Relativistic Shifts of g_μ in Muonic Atoms

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Precise measurements of the magnetogyric ratios of negative muons in the ground states of muonic atoms of ^{12}C, ^{16}O, ^{24}Mg, ^{28}Si, ^{32}S, ^{40}Ca, ^{nat}Ti, ^{nat}Zn, ^{nat}Cd and ^{nat}Pb have been achieved in high field μ^- spin precession experiments using a backward muon beam with a substantial transverse spin polarization. The precision for ^{12}C μ^- is ± 23 ppm, of which only 6 ppm is statistical; for ^{nat}Zn μ^- the precision is ± 269 ppm and for ^{nat}Pb μ^- it is ± 0.23%. Such results may provide a new testing ground for quantum electrodynamics in very strong Coulomb fields.

"Who Ordered That?"

- I.I. Rabi, around 1946,
upon learning of the "heavy electron"

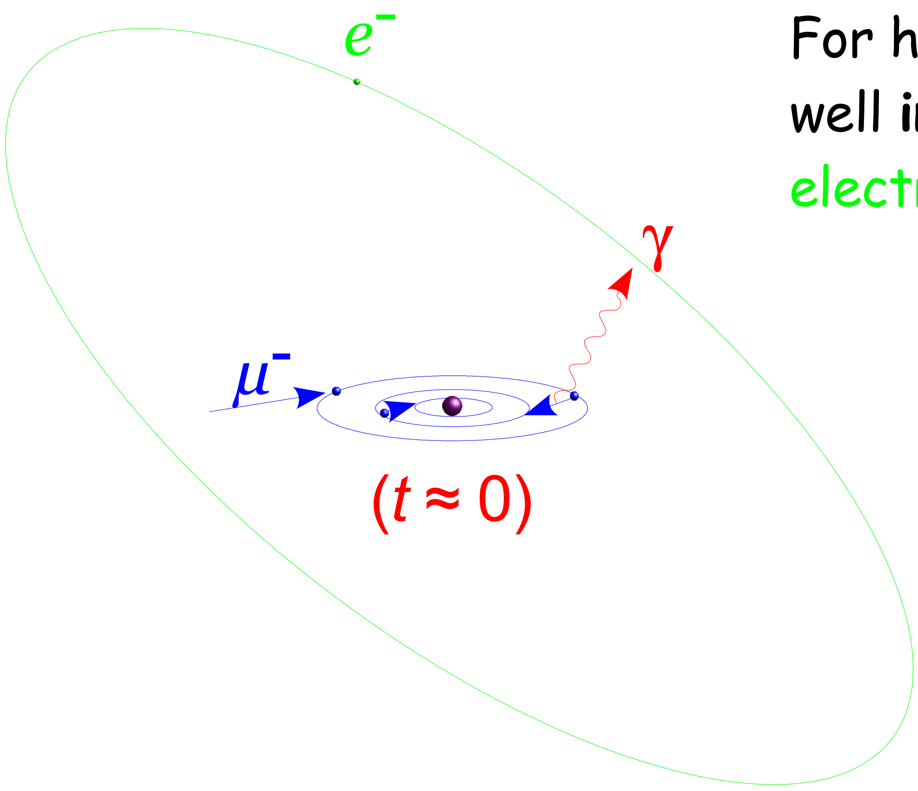
μ^-

The answer is now finally available:

I did, and I'll have mine with a side of fries!

Deeply Bound Hydrogenic States

Muonic orbitals are **207** times **smaller** than electronic.



For high Z, the muon is well **inside** even core electronic orbitals.

Relativistic shift of lepton's **magnetogyric ratio** (Breit, 1924): for pointlike nuclei,

$$\frac{g_{\text{free}} - g}{g_{\text{free}}} = \frac{2}{3}\left(1 - \sqrt{1 - \alpha^2 Z^2}\right) \approx \frac{1}{3}\left(\frac{\bar{v}}{c}\right)^2$$

Facility & Method used:

