Quantum Interferometry and Gravity with Positronium

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QUPLAS

QUantum Interferometry, decoherence and gravitational studies with Positrons and LASers

Outline of talk:

- **Theoretical motivation**
- **Talbot Quantum Interferometry**
- **Design of QUPLAS-0**
- **QUPLAS-I and Ps Interferometry**
- **Positronium fall (QUPLAS-II)**

Home of the Experiment:

L-NESS Laboratory of the

Milano Politecnico in Como

The QUPLAS Collaboration

Università degli Studi di Milano and Infn Milano

S. Castelli, S. Cialdi, E. Dei Cas, M. Giammarchi*, M. Longhi, G. Maero, L. Miramonti, Z. Mazzotta, S. Olivares, M. Paris, M. Potenza, M. Romè, S. Sala, S. Siccardi, D. Trezzi

Politecnico Como (Milano)

S. Aghion, M. Bollani (IFN del CNR), G. Consolati, C. Evans, M. Leone, R. Ferragut

Albert Einstein Center – Laboratory for HEP – University of Bern

A. Ariga, T. Ariga, A. Ereditato, C. Pistillo, P. Scampoli

Dep.t of Chemistry, University of Bath

K. Edler

R. Greaves (Los Angeles, formerly at First Point Scientific)

(reference person underlined)

Ps : the truly elementary atom

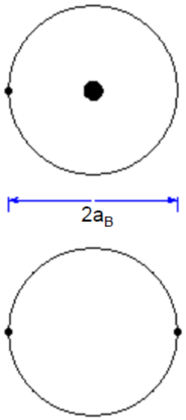
Energy levels of hydrogen and positronium

$$E_n(H) = -\frac{\mu e^4}{2\hbar n^2} = -\frac{1}{n^2}\times 13.6eV$$

$$\mu_H = \frac{m_e M}{m_e + M} \approx m_e$$

$$\mu_{Ps} = \frac{m_e^2}{2m_e} = \frac{m_e}{2}$$

$$E_n(Ps) = -\frac{1}{n^2}\times 6.8eV$$



A pure QED system where spin-orbit and hyperfine effects are of the same order

The metastable electron-positron bound state can exist in different configurations depending on the relative spin states of the positron and the electron. These are known as para-positronium (p-Ps), with total spin S = 0 and ortho positronium (o-Ps) with S = 1.

These spin states have very different lifetimes:

$$|S,m\rangle = |0,0\rangle = \frac{1}{\sqrt{2}}\left(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle\right)$$

$$|S,m\rangle = |1,0\rangle = \frac{1}{\sqrt{2}}\left(|\uparrow\downarrow\rangle + |\downarrow\uparrow\rangle\right)$$

$$|S,m\rangle = |1,1\rangle = |\uparrow\uparrow\rangle$$

$$|S,m\rangle = |1,-1\rangle = |\downarrow\downarrow\rangle$$

$$\tau_{\text{p-Ps}} = 125 \text{ ps}$$

$$\tau_{\text{o-Ps}} = 142 \text{ ns}$$

Any process that converts o-Ps to p-Ps is easy to see in lifetime spectra

1951: First production of positronium by Martin Deutsch

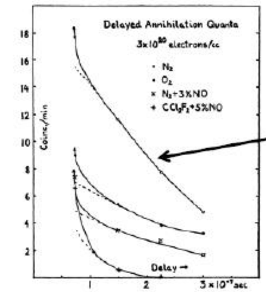
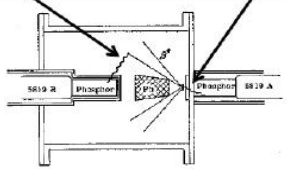


FIG. 1. Decay curves of positrons in several gases. The dotted lines are corrected for time resolution of the instrument.

100 ns lifetime of triplet Ps

Separation of Ps from Radioactive source



From M. Deutsch Phys. Rev. **82**, 455 (1951)

Our systems of interest :

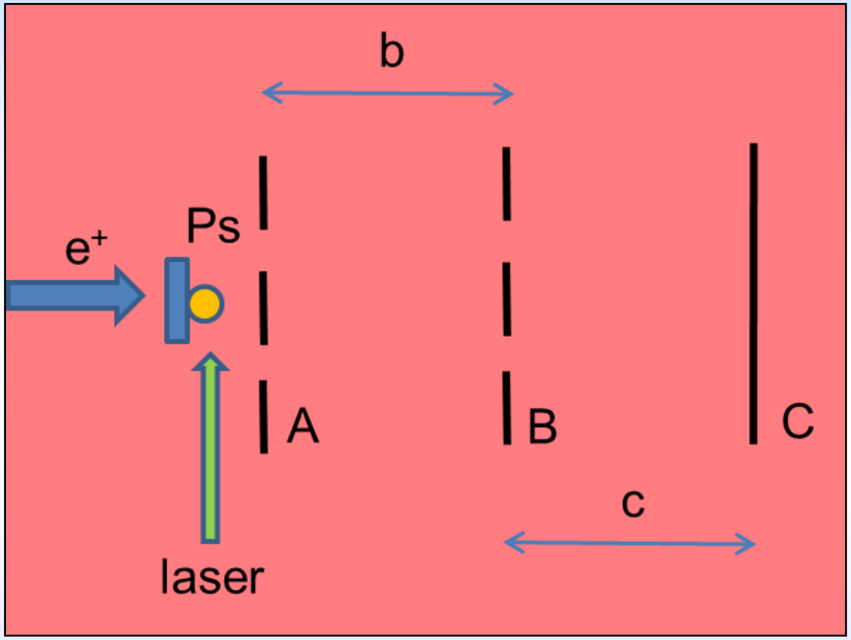
- Electron (an elementary fermion)
- Positron (the antifermion)
- Positroniuim (Ps, a particle/antiparticle symmetric system)

Introduction to the concept of Quantum Interferometry of Ps

The typical structure of a Quantum Mechanical Experiment

Preparation :

- e+ beam
- Ps beam
- Target
- Laser (excitation)
- First grating



Detection :

- Recording interference pattern
- Projection on measurement eigenstates

Preparation

Interaction
Propagation
Interference

Detection

Non – ideality :
Incoherence

Non – ideality :
Decoherence

Theoretical movitation

Here is a (Lee Smolin's inspired) arbitrary list of outstanding problems in Theoretical, Particle Physics and Cosmology that are related to QUPLAS:

- **Theoretical motivation**
- Talbot Quantum Interferometry
- Design of QUPLAS-0
- QUPLAS-I and Ps Interferometry
- Positronium fall (QUPLAS-II)

The problem of Quantum Gravity: Combine General Relativity and Quantum Theory into a single theory that can claim to be the complete theory of nature.

The foundational aspects of Quantum Mechanics: Address the interpretational and epistemological aspects in the foundations of Quantum Mechanics.

The unification of particles and forces: Determine whether or not the various particles and forces can be unified in a theory that explains them all as manifestations of a single, fundamental entity.

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QUPLAS-0) CPT test on fundamental fermions

QUPLAS-I) Test of Decoherence and of the Born Interpretation of the Wave Function

QUPLAS-II) Test of the Weak Equivalence Principle (WEP) for the simplest atom: positronium.

Gravity and the Particles

General Relativity is the current Theory of Gravity

It is a classical (geometric) theory

It has never been tested at the level of elementary particles

It has no quantum version (approximations in weak field can be quantized with graviton)

From the particle physics point of view, it could be mediated by a tensor (spin-2) carrier

Gravity and the Particles (CPT)

Dynamical meaning

$$F = m_I\, a$$

The gravitational «charge»

$$F = -G\, m_G M_G / r^2$$

According to the WEP

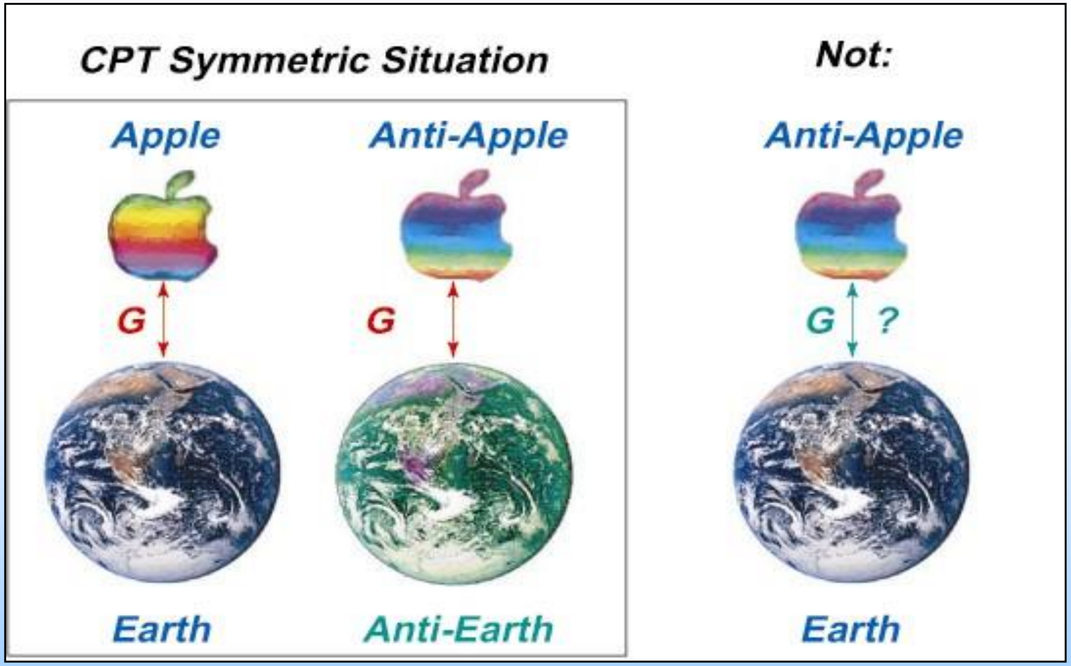
$$m_I = m_G$$

CPT Theorem $\Rightarrow$ $m_I = \overline{m}_I$ $\not\Rightarrow$ $m_G = m_I = \overline{m}_I \; ? \; \overline{m}_G$

Which means that

$$m_G \neq \overline{m}_G$$

Would not mean that CPT is broken



Gravity and the Particles

In many Quantum Gravity models (in the classical static limit), one has :

$$V = -GmM/r\left(1 \mp a e^{-r/v} + b e^{-r/s}\right)$$

Graviton

Gravi-Vector

Gravi-Scalar

- The sign of the Gravi-Vector can be different between Matter and Antimatter
- Ranges and strength unknowns

From the Particle Physics point of view, it could be mediated by a tensor (spin-2) carrier, with the charge being mass-energy.

	Matter-Matter (e- e-)	**Antimatter-Matter (e+ e-)**	**Quantum Gravity**
Scalar	attractive	attractive	gravi-scalar
Vector	repulsive	attractive	gravi-vector
Tensor (Gravity)	attractive	attractive	graviton
Tensor (Antigravity)	attractive	Repulsive (CPT violating)	

Gravity and the Particles

Experimental tests of the Weak Equivalence Principle

Where do we stand ?

