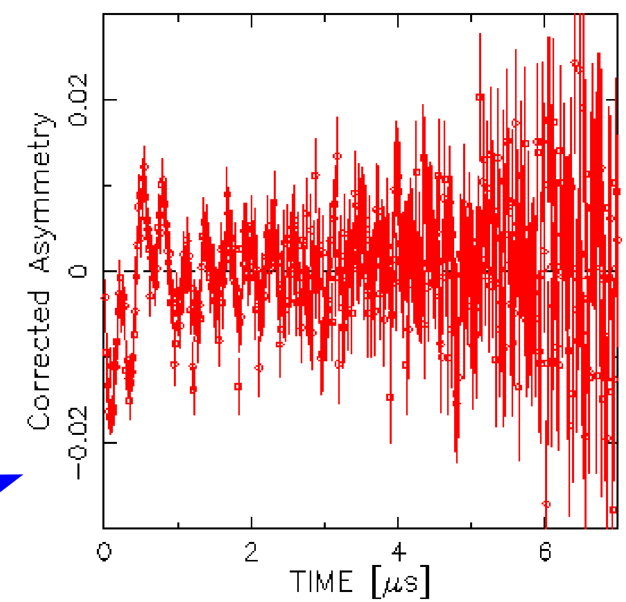

Asymmetry spectrum

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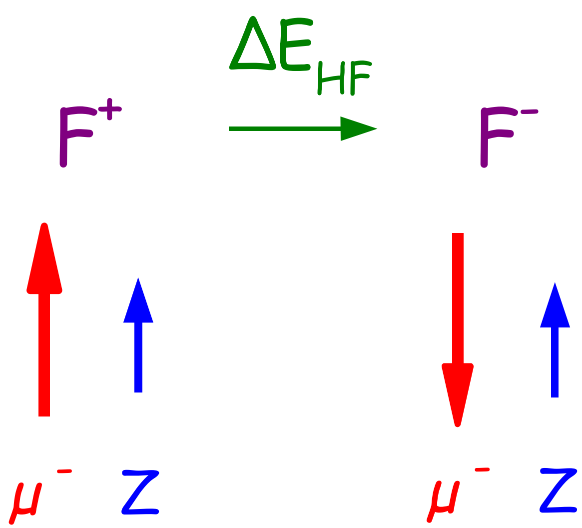
Characteristic precession frequencies of $F^{\pm}$ hyperfine states in selected low-Z muonic atoms



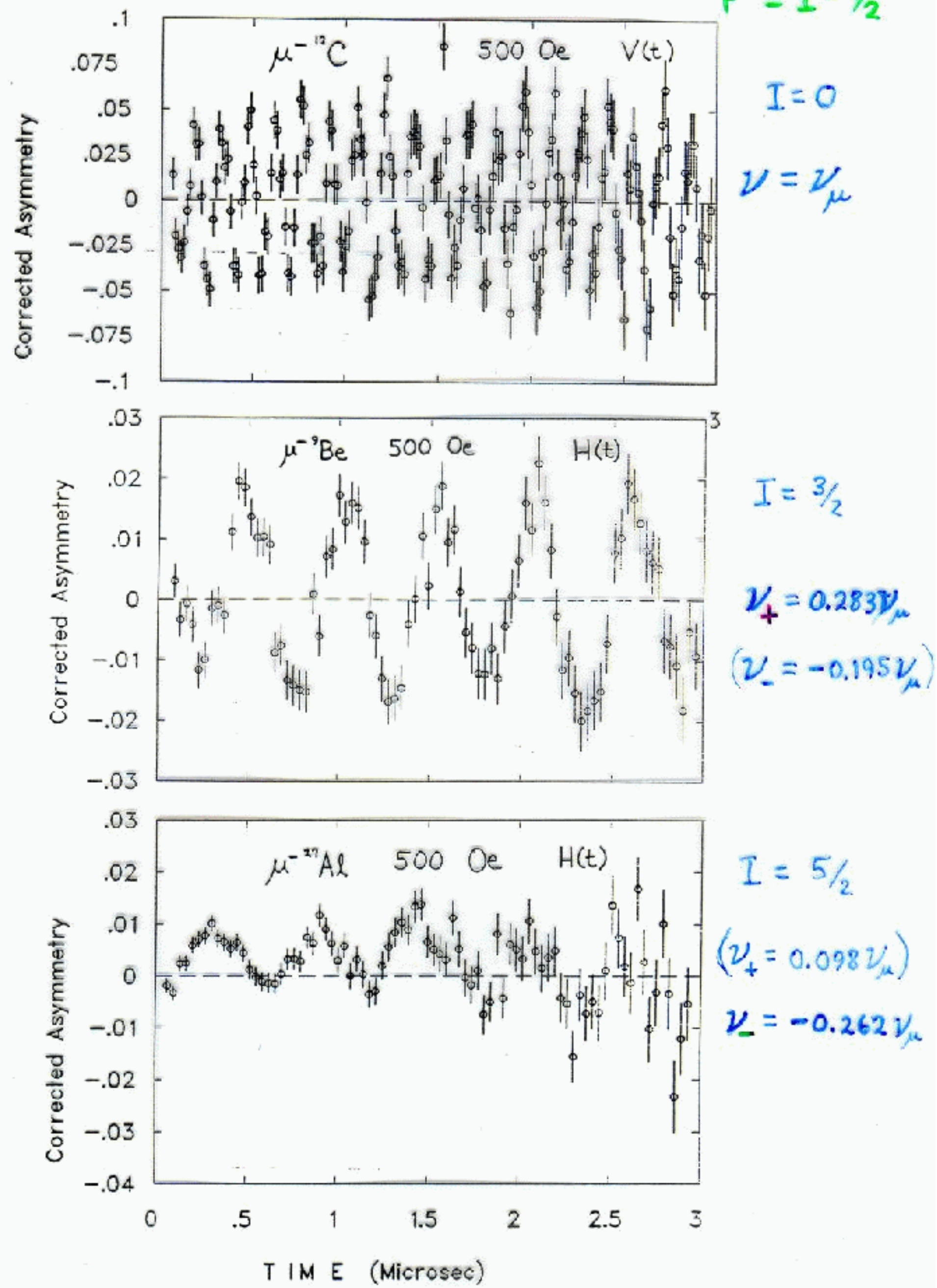
Isotope $^{A}El_{Z}$	Nucl. Spin	Natural Abundance	Moment μ_N/μ_μ	Frequency Ratios F^+/μ^-	F^-/μ^-
$^{1}H_{1}$	1/2	≈ 1	−0.314109	0.342946	0
$^{2}H_{1}$	1	≈ 0	−0.096436	0.301188	−0.397624
$^{6}Li_{3}$	1	0.07	−0.092454	0.302515	−0.394969
$^{7}Li_{3}$	3/2	0.93	−0.366253	0.158437	−0.402606
$^{9}Be_{4}$	3/2	≈ 1	0.132447	0.283112	−0.194814
$^{10}B_{5}$	3	0.19	−0.202528	0.113925	−0.181434
$^{11}B_{5}$	3/2	0.81	−0.302380	0.174405	−0.375992
$^{13}C_{6}$	1/2	0.01	−0.079000	0.460500	0
$^{14}N_{7}$	1	≈ 1	−0.045394	0.318202	−0.363596
$^{19}F_{9}$	1/2	≈ 1	−0.295666	0.352167	0
$^{23}Na_{11}$	3/2	≈ 1	−0.249406	0.187648	−0.353919
$^{25}Mg_{12}$	5/2	0.10	0.096197	0.182700	−0.144221
$^{27}Al_{13}$	5/2	≈ 1	−0.409555	0.098408	−0.262229