μSR *otation* / *elaxation* / *esonance*

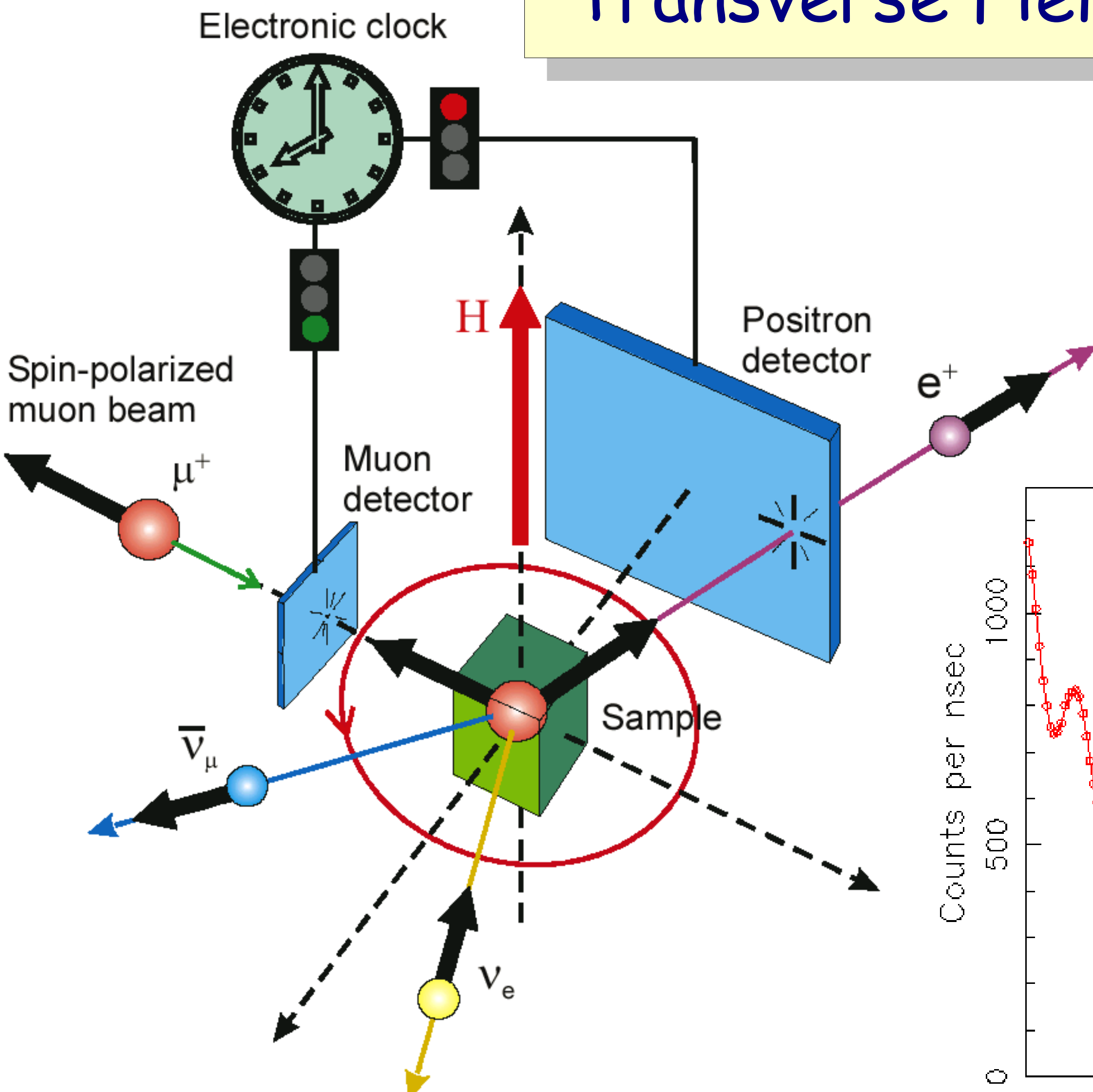
m	*s*	Applied*
u	*p*	Elementary
o	*i*	Particle
n	*n*	Physics

