Study of fundamental Laws with Positronium and AntiHydrogen

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A E ḡ I S

Antimatter

Experiment

Gravity

Interferometry

Spectroscopy

Outline of talk:

- **Theoretical motivation**
- **General experimental strategy**
- **Gravity measurement**
- **Positronium physics**
- **Status and Results**

AEGIS: AD-6 Experiment

at CERN – Geneva (CH)

http://aegis.web.cern.ch/aegis/

Antimatter history in a slide

- 1928: relativistic equation of the ½ spin electron (Dirac)
- 1929: electron sea and hole theory (Dirac)
- 1931: prediction of antimatter (Dirac, Oppenheimer, Weyl)
- 1932: discovery of positron in cosmic rays (Anderson)
- 1933: discovery of e-/e+ creation and annihilation (Blackett, Occhialini)
- 1937: symmetric theory of electrons and positrons
- 1955: antiproton discovery (Segre', Chamberlain, Wiegand)
- 1956: antineutron discovery (Cork, Lambertson, Piccioni, Wenzel)
- 1995: creation of high-energy antihydrogen (CERN, Fermilab)
- 2002: creation of 10 K antihydrogen (Athena, Atrap)
- 2011: antihydrogen confinement (Alpha)

→ Future: study of Antimatter properties !!

AEGIS Collaboration

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AD (Antiproton Decelerator) at CERN

3 x 10^7 antiprotons / 100 sec   5.3 MeV 10^4 $\bar{p}$ / 100 sec

Typical experiment

Theoretical Motivation

Physics with Antimatter is at the very foundation of Modern Physics:

CPT Physics

WEP (Weak Equivalence Principle)

CPT Theorem

Charge conjugation (C) : reversing electric charge and all internal quantum numbers

Parity (P): space inversion; reversal of space coordinates

Time reversal (T): replacing t by –t. Reverses time derivatives

Any local, Lorentz invariant Lagrangian is CPT symmetric (Lüders, Pauli 1959). CPT is proven in axiomatic Quantum Field Theory.

Consequences:

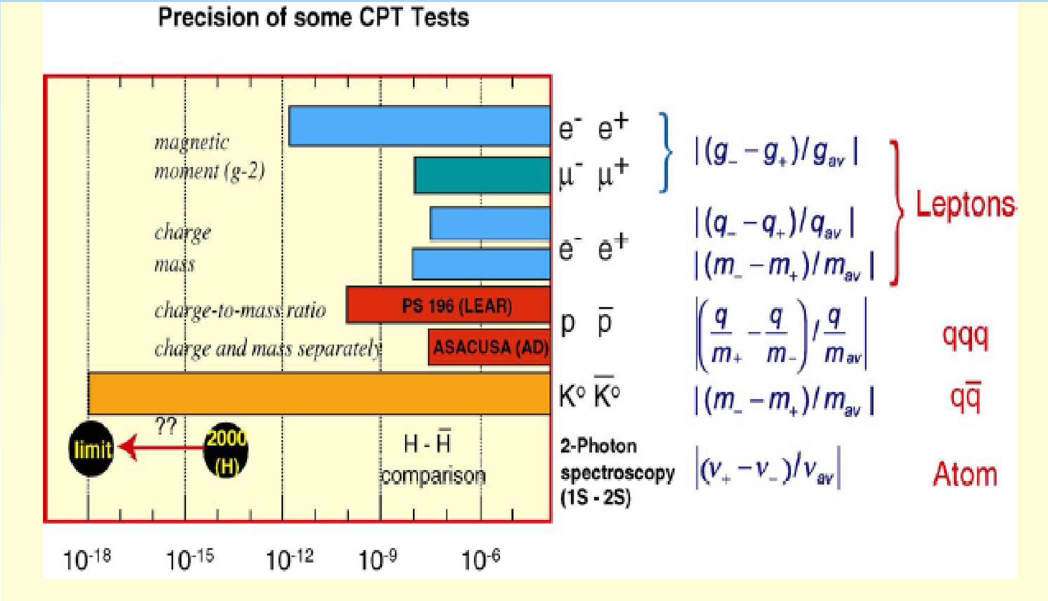
Particles and antiparticles have identical masses and lifetimes

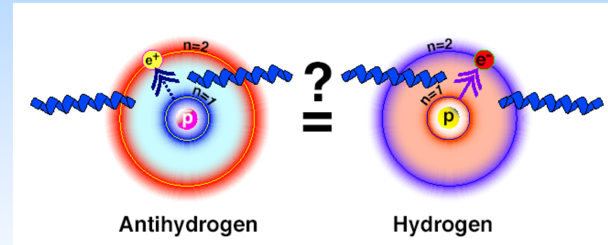
All internal quantum numbers of antiparticles are opposite to those of particles

CPT conserved to the best of our knowledge. So why look for violations?

1) A test of CPT is not only a test of a discrete symmetry. It is a test of the validity of Quantum Field Theory
2) CPT could break down in a Quantum Theory of Gravity

Experimental CPT tests





.....$\Delta\nu/\nu < 10^{-15}$

Results achieved on Hydrogen

1S-2S ν=2 466 061 413 187 103 (46) Hz
Natural width: 1.3 Hz

$\Delta\nu/\nu$ = 1.5 10^{-14} Cold beam $E \approx 100\ mK$

PRL84 5496 (2000) M. Niering et al

$\Delta\nu/\nu$ = 10^{-12} Trapped H $E \approx 100\,\mu K$

PRL 77 255 (1996) C. Cesar et al

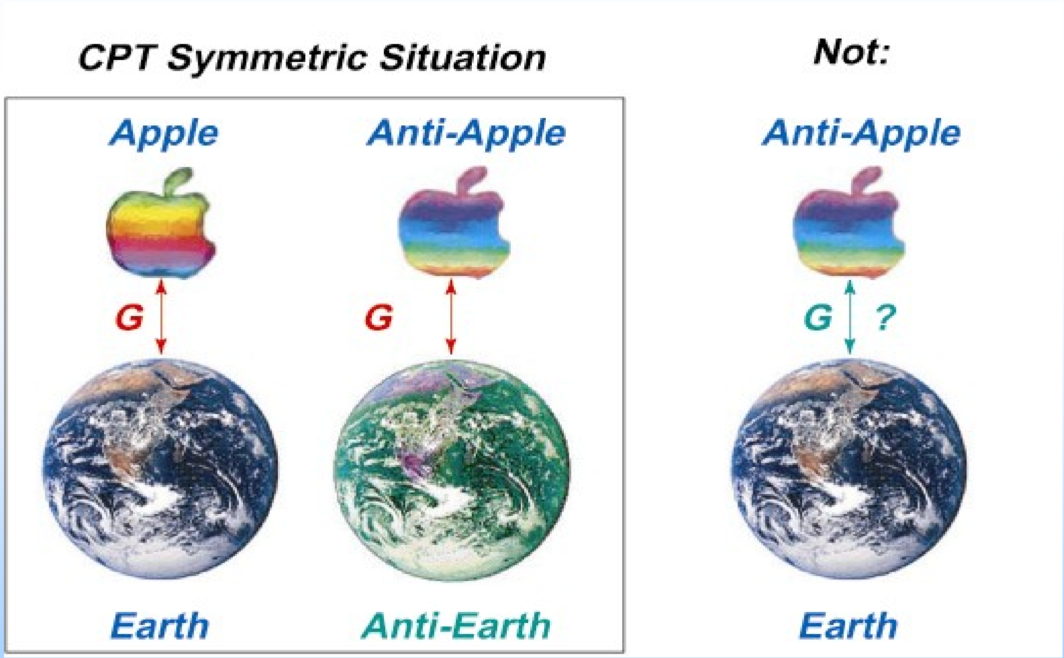
Requires antihydrogen at mK temperature

WEP: Weak Equivalence Principle

The trajectory of a falling test body depends only on its initial position and velocity and is independent of its composition (a form of WEP)

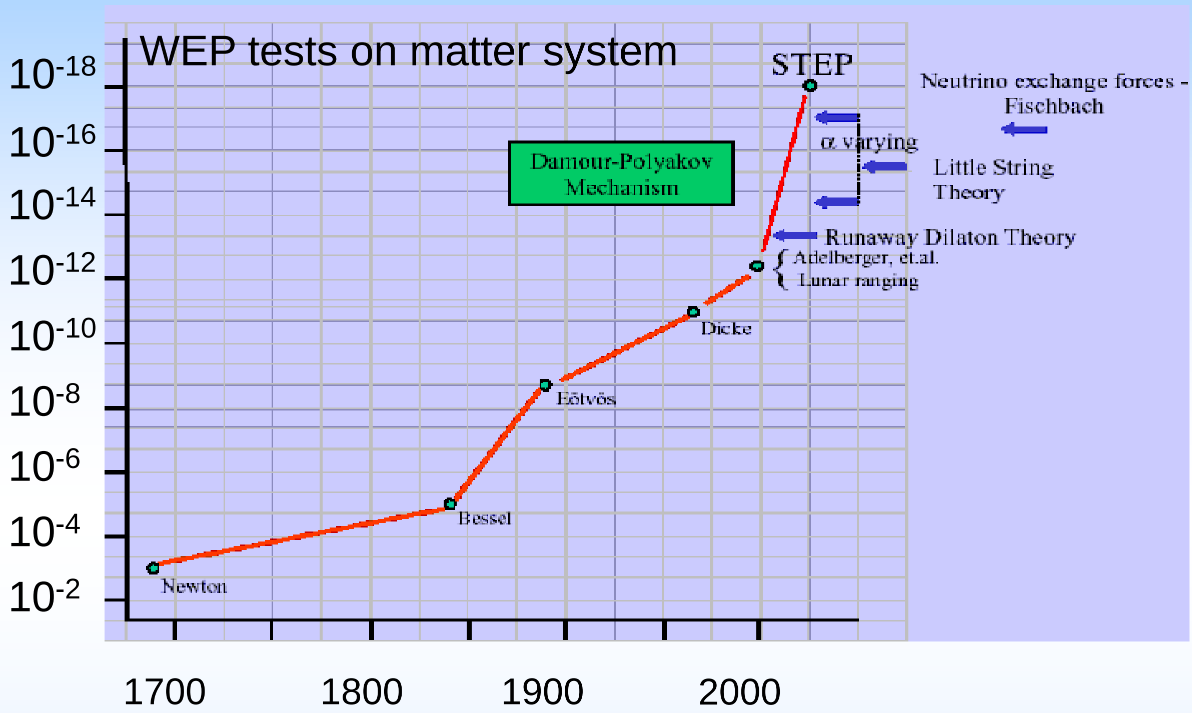
All bodies at the same spacetime point in a given gravitational field will undergo the same acceleration (another form of WEP)

1. Direct Methods: measurement of gravitational acceleration of H and Hbar in the Earth gravitational field
2. High-precision spectroscopy: H and Hbar are test clocks (this is also CPT test)

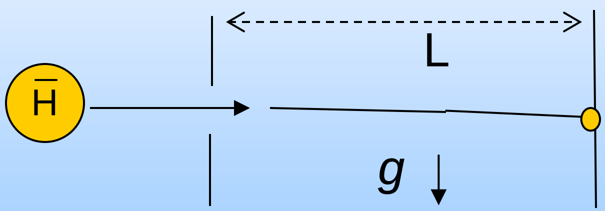


Experimental tests of the Weak Equivalence Principle

- No direct measurements on gravity effects on antimatter
- "Low" precision measurement (1%) will be the first one



Can be done with a beam of Antiatoms flying to a detector!



$$h = \frac{1}{2} g T^2 = \frac{g}{2} \left(\frac{L}{v_z} \right)^2$$

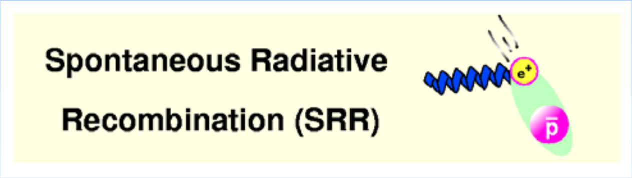
AEGIS first phase

General experimental strategy

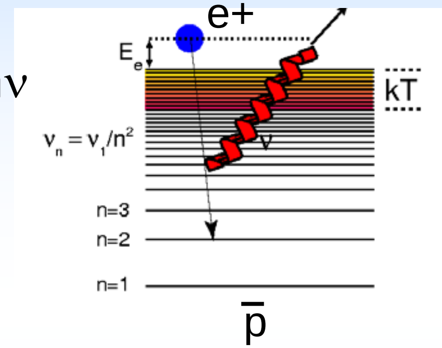
Production Methods

I. ANTIPROTON + POSITRON (exp.demonstration: ATHENA and ATRAP)

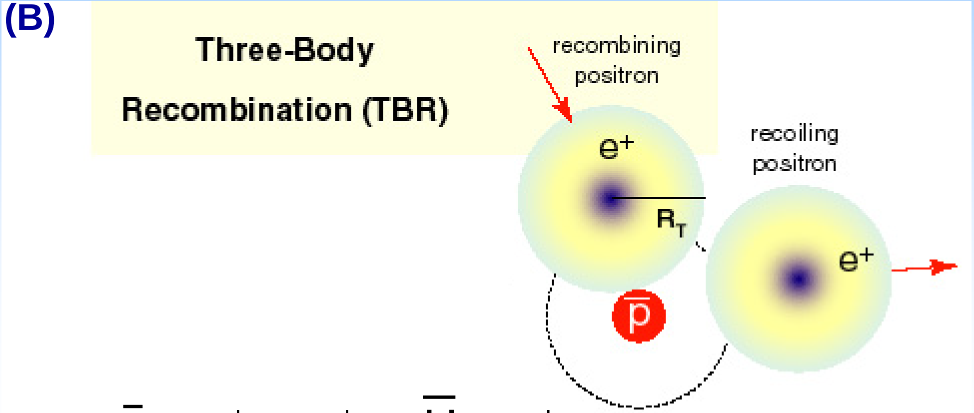
(A)



$\bar{p} + e^{+} \rightarrow \bar{H} + h\nu$



(B)



$\bar{p} + e^{+} + e^{+} \rightarrow \bar{H} + e^{+}$

EXPERIMENTAL RESULTS:

- TBR seems to be the dominant process (highly exicited antihydrogen)
- Warm antihydrogen atoms (production when $v_{antiproton} \sim v_{positron}$)

II. ANTIPROTON + RYDBERG POSITRONIUM (exp.demonstration: ATRAP)

$\bar{p} + Ps^{*} \rightarrow \bar{H} + e^{-}$

PROMISING TECHNIQUE:

- Control of the antihydrogen quantum state
- Cold antihydrogen atoms ($v_{antihydrogen} \sim v_{antiproton}$)

→ Production Method in AEGIS

AEGIS strategy to produce Antihydrogen:

1. COLD ANTIHYDROGEN PRODUCTION

- Nested Penning Trap (warm antihydrogen / highly excited antiatoms)
- Charge Exchange with Rydberg Positronium

$$\overline{p} + (Ps)^* \rightarrow \overline{H}^* + e^-$$

- Slow antiprotons (cold antihydrogen)
- Rydberg Positronium
  - Positronium formation
  - Positronium excitation

Do not try to confine charged particles (Penning trap) and Antihydrogen (by radial B gradients) as being done in Alpha.