Matter

- Weak Equivalence Principle tested on many different systems
- Torsion Balance Measurement
- 10^{-13} level reached

Antimatter

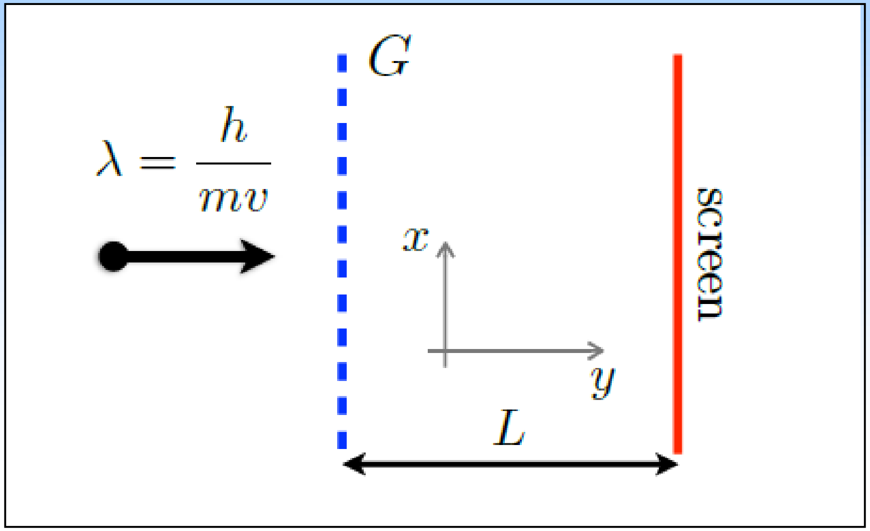
- g not measured
- Antihydrogen program at CERN (e. g. The AEgIS experiment)
- Aiming at 1% accuracy

Positronium

- Matter/Antimatter system

?

Talbot Quantum Interferometry



- Theoretical motivation
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Period D   Slit width a
Open fraction a/D

De Broglie wave impinging on a grating
- Classical propagation in the y direction
- Schroedinger dynamics in the x direction
- Neglect z-axis diffraction

Interference on the screen given by «Fresnel» integral :

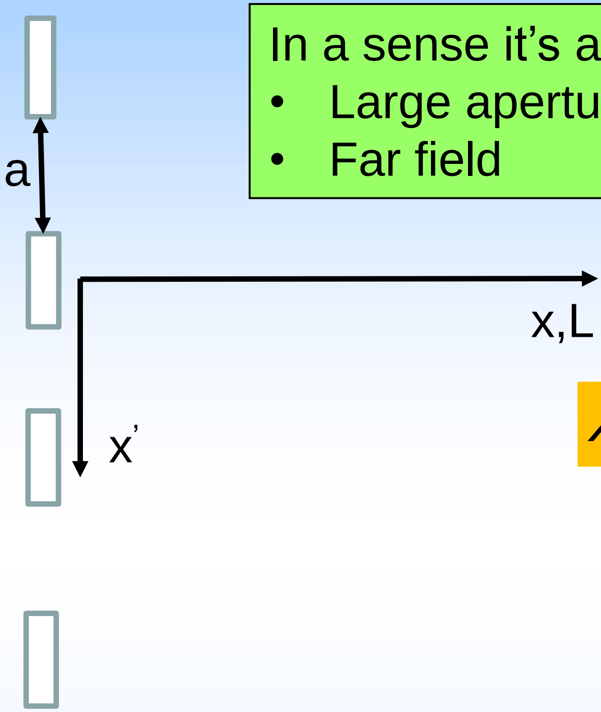
$$\psi^{(N)}(x,t=0) \approx \sum_{n=1}^{N} \psi_n(x,t=0)$$

$$H_{eff} = \frac{p_x^2}{2m}$$

$$I(x) = \left| \psi^{(N)}(x,t=L/v) \right|^2$$

$$\psi^{(N)}(x,t) = \frac{1}{\sqrt{\lambda L}} \int_{-\infty}^{+\infty} \exp\left[i \frac{\pi}{\lambda L} (x-x')^2 \right] \psi^{(N)}(x',0)\, dx'$$

Talbot and Fraunhofer



In a sense it's all

- Large aperture $a >> \lambda$
- Far field $x, L >> \lambda$

$$\frac{a}{\lambda} \; ? \; \frac{L}{a}$$

$$\lambda << a << L$$

$$\frac{a}{\lambda} >> \frac{L}{a} \Rightarrow L << \frac{a^2}{\lambda}$$ Talbot regime

$$\frac{a}{\lambda} << \frac{L}{a} \Rightarrow L >> \frac{a^2}{\lambda}$$ Fraunhofer regime

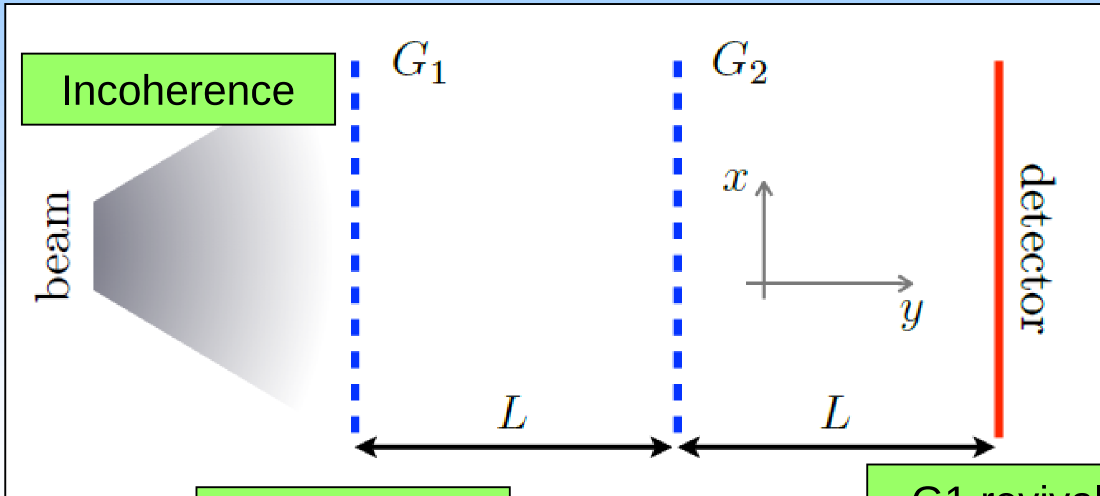
Considering the usual expansion, one can define the F parameter

$$\left|\vec{x} - \vec{x}'\right| = \sqrt{\vec{x}'^2 + \vec{x}^2 - 2\vec{x}\vec{x}'} = \left|\vec{x}\right| \sqrt{1 + \frac{\vec{x}'^2}{\vec{x}^2} - 2\frac{\vec{x}\vec{x}'}{\vec{x}^2}}$$

$$F = k\frac{\vec{x}'^2}{\vec{x}^2} = \frac{2\pi}{\lambda}\frac{\vec{x}'^2}{\vec{x}^2} \approx \frac{1}{\lambda}\frac{a^2}{L}$$

F << 1 in the Fraunhofer case
F > 1 in the Talbot case

The Talbot-Lau Effect vs Fraunhofer



Incoherence

$$L_T = \frac{a^2}{\lambda}$$

Talbot length

The Talbot case

Generates coherence

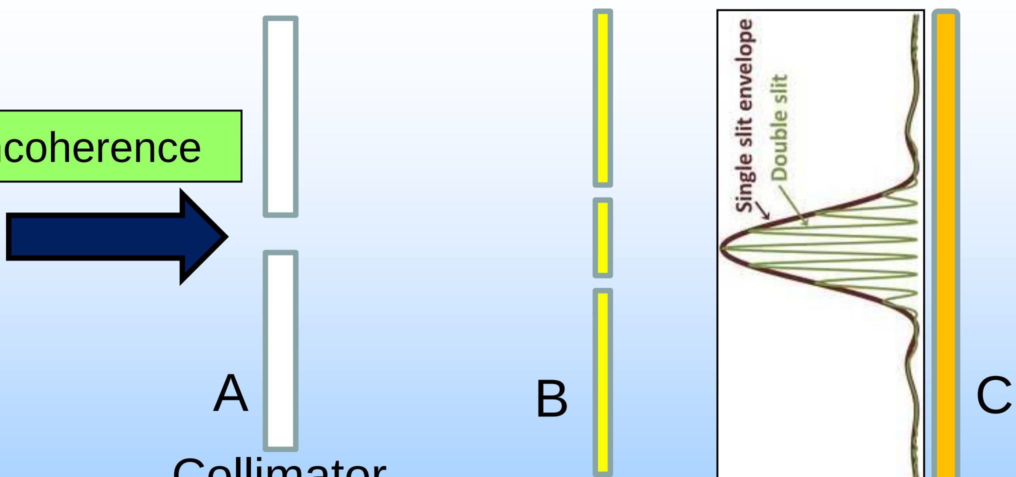
Interference

G1 revival

$$L = L_T$$

Pattern at C

Incoherence



Collimator

The Fraunhofer case

$$L >> L_T$$

$$(BC >> L_T)$$

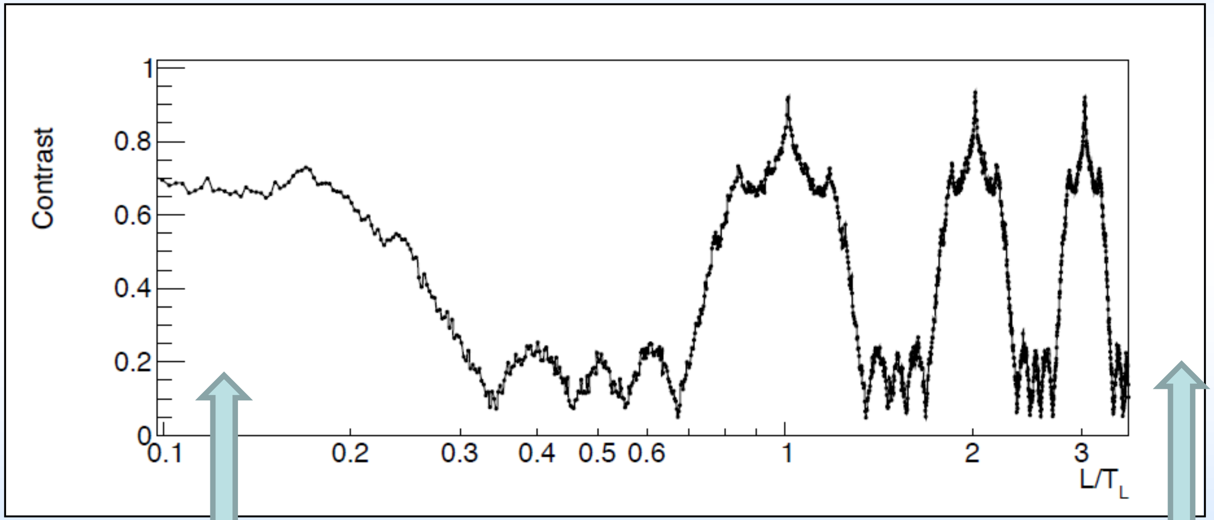
Talbot carpets

The characteristic pattern of the Talbot effect can be used to make sure the observed effect is the Talbot effect **for the specified wavelength**

Units Talbot length

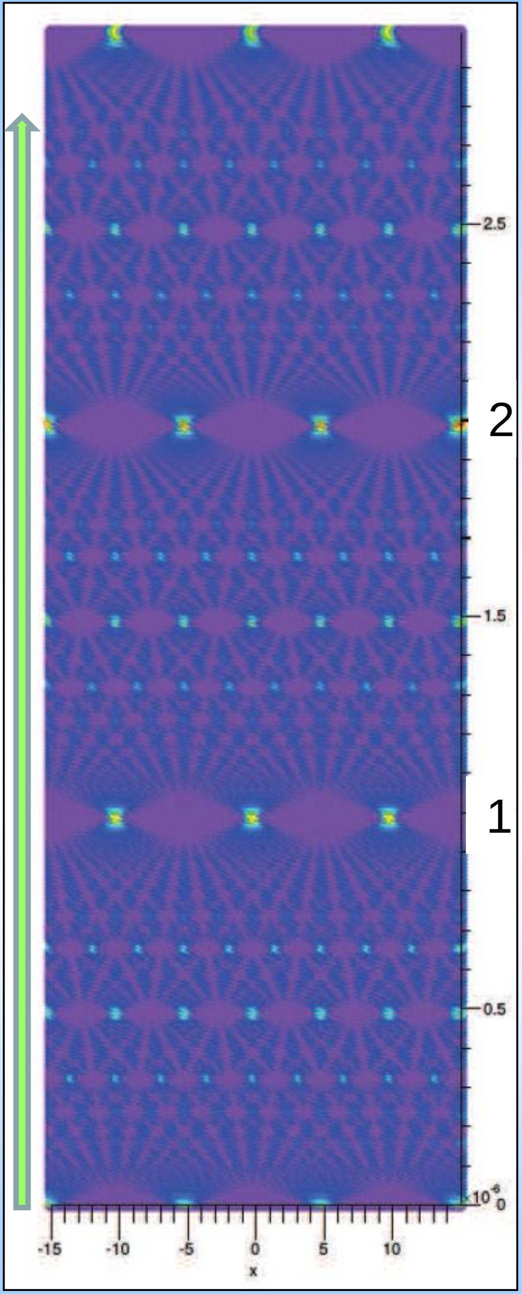
Fringes visibility **for the given wavelength**

$$c = \frac{I_{\max} - I_{\min}}{I_{\max} + I_{\min}}$$



«Ballistic» moiré regime

Fraunhofer regime setting in when $L >> L_T$



Design of QUPLAS-0

The Como continuous e+ beam

The VEPAS Laboratory at the L-Ness Politecnico di Milano at Como (R. Ferragut).