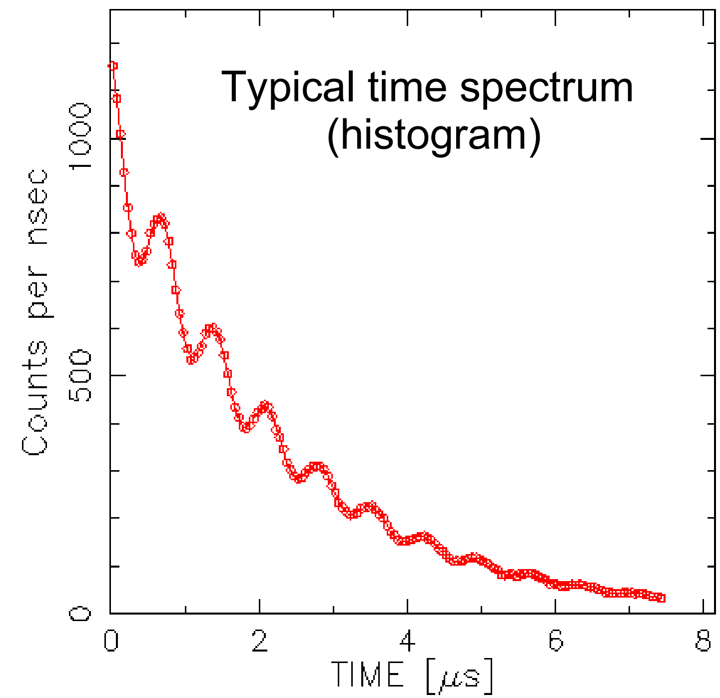
*(to basic research in
Materials Science
and Chemistry)

[and "Fundamental" Physics]

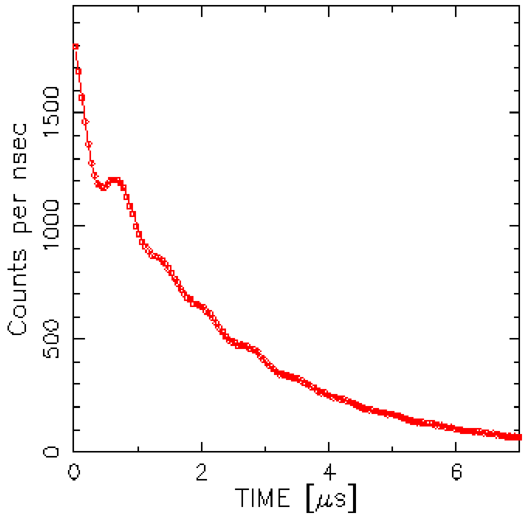
Visit **http://musr.org**

Transverse Field (TF) μ^+SR





μ^+SR *vs.* μ^-SR

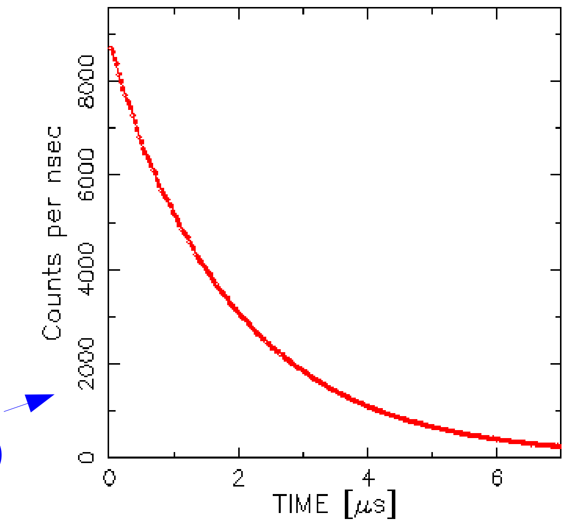


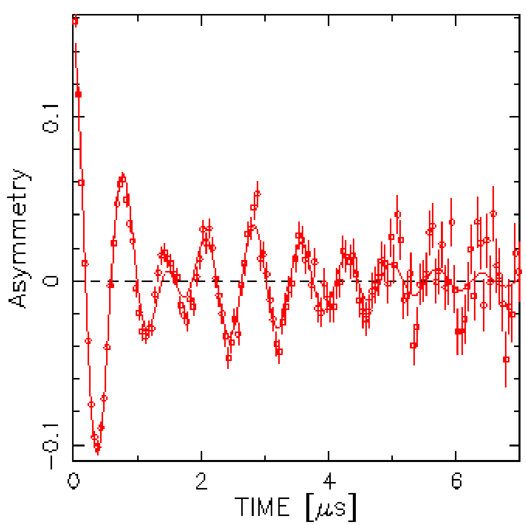
Typical time spectrum (histogram)

Single lifetime

τ_μ = 2.197 μs

Multiple lifetimes
(some very short!)

