Title: Strange and exciting world of muonic atoms

Date: May 12, 2015 10:00 AM

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Abstract: <p>Recent landmark measurement of the muonic hydrogen Lamb shift generated more questions than answers, as it stands in a sharp disagreement with what was predicted based on known properties of muons and protons. It adds on top of the existing anomalies in the muon sector (discrepancy in g-2 and in radiative muon capture). I will critically review some suggestions for the new physics explanations of these anomalies, and describe their implications. One of the outstanding effects, not tested for muons, is the parity violation in the neutral current channel, which has proven to be an extremely difficult problem, and where the enhancement relative to the standard model prediction is still possible. Following my suggestion for a new way to approach this measurement, this summer the Paul Scherrer Institute in Switzerland will conduct a preliminary muonic atom experiment, tentatively called mu-ARC.</p>


Strange and exciting world of muonic atoms
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PI

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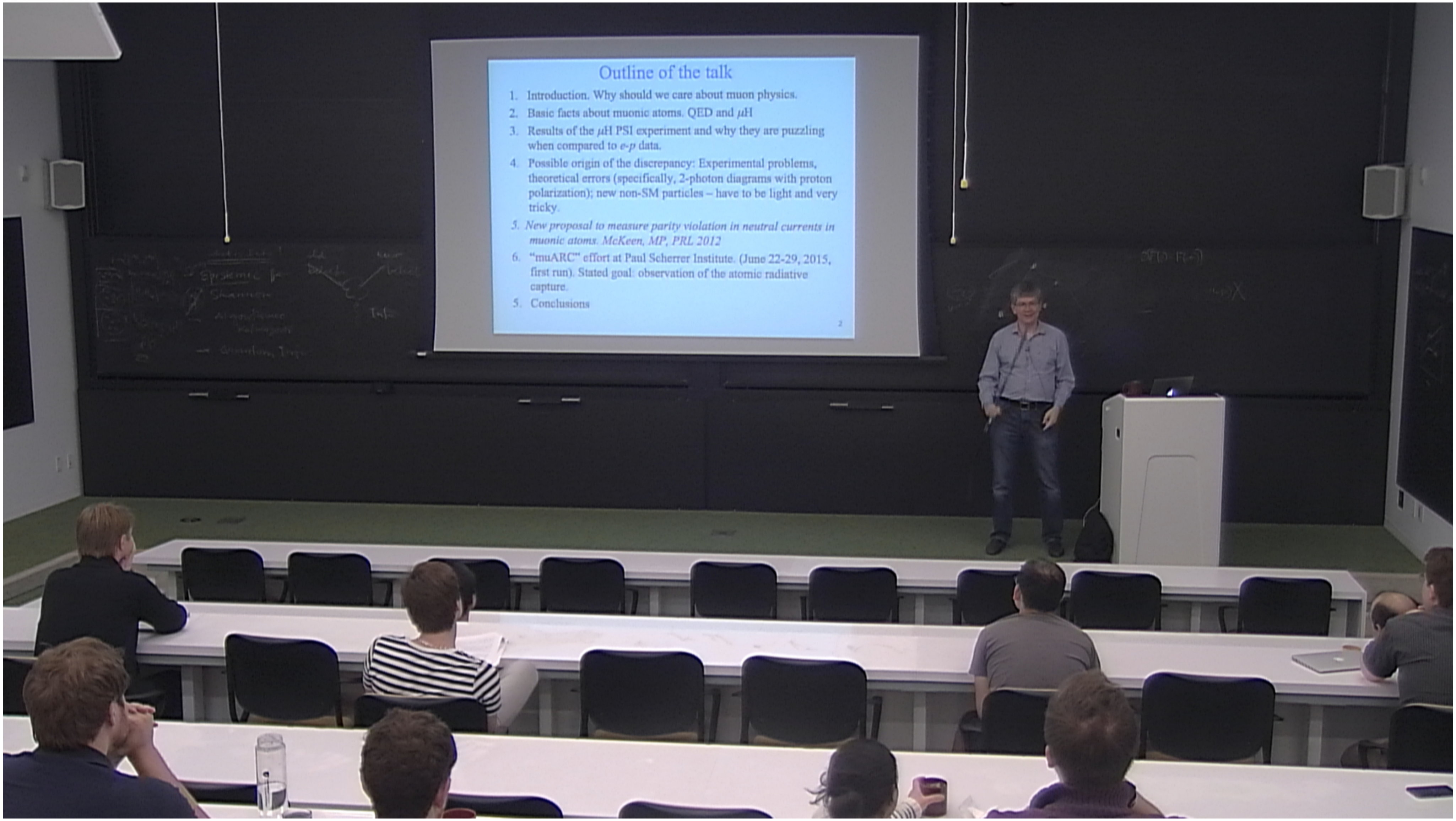
PERIMETER INSTITUTE FOR THEORETICAL PHYSICS

Outline of the talk

1. Introduction. Why should we care about muon physics.
2. Basic facts about muonic atoms. QED and μH
3. Results of the μH PSI experiment and why they are puzzling when compared to *e-p* data.
4. Possible origin of the discrepancy: Experimental problems, theoretical errors (specifically, 2-photon diagrams with proton polarization); new non-SM particles – have to be light and very tricky.
5. *New proposal to measure parity violation in neutral currents in muonic atoms. McKeen, MP, PRL 2012*
6. "muARC" effort at Paul Scherrer Institute. (June 22-29, 2015, first run). Stated goal: observation of the atomic radiative capture.
5. Conclusions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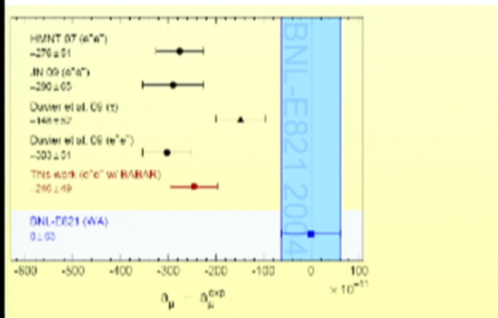
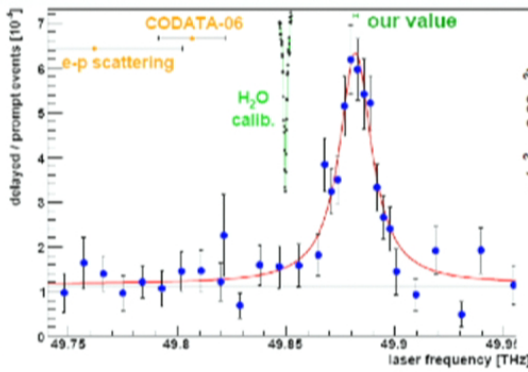
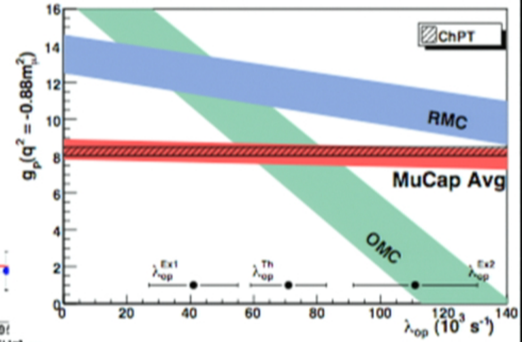
Muons are misbehaving; have we tested them enough?



✱ Davier et al. arXiv:0906-5443





May be something happens with muonic "neutral" channels at low energy. We do not know – therefore it would be quite foolish not to explore additional possibilities of testing "NC-like" signatures in muons at low energy.

Resolution of current puzzles (r_p, g-2 etc) may come not necessarily from trying to re-measure same quantities again (also important), but from searches of new phenomena associated with muons.

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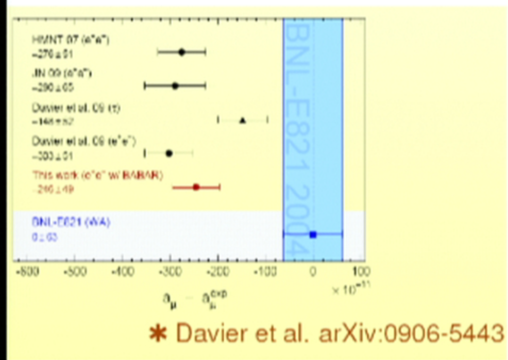

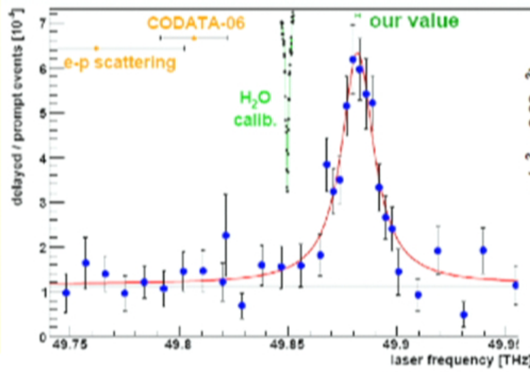

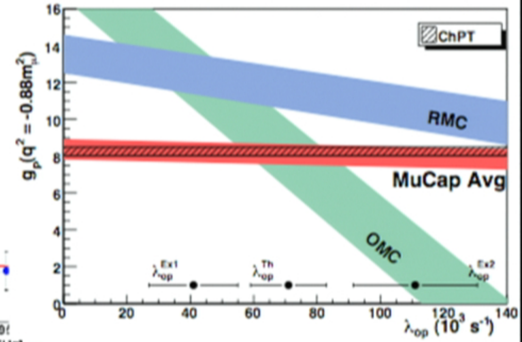

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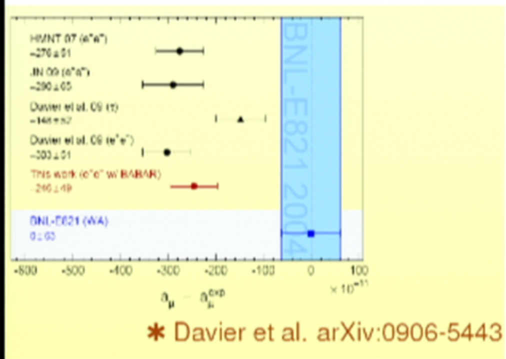
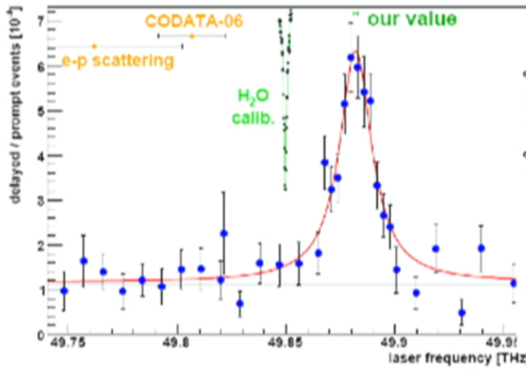
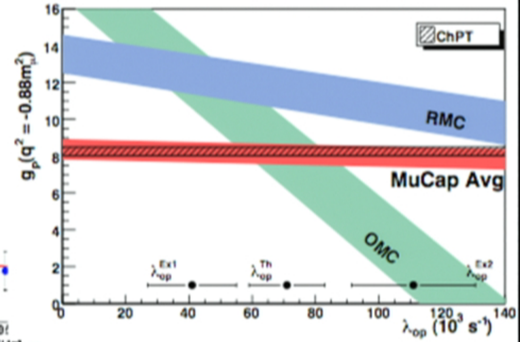
If New Physics, heavy or light?







