Antimatter-wave interferometry in QUPLAS

Simone Sala

1° year PhD workshop – 20/10/2016

UNIVERSITÀ DEGLI STUDI DI MILANO

QUPLAS: QUantum interferometry and gravitation with Positrons and LASers

An experimental project involving people from several institutions:

Istituto Nazionale di Fisica Nucleare

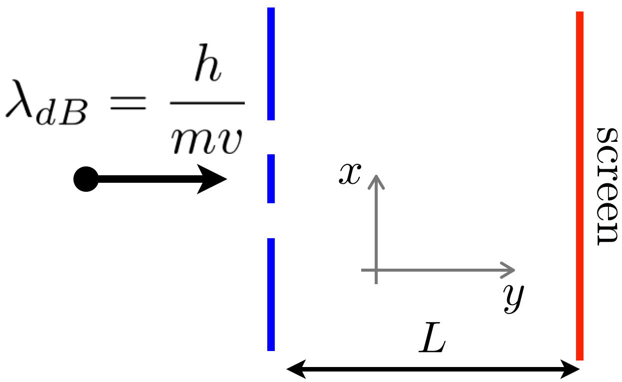
POLITECNICO MILANO 1863

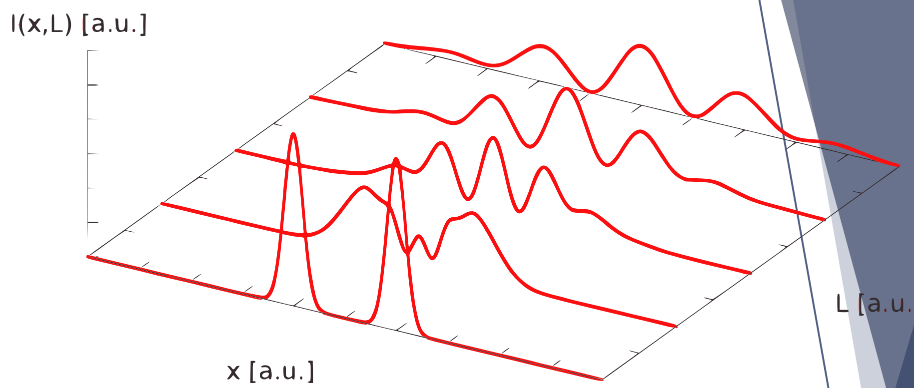
UNIVERSITÄT BERN

Consiglio Nazionale delle Ricerche

UNIVERSITÀ DEGLI STUDI DI MILANO

Our tool: matter-wave interference





The simplest experiment: Young double-slit

A.Tonomura et al. ,
Am. J. Phys., 57 (1989)

Analogy to classical optics at the de Broglie wavelength

$$\lambda_{dB} = \frac{h}{mv}$$

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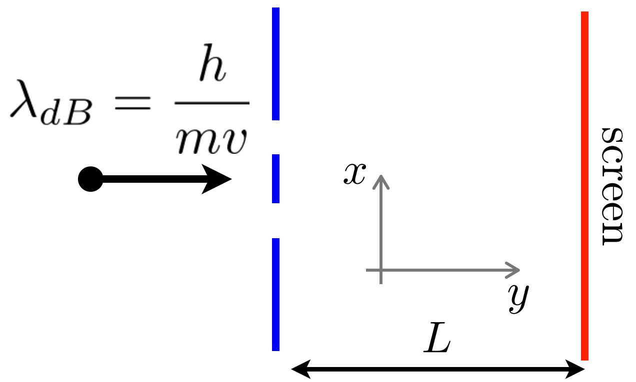

