Quantum Interferometry and Gravity with Positronium

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On behalf of the QUPLAS Collaboration

Q U P L A S

QUantum Interferometry, decoherence and gravitational studies with Positrons and LASers

Outline of talk:

- **Basic quantum model of diffraction**
- **Fraunhofer and Talbot regimes**
- **Incoherence effects**
- **Other effects and Decoherence**
- **Positrons and Positronium experiments**

Home of the Experiment:

L-NESS Laboratory of the

Milano Politecnico in Como

Ps : the truly elementary atom

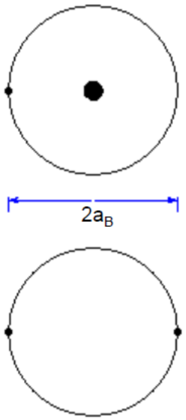
Energy levels of hydrogen and positronium

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

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

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

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



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:

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

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

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

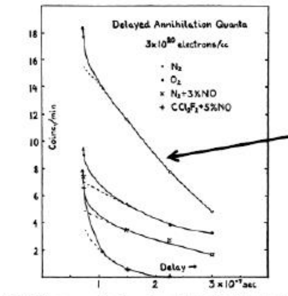
$$|S,m\rangle = |1,-1\rangle = |\downarrow\downarrow\rangle$$

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

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

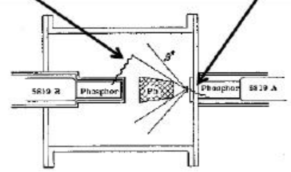
Any process that converts o-Ps to p-Ps is easy to see in lifetime spectra

1951: First production of positronium by Martin Deutsch



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)

The QUPLAS Collaboration

Università degli Studi di Milano and Infn Milano

S. Castelli, S. Cialdi, M. Giammarchi*, M. Longhi, G. Maero, 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

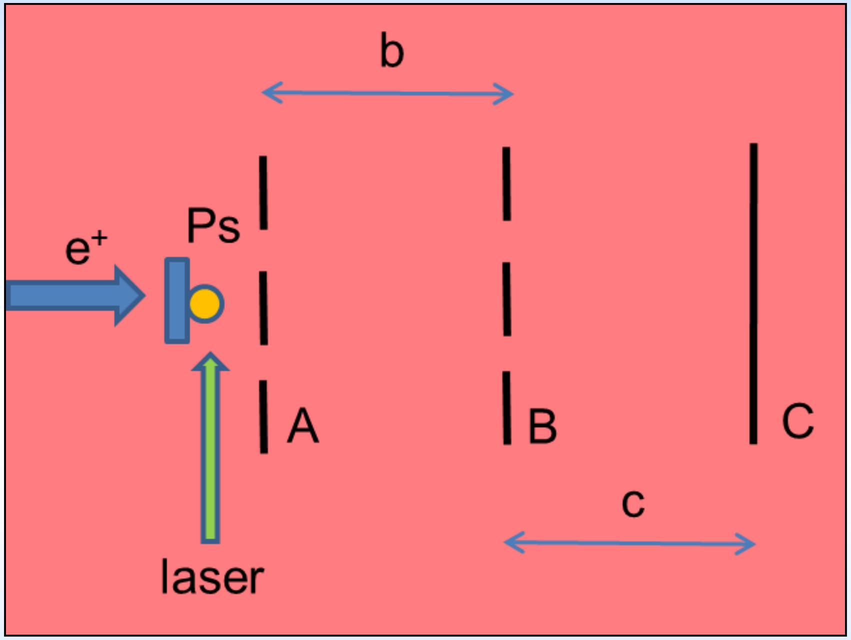
R. Greaves (Los Angeles, formerly at First Point Scientific)

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

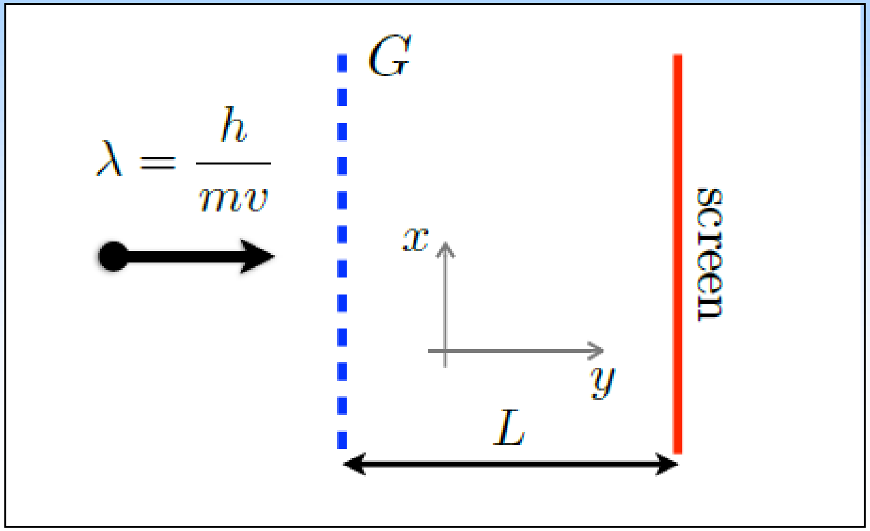
Interaction
Propagation
Interference

Detection

Non – ideality :
Incoherence

Non – ideality :
Decoherence

Basic quantum model of diffraction



- **Basic quantum model of diffraction**
- Fraunhofer and Talbot regimes
- Incoherence effects
- Other effects and Decoherence
- Positrons and Positronium experiments

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 :

