

The Legacy of E. Zavattini

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Cargèse International School on QED, & Quantum Vacuum, Low Energy Frontier - 2012



2005: QED, Quantum Vacuum and the
Search for New Forces, Les Houches

2000: Frontier tests of QED and physics of the
vacuum, Trieste

1998: Frontier tests of QED and physics of the
vacuum, Sandansky

1994: Workshop on physics of exotic atoms, Erice

The Legacy of E.Zavattini





The Legacy of E.Zavattini

In the 1980's, in Dubna:

muon physics research, related to
"muon catalyzed fusion".

E.Zavattini had already measured:

- muon capture rate
- muon life time
- cross sections with muonic atoms

The Legacy of E.Zavattini



- Precision experiments, which:
 - test fundamental theories
 - are aimed at solving key problems
 - display the interplay of weak, strong and EM interactions
 - consider alternative models

Precision experiments



Concluding remarks at the International Conference on a European Hadron Facility, Mainz 1986:

1. Muon capture rate and weak lepton-hadron form factors g_A and g_P
2. BNL proposal on the anomalous magnetic moment of the muon a_μ .

Testing QED



Particular interests:

Vacuum polarization and radiative effects:

- exotic atom spectroscopy
- muon anomaly measurements
- nonlinear QED effects

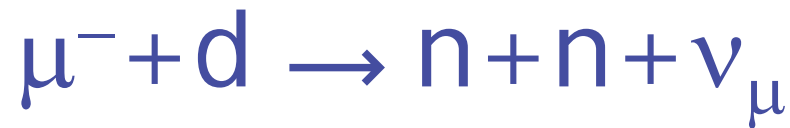


Of the Legacy of E.Zavattini:

Three selected topics:

- Nuclear muon capture
- Nonlinear effects of QED
- Exotic atom spectroscopy

Muon capture by nuclei



6 form factors at $q^2 \sim 0.88m_\mu^2$

$g_V(q^2)$, $g_M(q^2)$, $g_S(q^2)$, $g_A(q^2)$,
 $g_T(q^2)$, $g_P(q^2)$

Muon capture in H gas

First measurement of $\mu^- + p \rightarrow n + \nu_\mu$

PHYSICAL REVIEW

VOLUME 177, NUMBER 5

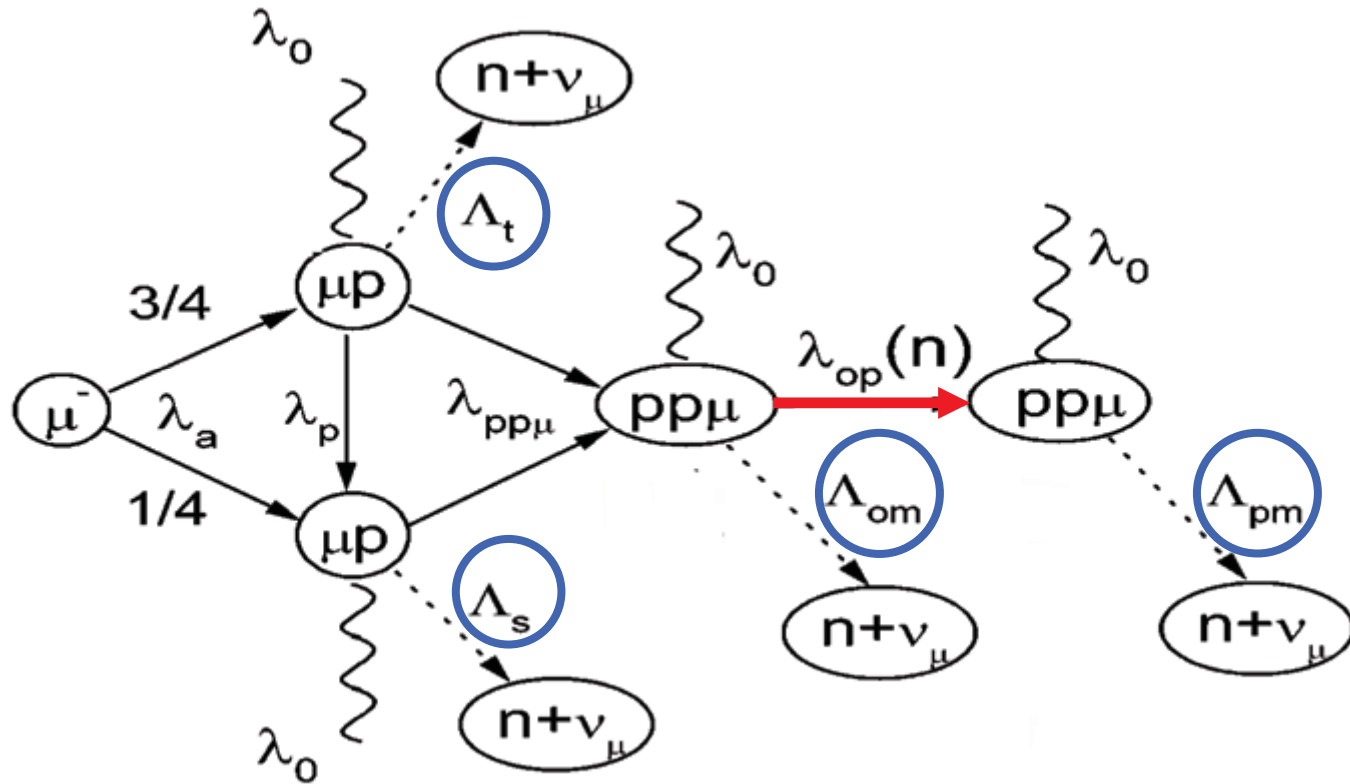
25 JANUARY 1969

Muon Capture in Gaseous Hydrogen

The experimental result is $\Lambda_{\text{expt}} = 651 \pm 57 \text{ sec}^{-1}$, which has to be compared with the theoretical rate $\Lambda_{s, \text{theor}} = 626 \pm 26 \text{ sec}^{-1}$. From the experimental capture rate, and within the framework of the currently accepted theory, we have obtained for the induced pseudoscalar coupling constant $g_p = (-7.3 \pm 3.7)g_V$. The results of the present experiment are analyzed, together with results obtained from stopping negative muons in liquid hydrogen.

To compare with: $\Lambda_S = 725.0 \pm 17.4$, $g_p = 7.3 \pm 1.1$
(MuCAP experiment, 2007)

Muon capture in liquid H



Muon capture in liquid H

Nuclear Physics A352 (1981) 365–378 © North-Holland Publishing Co., Amsterdam

A NOVEL MEASUREMENT OF THE MUON CAPTURE RATE IN LIQUID HYDROGEN BY THE LIFETIME TECHNIQUE

Abstract: The muon nuclear capture rate by protons has been measured by comparing the lifetime τ_{μ^-} of negative muons stopped in liquid hydrogen with the lifetime τ_{μ^+} of positive muons. We get $\tau_{\mu^-} = 2194.903 \pm 0.066$ ns and $\tau_{\mu^+} = 2197.182 \pm 0.121$ ns. Taking into account also the previous determinations of τ_{μ^+} , we present the updated determination of the muon lifetime.

Improved to $\tau_{\mu^+} = 2197.078(0.073)$ ns [PLB137(1984)]

To compare with MuLAN (2007), similar method used:

$$\tau_{\mu^+}(\text{MuLan}) = 2196980.3(2.2) \text{ ps.}$$

Ortho-para transitions in liquid H

Volume 104B, number 4

PHYSICS LETTERS

3 September 1981

MEASUREMENT OF THE ORTHO-PARA TRANSITION RATE IN THE $p\mu p$ MOLECULE AND DEDUCTION OF THE PSEUDOSCALAR COUPLING CONSTANT g_p^μ

The ortho-para transition rate in the $p\mu p$ molecule has been found experimentally to be $\lambda_{OP} = (4.1 \pm 1.4) \times 10^4 \text{ s}^{-1}$. Our recent result for the muon capture rate in liquid hydrogen can now be interpreted to extract the ortho-molecular capture rate: $\lambda_{OM} = (531 \pm 33) \text{ s}^{-1}$. A deduction of the pseudoscalar coupling constant g_p^μ is presented: we find $g_p^\mu = 8.7 \pm 1.9$.