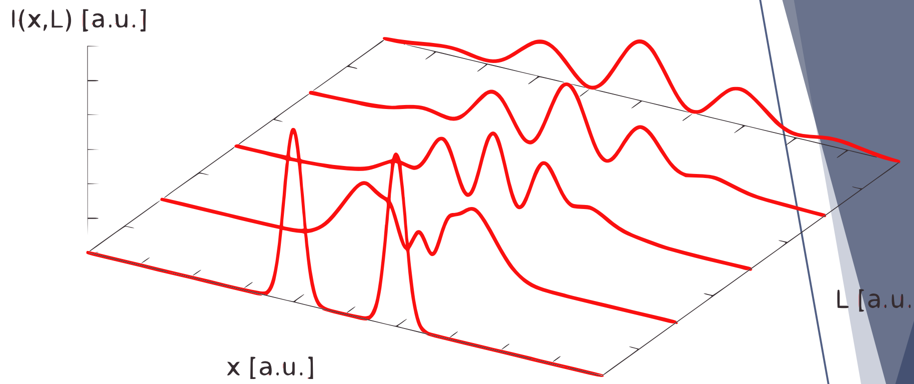

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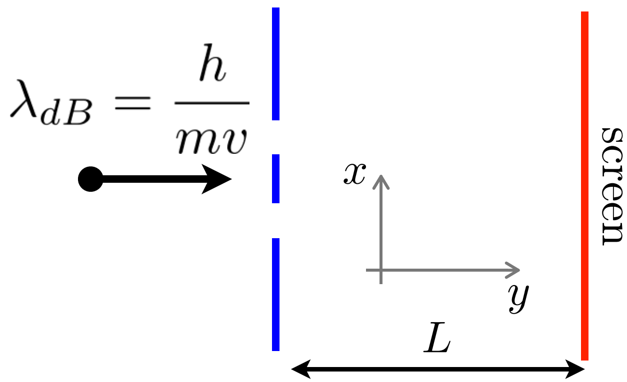

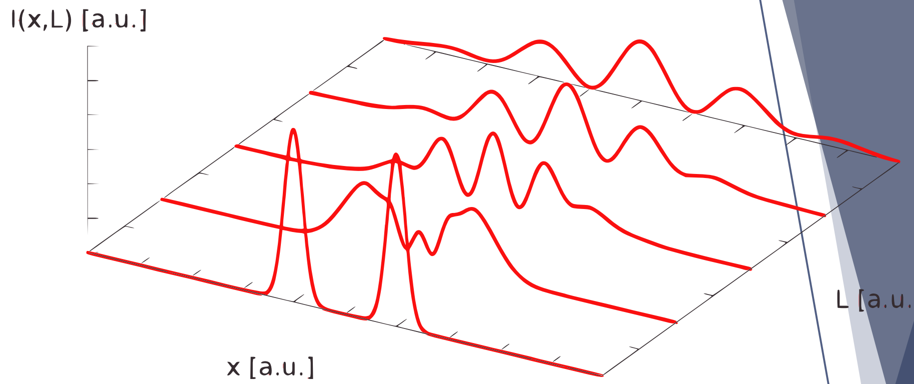

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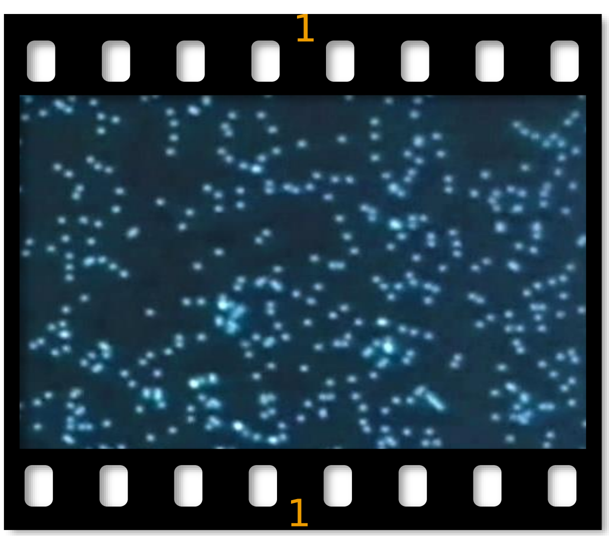

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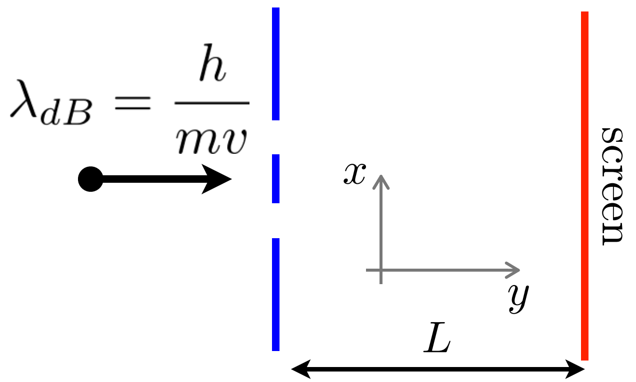