http://www.como.polimi.it/positron

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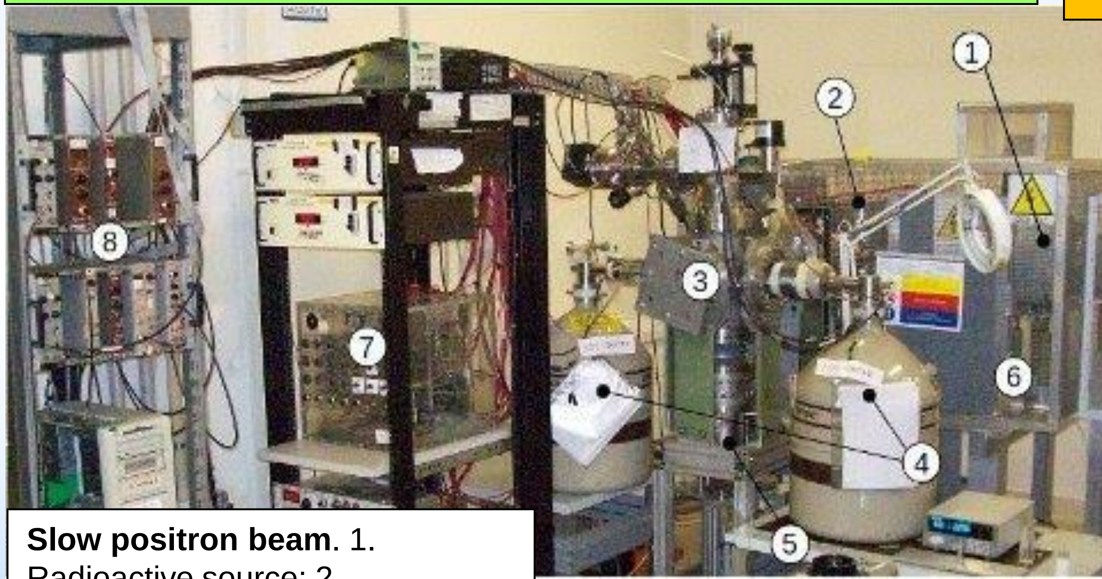
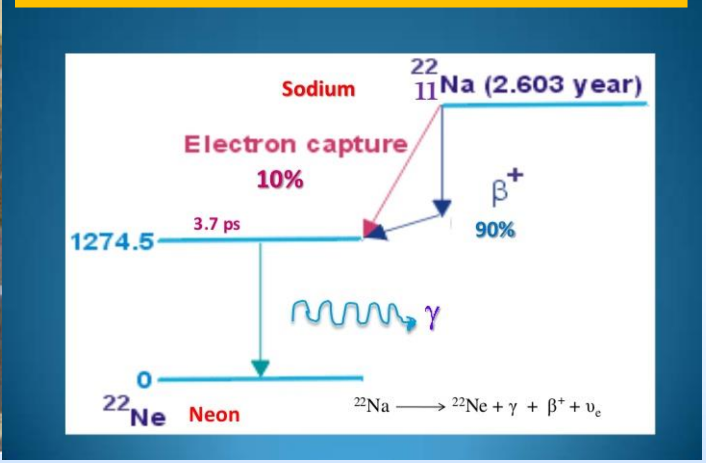


Slow positron beam. 1. Radioactive source; 2. Electrostatic optics; 3. Sample chamber; 4. HpGe detectors; 5. Cryostat; 6. High voltage protection cage; 7. Power suppliers; 8. Detector electronics.

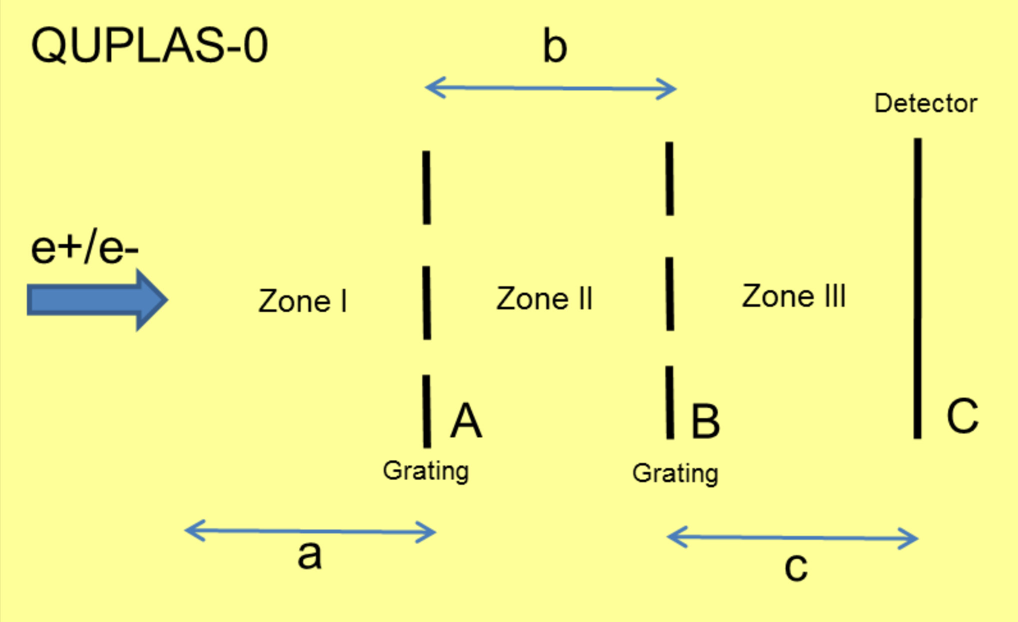
$$^{22}Na \rightarrow {}^{22}Ne + e^{+} + \nu_e + \gamma$$



Original intensity of the source: 50 mCi (current : ~ 13 mCi)
Tungsten moderator → reduces E down to a few eV
Electrostatic transport → positron beam

QUPLAS - 0

- Interferometry with positrons
- Interferometry with electrons (in the same apparatus)
- Comparison
- A new CPT test



The positron/electron beam :

T = 10 keV (typical)

The gratings (~µm thickness):

SiNx based substrates
Electron Beam Litography

The detector :

Nuclear Emulsions (~µm resolution)

S. Aghion et al., JINST 8 (2013) P08013.

Positron beam energy: from a few keV up to 20 keV

Reference value: 10 keV

Intensity: ~ 4 x 10^4 e^+/s

$$T = 10 \quad keV \qquad v = 6\times10^7 \quad m/s$$

The de Broglie wavelength

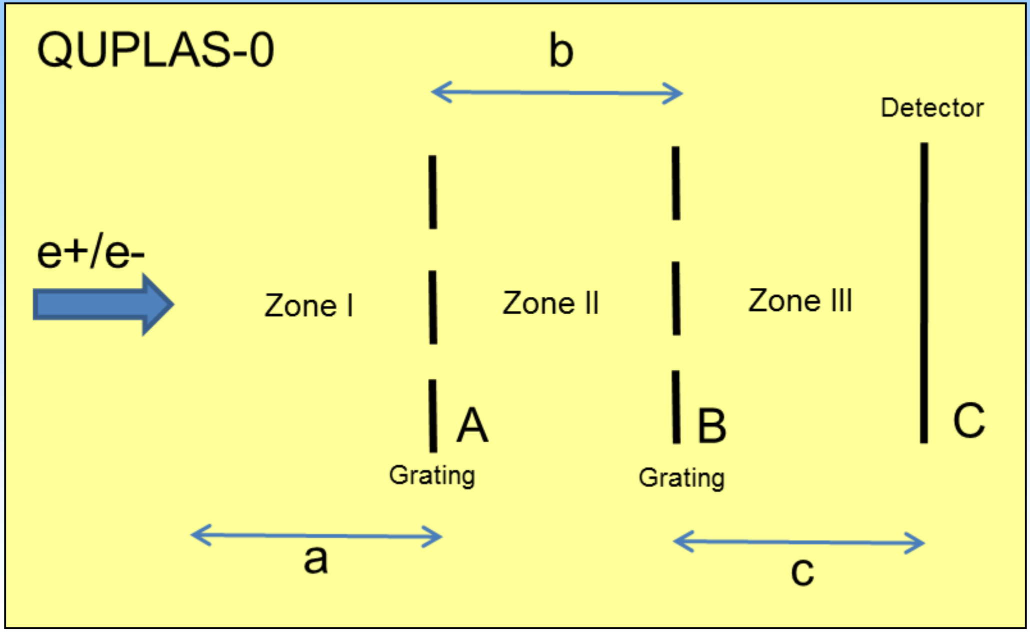
$$\lambda = \frac{h}{mv} = 1.2 \times 10^{-11} \quad m$$