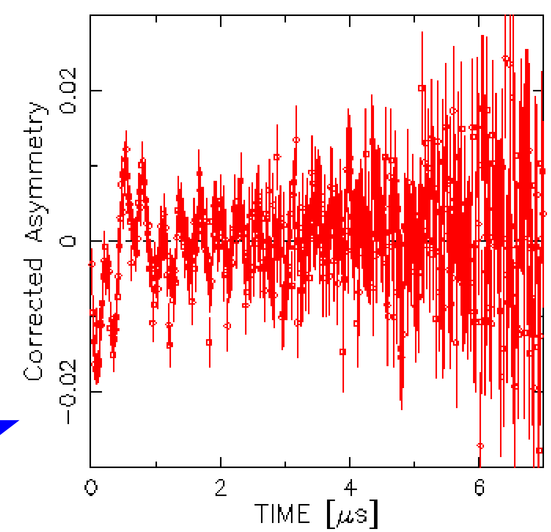




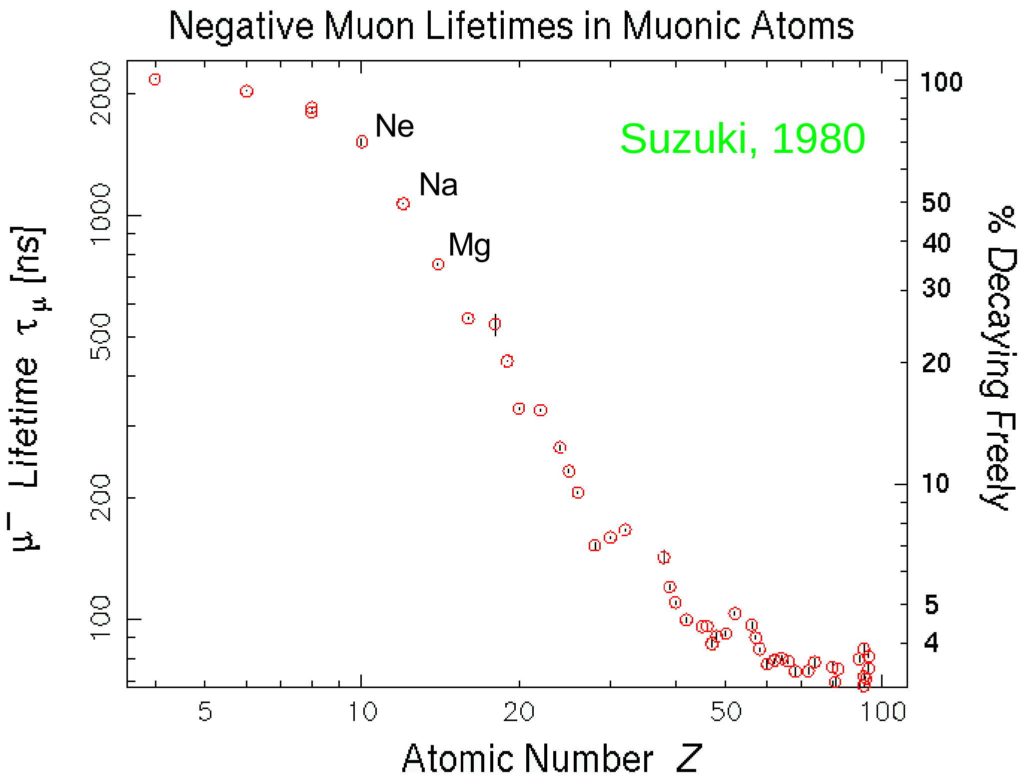
Asymmetry spectrum

Large amplitudes

Small amplitudes



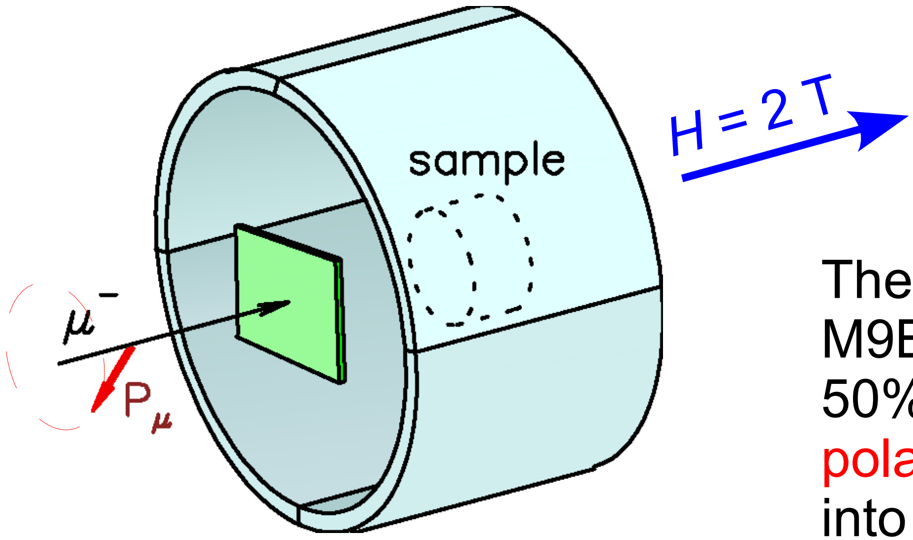
Nuclear μ^- Capture



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

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

Helios on M9B



The *Helios* μSR spectrometer of the TRIUMF CMMS facility enables TF-μSR at fields up to 2 T, using 4 *e* detectors in a cylindrical array around the target sample.

The negative muon beam of M9B at TRIUMF has nearly 50% transverse spin polarization, allowing injection into a strong magnetic field parallel to the beam momentum but (partially) transverse to the spins. Strong TF allows high precision measurements of the muon Larmor frequency and thus of g_μ.

Raw Data

Sample	Frequency [MHz]
μ^+ in graphite	271.69888 ± 0.00072
μ^+ in Al metal	271.58520 ± 0.00038
μ^- on ^{12}C (graphite)	271.3684 ± 0.0016
μ^- on ^{16}O (H_2O)	271.258 ± 0.010
μ^- on ^{24}Mg (metal)	270.9259 ± 0.0027
μ^- on ^{28}Si	270.6502 ± 0.0069
μ^- on ^{32}S (powder)	270.406 ± 0.008
