What’s Up with the Proton’s Radius?

“*The Proton Size Puzzle*”

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APS Meeting Anaheim, CA

May 3, 2011

BROOKHAVEN
NATIONAL LABORATORY

the Bulletin

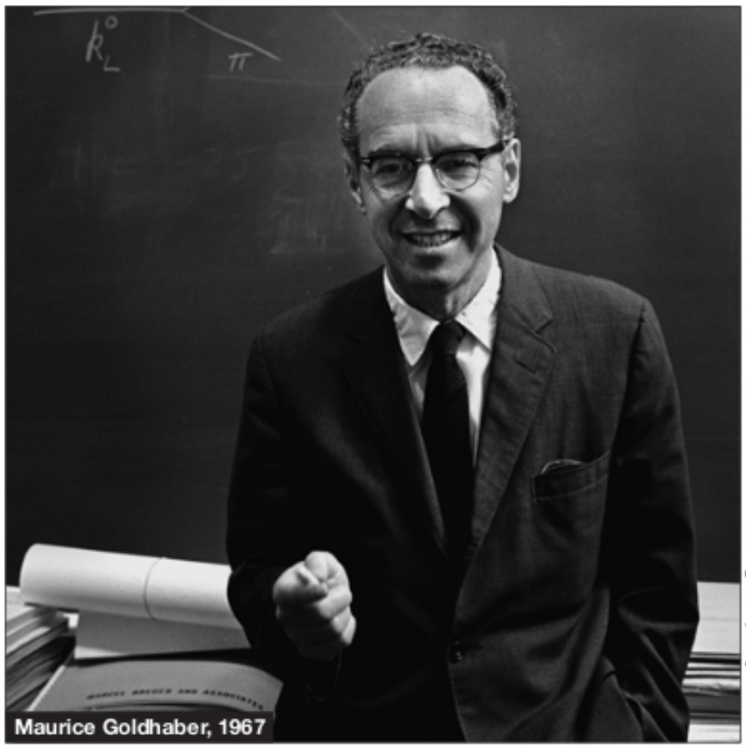
BROOKHAVEN NATIONAL LABORATORY

Vol. 65 - No. 13 April 15, 2011

Former BNL Director Maurice Goldhaber Turns 100

On Monday, April 18, BNL will celebrate the 100th birthday of Distinguished Scientist Emeritus Maurice Goldhaber, a highly honored physicist and former BNL Director whose long and extremely productive career has won him many awards, including the Tom W. Bonner Prize in Nuclear Physics in 1971, the J. Robert Oppenheimer Memorial Prize in 1982, the National Medal of Science in 1983, the Wolf Prize in Physics in 1991, and the Enrico Fermi Award in 1999.

Born in Austria, Goldhaber earned his Ph.D. in physics at the University of Cambridge in 1936. Two years earlier, in 1934, with James Chadwick from the Cavendish Laboratory at Cambridge, he had been the first to measure accurately the mass of the subatomic particle known as the neutron, showing that it was not a compound of a proton and an electron as was believed at the time, but a new particle.



Maurice Goldhaber, 1967

Doug Humphrey 10-339-67

Goldhaber's research in the fields of nuclear physics and

ample: while on an experiment on proton decay, which would

Birthday Wishes to Maurice

From Sam Aronson, BNL

We'll celebrate a wonderful milestone n Monday, April 18 — the 100th birthday of former BNL Director Maurice Goldhaber, a Distinguished Scientist Emeritus whose outstanding contributions to science and to Brookhaven Lab have been honored throughout his career. He is also a valued friend of many, known for his sparkling wit and appreciated for his courtesy to all. Happy birthday, Maurice, from all of us.

From Nicholas Samios, BNL

Maurice Goldhaber is one of the great physicists of the twentieth century. His physics interests are global, from the neutron to the periodic table of nuclei, to the neutrino and all its complexity and then back to the stability of the proton. He is a human physics google. His essence can be encapsulated by his elegant proposition for measuring the helicity of the neutrino, accomplished with A.W. Sunyar and L. Grodzins. It required his encyclopedic knowledge of esoteric nuclei and complete command of the complex physics involved. Without Maurice it may not have been done even up to today. A most productive and imaginative physicist.