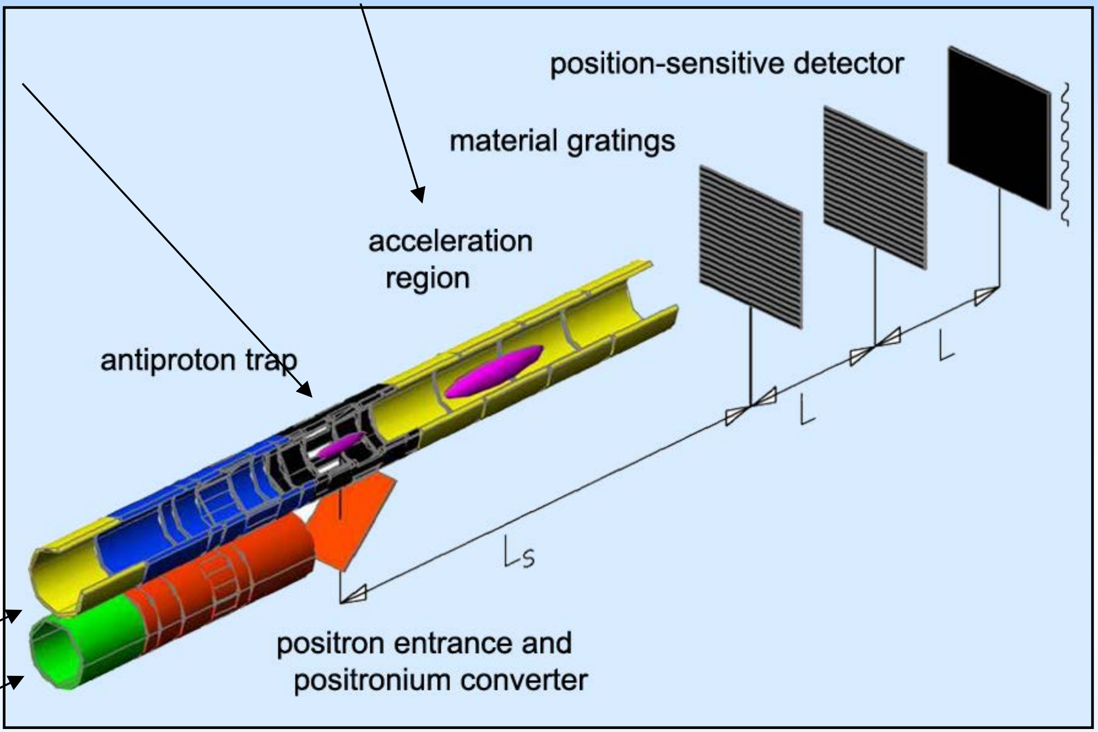
- Have a charged particle trap only
- Form a neutral (antihydrogen) beam → g measurement
- Confine only neutrals (future) → (CPT physics)

A E $\bar{g}$ I S in short

Acceleration of antihydrogen.

Formation of antihydrogen atoms

The antihydrogen beam will fly (v~400 m/sec) through a classical moire' deflectometer



Antiprotons

Positrons

The vertical displacement (gravity fall) will be measured on the last (sensitive) plane of the deflectometer

Antimatter Gravity first precision (percent) measurement

Ultracold Antiprotons

•The CERN AD (Antiproton Decelerator) delivers 3 x 10^7 antiprotons / 80 sec

•Antiprotons catching in cylindrical Penning traps after energy degrader

•Catching of antiprotons within a 3 Tesla magnetic field, UHV, 4 Kelvin, e^- cooling

•Stacking several AD shots (10^4/10^5 subeV antiprotons)

•Transfer in the Antihydrogen formation region (1 Tesla, 100 mK)

•Cooling antiprotons down to 100 mK

•10^5 antiprotons ready for Antihydrogen production

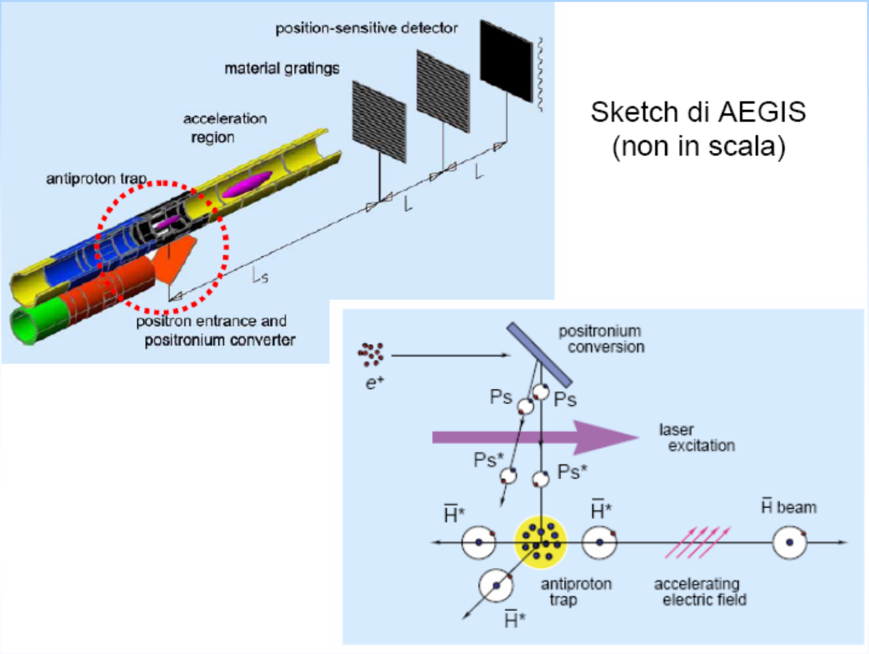
Antiprotons	
Production	GeV
Deceleration	MeV
Trapping	keV
Cooling	eV

• Resistive cooling based on high-Q resonant circuits

• Sympathetic cooling with laser cooled Os^- ions

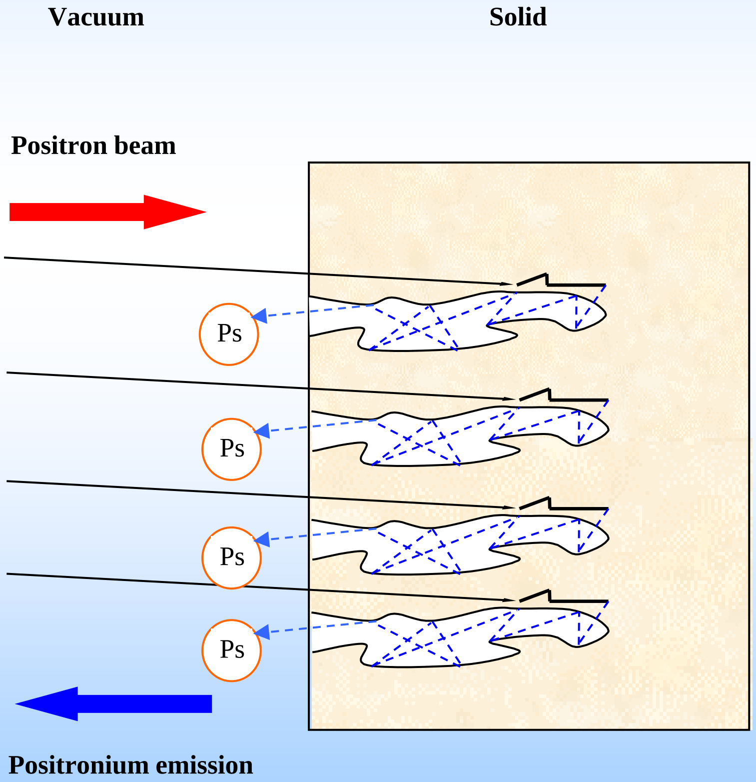
U. Warring et al., PRL 102 (2009) 043001

Positrons and Positronium (Ps) production



Technique: have a bunch of 10^8 e^+ in 20 ns

Have them impinge at ~keV energy on a (likely porous Silica) target



Orto-Ps produced in the bulk and "thermalized" by collision on pore walls

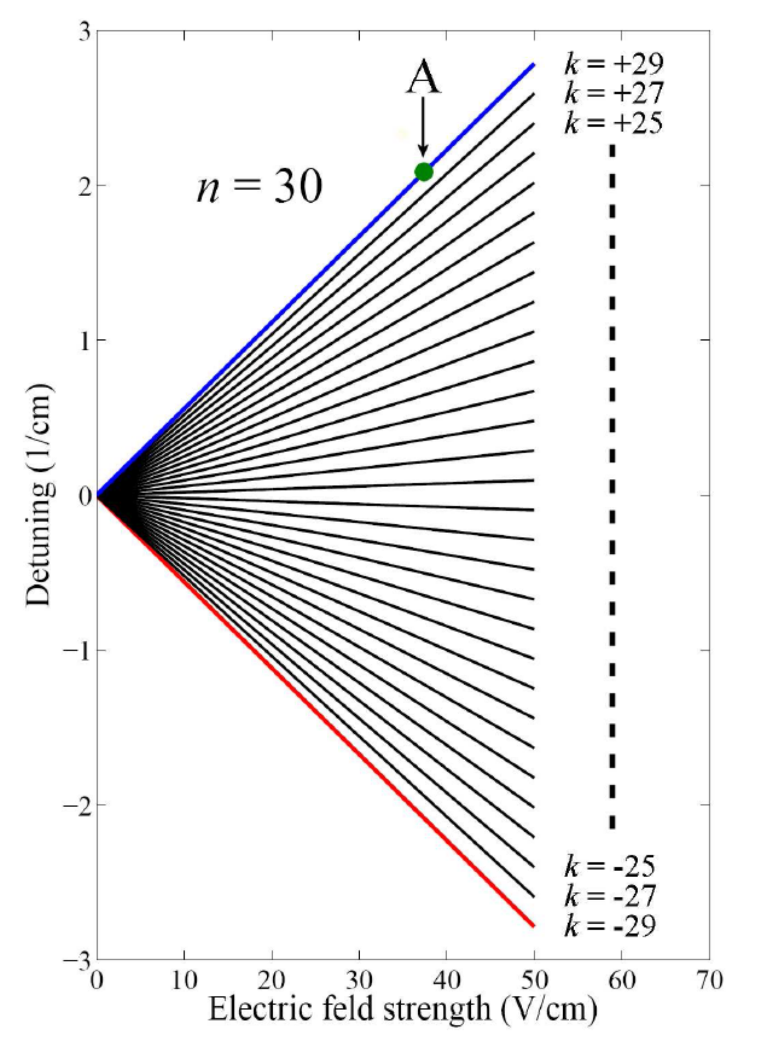
Ps used for the reaction:

$$\overline{p} + (Ps)^* \rightarrow \overline{H}^* + e^-$$

Stark acceleration

Energy levels of H in an electric field :

$$E = -\frac{1}{2n^2} + \frac{3}{2}nkF,$$



AEGIS: acceleration of Hbar by means of an inhomogeneous time dependent electric field (though the Stark effect)

Experiments done at ETH have shown that a Rydberg H beam with a 700 m/s velocity and n=15-40 can be stopped in 5μs over a 1.8 mm distance

AEGIS experimental strategy

1) Produce ultracold antiprotons (100 mK)