TF - μ^- Spin Rotation in Muonic Atoms (μ^-Z) with NUCLEAR SPIN :

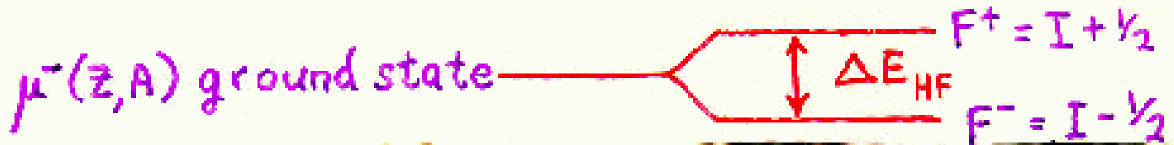
JHB 1982

$F^+ = I + 1/2$

$F^- = I - 1/2$



HFS of Selected "Bare" Muonic Atoms:



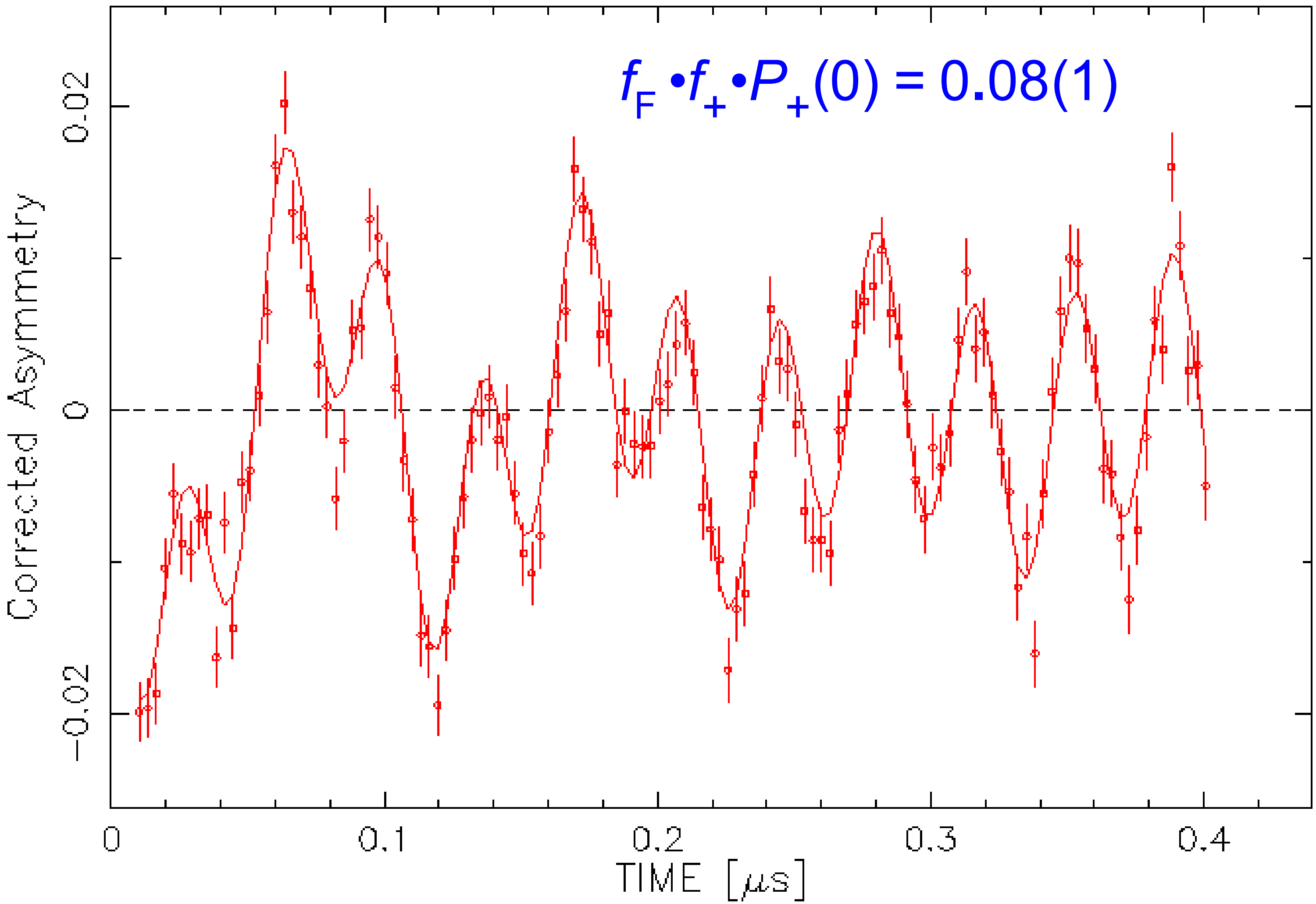
^{A}ELEMENT$_{Z}$	ΔE_{HF} (eV)	effective field B_{HF} (G)	Lowest e^- SHELL ejected [B.E. (eV)]	$F^+ \to F^-$ RATE R (μs^{-1}) THEOR	EXPT	REF
$^{1}H_{1}$	0.1817	3.24×10^{9}	NONE	1.3×10^{4} (ρ/ρ_0)		Ponomarev '78; Smilga & Fil'chenkov '83
$^{3}He_{2}$	1.373	2.45×10^{10}	NONE	nil		
$^{11}B_{5}$	18	3.2×10^{11}	L_1 [9.3]	0.25	0.33(5)	Winston '63; Favart et al '70