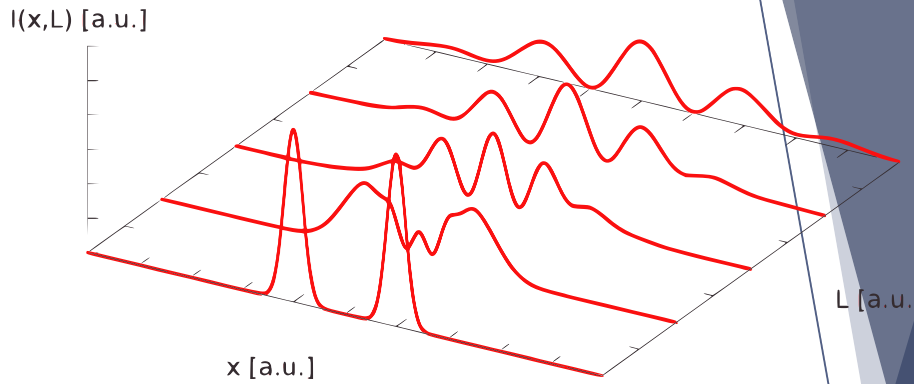

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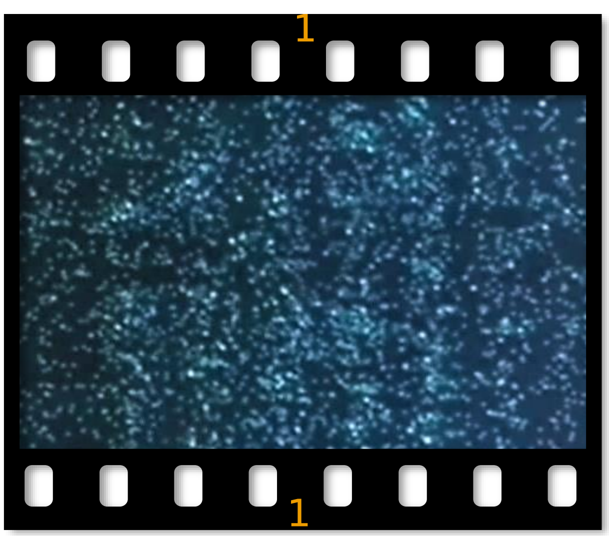

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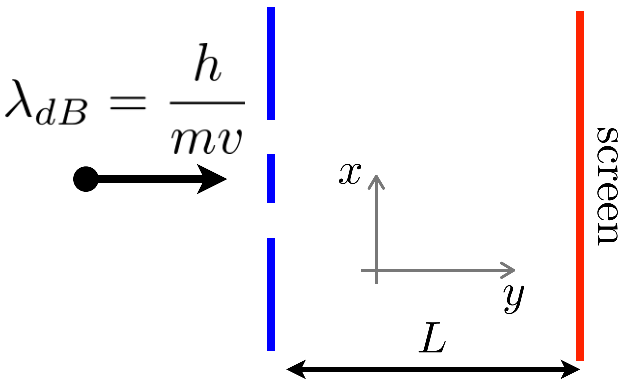

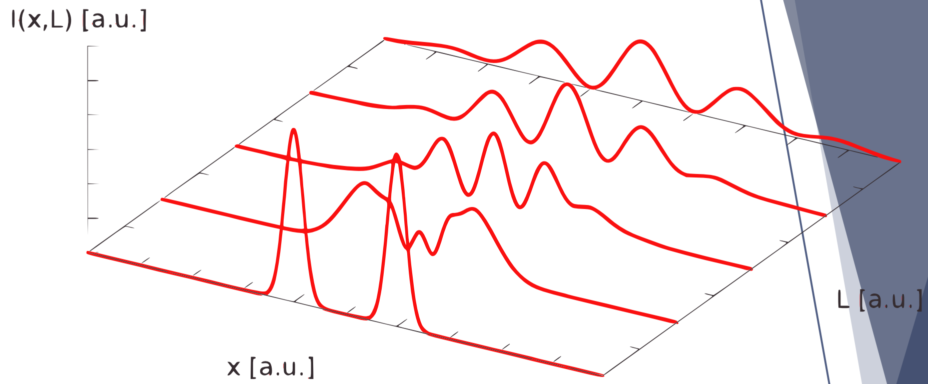

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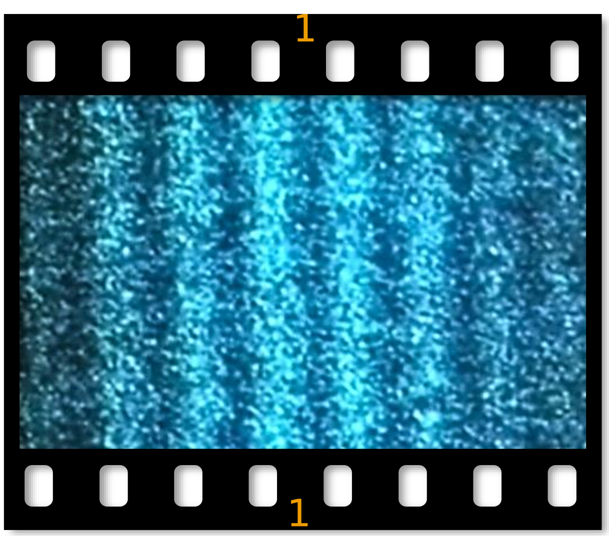

Analogy to classical optics at the de Broglie wavelength

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Just like classical optics ?