Can result from

New Physics at

100 GeV scale or MeV

scale

IF it is NP, it can only be light

(NB: in similar vein to last week P. Schuster's talk about light freeze-out dark matter that also requires stronger-than-weak interactions)

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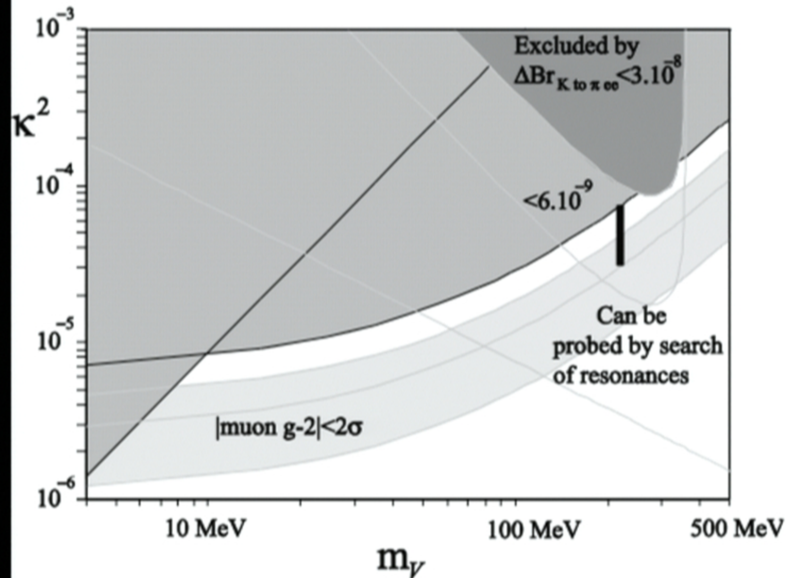
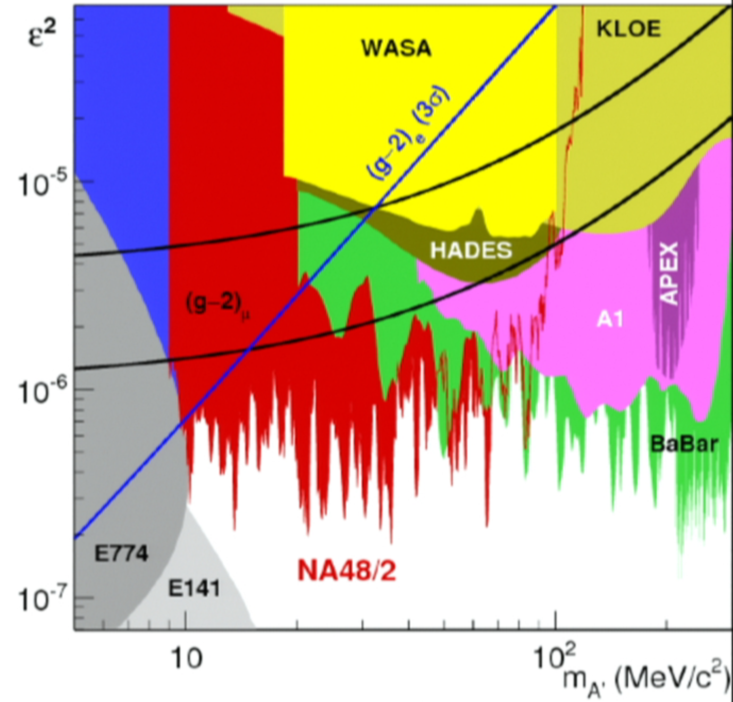
Sometimes New Physics hypotheses can be ruled out faster than origin for discrepancy is found



MP, 2008



aggregate exclusion plot, 2015

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Exotic atoms

- 2.5 micro-second lifetime of a muon is many orders of magnitude larger than the typical time scales in muonic atoms – *gives plenty of time to study properties of muonic atoms*

….

- 1960s-1980s: Dedicated studies of muonic cascades, best data on charge distribution inside nuclei with $Z > 10$. *This program is finished*

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- 1990s -- now: Laser manipulation of exotic atoms (!!). Precision tests of QCD, best measurements of charged hadron masses (π-), starting from 2010 – best data on charge radius of proton, (deuteron, He3 and He4, still unpublished).

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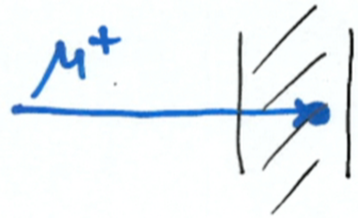
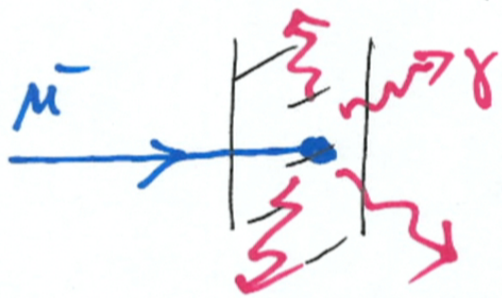
Muonic cascade



μ^+ just stops



μ^-

1. Stops
2. Replaces an electron on $r \sim a_{Bohr}$ orbit ($n \cong 14$)
3. Cascades down to g.s emitting $O(10)\ \gamma$

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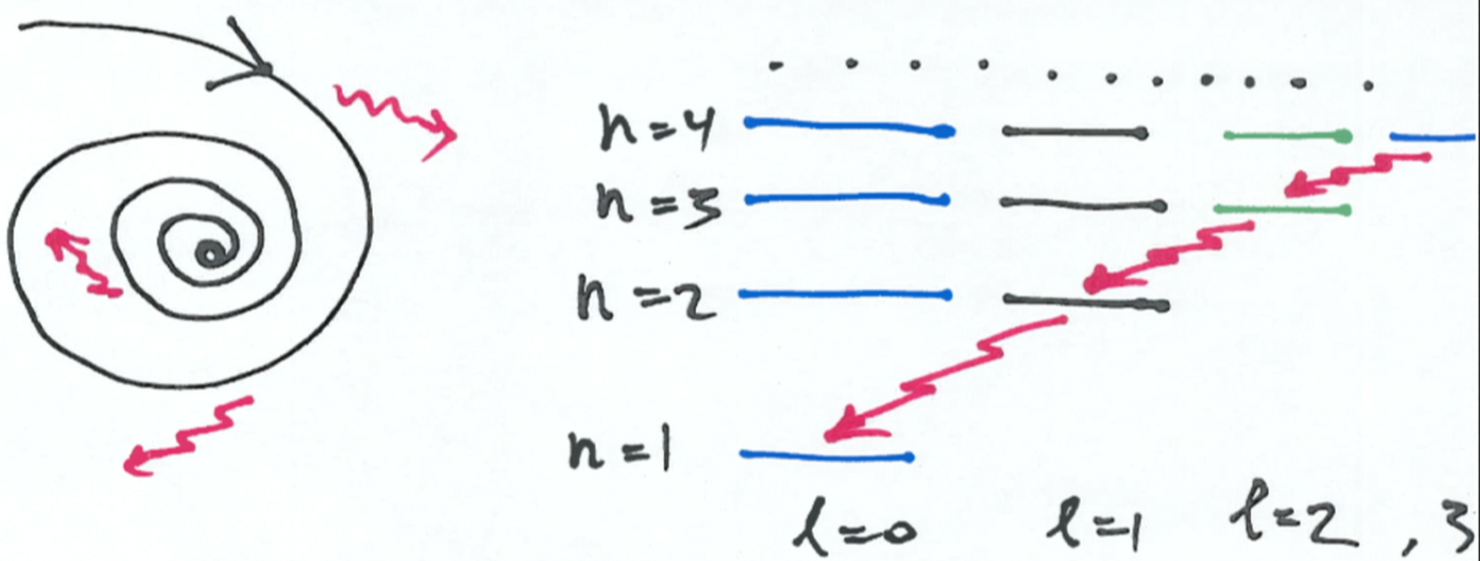
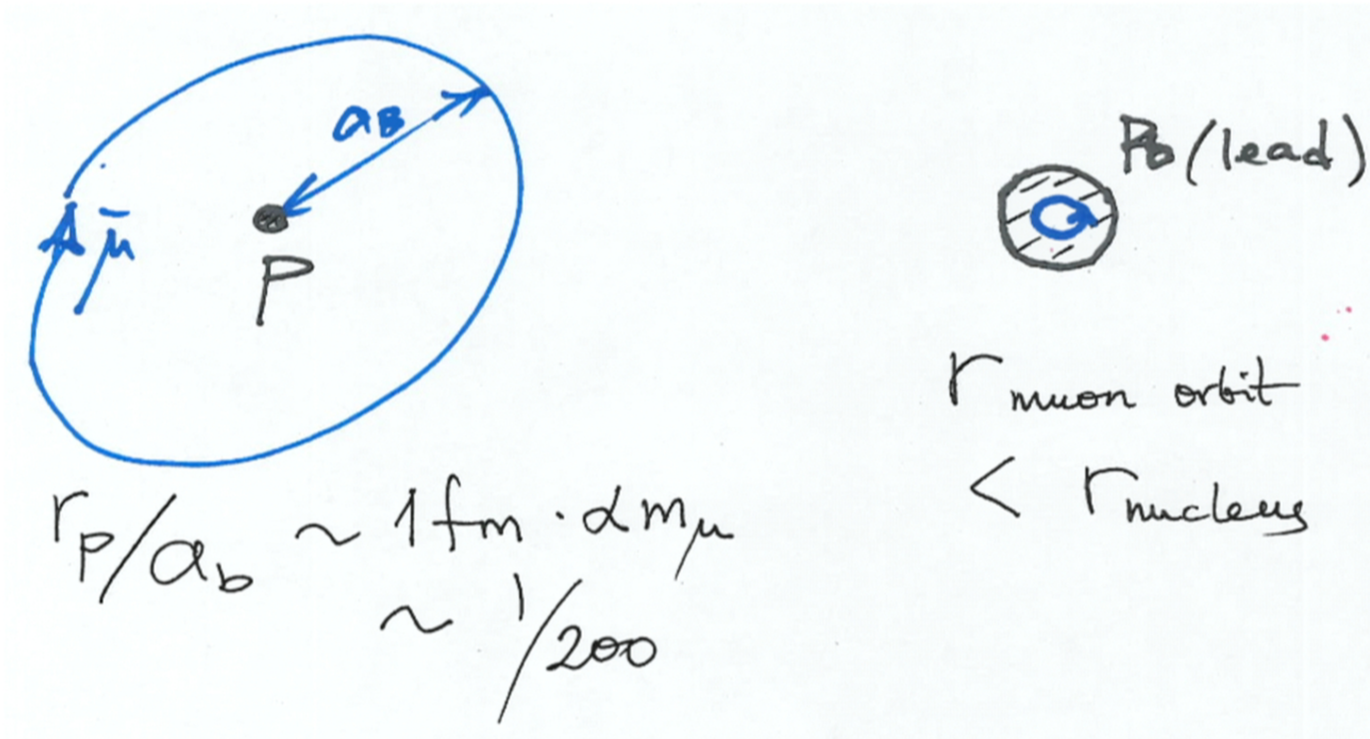
The binding energy in the ground state $E_b = \alpha^2 m_\mu/2 = 13.6\text{eV}\ (m^{red}_\mu/m_e)$
$= 2.5$ keV

