Can we measure the gravitational quantum states of Positronium?

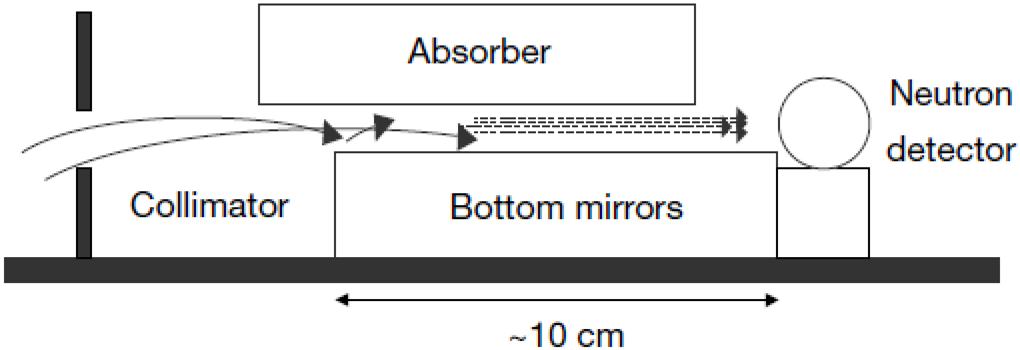
Paolo Crivelli

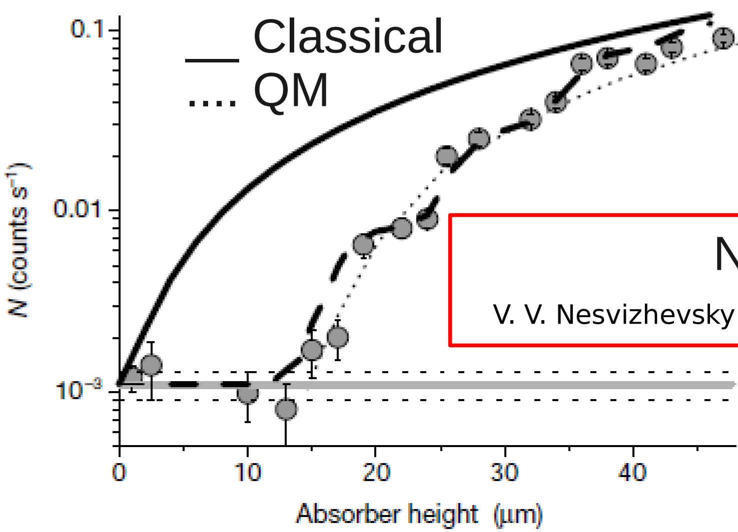
Institute for Particle Physics, ETH Zurich

GRANIT Workhop, Les Houches, 5th of February 2014

My work is supported by the Swiss National Science Foundation (Ambizione grant) and the ETH research grant ETH-47-12-1

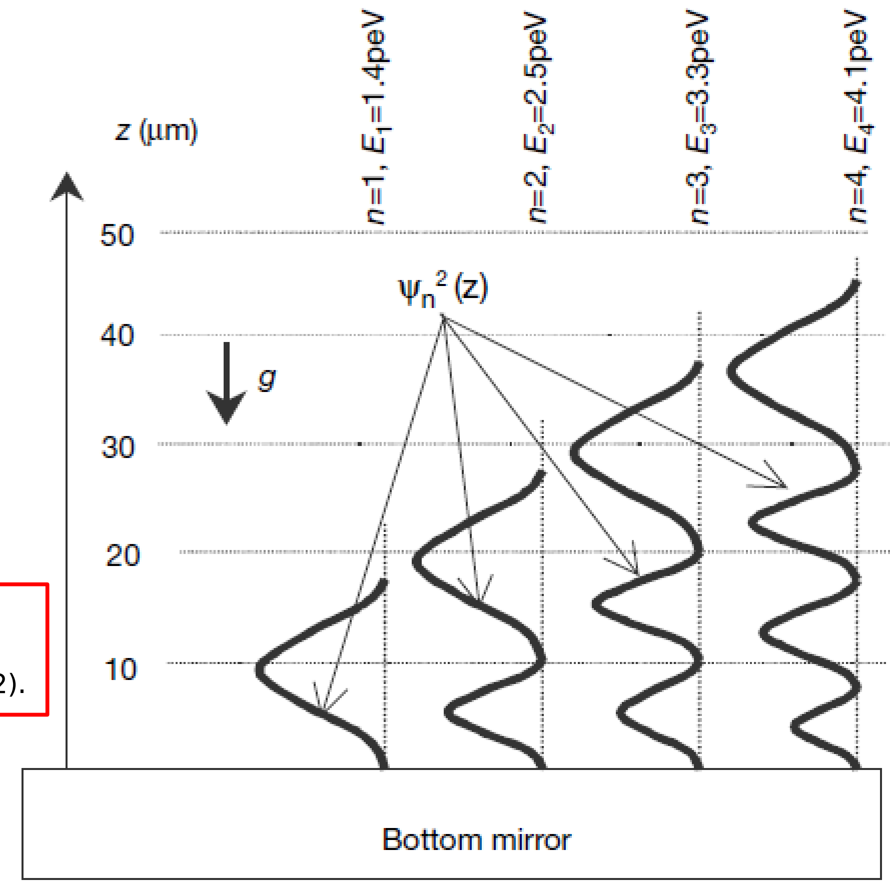
Gravitational QM states





Neutrons

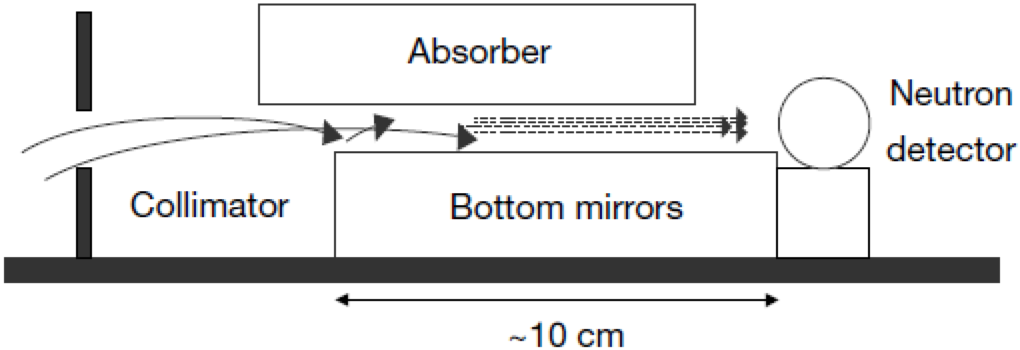
V. V. Nesvizhevsky et al., Nature 415, 297 (2002).