Given a grating with

$$d = 2 \quad \mu m$$

The Talbot length

$$L_T = \frac{d^2}{\lambda} = 33 \quad cm$$



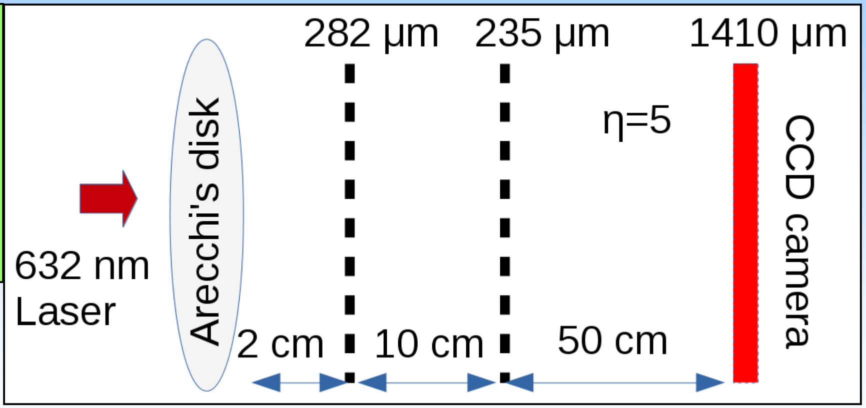
One can choose b = c = 33 cm

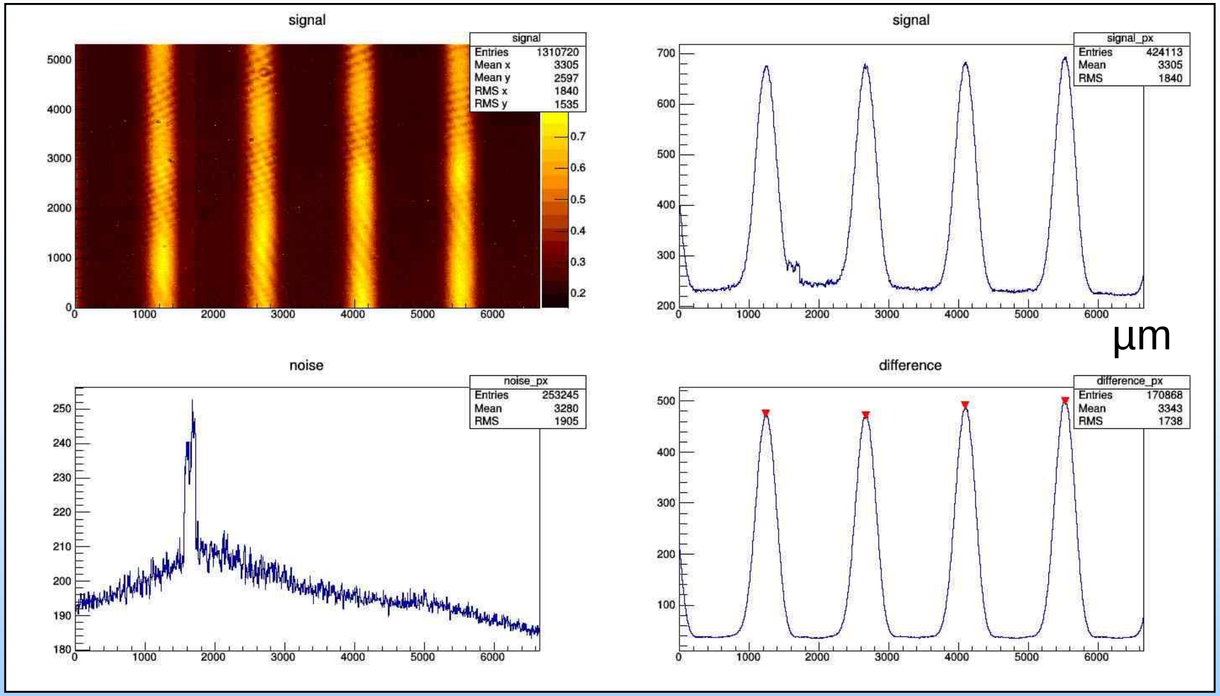
To have a 2 µm periodicity pattern on C

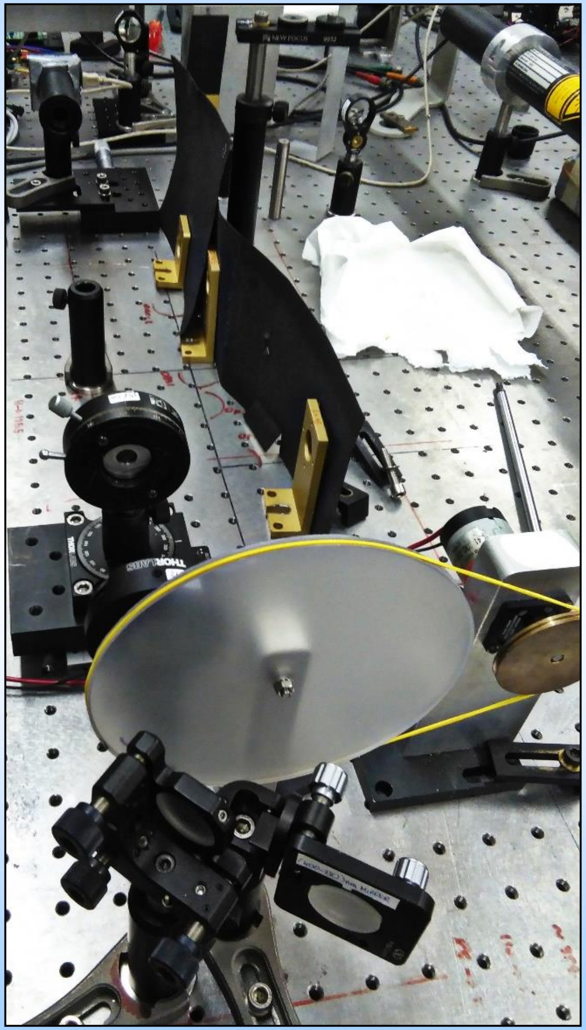
- Setup preparation
- Exposure to the e^+ beam
- Integration on the emulsion detector C

QUPLAS-0 tests: Talbot Optics in the Laboratory

Classical Optics experiments to guideline the particle experiments

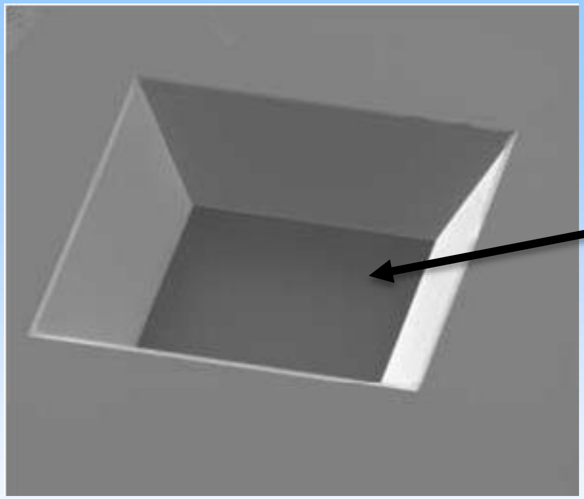






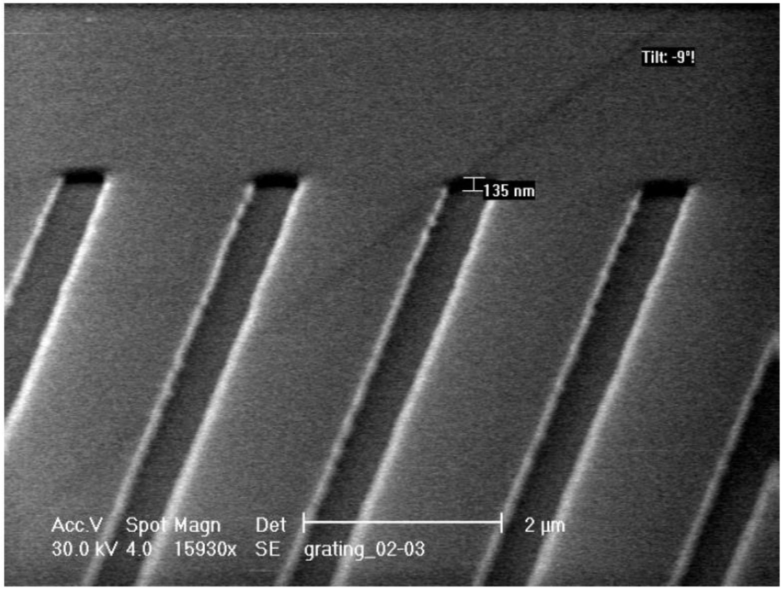
QUPLAS-0 tests: gratings construction

Micrometric (and nanometric) gratings being developed on SiN substrates



SiN
thickness 200/500 nm
5 mm x 5 mm

Stripe = 2 µm



Thickness = 135 nm

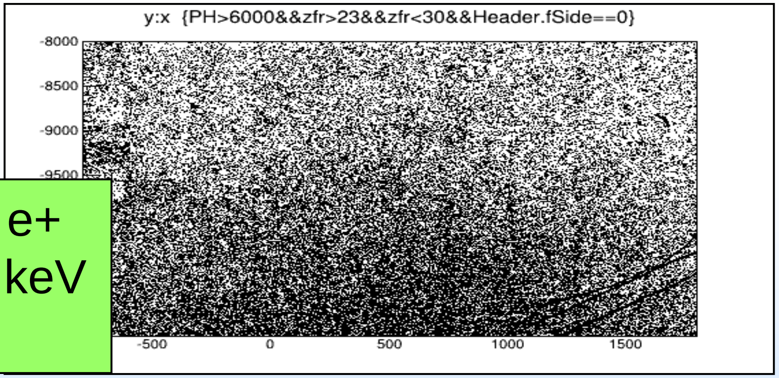
Stripes prototype made by Electron Beam Lithography

QUPLAS – 0 : positrons and electrons

An experimental activity that has already started with low-cost tests:

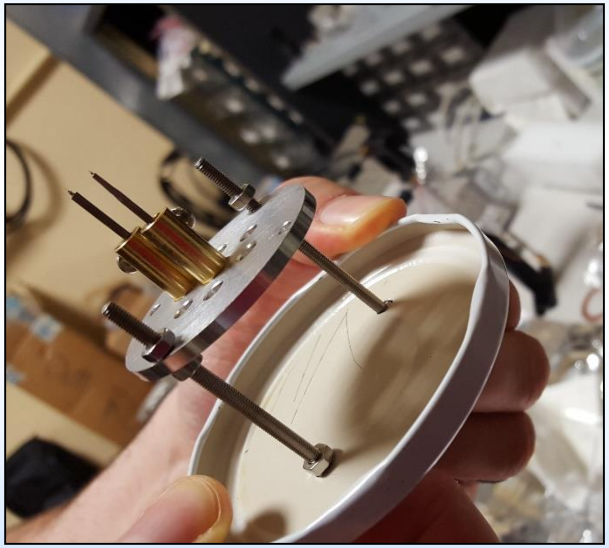
Emulsion exposures to the VEPAS e+ beam

first exposure made at an energy of 15 keV



Preliminary result: e+ visible down to 15 keV in emulsions!

Positron source → Electron source in preparation in the same apparatus (electron emitting tips) :

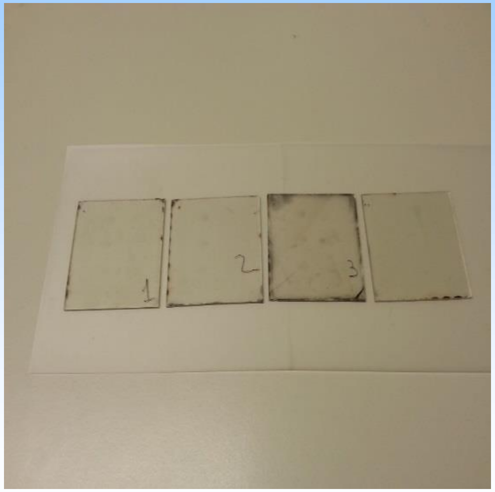


- Quantum Interferometry with 15 keV positrons
- Quantum Interferometry with 15 keV electrons (in the very same apparatus)

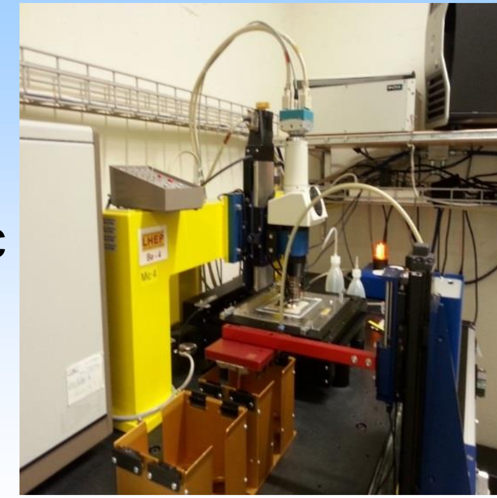
a teeny-tiny CPT test (fermion/antifermion comparison never done before) to start with

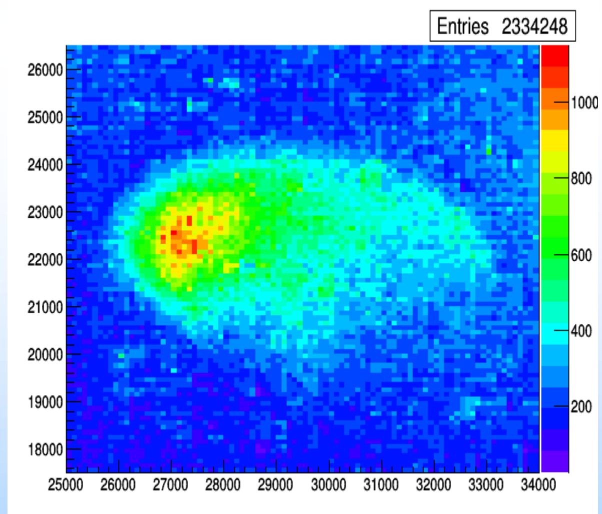
QUPLAS – 0 : positrons (slide by C. Pistillo)

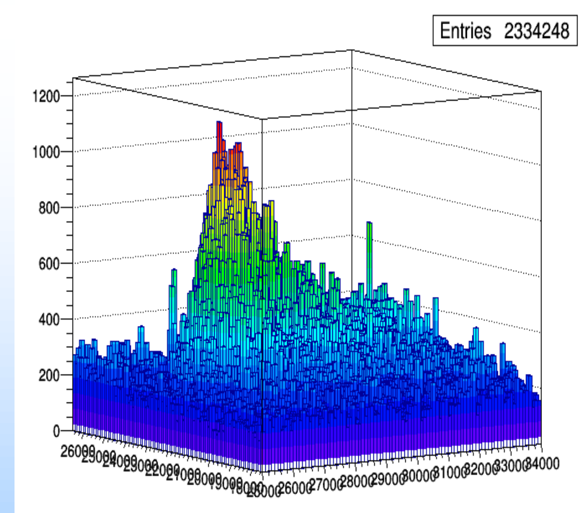
New type of emulsions produced at LHEP



Scanning with the LHEP microscopes driven by ad hoc software







exposures in Como: positrons successfully reconstructed in the 9-18 keV energy range

QUPLAS at work

QUPLAS-I and Ps Interferometry

Problems to face :
- Positronium is a neutral atom
- Positronium has a very short lifetime

Detection through ionization required.