Theoretical calculations: $\lambda_{op} = 7.1 \pm 4.1 \times 10^4 \text{ s}^{-1}$
Still an open problem.

Nonlinear QED effects



Vacuum birefringence in strong B:

$$n_{\perp} \neq n_{\parallel}$$

Leading to ellipticity and rotation of
linearly polarized light

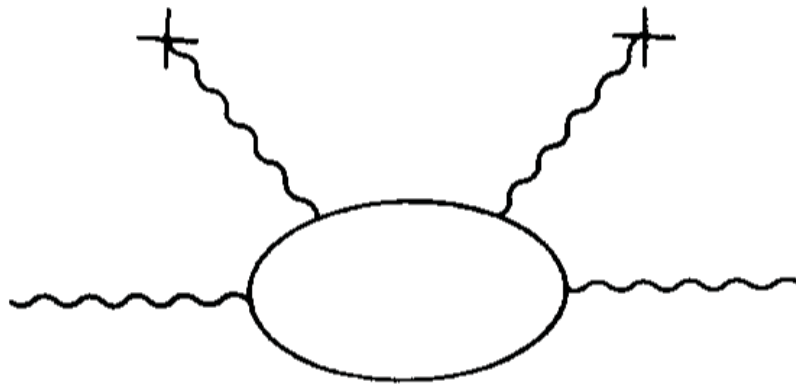
(Analogous to Cotton-Mouton effect)

Vacuum birefringence in B

Euler-Heisenberg theory:

$$L = (E^2 - B^2) / (8\pi)$$

$$+ (A/4\pi)((E^2 - B^2)^2 + 7(E \cdot B)^2), \quad A = O(\alpha^2)$$



+h.o.t.

Experimental method

Volume 85B, number 1

PHYSICS LETTERS

30 July 1979

EXPERIMENTAL METHOD TO DETECT THE VACUUM BIREFRINGENCE INDUCED BY A MAGNETIC FIELD

E. IACOPINI and E. ZAVATTINI

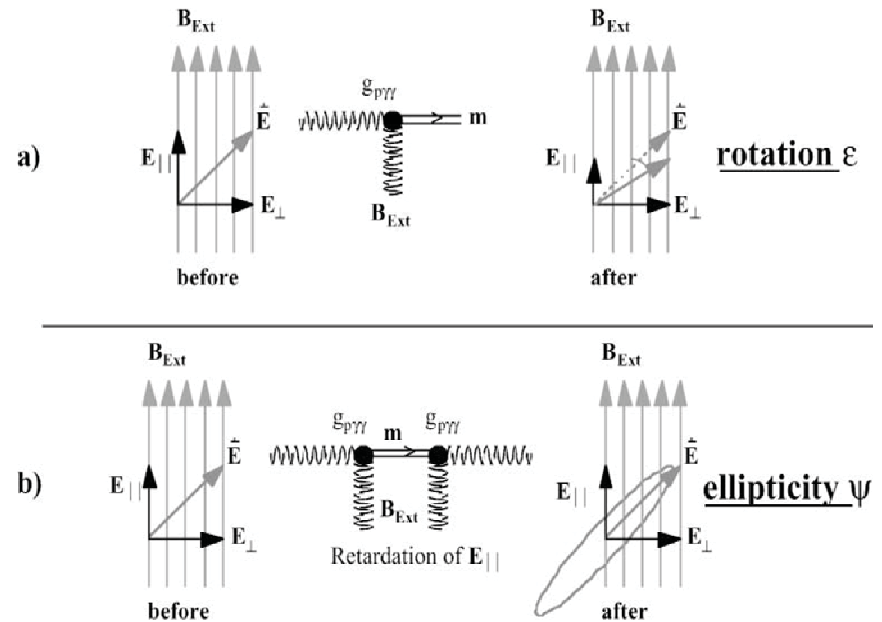
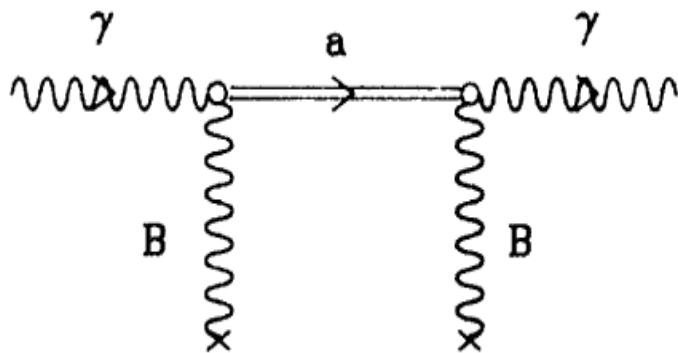
CERN, Geneva, Switzerland