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

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

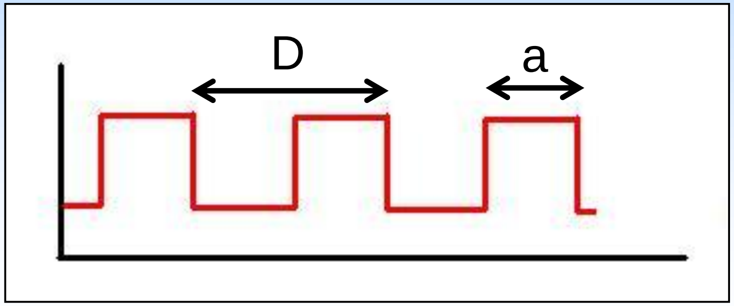
$$I(x) = \left|\psi^{(N)}(x,t=L/v)\right|^2$$

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

Possible choices of the initial wavefunction :

Period D
Slit width a
Open fraction a/D

Characteristic functions :

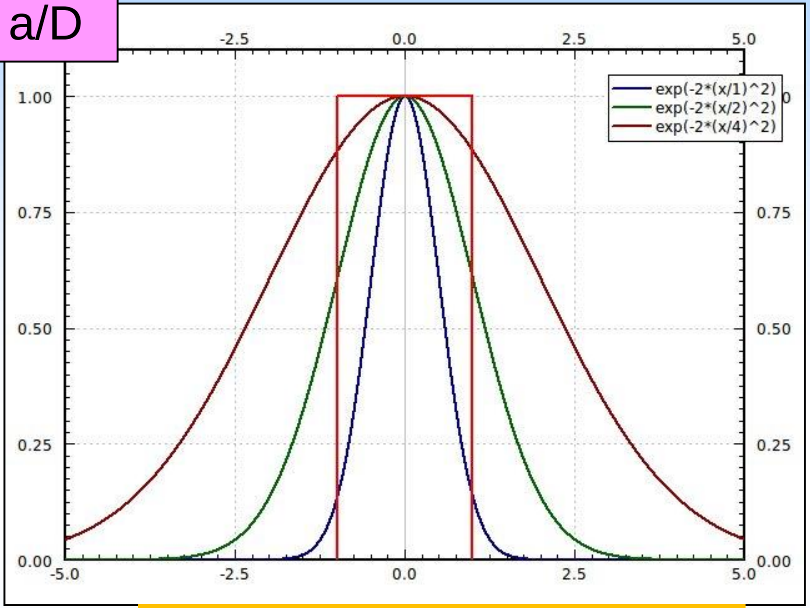


$$\psi_n(x,0) = \frac{1}{a}\chi_{\left[\frac{-a}{2}+nD,\frac{+a}{2}+nD\right]}(x)$$

$$\chi_\Omega(x) = 1 \quad if \quad x \in \Omega$$
$$\chi_\Omega(x) = 0 \quad if \quad x \notin \Omega$$

Meaning of parameters : crystal clear
Total optical analogy
Cumbersome calculations

Gaussian functions :



$$\psi_n(x,0) = \exp\left[-\frac{(x-nD)^2}{4\sigma^2}\right]$$

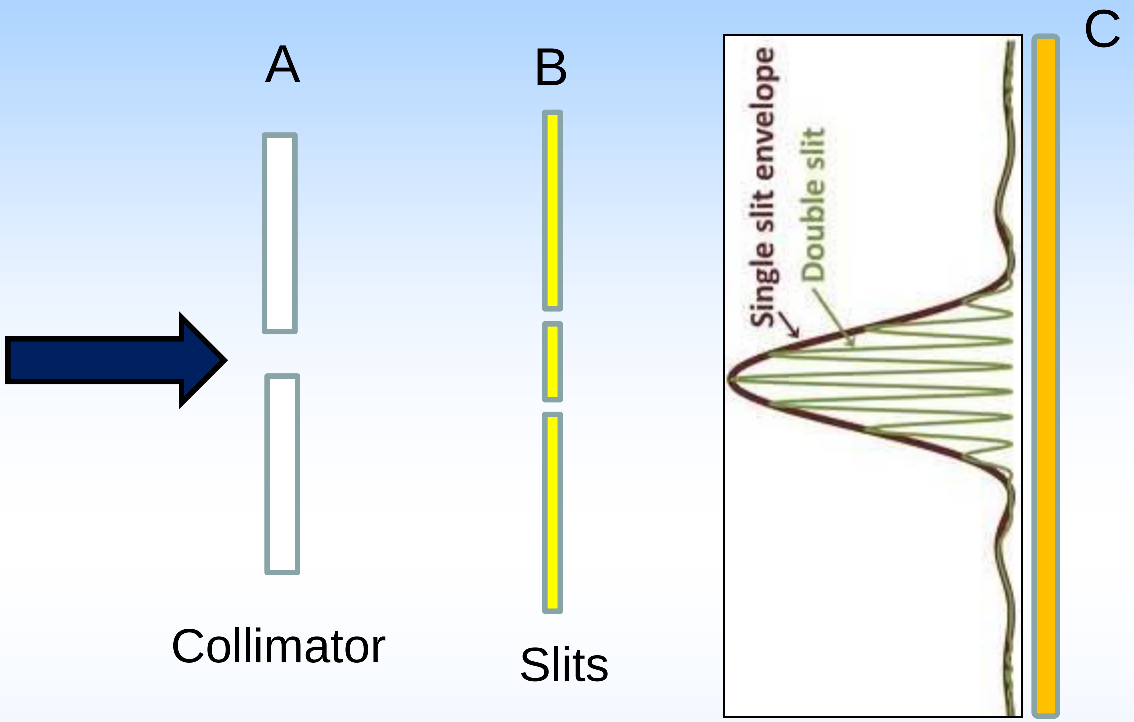
Meaning of parameters : from optical analogy

$$\sigma = a/\left(2\sqrt{2\pi}\right)$$

Calculations are easier

On the choice of the initial single slit wavefunction

Assuming a typical Fraunhofer configuration:
- Radiation beam
- Collimator
- Coherent illumination
- 2 slits
- Detection