Laser excitation required.

- Theoretical motivation
- Talbot Quantum Interferometry
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- **QUPLAS-I and Ps Interferometry**
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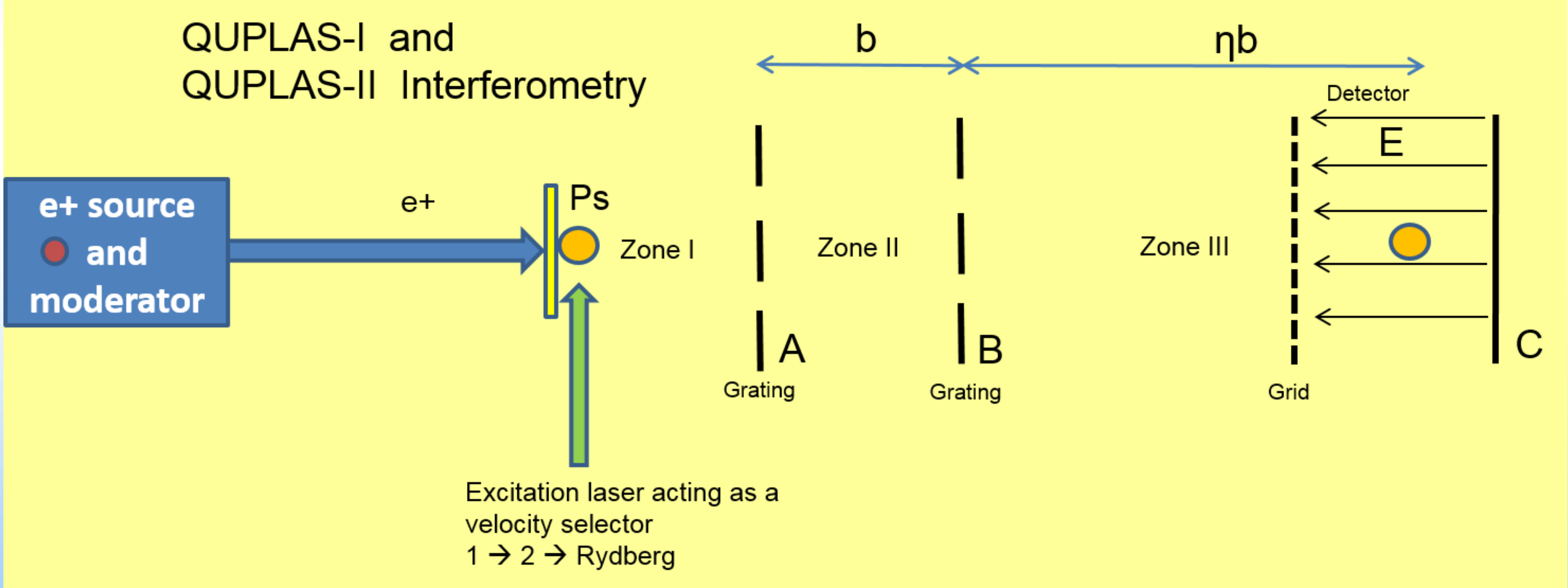
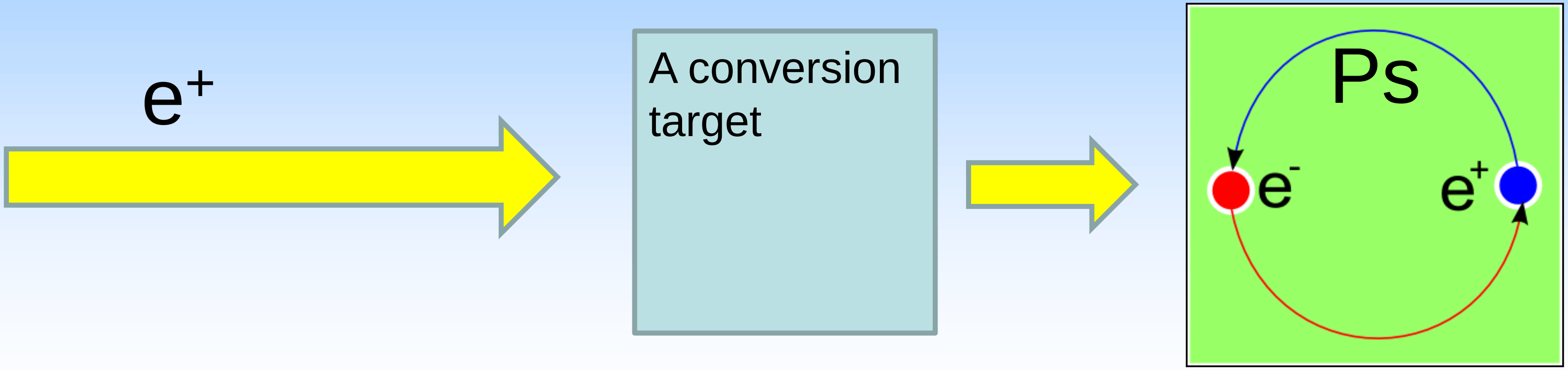


Positrons and Positronium (Ps)



ortho-Ps is short lived

But its lifetime can be increased by exciting it on a Rydberg (high-n) state

$$\tau \approx n^3 \, l^2$$

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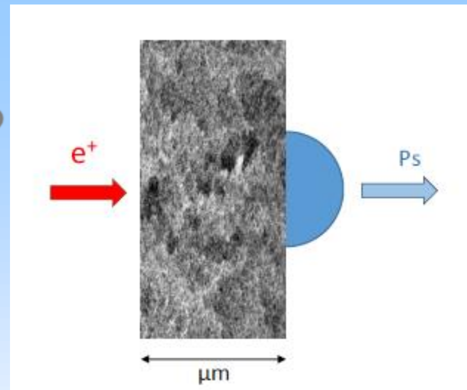
$$|S,m\rangle = |1,-1\rangle = |\downarrow\downarrow\rangle$$

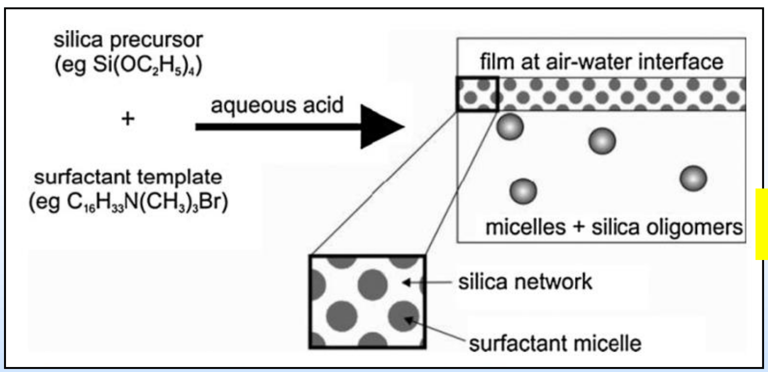
$$\tau_{\text{p-Ps}} = 125 \text{ ps}$$

$$\tau_{\text{o-Ps}} = 142 \text{ ns}$$

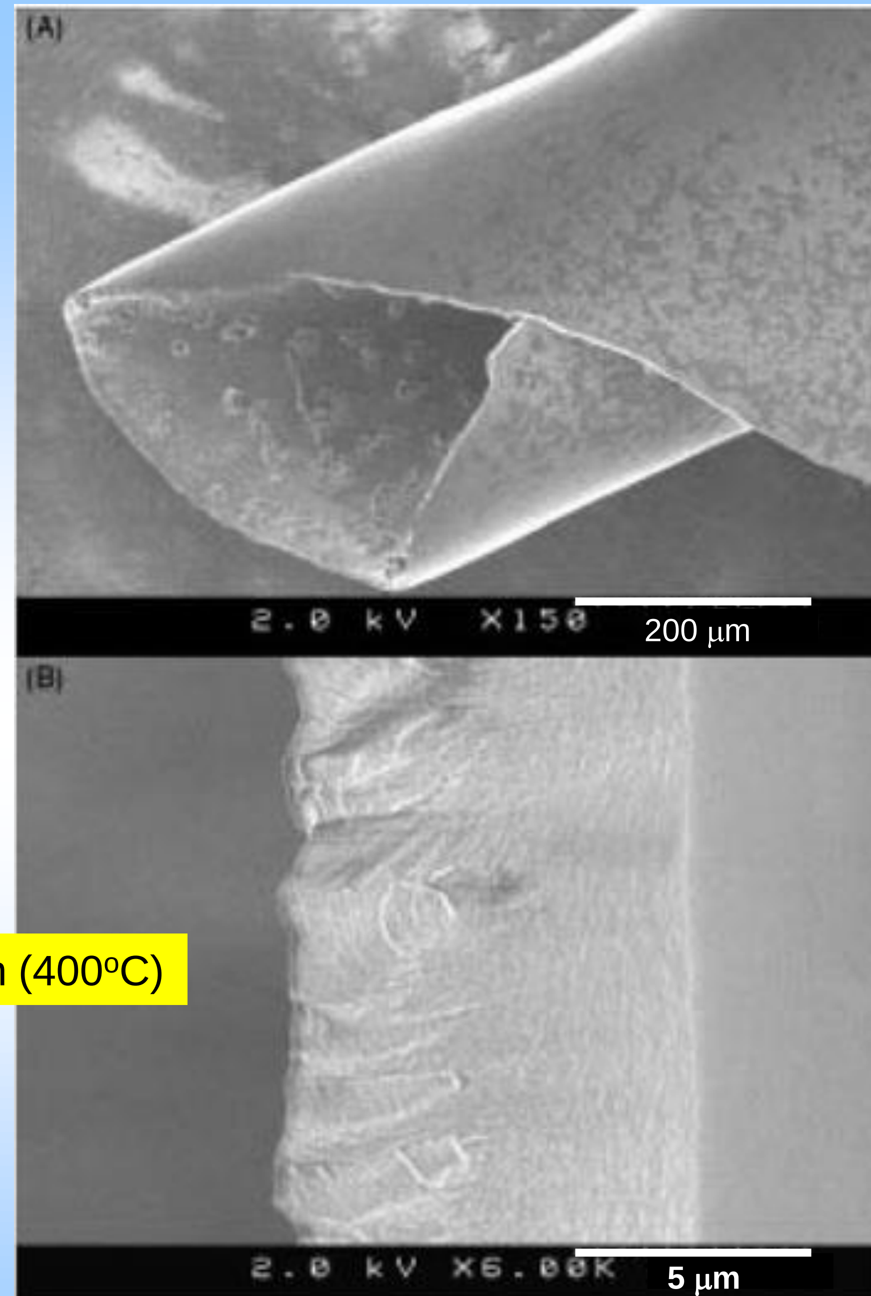
Samples.
Micrometre membranes



Synthesis route to the growth of free-standing surfactant-template films of silica (Chemistry Department, University of Bath, Claverton Down, Bath) [1]



