AEGIS at CERN: measuring Antihydrogen fall

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A E $\bar{g}$ I S

Antimatter

Experiment

Gravity

Interferometry

Spectroscopy

Outline of talk:

- Theoretical motivation
- General experimental strategy
- Antimatter beam preparation
- Gravity measurement

AEGIS: AD-6 Experiment

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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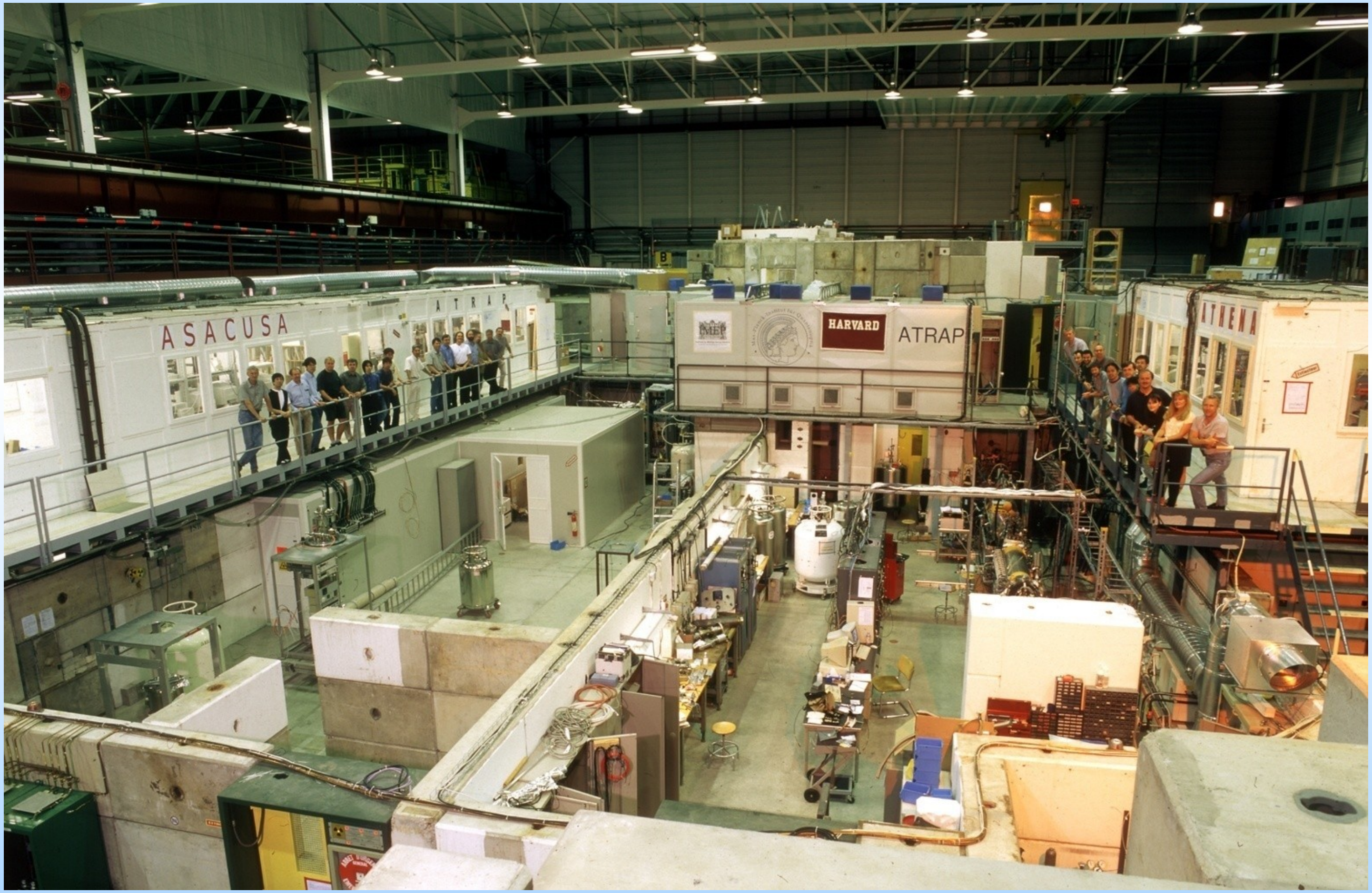
AD (Antiproton Decelerator) at CERN

3×10^7 antiprotons / 100 sec | 6 MeV | $10^4\ \bar{p}$ / 100 sec



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:

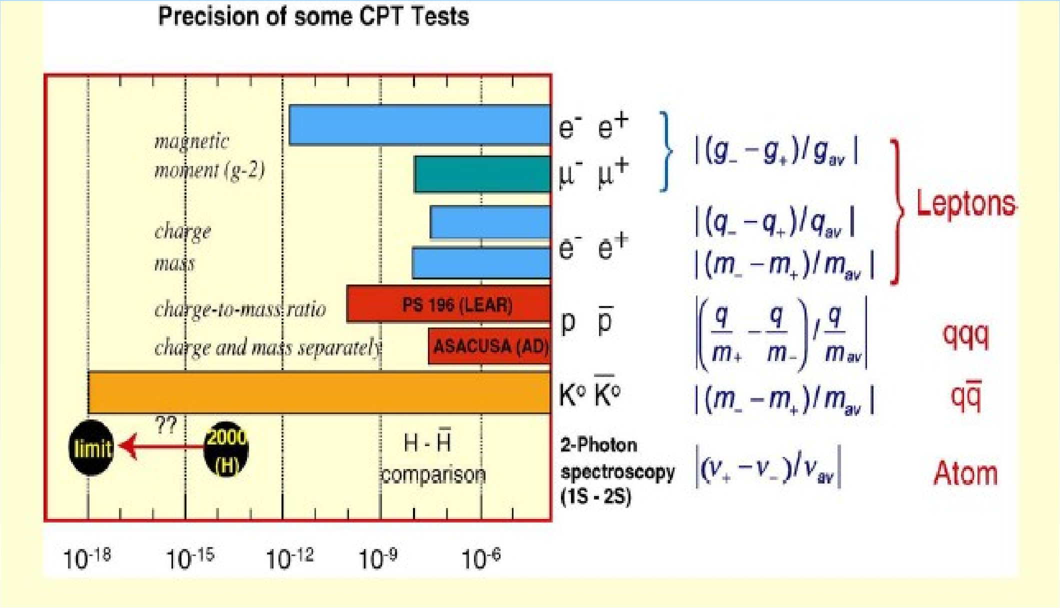
Particles and antiparticles have identical masses and lifetimes

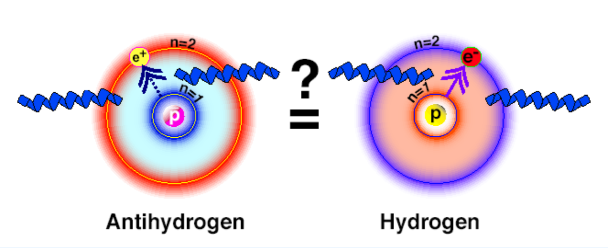
All internal quantum numbers of antiparticles are opposite to those of particles

