Slow positronium with high intensity for the antihydrogen project:

new results using a pulsed positron source and laser excitation

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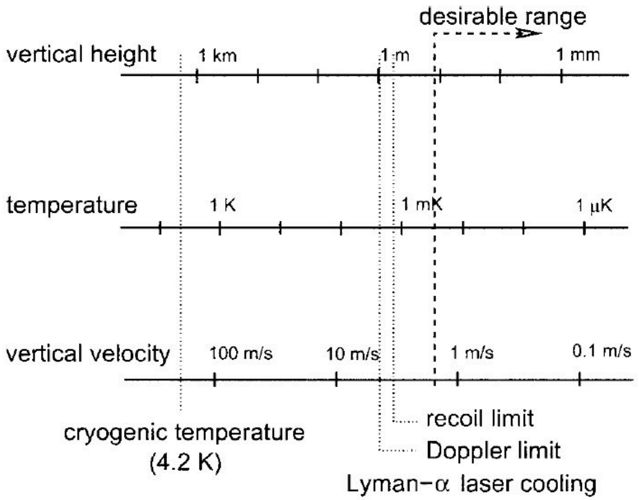
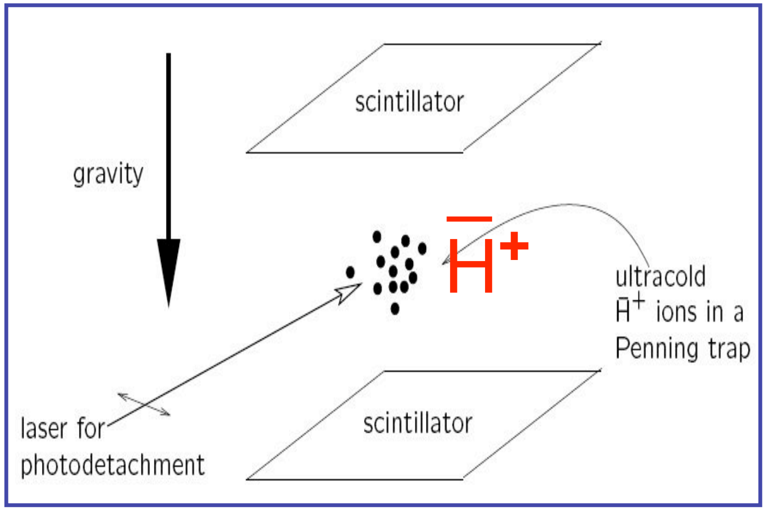
Outline

- introduction:
  - antihydrogen project
  - search for a positron-positronium converter
- efficiency and energy measurements (CERN)
- efficiency and energy measurements with high flux (Univ. of California, Riverside)
- conclusions, outlook

Direct gravitational measurement on antihydrogen





J.Walz & T. Hänsch,
General Relativity and Gravitation, **36** (2004) 561.

Gravitational free fall measurement (neutral antihydrogen)

• temperature of ~ 10 μK needed

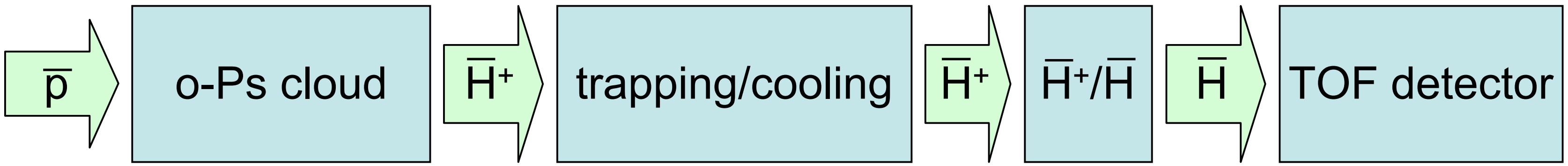
• cooling to this energy is feasible with positively charged antihydrogen ions

Positive antihydrogen ion production

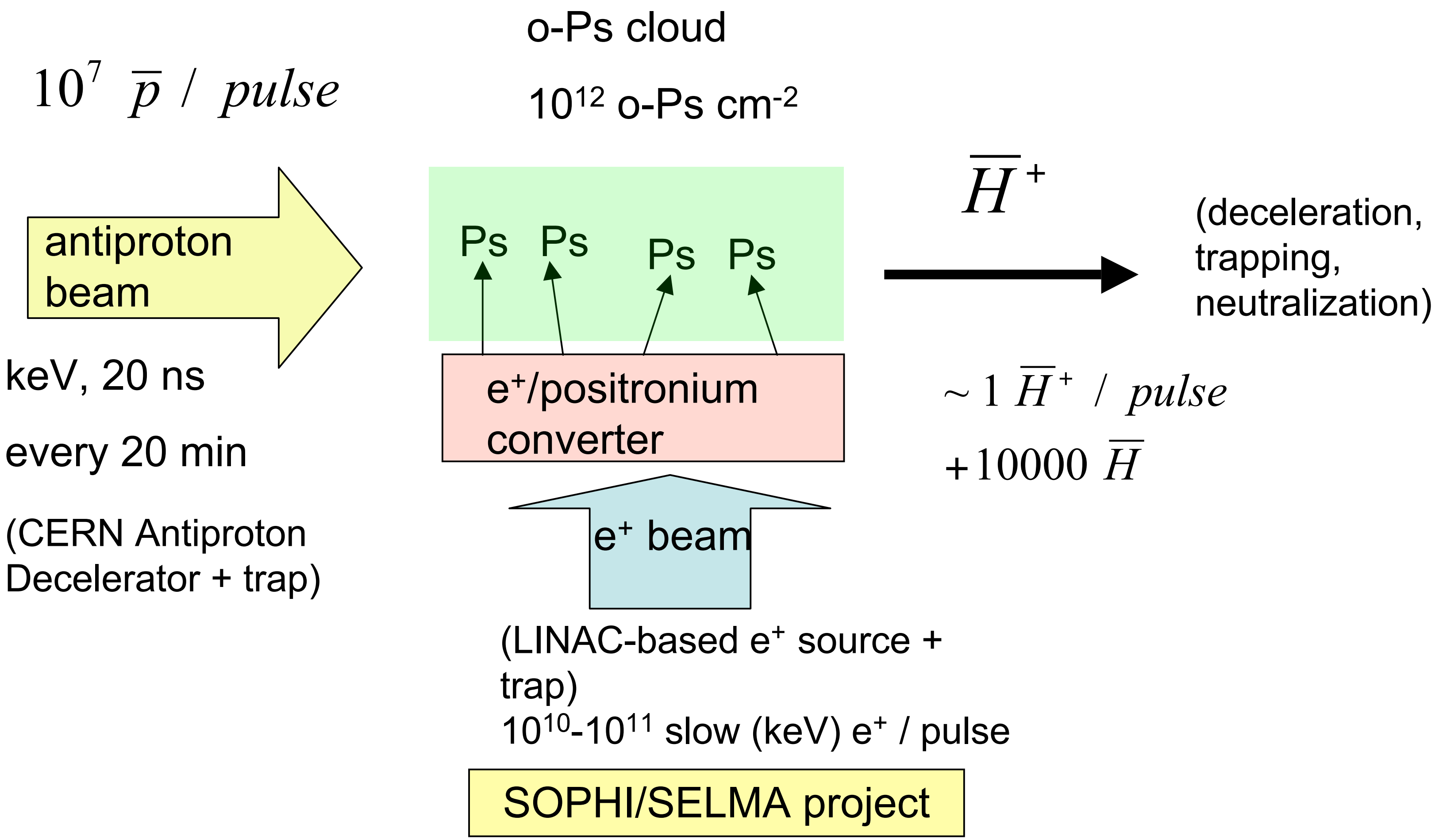
$$\bar{p} + Ps \rightarrow \bar{H} + e^-$$

$$\bar{H} + Ps \rightarrow \bar{H}^+ + e^-$$

- second step possible if the Ps density is high enough



Positive antihydrogen ion production /2



Positronium (Ps)

e^+ - e^- bound system

⇑ ⇓

para-positronium (*p*-Ps)
spin singlet state:

125 ps lifetime in vacuum

annihilates with
two 511 keV photons ($\pm\Delta E$)