Received 28 May 1979

In this letter a method of measuring the birefringence induced in vacuum by a magnetic field is described: this effect is evaluated using the non-linear Euler–Heisenberg–Weisskopf lagrangian. The optical apparatus discussed here may detect an induced ellipticity on a laser beam down to 10^{-11} .

Vacuum birefringence in B

Other possible sources: axions



From: Phys.Rev.D47(1993)3707 [left], Nucl.Instrum.Meth. A461(2001)329 [right]

Search for "axions" (BFRT)

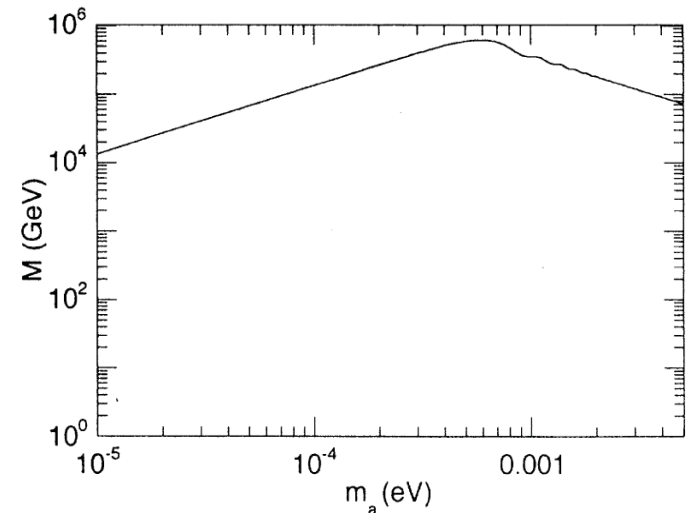
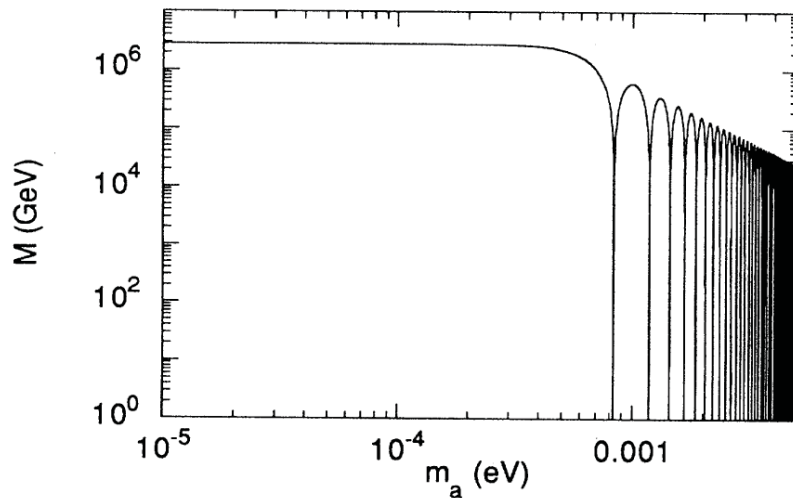
PHYSICAL REVIEW D