μ^- on ^{40}Ca (metal)	270.164 ± 0.069
μ^- on Ti (metal)	269.719 ± 0.066
μ^- on Zn (metal)	268.440 ± 0.072
μ^- on Cd (metal)	$265.73^{+0.46}_{-0.57}$
μ^- on Pb (metal)	$264.50^{+0.59}_{-0.62}$

Only *statistical* uncertainties are shown, to emphasize the potential accuracy of such measurements.

In this experiment, *systematic* uncertainties were dominant for the *light* elements.

Results

Sample	g_μ Shift [%]
μ^+ in graphite	0.0499 ± 0.0023
μ^+ in Al metal	0.0080 ± 0.0004
μ^- on ^{12}C (graphite)	-0.0718 ± 0.0023
μ^- on ^{16}O (H_2O)	-0.1124 ± 0.0042
μ^- on ^{24}Mg (metal)	-0.2348 ± 0.0025
μ^- on ^{28}Si	-0.3363 ± 0.0034
μ^- on ^{32}S (powder)	-0.4262 ± 0.0036
μ^- on ^{40}Ca (metal)	-0.5155 ± 0.025
μ^- on Ti (metal)	-0.679 ± 0.024
μ^- on Zn (metal)	-1.150 ± 0.026
μ^- on Cd (metal)	$-2.15^{+0.17}_{-0.21}$
μ^- on Pb (metal)	$-2.60^{+0.22}_{-0.23}$

Fractional shifts (in %) of the negative muon's *g* factor due to ***relativistic*** effects in the deeply bound ground state of the muonic atom.

(In Pb, most of the muon's orbital lies *inside* the nucleus!)