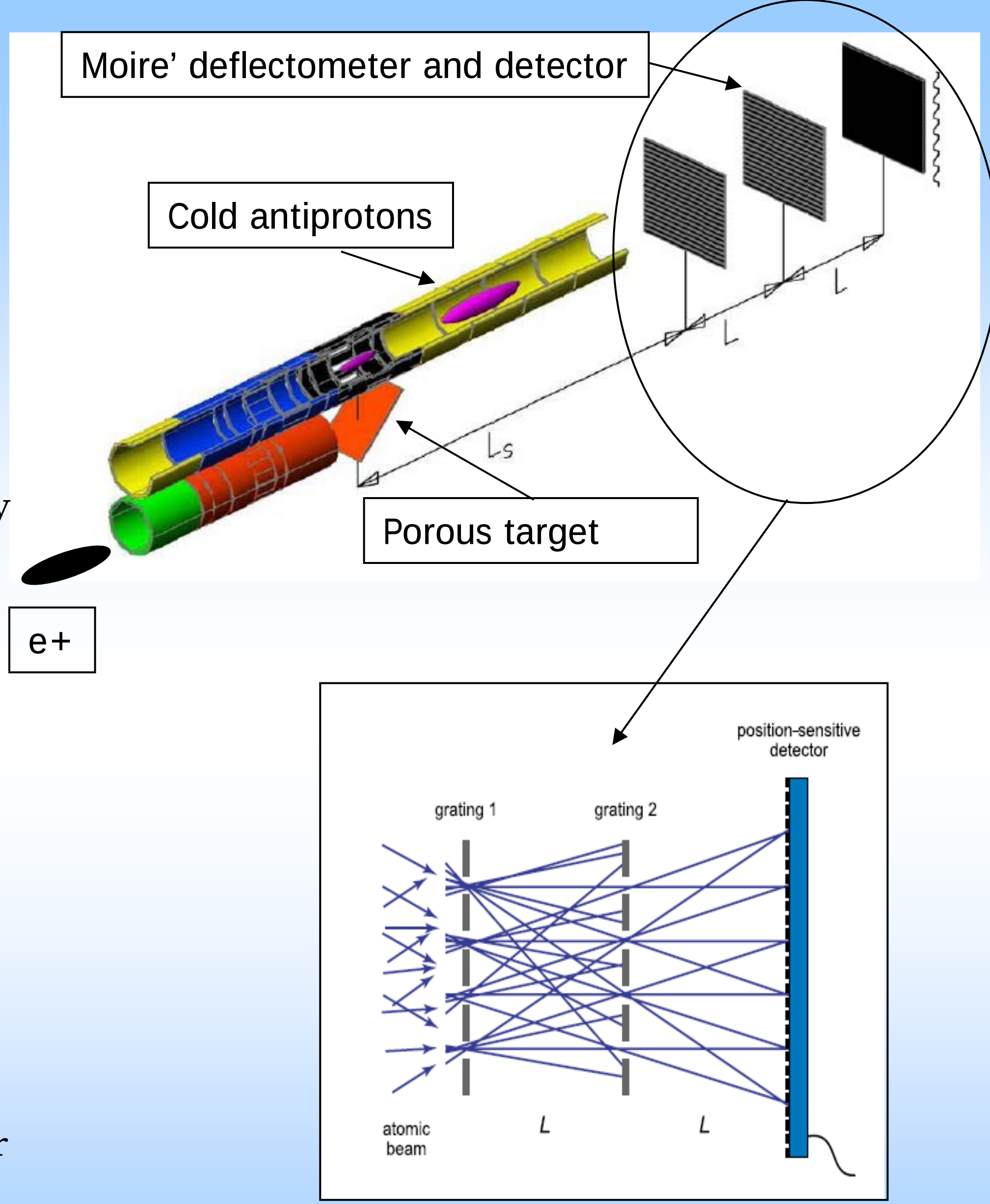
2) Accumulate e+

3) Form Ps by interaction of e+ with porous target

4) Laser excite Ps to get Rydberg Ps

5) Form Rydberg cold (100 mK) antihydrogen by

$$\bar{p} + (Ps)^* \rightarrow \bar{H}^* + e^-$$

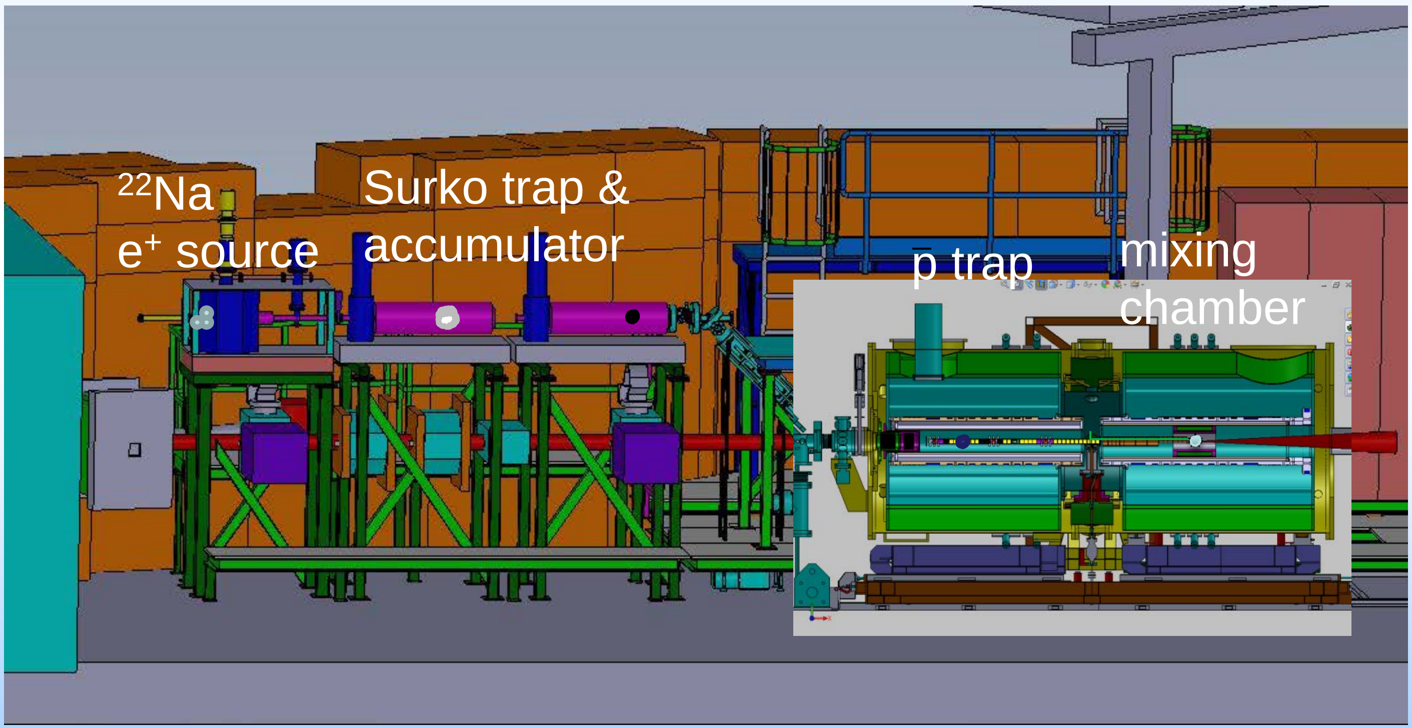


6) Form a beam using an inhomogeneous electric field to accelerate the Rydberg antihydrogen

7) The beam flies toward the deflectometer which introduces a spatial modulation in the distribution of the Hbar arriving on the detector

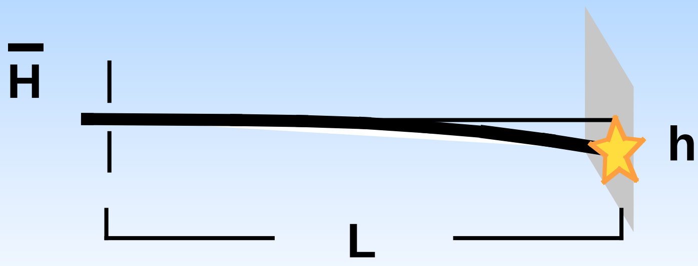
8) Extract g from this modulated distribution

AEGIS: Antimatter Experiment: Gravity, Interferometry, Spectroscopy



Gravity measurement

Antihydrogen fall and detection



$$h = \frac{1}{2} g T^2 = \frac{g}{2} \left(\frac{L}{v_z} \right)^2$$

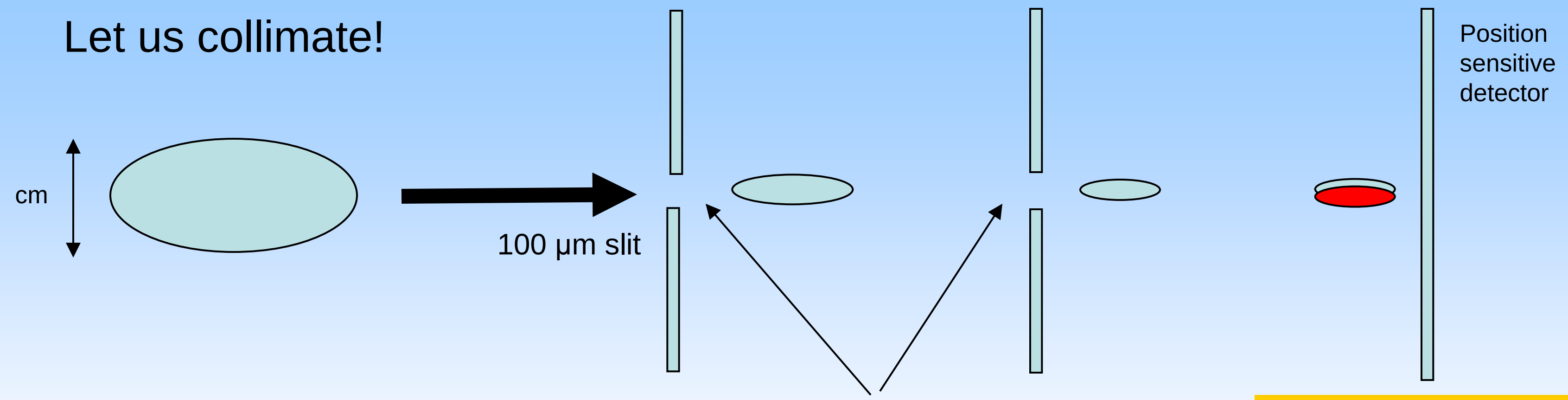
AEgIS realistic numbers:
- horizontal flight path L ~ 1 m
- horizontal velocity v_z ~ 500 m/s

→ **vertical deflection ~ 20 μm**

BUT: - antihydrogen has a radial velocity (related to the temperature)
- any anti-atom falls by 20 μm, but, in addition it can go up or down by few cm
- beam radial size after 1 m flight ~ several cm (poor beam collimation)

DISPLACEMENT DUE TO GRAVITY IS IMPOSSIBLE TO DETECT IN THIS WAY

Let us collimate!

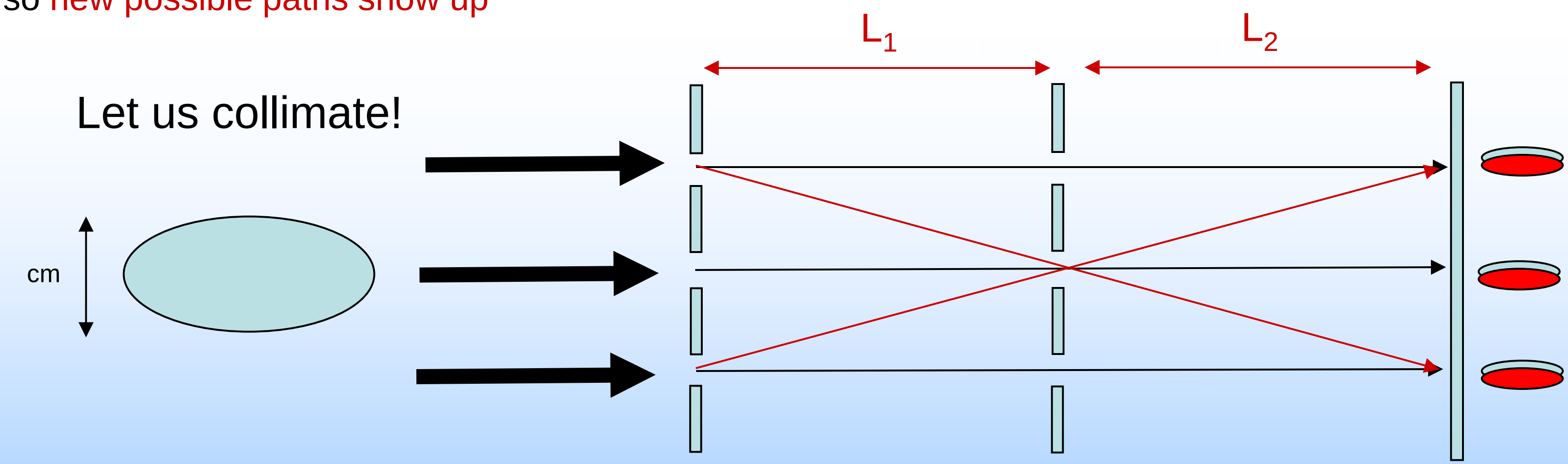


$$\frac{\Delta h}{h} \cong \frac{30\,\mu m}{100\,\mu m} = 0.3$$

Now displacement easily detectable. At the price of a huge loss in acceptance

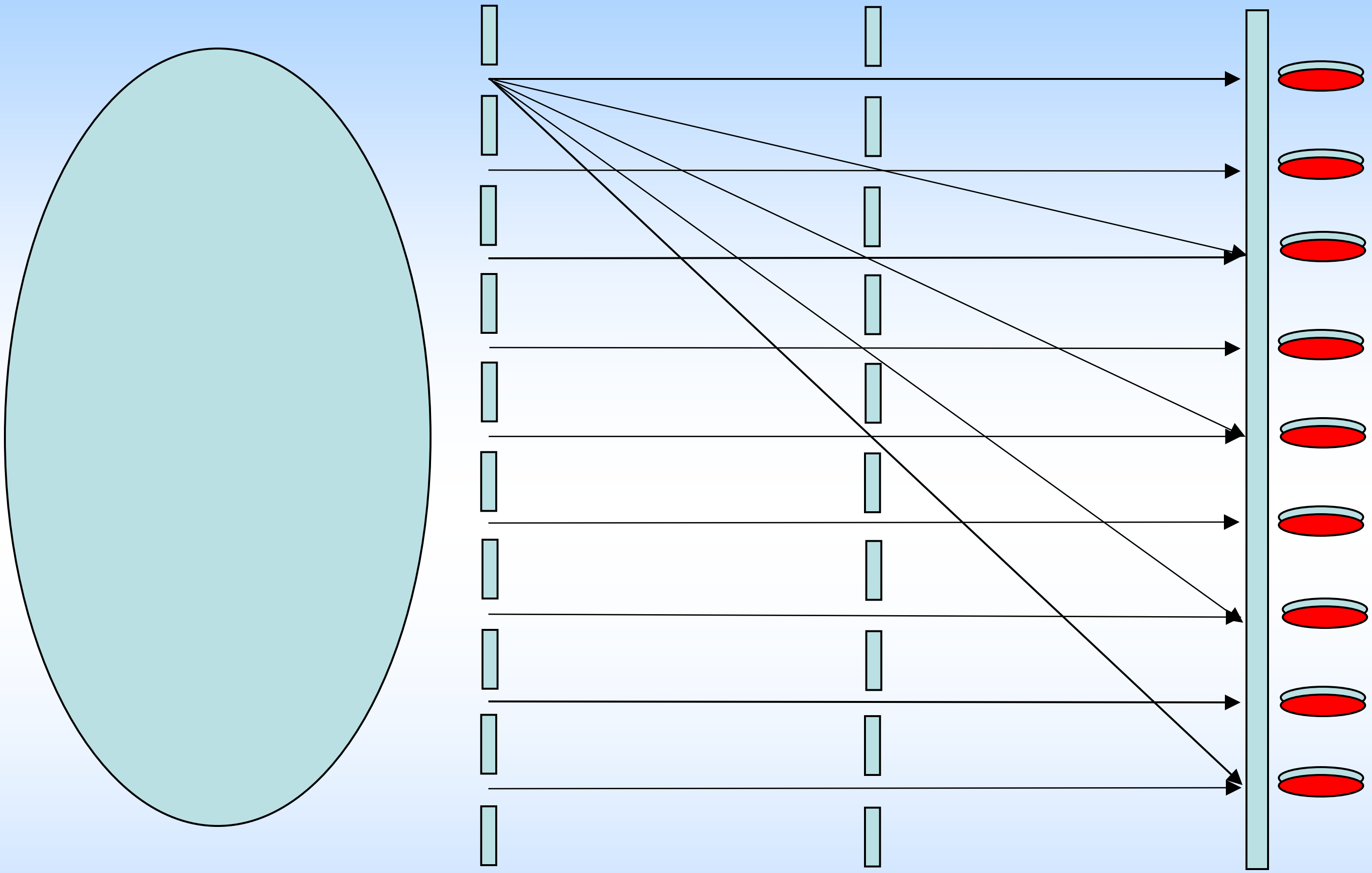
Acceptance can be increased by having several holes. In doing so new possible paths show up

Let us collimate!



If $L_1 = L_2$ the new paths add up to the previous information on the 3rd plane

Based on a totally geometric principle, the device is insensitive to a bad collimation of the incoming beam (which however will affect its acceptance)



Moiré Deflectometry is an interferometry technique, in which the object to be tested (either phase object or secular surface) is mounted in the course of a collimated beam followed by a pair of transmission gratings placed at a distance from each other. The resulting fringe pattern, i.e., the moiré deflectogram, is a map of ray deflections corresponding to the optical properties of the inspected object.