Calcination (400^{o}C)

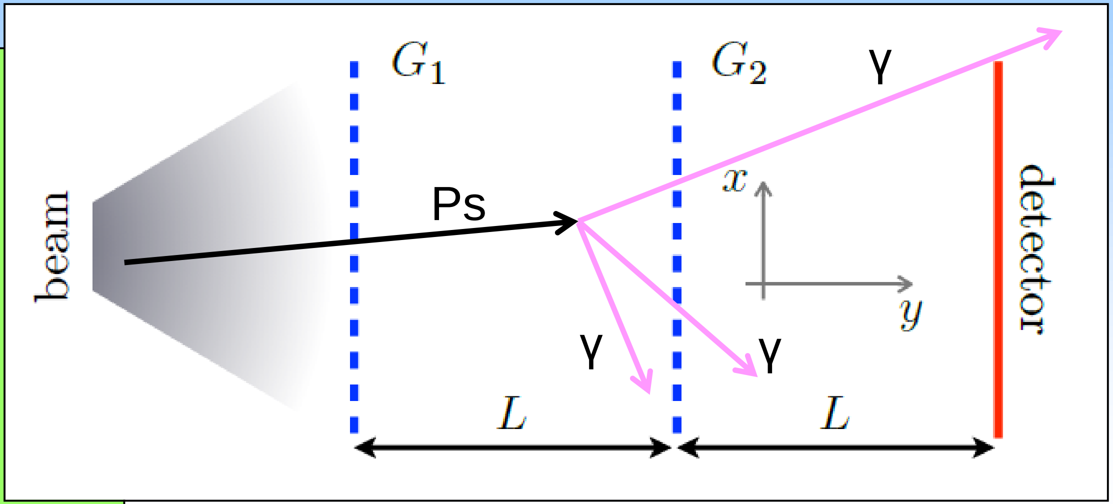


[1] K.J. Edler* and B. Yang, *Chem. Soc. Rev.*, 2013 **42**, 3765

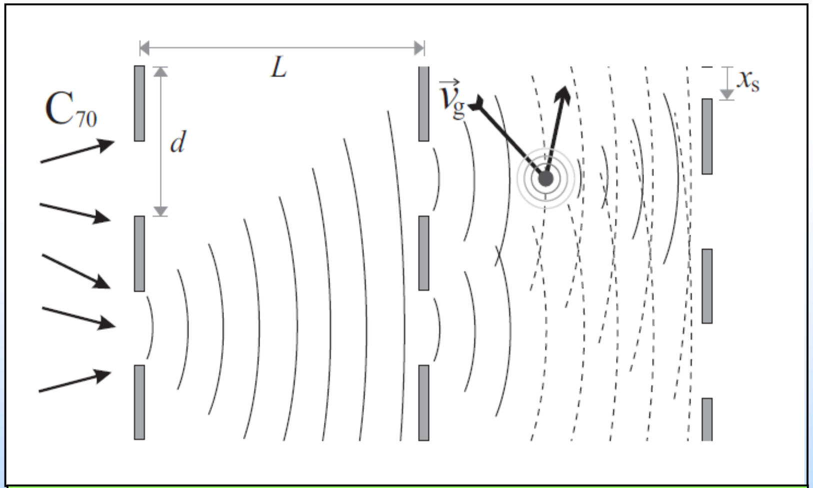
Problems related to QUPLAS-I (Ps interferometry)

A variety of effects can disturb an interference pattern that cannot be really considered «Incoherence» :

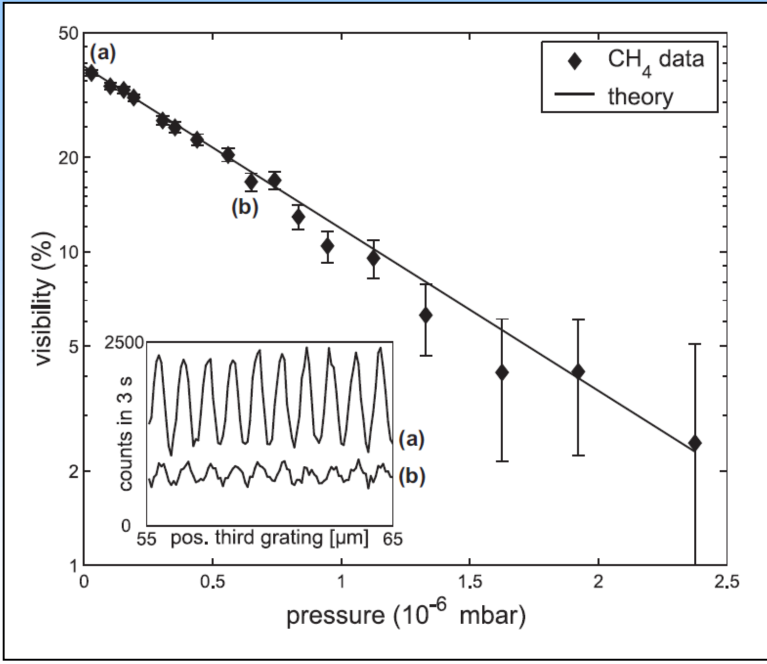
- Particle Decay in Flight
- Slits physical effect
- Decoherence



Decoherence : loss of the quantum phases between the components of a system in a quantum mechanical superposition. It leads to classical or probabilistically additive behavior. Decoherence occurs when a system interacts with its environment in an irreversible way.



Gas molecules of the background inducing decoherence on C_{70}



Residual pressure in the vacuum chamber is used as a «decoherence parameter»

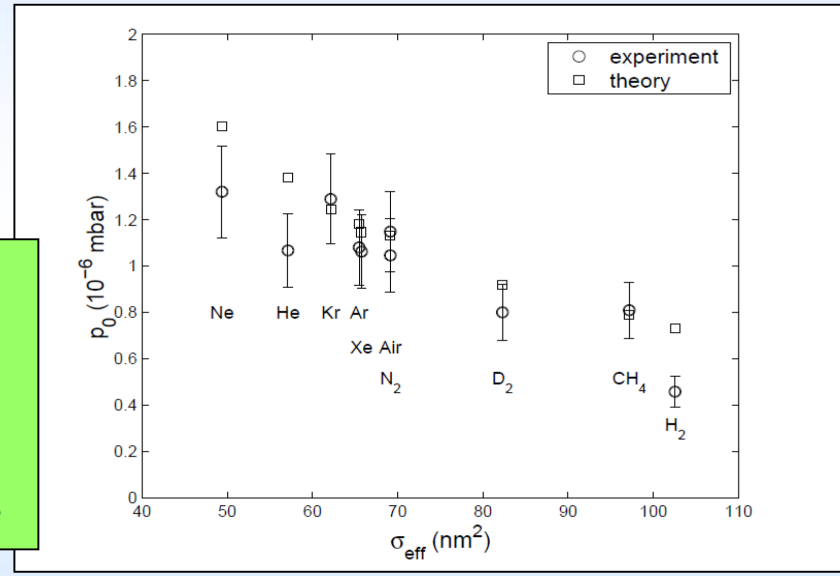
Assumption in the decoherence model :

- Scattering gas massless
- Isotropic velocity distribution of C_{70}

A Master Equation is solved

Model works for different background gases !

p a good parameter to describe decoherence



Collisional Decoherence Observed in Matter Wave Interferometry

Klaus Hornberger, Stefan Uttenthaler, Björn Brezger, Lucia Hackermüller, Markus Arndt, and Anton Zeilinger*
Universität Wien, Institut für Experimentalphysik, Boltzmanngasse 5, A-1090 Wien, Austria
(Dated: March 14, 2003)

QUPLAS – 0 and QUPLAS – I summary

Positronium Quantum Interferometry concept

- Positron Interferometry
- Electron Interferometry
- Positronium Interferometry

An elementary fermion
The relevant antifermion

The bound fermion-antifermion system
(also, the simplest atom)

Problems to face :

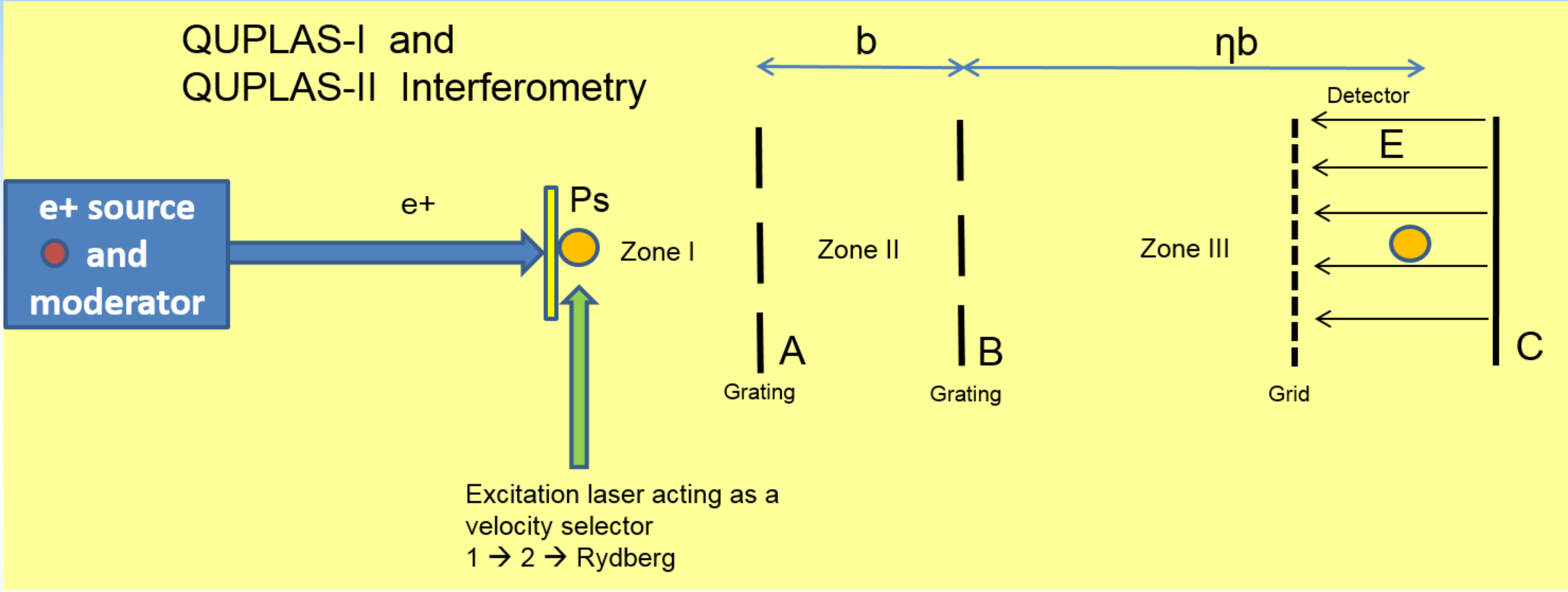
- Positronium is a neutral atom
- Positronium has a very short lifetime

Detection of the interference pattern is not going to be easy. Ionization required.

Excitation on Rydberg state is necessary. Laser excitation required.