VOLUME 47, NUMBER 9

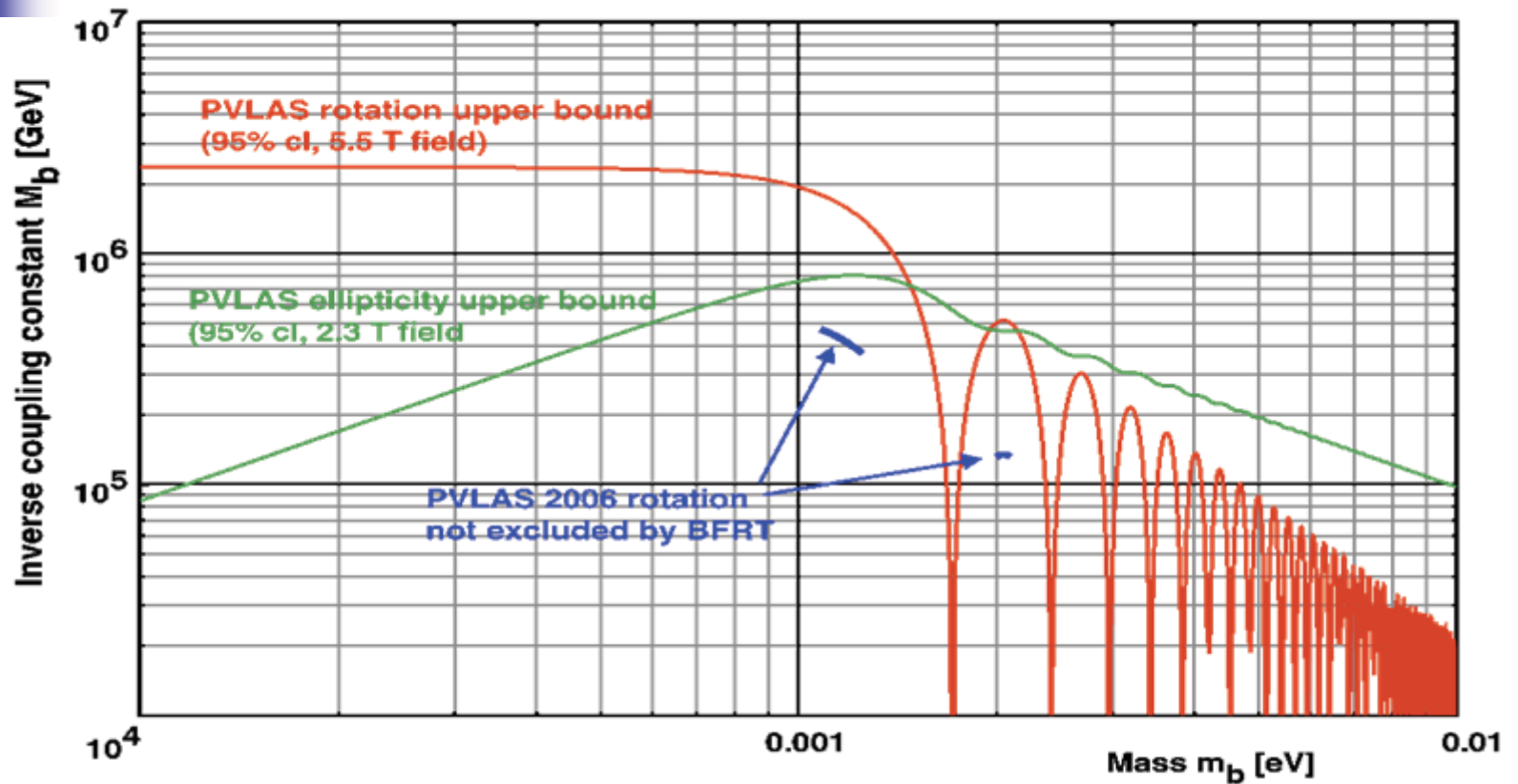
1 MAY 1993

ARTICLES

Search for nearly massless, weakly coupled particles by optical techniques



Search for "axions" (PVLAS)



From: Phys.Rev.D77(2008)032006

Vacuum birefringence in B



- Vacuum birefringence in strong field: not yet observed
- Improved sensitivity experiments: in progress (BMV,...)
- Search for weakly interacting nearly massless particles: in progress
- Photon regeneration experiments...

Exotic atom spectroscopy



The electron replaced by a heavy charged particle.

$r \sim a_0 / (m/m_e)$: enhanced nucl.str.eff.