Collimation of the beam with a classical M o i r é deflectometer

PHYSICAL REVIEW A VOLUME 54, NUMBER 4 OCTOBER 1996

Inertial sensing with classical atomic beams

Markus K. Oberthaler, Stefan Bernet, Ernst M. Rasel, Jörg Schmiedmayer, and Anton Zeilinger
Institut für Experimentalphysik, Universität Innsbruck, Technikerstrasse 25 A-6020 Innsbruck, Austria

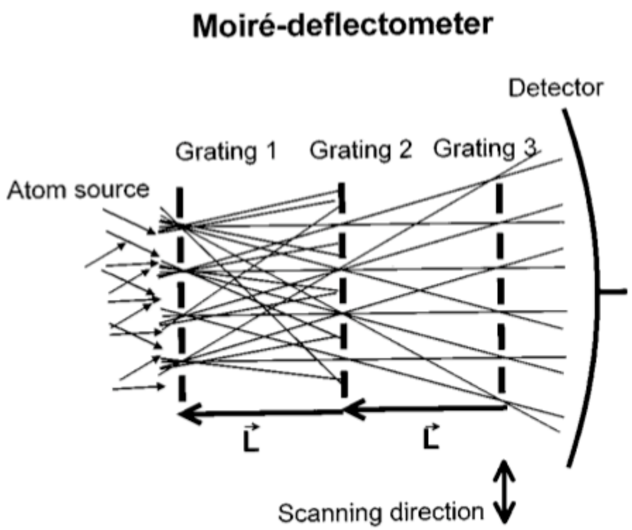
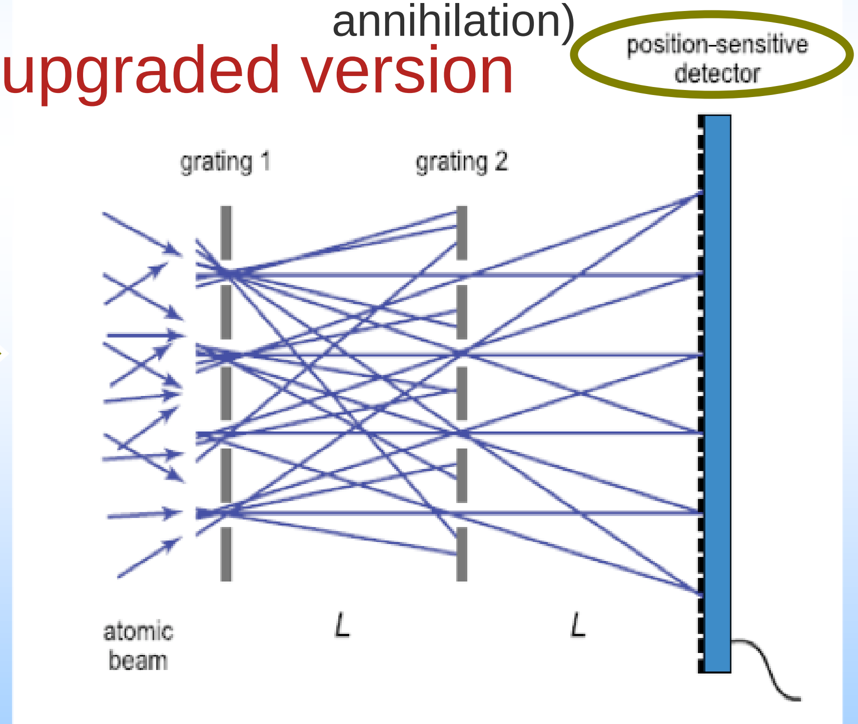


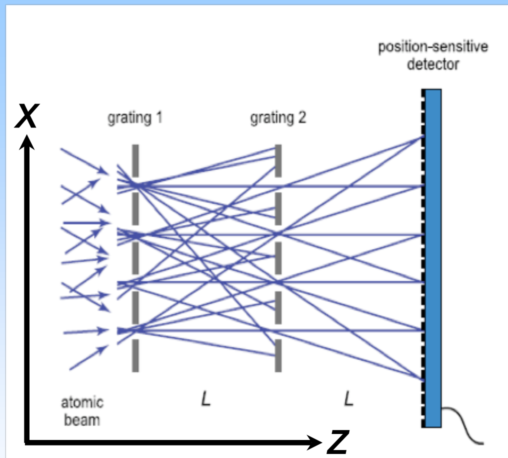
FIG. 1. Principle of a Moiré deflectometer. The first two identical gratings collimate the originally undirected atoms into various directions. After a distance *L* corresponding to the distance between the first two gratings, an image of the collimation gratings is formed. At this position, a third identical probe grating is placed. Its translation along the indicated direction leads to a periodic modulation of the transmitted intensity.

new position-sensitive detector (to detect antihydrogen annihilation)

upgraded version



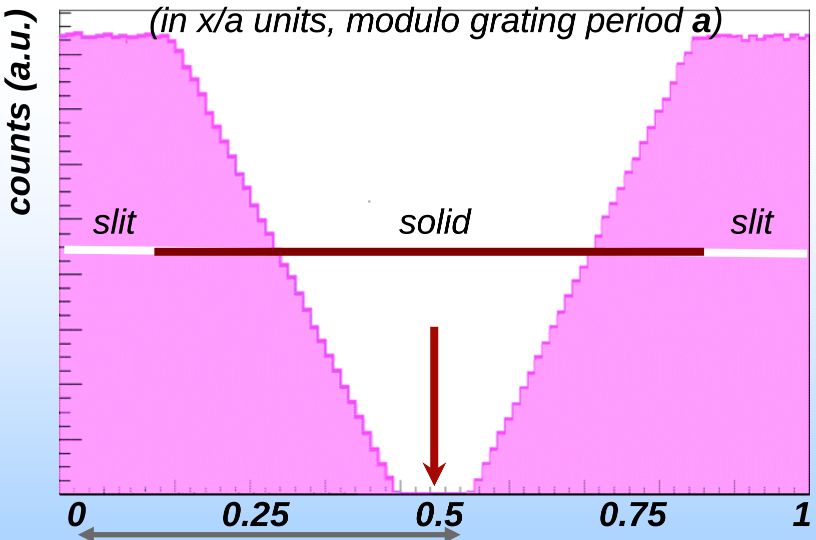
Moiré deflectometer



Grating transparency = 30%
(total transmission 9%)

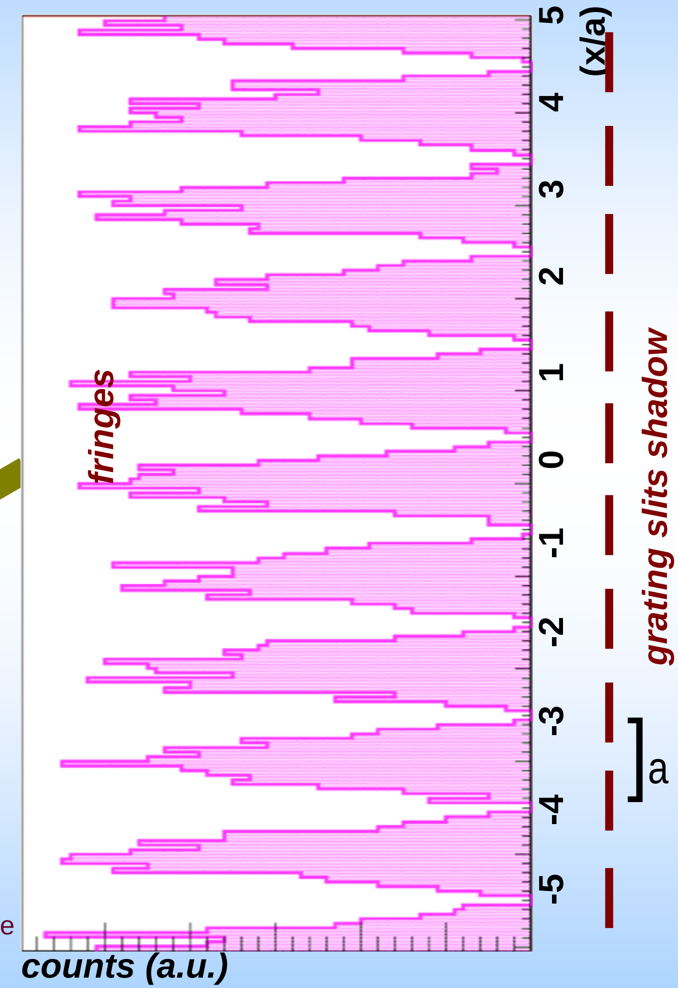
Suppose:
- L = 40 cm
- grating period a = 80 μm
- grating size = 20 cm (2500 slits)
- no gravity

annihilation hit position on the final detector
*(in x/a units, modulo grating period **a**)*



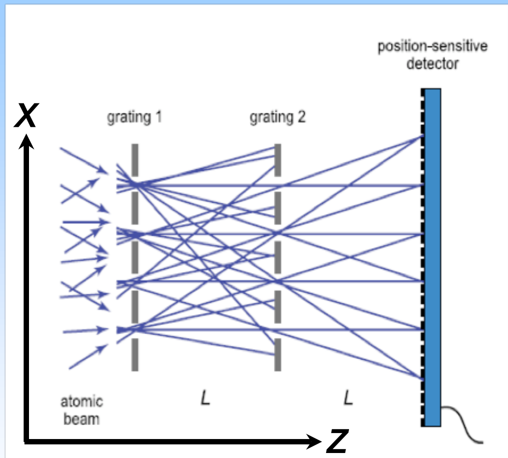
Δ_0 (calculated experimentally)

annihilation hit position on the final detector
(in x/a units)



depends on the alignement between the gratings, and on the alignment between them and the center of the antihydrogen cloud. It is indepentend to the radial antihydrogen velocity and profile

Moiré deflectometer



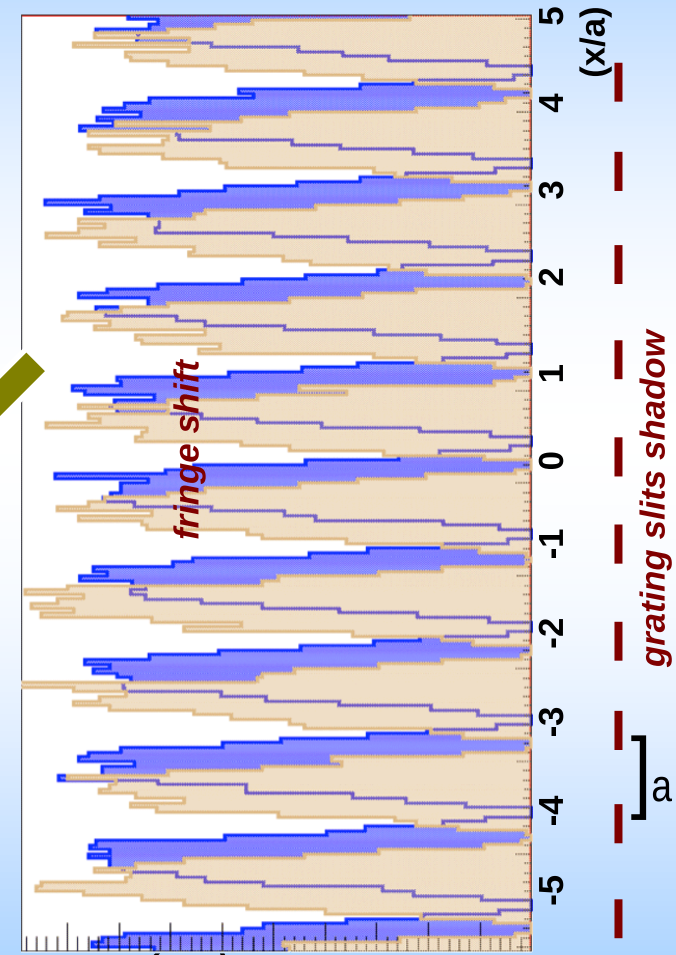
Grating transparency = 30%
(total transmission 9%)

Suppose:
- L = 40 cm
- grating period a = 80 μm
- grating size = 20 cm (2500 slits)
- gravity

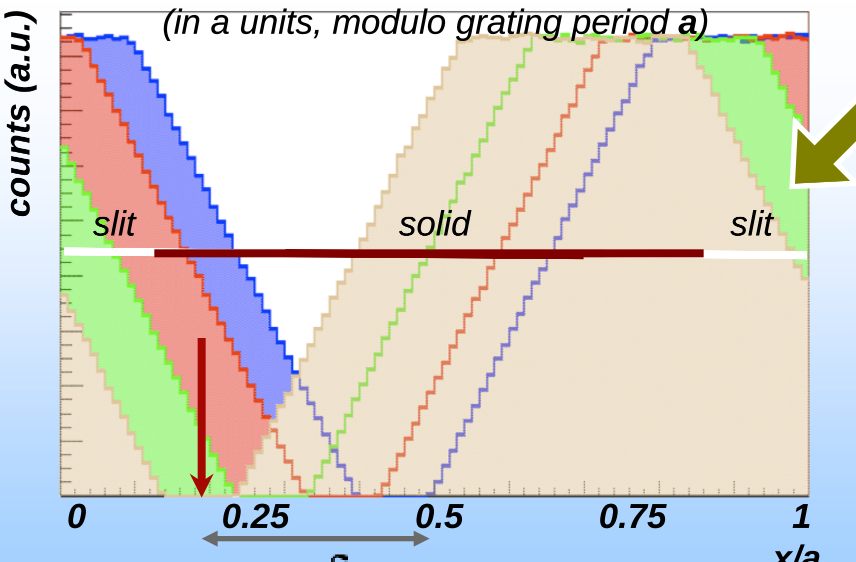
beam horizontal velocity

v_z = 600 m/s
v_z = 250 m/s

annihilation hit position on the final detector
(in a units)



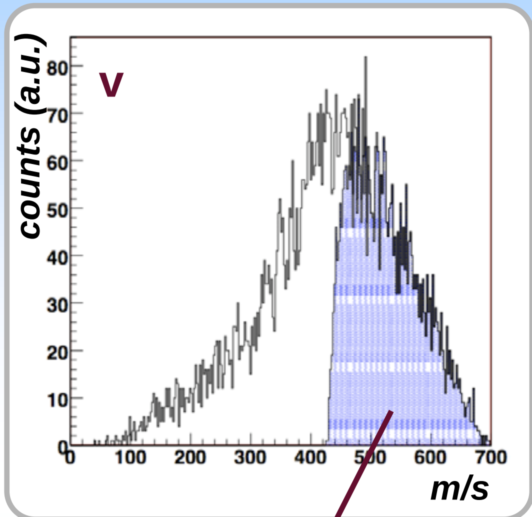
annihilation hit position on the final detector
*(in a units, modulo grating period **a**)*

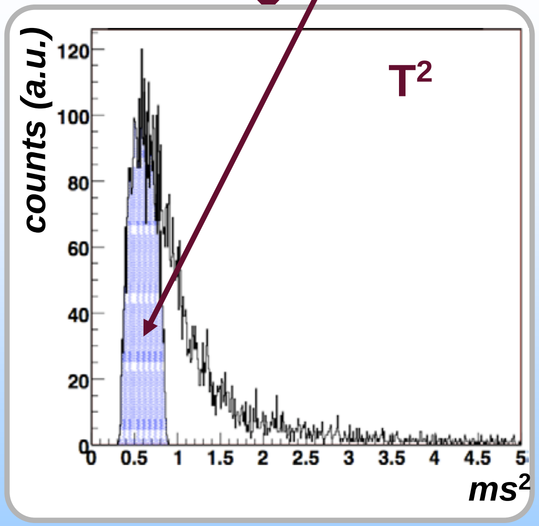


Fringe shift !