QUPLAS – I physics program:
- Quantum Decoherence with an unusual system
- Wave function interpretation
- Optical gratings and laser interaction and cooling

Positronium fall (QUPLAS-II)



QUPLAS – I : detecting an interferometry pattern in the Talbot mode

QUPLAS – II : detecting a (gravity induced) SHIFT in the interferometry pattern

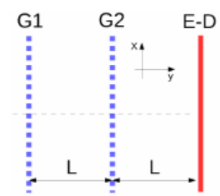
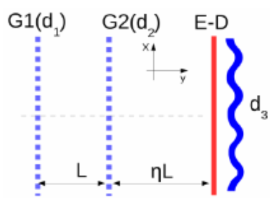
Gravity shift of 4 micron over the distance of a meter (for 10^3 m/s positronium)

Measuring gravity

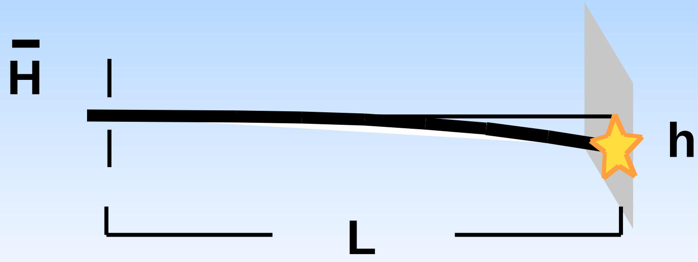
Methods to measure the Interference Pattern Shift

1.Quantum Talbot Interferometry (pitch of ~ 100 microns) S. Sala et al., submitted to J. of Phys. B, Atomic, Molecular and Optical Physics, 48 (2015) 195002.

2.Moiré classical deflectometry (pitch of ~ mm) S. Aghion et al., Nature Comm doi:10.1038/ncomms5538.

Common parameters	$v = 800\,\mathrm{m/s}$ $\lambda_{\mathrm{Ps}} = 454\,\mathrm{nm}$ $L^{(\mathrm{TOT})} \approx 1\,\mathrm{m}$ $a = 9.81\,\mathrm{m/s^2}$	
	Talbot	**Moirè**
Symmetric 	$L^{(\mathrm{TOT})} = 2\frac{d_2^2}{\lambda} = 2T_L$ $d_1 = d_2 = d_3 = 476\,\mu\mathrm{m}$ $\tau = 6.25 \cdot 10^{-4}\,\mathrm{s}$ $\Delta x = 3.83\,\mu\mathrm{m}$ $\Delta x/d_3 = 8.0 \cdot 10^{-3}$	$d_1 = d_2 = d_3 \gtrsim 800\,\mu\mathrm{m}$ $L^{(\mathrm{TOT})} = 1\,\mathrm{m} \gg 2T_L$ $\tau = 6.25 \cdot 10^{-4}\,\mathrm{s}$ $\Delta x = 3.83\,\mu\mathrm{m}$ $\Delta x/d_3 \lesssim 4.0 \cdot 10^{-3}$
Asymmetric $(\eta = 3)$ 	$L^{(\mathrm{TOT})} = \frac{(\eta+1)^2}{\eta} T_L$ $d_2 = 291\,\mu\mathrm{m}$ $d_3 = \eta d_1 = \eta d_2 \frac{(\eta+1)}{\eta}$ $\tau = \frac{d_1 T_L}{d_2 v} = 3.1 \cdot 10^{-4}\,\mathrm{s}$ $\Delta x = a\frac{\eta(\eta+1)}{2}\tau^2 = 5.70\,\mu\mathrm{m}$ $\Delta x/d_3 = 4.8 \cdot 10^{-3}$	$d_2 \gtrsim 800\,\mu\mathrm{m}$ $d_3 = \eta d_1 = \eta d_2 \frac{(\eta+1)}{\eta}$ $L^{(\mathrm{TOT})} = 1\,\mathrm{m} \to L = 0.25\,\mathrm{m}$ $\tau = \frac{L}{v} = 3.1 \cdot 10^{-4}\,\mathrm{s}$ $\Delta x = a\frac{\eta(\eta+1)}{2}\tau^2 = 5.70\,\mu\mathrm{m}$ $\Delta x/d_3 \lesssim 2 \cdot 10^{-3}$

Gravity fall detection with moiré deflectometery



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

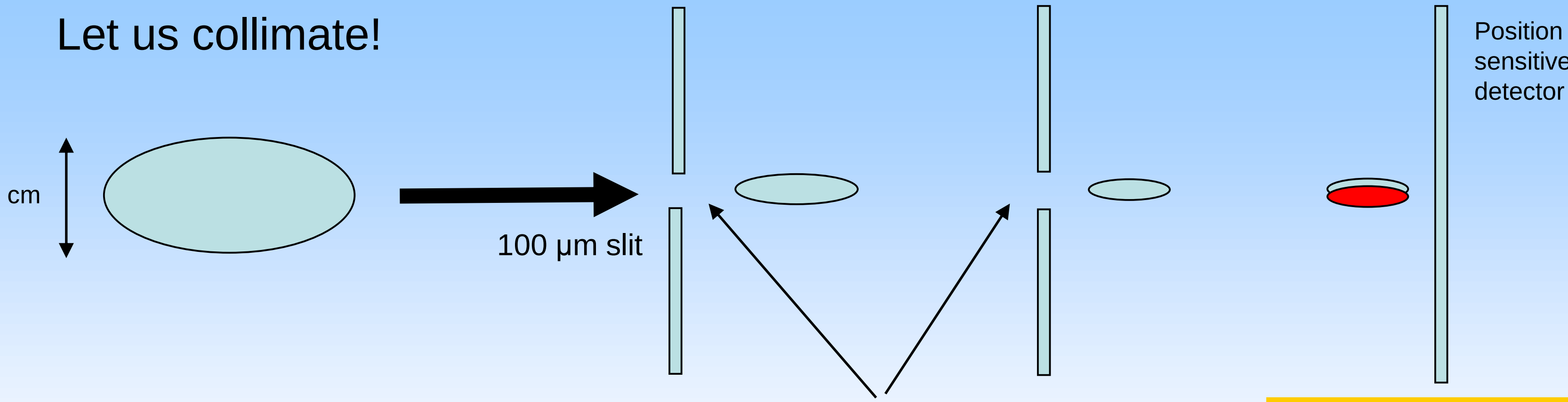
Let us assume realistic numbers:
- horizontal flight path L ~ 1 m
- horizontal velocity v_z ~ 500 m/s

→ **vertical deflection ~ 20 µm**

BUT: - The Ps will have radial velocity (related to the production)
- any Ps 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!

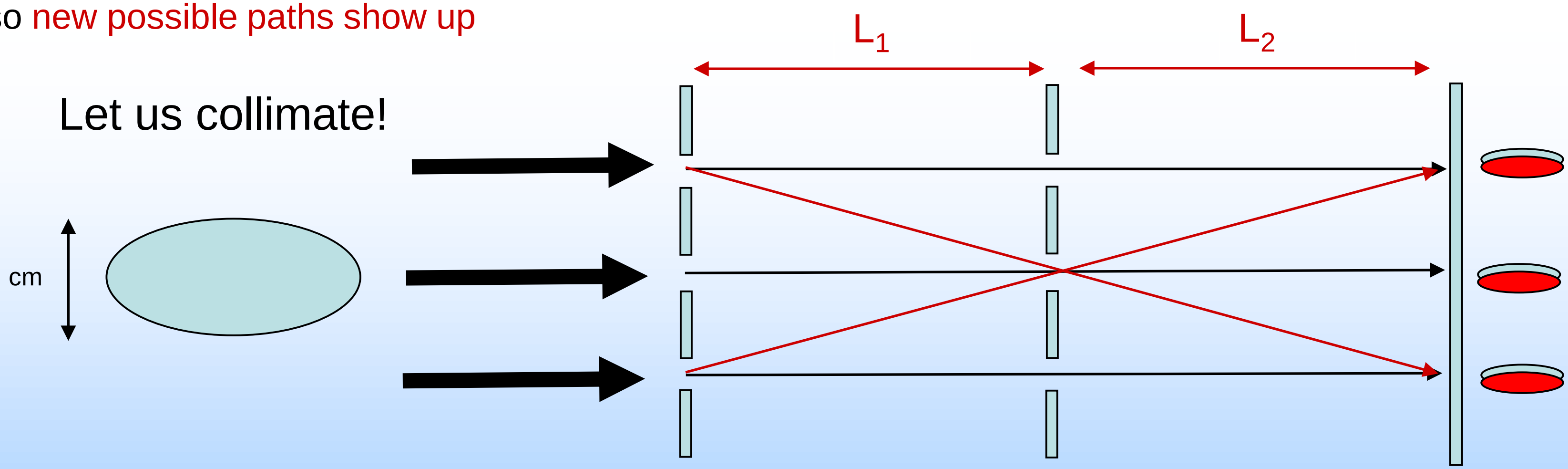


Now displacement easily detectable. At the price of a huge loss in acceptance

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

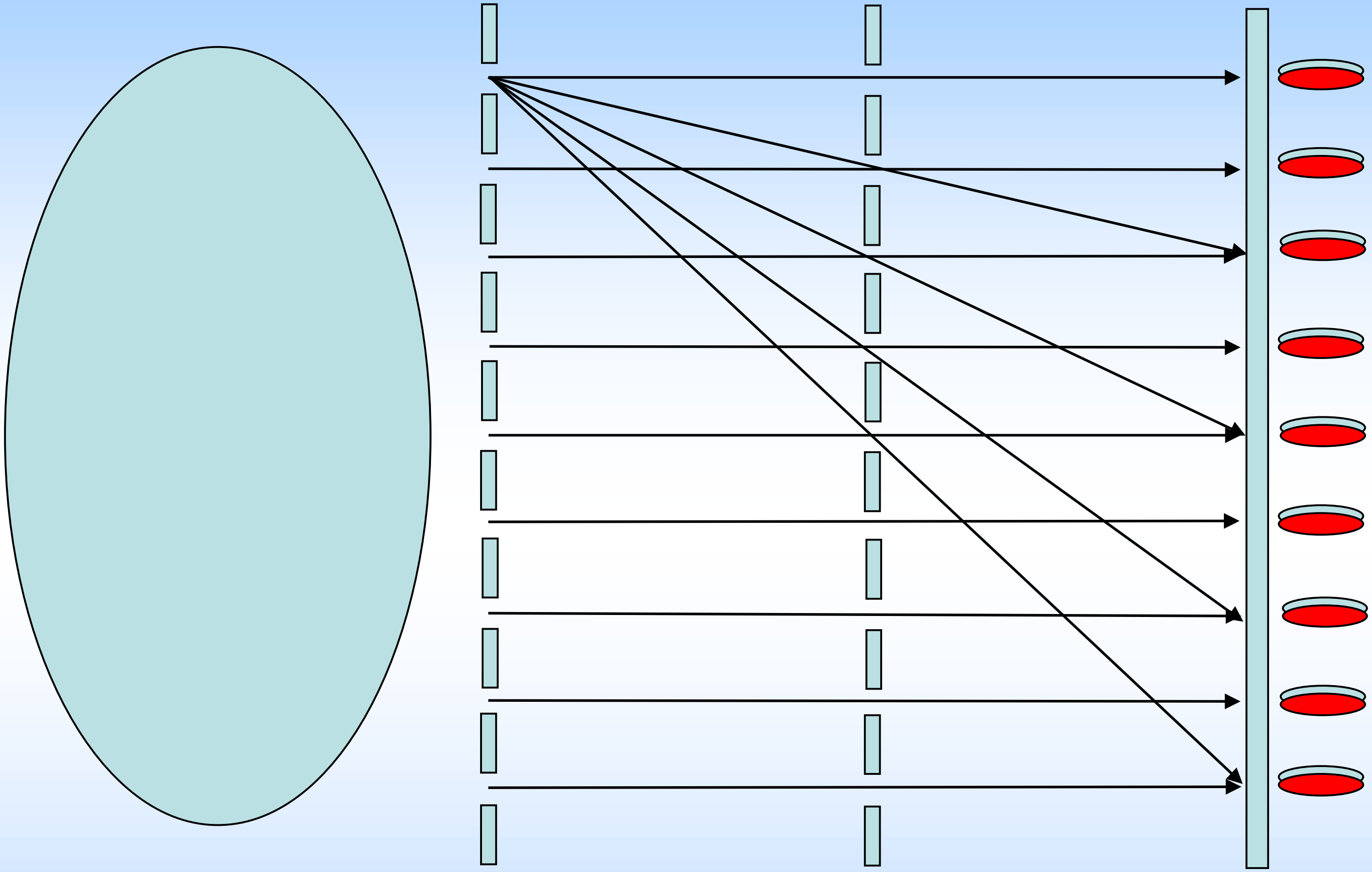
Acceptance can be increased by having several holes. In doing so new possible paths show up

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.