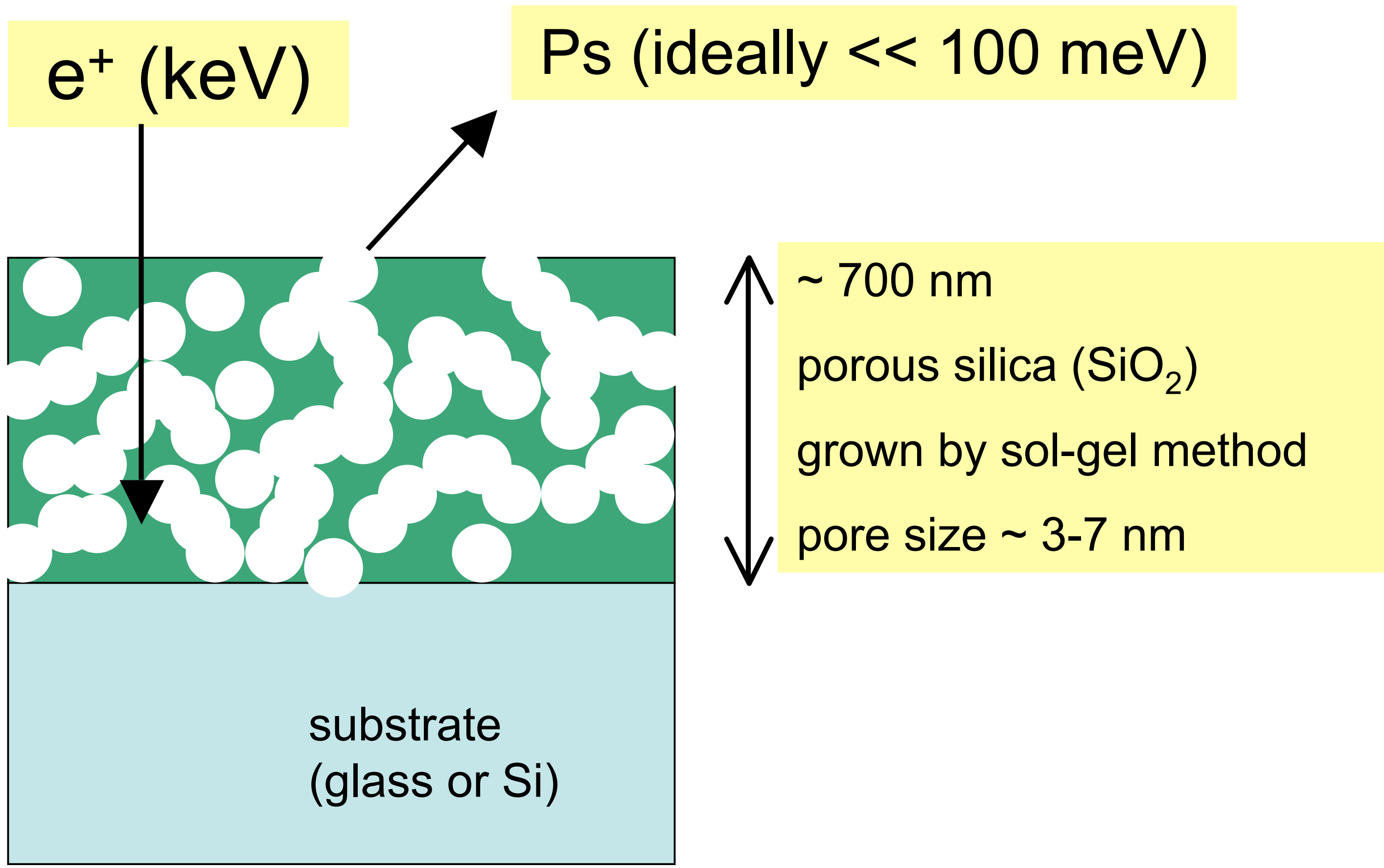
⇑ ⇑

ortho-positronium (*o*-Ps)
spin triplet state:

142 ns lifetime in vacuum

annihilates with
three photons ($0<E<511$ *keV*)

Positron-positronium converter



Results of development of a suitable system for positron – positronium converter

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⇨

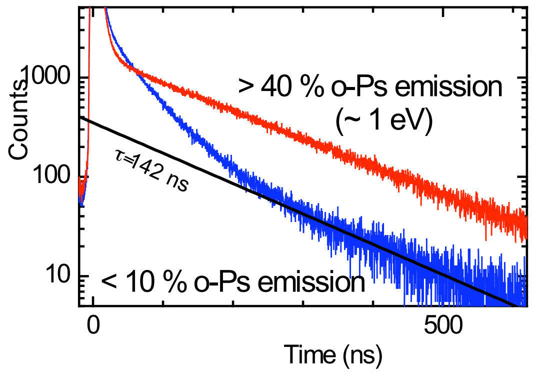
development of a suitable converter material

mesoporous silica thin film with 3-7 nm pore size

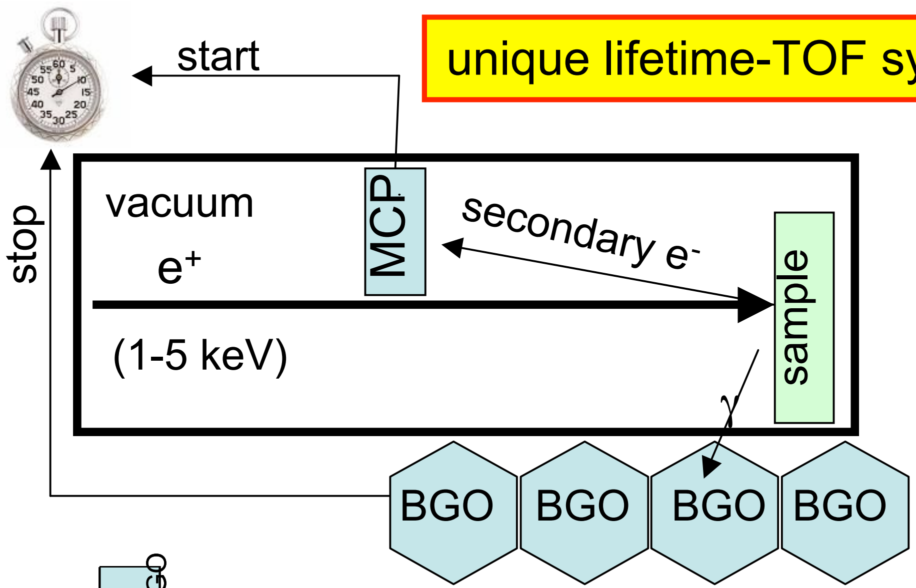
o-Ps escape probability > 30 % at less than 100 meV o-Ps energy

The CEA/IRFU-ETHZ slow positron beam-based positronium spectrometer at CERN

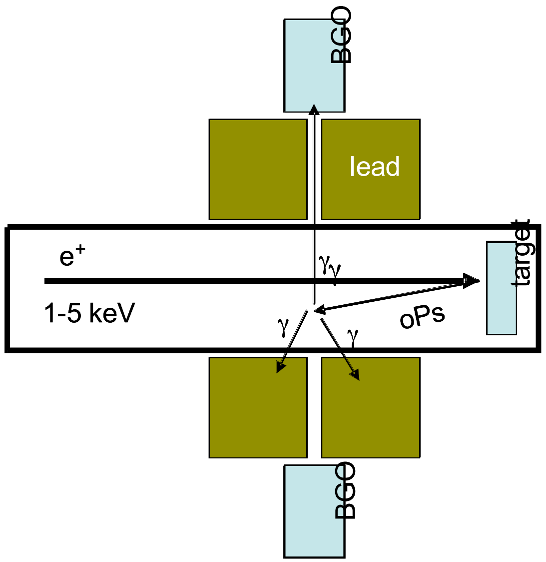
ortho-positronium lifetime spectrometer
(precise detection of emitted o-Ps)