$E \sim E_0^* (m/m_e)$: different freq. range

- Kaonic atoms (DEAR)
- Antiprotonic atoms (Obelix)
- Muonic atoms (CERN, SIN)

Vacuum polarization in $(\mu\text{He})^+$

$2S_{1/2}-2P_{3/2}$ level difference

Nuclear Physics A278 (1977) 381 – 386;

PRECISE MEASUREMENT OF THE $2S_{1/2}-2P_{3/2}$ SPLITTING IN THE $(\mu^-{}^4\text{He})^+$ MUONIC ION

Abstract: The results of a new measurement of the $2S_{1/2}-2P_{3/2}$ splitting S^1 in the muonic ion $(\mu^-{}^4\text{He})^+$ are presented. We found $S_{\text{exp}}^1 = 1527.5 \pm 0.3 \text{ meV}$. Using the new, recently determined, value of the rms charge radius for ${}^4\text{He}$ we obtain for the difference D , between S_{exp}^1 and the corresponding theoretical prediction, the value $D = 0.2 \pm 4.2 \text{ meV}$: this value directly confirms, assuming μ -e universality, the QED vacuum polarization prediction to 0.25 %.

NOT reproduced by P.Hauser et al., PRA(1992) (low P)

Vacuum polarization in $(\mu\text{He})^+$

$2S_{1/2}-2P_{1/2}$ level difference

Volume 73B, number 2

PHYSICS LETTERS

MEASUREMENT OF THE $2S_{1/2}-2P_{1/2}$ SPLITTING IN THE $(\mu^{-4}\text{He})^+$ MUONIC ION

The measurement of the $2S_{1/2} \rightarrow 2P_{1/2}$ energy transition in muonic helium is presented. The energy difference S^1 is found to be $S_{\text{exp}}^1 = 1381.3 \pm 0.5$ meV. This result agrees with the expected value $S^1 = 1381.2 \pm 0.3$ meV obtained assuming the previously measured value for the $2S_{1/2} \rightarrow 2P_{3/2}$ energy difference.

Confirmed by theory: 1381.716 meV (Martynenko 2006)

Metastability of $(\mu\text{He})^+_{2S}$ at 40 A?

VOLUME 33

29 JULY 1974

NUMBER 5

Measurement of the Initial Population and Decay Rate of the $(\mu^4\text{He})_{2S}^+$ System
in a Helium Target at 50 atm

Experimentally observed:

2S-fraction: $\sim 4\%$

2S-lifetime: $\sim 1\mu\text{s}$ at 50 At.

Metastability of $(\mu\text{He})^+_{2S}$ at 40 A?

PHYSICAL REVIEW A

VOLUME 41, NUMBER 5

**Formation and disappearance rates of metastable muon- α levels
in high-pressure helium targets**

Semi-quantitative theoretical model:
prompt formation of excited clusters
 $[(\mu^- \text{He})_{2S} - \text{He}]^*$, $[(\mu^- \text{He})_{2S} - \text{He} - \text{He}]^*$, ...

Metastability of $(\mu\text{He})^+_{2S}$ at 40 A?



But:

M.Eckhause et al., PRA33(1986) found:
at 40 At, the lifetime of $(\mu\text{He})^+_{2S}$ is 40 ns.

2S-metastability: an open problem.

Future experiments expected (PSI?)

Born-Infeld theory (1983)

IL NUOVO CIMENTO

VOL. 78 B, N. 1

11 Novembre 1983

Vacuum Polarization Effects in the $(\mu^{-4}\text{He})^+$ Atom and the Born-Infeld Electromagnetic Theory.

$$L = b^2 \left(1 - \sqrt{1 - (E^2 - B^2)/b^2 - (E \cdot B)^2/b^4} \right)$$

Lamb shift in $(\mu\text{He})^+$ can be reproduced by adjusting b

No vacuum birefringence produced



Antiprotonic helium spectroscopy (Obelix Collaboration)

- Delayed annihilation of antiprotons stopped in Helium
- Dependence on contaminants
- Alternative mechanism suggested:
formation of $[(p\text{-He})^+\text{He}]^*$
(not confirmed)