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

Current status and possible improvements





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

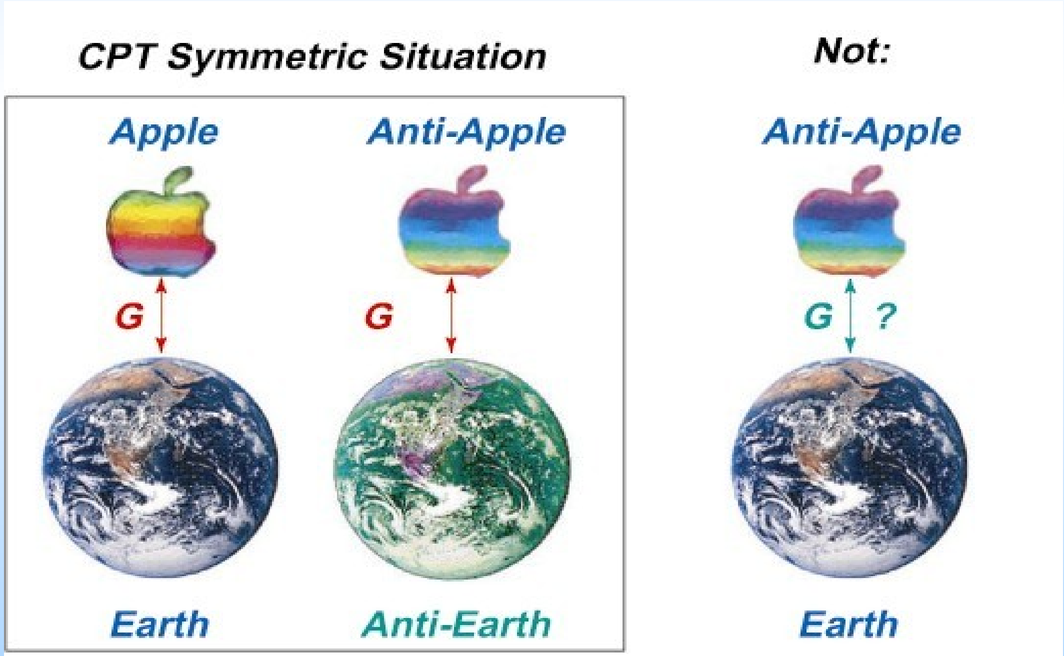
Requires antihydrogen at

mK temperature

WEP: Weak Equivalence Principle

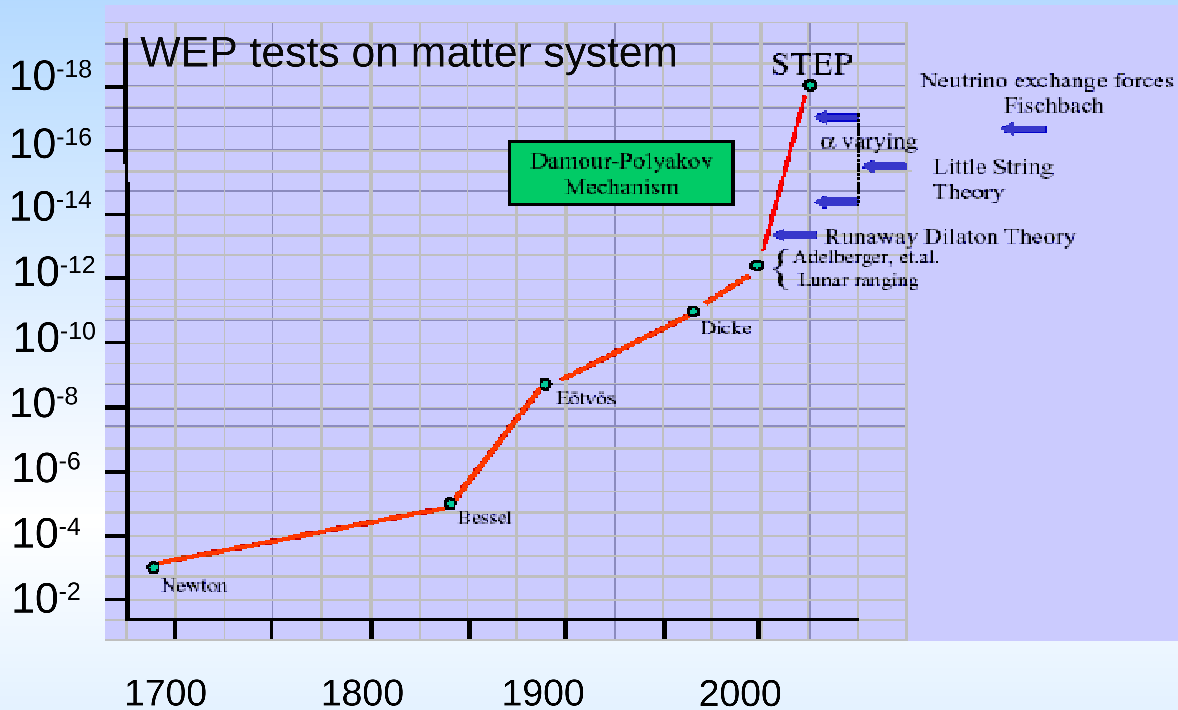
The trajectory of a falling test body depends only on its initial position and velocity and is independent of its composition (a form of WEP)
All bodies at the same spacetime point in a given gravitational field will undergo the same acceleration (another form of WEP)

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)

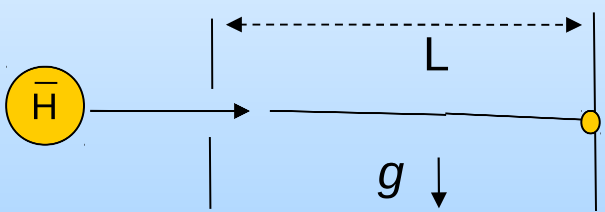


Gravitational Physics: Weak Equivalence Principle

- 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

ANTIHYDROGEN PROGRAM @ CERN

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

ATHENA (**A**pparaTus 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)

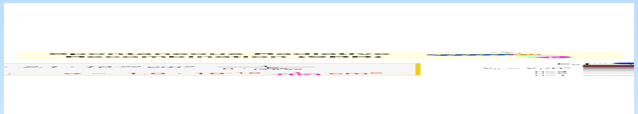
ASACUSA

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

Production Methods

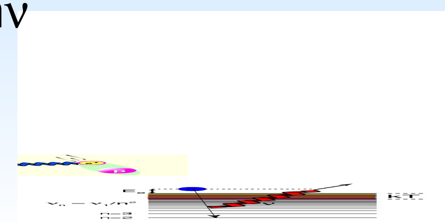
I. ANTIPROTON + POSITRON (exp.demonstration: ATHENA and ATRAP)

(A)