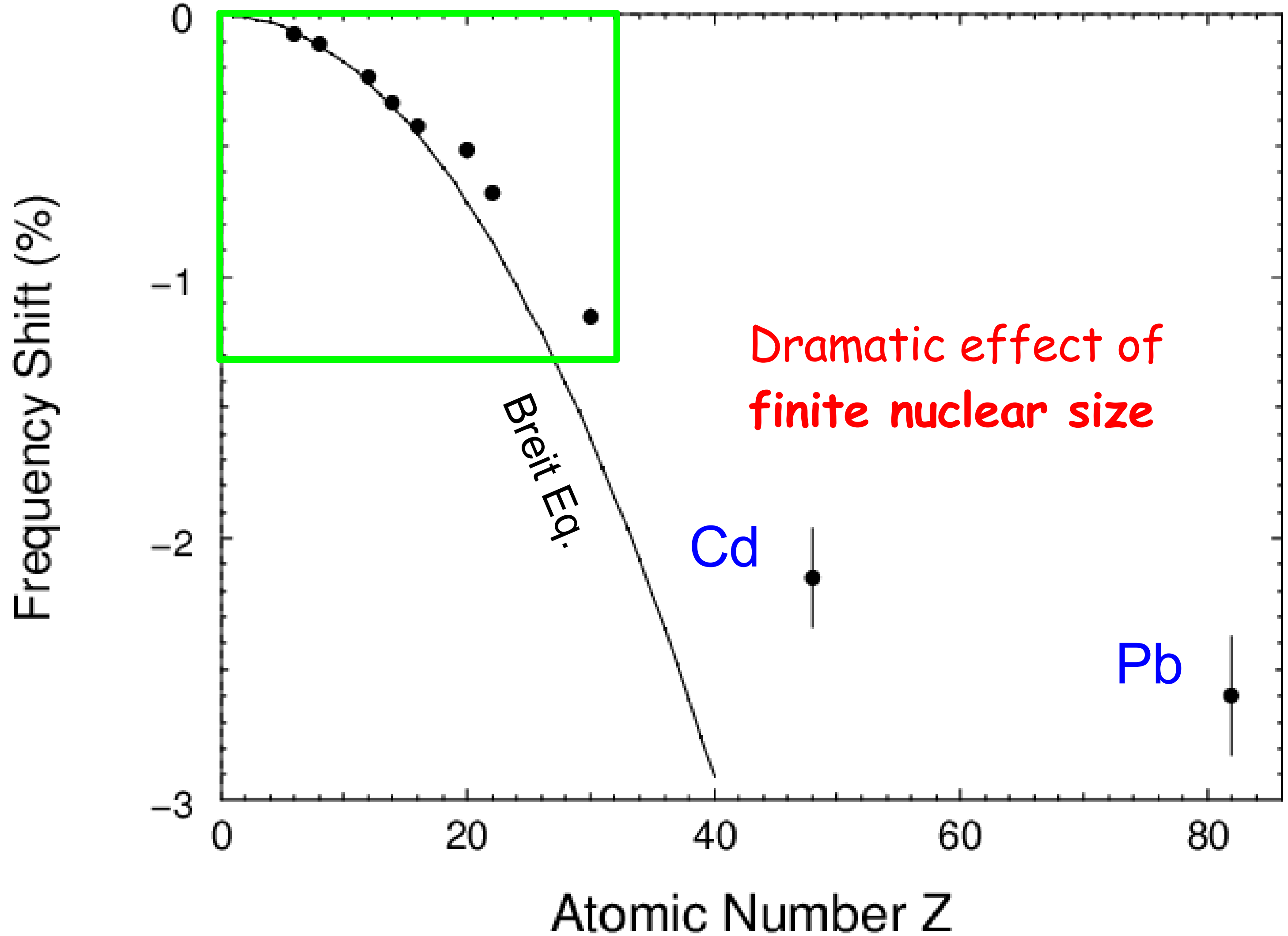
So what? What does it all **mean**?