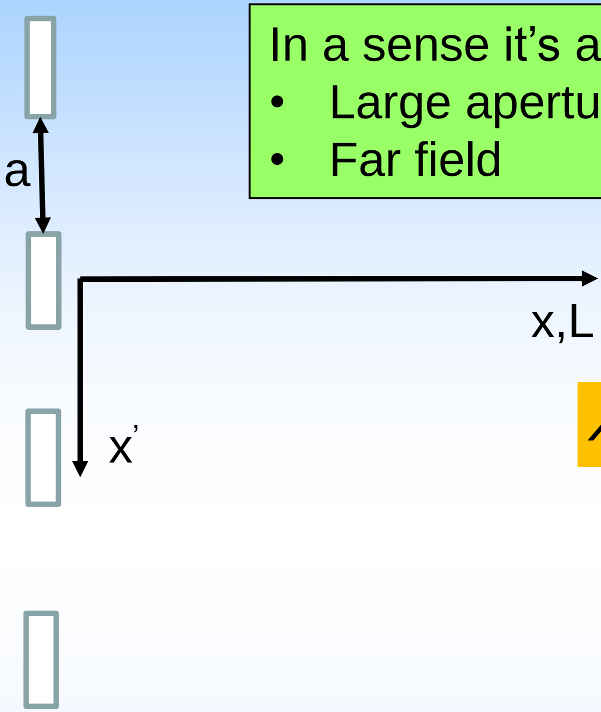


One can demonstrate that – similar to classical optics :

The choice of the single-slit wavefunction impacts only on the envelope of the intensity pattern and not its oscillatory behavior

For more details :
- S. Sala et al., arxiv:1505.01639 [quant-ph]
- S. Sala Master Thesis – University of Milano 2015 – simone.sala@mi.infn.it

Fraunhofer and Talbot regimes



In a sense it's all
- Large aperture $a >> \lambda$
- Far field $x, L >> \lambda$

- Basic quantum model of diffraction
- **Fraunhofer and Talbot regimes**
- Incoherence effects
- Other effects and Decoherence
- Positrons and Positronium experiments

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

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

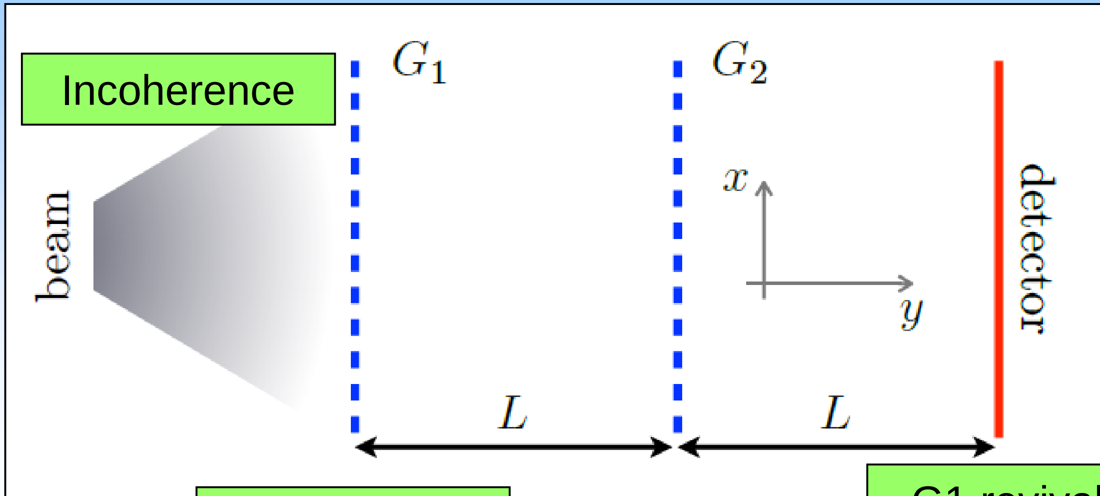
$$\left|\vec{x} - \vec{x}'\right| = \sqrt{\vec{x}'^2 + \vec{x}^2 - 2\vec{x}\vec{x}'} = \left|\vec{x}\right| \sqrt{1 + \frac{\vec{x}'^2}{\vec{x}^2} - 2\frac{\vec{x}\vec{x}'}{\vec{x}^2}}$$

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

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

The Talbot-Lau Effect (and Talbot «carpets»)