2.5 keV excess energy is shed in the cascade



Muonic cascade is the only known way to make muonic atoms

Even though it is only 1 muon, muonic atoms are *quite diverse*



Emitted gammas range from X-ray of keV to ~ 10 MeV

10

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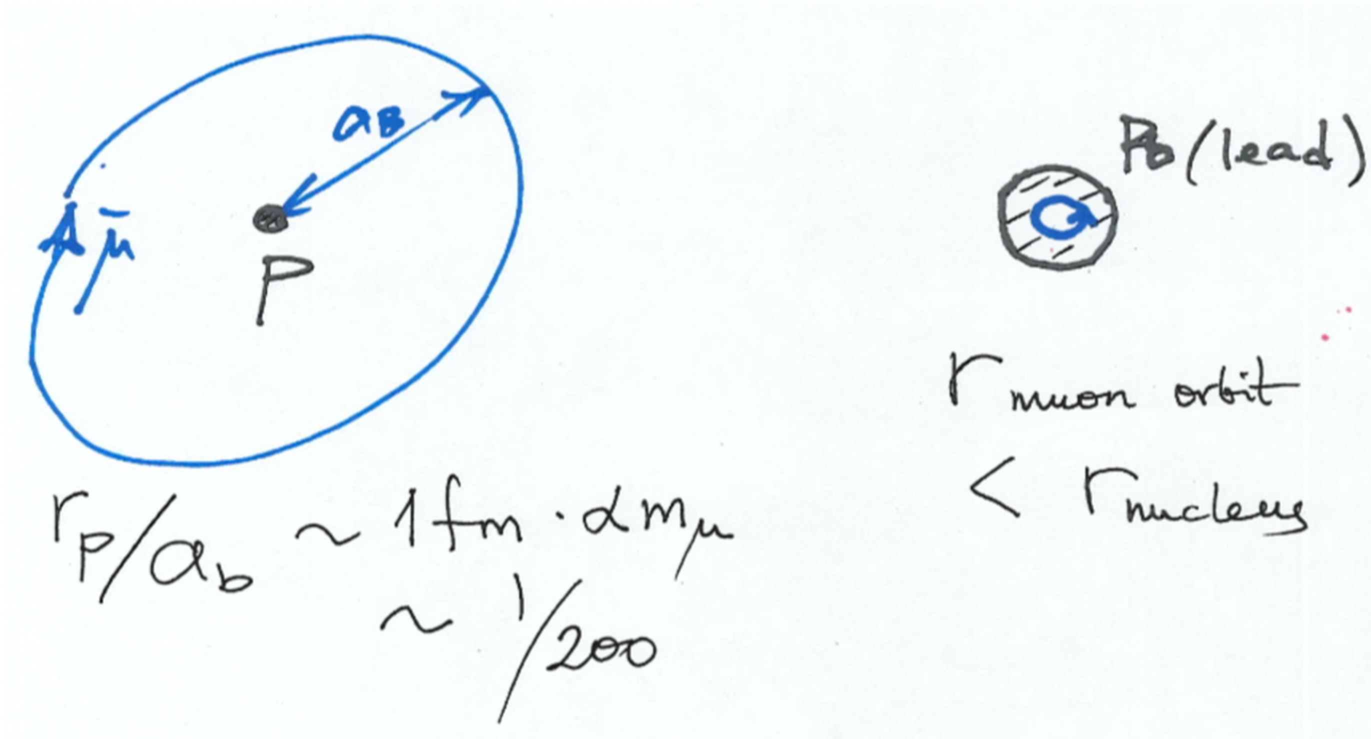

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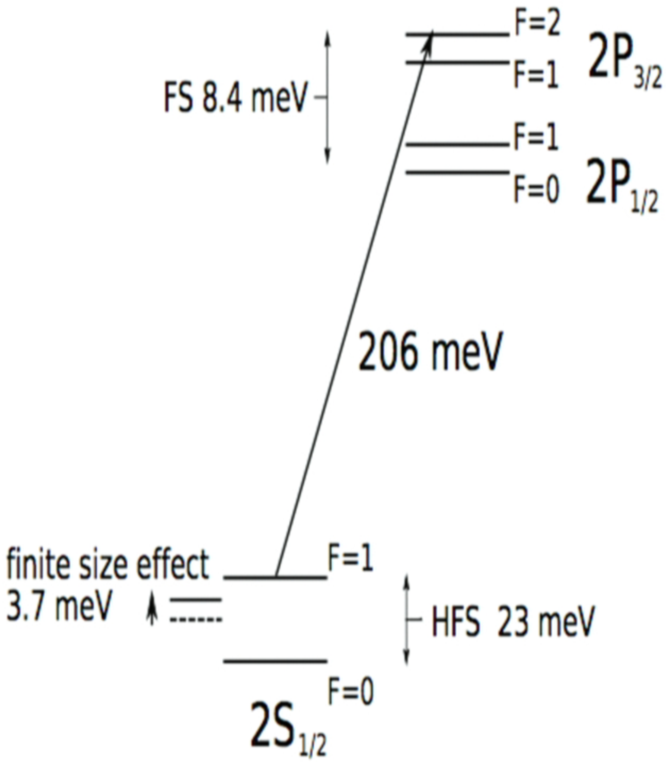
Basic facts about muonic H energy levels



Electron vacuum polarization (Uehling-Serber potential, 1935) pulls 2S level down, finite charge radius pushes it up. In μH quantum effects win (Galanin, Pomeranchuk) and

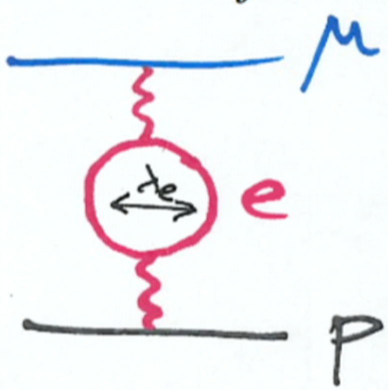
E_{2P}-$E_{2S}(\mu H) > 0$ unlike "usual" E_{2P}-$E_{2S}(eH) < 0$.

Eventually charge radius "wins" and E_{2P}-$E_{2S}(\mu Z, Z>5) < 0$.

Why is the sign of the muonic Lamb shift is opposite to electron H ? 11

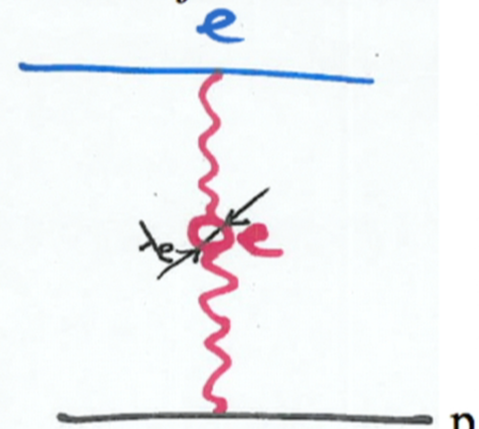
Vacuum polarization

Dominant for L.S. in mu-H



$$\lambda_e \sim 1/m_e \sim a_B(\mu) = 1/\alpha m_\mu$$

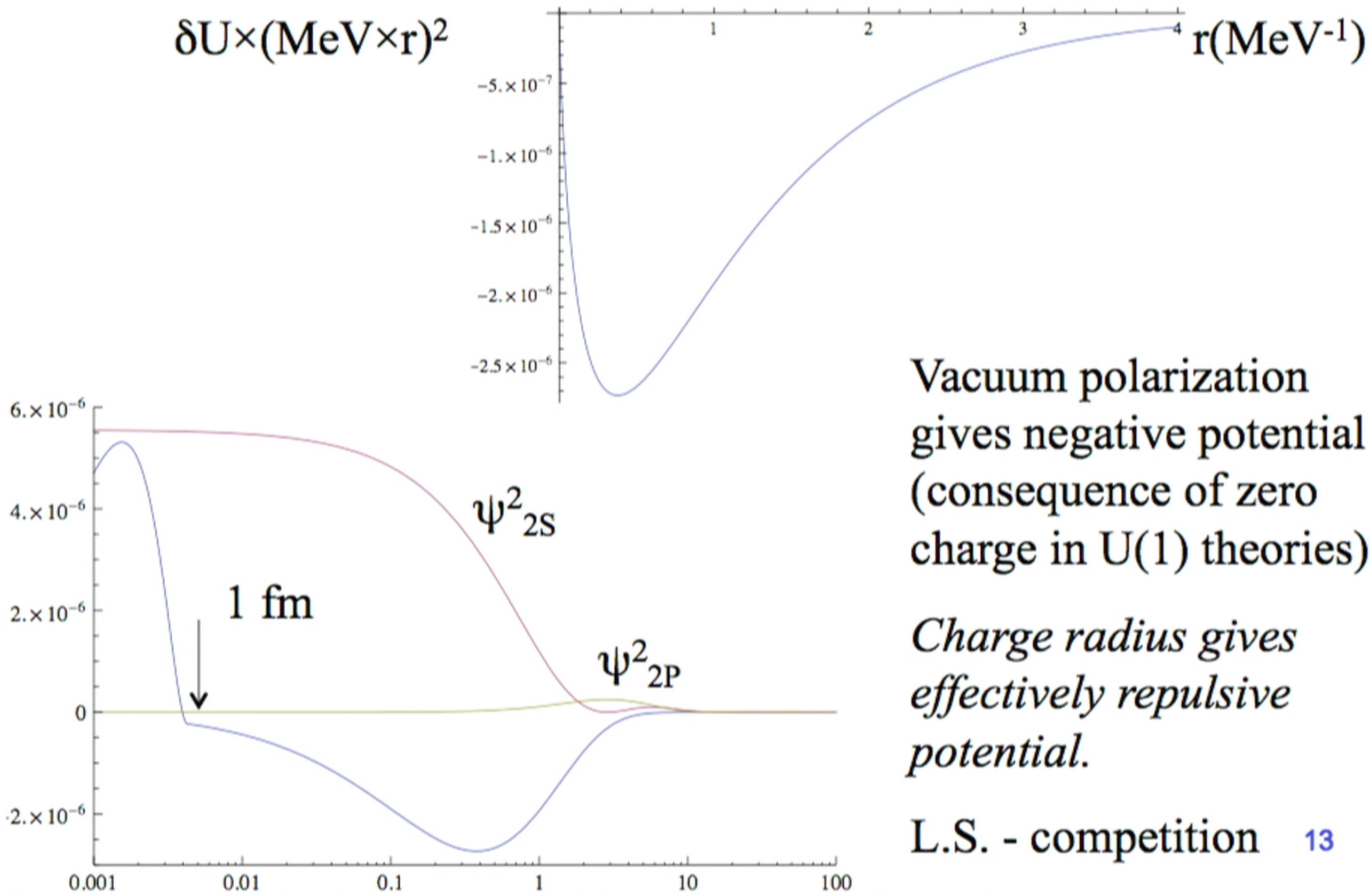
Subdominant for L.S. in e-H



$$a_B \sim 137\lambda_e$$

Muonic atom Lamb shift directly measures electron vacuum polarization

Uehling-Serber potential and charge radius correction

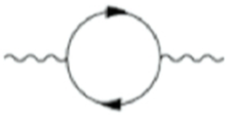


Vacuum polarization gives negative potential (consequence of zero charge in U(1) theories)

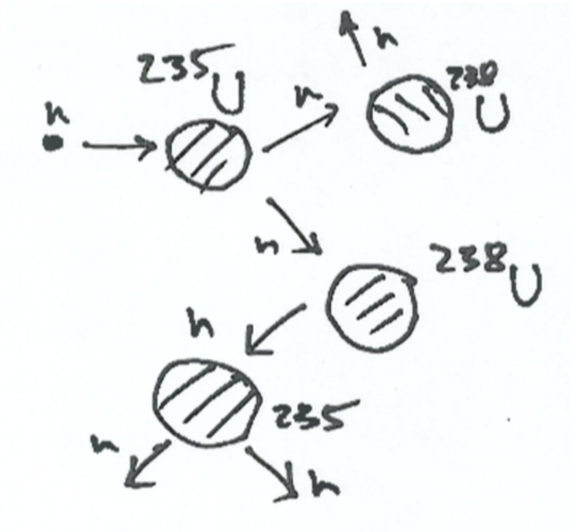
Charge radius gives effectively repulsive potential.

L.S. - competition

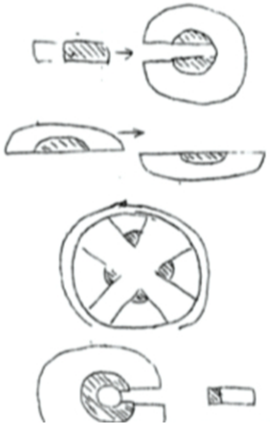
R. Serber: both loop- and tree-level calculations were correct



First loop calculation (1935)



The most relevant at the time tree level calculation (1941-42)



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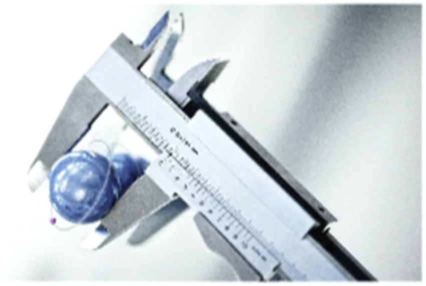
Since 2010 – r_p puzzle, Pohl et al, Nature2010

(just 75 years after Uehling & Serber)



After ~ 20 years of efforts the PSI experiment have worked, and we now have the most precise measurement of the [rather important for hadronic physics] observable

$$r_p = 0.84087(39)\text{ fm}$$

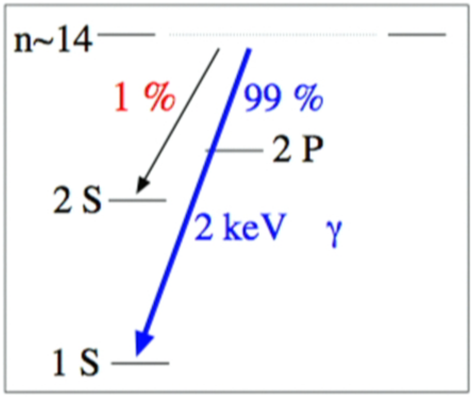
This is A. much more precise than previous e-p determinations

B. it is now ~7σ below the normal H LS and scattering results.

After ~5yr of collective efforts [to check, find source of errors etc] the issue remains unresolved.