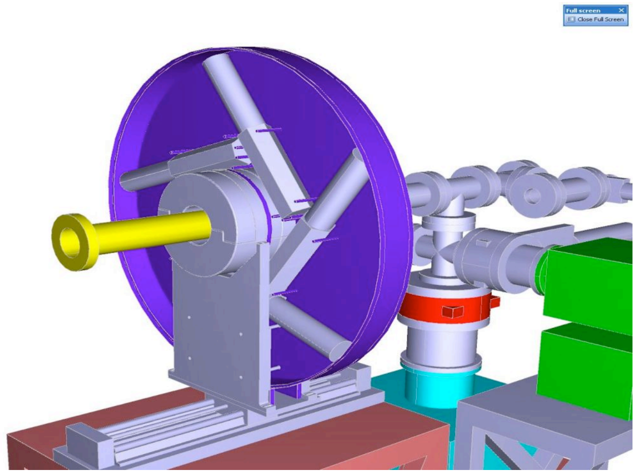


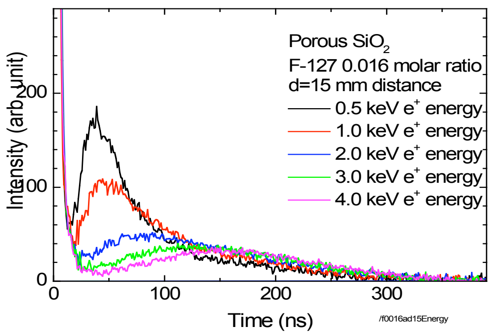
unique lifetime-TOF system



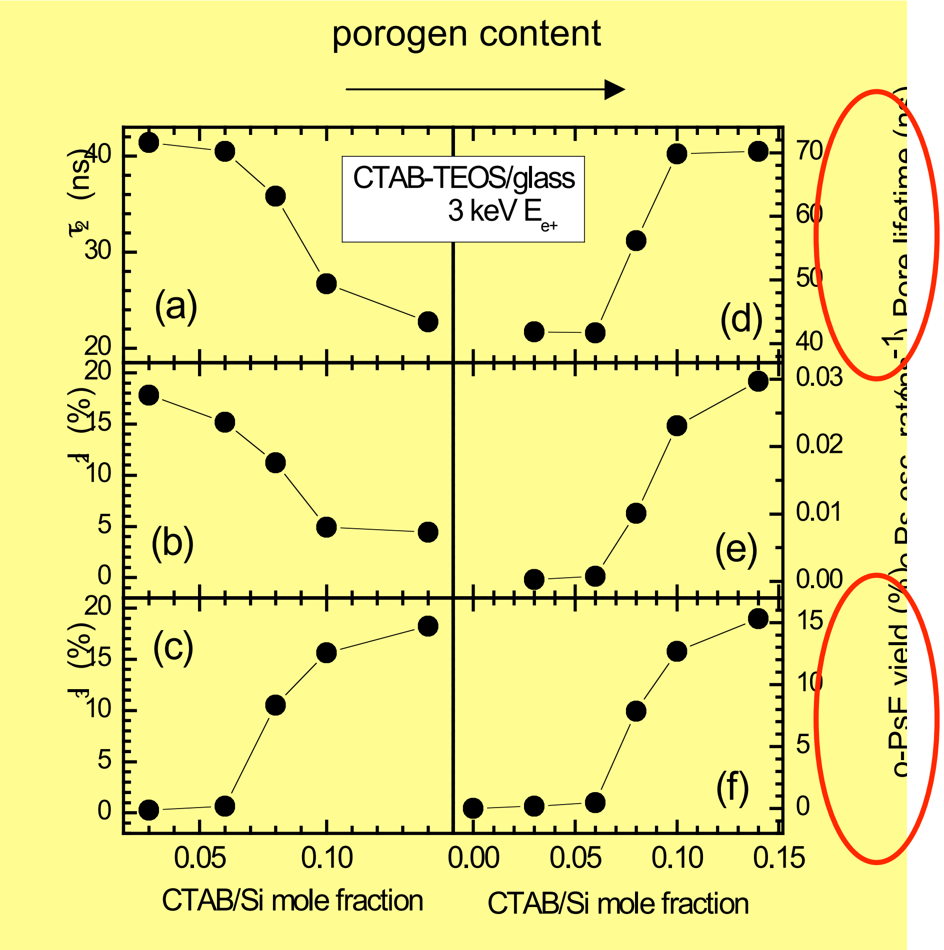
ortho-positronium
time-of-flight (TOF)
spectrometer







o-Ps emission and effective pore size in thin mesoporous silica films (LMC/X) from lifetime studies (CERN)



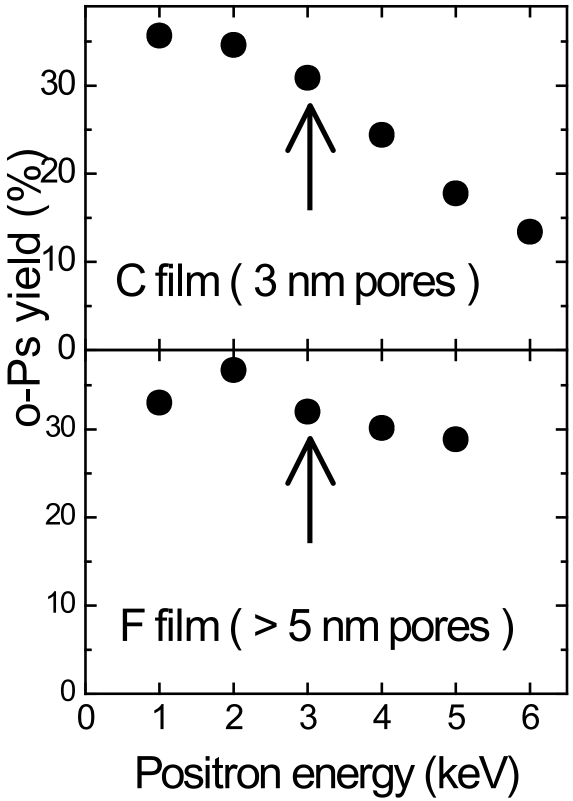
• threshold for o-Ps emission

→ change in the pore structure

• effective pore size seen by o-Ps grows at threshold

L. Liszkay et al, Applied Physics Letters **95**,124103 (2009)

o-Ps yield (IRFU-ETHZ lifetime measurement)

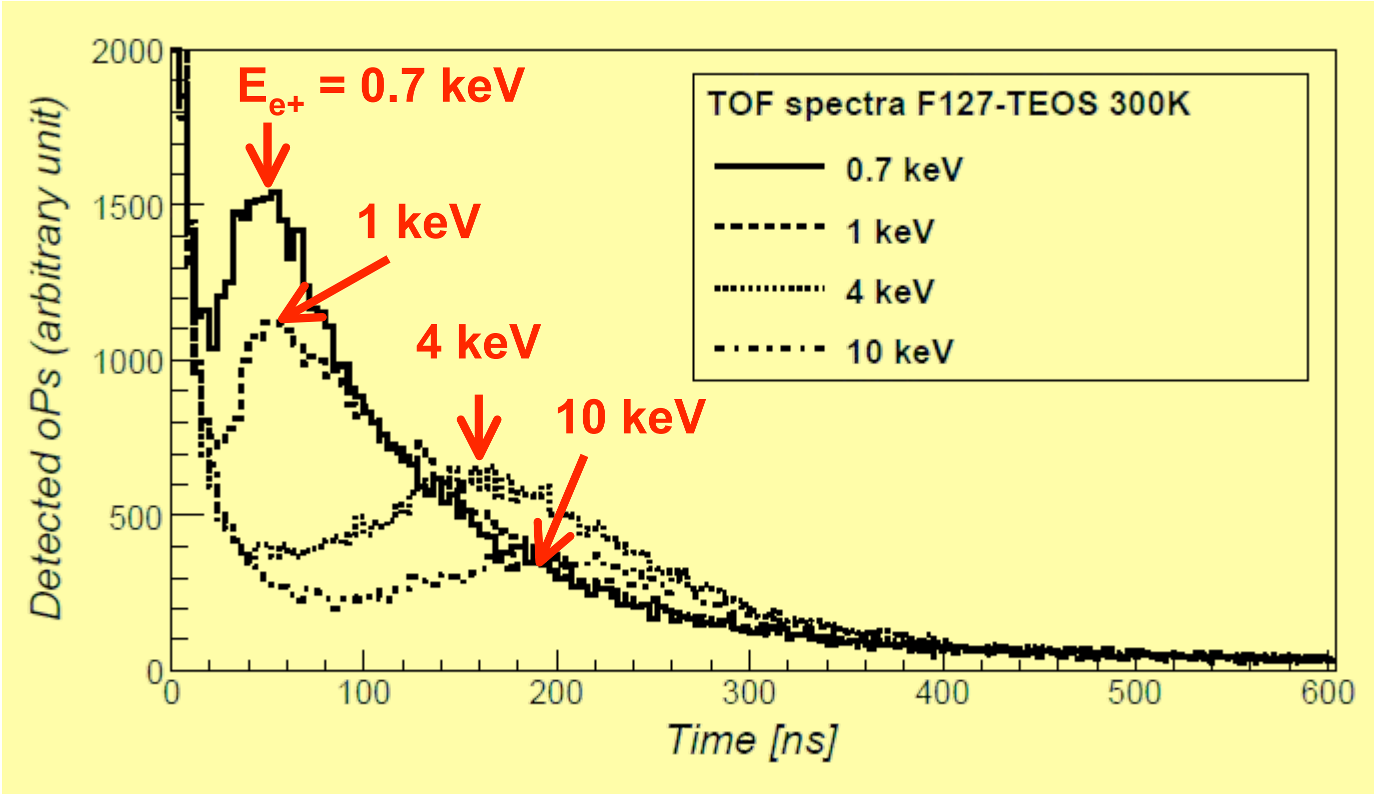


for the correct determination of the o-Ps yield one has to determine the correct lifetime intensities