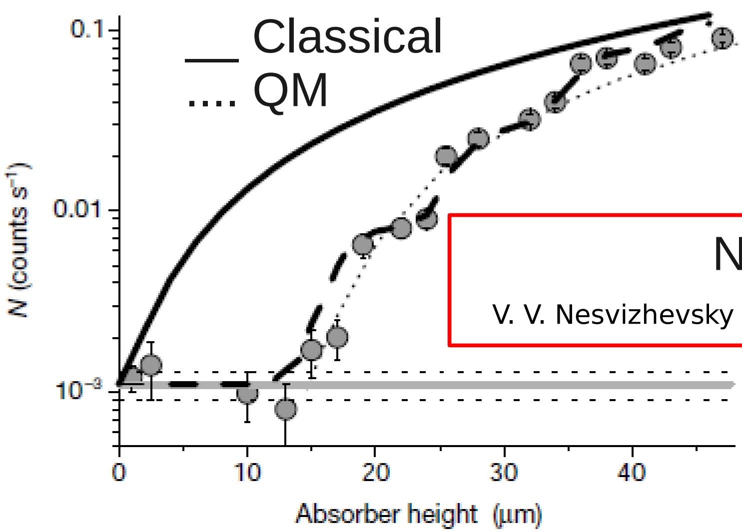


$$E_n \cong \sqrt[3]{\left(\frac{9 \cdot m}{8}\right) \cdot \left(\pi \cdot \hbar \cdot g \cdot \left(n - \frac{1}{4}\right)\right)^2}$$

$$z_0 = \sqrt[3]{\frac{\hbar^2}{2 \cdot m^2 \cdot g}}$$

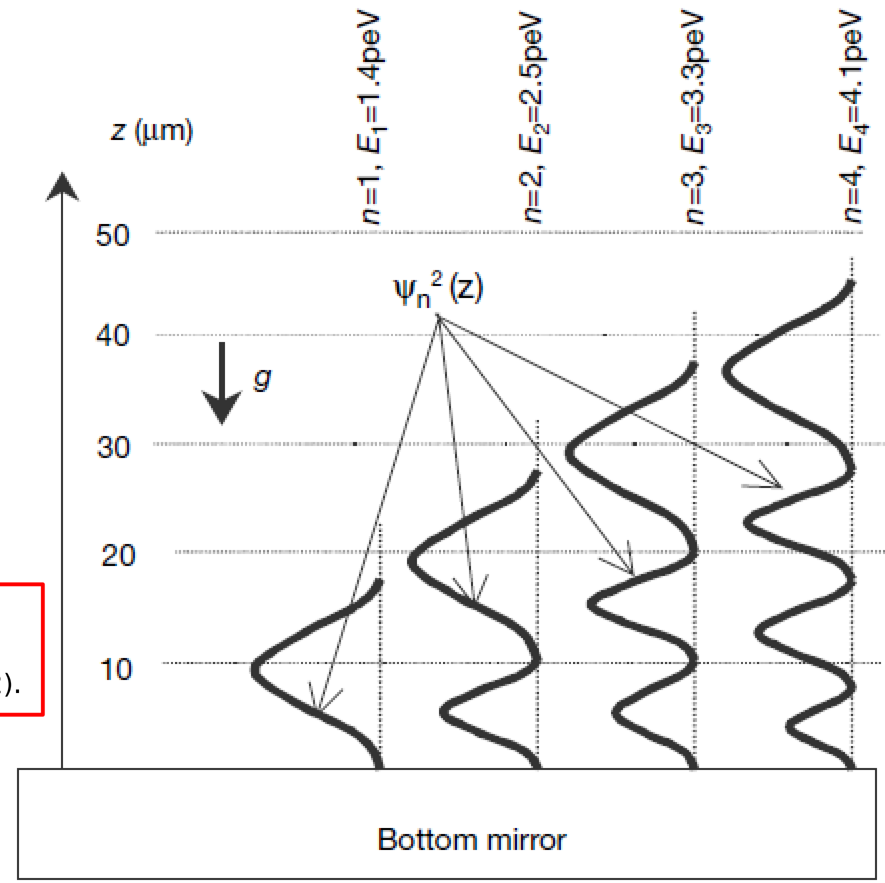
Gravitational QM states





Neutrons

V. V. Nesvizhevsky et al., Nature 415, 297 (2002).



$$E_n \cong \sqrt[3]{\left(\frac{9 \cdot m}{8}\right) \cdot \left(\pi \cdot \hbar \cdot g \cdot \left(n - \frac{1}{4}\right)\right)^2}$$

$$z_0 = \sqrt[3]{\frac{\hbar^2}{2 \cdot m^2 \cdot g}}$$

Positronium: z_1= 1.2 mm, E_1= 0.13 peV

Requirements for observation with Ps

To observe QM behavior:

1) Ps vertical velocity so that $Ekin_y \sim E_1 \sim 0.1$ peV

Requirements for observation with Ps

To observe QM behavior:

1) Ps vertical velocity so that $Ekin_y \sim E_1 \sim 0.1$ peV

2) Interaction time $\Delta t > h/\Delta E = 4.5$ ms

Requirements for observation with Ps

To observe QM behavior:

1) Ps vertical velocity so that $Ekin_y$~E_1 ~ 0.1 peV

Is it possible to get a some Ps with vertical velocities vy< 0.15 m/s and horizontal velocities vx,z<50 m/s (to keep the size of the apparatus to 0.5 m in 10 ms)?

2) Interaction time $\Delta t > h/\Delta E$ =4.5 ms

Requirements for observation with Ps

To observe QM behavior:

1) Ps vertical velocity so that $Ekin_y \sim E_1 \sim 0.1$ peV

Is it possible to get a some Ps with vertical velocities vy< 0.15 m/s and horizontal velocities vx,z<50 m/s (to keep the size of the apparatus to 0.5 m in 10 ms)?

2) Interaction time $\Delta t > h/\Delta E = 4.5$ ms

Ps (triplet) lifetime in ground state 142 ns
-> excitation to a Rydberg state n=33 and l = 32 mean time to emit the first photon will be about 10 ms.
(Mills & Leventhal, NIMB 192 (2002) 102–106)

Positron source

LINAC,
10MeV, $10^{15}e^-/s$

Target
$\gamma \to e^+e^-$

Moderator
MeV->eV e^+'s

See P. Debu's talk tomorrow

2.8×10^8 positrons/s (target value of GBar experiment)

See previous talk of D. Cassidy

Oshima et, al.Journal of Applied Physics 103 , 094916 (2008)

Trap (20%)
eV->meV e^+'s

Bunches 1.4×10^7
~4Hz Rep. Rate,
1mm in 0.1T field

Remoderation Ni(100)
and extraction
from B- field ($\varepsilon \sim 10\%$)

C. M. Surko and R. G. Greaves, Phys. Plasmas 11, 2333 (2004)

5.6×10^6 positrons/s, 50 microns

meV -> keV to form positronium into vacuum

Positron implantation

By varying the positron implantation energy one can tune the mean implantation depth in a given material.