From Peter Bond, BNL

Maurice: I fondly recall our various interactions over the years which began with my visit to BNL in 1972 and your graciously taking me to dinner with Trudy, the Sunyars and the Sprouses at the Bellport Inn. While in the early years we didn't have many occasions to talk, I began to learn about what an extraordinary scientist you were. One of the greatest compliments I heard about your science was from Nobel Prize

See Detailed APS Talks By

R. Pohl: *"The Size of the Proton"*

J. Bernauer: *"The Mainz high-precision proton Form Factor Measurement"*

S. Karshenboim: *"Theory of the Lamb Shift in Muonic Hydrogen"*

Outline

1. The Proton Size Puzzle (r_p(ep) vs $r_p(\mu p)$ atom)

   Somethings gotta give: 5-8 sigma difference

2. New Physics Scenarios

   r_p (5-8σ) & g_μ-2 (3.6σ) Discrepancies

   Can the same "New Physics" Explain Both?

   ➔ ***New Light Gauge or Scalar Interaction?***

   Viewer Discretion Advised

3. Neutrino Oscillations in Matter (ν_μ vs ν_e)
4. A Really Light Higgs O(1-10MeV)?
5. Conclusion & Outlook

1. The Proton Size Puzzle (ep vs μp atom)

How large is the proton (rms) radius?

About a Fermi (fm) $=10^{-13}$cm

$r_p = \lim_{Q2 \rightarrow 0} -6\, dF(Q^2)/dQ^2$

CODATA: $r_p \cong$ 0.8768(69)fm from hydrogen spectrum
(2010) (Main sensitivity - Lamb Shift)
Depends on Rydberg Constant
$R_\infty = 1.0973731568525(73) \times 10^7 m^{-1}$

Confirmation from ep scattering $r_p \cong$ 0.8950(180)fm

$r_p \cong$ 0.879(8)fm (Recent Mainz)

$r_p \cong$ 0.875(10)fm (Recent JLAB)

Current Electron Average: r_p=0.8772(46)fm

New PSI μp atomic Lamb shift experiment

$\Delta E(2P_{3/2}-2S_{1/2})=209.9779(49)-5.2262r_p^2+0.0347r_p^3$ meV

R. Pohl, A. Antognini et al. Nature July 2010

Very Elegant!

Stop μ^- in Hydrogen, About 1% populate 2S (1μsec)

Excite resonance with laser to 2P→1S

μp atomic Lamb Shift ***very*** sensitive to R_p

$(m_\mu/m_e)^3 = 8\times10^6$ enhancement

Proton Finite Size ≈ -2%

20ppm experiment

12years in the making (1998-2010)

$\Delta E(2P_{3/2}-2S_{1/2})^{exp} = 206.2949\pm0.0032$ meV

r_p=<u>0.84184(67)fm</u> (μp atom)

10x More Precise & 5 - 8 sigma below ep value!

$r_p \cong$ <u>0.8768(69)fm</u> (ep atom)

$r_p \cong$ <u>0.8772(46)fm</u> + (ep scattering)

Atomic ep Theory? <u>Rydberg Constant(</u>R_∞) (Off by 5σ?)

R_∞ k**nown to 13 significant figures!**

$=1.097373156852 5(73)\times10^{7}m^{-1}$

"One of the Two most accurately measured fundamental physical constants".

Could R_∞ really be wrong?

also

ep scattering wrong!

<u>Perhaps the most likely solution</u>

μp atomic theory or experiment wrong?

Proton Polarizability? QED Corrections (γγ)?

μp Experiment? (seems solid)

Follow up Experimental & Theoretical Work appear to confirm original results!

Can all three r_p determinations be correct?