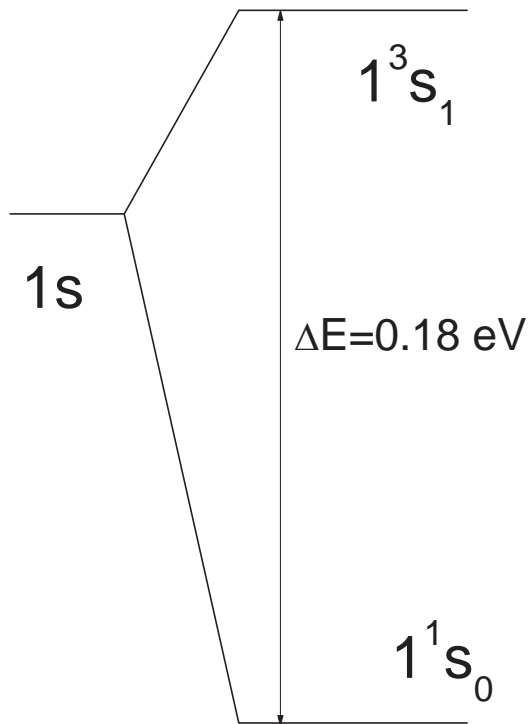
Muonic hydrogen spectroscopy



- Elastic scattering cross sections
- Muon transfer to heavier gases (xenon)
- Laser spectroscopy in excited states
- heavier elements muonic atoms

Hyperfine splitting in $(\mu\text{H})_{1\text{S}}$?

HFS in hydrogen-like atoms



$$\Delta E = \Delta E^F (1 + \delta^{\text{QED}} + \delta^{\text{str}})$$

$$\delta^{\text{str}} = \delta^{\text{rigid}} + \delta^{\text{pol}} + \delta^{\text{hvp}} + \dots$$

$$\delta^{\text{rigid}} = \delta^{\text{Zemach}} + \delta^{\text{recoil}}$$

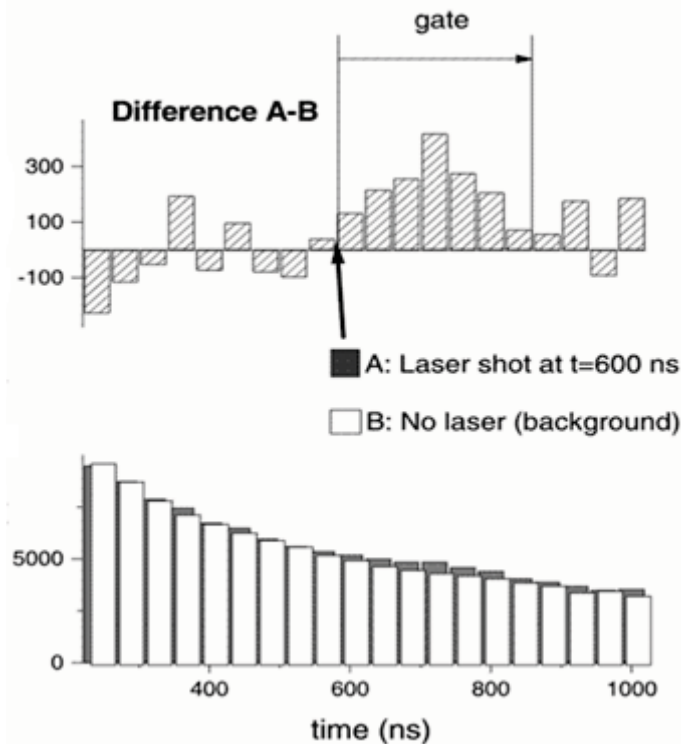
$$\delta^{\text{Zemach}} = -2\alpha m R_p + O(\alpha^2)$$

$$R_p = \langle r \rangle_{E^{\circ}M}; R_p^2 \neq r_{\text{sq}}^2$$

$\Delta^{\text{pol}} \leftrightarrow$ polarizability 'a' ?

Two parameters (a , R_p) from measurements in H & μH ?

Hyperfine splitting in $(\mu\text{H})_{1\text{S}}$



- Time distribution of the events of μ^- transfer to:
 - walls of target volume
 - nuclei of appropriate heavier gas admixture
- Tunable IR laser source

Nuclear Instruments and Methods in Physics Research A 341 (1994)
Compact waveguide FEL for spectroscopic measurements in muonic hydrogen

From: Hyperf.interact.136(2001)1

The Legacy of E.Zavattini



Ongoing experimental activities

- MuLAN & MuCAP
- Vacuum birefringence
- Muonic helium spectroscopy
- Muonic hydrogen hyperfine structure

...