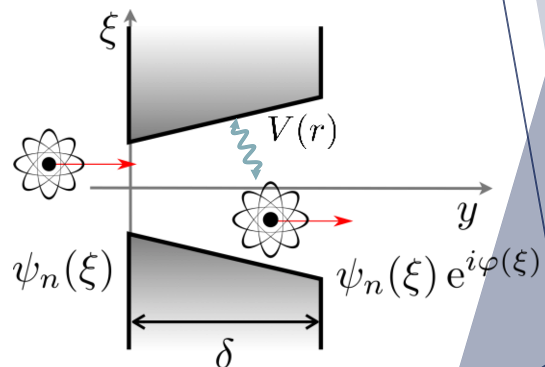
- Helmholtz equation:

$$\nabla^2 u(\mathbf{x}) + k^2 n^2(\mathbf{x}) u(\mathbf{x}) = 0 \leftrightsquigarrow \boxed{\text{Classical optics}}$$

- Schrödinger equation:

$$\nabla^2 \psi(\mathbf{x}) + k_{dB}^2 \underbrace{[1 - V(\mathbf{x})/E]}_{n^2(\mathbf{x})} \psi(\mathbf{x}) = 0 \leftrightsquigarrow \boxed{\text{Matter wave optics !}}$$

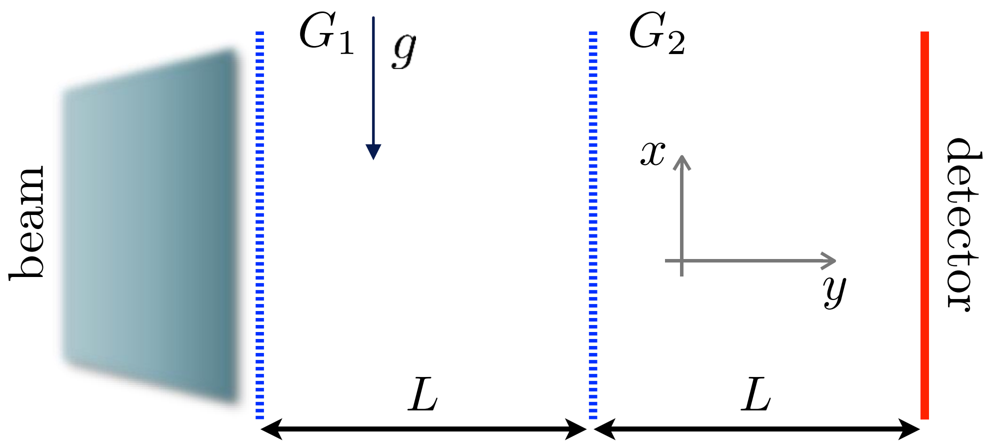
- $V(r) = -\dfrac{C_3}{r^3}$ van der Waals atom-surface
- $V(r) \propto \dfrac{1}{r^2}$ Image-charge



"Refractive index" contains the interactions with the environment

Experimental access to atomic properties, C_3, α, etc. with a very accurate instrument.

Beyond double slits: Talbot-Lau near-field interferometer



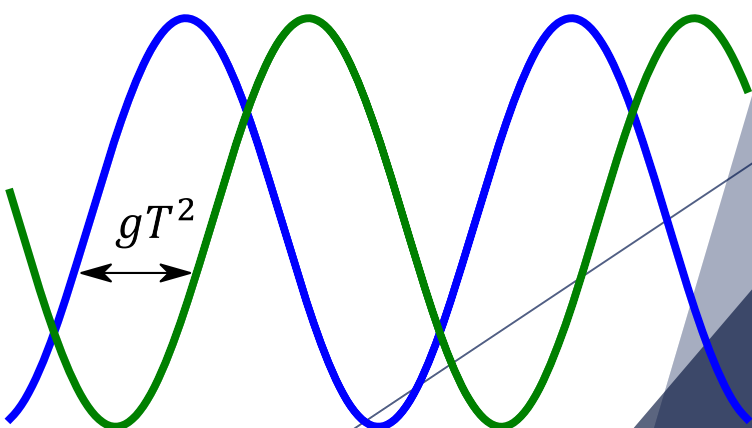
$$L = L_T = \frac{d^2}{\lambda_{dB}}$$

$$T = \frac{L}{v}$$

Short, works with uncollimated beams, high flux, and…

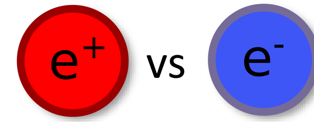
Gravity induces a fringe shift
$\Delta x = gT^2$

A good gravimeter !