$^{13}C_{6}$	11	2.0×10^{11}	L_2 [8.3]		0.026(12)	Boom '83
$^{14}N_{7}$	7.5	1.3×10^{11}	NONE	nil	0.092(33)	"
$^{19}F_{9}$	126	2.2×10^{12}	L_1 [30]	5.8	6.1(7) [neutrons]	Winston '63
$^{27}Al_{13}$	263	4.7×10^{12}	L_1 [89]	41	41(9)	" & Brewer '83
$^{51}V_{23}$	1220	2.2×10^{13}	L_1 [565]	700		Winston '63
$^{93}Nb_{41}$	~5000	$\sim10^{14}$				
$^{209}Bi_{83}$	4660	8.3×10^{13}	MEASURED VIA SPLITTING of X-RAY ENERGY			

μ^-SR in Teflon $[(CF_2)_n]$:

High frequency signal: μ^-C

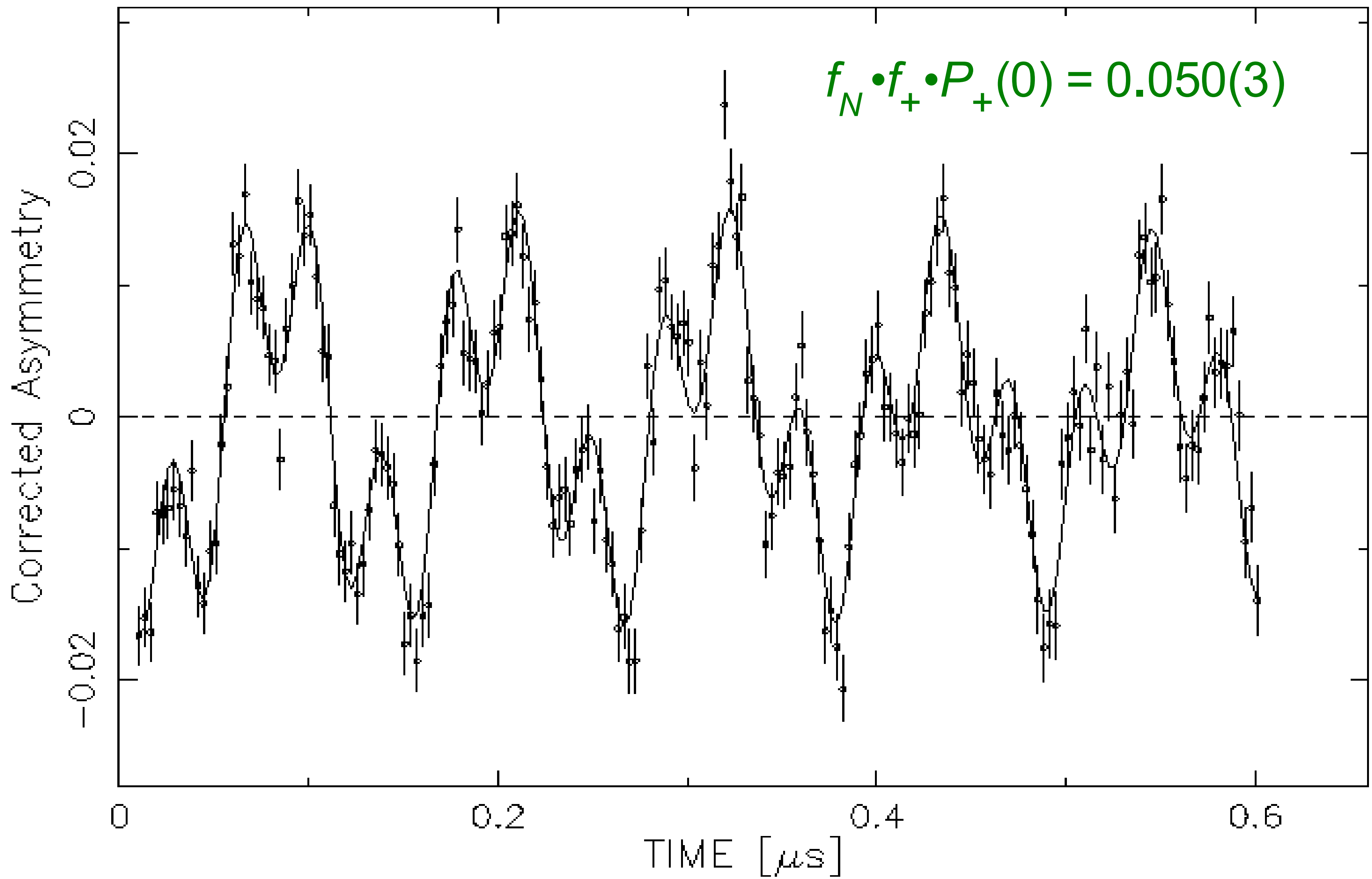
Low frequency signal:

F^+ (triplet) state of $^{19}F\mu^-$ —HF transition rate, $R_{HF} = 5.2(5)\ \mu s^{-1}$→ F^- (singlet) state



μ^-SR in Melamine ($C_3H_6N_6$):

High frequency signal: μ^-C Low frequency signal: F^+ state of $^{14}N\mu^-$

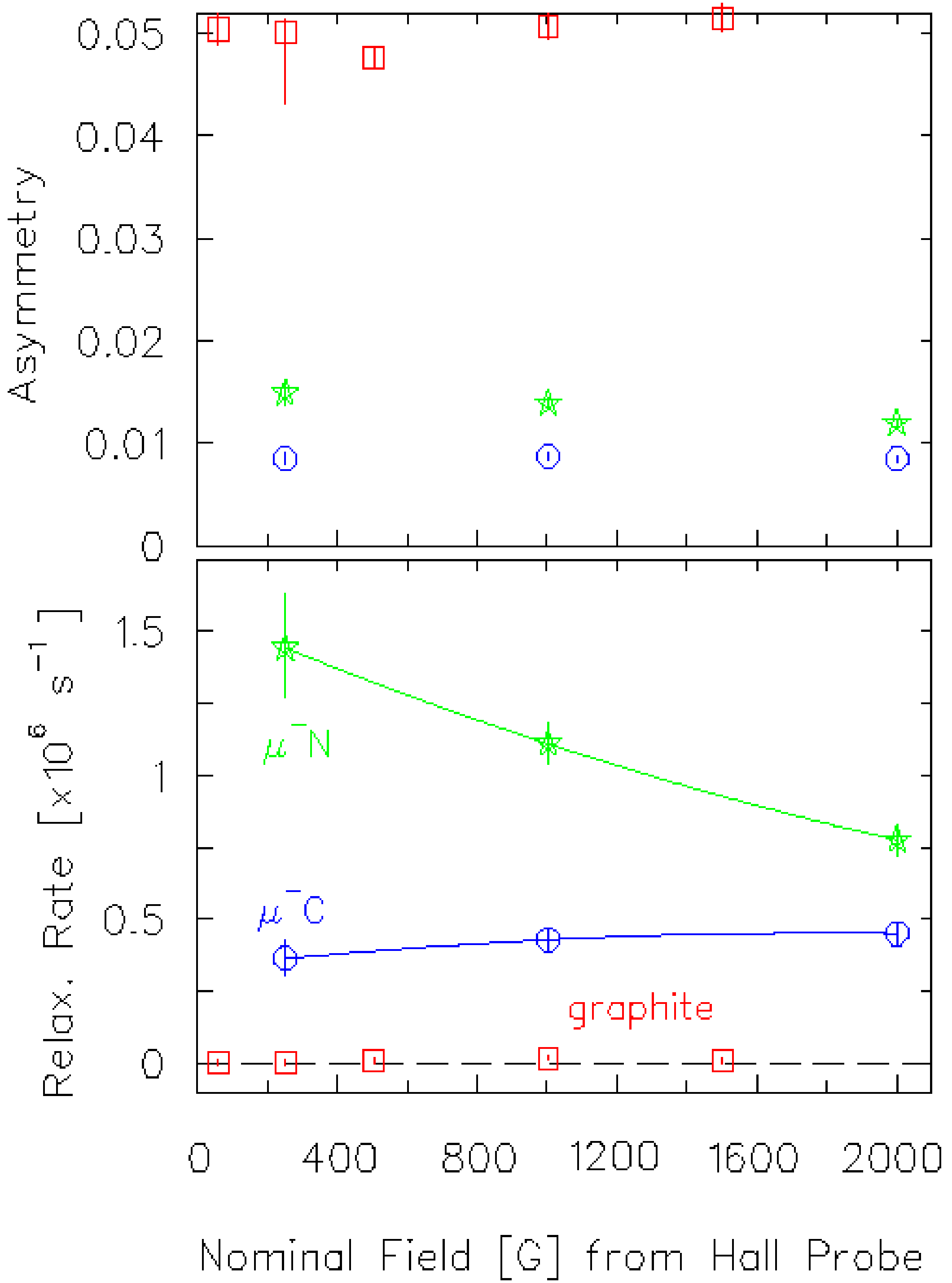


$\mu^{-}SR$ in Melamine ($C_3H_6N_6$)