Moiré deflectometer

Out beam is not monochromatic
(T varies quite a lot)



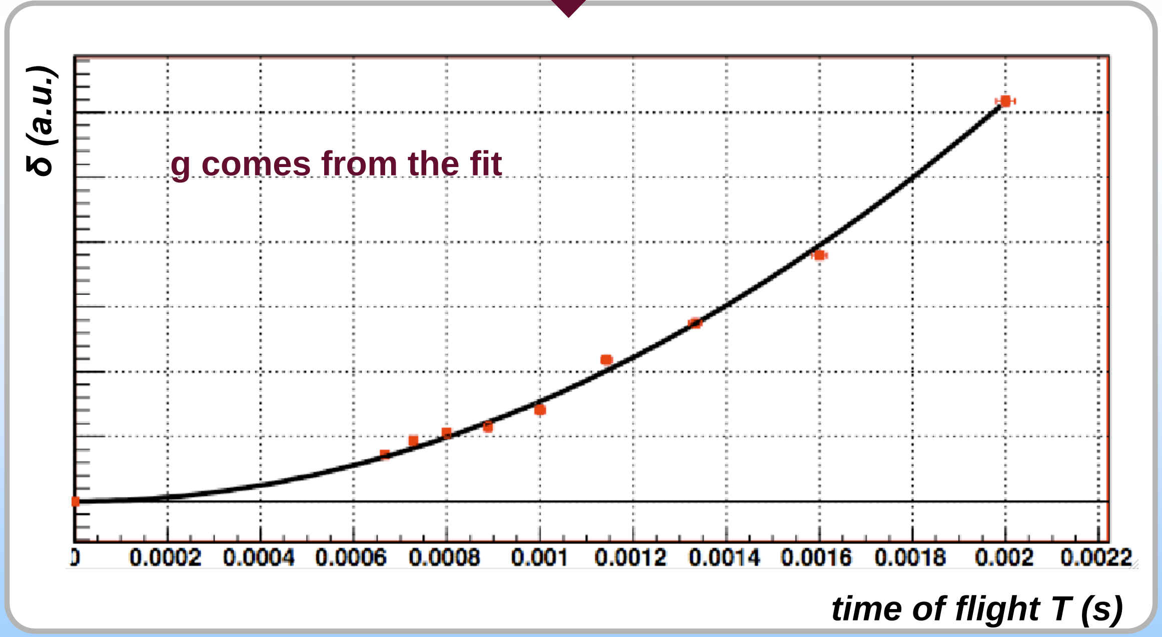


$$\delta = \frac{gT^2}{a}$$

fringe shift of the shadow image

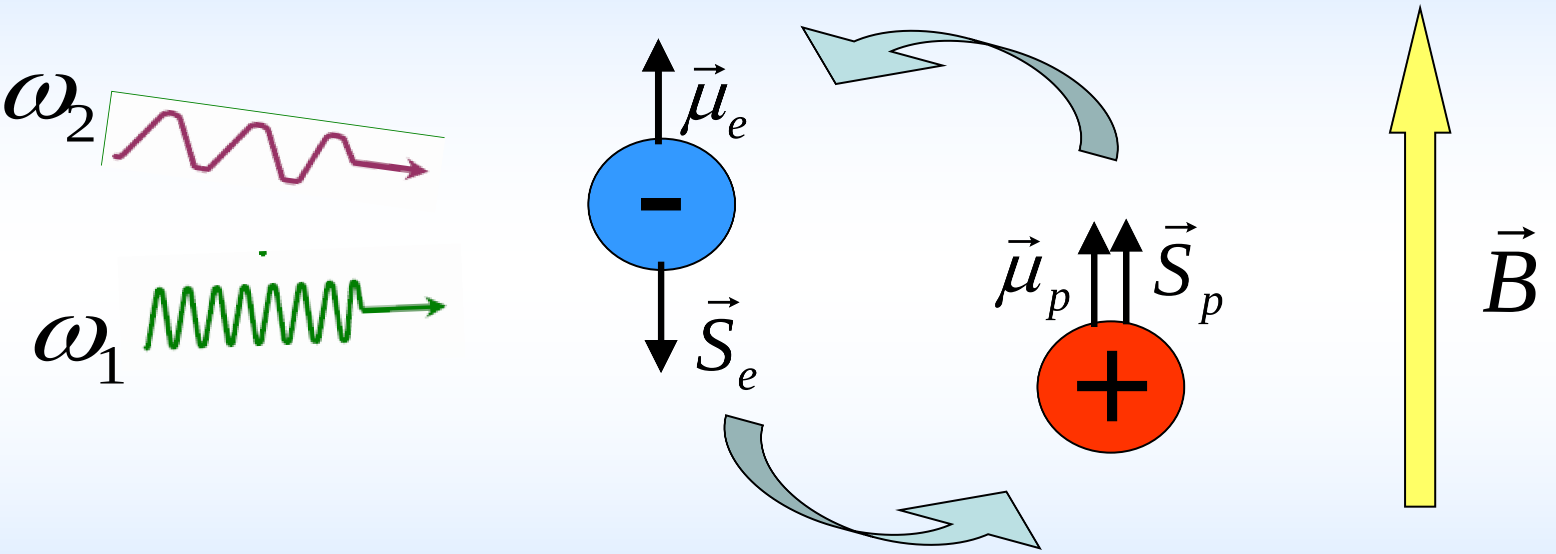
T = time of flight = [t_{STARK} - t_{DET}] (L~ 1 m, v ~ 500 m/s ➡**T ~ 2 ms**)

Binning antihydrogens with mean velocity of 600-550-500-450-400-350-300-250-200 m/s,
and plotting δ as a function of $\sqrt{< T^2 >}$



Positronium Physics

Positronium Excitation and Spectroscopy



Positronium (Ps): a pure leptonic atom!
QED at work!

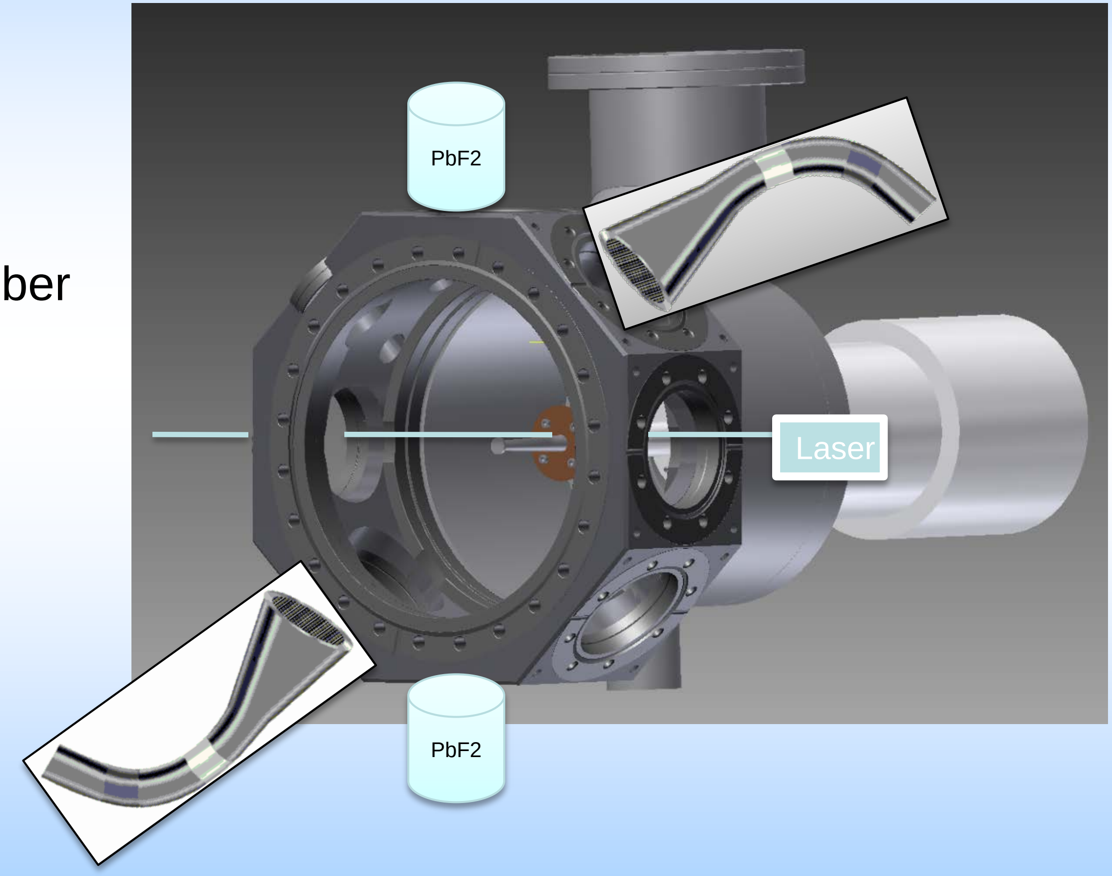
Experimental scheme for Ps studies

Trento – Milano – Orsay (in AEGIS)

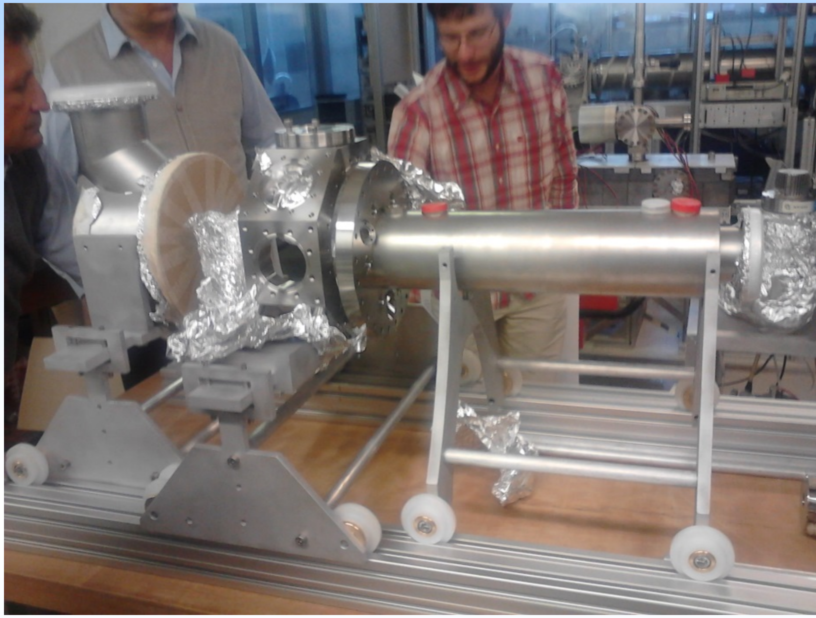
Experimental Chamber

Laser Systems

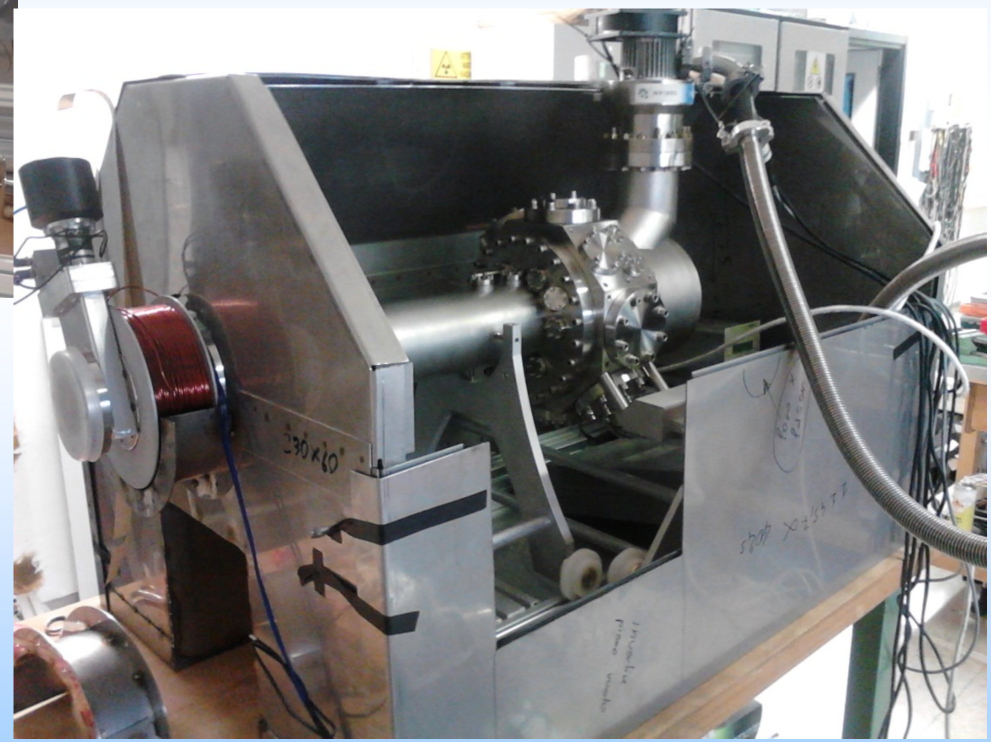
Detector Systems



Setting up the positronium chamber (Trento)



Mu-metal shield prototype made in Milano



Ps spectroscopy: proposals in AEGIS

General idea:

♪ Produce a positron bunch as foreseen for antihydrogen production

♪ Send the bunch to the dedicated Ps-table

♪ Use same converters as for antihydrogen

♪ Excite with the same laser system as for antihydrogen production

♪ Study the effect of magnetic field (useful for antihydrogen!)