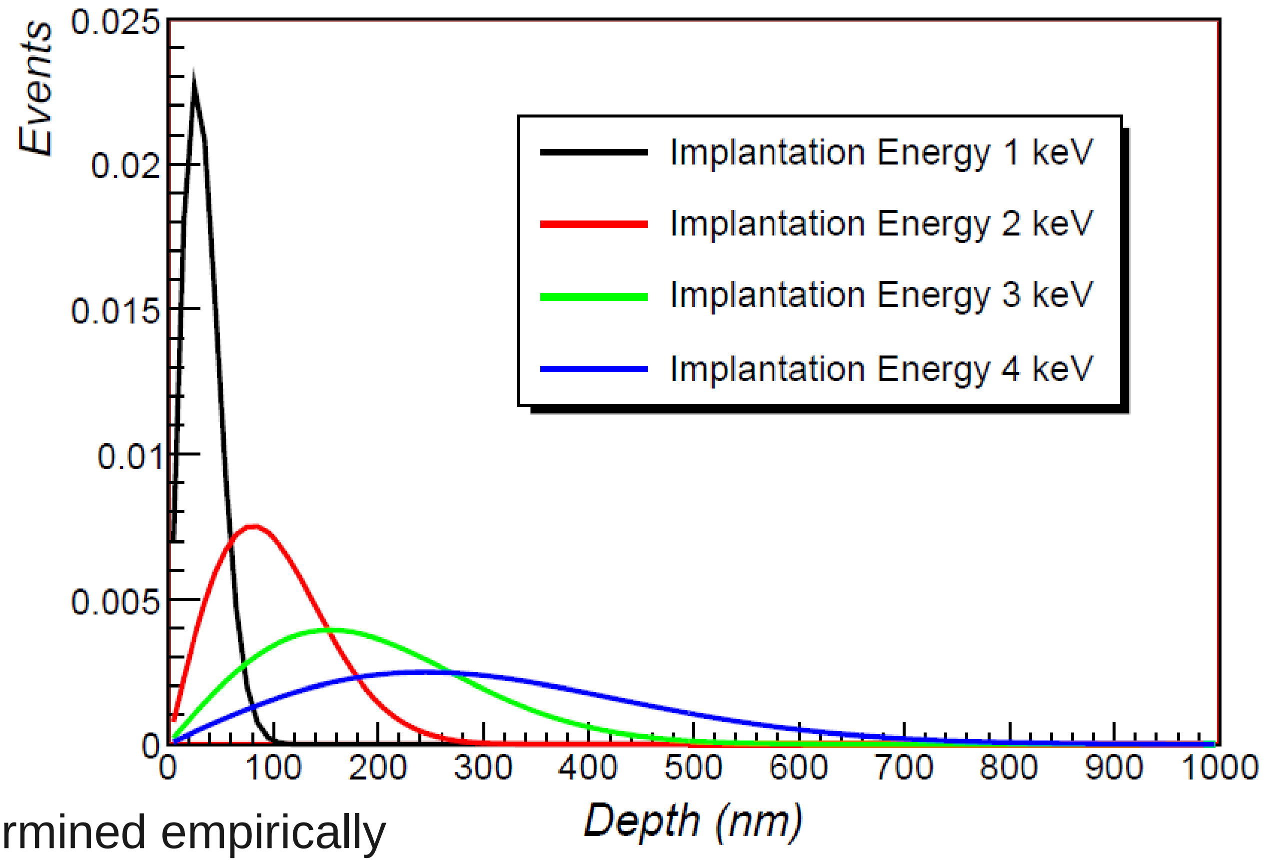
Makhovian profile

$$P(x,E) = \frac{m x^{m-1}}{x_0^m} e^{-(x/x_0)^m},$$

$$x_0 = \frac{x_m}{\Gamma((1/m)+1)},$$

$$x_m = \frac{40}{\rho} E^{1.6},$$

Dependent on the material, determined empirically



Positronium production

Very good conversion of about 30 % can be achieved with different methods.

1) Thermal desorption from Al(111) kept at 600K -> 30%
   Lower temperature reported with oxygen monolayer at the surface
   but very unstable.

A. P. Mills, Jr, Phys. Rev. Lett. 41, 1828 (1978);
K. G. Lynn, Phys. Rev. Lett. 43, 391 (1979);

2) Nano-channeled silicon (5-8 nm) -> 7% at 150 K

Brusa et al., PRL 104, 243401 (2010)

3) Emission from Si(100) surface via exciton-like formation, 0.16 eV

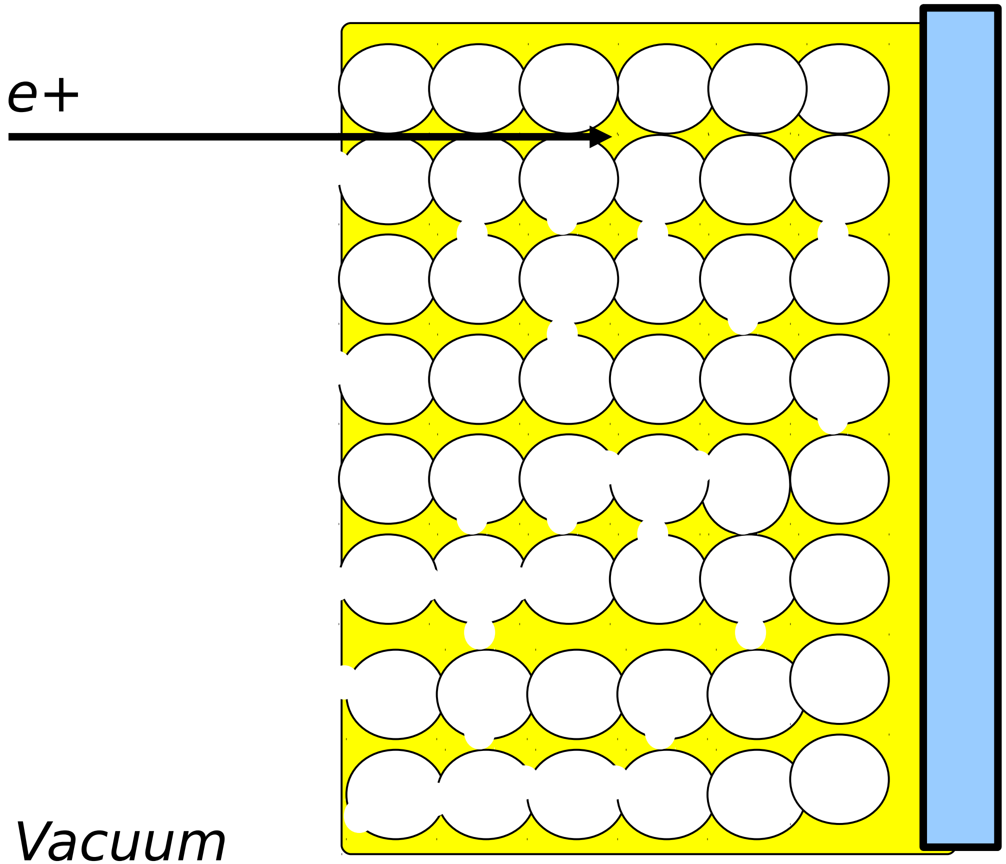
D. Cassidy et a, PRL 106, 133401 (2011)