How the experiment works (R. Pohl et al)

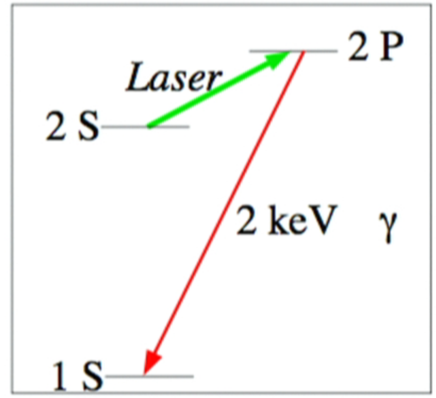
"prompt" ($t \sim 0$)



μ^- stop in H_2 gas
$\Rightarrow \mu p^*$ atoms formed ($n \sim 14$)

99%: cascade to μp(1S),
emitting prompt K_α, K_β ...

"delayed" ($t \sim 1\ \mu s$)



fire laser ($\lambda \approx 6\ \mu m$, $\Delta E \approx 0.2$ eV)

$\Rightarrow$ induce μp(2S) $\rightarrow \mu p$(2P)

$\Rightarrow$ observe delayed K_α x-rays

Measuring the 2 keV transition frequency to 1ppm precision is impossible. Therefore one opts to create long-lived 2s state and induce 2s-2p transition detecting it via 2p decay. The experiment is *very difficult* because 2s state is fragile and one has to work at low pressure 17

How the experiment works (R. Pohl et al)

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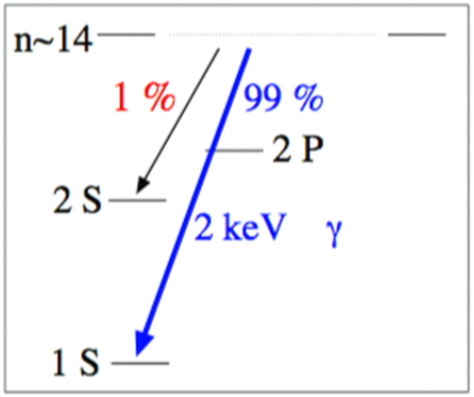

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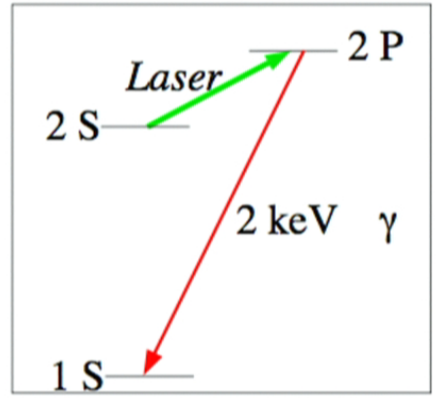

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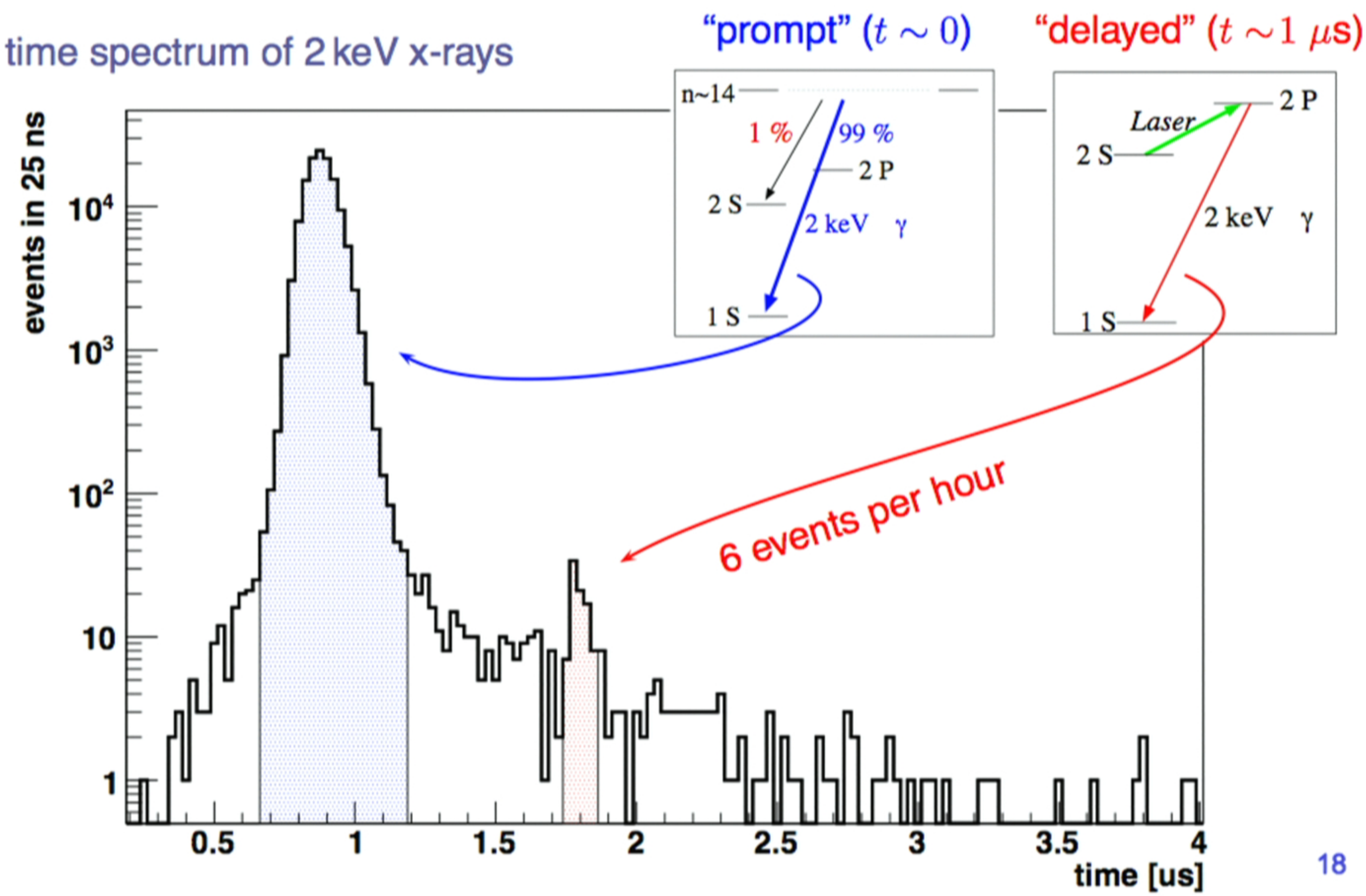
How the experiment works



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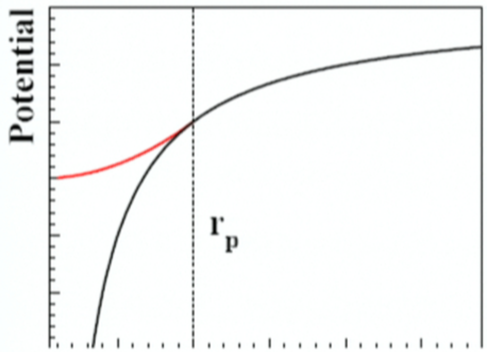
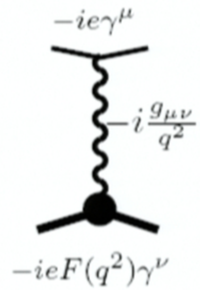
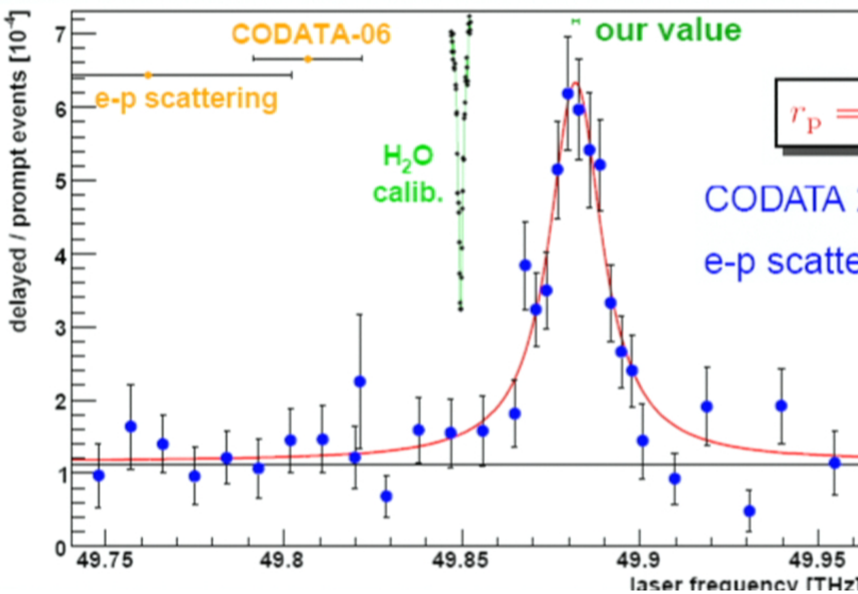
Published 2010 resonance





The experiment is very hard to make work [low counting rates, hard to find resonance]. But once resonance is found, even O(100) events will lead to robust r_p measur.



$r_p = 0.84184(67)$ fm $\quad u_r^{th} = 8 \times 10^{-4}$

CODATA 2006: $r_p = (0.8768 \pm 0.0069)$ fm, from H

e-p scattering: $r_p = (0.895 \pm 0.018)$ fm (2%)

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Current status

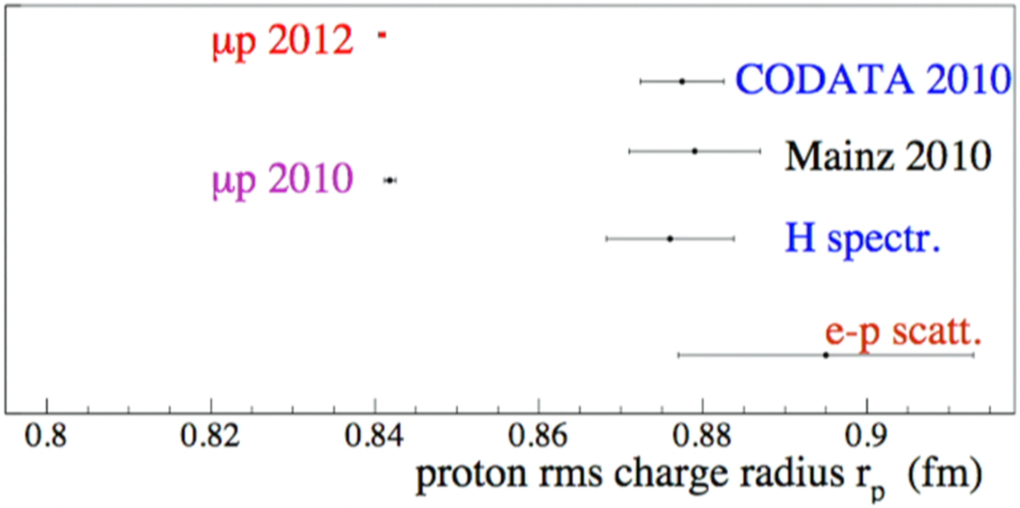
$\nu(2S_{1/2}^{F=1} \rightarrow 2P_{3/2}^{F=2})$ = 49881.88(76) GHz — R. Pohl *et al.*, Nature 466, 213 (2010)

49881.35(64) GHz — preliminary

$\nu(2S_{1/2}^{F=0} \rightarrow 2P_{3/2}^{F=1})$ = 54611.16(1.04) GHz — preliminary

Proton charge radius: $r_p = 0.84089\ (26)_{\rm exp}\ (29)_{\rm th} = 0.84089\ (39)$ fm (prel.)