only possible with the unique IRFU-ETHZ spectrometer at CERN

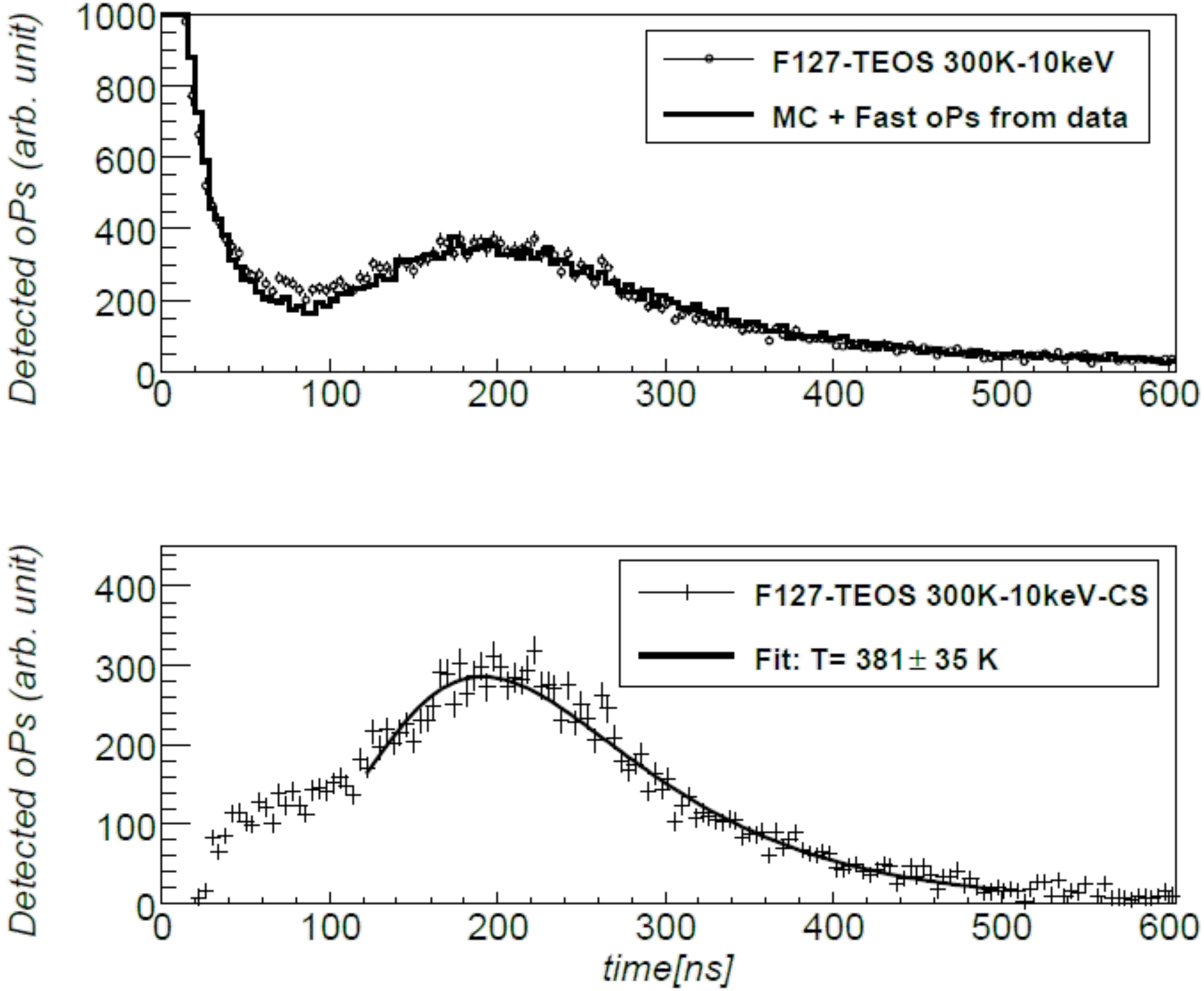
L. Liszkay et al, Applied Physics Letters **92**,063114 (2009) and **95**,124103 (2009)

Ortho-positronium TOF spectra

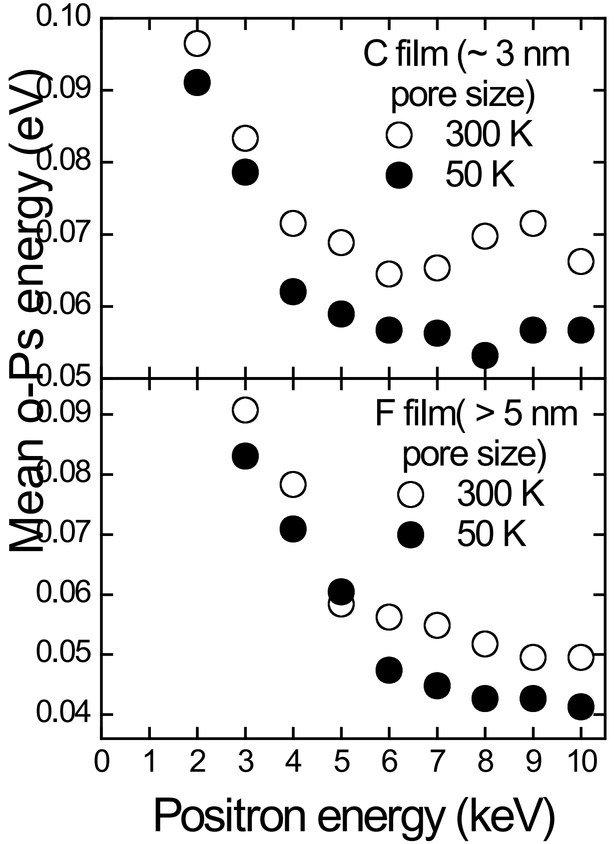


increasing e^+ beam energy → decreasing o-Ps energy

Monte-Carlo simulation (GEANT 4)



o-Ps mean energy perpendicular to the sample surface (IRFU/ETHZ TOF)



~ 3 nm pore size

> 5 nm pore size

- ~ 55 meV mean energy in the CTACl-TEOS samples
- ~ 40 meV mean energy in the F-127-TEOS samples
- no complete thermalization
- reduced energy at low temperature but no large difference

Measurements at UCR: test with an intense pulsed positron source

- ETHZ-IRFU spectrometer: 25000 e^+/s continuous source

- University of California Riverside (D.B. Cassidy, A. Mills):

  $2x10^7$ positrons in a 20 ns pulse

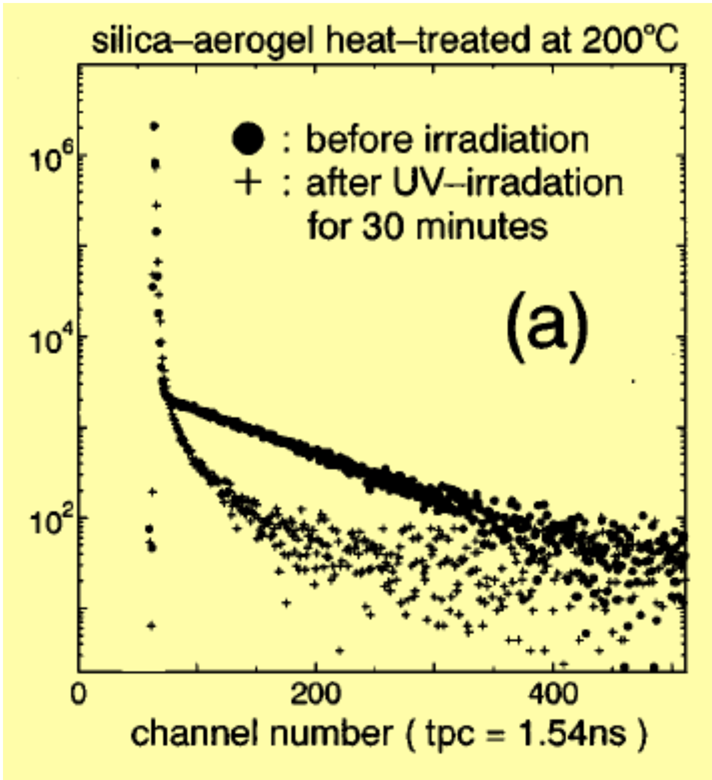
  (> 10^{11} times higher e^+ flux)