4) Porous silica films, 30%, 40 meV

P. Crivelli et al., Phys. Rev. A. 81, 052703 (2010)

Positronium formation

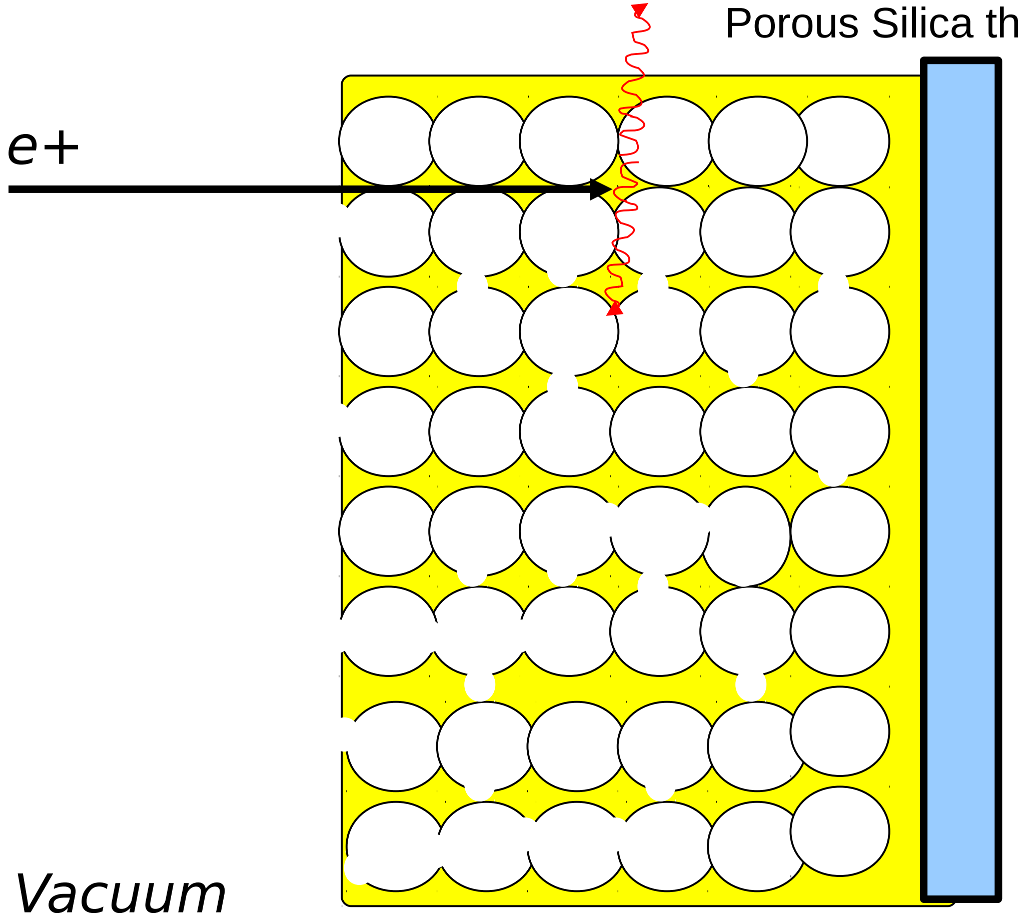
Porous Silica thin film ~1000nm 3-4 nm pore size



- Positron implanted with keV energies
- Rapidly thermalizes in the bulk (~ps)

Positronium formation

Porous Silica thin film ~1000nm 3-4 nm pore size

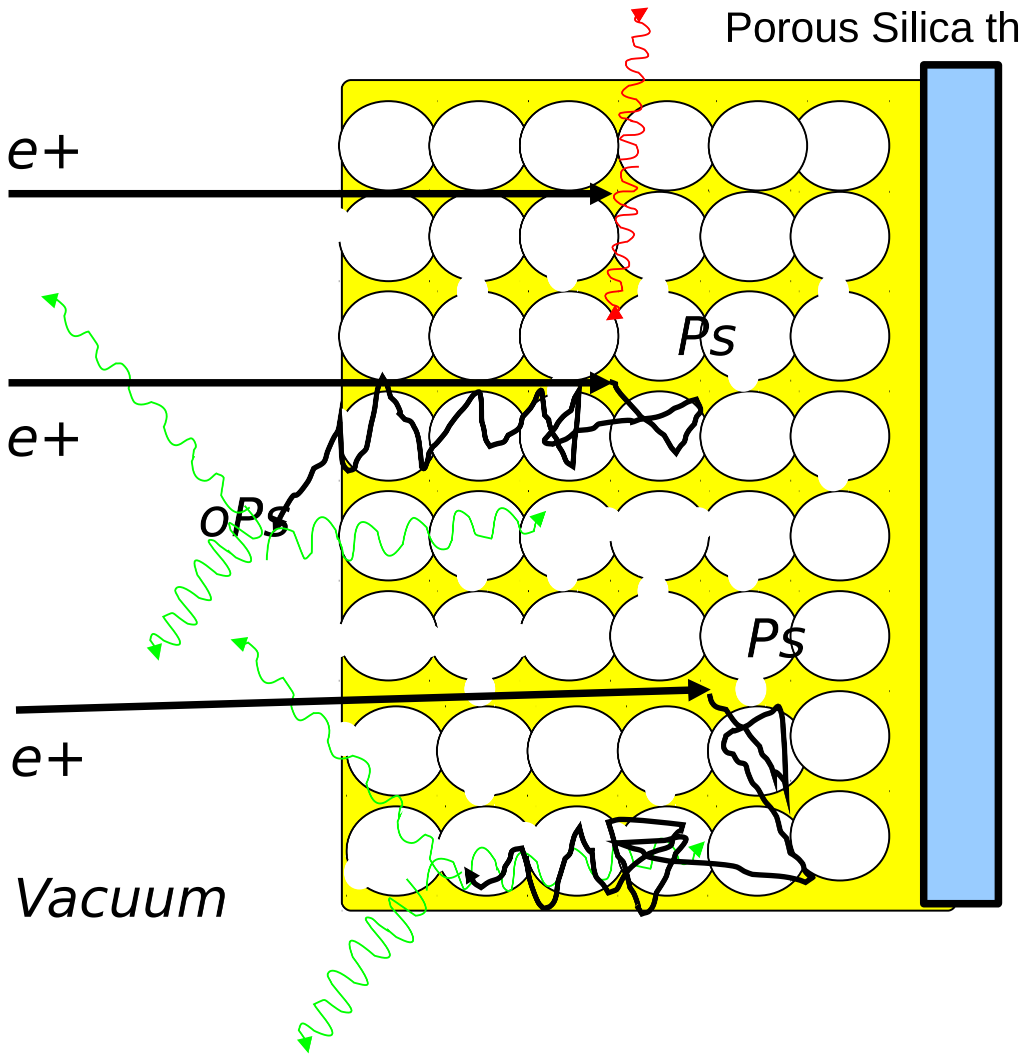


- Positron implanted with keV energies
- Rapidly thermalizes in the bulk (~ps)