♪ UV Excitation of the n=3 level (+ microwave)

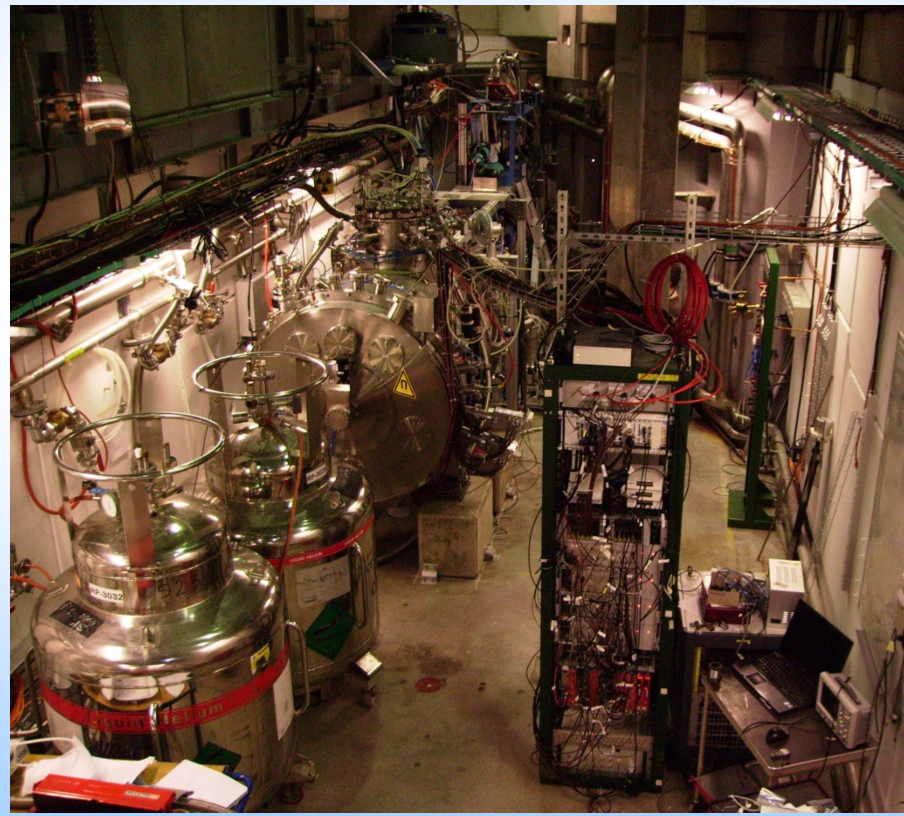
♪ IR Spectroscopy of Rydberg levels

♪ Future topics (Rydberg spectroscopy, Doppler free, laser cooling)

Status and Results

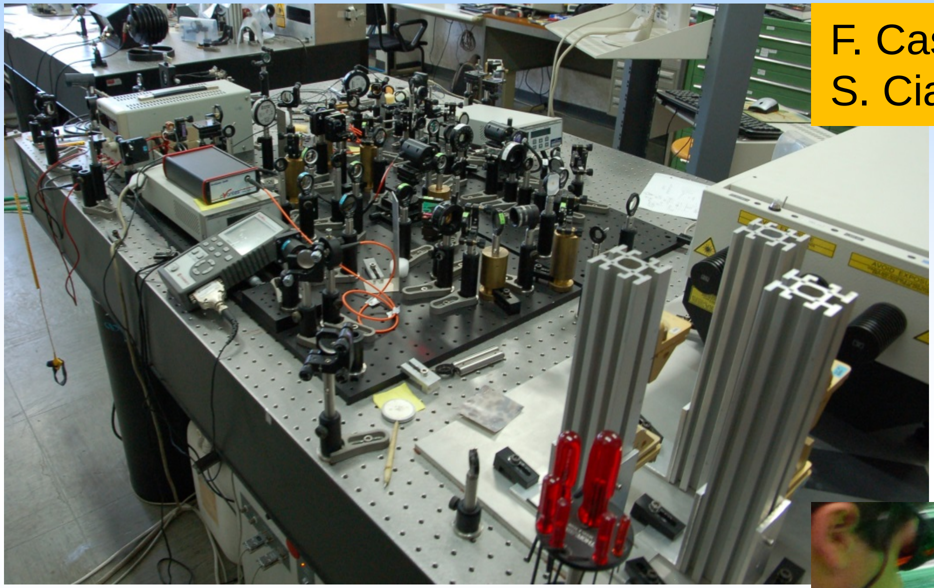
AEGIS : installation of the detector during 2012

September 2011



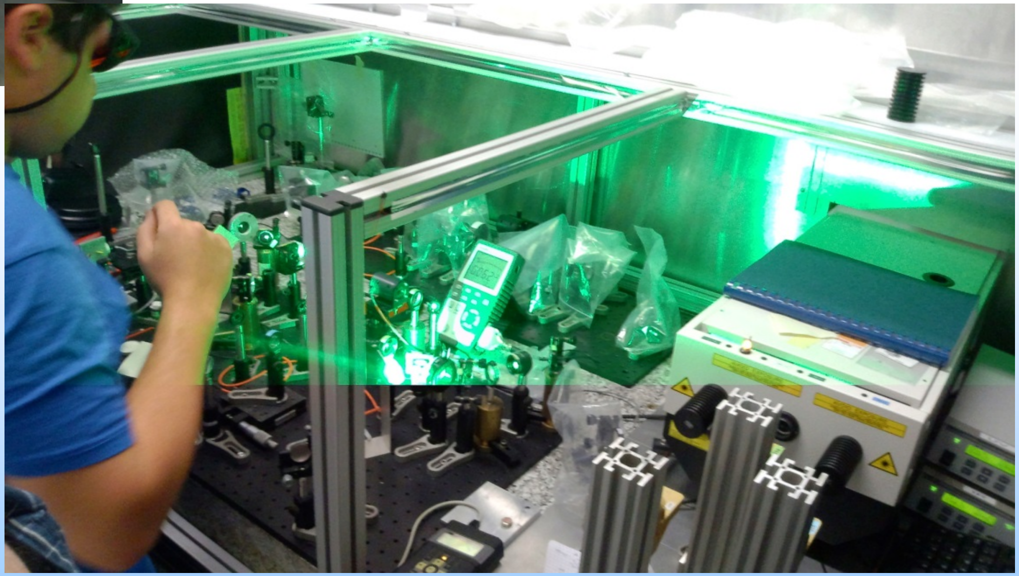
June 2012

AEGIS : the laser system



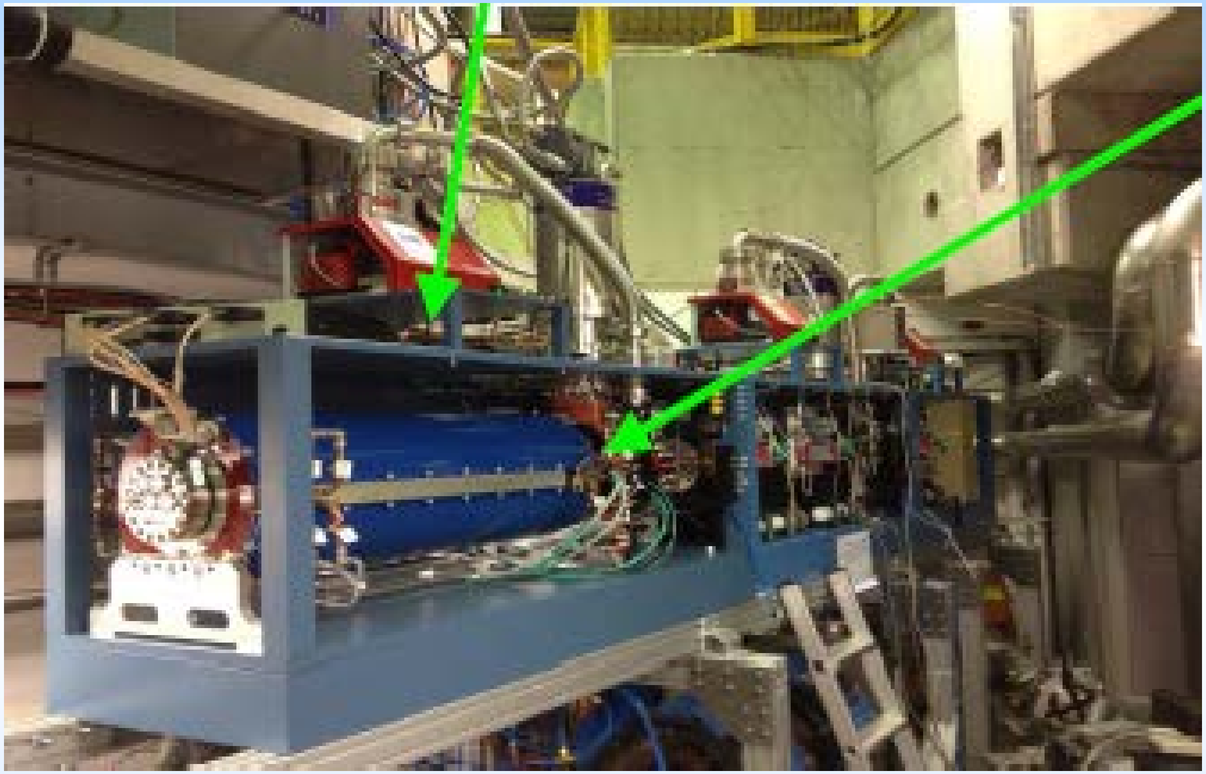
F. Castelli et al., Phys. Rev. A 78 (2008) 052512
S. Cialdi et al., NIM B 269 (2011) 1527

June 2012 (Milano)



May 2013 (CERN)

AEGIS : the positron system

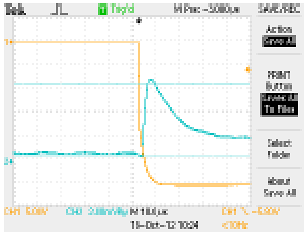


Positron system and accumulator installed and tested during 2012

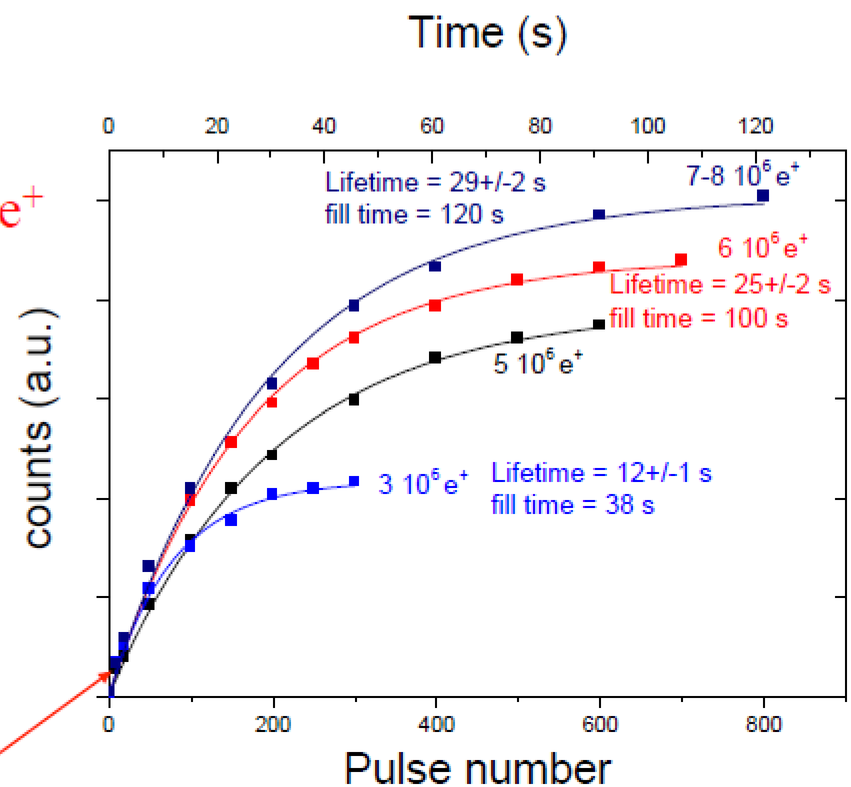
Activity on conversion mesoporous targets