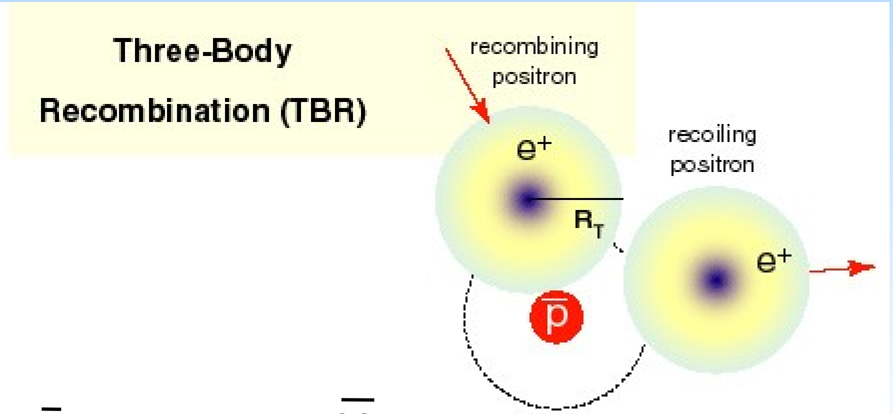
e+

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



$\bar{p}$

(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

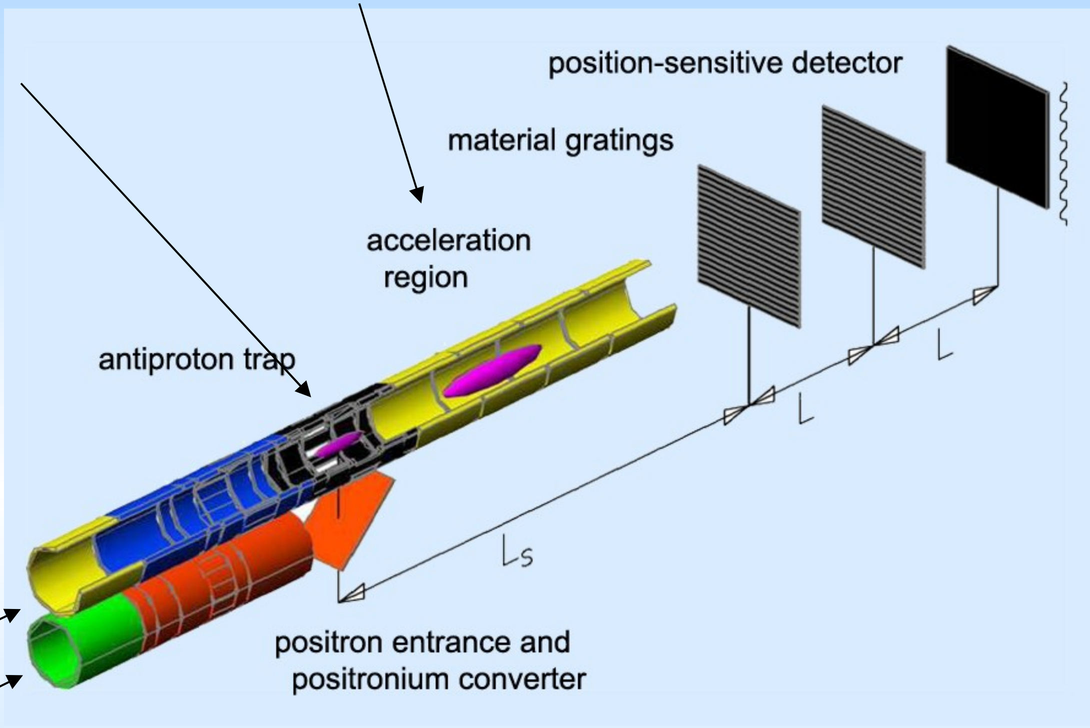
Avoid the problem of a particle trap able to simultaneously confine charged particles (Penning trap) and Antihydrogen (by radial B gradients).

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

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

Acceleration of antihydrogen.

Formation of antihydrogen atoms



The antihydrogen beams will fly (with v~400 m/sec) through a Moire' deflectometer, the classical counterpart of a matter wave interferometer

Antiprotons

Positrons

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

Such measurement would represent the first direct determination of the gravitational effect on antimatter

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

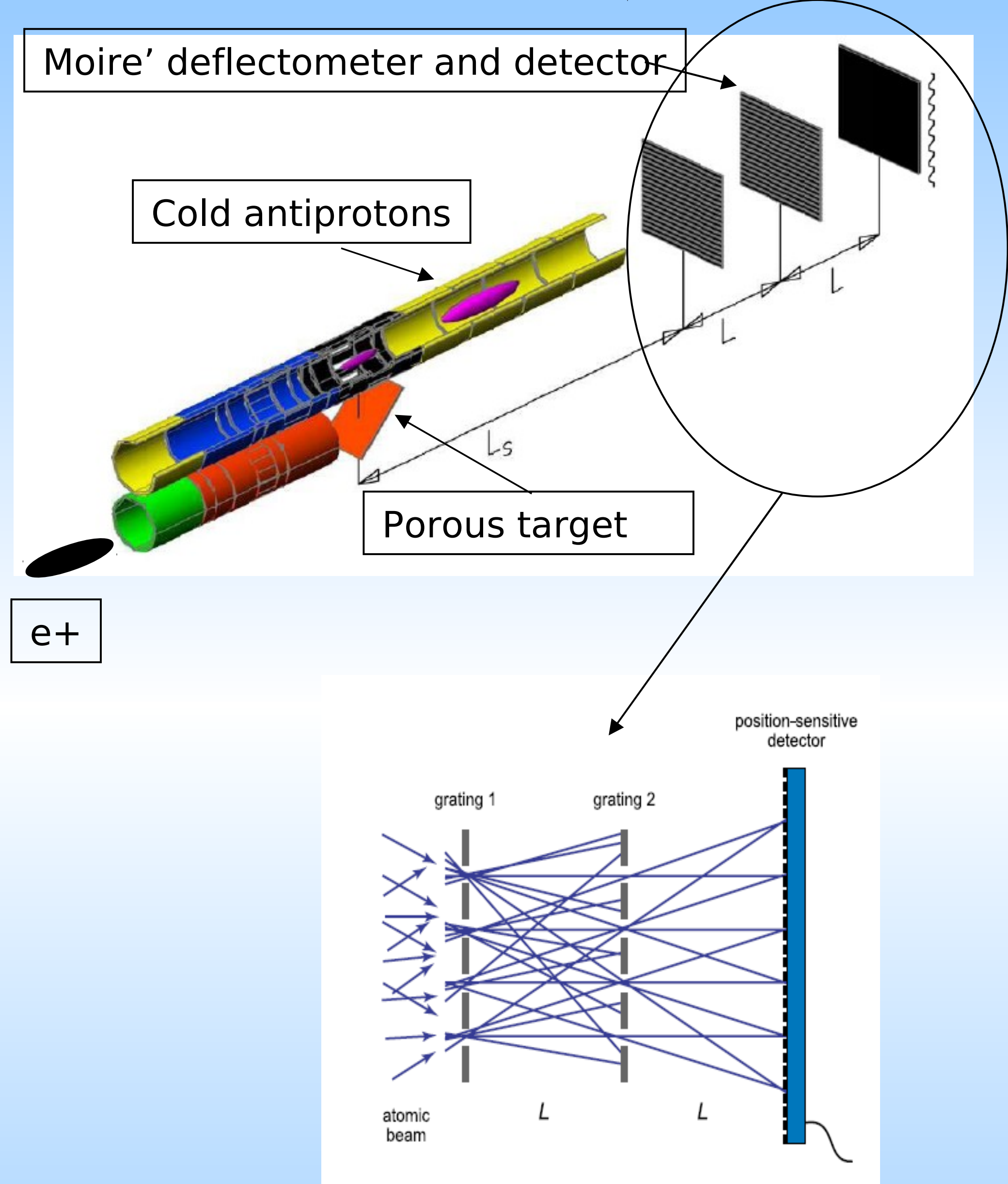
5) Form Rydberg cold (100 mK) antihydrogen by

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

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



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

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 $\bar{p}$)