- Positron diffusion and annihilation

Positronium formation

Porous Silica thin film ~1000nm 3-4 nm pore size



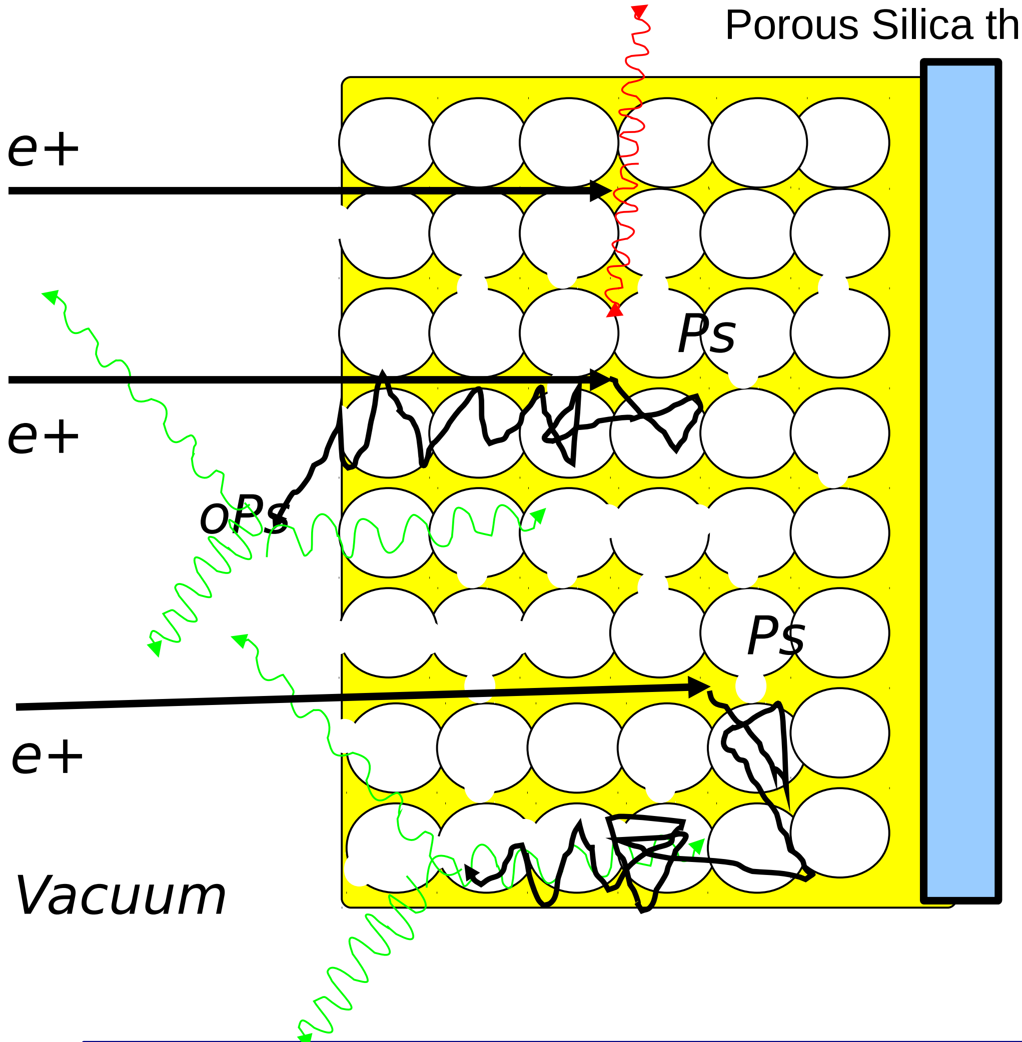
- Positron implanted with keV energies
- Rapidly thermalizes in the bulk (~ps)

- Positron diffusion and annihilation

- Positronium formation (1/4 pPs, 3/4 oPs) in SiO_2 by capturing 1 ionized electron
- Diffusion to the pore surface and emission in the pores:
- $W_{Ps}=\mu_{Ps} + E_B - 6.8$ eV=-1 eV
- Thermalization via collisions and diffusion in interconnected pore network

Positronium formation

Porous Silica thin film ~1000nm 3-4 nm pore size



- Positron implanted with keV energies
- Rapidly thermalizes in the bulk (~ps)

- Positron diffusion and annihilation

- Positronium formation (1/4 pPs, 3/4 oPs) in SiO_2 by capturing 1 ionized electron
- Diffusion to the pore surface and emission in the pores:
- $W_{Ps} = \mu_{Ps} + E_B$ - 6.8 eV=-1 eV
- Thermalization via collisions and diffusion in interconnected pore network

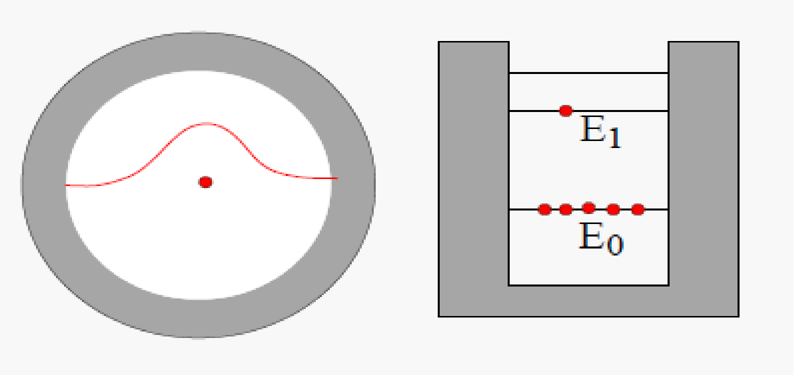
30% of the incident positrons are converted in positronium at 40 meV.