Importance of testing at high positron current density

possible loss of conversion efficiency through:

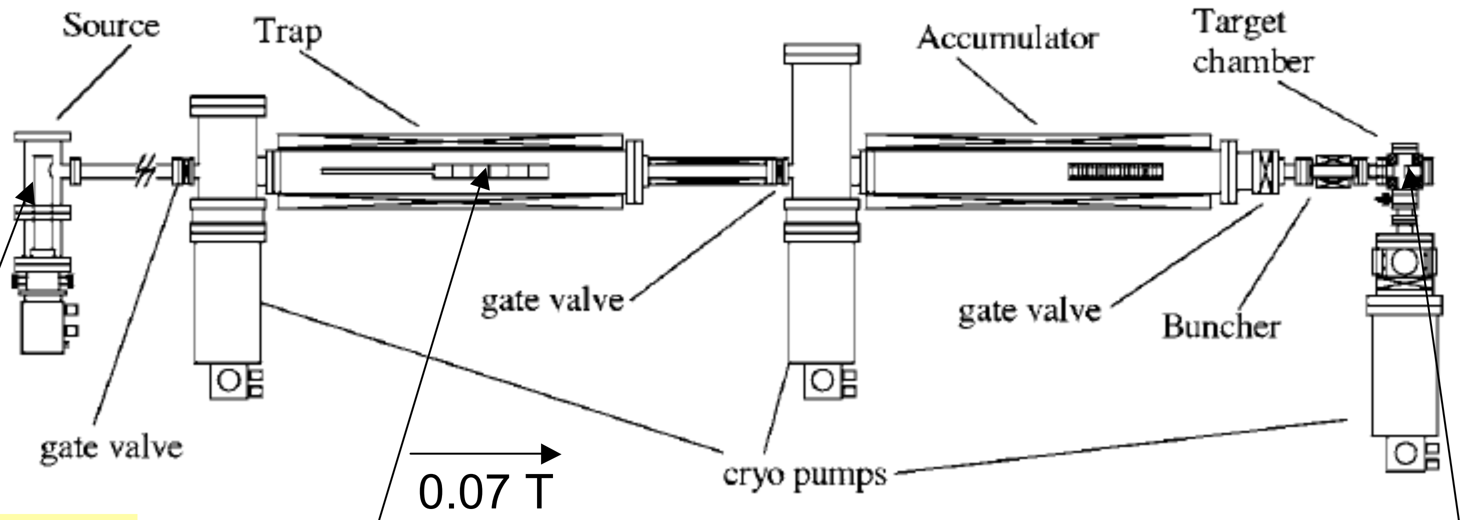
• quenching through positronium - positronium interaction (spin exchange)
(unlikely with Ps-Ps track distance of ~ 300 nm)

• ortho-positronium quenching at paramagnetic defects induced by radiation
(possible)



H. Saito and T. Hyodo, Phys. Rev. B 60, 11070 (1999)

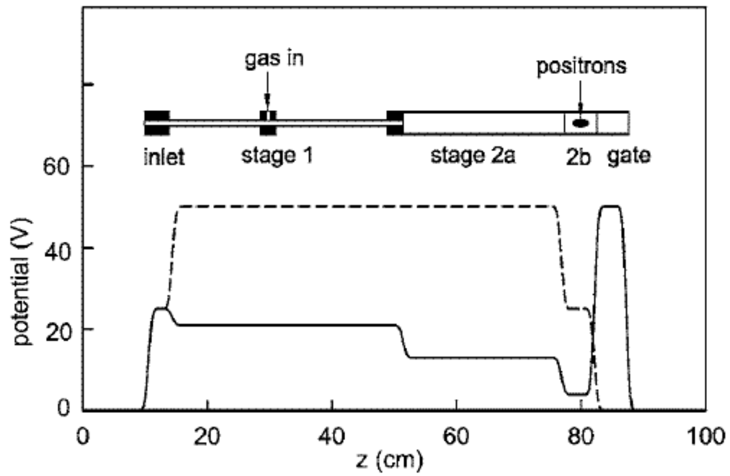
Trap-based positron source at UCR



^{22}Na
~ 25 mCi

solid Ne e^+
moderator

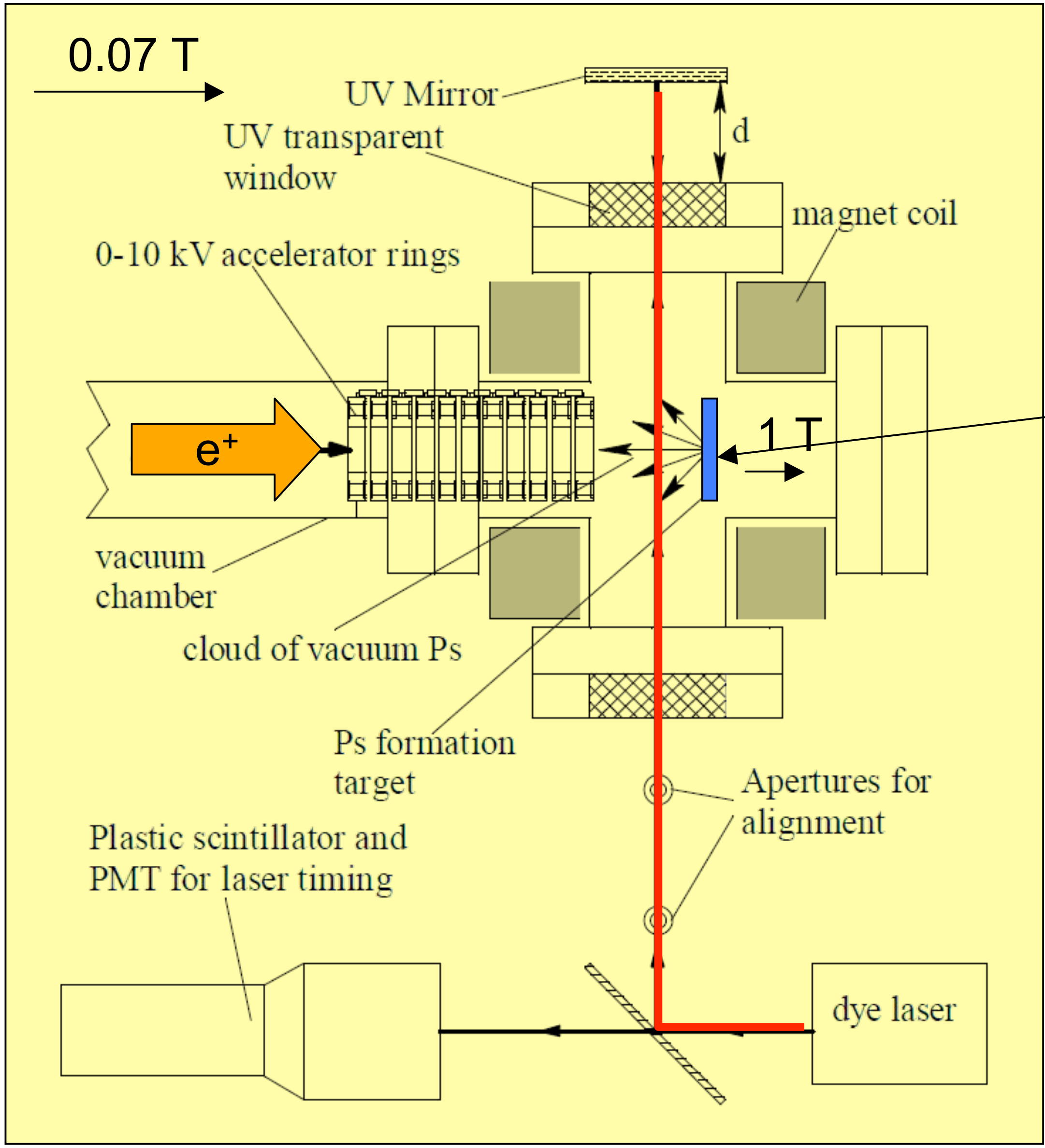
e^+ cooling by
N_2 gas



pulsed
magnet to
compress
beam
(~ 1 T)