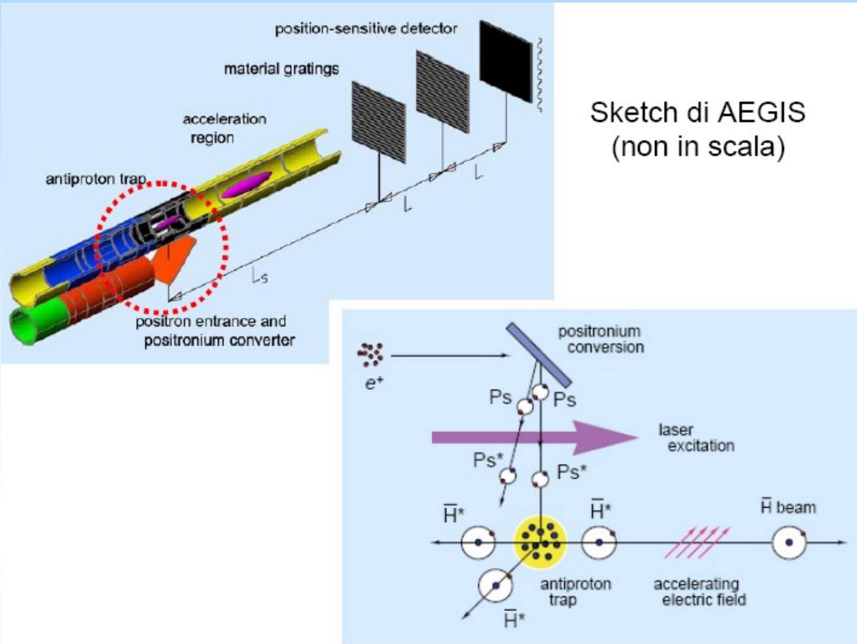
- Source and moderator
- Trap
- Accumulator (Surko-type)

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)

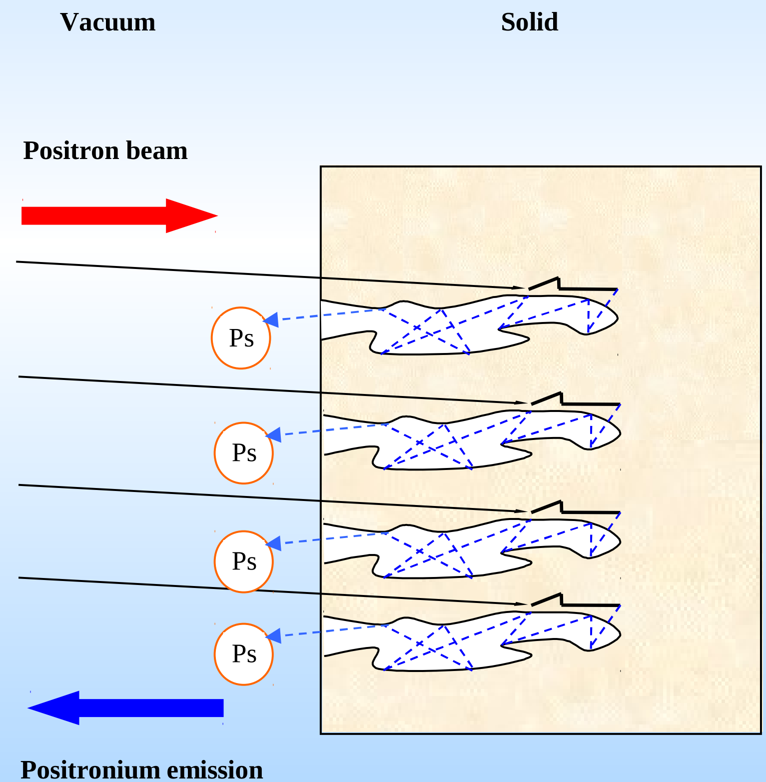
Positrons and Positronium (Ps) production



Sketch di AEGIS (non in scala)

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:

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

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

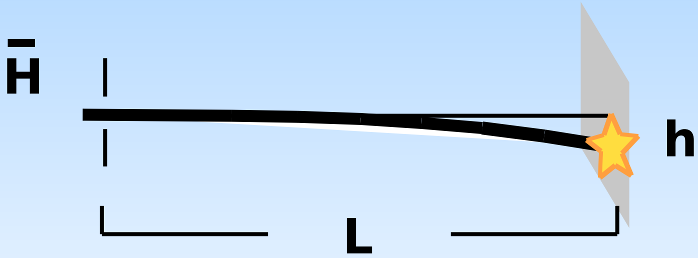
The cross-section is strongly dependent on the principal quantum number:

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

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

Antihydrogen fall and detection



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

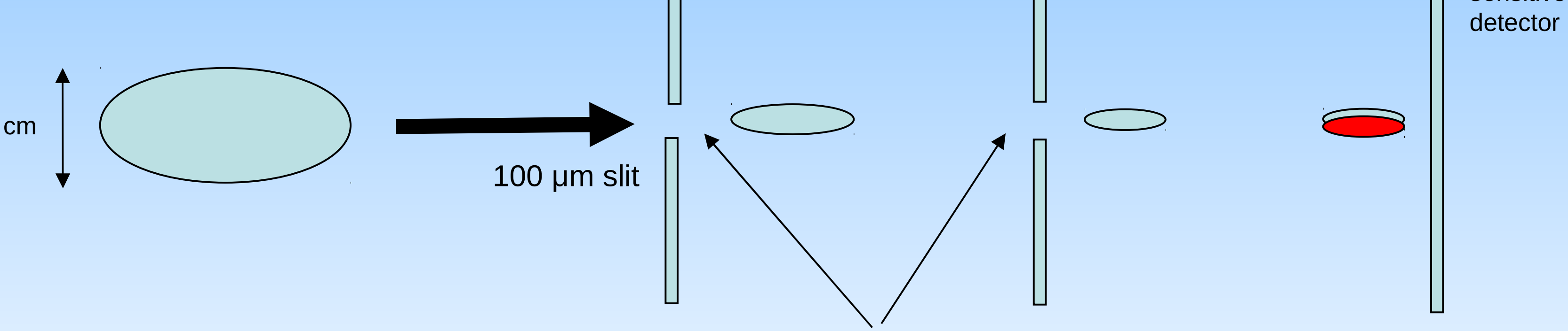
AEgIS realistic numbers:
- horizontal flight path L ~ 1 m
- horizontal velocity v_z ~ 500 m/s

→ **vertical deflection ~ 20 µm**

T: - 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!