P. Crivelli et al., Phys. Rev. A. 81, 052703 (2010)

Ps as a particle in a box

Ps de Broglie wavelength at kinetic energy E_{Ps},

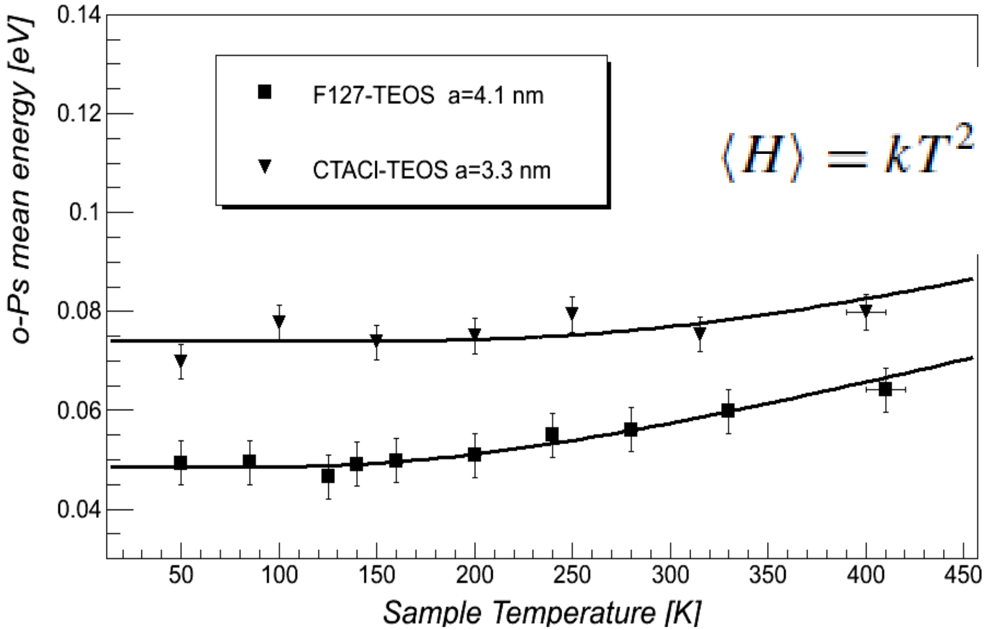
$$\lambda_{\mathrm{Ps}} = h(2m_{\mathrm{Ps}}E_{\mathrm{Ps}})^{-1/2} \sim 0.9\,\mathrm{nm}(1\,\mathrm{eV}/E_{\mathrm{Ps}})^{1/2},$$



For Ps with 100 meV, λ_{Ps} is comparable with the pore size.

$$E_{\mathrm{Ps}} = \frac{h^2}{2m\,d^2} \approx 0.8\,\mathrm{eV}(1\,\mathrm{nm}/d)^2$$

⇨ QM effects!



$$\langle H\rangle = kT^2\left(\frac{1}{Z(a)}\frac{dZ(a)}{dT} + \frac{1}{Z(b)}\frac{dZ(b)}{dT} + \frac{1}{Z(c)}\frac{dZ(c)}{dT}\right)$$

Z is the partition function defined as

$$Z(a) = \sum_{n=1}^{\infty} e^{-\frac{h^2n^2}{8ma^2}/kT},$$

P. Crivelli et al. , Phys. Rev. A81, 052703 (2010)

Colder Ps from porous materials?

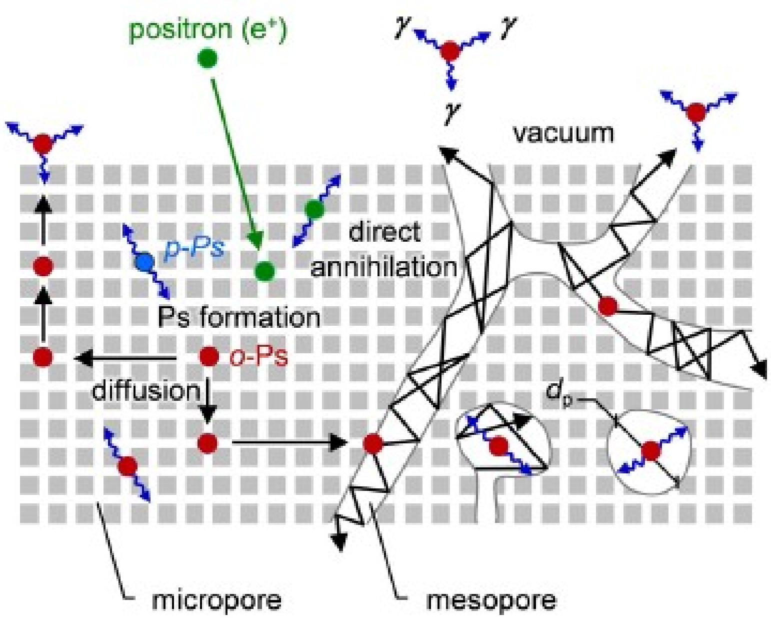
In principle it should be easy: use larger pores of 8-10 nm confinement energy ~100K (for muonium we did reach 100 K with 4 nm since de Broglie wavelength much smaller)

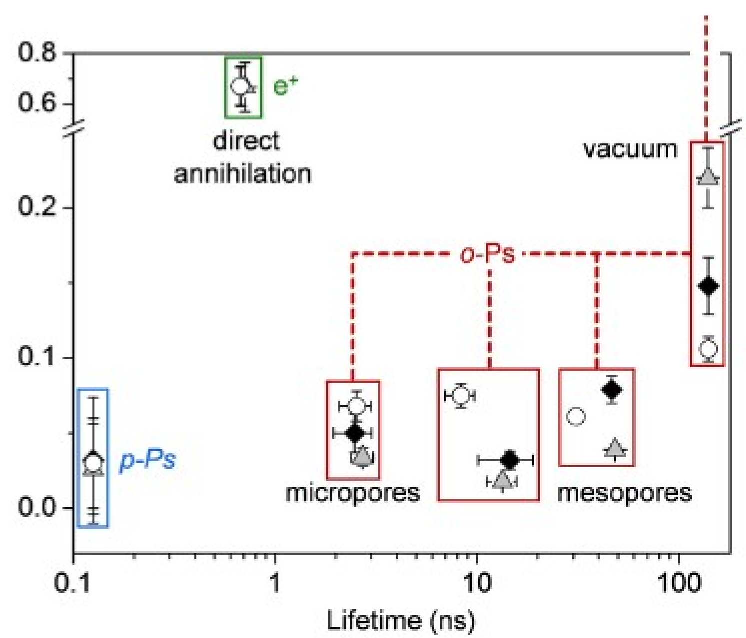
A, Antognini, P. Crivelli et al., PRL 108, 143401 (2012)

In practice: not easy to find the right recipe...work in progress (in collaboration with CEA Saclay).