μp theory: A. Antogini *et al.*, arXiv :1208.2637 (atom-ph)



Importantly, *Zeemach radius* extracted from 2 lines is perfectly consistent with previous (normal hydrogen) determinations

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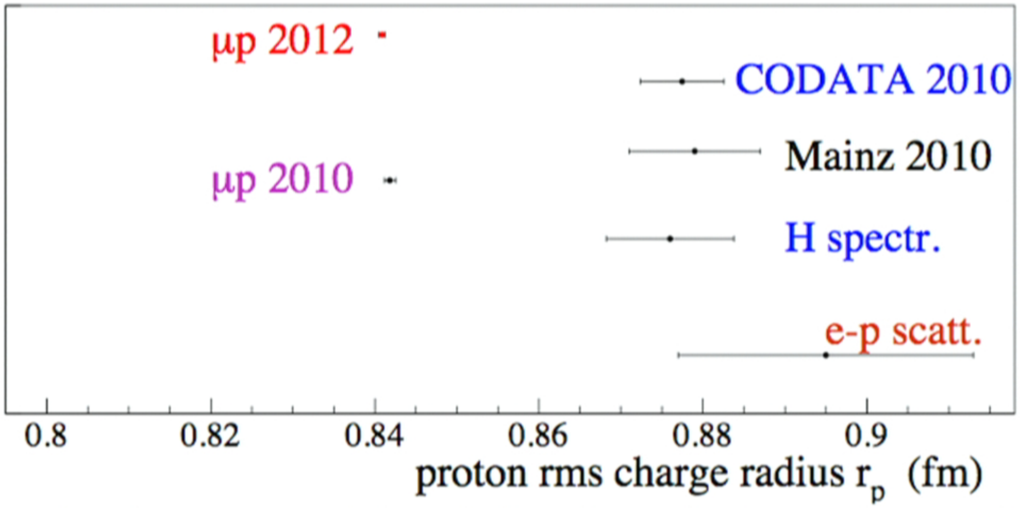

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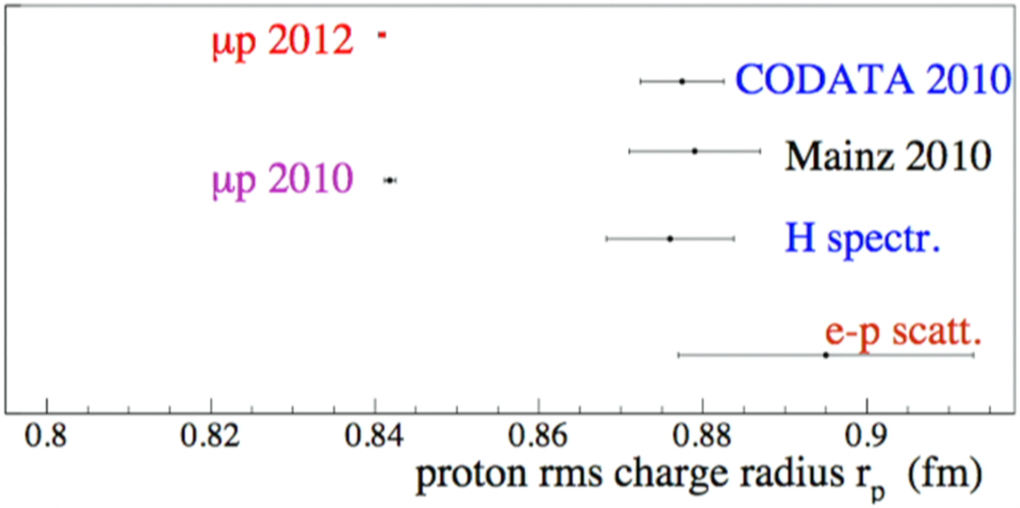

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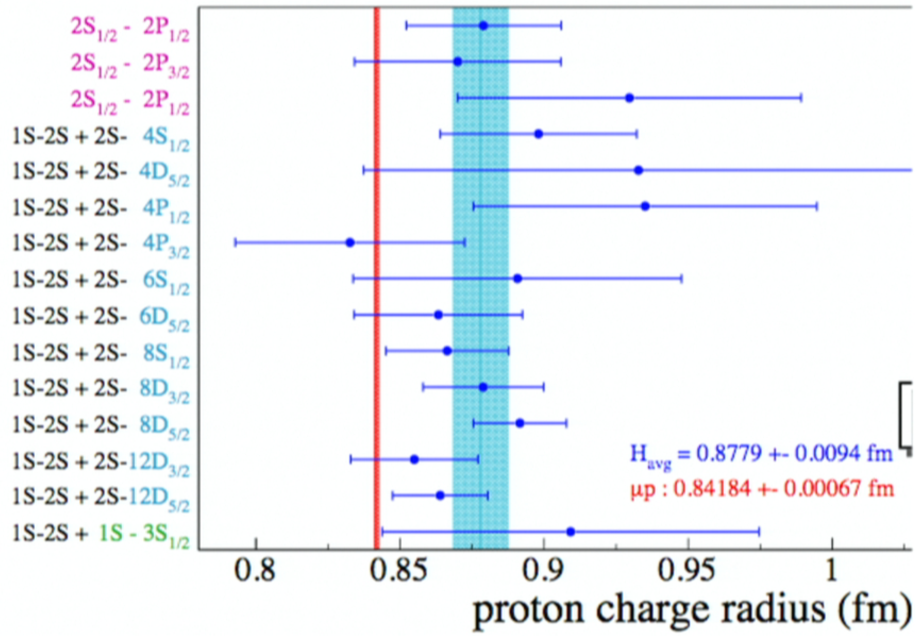
r_p from Normal Hydrogen

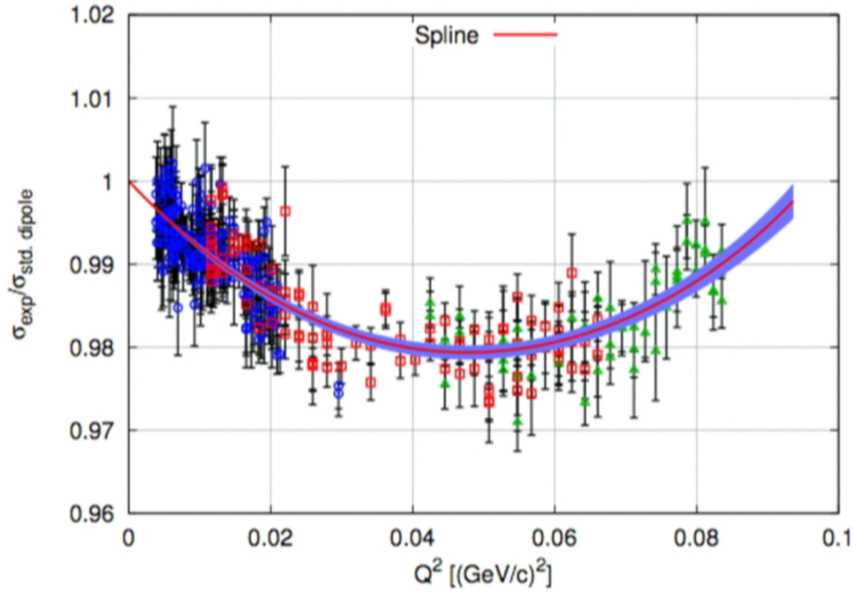


Red line – muonic hydrogen result

Blue band – fitted value of r_p from precision spectroscopy of normal hydrogen.

It is a serious 4σ discrepancy (but only when one takes into account many transitions!)

r_p from *e-p* scattering



Mainz (2010) data, Bernauer et al, provide an unprecedented massive set of very precise data at reasonably low Q^2. (from a talk by J. Bernauer at Trento workshop, 2012)

Final result from flexible models

$$\langle r_E^2 \rangle^{\frac{1}{2}} = 0.879 \pm 0.005_{\text{stat.}} \pm 0.004_{\text{syst.}} \pm 0.002_{\text{model}} \pm 0.004_{\text{group}}\ \text{fm},$$

$$\langle r_M^2 \rangle^{\frac{1}{2}} = 0.777 \pm 0.013_{\text{stat.}} \pm 0.009_{\text{syst.}} \pm 0.005_{\text{model}} \pm 0.002_{\text{group}}\ \text{fm}.$$

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Arrington, Sick, 1505.02680, today's paper

Source	r_E [fm]	r_M [fm]
Published results		
μH [9]	0.8409(4)	0.870(60)
eH [8]	0.8758(77)	-
Mainz A1 [7, 45]	0.8790(110)	0.777(19)
Zhan [3]	0.8750(100)	0.867(20)
Sick [5, 6]	0.8870(80)	0.855(35)
CODATA12 average [8]	0.8775(51)	-
New updates		
Mainz updated	0.8750(150)	0.799(28)
world updated	0.8810(110)	0.867(20)
naive global average	0.8790(90)	0.844(16)
suggested global average	0.8790(110)	0.844(38)

Discrepancy in r_p

$$\begin{aligned} r_{p,1} &= 0.8768(69)\ \text{fm} && \text{atomic H, D,} \\ r_{p,2} &= 0.879(8)\ \text{fm} && e-p\ \text{scattering,} \\ r_{p,3} &= 0.84184(67)\ \text{fm} && \text{muonic H.} \end{aligned}$$

The following pattern for the discrepancy emerges:

$$r_{p,1} \simeq r_{p,2} > r_{p,3},$$
$$\Delta r^2 \equiv (r_p)^2_{e-p\ \text{results}} - (r_p)^2_{\mu-p\ \text{results}} \simeq 0.06\ \text{fm}^2.$$

On one hand it is a tiny number, especially compared to the atomic physics scales. On the other hand, it is a *gigantic* number if compared to the particle physics scales where traditionally you would expect new physics. 0.06 fm^2e^2 is *four orders of magnitude larger than Fermi constant*.

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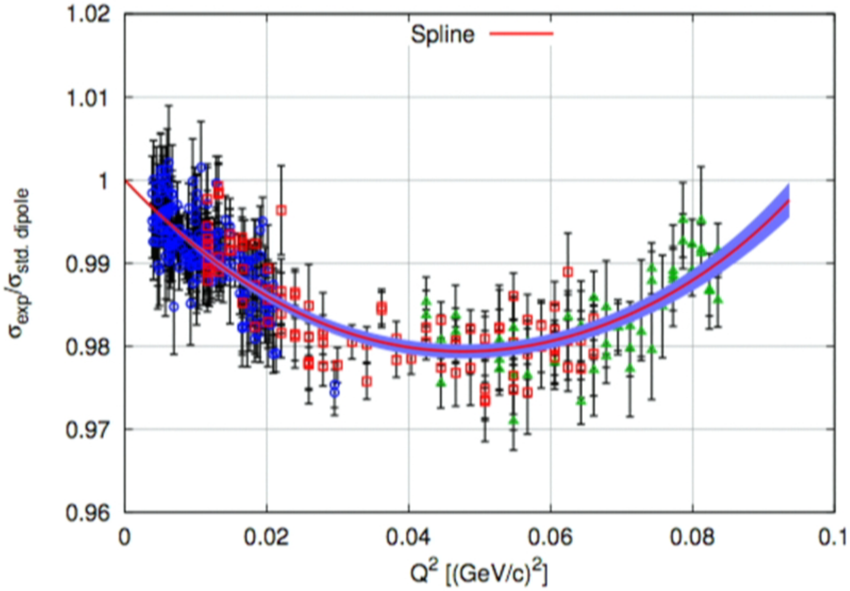
r_p from e-p scattering



Mainz (2010) data, Bernauer et al, provide an unprecedented massive set of very precise data at reasonably low Q^2. (from a talk by J. Bernauer at Trento workshop, 2012)

Final result from flexible models

$$\langle r_E^2 \rangle^{\frac{1}{2}} = 0.879 \pm 0.005_{\mathrm{stat.}} \pm 0.004_{\mathrm{syst.}} \pm 0.002_{\mathrm{model}} \pm 0.004_{\mathrm{group}}\ \mathrm{fm},$$
$$\langle r_M^2 \rangle^{\frac{1}{2}} = 0.777 \pm 0.013_{\mathrm{stat.}} \pm 0.009_{\mathrm{syst.}} \pm 0.005_{\mathrm{model}} \pm 0.002_{\mathrm{group}}\ \mathrm{fm}.$$

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What are the possible origins of discrepancy?