Incoherence



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

Talbot length

The Talbot case

Generates coherence

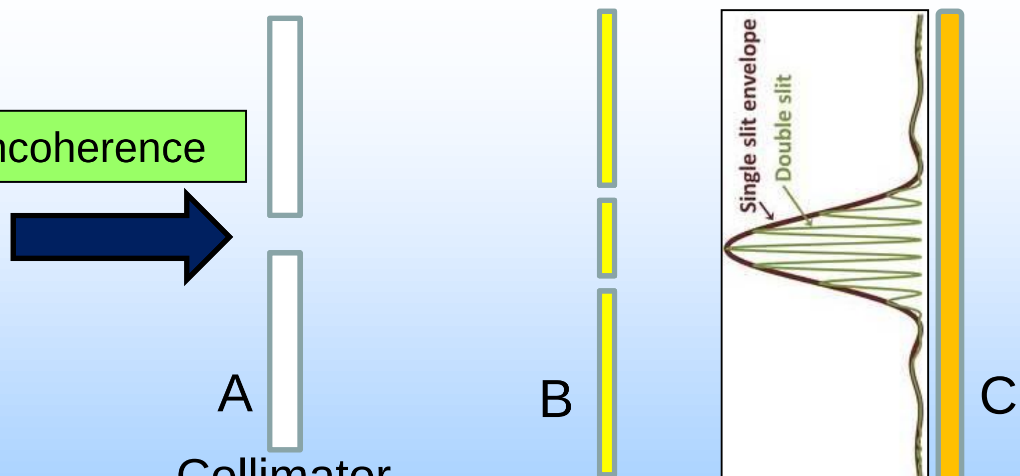
Interference

G1 revival

$L = L_T$

Pattern at C

Incoherence



Collimator

The Fraunhofer case

$L >> L_T$

$(BC >> L_T)$

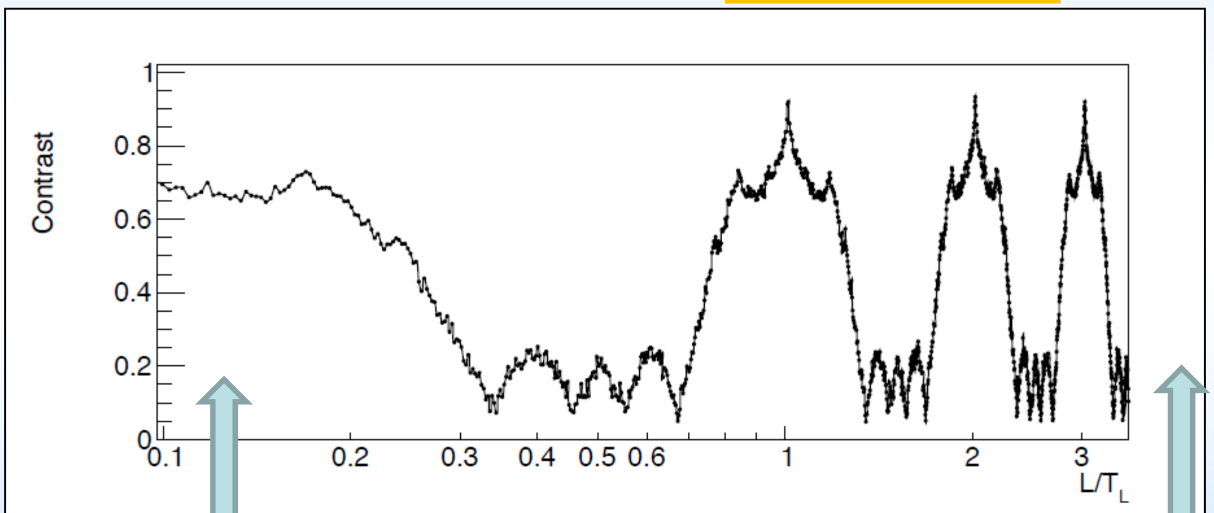
Talbot carpets

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

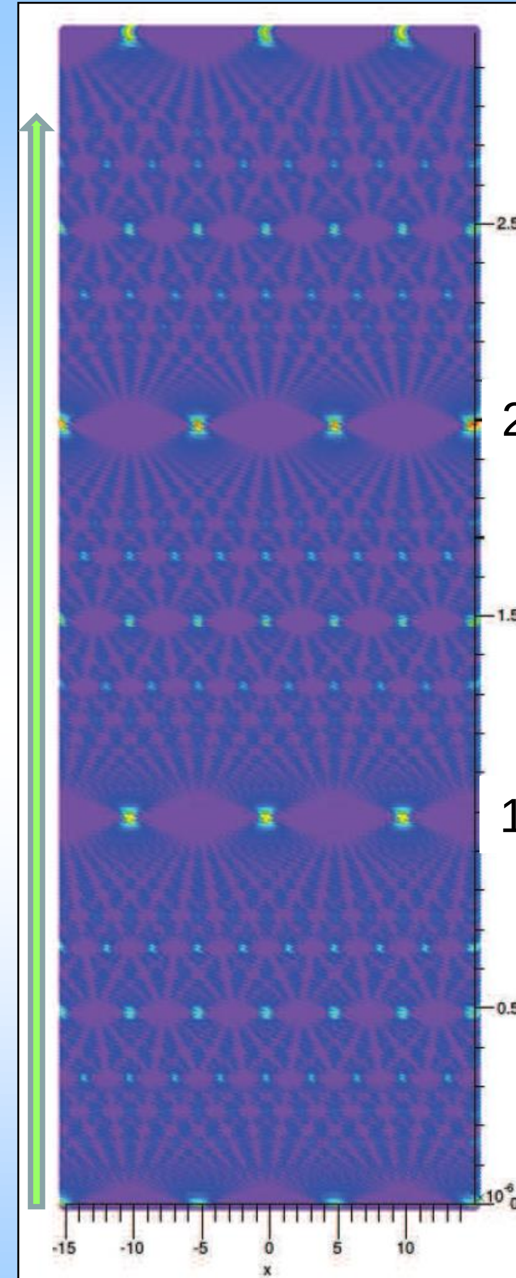
Fringes visibility **for the given wavelength**