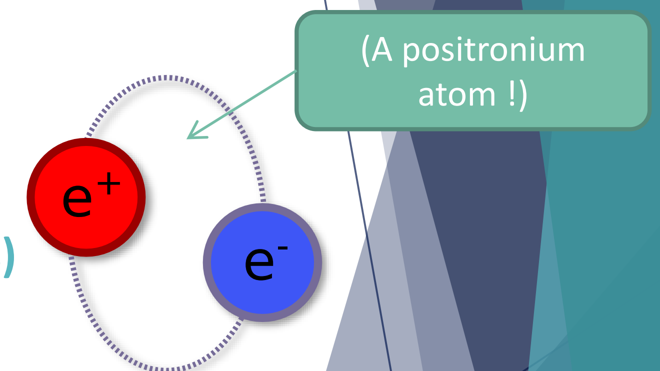


QUPLAS: studying antimatter using quantum interference

- **QUPLAS-0**: Talbot-Lau interference of **positrons (e^+)**



  - Comparison with electrons (e^-)
  - A new "CPT test": $\lambda_{dB} \stackrel{?}{=} \overline{\lambda}_{dB}$



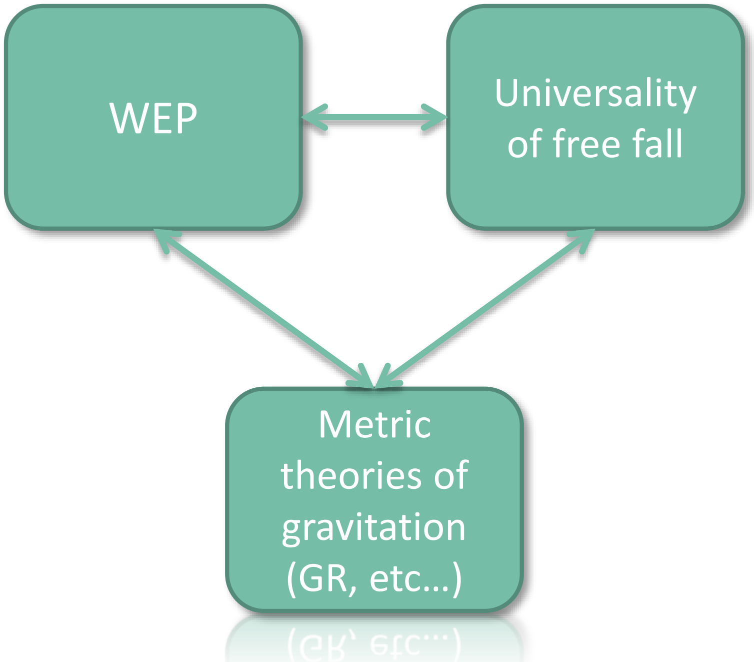
- **QUPLAS-I**: Talbot-Lau interference of **positronium (Ps)**
  - Measurement of atomic properties
  - Tests of decoherence

$$\tau = 142\,\mathrm{ns}$$

- **QUPLAS-II**: **Measure the gravitational acceleration of Ps.**

Testing the Weak Equivalence Principle (WEP)

WEP tests on antimatter: motivation



Annual Review of Cold Atoms and Molecules, **2013, pp. 473-515*

Experimental tests*	Accuracy
Be-Ti test masses	10^{-13}
Moon-Earth	10^{-13}
Cs atoms	10^{-9}
^{85}Rb, ^{87}Rb atoms	10^{-7}
Antihydrogen (CERN ?)	10^{-2}
Positronium (QUPLAS ?)	10^{-2}

Positronium measurement complementary to antihydrogen

- **Matter-antimatter symmetric**
- **Binding energy is purely electromagnetic**

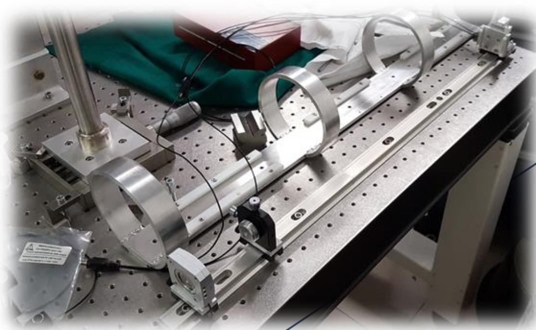
QUPLAS status: preparing for Q-0

Home of the experiment: L-NESS lab (Politecnico di Milano) in Como

Positron beam:

- ^{22}Na source
- Continuous mode
- Tungsten moderated
- Electostatically guided
- 0-20 keV energy
- 1% energy spread
- Flux : 8 x 10 ^{3} e^+/s