Testing different porous materials: hierachical zeolites and metal organic frameworks

http://arxiv.org/abs/1309.6497





Collimation

Ps from silica monoenergetic (Ps velocity 10^5 m/s determined by pore size) with an angular distribution proportional to cos(θ) (from random orientation of the pores at the surface):

Collimation: vy<0.15 m/s and vx<50 m/s -> **2×10^{-9}**

What about vz (velocity normal to the surface)?

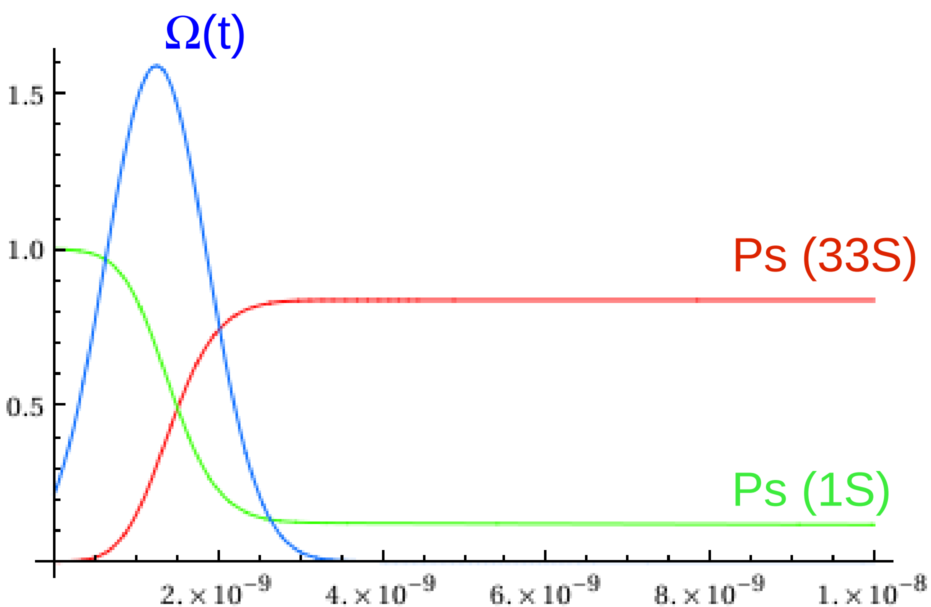
In 10 ms a Ps atom woud have traveled (~1km) -> not very practical for the experiment...

Two photons Rydberg excitation

To resolve the qm gravitational state Ps has to live at least 4.5 ms
-->Ps in Rydberg state

Ziock et al., Phys.Rev. Lett 64, 2366 (1990), Cassidy et al.Phys. Rev. Lett. 108, 043401 (2012)

Pulsed Nd:YAG → Dye laser @ 730 nm → SHG → 6 mJ, 5ns; 365 nm; 2 GHz linewidth



time [s]

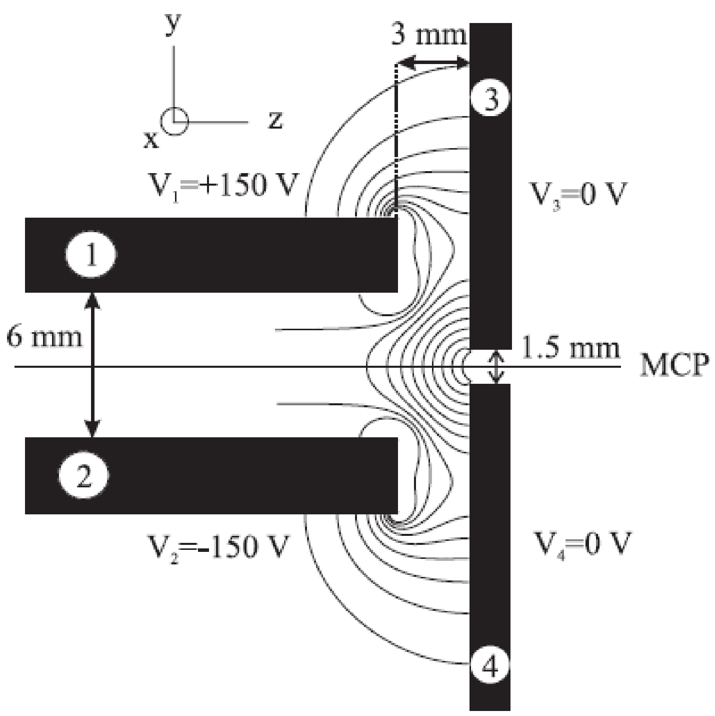
An efficiency of more than 50% of Ps in n=33 atoms seems achievable. Circularly polarized MW radiation to spun up the Ps to l=32 (estimated efficiency of 10%).

Rydberg Ps deceleration

Large dipole moment 3/2 $a_0$enk of Rydberg atoms -> deceleration with inhomogenous electric fields.
(where a0, e, and k are the Bohr radius, the elementary charge, and the difference between the parabolic quantum numbers n1 and n2)

Hydrogen stark decelaration and trapping demonstarted in this way by Merkt's group (ETHZ).

see , e.g.S. Hogan, F. Merkt, PRL 100, 043001 (2008)



$$a(\mathrm{m\,s^{-2}}) = 76\,\nabla F(\mathrm{V\ cm^{-2}})\frac{1}{m(u)}nk$$

For H (n=25) a= 2 x 10^8 m/s^2

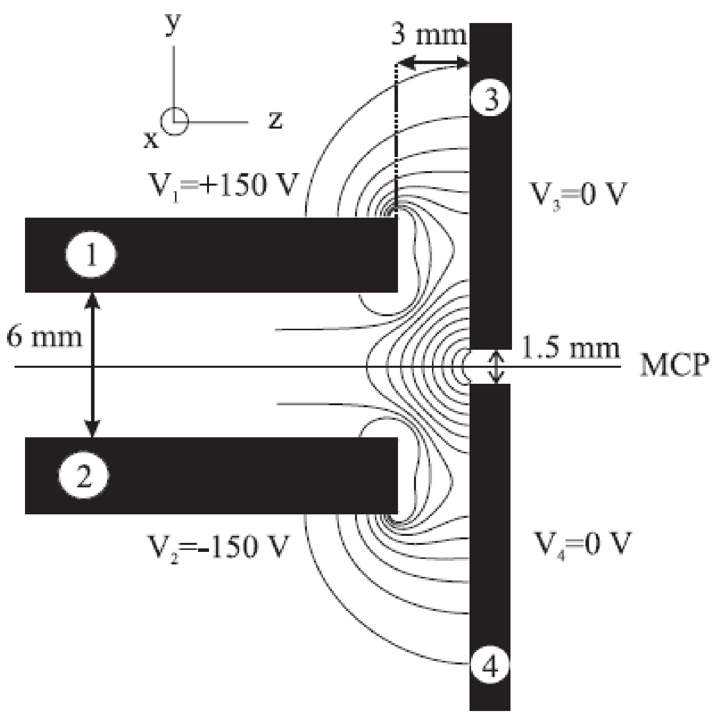
From 700 m/s -> at rest for a 3 mm gap with an efficiency of 80%