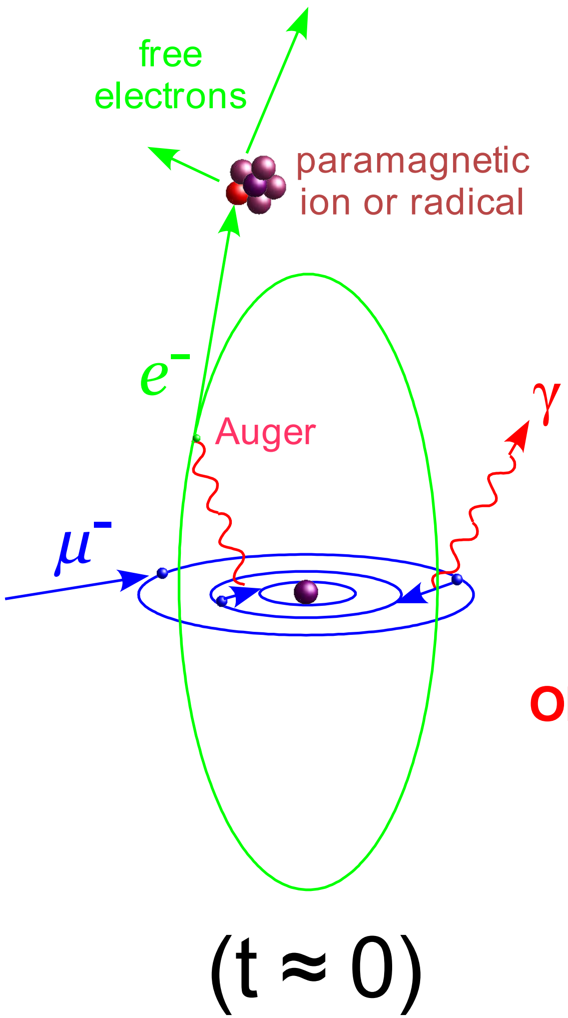
$f_N \bullet f_+ \bullet P_+(0)$ decreases with ***B***

Λ_N decreases with ***B*** and is much too large to be caused by either R_{HF} or neighbouring nuclear dipoles.

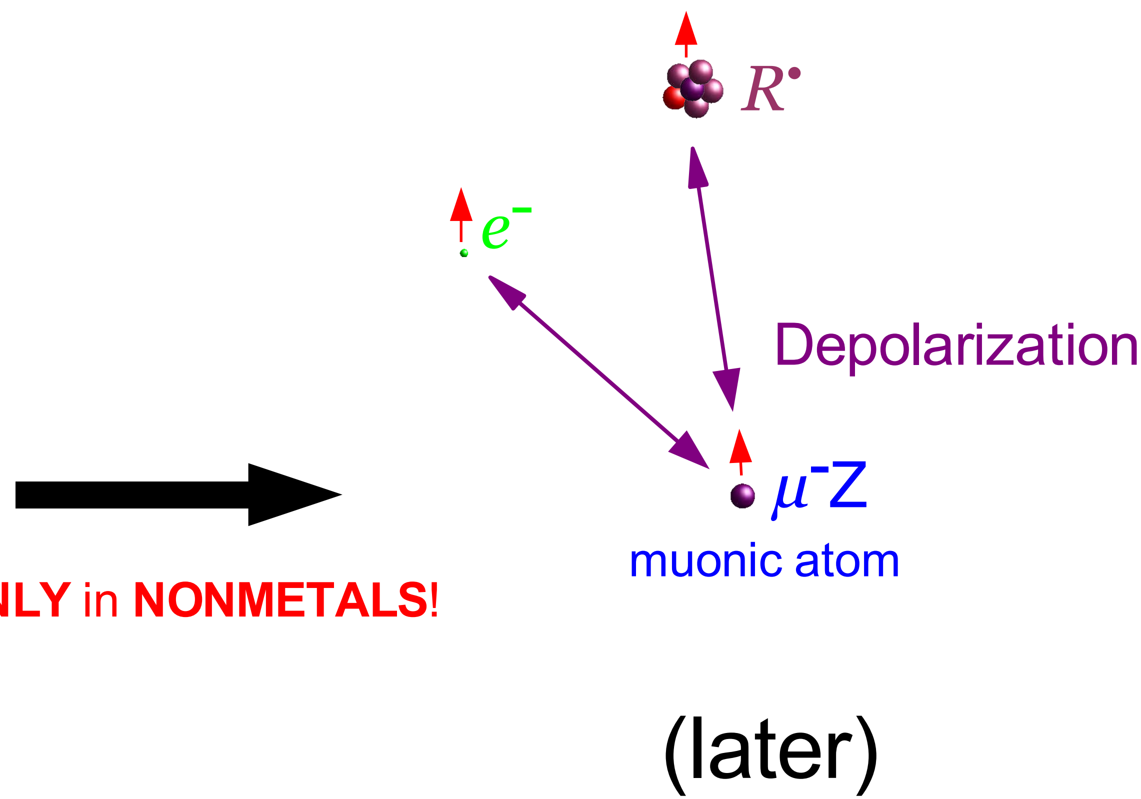
Λ_C is also anomalously fast.