D. B. Cassidy et al, Rev. Sci. Instr. 77, 073106 (2006)

Experimental setup (UCR)

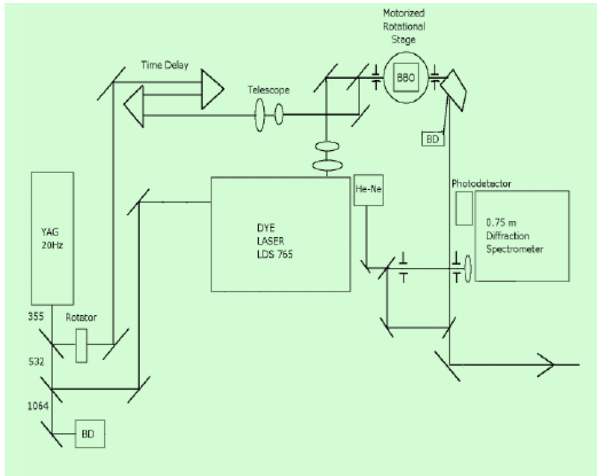


+ $PbWO_4$ – based scintillation detector
+ oscilloscope (single-shot lifetime measurements)

sample (C film from Saclay)

Laser

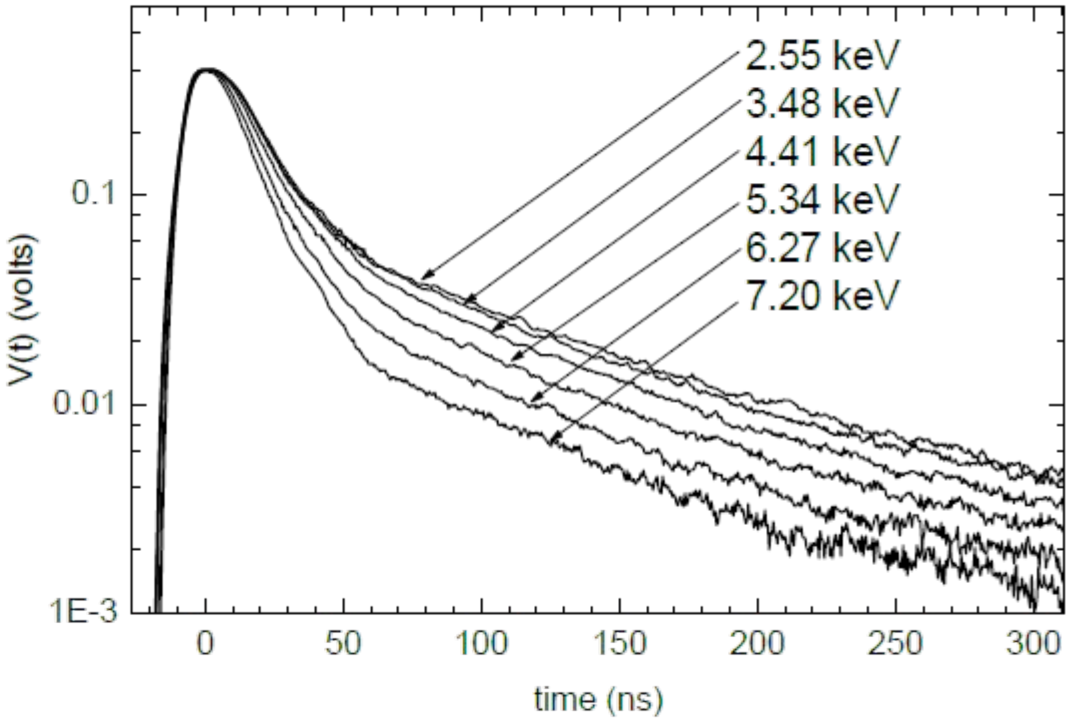
243±5 nm, max. 350 μJ/pulse



Measurements at UCR
(D.B. Cassidy, Univ. of California Riverside)

(1) single-shot positron lifetime measurement
→ o-Ps escape from the porous film
(results to be compared with the ETHZ-CEA large angle lifetime setup at CERN)

Intensity of emitted o-Ps from single-shot lifetime measurement



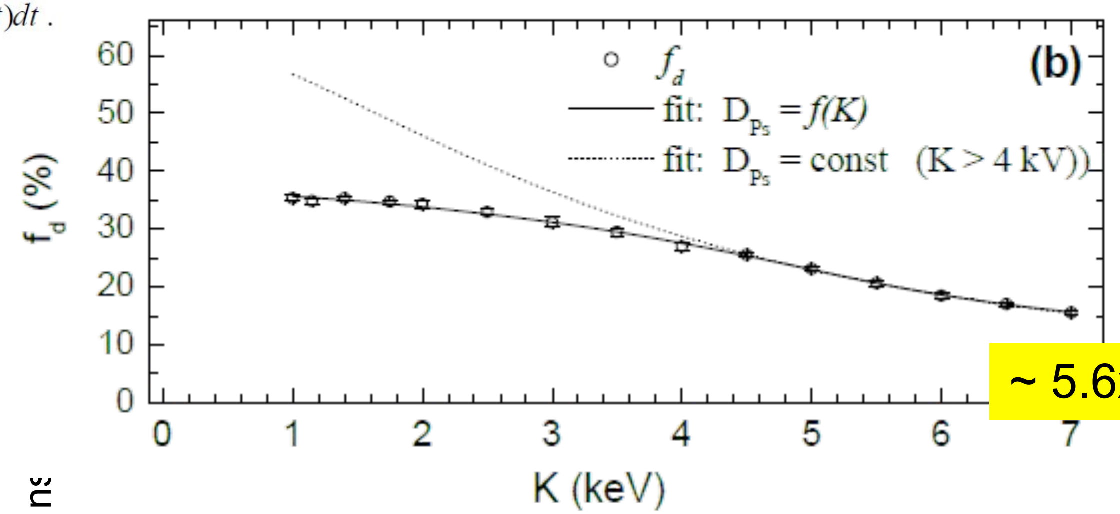
data analysis: “delayed fraction”

$$f_d = \int_{50ns}^{300ns} V(t)dt \Big/ \int_{-50ns}^{300ns} V(t)dt \,.$$

o-Ps reemission: comparison CERN / UCR

$$f_d = \int_{50ns}^{300ns} V(t)dt \Big/ \int_{-50ns}^{300ns} V(t)dt .$$

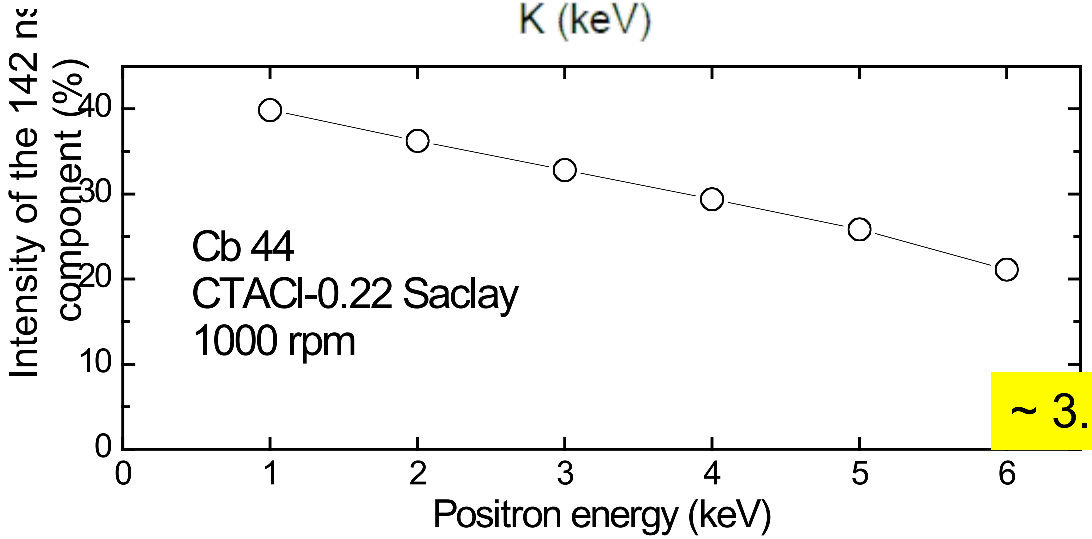
Measurement at UCR



~ 5.6x10^{16} $e^+cm^{-2}s^{-1}$

> 10^{11}x

Measurement at CERN



~ 3.5x10^5 $e^+cm^{-2}s^{-1}$

No loss in conversion efficiency due to the high e+ intensity is observed

Measurements at UCR
(D.B. Cassidy, Univ. of California Riverside)