Rydberg Ps deceleration

Large dipole moment 3/2 $a_0$enk of Rydberg atoms make it possible to decelerate them with inhomogenous electric fields
(where a0, e, and k are the Bohr radius, the elementary charge, and the difference between the parabolic quantum numbers n1 and n2)

Hydrogen stark decelaration and trapping demonstarted in this way by Merkt's group (ETHZ).

see , e.g.S. Hogan, F. Merkt, PRL 100, 043001 (2008)



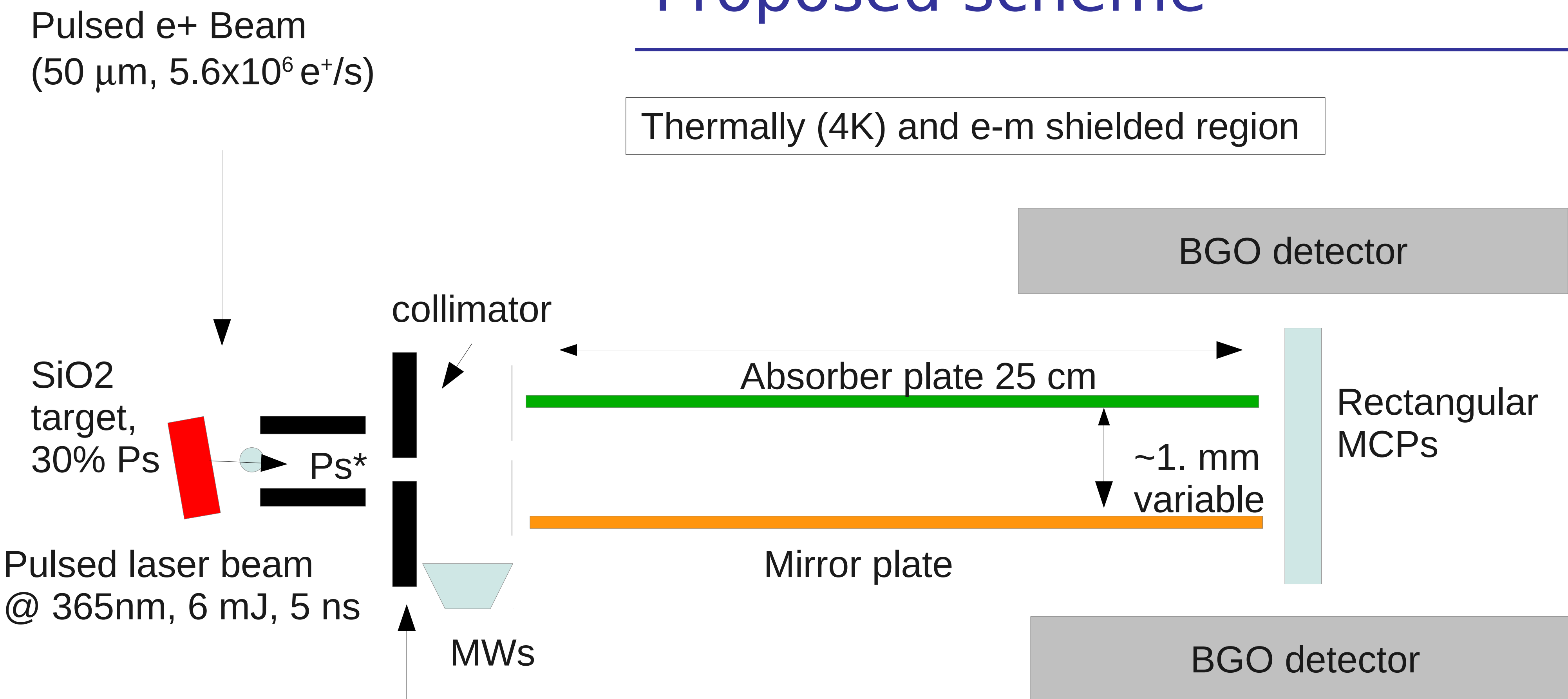
$$a(\mathrm{m\,s^{-2}}) = 76\,\nabla F(\mathrm{V\ cm^{-2}})\frac{1}{m(u)}nk$$

For H (n=25) a= 2 x 10^8 m/s^2

From 700 m/s -> at rest for a 3 mm gap with an efficiency of 80%

For Ps (n=25) a= 4x 10^{11} m/s^2
From 10^5 m/s -> vz<50 m/s
Seems achievable with an efficiency of 20%
-> simulation is in progress...)

Proposed scheme



<u>Mirror:</u>

- Use wires with constant current.

- Gradient of magnetic fields: $\mathbf{F} = \mu\ \mathbf{grad}\ B$

- To equate Ps E_{kin}=0.1 peV -> grad B ~ 17 mG

Estimated signal rate

Expected signal rate is given by:

$R_{signal} = R_{e+}\ \varepsilon_{Ps}\,\varepsilon_{n33}\,\varepsilon_{l32}\,\varepsilon_{tails}\,\varepsilon_{tau}\,\varepsilon_{det}\varepsilon_{dec} = 4 \times 10^{-5}$ events/ s

where

$R_{e+} = 5. \times 10^{6}$ positrons/s,

ε_{Ps} = 0. 3 the fraction of Ps emitted into vacuum,

ε_{n33} = 0. 5 the excitation probability in the n=33 state,

ε_{l32} = 0. 1 the efficiency to spun the Ps in the l=32 state,

$\varepsilon_{tails} = 2\times10^{-9}$ fraction of Ps atoms after collimator ($v_x <$ 50 and $v_y <$ 0. 15),

ε_{tau} = 0.6 fraction of atoms surviving the 5 ms time-of-flight,

ε_{det} = 0.5 efficiency of signal detection.

ε_{dec} = 0.2 efficiency of stark deceleration

This means that 3 events/day with a background of 0.06 bkg/day (requirement of MCP signal + TOF + back-2-back 511 keV photons) should be detected.

Concluding remarks

- A measurement of the Ps gravitational QM state looks very challenging indeed but maybe not impossible.

- This experiment would profit greatly if a source of cold Ps could produced.

- Futher simulations/calculations are needed to understand all the efficiencies and sources of systematic effects.

- Preliminary experiments to understand of cold enough Ps atoms could be produced and the best way to Ps mirror seems to be justified.

- Any advise/remark or comment is more than welcome!

Thank you for your attention!

Specials thanks to V. Nesvizhevsky and A. Voronin for the very useful discussions.