Gravity measurement count rate

Count rate for a typical gravity experiment

50 mCi source with a RGM moderator (0.4% efficiency) → 7 x 10^6 e+/s

e+ → Ps conversion (10%) and reemission (30%) by converters → 2 x 10^5 /s

Ps solid angle of emission and interferometer geometry (0.1%) → 200/s

Ps excitation efficiency is high but the spectral selection will introduce 10% → 20/s

Transparency of the gratings 25% → 5/s

Sensitivity to g for Ps (only Talbot, interferometric methods)

Given 0.5 dots/s on the emulsion, one has, for a very realistic 50% contrast, d_3 = 476 μm, Δx = 4 μm :

$$\frac{\sigma(g)}{g} \cong \frac{1}{2\pi C}\frac{1}{\sqrt{N}}\frac{d_3}{\Delta x(g)}$$

(only statistical error)

- 2% in a WEEK
- 1% in a MONTH
- <0.1% in a YEAR

Conclusions

Positrons, Electrons, Positronium are interesting !

- Quantum Interference as a key to explore new physics with e^+/e^-/Ps
- QUPLAS is a staged project to tackle these subjects
- QUPLAS-0 : Positron and Electron (charged particles) quantum interference and comparison between them (CPT test)
- QUPLAS-I : Positronium Quantum Interferometry (and a lot of technical development to reach this ambitious goal).
- QUPLAS-II : Positronium Gravity as a test of the Weak Equivalence Principle

Thank you for your attention !

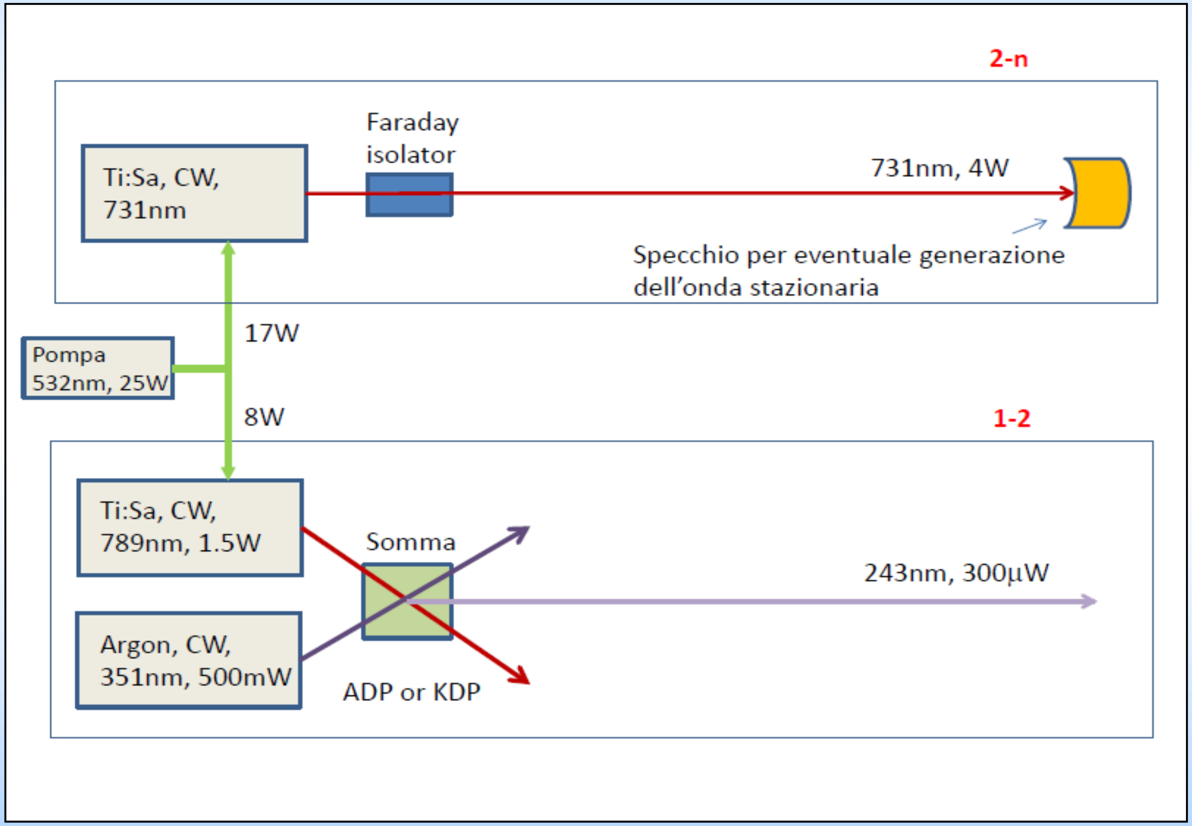
Backup Slides

The QUPLAS Laser system for velocity-selective excitation of a continuous Ps beam

Excitation of Rydberg states :

1→2 243 nm   2→n ~ 732 nm

$$\tau \approx n^3 \, l^2$$



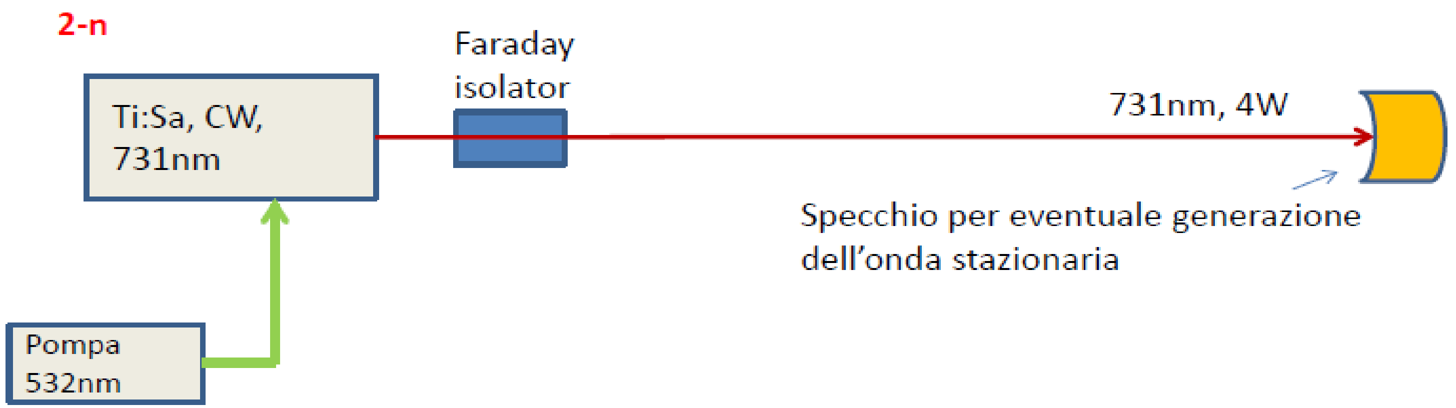
$v = 10^3$ m/s

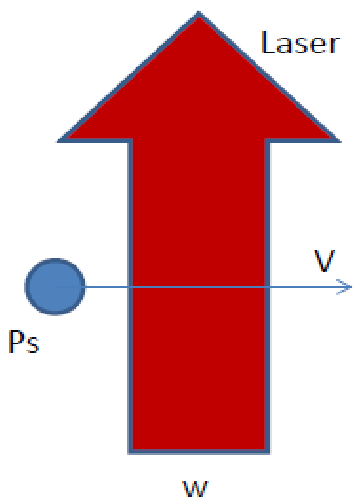
L(tot) = 1 m

τ ~ 1 ms

n ~ 80-90

The QUPLAS system for velocity-selective excitation of a continuous Ps beam



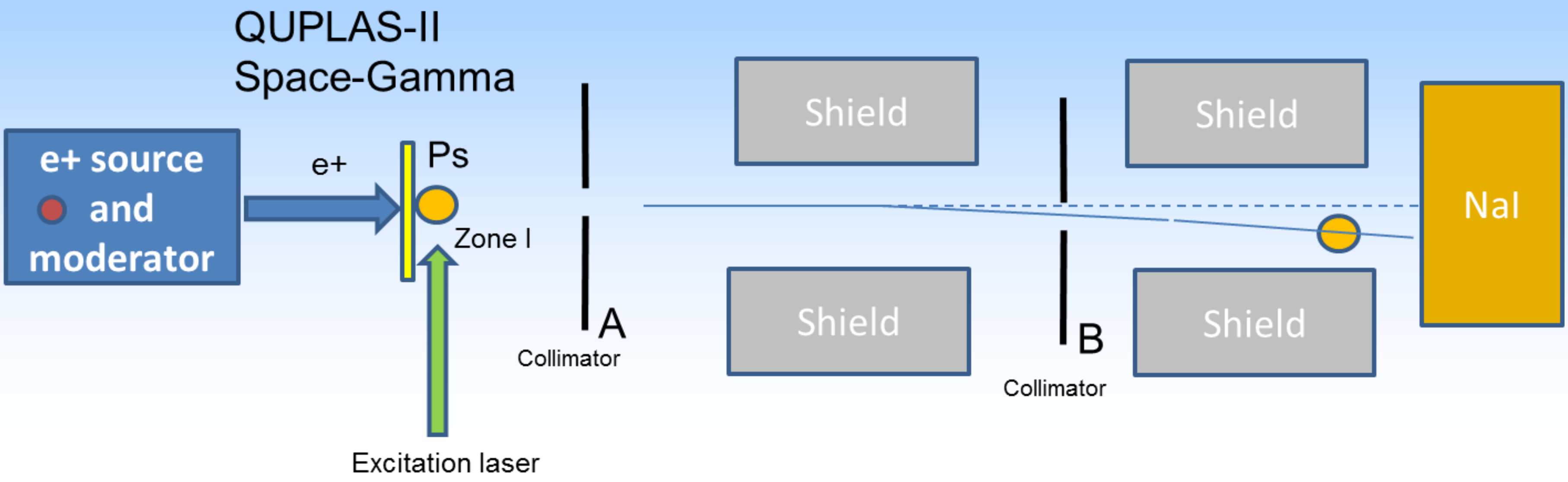


Al momento considero una velocità di 10^4m/s e determino l'intensità che il fascio laser deve avere per eccitare al 100% (picco dell'oscillazione di Rabi).
Il Ps deve essere eccitato prima del decadimento del livello n=2 quindi prendo 2ns come tempo di riferimento per arrivare al picco dell'oscillazione di Rabi.
Quindi lo spot del fascio laser deve essere:

$$w = 2 \cdot 10^{-9}\text{s} \cdot 10^4\text{m/s} = 20\mu\text{m}$$

Quindi avrò bisogno di una lente di focalizzazione

The third method to measure gravity («space – gamma»)



3. Simple method of tracing a given velocity selected by the laser (highly efficient on NaI)

Three different methods to measure g

1. Talbot interferometry
2. Moiré deflectometry

Different picthes for the gratings but similar systematics and blank measurements

3. Space-gamma

Entirely different systematics