1. Problems with experiments: either with μH, or with scattering and normal H. ??
2. Problems with QED calculations, either in μH or eH ??
3. A completely miscalculated "hadronic effect" in the two-photon proton polarization diagram ??

…

4. *May be some very new forces (= new physics) are at play that would have to be much weaker than EM and much stronger than EW*. ??

More info on the whole issue can be found in the slides from workshops:
http://www.mpq.mpg.de/~rnp/wiki/pmwiki.php/Workshop/Talks

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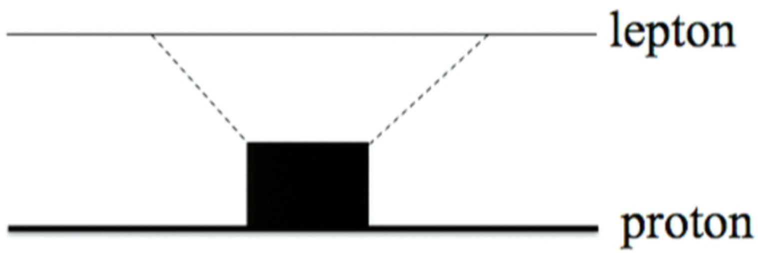
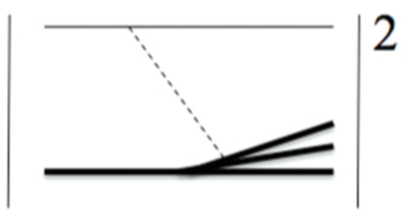
Proton polarization diagram



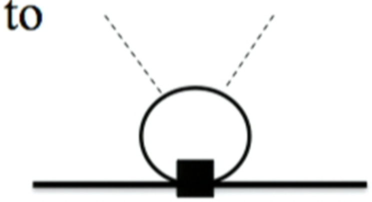
This diagram is proportional to the mass^2 of the external lepton.

If on is allowed to treat this diagram as a complete “black box”, and choose the “size of the box” by hand, one can always get a desirably large result (G. Miller et al).

More sensible approach is to use unitarity and relate it to



and a *subtraction* piece that is usually calculated using magn polarizability input and ChPT.



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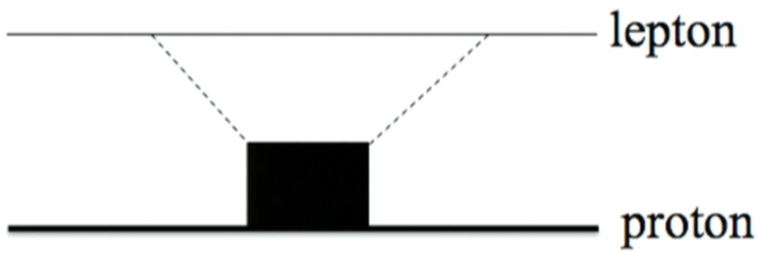

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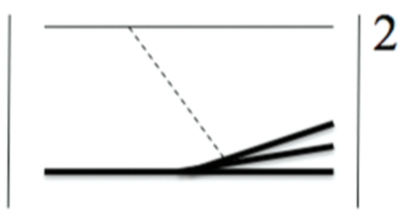

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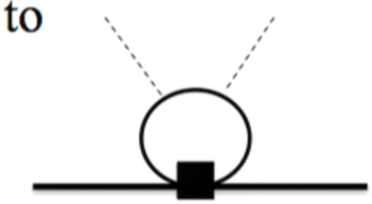

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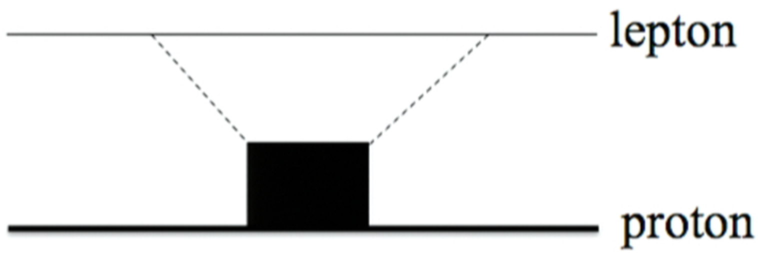
Proton polarization diagram



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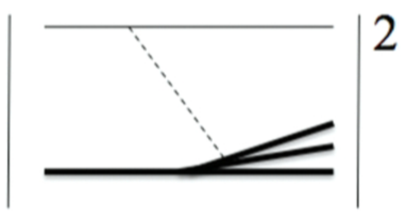

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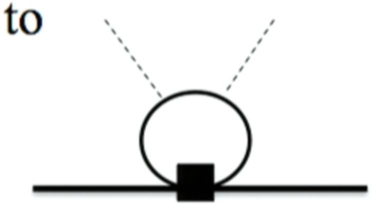

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Estimated size of proton polarization contrib.

Several group have calculated it over the years (Friar; Pachucki; Birse, McGovern; Carlson, Vanderhaeghen; also Hill, Paz)

(μeV)	this work	Ref. [11, 12]	Ref. [21]
ΔE^{subt}	5.3 ± 1.9	1.8	2.3
ΔE^{inel}	-12.7 ± 0.5	-13.9	-13.8
ΔE^{el}	-29.5 ± 1.3	-23.0	-23.0
ΔE	-36.9 ± 2.4	-35.1	-34.5

From Carlson, Vanderhaeghen

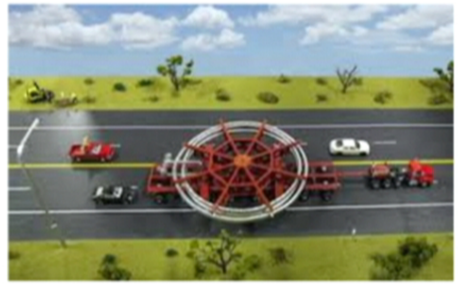
To account for the discrepancy one needs -300

Very recently Mohr, Griffith, Sapirstein have calculated proton polarization within a constituent quark model, without any use of unitarity, structure functions etc – and found good agreement with above!

If nevertheless one proceeds to "engineer black box" by hand, one also typically generates large contributions to Δm_p, and Compton scattering/ DVCS. If *somehow* the discrepancy is due to this box diagram, one would need to explain why polarizabilities α, β are not ~100 larger.

Why should we care about r_p problem?

g-2 experiment “migrated” from BNL to Fermilab. Cost of new exp can approach hundred M$



r_p problem is a huge challenge: if by any chance the muon-proton interaction is “large”: either the two-photon strong interaction diagram or “light new physics”, then g-2 is not really calculable with required precision!

$$\Delta\mathcal{L} \simeq C(\bar{\psi}_\mu \psi_\mu)(\bar{\psi}_p \psi_p),$$

$$C \text{ needs to be } \sim (4\pi\alpha) \times 0.01 \text{ fm}^2$$

$$\Delta(a_\mu) \sim -C \times \frac{\alpha m_\mu m_p}{8\pi^3} \times \begin{cases} 1.7; & \Lambda_{\rm had} \sim m_p \\ 0.08; & \Lambda_{\rm had} \sim m_\pi \end{cases}$$

$$5 \times 10^{-9} \lesssim |\Delta(a_\mu)| \lesssim 10^{-7}.$$

Shift is much larger than hadronic LBL error! Larger than discrepancy…

New physics attempts

Barger, Marfatia, Chiang, Keung; Tucker-Smith, Yavin;
Batell, McKeen, MP; Brax, Burrage; Carlson, Winslow.

Common features of these attempts:

1. If *all* experiments and SM calculations are to be believed, it got to be a new force, that differentiates between e-p and μ-p.
1. Light, e.g. ~10 MeV in mass, particles are involved as careers.
2. Typically one or more of other constraints require additional tuning (g-2 of the muon, neutron scattering) – and one has to "model-build" yourself out of trouble.
3. Each model has its own problems (scalar model – needs to tune down neutronYukawa coupling; vector models – have to couple to μ_R) *Nobody on this list would ever claim that these are very natural or believable models.*

"Dark photon" model cannot explain all discrepancies

Dark photon model (Okun, Holdom) can explain larger r_p measured in scattering compared to atoms. It cannot explain difference between r_p extracted from normal and muonic H Lamb shift.

So, the expected pattern for a dark photon model aligns *apparent* charge radii according to q^2:

r_p(normal H) < r_p (muonic H) < r_p (e-p or μ-p scattering)

However, what is observed is this pattern:

r_p (muonic H) < r_p (normal H) ~ r_p (e-p scattering)

One needs a new interaction, that distinguishes muons and electrons, for example, $(\mu\gamma_\nu\mu)(p\gamma_\nu p)$ or $(\mu\mu)(pp)$ with coefficient ~ $10^4 G_F$

New U(1) forces for right-handed muons

Batell, McKeen, MP, PRL 2011 – Puts a new force into SM

Despite considerable theoretical difficulties to build a consistent model of "muonic forces" relevant for r_p discrepancy, gauged RH muon number could be still alive:

$$\mathcal{L} = -\frac{1}{4}V_{\alpha\beta}^2 + |D_\alpha\phi|^2 + \bar{\mu}_R i \not{D} \mu_R - \frac{\kappa}{2} V_{\alpha\beta}F^{\alpha\beta} - \mathcal{L}_m$$

Main logical chain leading to this:

1. Scalar exchange is disfavored because of the neutron scattering constraints, and meson decay constraints. (We need to *revisit* this in light of possible mu-D discrepancy)
2. Vector force has to NOT couple to left-handed leptons – otherwise huge new effects for neutrinos. Then has to couple to RH muons, $V_\alpha \bar{l}\gamma_\alpha l \subset V_\alpha(c_1\bar{L}\gamma_\alpha L + c_2\bar{R}\gamma_\alpha R),\ c_1 \neq -c_2.$

32

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Even more "ad hoc" model for muonic force

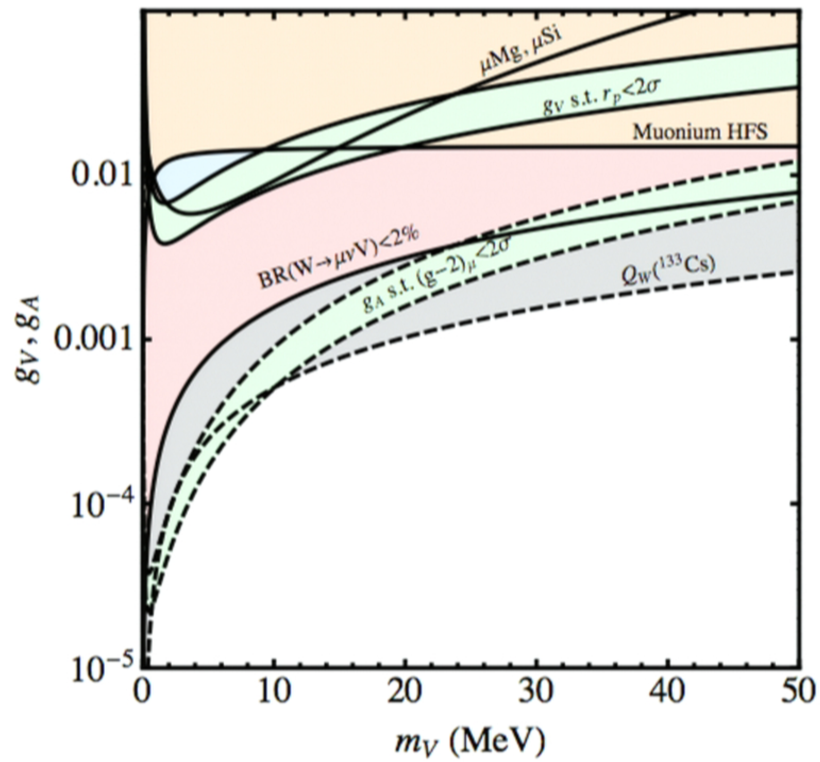
For the sake of discussion, one can introduce a model with additional couplings for muons without caring too much of embedding it into the SM.

$$\mathcal{L}_{\rm int} = -V_\nu \left[\kappa J^{\rm em}_\nu - \bar{\psi}_\mu (g_V \gamma_\nu + g_A \gamma_\nu \gamma_5)\psi_\mu\right]$$
$$= -V_\nu \left[e\kappa \bar{\psi}_p \gamma_\nu \psi_p - e\kappa \bar{\psi}_e \gamma_\nu \psi_e - \bar{\psi}_\mu ((e\kappa + g_V)\gamma_\nu + g_A \gamma_\nu \gamma_5)\psi_\mu + ...\right],$$

Can one find g_V and g_A that will satisfy all constraints?