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



«Ballistic» moiré regime

Fraunhofer regime setting in when $L>>L_T$



Incoherence effects

We call **Incoherence Effects…**

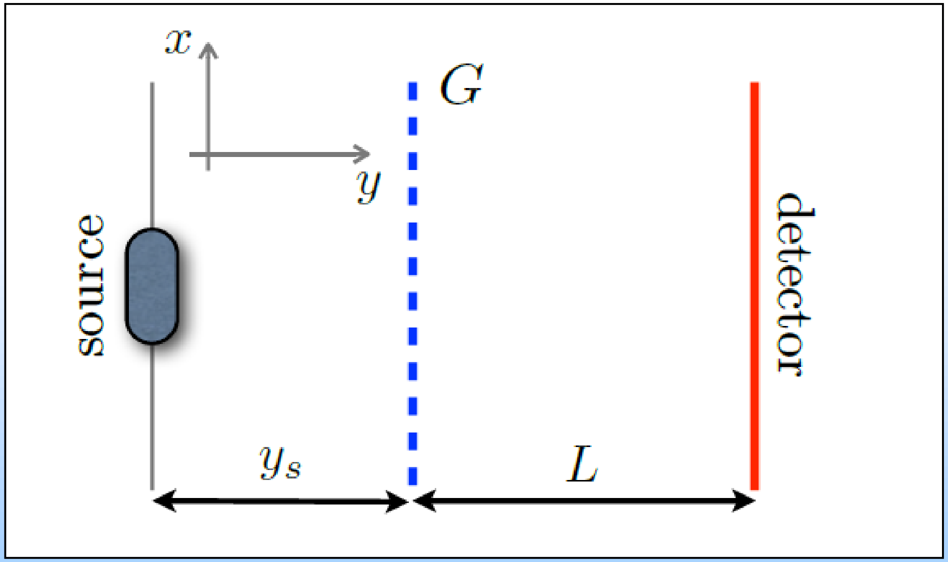
any effect that could be in principle greatly decreased by a better «classical» **Preparation** of the Experiment.

- Basic quantum model of diffraction
- Fraunhofer and Talbot regimes
- **Incoherence effects**
- Other effects and Decoherence
- Positrons and Positronium experiments

Incoherence effects are typically due to the source and can often be divided into: transversal (spatial) and longitudinal (time) coherence

Most common examples:

- Spatial extension of the source (typically transverse)
- Non-monochromaticity of the particle velocity spectrum (typically longitudinal)



Treatment of Incoherence Effects

Physical parameters that can classically fluctuate with a classical distribution. They decrease the visibility

$$\vec{q} = (q_1, q_2, \ldots)$$

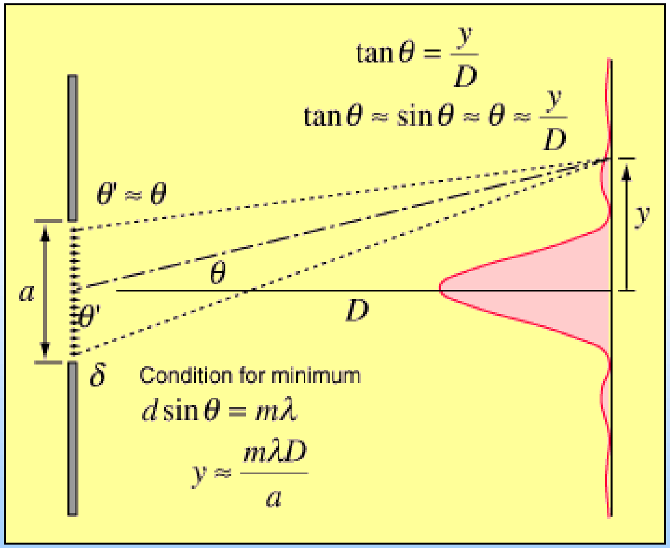
$$p(\vec{q})$$

The effect can be treated by averaging the ideal intensity :

$$I(x,t\,|\,\vec{q}) \rightarrow \bar{I}(x,t\,|\,\vec{q}) = \int I(x,t\,|\,\vec{q})\, p(\vec{q})\, d\vec{q}$$

The effect sets in, for instance, in limiting the number of actual slits taking coherently part to the interference process

A collimator acting on a beam



An area being coherently illuminated

Other effects and Decoherence

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

- Particle Decay in Flight
- The physical effect of the grating slits
- Decoherence

- Basic quantum model of diffraction
- Fraunhofer and Talbot regimes
- Incoherence effects
- **Other effects and Decoherence**
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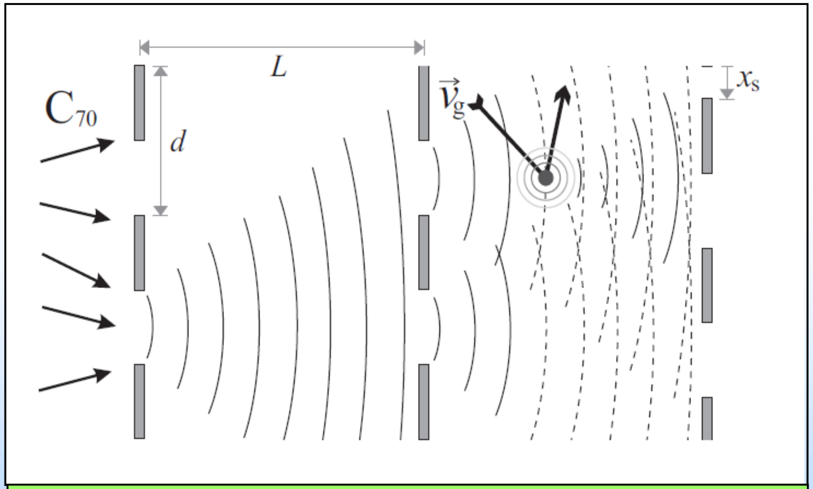
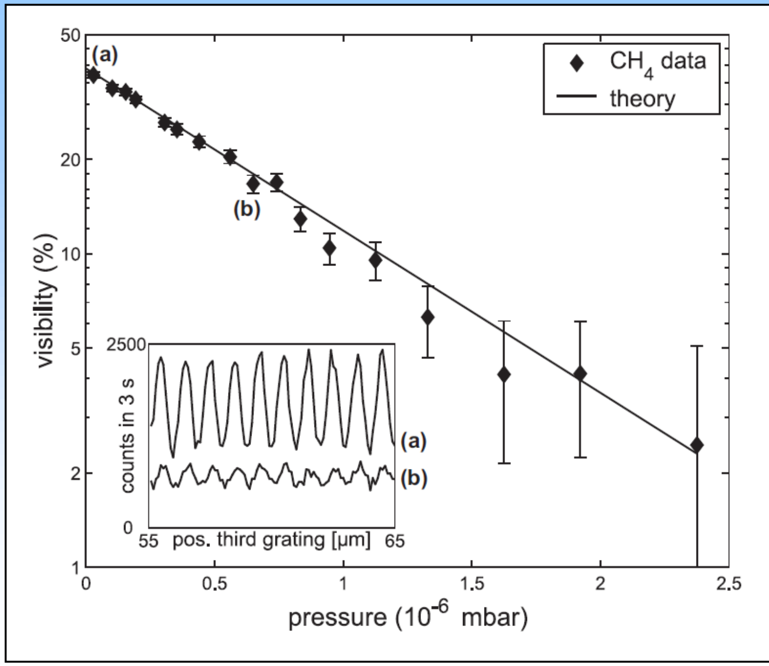
Decoherence : loss of the quantum phases between the components of a system in a quantum mechanical superposition. It leads to classical or probabilistically additive behavior. Decoherence occurs when a system interacts with its environment in an irreversible way.