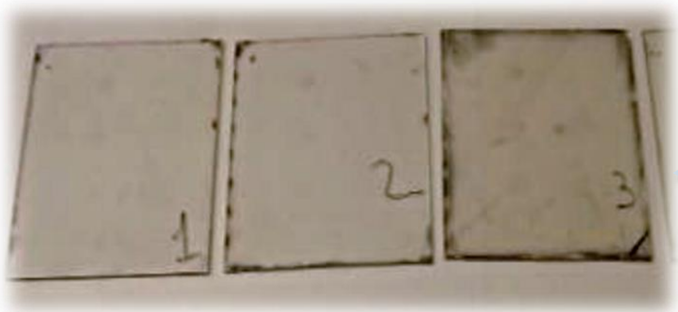
Interferometer housing and mu-metal shield



Nuclear emulsion technology

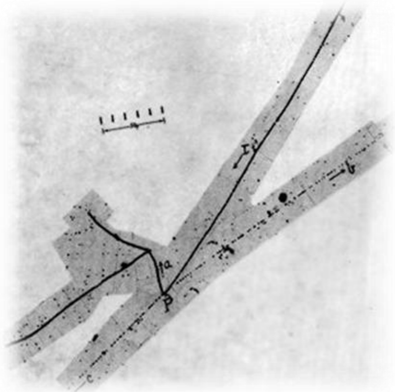
…an old technology, still valuable to this day (OPERA, T2K, AEGIS,…)

Working principle is the same as photographic film



Emulsion plates used for early QUPLAS testing

- Gel enriched with AgBr crystals
- Poured on glass substrate for improved stability