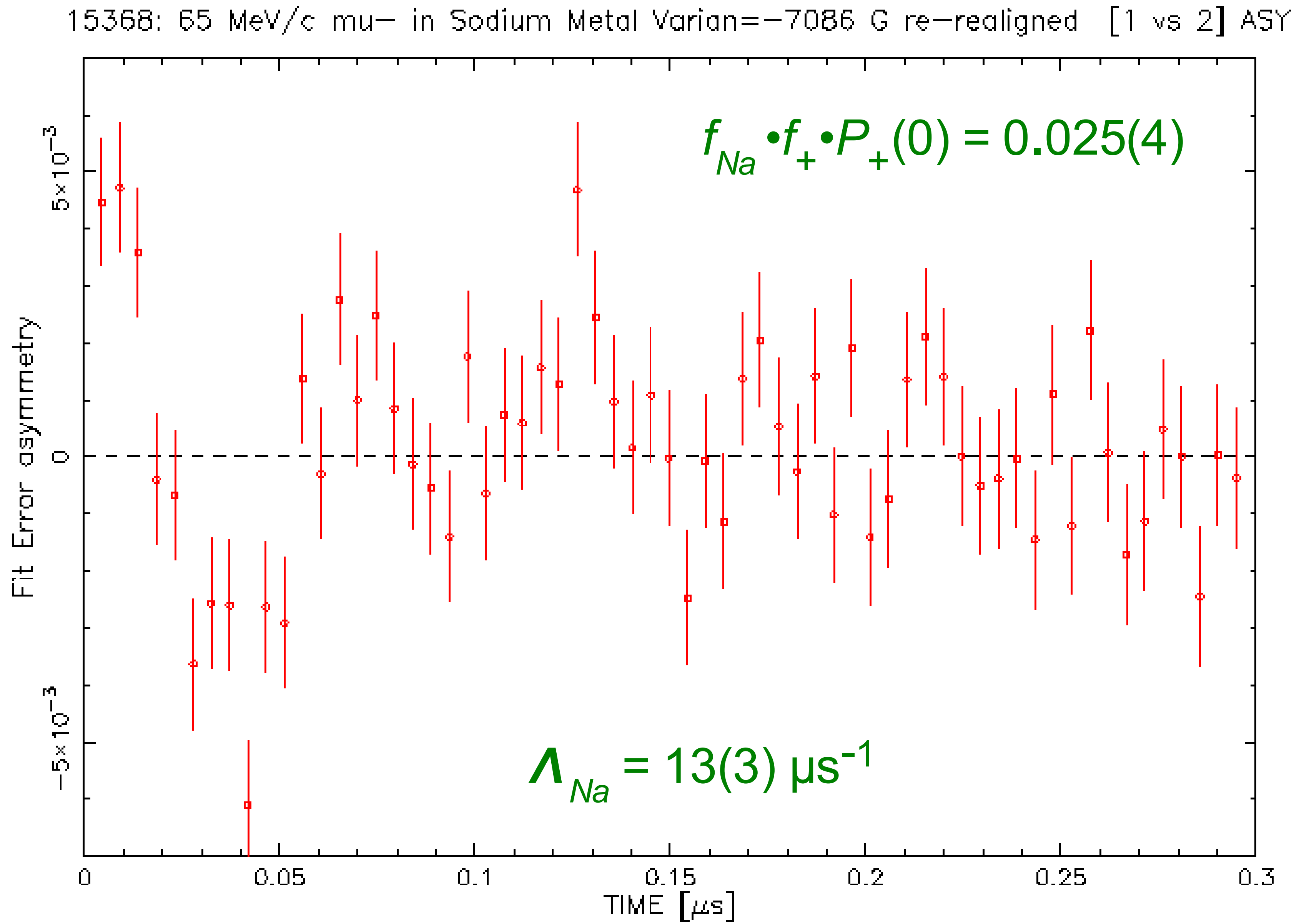
"Coulomb Explosion" Leftovers



ONLY in **NONMETALS**!



First observation of $\mu^{-}SR$ in Sodium Metal



Finis

Linux

and

OpenOffice

RULE!

"Themes" in $\mu^{\pm}SR$

μ^+ only (?)

Muonium as light Hydrogen

(Mu = μ^+e^-) (H = p^+e^-)

- **Mu vs. H atom Chemistry:**
  - gases, liquids & solids
  - Best test of reaction rate theories.
  - Study "unobservable" H atom rxns.
  - Discover new radical species.
- **Mu vs. H in Semiconductors:**
  - Until recently, $\mu^+SR \longrightarrow$ **only** data on metastable H states in semiconductors!

μ^+ or μ^-

The Muon as a Probe

- **Probing Magnetism:** unequalled sensitivity
  - Local fields: electronic structure; ordering
  - Dynamics: electronic, nuclear spins
- **Probing Superconductivity:** (esp. HT_cSC)
  - Coexistence of SC & Magnetism
  - Magnetic Penetration Depth λ
  - Coherence Length ξ