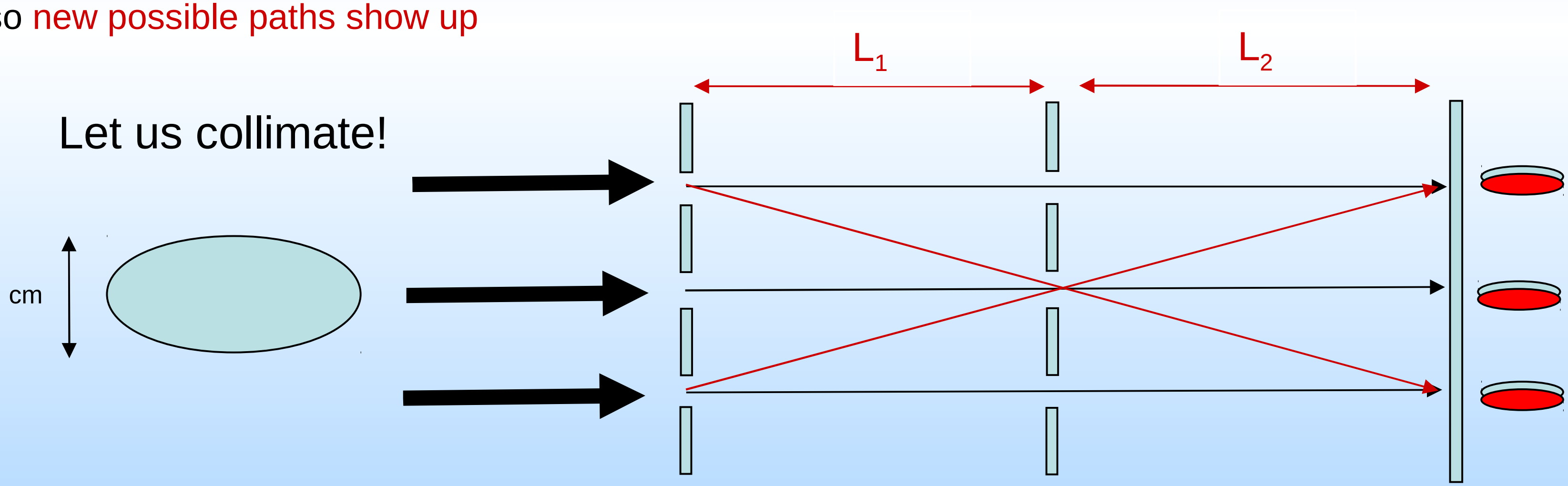


$$\frac{\Delta h}{h} \cong \frac{30\,\mu m}{100\,\mu m} = 0.3$$

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

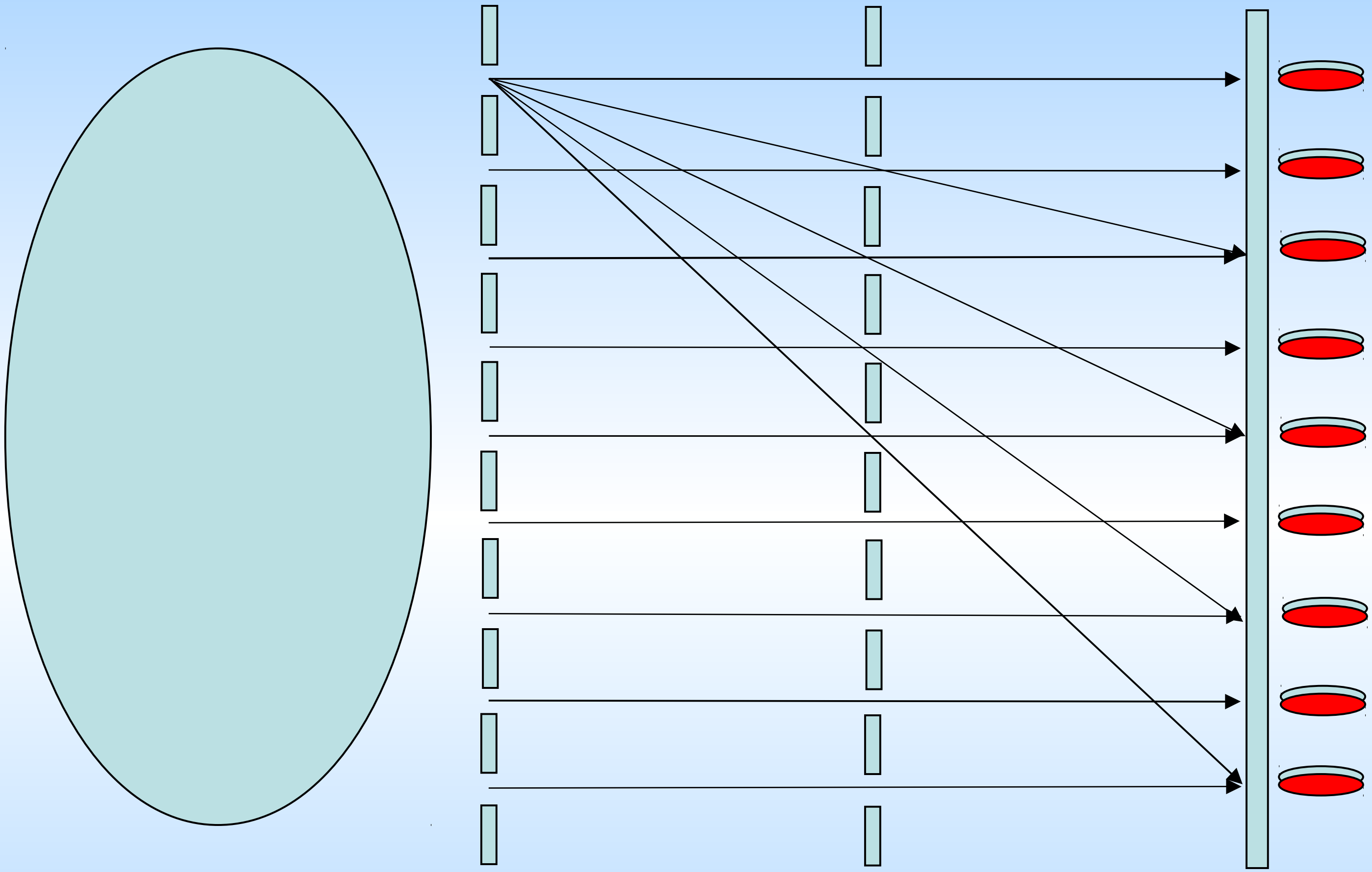
Acceptance can be increased by having several holes. In doing so new possible paths show up

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.

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

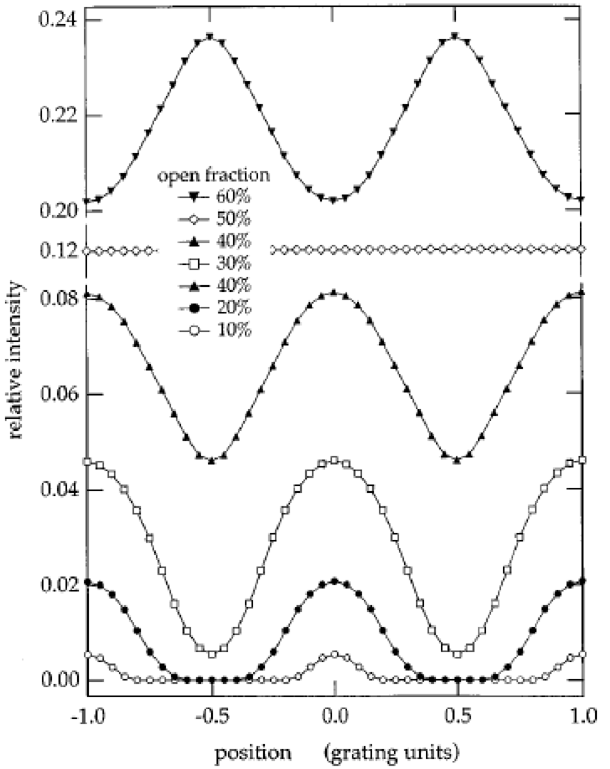


FIG. 2. Fringe patterns, as obtained by translating the third grating, calculated for various open fractions f_{open} of the gratings. For $f_{open}<25\%$ the fringe pattern shows distinct peaks at the position of the shadow image. For $25\%<f_{open}<50\%$ the fringes show an increasing constant background, 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).