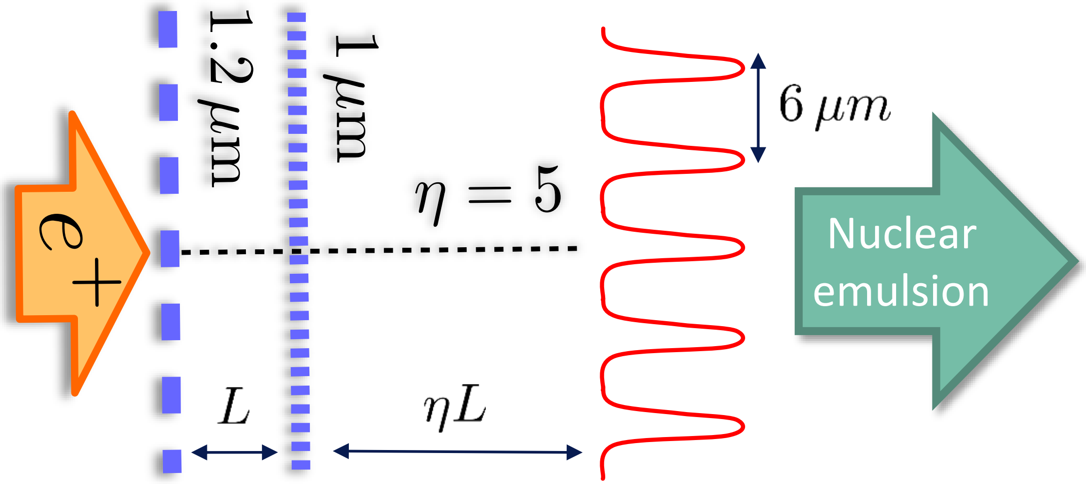


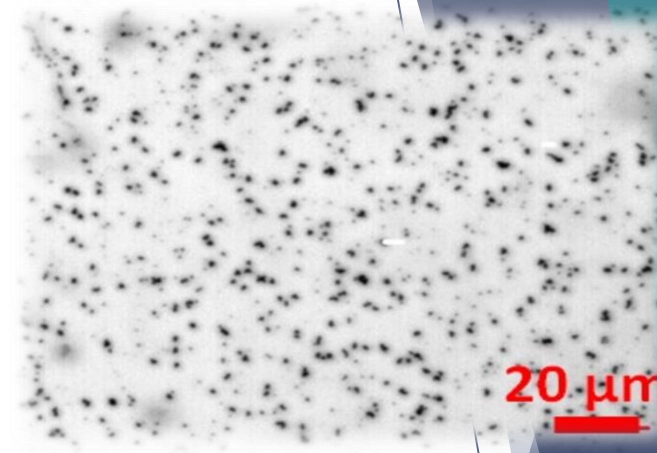
Pion discovery, C. Powell 1950

Automated emulsion scanning facility in Bern

- Automated scanning
- Advanced track reconstruction algorithms

The QUPLAS-0 interferometer





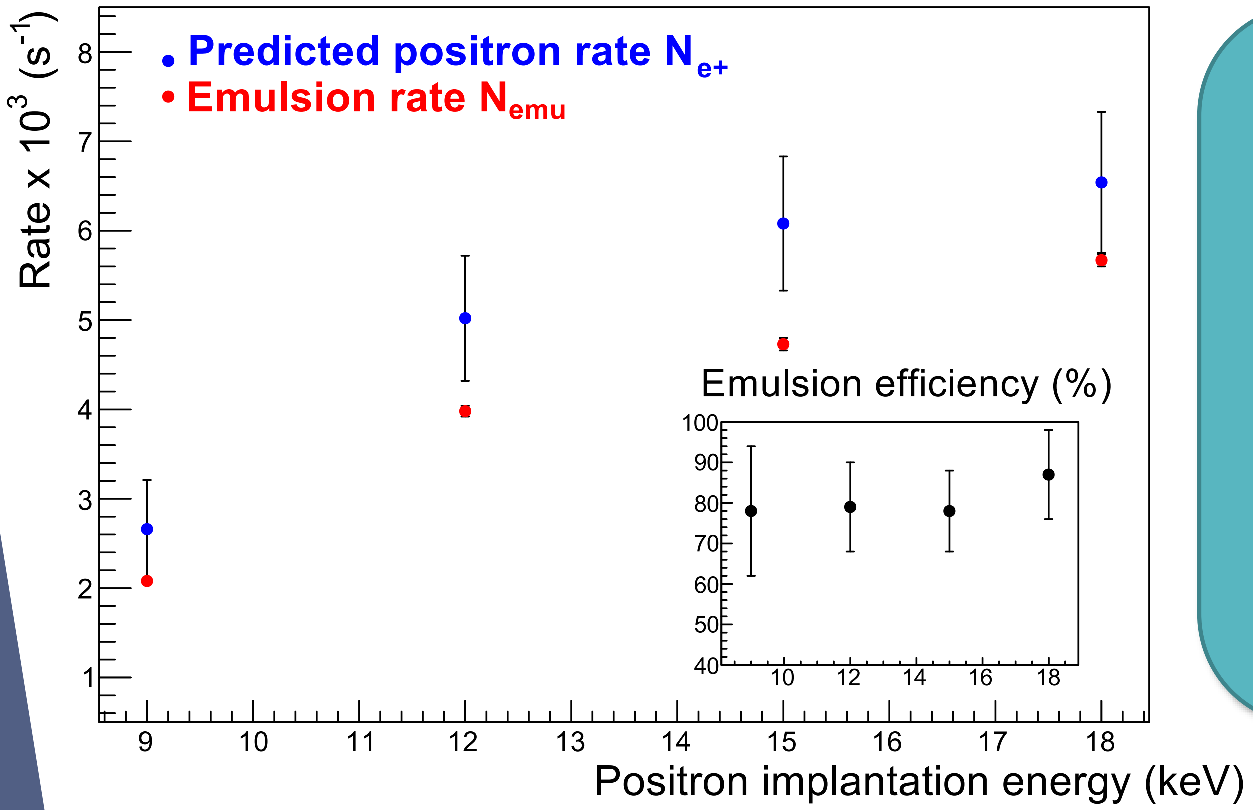
«Asymmetric» Talbot- Lau setup will provide fringe period magnification [1,2]

We see individual positrons [3] !
(Recall the Tonomura experiment…)

[1] S. Sala et al., *Phys. Rev. A*, 94 (2016), p. 033625
[2] S. Sala et al., *J. Phys. B: At. Mol. Opt. Phys.*, 48 (2015)
[3] S. Aghion et al., *J. Instrum.* , 11 (2016), p. P06017

Testing emulsions for e^+ detection

Preliminary experimental test at L-NESS, detector characterization [1]

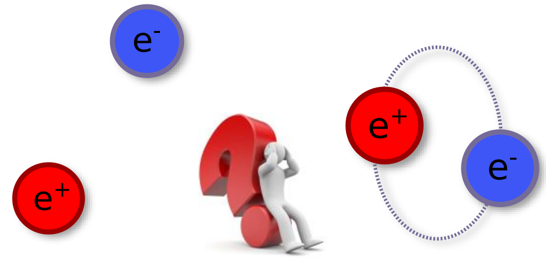


Emulsion detector:

- High efficiency (80%) [1]
- High resolution (1 μm)
- Low background noise
- Insensitive to gamma
- Automated scanning
- 10-20 keV energy
- Large area

[1] S. Aghion et al., *J. Instrum.* , 11 (2016), p. P06017

Summary



- QUPLAS intends to study antimatter (e^+ / Ps)
- Using quantum interference via mechanical gratings
- And direct high-resolution detection with nuclear emulsions
- Aims to improve positronium manipulation techniques
- **Hopefully leading to a WEP test on positronium**

Thank you for your attention !