For pointlike nuclei (Breit, 1928):

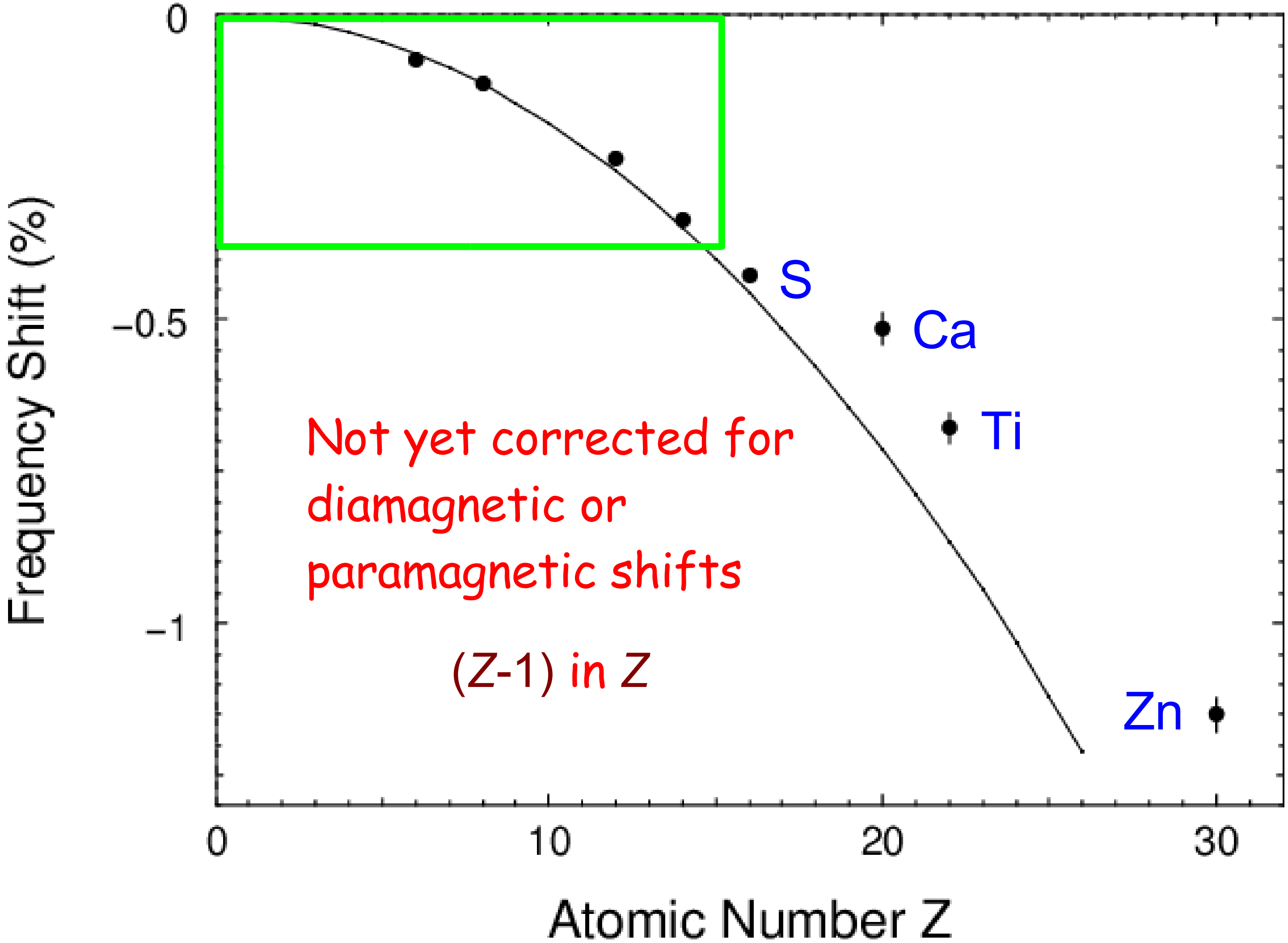
$$\frac{g_{\rm free} - g}{g_{\rm free}} = \frac{2}{3}\left(1 - \sqrt{1-\alpha^2 Z^2}\right) \approx \frac{1}{3}\left(\frac{\bar{v}}{c}\right)^2$$

Improved by Margeneau (1940) and later by Ford *et al.* (1962) in response to first μ^-SR measurements by Hutchinson *et al.* (1961) in light elements. First high-*Z* measurements by Yamazaki *et al.* (1974) challenged by Mamedov *et al.* (2003). Meanwhile electronic spectroscopy of high *Z* hydrogenlike ions has become possible [*e.g.* Häffner *et al.* (2000)].