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



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

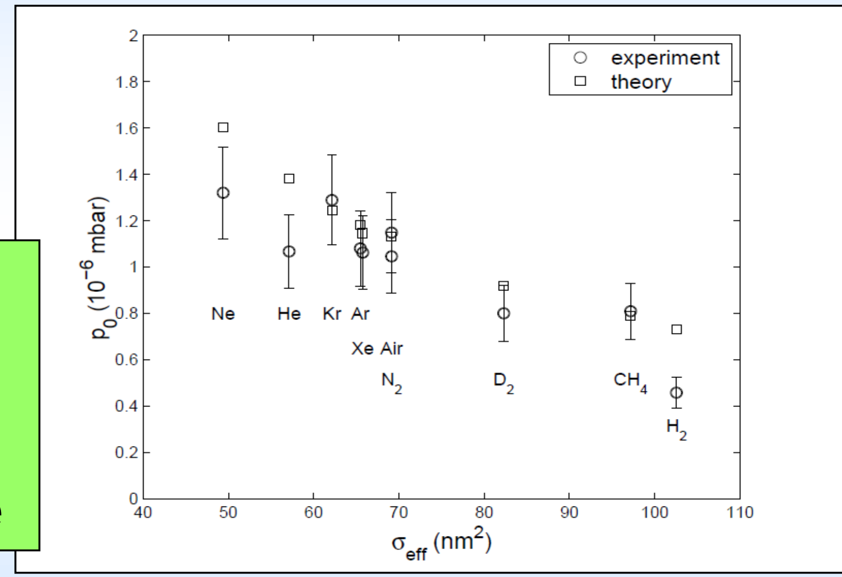
Assumption in the decoherence model :

- 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

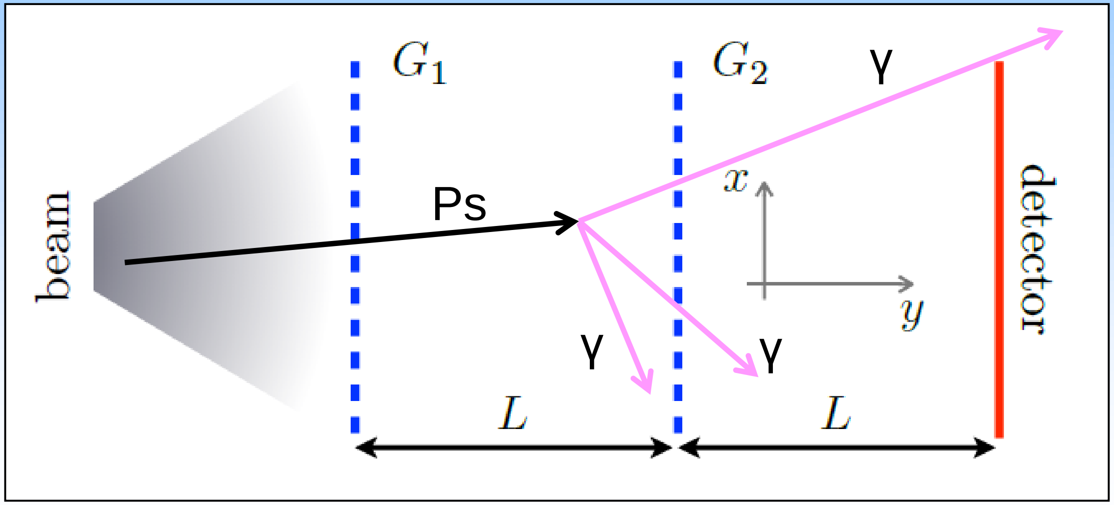
Klaus Hornberger, Stefan Uttenthaler, Björn Brezger, Lucia Hackermüller, Markus Arndt, and Anton Zeilinger*
Universität Wien, Institut für Experimentalphysik, Boltzmanngasse 5, A-1090 Wien, Austria
(Dated: March 14, 2003)

Particle Decay

Positronium states that are useful : ortho-Ps

Decay probability in flight :

$$P(x) \approx \exp\left(-v\tau / x\right)$$



$$o - Ps \rightarrow \gamma\gamma\gamma$$

The 3-gamma decay of ortho-Ps actually removes the particles from the beam

It does not «blur» the interference pattern in general

So, it is a kind of «attenuation factor» related to a loss of unitarity

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:

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

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

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

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

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

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

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

Interaction with the slits

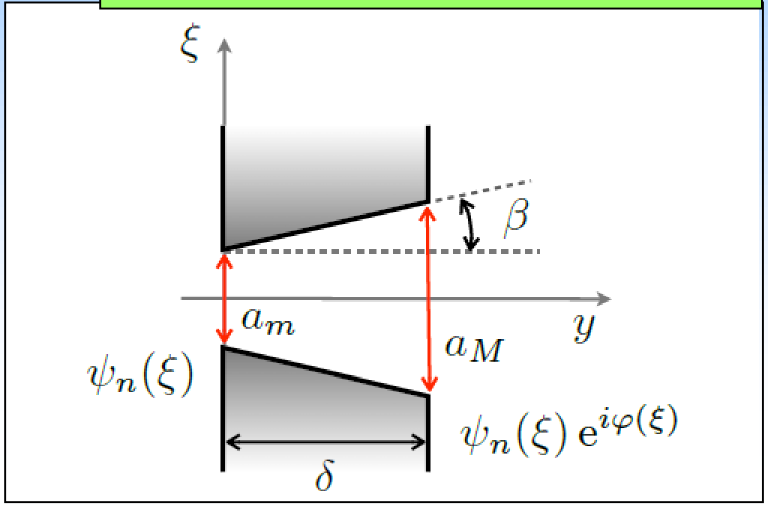
The ideal grating is a perfect 0-1 intensity mask. With no phase effects.

Real gratings have phase effects, instead.

$$\psi_n(\xi,0) \rightarrow \psi_n(\xi,0)\exp[i\,\varphi(\xi)]$$

$$\varphi(\xi) = -\frac{1}{\hbar v}\int V(\xi,y)\,dy$$

Beam particle crossing a slit



If the interaction is sufficiently weak, it can be treated by a rescaling of the slit opening a → a_{eff}

Starting from the nominal thickness of 500 nm Correction for positrons and antiprotons :

Energy [keV]	a_{eff} e^+ [nm]	a_{eff} $\overline{p}$ [nm]
0.1	401.3	148.1
1	477.2	285.8
10	497.1	397.4
100	499.7	460.0

S. Sala et al., arxiv:1505.01639 [quant-ph]

Positrons and Positronium experiments

Why experiments with positrons and Ps ?

A new type of interferometry

- Positron is a fundamental lepton
- It is the antiparticle of the electron
- Ps is the most fundamental atom

e+,e-,Ps interferometry and gravity

- Basic quantum model of diffraction
- Fraunhofer and Talbot regimes
- Incoherence effects
- Other effects and Decoherence
- **Positrons and Positronium experiments**

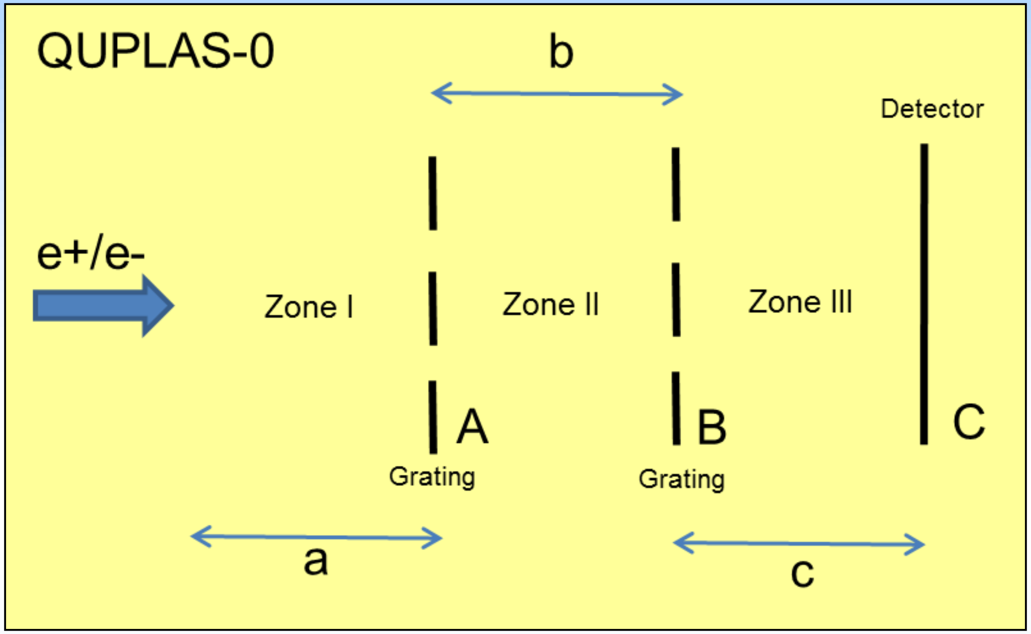
The QUPLAS program

- QUPLAS-0) Positron Interferometry
- QUPLAS-I) Positronium Interferometry
- QUPLAS-II) Ps gravity

Will describe mostly QUPLAS-0 here

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 :