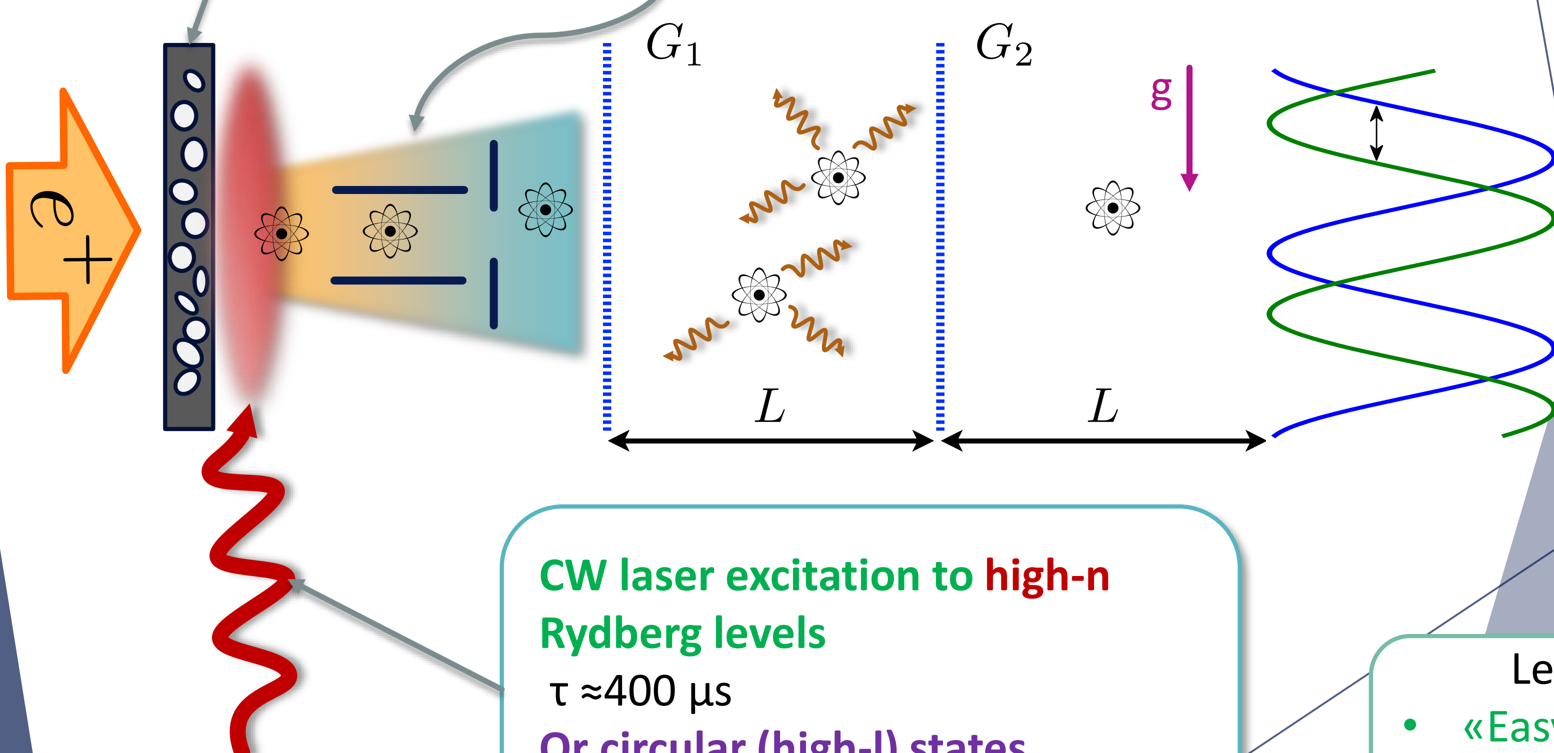
How to measure the fall of Ps ?

e+ → Fast Ry Ps (10^5 m/s) → Slow Ry Ps (10^3 m/s) → T.-L. setup (1m long)

µm level fringe shift

Thin mesoporous silica converter

Stark decelerator



CW laser excitation to high-n Rydberg levels

τ ≈400 µs

Or circular (high-l) states

τ ≈1000 µs

Legend:

- «Easy»
- Difficult
- Very difficult

How accurate do we need to be ?

- No current theory is able to <u>quantitatively</u> predict violations of the WEP in a given system
- What you can do is parametrize the violation and constrain the parameters experimentally

A minimal WEP violating Lagrangian for a composite system reads*:

$$\mathcal{L} = -m_0c^2 + \frac{1}{2}m_0v^2 + (m_0 + \boxed{\delta m_p})U(x)$$

Gravitational potential

Result of anomalous coupling between the composite object and the source of U.

C. Will – Theory and experiment in gravitational physics,* **1993