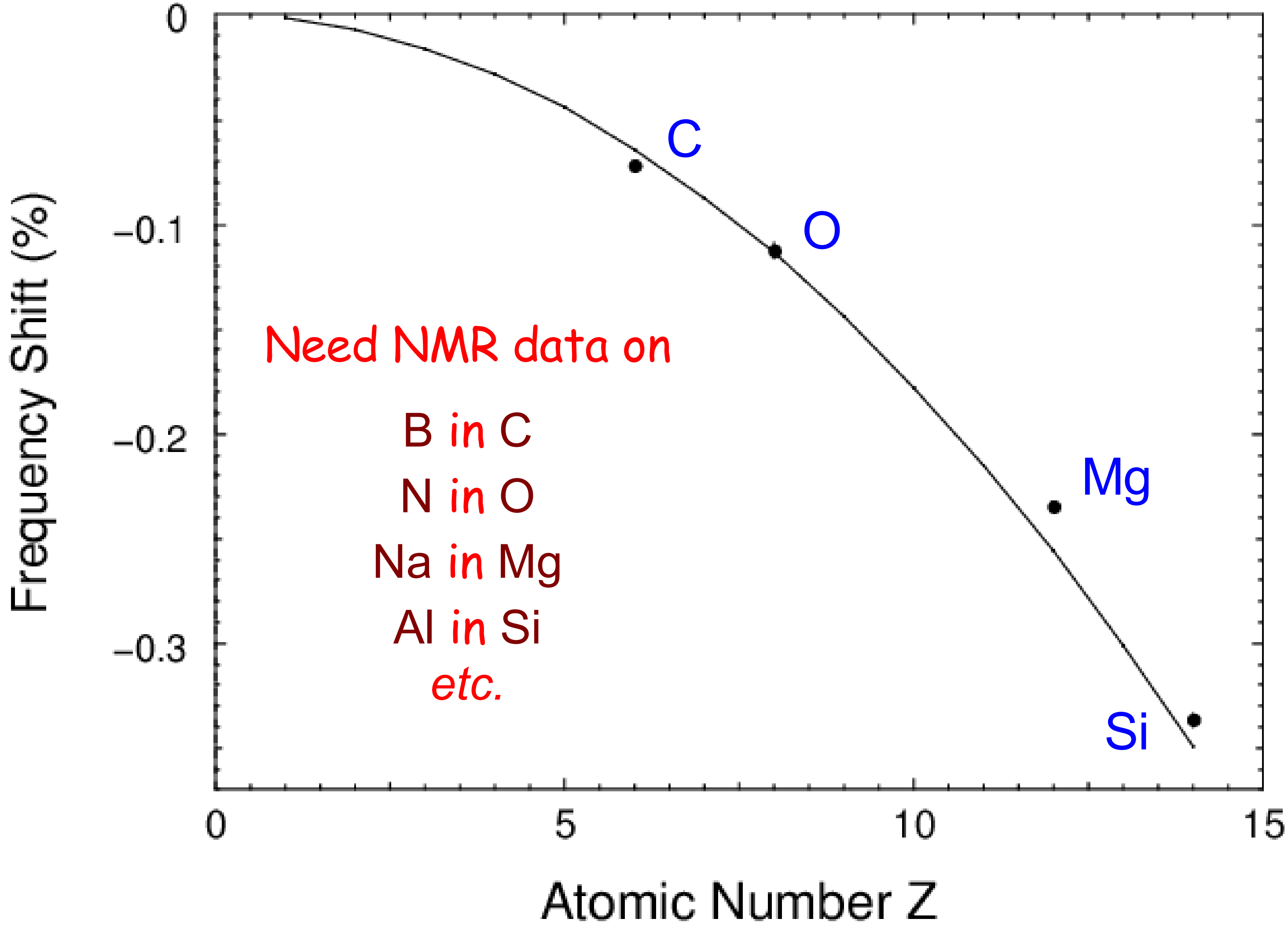
Relativistic Shift of μ^- Frequency



Relativistic Shift of μ^- Frequency



Relativistic Shift of μ^- Frequency



Phil Anderson:

(at a High T_c Superconductivity conference)

"Experimentalists should not attempt to interpret their own data."

[paraphrased]

Darth Vader:

"Leave that to me."

Finis

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and
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