(and forget for now about embedding it into SM)

Summary of constraints on g_V, g_A



All vector-based models have to be tuned (g-2 of muon, atomic PNC)

Karshenboim, MP, McKeen, 2014. μ_r is the only known SM embedding 38

Other possibilities??

- How about the scalar force – call it *S* – that provides e-p repulsion and fixes r_p discrepancies at least between normal H and μH (Tucker-Smith, Yavin proposal)?

$$\mathcal{L}_\phi = \frac{1}{2}(\partial_\mu \phi)^2 - \frac{1}{2} m_\phi^2 \phi^2 + (g_p \bar{p} p + g_e \bar{e} e + g_\mu \bar{\mu} \mu)\phi$$

- Couplings will be very small, and the mass will be small, O(200 keV), $y_e y_p / e^2 \sim -10^{-8}$.
- This turns out to be somewhat of a blind spot in terms of astro and cosmo constraints
- Izaguirre, Krnjaic, MP: use small *underground accelerators* coupled with large scale detectors such as *Borexino, Super-K* etc… Up to ~ 20 MeV kinematic reach is available due to nuclear binding

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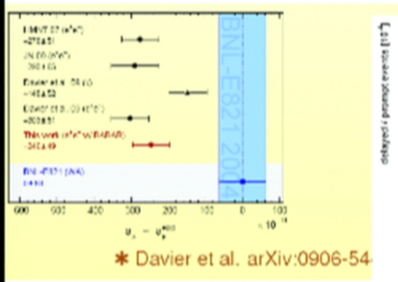
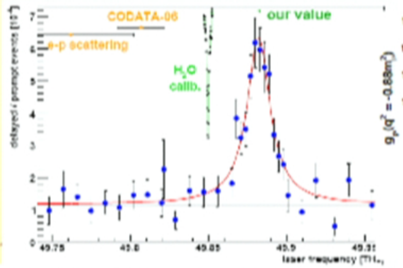
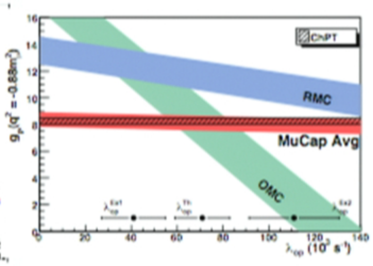
Neutral Channels (NC) show discrepancies ? New tests?







Muon PNC in NC

?

May be something happens with muonic "neutral" channels at low energy. We do not know – therefore it would be quite foolish not to explore additional possibilities of testing "NC-like" signatures in muons at low energy.

Resolution of current puzzles (r_p, g-2 etc) may come not necessarily from trying to re-measure same quantities again (also important), but from searches *of new phenomena* associated with muons.

Idea #1: PNC in muon scattering

$$A_{\rm LR} = \frac{d\sigma_{\rm L} - d\sigma_{\rm R}}{d\sigma_{\rm L} + d\sigma_{\rm R}} \simeq -\eta\beta \frac{Q^2}{Q^2 + m_V^2} \frac{1 + \cos(\theta)}{1 - \beta^2 \sin^2(\theta/2)}$$

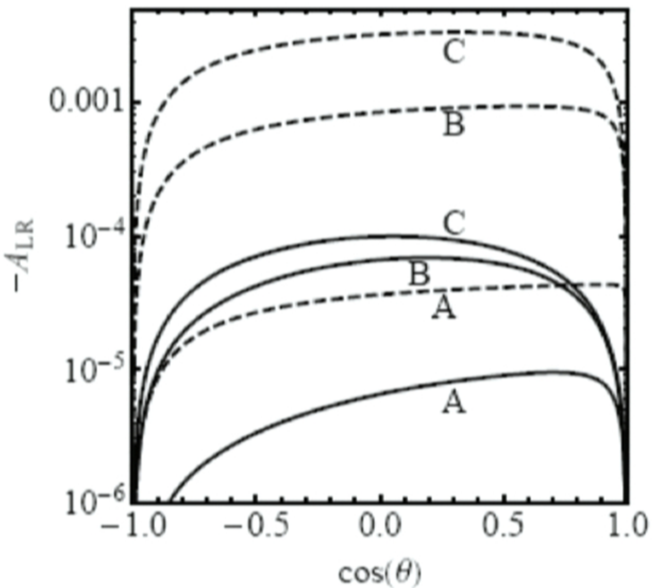


FIG. 1: The asymmetry $A_{\rm LR}(\theta)$ defined in Eq. (13) for the benchmark points labeled A, B, and C in Table I. The solid curves are for $p = 29$ MeV/c and dashed curves for $p = 100$ MeV/c.

Considering that in e-p scattering the accuracy on parity asymmetry ~ 10 ppb, one would think that asymmetry of 10^{-3} for muons can be easily observable?

No: it is difficult to reliably reverse muon polarization

μ PNC via scattering on nuclei

- Although muons come from pion decays with longitudinal polarization, it is difficult to flip this polarization in flight with enough reliability.
- In the future new sources of muons via intermediate muonium states (JPARC) would allow manipulation with muon spin.
- Muon storage rings, where dynamics of muon spin is well studied could be used for the PNC scattering experiment.

42

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Attempt 2: PNC in muonic atoms - revisited

- Old (1980s) proposal (Going back to Chen & Feinberg. See Missimer & Simons review):

1. Start with slowing down muons in cyclotron trap (they loose their polarization), send them on Z~5 low density gas target
2. Let muon cascade take place; nl->n-1,l-1…. Some 1% reaches 2S states. Look for one photon decay of 2S which occurs due to suppressed M1 amplitude and parity suppressed E1. Beta-decay of the muon will provide a correlated direction of beta electron and M1(E1) gamma. Did not work out…

- New proposal (MP and McKeen), PRL 2012

1. Use fast (~50 MeV) polarized muons with high intensity beam,
2. Use thin target of Z~30 (perhaps best is Z=36, Kr) does not capture muons apart from small fraction that gets into 2S state via *atomic radiative capture* (ARC) , $\mu^- +$ Atom -> (μAtom) + γ
3. The signal is parity-violating forward-backward asymmetry of 2S-1S gamma.

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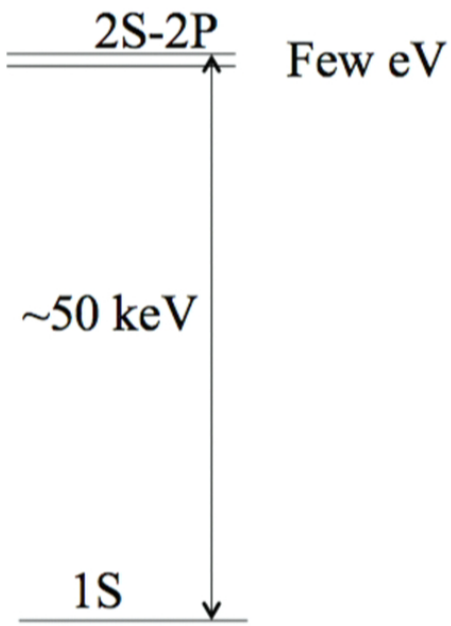
Level structure (schematically)

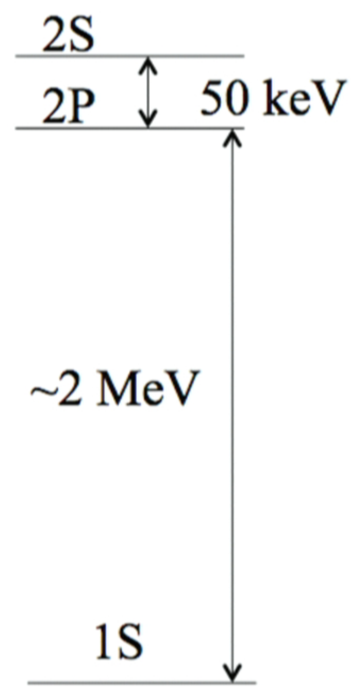
2s is pushed down by QED and up by finite nuclear charge

- Z~5



2S-1S and 2P-1S transitions cannot be distinguished on event by event basis

Z~30



2S-1S and 2P-1S transitions can be distinguished (but was never observed)

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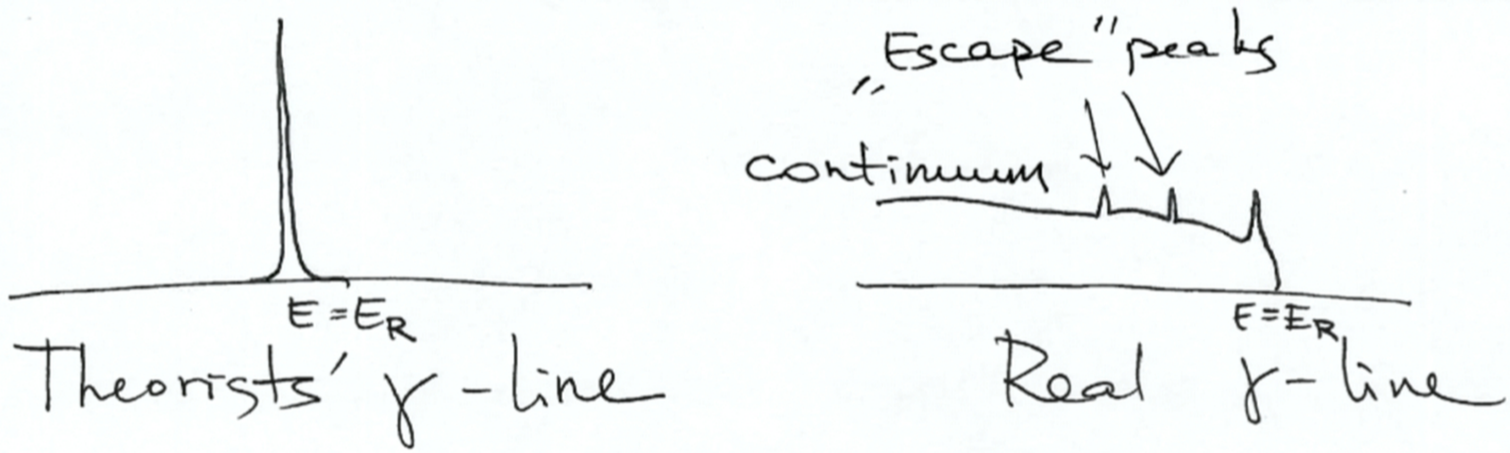
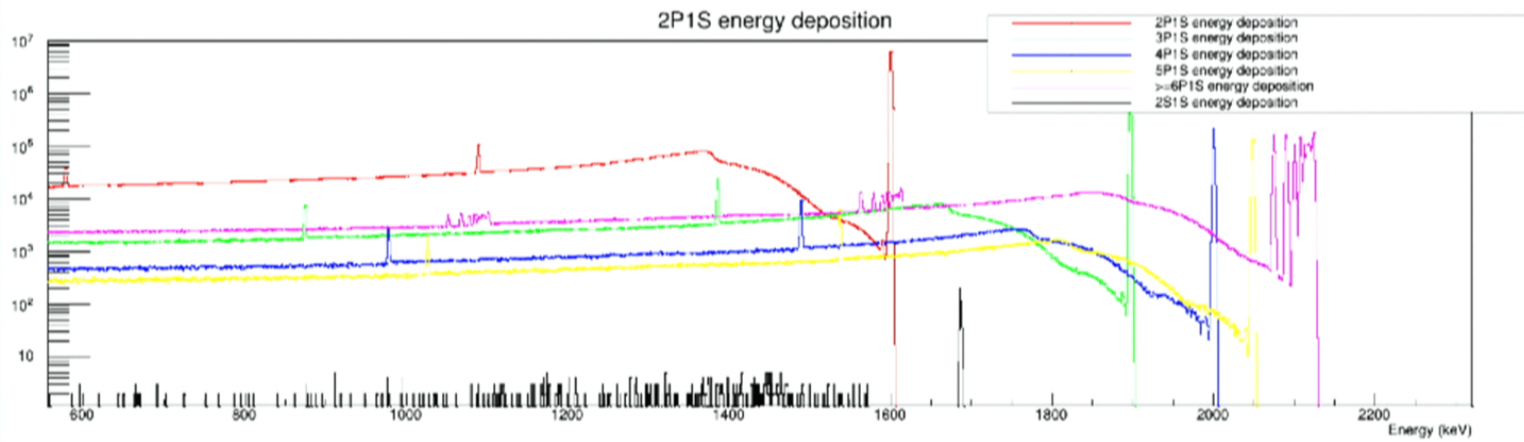
Difficulty with cascade: for 2S-1S S/B < 1%



Much more frequent nP-2S transitions from the cascade bury 2S-1S transition under their continuum !!.