G. Consolati et al., Chem Soc. Rev. 42 (2013) 3821
F. Moia, R. Ferragut et al., Eur. Phys. J. D (2012) 66

Positron accumulator performance



Number of stored e^+ and lifetime



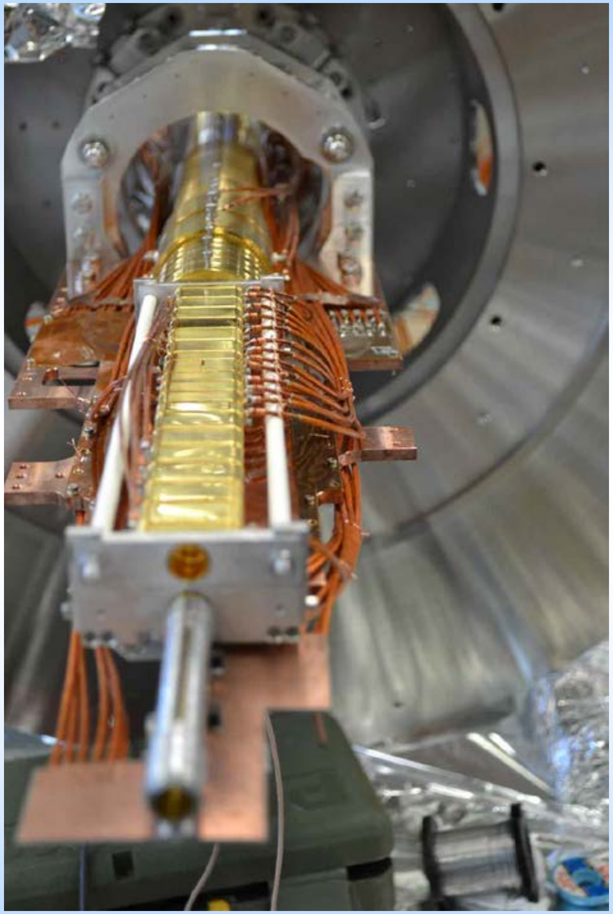
Dump intensity 7-8 10^6 e^+

Lifetime ~30 s

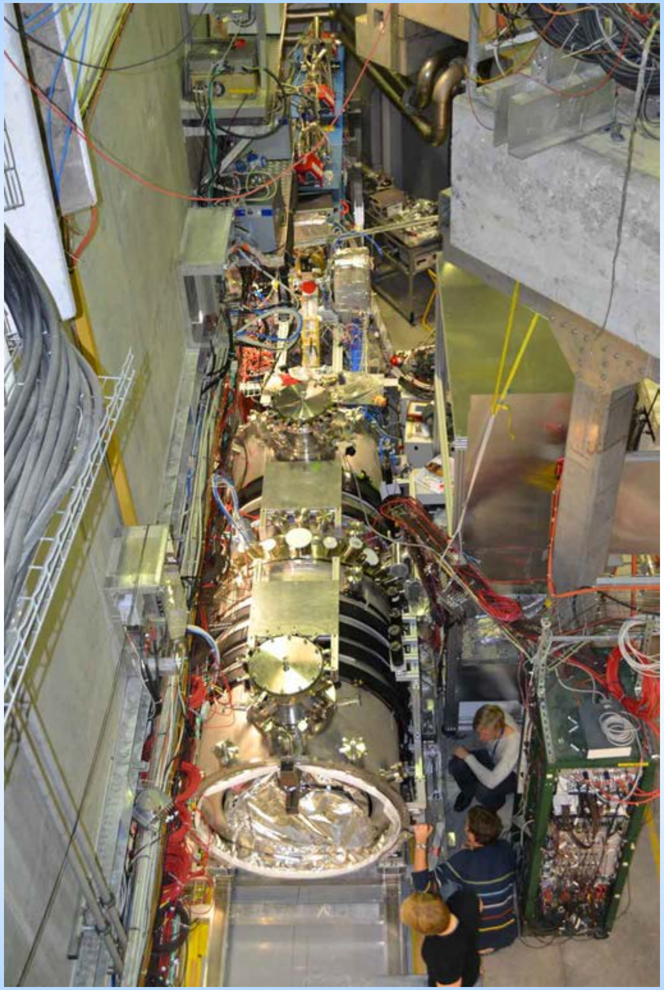
Fill time ~120 s

1 pulse from trap 5-6 10^4 e+

AEGIS : the installation of the central detector

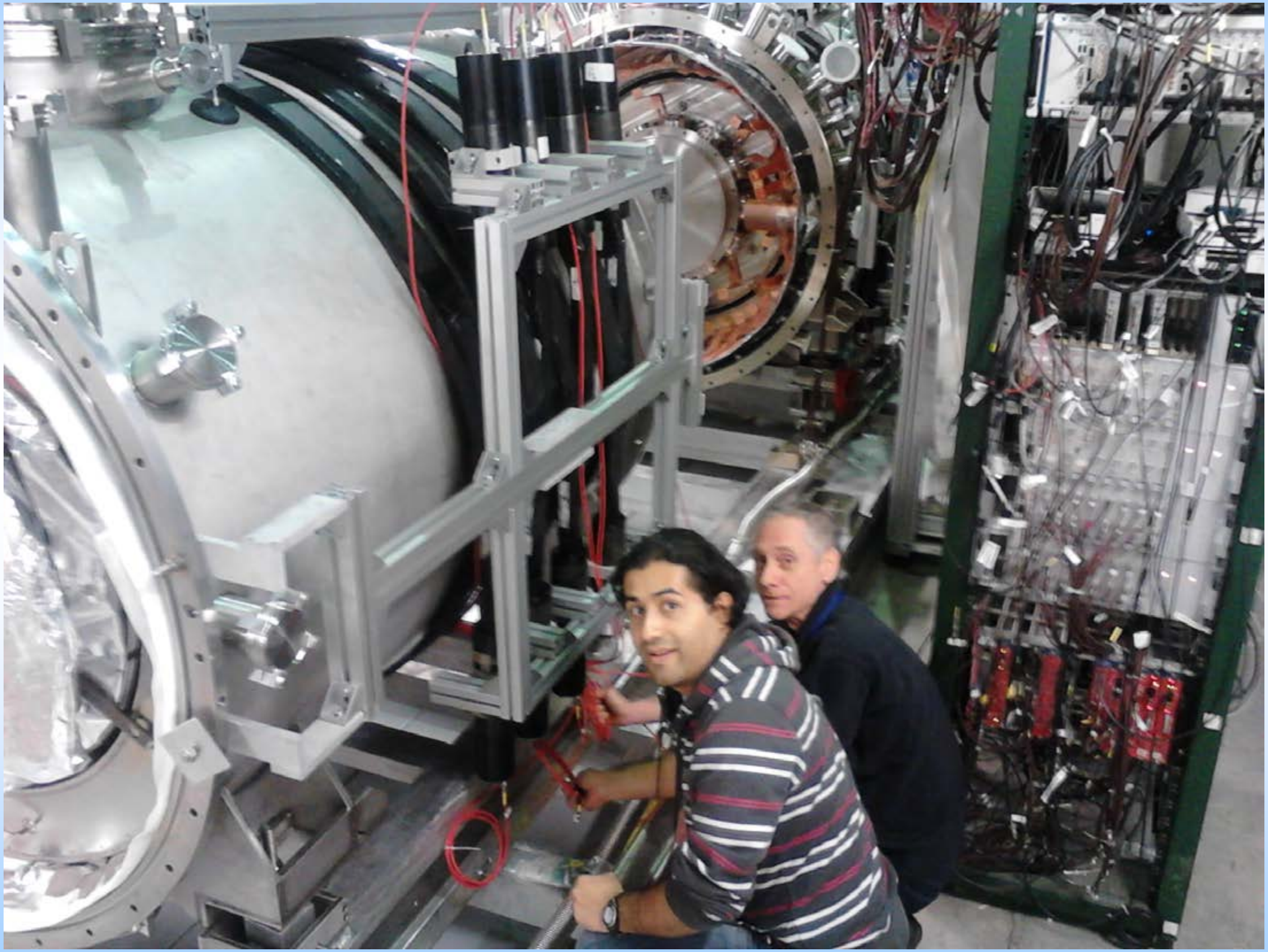


Antiproton and positron traps



The 5 Testla main flange installation

Installation of the AEGIS detector system between the 5 and 1 T magnets



AEGIS : the 2012 run

From May to December 2012

Installation of apparatus (took place during the run)

Physics results?

- Antiproton trapping capability in the 5 Tesla system
- Positron system developments
- Operation of emulsions with antiprotons
- Measurement of atto-Newton (10^-18 Newton) forces acting on antiprotons

Antiproton catching :

5 Tesla trap (with two fast switching electrodes)

Electron cooling

Lifetime measurement (not very good because of «poor» vacuum)

Trapped up to 9 kV

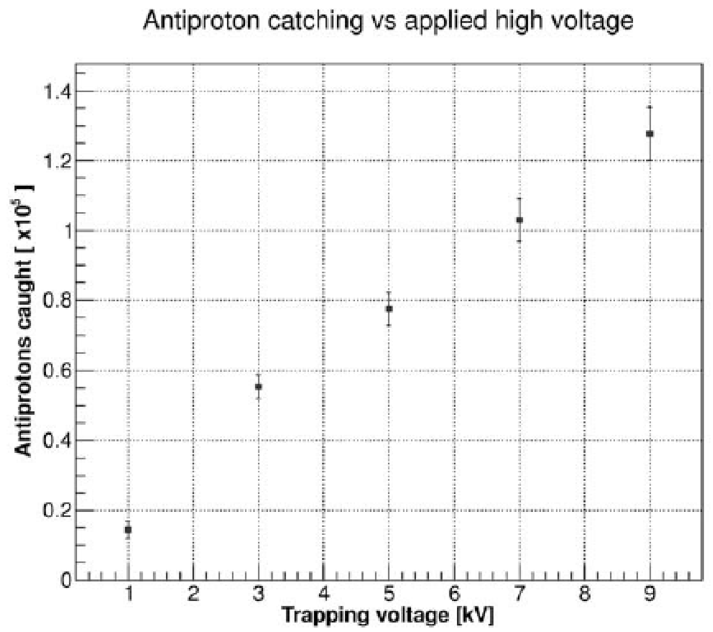


FIGURE 6. Number of antiprotons caught vs. trapping voltage for 3.1×10^7 incident antiprotons. Antiprotons were confined for 5 s in a 46 cm-long high voltage trap before being released towards the degrader foil.

Nuclear Emulsions in vacuum:

Antiprotons detected at the end of the 1 T
Work in vacuum: solve the cracking problem
Glicerine treatment

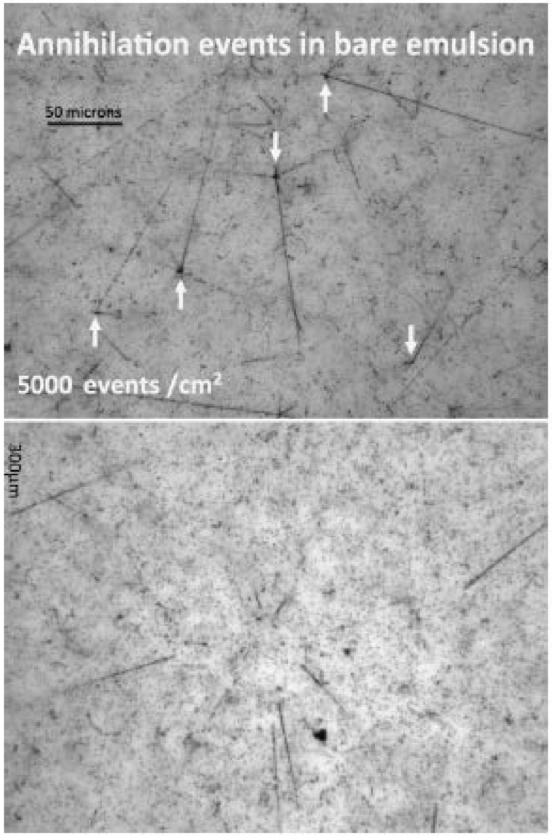
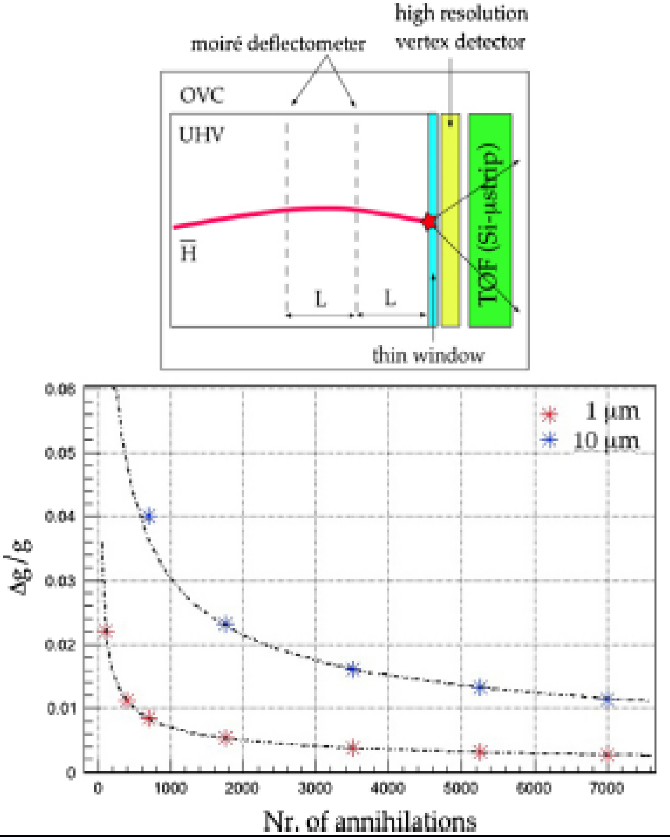


Fig. 4. Top: Typical antiproton annihilation vertices in the bare emulsion. Bottom: Tracks observed behind a thin silver foil in which the antiprotons annihilate.



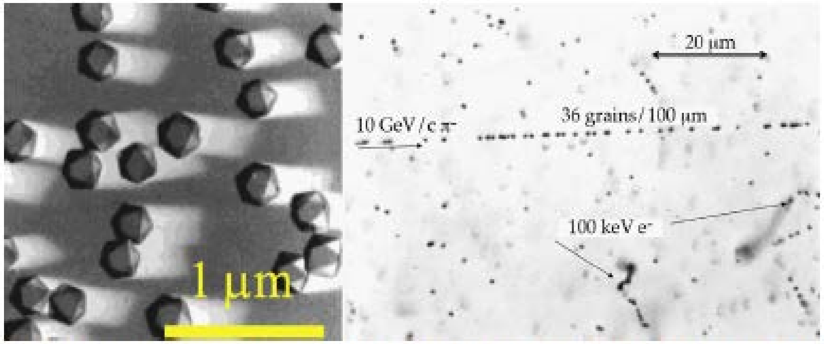


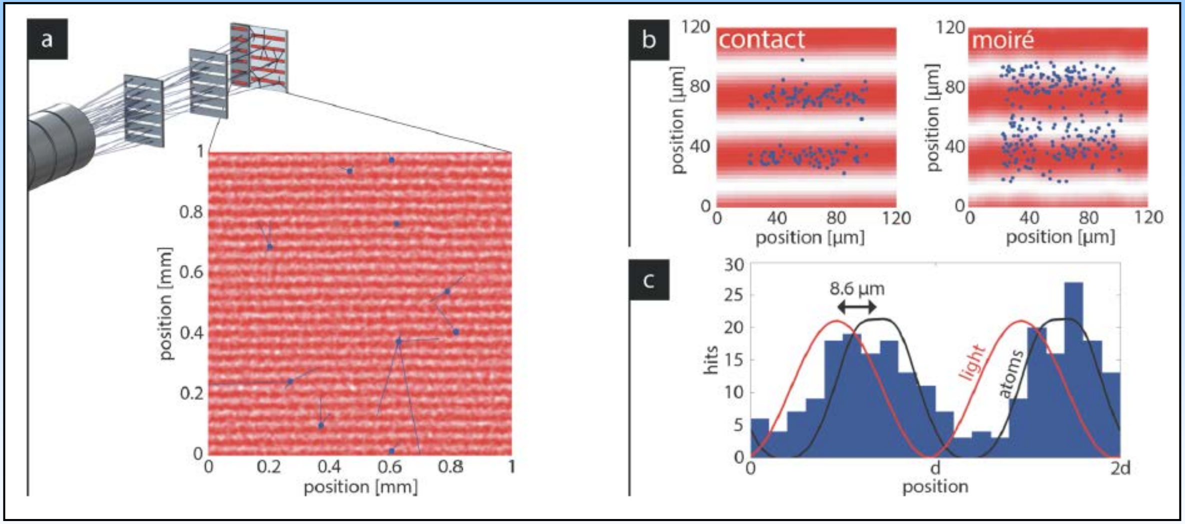
Fig. 2. Left: AgBr crystals in emulsion layers observed with a scanning microscope. Right: A minimum ionizing track from a 10 GeV/c pion.

Detection of attoNewton forces (in preparation):

AEGIS Antiproton beam

Mini-moirè deflectometer

Nuclear Emusion detector



Recent selected bibliography:

- M. Doser et al. Exploring the WEP with a pulsed beam of antihydrogen. Classical and Quantum Gravity 29 (2012) 184009.
- AEgIS Experiment Commissioning at CERN, AIP Conf. Proc. 1521, 144 (2013)
- M. Kimura et al., Development of nuclear emulsions with 1 µm spatial resolution for the AEgIS experiment doi: 10.1016/j.nima.2013.04.082
- S. Aghion et al., Detection of attonewton forces acting on antiprotons. To be submitted.

Conclusions

AEGIS to develop a new “staged approach” to antimatter studies

Produce a beam of cold Antihydrogen starting from ultracold protons

Stark-effect accelerate Antihydrogen atoms

Let the beam fall in a Moire’ deflectometer

Measure the fringe shift and the arrival times on the final detector

Goal: 1% precision in the measurement of g for Antihydrogen

Positronium Physics studies

Second phase of the experiment: CPT violation studies

Setting up the experiment (installation almost finished)

Preliminary results on positron bunches and antiprotons trapping

Thank you for your attention

Backup slides

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On the CPT Theorem

Proof by Luders (1957):

- Spin 0,½,1 quantum fields
- Local interactions
- Lorentz group invariance
- Spin-Statistics (Pauli) Theorem

More general proof by Pauli :

- Fields of the same general character (?)
- Includes higher spin fields
- Makes use of the finite representations of the proper Lorentz group

Antihydrogen program at CERN

A low-energy Antimatter research program based on the Antiproton Decelerator

PHASE I: Production of "cold" antihydrogen atoms (2000-2004)

ATHENA (**A**ppara**T**us for **H**igh precision **E**xperiment on **N**eutral **A**ntimatter,or shortly **A**n**T**i**H**ydrog**EN** **A**pparatus)

ATRAP (**A**ntihydrogen **TRAP**)

PHASE II: Cold-Antihydrogen Physics (2006….)

ATRAP

ALPHA (**A**ntihydrogen **L**aser **PH**ysics **A**pparatus)

ASACUSA

AEGIS (**A**ntimatter **E**xperiment: **G**ravity, **I**nterferometry, **S**pectroscopy)

A few comments on AEGIS strategy (and timing) to produce Antihydrogen:

Use of 10^8 positrons in a bunch

Bunch of 20 ns and 1 mm beam spot

500 sec accumulation time

Catch $\bar{p}$ from AD, degrade the energy

Cool down the $\bar{p}$ with e^-

500 sec accumulation time (a few AD shots, 10^5 $\bar{p}$)

- Source and moderator
- Trap
- Accumulator (Surko-type)

An antihydrogen production shot every 500 sec

Avoid the problem of a particle trap able to simultaneously confine charged particles (Penning trap) and Antihydrogen (by radial B gradients).