2 out of 3 correct?

1 out of 3 correct?

0 out of 3 correct?

Some recent theory studies

- Carroll, Thomas, Rafelski & Miller

  (Dirac Eq., Coulomb + Finite Size)

  Hill & Paz (Form Factor Analysis)

  Cloet & Miller (Zemach Radius **r_p^3 term)**

  Distler, Bernauer, Walcher (Zemach Moments)

+ others

2. New Physics Scenarios

New Physics Effect? (seems unlikely, but…)

Interesting/Provocative

Too big to be short-distance phenomenon

eg SUSY, Heavy Z'…

More likely light new vector or scalar boson

(1-100MeV weak coupling $\alpha' = 10^{-6}\alpha$)

Long Distance Physics!

Low Energy Frontier

Light Vector Boson with coupling e'

$e'^2/4\pi = \alpha' << \alpha = 1/137$

New Vector Boson Interaction Shifts Atomic Spectrum in a way that mimics a proton charge radius

(Based on calculation by A. Czarnecki)

$\Delta r_p/r_p \sim -2\alpha'/\alpha^3(1+m_V/\alpha m_\mu)^2$

Experiment→ $\Delta r_p/r_p \sim -4\%$

example $\alpha' = 2.5\times10^{-6}\alpha$, $m_V \leq 1$MeV works

(Heavier m_V requires larger coupling)

Can it be the "Dark Photon"?

Light gauge boson from Dark Matter Sector that mixes with the photon (small coupling)

"New Physics" & The g_μ-2 Discrepancy

$a_\mu=(g_\mu-2)/2$

$\Delta a_\mu = a_\mu^{exp} - a_\mu^{SM} = 287(63)(49)\times10^{-11}$ (3.6σ!)

leading candidate supersymmetry

What about light vector boson with $m_V<m_\mu$?

$\Delta a_\mu \sim \alpha'/2\pi$ like Schwinger term

$=2.9\times10^{-9} \rightarrow \alpha' \sim 2.5\times10^{-6}\alpha$

Dark Photon = natural solution to g_μ-2 Discrepancy

So, a light vector boson with mass ≤ 1MeV
and $\alpha' \sim 2.5\times10^{-6}\alpha$ coupling for μp and $\mu\mu$
solves both proton size puzzle & g_μ-2

Can it be the Dark Photon?