I.e. too much background

2S-1S line is well-hidden under the nP-1S background in the cascade. Simulation for Z=30 by F. Wauters



It will be very difficult to see the line in the cascade. But perhaps not impossible.

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PNC in muonic atoms - revisited

- Old (1980s) proposal

$$... \to 2S_{1/2} \xrightarrow{M1-E1} 1S_{1/2} + \gamma; \ (\mu^-)_{1S} \to e^- \nu_\mu \bar{\nu}_e$$

- New proposal (avoid the cascade)

$$\mu^-_{\rightarrow} + Z \to (\mu^-_{\rightarrow} Z)_{2S_{1/2}} + \gamma_1; \ \ 2S_{1/2} \xrightarrow{M1-E1} 1S_{1/2} + \gamma_2. \quad (8)$$

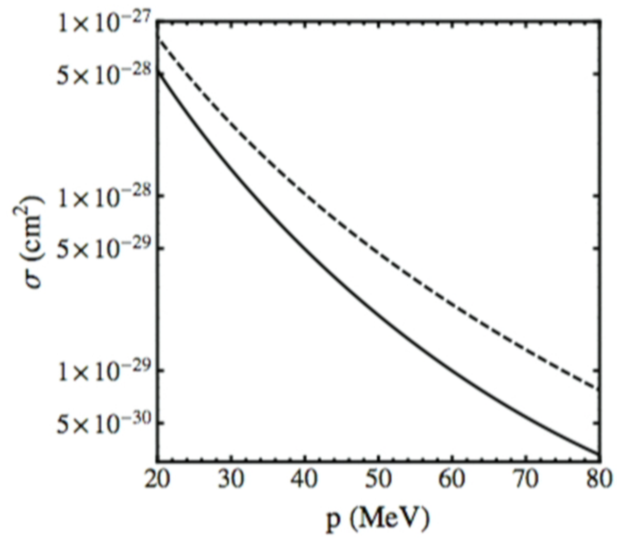
- *Single (M1) 2S-1S transition in muonic atoms have never been observed*
- *Atomic radiative capture (ARC),*
  μ^- (in flight)+ Atom → (μAtom) + γ, have never being observed

Initial data on muons passing through Zr target were taken at TRIUMF (Pienu experimental group) ~ 1day of data with low intensity beam.

Atomic radiative capture

$$\sigma_{\rm ARC} = \frac{2\omega^2}{p^2}\sigma_{PE};\ \sigma_{PE} = \eta(p, R_c, Z, n, l) \times \sigma_{PE}^{(0)}(nl),$$

$$\sigma_{PE}^{(0)}(2S) = \frac{2^{14}\pi^2\alpha a^2 E_2^4}{3\omega^4}\left[1 + \frac{3E_2}{\omega}\right]\frac{\exp\{-\frac{4}{pa}\cot^{-1}\frac{1}{2pa}\}}{1 - \exp(-2\pi/pa)}$$



- Probability for ARC capture into the 2S state in a thin target approaches 10^{-6}.

Size of the effect, counting rate, etc

$$\mathcal{L}_{\rm SM} = -\frac{G_F}{2\sqrt{2}}\bar{\mu}\gamma_\nu\gamma_5\mu\,(g_n\bar{n}\gamma_\nu n + g_p\bar{p}\gamma_\nu p)\,,$$

$$\mathcal{L}_{\rm NP} = \bar{\mu}\gamma_\nu\gamma_5\mu\frac{4\pi\alpha g_\mu^{\rm NP}}{m_V^2+\Box}\,(g_n^{\rm NP}\bar{n}\gamma_\nu n + g_p^{\rm NP}\bar{p}\gamma_\nu p)$$

$$\mathcal{A}_{\rm FB} = \frac{N_{\gamma_2}(\theta>\frac{\pi}{2}) - N_{\gamma_2}(\theta<\frac{\pi}{2})}{N_{\gamma_2}(\theta>\frac{\pi}{2}) + N_{\gamma_2}(\theta<\frac{\pi}{2})} = 2\delta\frac{({\rm E1})_{2P-1S}}{({\rm M1})_{2S-1S}}$$

$$\simeq 680\times\left(\frac{36}{Z}\right)^3\times\delta,\ i\delta = \frac{\langle 2S_{1/2}|H_{PV}|2P_{1/2}\rangle}{\Delta E},$$

$$\delta_{\rm SM} \simeq \frac{3\sqrt{3}G_F}{8\sqrt{2}\pi Z\alpha R_c^2}\left(g_p + g_n\frac{A-Z}{Z}\right),$$

$$\delta_{\rm NP} = \frac{3\sqrt{3}g_\mu^{\rm NP}}{2Z\alpha R_c^2 m_\mu^2}\frac{m_V a}{(m_V a+1)^3}\left(g_p^{\rm NP} + g_n^{\rm NP}\frac{A-Z}{Z}\right)$$

$$\mathcal{A}_{\rm FB}[{\rm SM}] \simeq 0.5\times 10^{-4},\quad \mathcal{A}_{\rm FB}[{\rm NP}] = (0.5-11)\%.$$

$$T[{\rm SM}] \sim 10^8\ {\rm s}\times\frac{10^{11}\ {\rm s}^{-1}}{\Phi_\mu},$$

$$T[{\rm NP}] \sim 3\times 10^5\ {\rm s}\times\frac{10^7\ {\rm s}^{-1}}{\Phi_\mu}\times\left(\frac{0.1}{\mathcal{A}}\right)^2$$

Starting to be sensitive to [optimistic] NP within ~ few days, digging out Z-boson exchange would require new more powerful beams.

***** First steps need to be done towards the parity violation measurements: 1. observation of the ARC, new way of making muonic atoms; 2. observation of the 2S-1S transition, and verification that muon stays polarized. ******

"Mu-ARC" group:

Theoretical support:

Maxim Pospelov

David McKeen

Anthony Fradette

(more accurate calc. of capture rates, angular distributions etc.)

Experiment:

Klaus Kirch

Doug Bryman

Peter Kammel

Dorothea vom Bruch

Andreas Knecht

Frederik Wauters

....

- Use the existing Ge and scintillator detectors from **Al-Cap** experiment
- Investigate ARC in Zirconium (Z=40).
- ARC signal = many thousands of events
- First run June 22 – 29, 2015; PiE5 line

PAUL SCHERRER INSTITUT

PSI

Goals:

A. detect ARC process [new way of making muonic atoms];

B. B. try to detect 2S-1S transition either in the cascade or after ARC

C. Compare calculated ARC rates (MP+) and data

D. Explore the feasibility of the future PNC experiment

First simulations by A. Knecht, PSI

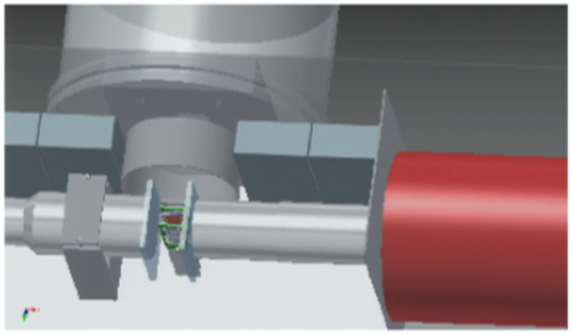


Figure 1: Setup of the planned experiment for the detection of the atomic radiative capture process.

The two veto detectors are currently under design and have not yet been finalized. They will feature a 5 to 10 mm thick scintillator of approximately $100 \times 100\,\text{mm}^2$.

The germanium and brillance detectors are placed opposite to each other and as close to the target as possible. We are aiming for a distance of 30 mm from the target center in order to obtain sufficient count rate.

3 DAQ

The DAQ will need to be able to process the signals from the four scintillators (entrance, exit, 2 x veto) and the germanium and brillance detectors. The trigger for the readout of the γ-detectors is given by a signal in the entrance detector and no signal in the exit or the veto detectors.

While it would be an advantage to have ADC/TDC information for the four scintillators and trigger logic from the DAQ it is not necessary and the discrimination and logic of these signals could be done in NIM electronics.

It is a must however to have ADC capabilities for the two γ-detectors that

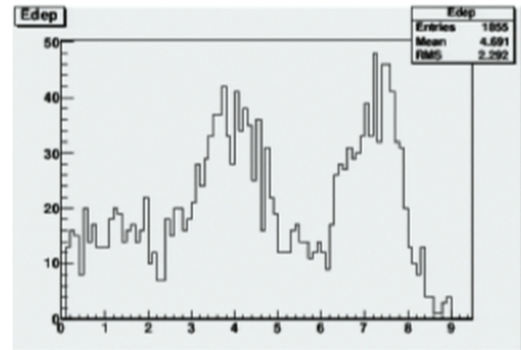


Figure 2: Deposited energy in the germanium detector over the course of a day from the radiative capture of negative muons. The bin size is 0.1 MeV.

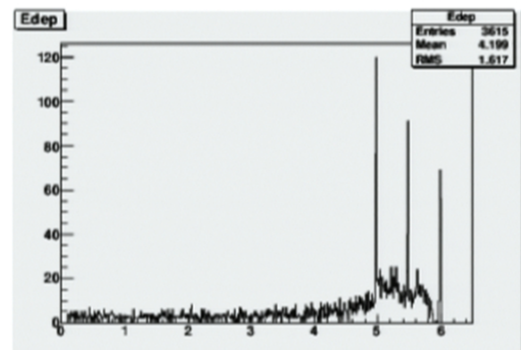


Figure 3: Deposited energy in the germanium detector from 6 MeV gammas. The bin size is 0.01 MeV.

Further ideas…

- Populating muonic atom levels with "ANEC" = atomic neutron emission capture: $\mu + A \rightarrow (\mu, A\text{-}1) + n$, utilizing kinetic energy of neutron + binding energy of muon to knock out a neutron. The rate will be larger than the ARC (MP, unpublished)
- Using low-lying nuclear excitations in deformed nuclei (Eu, Gd, Dy…) to search for parity violation in E2-E1 interference.
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Conclusions

- Measurement of Lamb shift in μH is very precise & discrepant by 7σ with expectations from r_p measured in scattering and hydrogen spectroscopy.
- This is not a crisis [yet], as many experiments with further checks are underway. At the same time, various theoretical checks find convergent answers, and no clear candidate for what can go wrong is in sight.
- New physics "explanations" are problematic because of $\sim 10^4 G_F$ size of the effect – difficult to embed in the SM. Have to tune many observables (g-2 of the muon, possibly neutron scattering)…
- At the same time, $\sim 10^4 G_F$ size effect gives us a chance to look for it in a symmetry-violating channel: new PNC-oriented activity at PSI.
- New proposal to search for very light mediators at underground accelerators.
- ARC (atomic radiative capture), and hopefully 2S-1S transition should be detected during the trial run this summer.

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