(2) Measurement using the Lyman-alpha laser:
Doppler spread of the line width of the Ps $1^3S - 2^3P$ transition

→ Ps velocity in the direction of the laser beam

(results to be compared with o-Ps time-of-flight at CERN)

<u>first ever measurement of this kind</u>

Laser excitation of o-Ps

o-Ps ↓ 243 nm laser pulse ↓ excited state ↓ optical transition to the ground state ↓

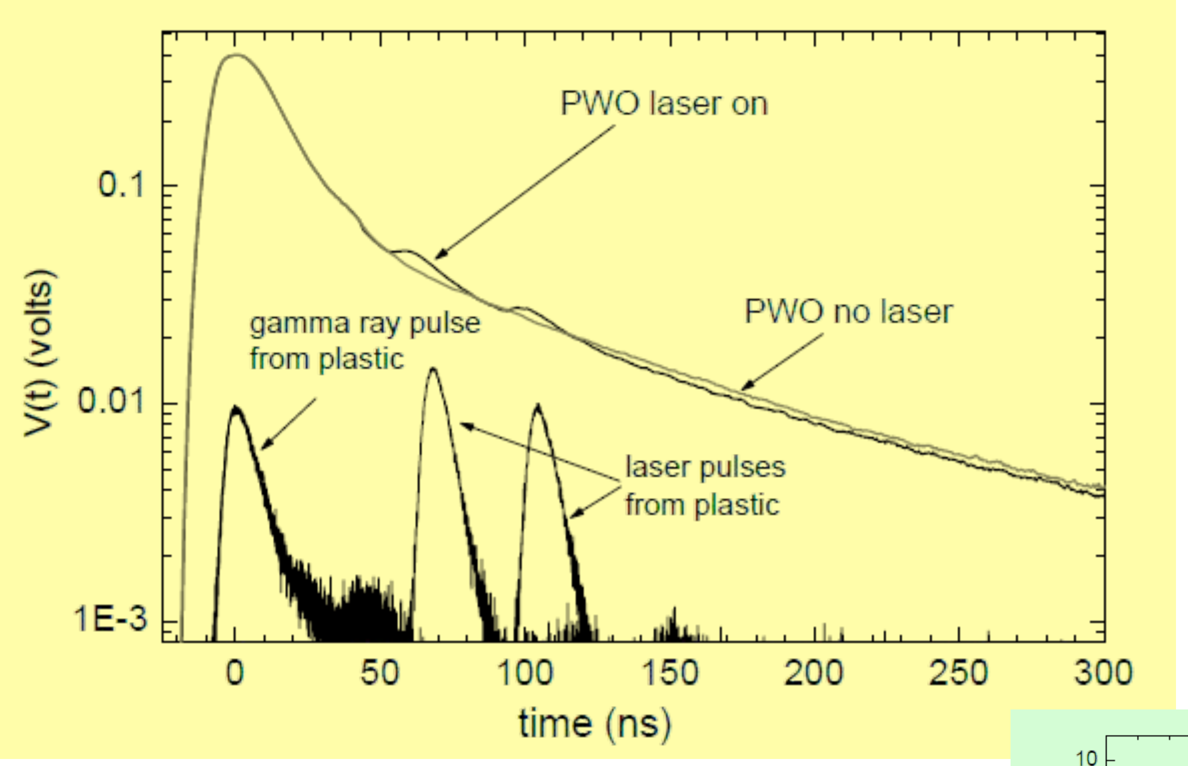
$$1^3S_1[142ns] + h\nu_0 \rightarrow \langle 2^3P_j + 2^1P_0 \rangle [3.2ns]$$

in magnetic field:

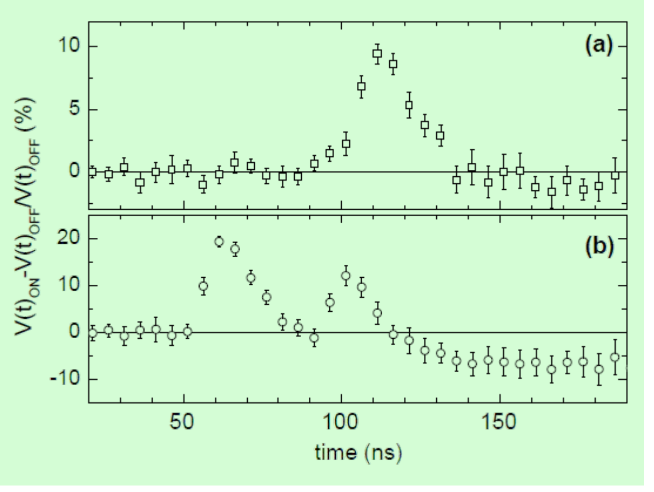
~ 12 % decays to singlet state (with short lifetime)