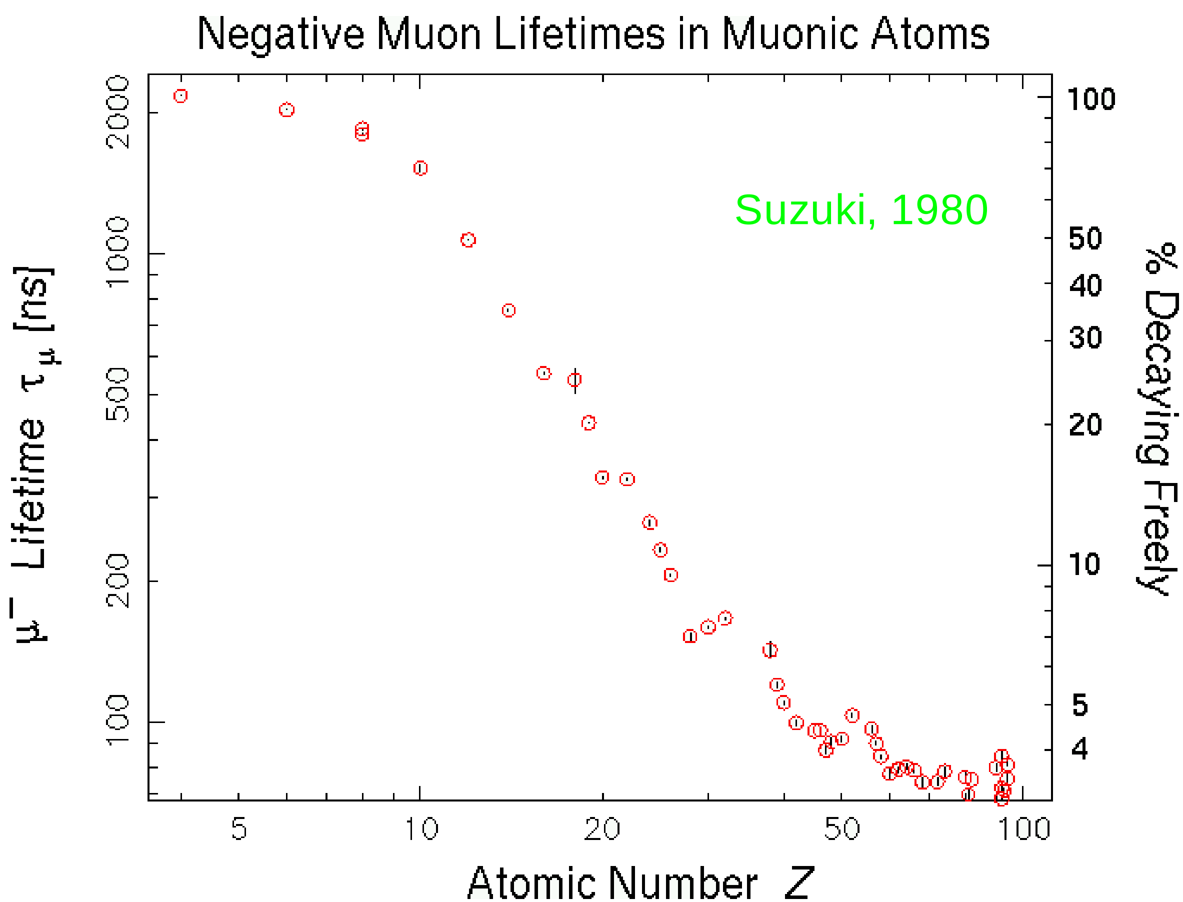
- **Quantum Diffusion:** μ^+ in metals (compare H^+); Mu in nonmetals (compare H).
- **Ultra-Heavy Hydrogen:** neutral muonic helium ($\alpha^{++}\mu^-e^-$) has m ≈ 4.11 m_H

$\mu^- SR$:

It is easy to get the impression that only positive muons are employed in μSR.

Although most μSR is $\mu^+ SR$, it is often desirable to use negative muons in the same way, albeit with more difficulty.

DRAWBACKS of $\mu^- SR$	→	PROPOSED **MITIGATIONS**
L•S Depolarization in the atomic cascade	→	"Tag" events with specific muonic X-rays
Nuclear Muon Capture: short lifetimes, few decay e^-	→	Look for neutron asymmetries in heavier elements
Giant Hyperfine Interaction with nonzero-spin nuclei	→	Observe characteristic $F^{\pm}$ precession signals