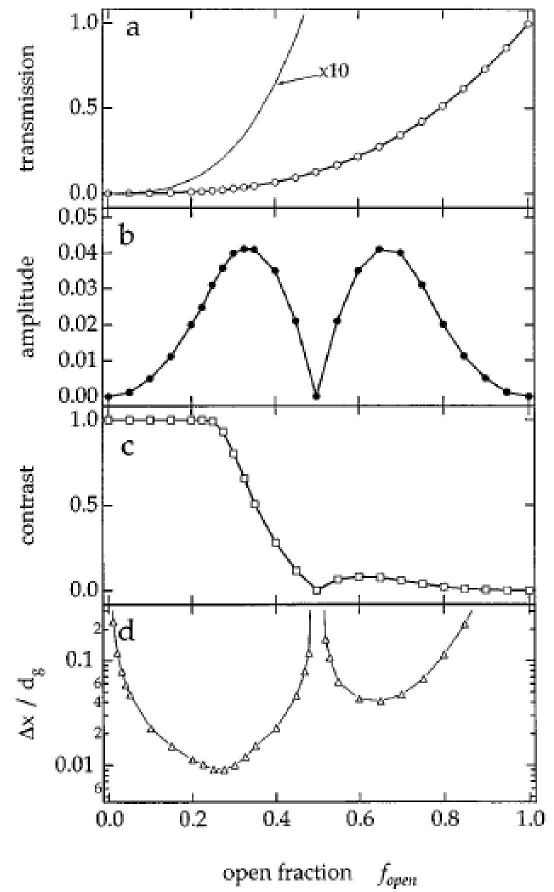
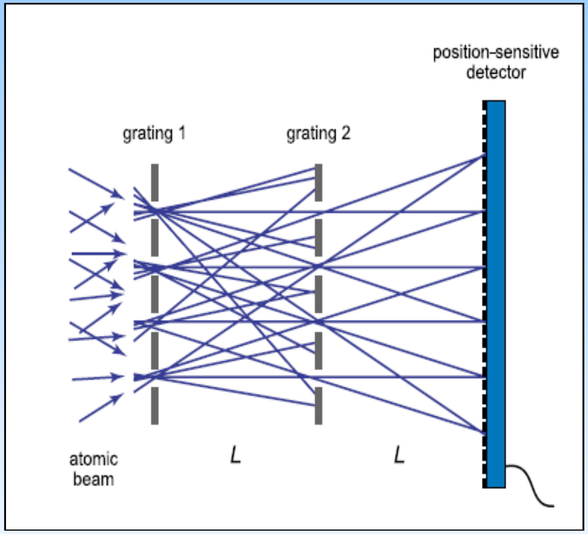


FIG. 3. Characteristic parameters of the Moiré deflectometer and their dependence on the open fraction f_{open} of the gratings. The top graph (a) shows the total transmission through the three-grating setup, (b) shows the amplitude of the obtained fringe pattern, and (c) the resulting contrast. The 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.



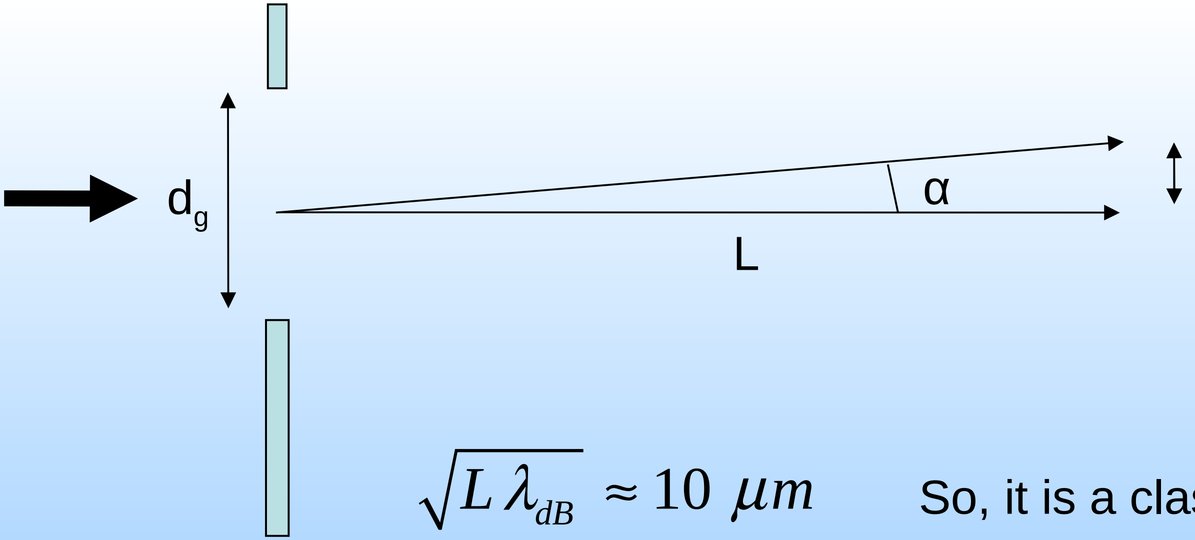
The final plane will be made of Silicon Strip detectors with a spatial resolution of about 10-15 μm

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

Collimation of the beam with a classical Moiré deflectomete

PHYSICAL REVIEW A VOLUME 54, NUMBER 4 OCTOBER 1996

Inertial sensing with classical atomic beams

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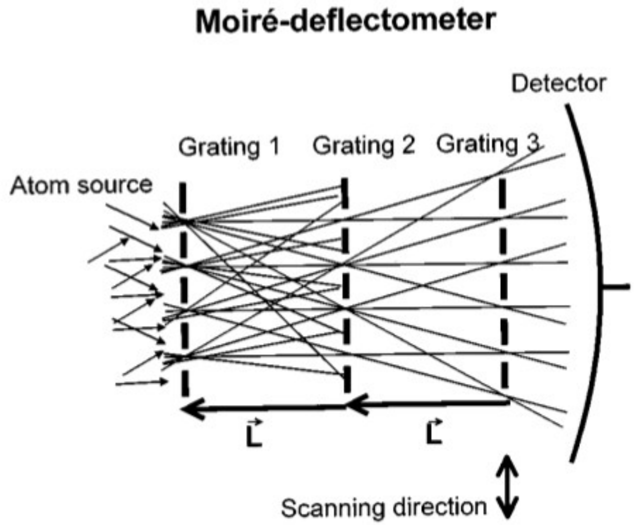
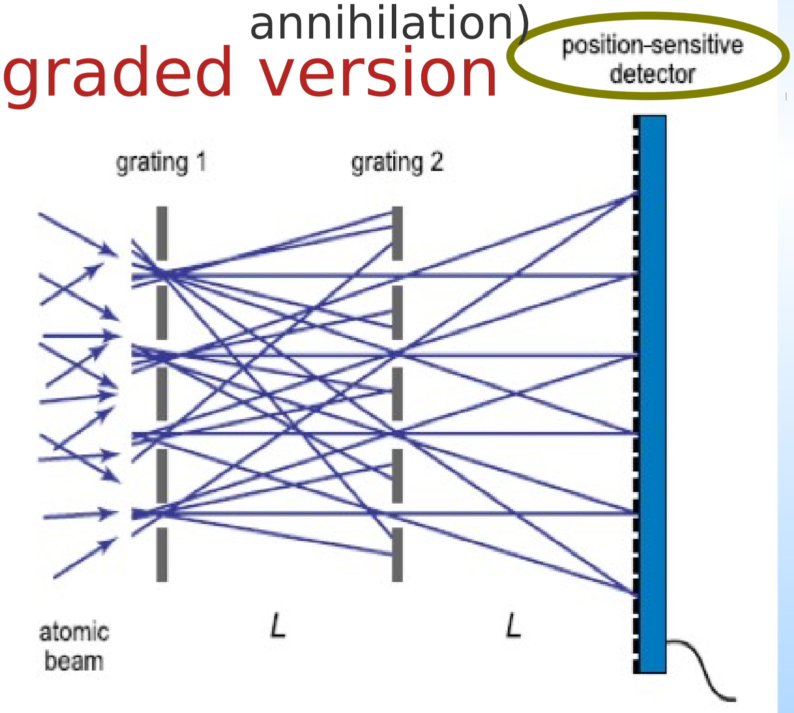


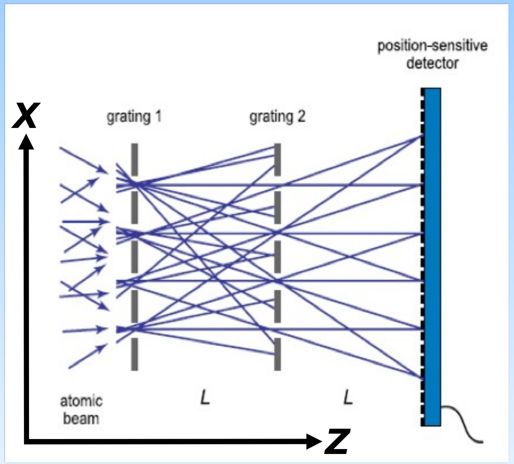
FIG. 1. Principle of a Moiré deflectometer. The first two identical gratings collimate the originally undirected atoms into various directions. After a distance L corresponding to the distance between the first two gratings, an image of the collimation gratings is formed. At this position, a third identical 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