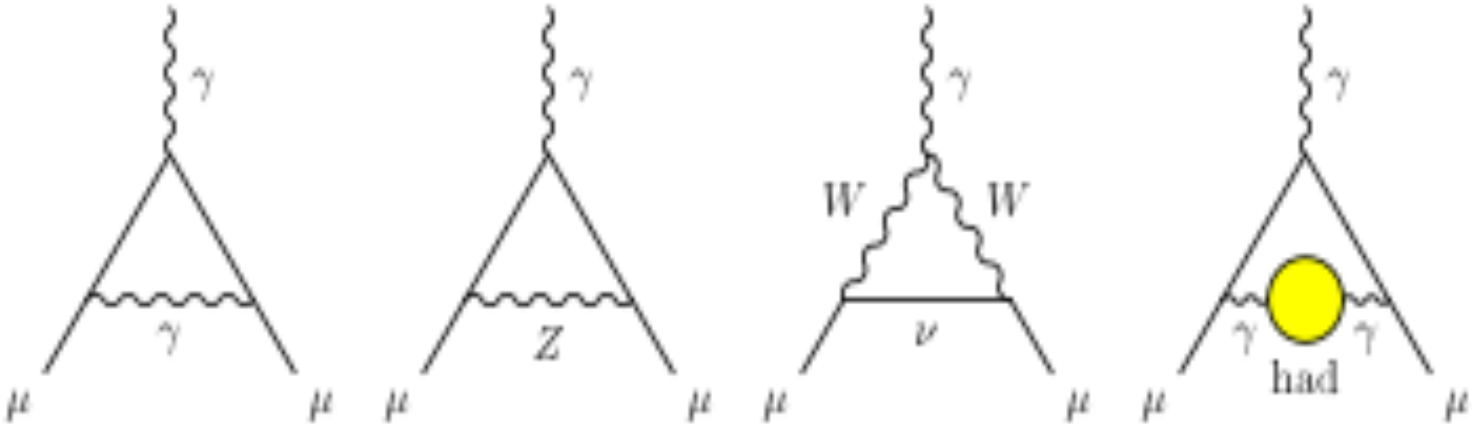


Figure 1: Representative diagrams contributing to a_μ^{SM}. From left to right: first order QED (Schwinger term), lowest-order weak, lowest-order hadronic.

<u>No</u>! O(1MeV) dark photon would also reduce r_p in ep atom

(Observation of Czarnecki & Pospelov)

and should have led to g_e-2 discrepancy

$$\Delta a_e = |a_e^{exp} - a_e^{SM}| < 10^{-11}!$$

It also runs into other experimental problems

<u>Possible Solution: violate e-μ Universality</u>

Egs Gauge B-3L_μ or B-3/2(L_μ+L_τ)… (Lee & Ma)

Anomaly Free, couples to baryons, **<u>not electrons</u>**

So, a light m_V~MeV & α'~2.5x$10^{-6}\alpha$ alleviates both r_p and a_μ problems if it doesn't couple (directly) to electrons!

What about neutrino physics? *(ν_μ vs ν_e)*

From Bjorken, Essig, Schuster and Toro Dark Photon (2009)