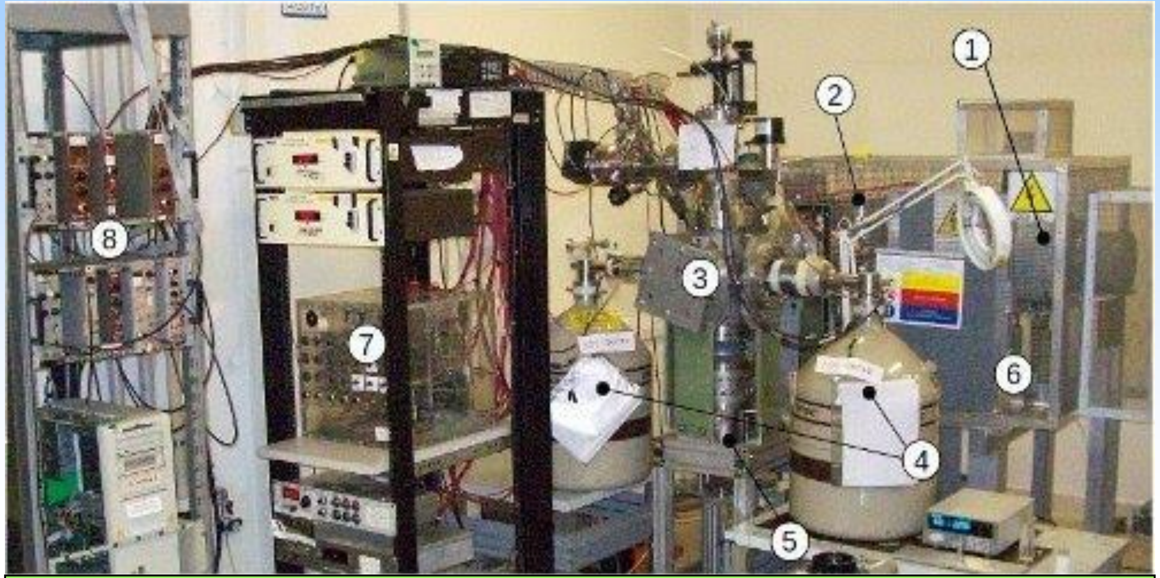
Nuclear Emulsions (~µm resolution)

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

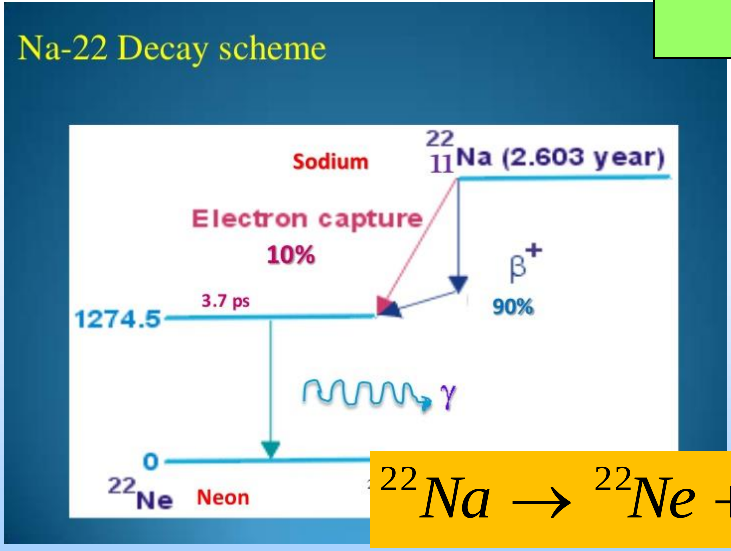
The facility: the Como continuous positron beam

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

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.



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



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

Original intensity of the source: 50 mCi
Current intensity: ~ 13 mCi

Tungsten moderator → reduces the energy from the beta spectrum down to a few eV
Electrostatic transport → positron beam

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

Reference value: 10 keV

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

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

The de Broglie wavelength

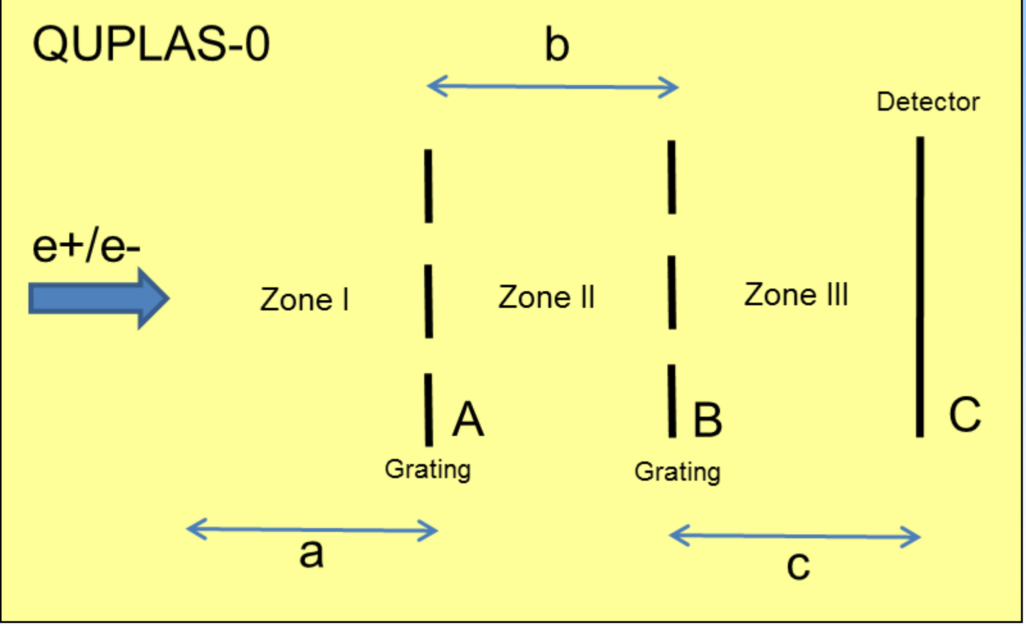
$$\lambda = \frac{h}{mv} = 1.2 \times 10^{-11} \quad m$$

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 - I

Positronium Quantum Interferometry concept

Why?

- 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

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

- Positronium has a very short lifetime

Excitation on Rydberg state is necessary. Laser excitation required.

QUPLAS - II

Positronium Gravity : why?

Answer : to test the Weak Equivalence Principle (test of General Relativity)

Universality of Free Fall

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

?

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