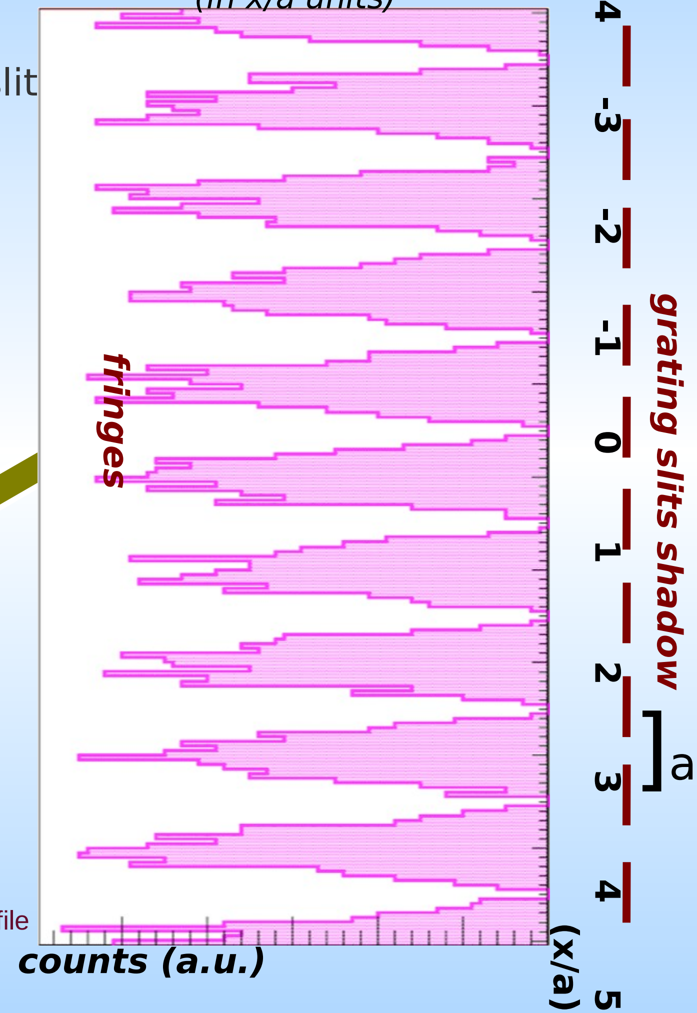
M o i r é deflectometer



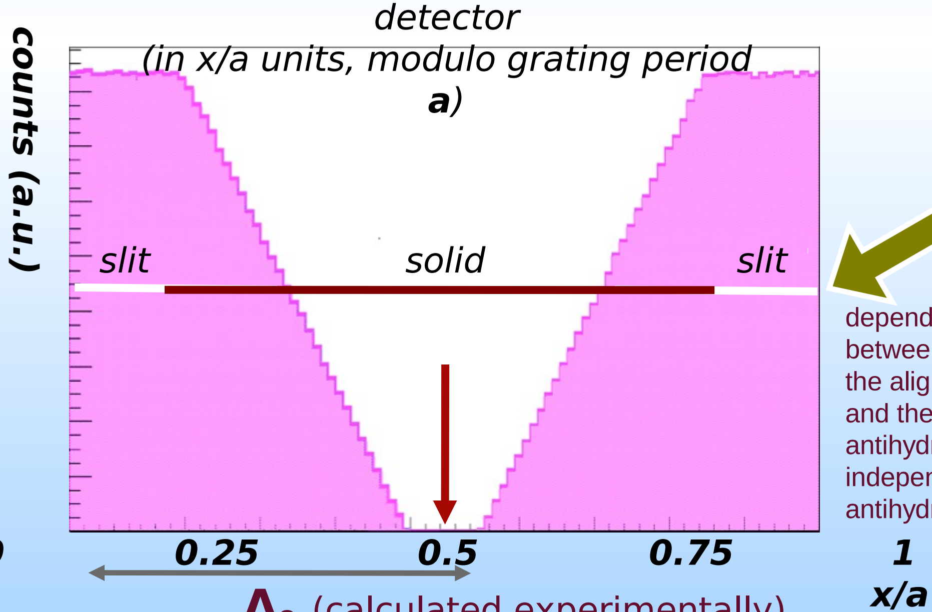
Grating transparency = 30%
(total transmission 9%)

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

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



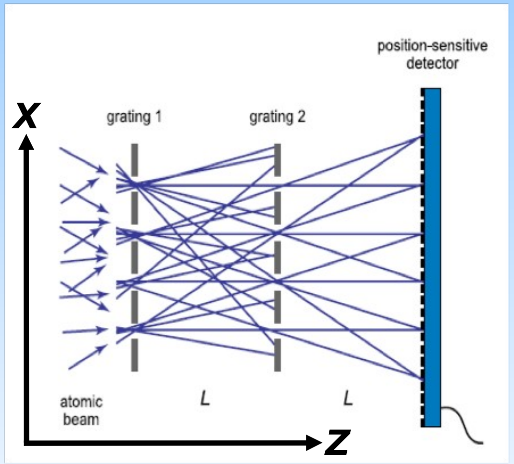
*annihilation hit position on the final detector (in x/a units, modulo grating period **a**)*



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

Δ_o (calculated experimentally)