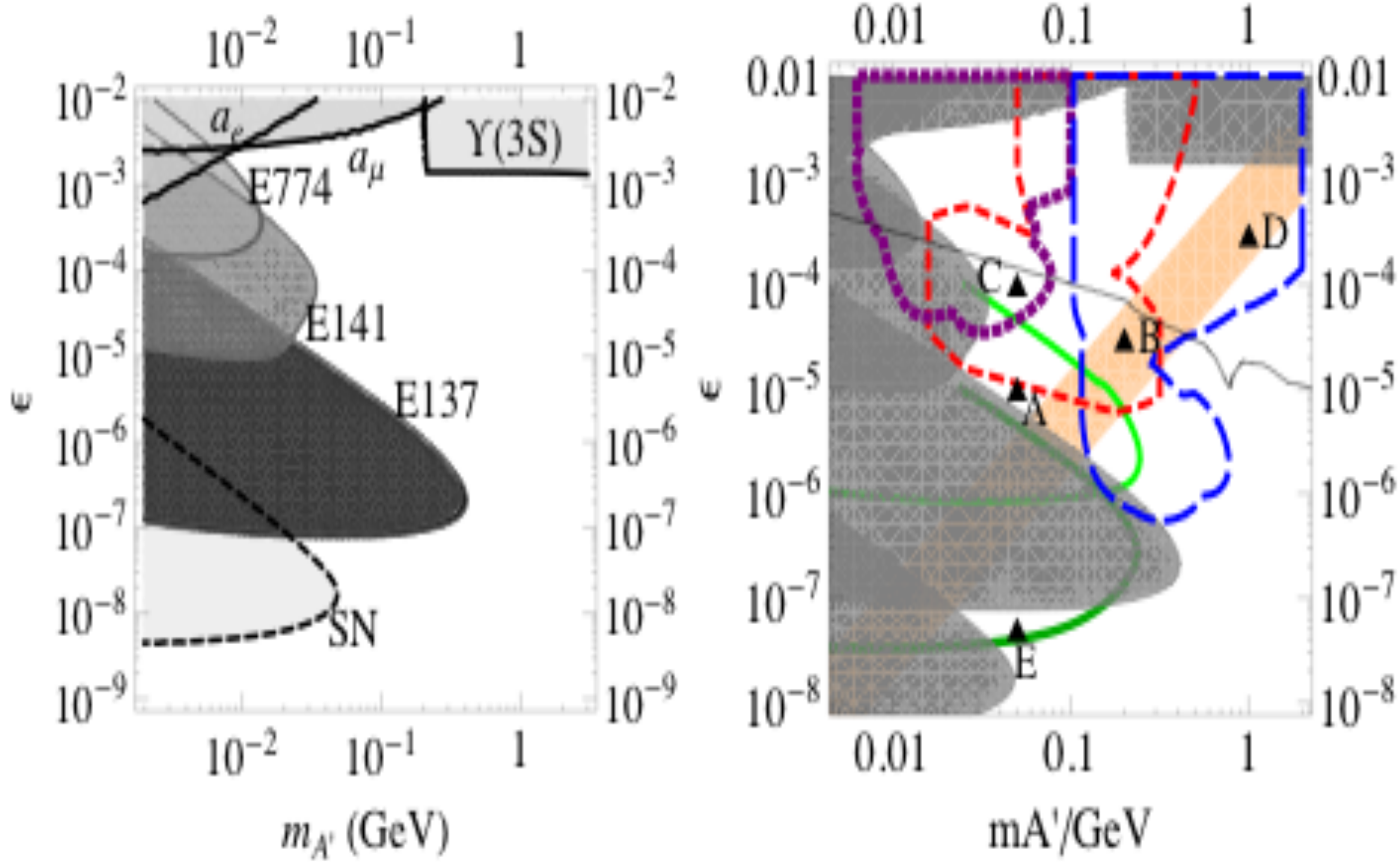


FIG. 1: **Left:** Existing constraints on an A'. Shown are constraints from electron and muon anomalous magnetic moment measurements, a_e and a_μ, the BaBar search for $\Upsilon(3S) \to \gamma\mu^+\mu^-$, three beam dump experiments, E137, E141, and E774, and supernova cooling (SN). These constraints are discussed further in Section III. **Right:** Existing constraints are shown in

3. <u>Neutrino Oscillations in Matter</u> (ν_μ vs ν_e)

New Vector Interaction Different for ν_μ & ν_e

Eg, if we gauge B-3L_μ with $\alpha' \sim 2.5 \times 10^{-6}\alpha$?

Implies new matter effect on the ν_μ index of refraction

Of $O(10^4 G_F N_B (1\text{MeV}/m_V)^2)$ <u>Very Large</u>!

m_V=1MeV Ruled Out! Quenches Oscillations!

<u>By a factor > 10,000!!</u>

Very hard to simultaneously solve r_p, a_μ and ν_μ matter osc

Neutrino Matter Effects are a <u>great</u> probe of long distance physics Oscillation Interferometry

Batell, McKeen & Pospelov: Gauge only μ_R (not neutrinos or e_R)

(creative but has other issues)

4. A Really Light Higgs Scalar O(1-10MeV)?

Normally 1 loop Higgs (>114GeV)

Contribution to g_μ-2 is negligible

But what if a Higgs is really light?

Kinoshita & WJM review long Ago

➔ $\Delta a_\mu = a_\mu^{exp} - a_\mu^{SM} \approx +3x10^{-9}$!

Could also explain r_p differences!

Something to think about

Runs into problems with neutron-Nuclei scattering

Barger, Chiang, Keung & Marfatia

Tucker-Smith & Yavin

Light Higgs Phenomenology

5. Conclusion & Outlook

3 r_p determinations: ep atom, ep scattering, μp atom

something likely wrong but which one(s)?

Rydberg Constant Vulnerable

What If all exps correct

Efforts to simultaneously address r_p & a_μ discrepencies suggests: **m_V~MeV & α'~$2.5\times10^{-6}\alpha$ solves both but requires violation of e-μ universality.**

Conflicts with neutrino oscillations in matter (Gauge $L_{\mu R}$?)

Alternative light Higgs like particle O(1MeV)

but neutron/proton coupling?

Who ordered that?

THE PUZZLE REMAINS UNSOLVED

Stay Tuned For More Developments