- Have a charged particle trap only
- Form a neutral (antihydrogen) beam → **g measurement**
- Confine only neutrals (future) → (CPT physics)

The charge-exchange reaction:

$$\overline{p} + (Ps)^* \rightarrow \overline{H}^* + e^-$$

Conceptually similar to a charge exchange technique based on Rydberg Cesium performed by ATRAP - C. Storry et al., Phys. Rev. Lett. 93 (2004) 263401

The cross-section is strongly dependent on the principal quantum number:

$$\sigma \approx 58\, n_{ps}^4\, \pi\, a_o^2$$

Laser excitation to Rydberg states of the Positronium atom is needed

The travel distance in 20 ns (pulse duration) is only 2 mm.
With a production of 10^7 oPs atoms per pulse (20 ns -10^8 e+)
a density of 10^{15} Ps/m^3 is expected

From M. K. Oberthaler et al., Phys. Rev. A 54 (1996) 3165

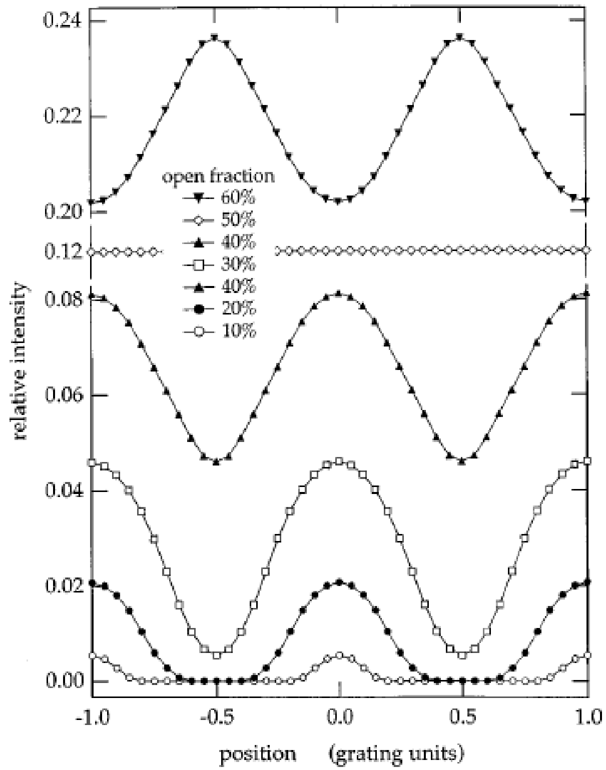


FIG. 2. Fringe patterns, as obtained by translating the third grating, calculated for various open fractions f_{open} of the gratings. For $f_{open}<25\%$ the fringe pattern shows distinct peaks at the position of the shadow image. For $25\%<f_{open}<50\%$ the fringes show an increasing constant background, and at $f_{open}=50\%$ they vanish completely. For $f_{open}>50\%$ the fringes reappear but are shifted by half a grating period (π fringe shift).

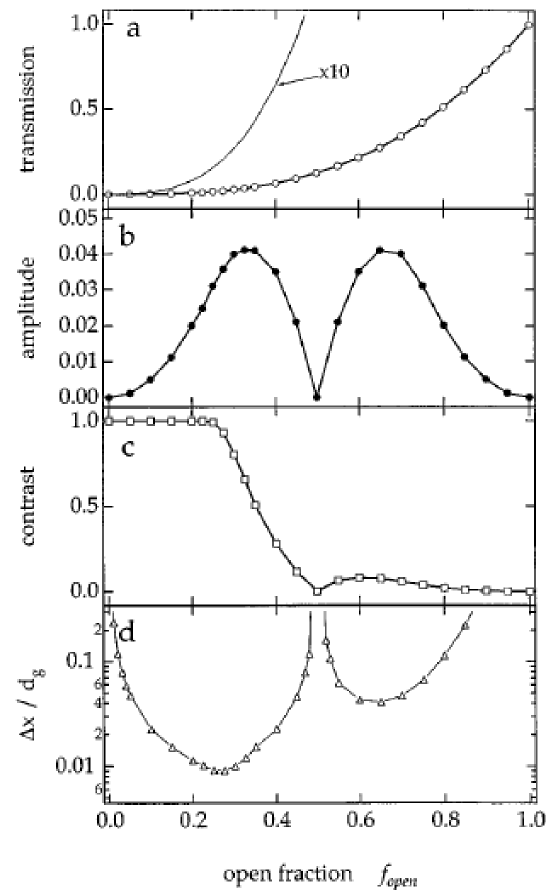
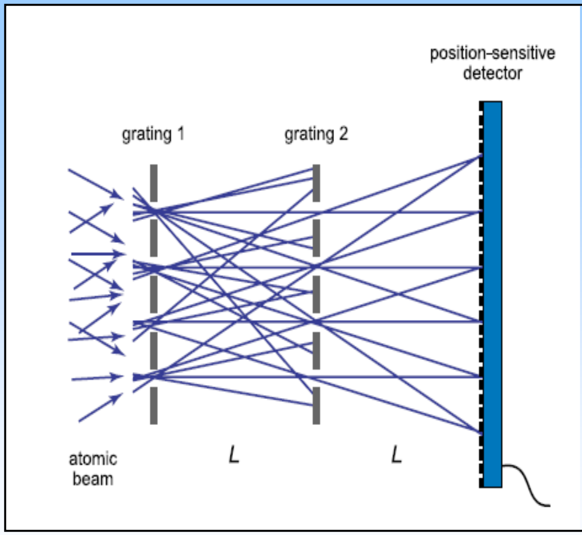


FIG. 3. Characteristic parameters of the Moiré deflectometer and their dependence on the open fraction f_{open} of the gratings. The top graph (a) shows the total transmission through the three-grating setup, (b) shows the amplitude of the obtained fringe pattern, and (c) the resulting contrast. The lowest graph (d) displays the minimal deflection in units of the grating period d_g that can be detected if 10 000 atoms impinge on the Moiré deflectometer.



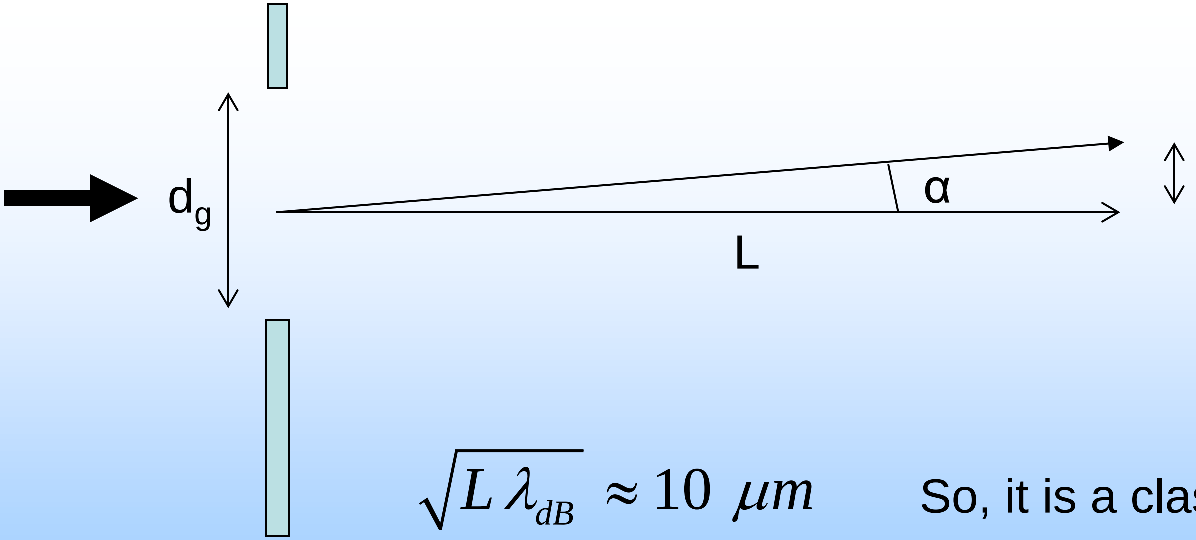
The final plane will be made of Silicon Strip detectors with a spatial resolution of about 10-15 μm

De Broglie wavelength of a 500 m/s H atom:

$$\lambda_{dB} = \frac{h}{mv} = \frac{2\pi}{c} 197\,(MeV)(10^{-15}\,m) \frac{1}{940\frac{MeV}{c^2}\,500\frac{m}{s}} = 8\times10^{-10}\,m$$

$$L\,\lambda_{dB} = 0.3\times8\times10^{-10}\;m^2 = 2.4\times10^{-10}\;m^2$$

Now, this is NOT a quantum deflectometer, because:



$$p_y \cong \frac{h}{d_g} \qquad tg\alpha \approx \frac{h}{d_g\,p}$$

$$L\frac{h}{d_g\,p} << d_g \qquad L\frac{h}{p} << d_g^2$$

$$L\,\lambda_{dB} << d_g^2$$

$$\sqrt{L\,\lambda_{dB}} \approx 10\;\mu m$$

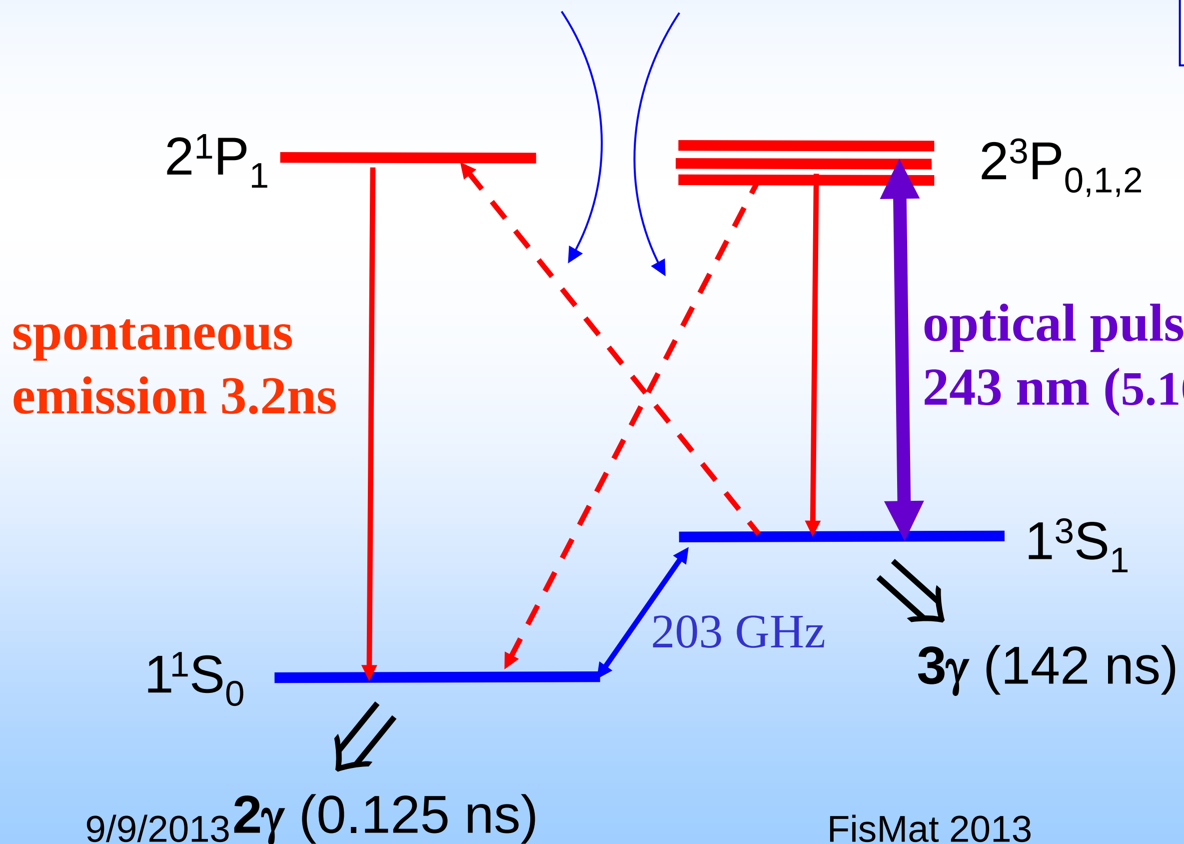
So, it is a classical device if d_g>> 10 μm

Optical saturation of $1^3S \leftrightarrow 2^3P$ (Lyman α)

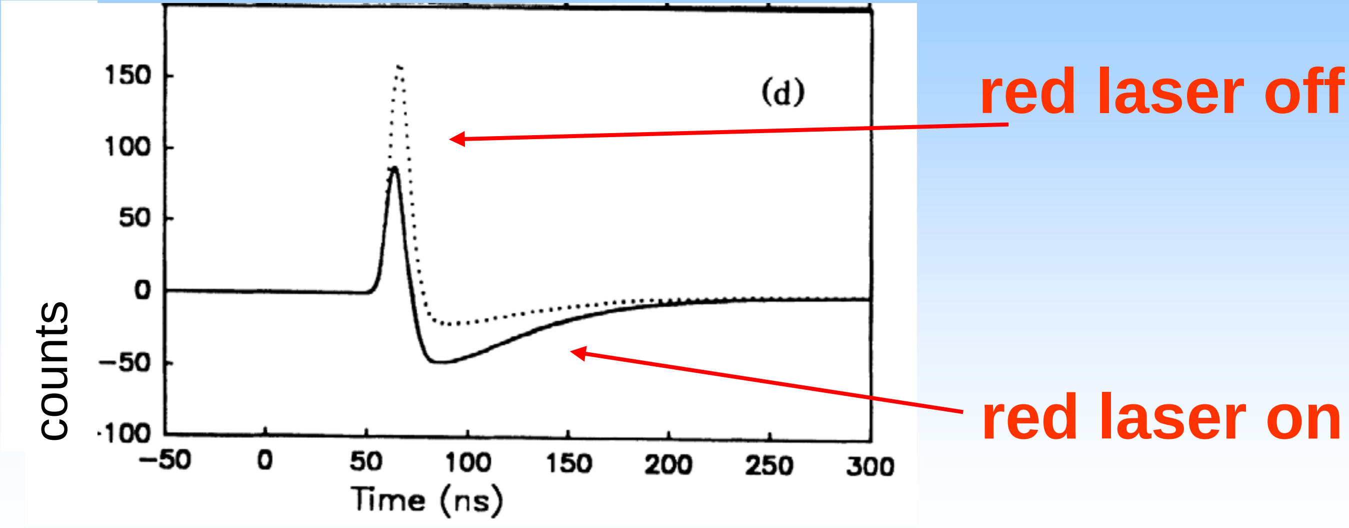
Ziock et al, J.Phys.B 23, 329 (1990)

Observation of enhanced 2γ annihilation rate at the time of laser on

transitions with singlet-triplet mixing (for equal m) in weak magnetic field (0.02T)



2γ annihilation rate variation (after singlet-triplet mixing in B field)



Decrease in ground state population with red laser on → Rydberg excitation