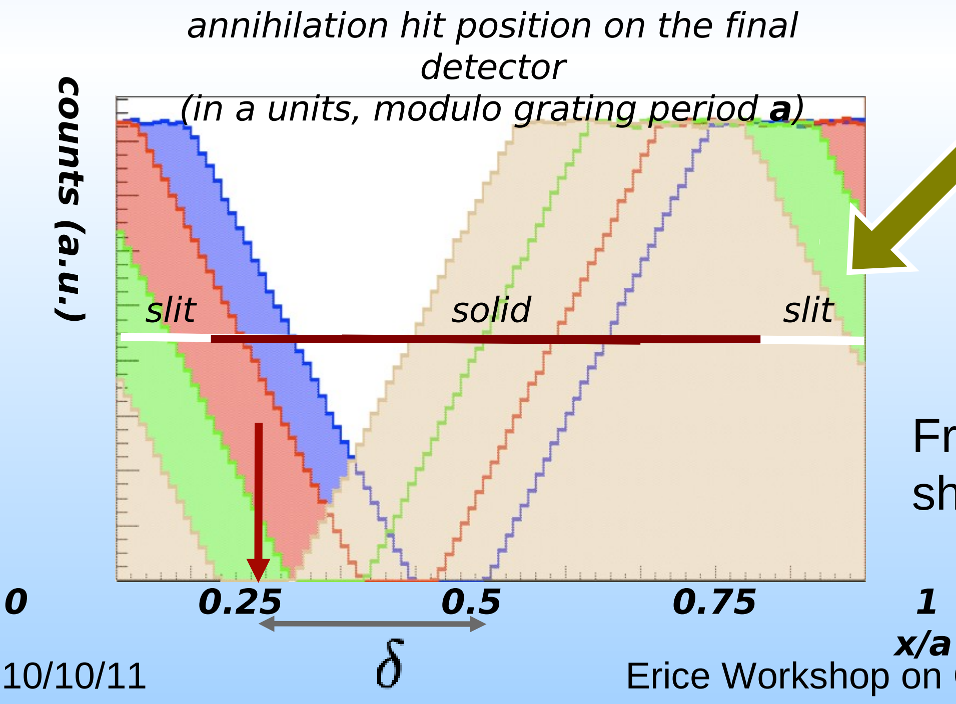
M o i r é deflectomete



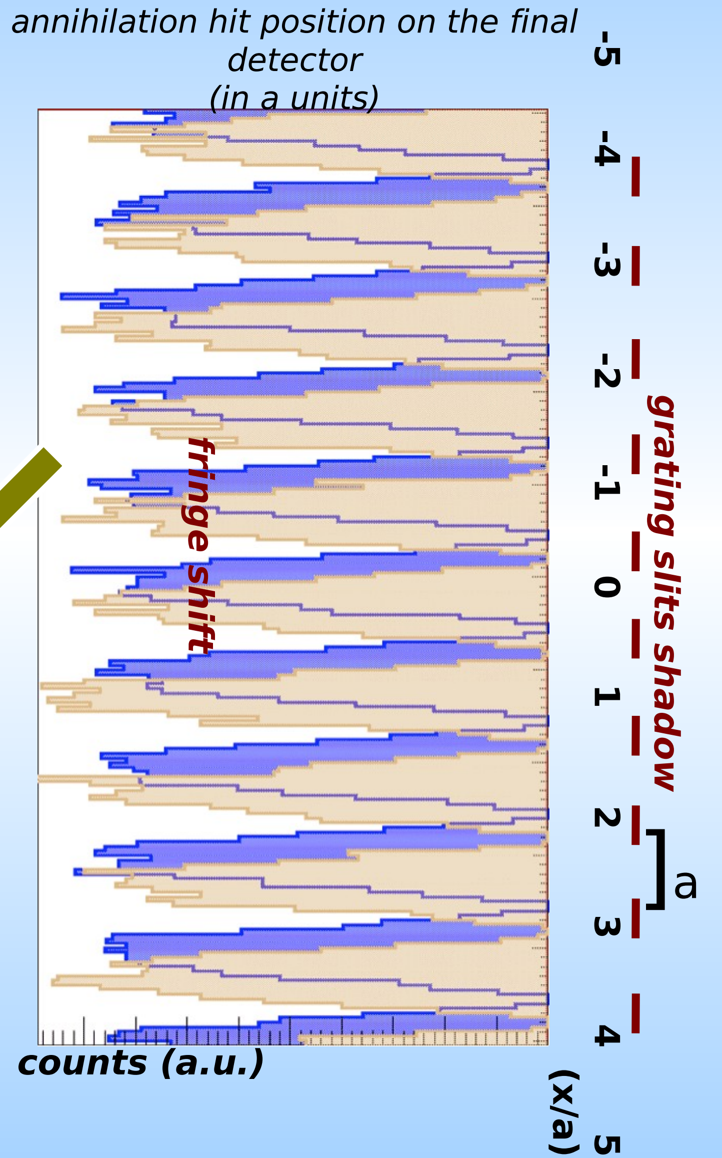
Grating transparency = 30%
(total transmission 9%)

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

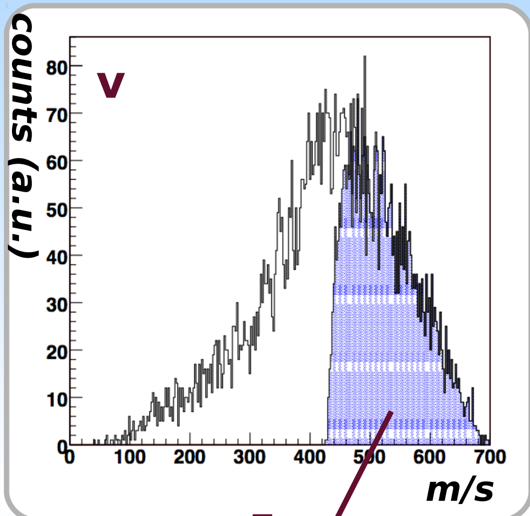


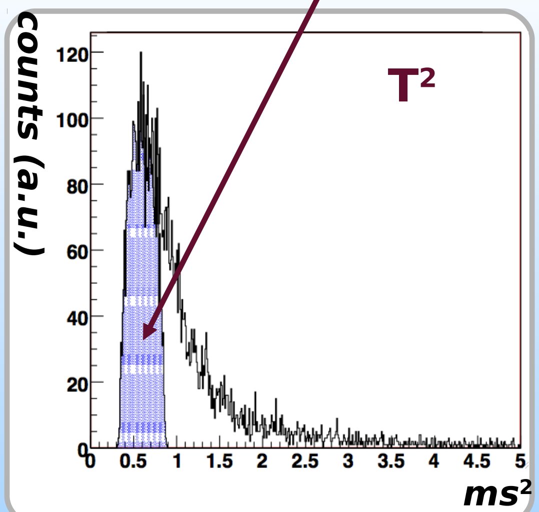
Fringe shift !



Moiré deflectomete

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

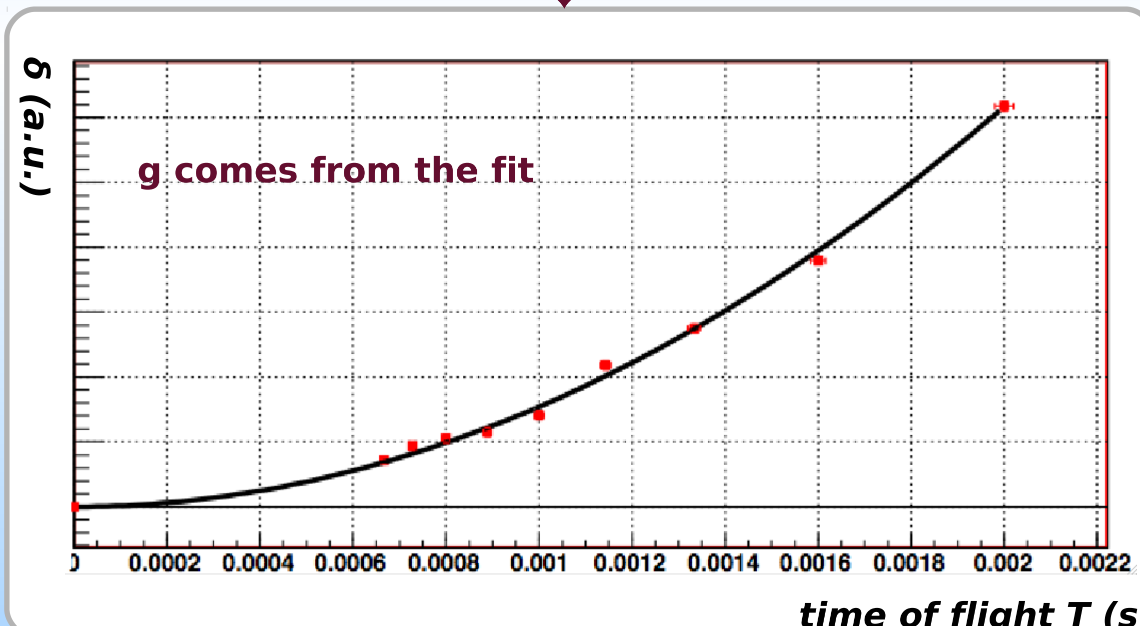




$$\delta = \frac{gT^2}{a}$$ **fringe shift of the shadow image**

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 $\sqrt{<T^2>}$



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

Experiment approved at CERN

…and by various funding agencies

Installation in experimental Hall began in 2011

Physics to begin in 2012