Nuclear μ^- Capture

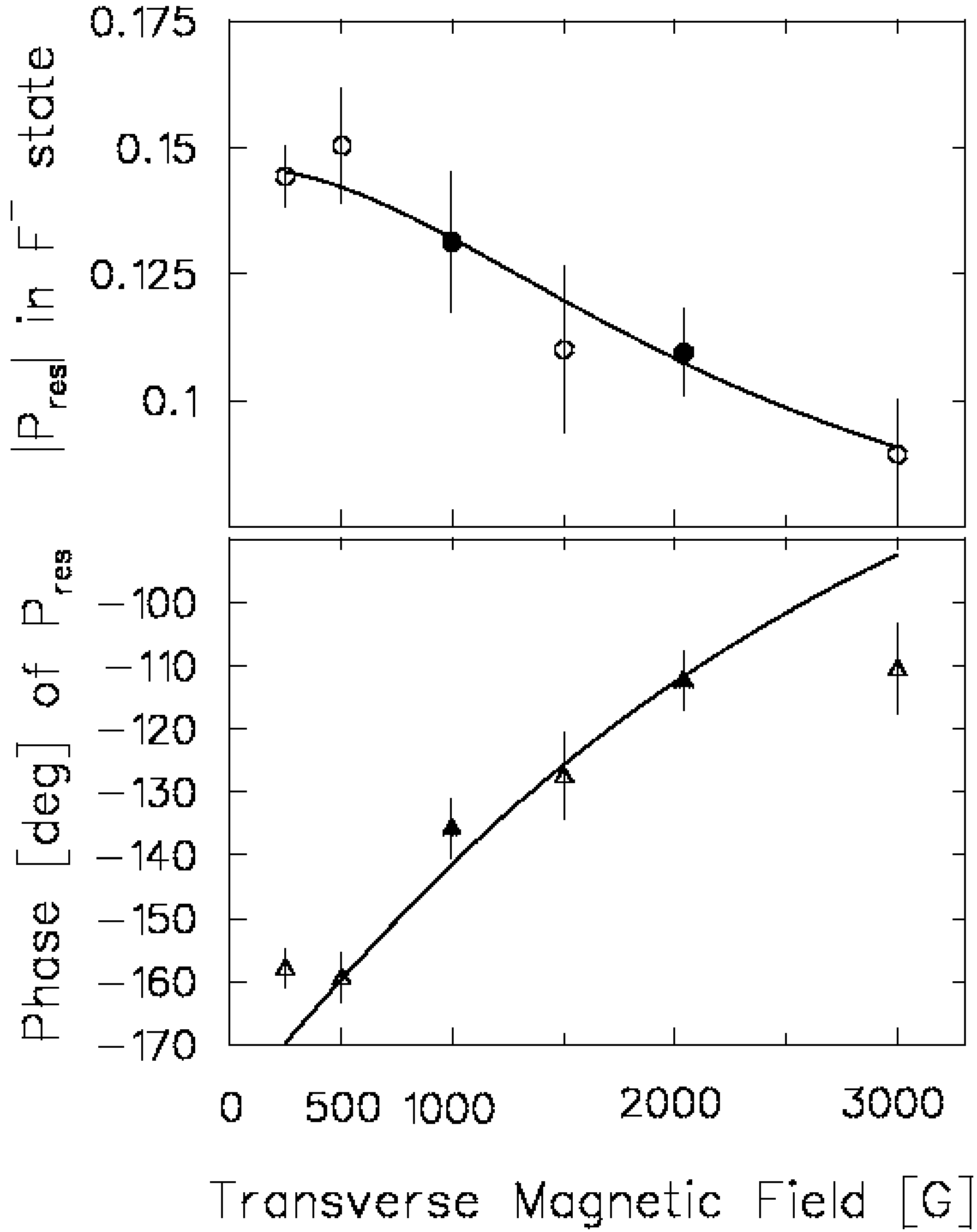
PROBLEM

$\mu^- p \rightarrow n \, \nu_\mu$ in a nucleus: rate comparable to that of $\mu^- \rightarrow e^- \, \nu_\mu \nu_e$ for $Z \geq 10$.

Possible Help: Many times a **fast neutron** is emitted from nuclear μ^- capture. Very few measurements have been made of the correlation of that neutron with the muon's spin direction. If cases are found where this **neutron asymmetry** is sizeable, we may be able to do neutron-triggered ***μ^-SR***, for which the event rate can be higher than in ***μ^+SR***.

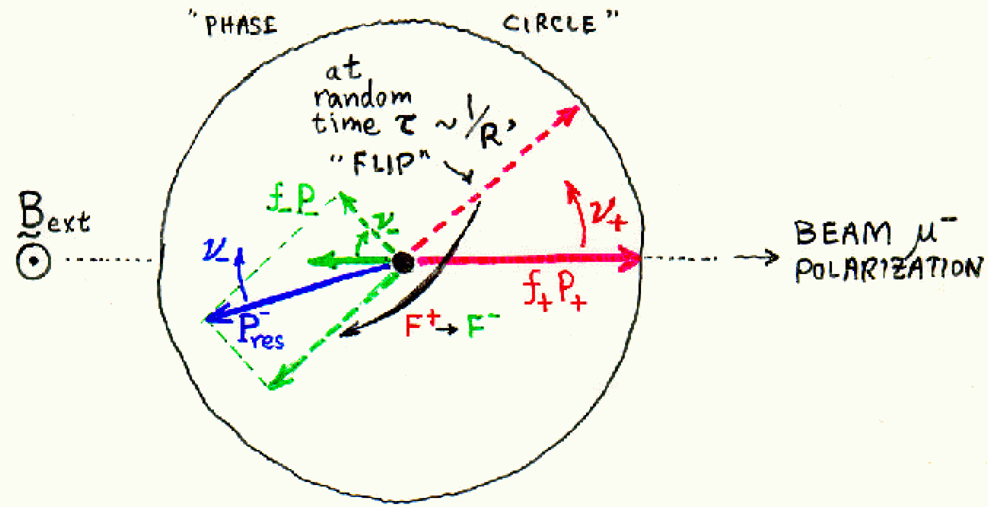
μ^-SR in ^{27}Al:

Residual F^- polarization after initial precession in F^+ HF state followed by spin-flip transition to F^- state



R_{HF} due to Auger of core electrons: measured value is consistent with the calculation of Winston (1963): $R_{HF} \approx 41\ \mu s^{-1}$.

"P^-_{res}(B) METHOD" for MEASURING $f_\pm P_\pm$ & R for LARGE R :



- MECHANISM RESULTS IN "EASILY" VISIBLE F^- PRECESSION FOR "ALL" $Z \gtrsim 20$ (i.e., where R is too fast to allow direct observation of F^+ state). (even in ^{93}Nb ! [?])

- In some cases (e.g., ^{23}Na or ^{27}Al), studying P^-_{res}(B) [APPARENT INITIAL AMPLITUDE & PHASE of F^- SIGNAL] as a function of field allows determination of f_+P_+ and f_-P_-.

E.g., in ^{27}Al, $f_+P_+ = 0.21(9)\, P_c$ vs 0.333 THEOR.

$f_-P_- = +0.045(20)\, P_c$ vs NEGATIVE predicted value!

NEED MORE DATA to CHECK BUKHVOSTOV!

Relativistic Shift of μ^- Frequency