$$\rightarrow 1^1S_0[125ps] + h\nu_0 \rightarrow 2\gamma$$

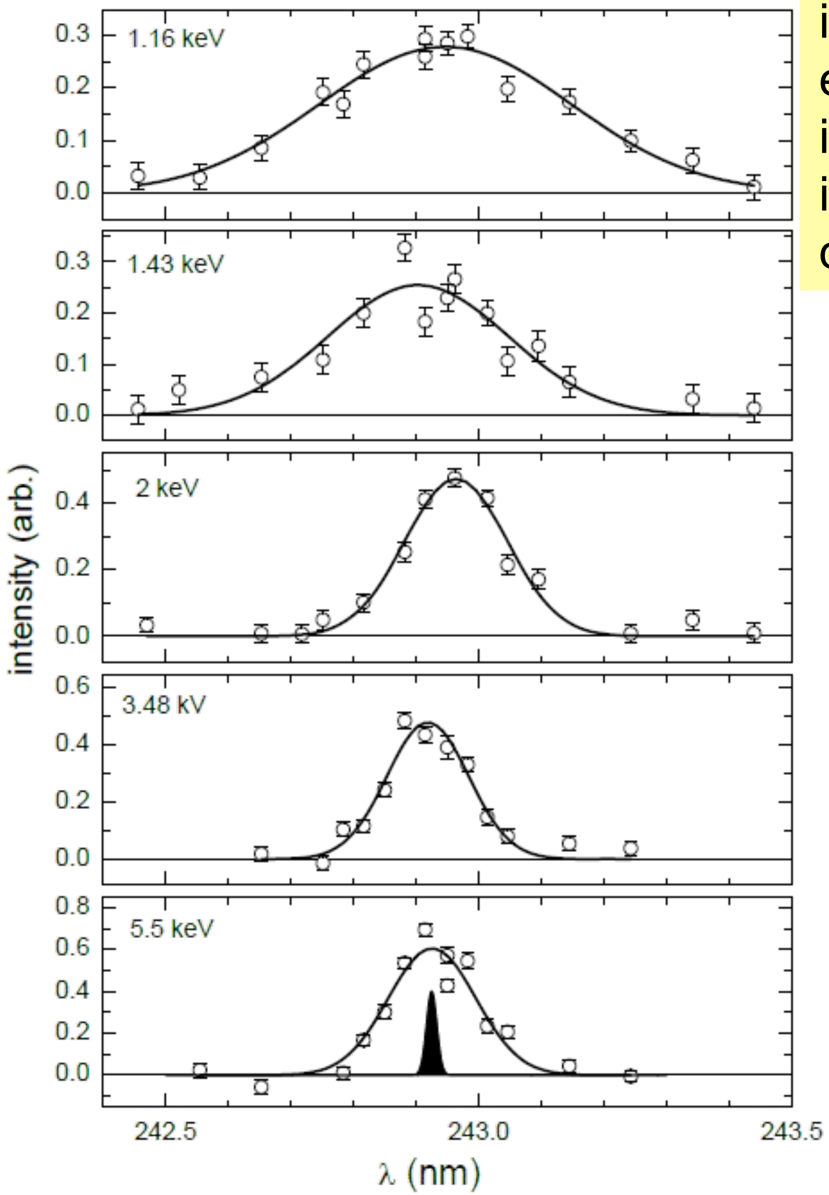
Observation of the excitation



difference curve



Measurement as a function of the wavelength

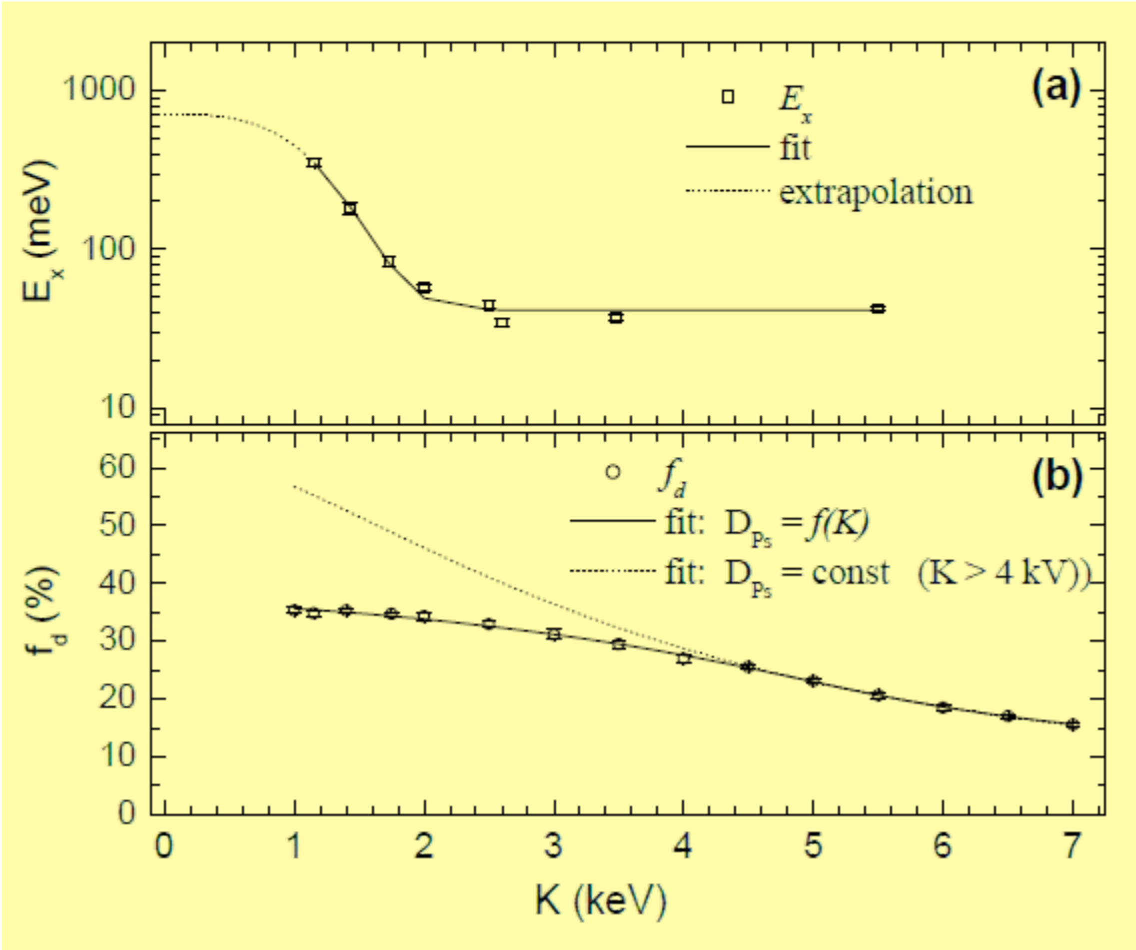


increasing e⁺ energy → increasing e⁺ implantation depth

decreasing line width

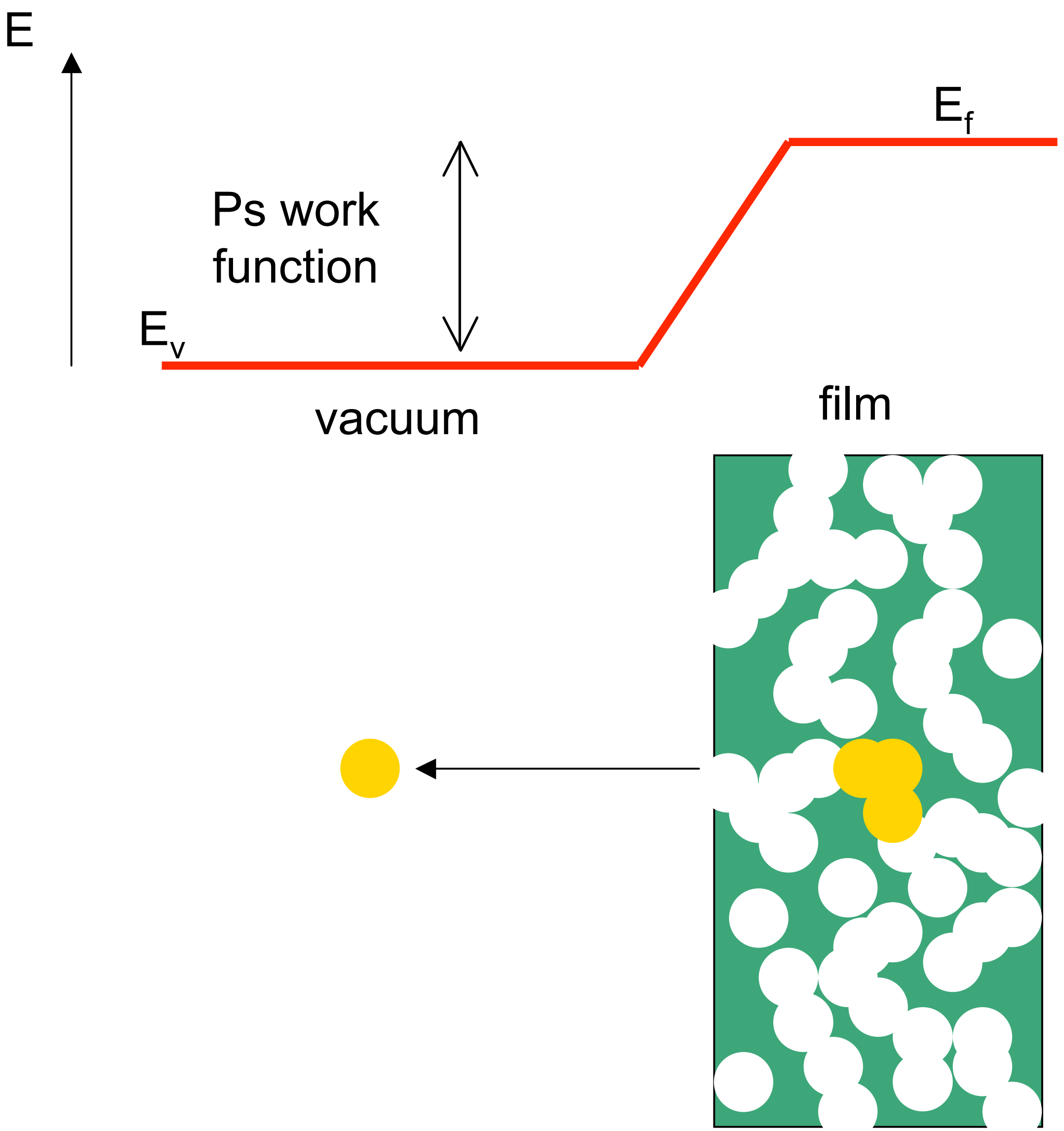
decreasing o-Ps energy

Mean kinetic energy (laser beam direction) as a function of E_{e+}



o-Ps cooling to 42±3 meV (laser beam direction)

Energetics of Ps escape



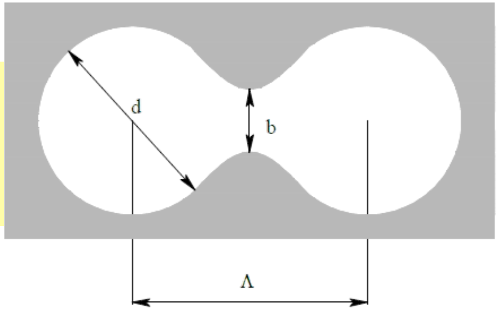
work function is most probably connected with confinement energy in the pores

Positronium in mesoporous systems: a need for a full QM description

de Broglie wavelength: $$\lambda_{Ps} = \frac{h}{\sqrt{2m_{Ps}E_{kin}}}$$

1 eV → 0.9 nm

100 meV → 2.8 nm → ~ pore size → QM model needed



Consequences:

- discrete energy levels of o-Ps localized in a pore
  → energy dissipation
  → kinetic energy of escaped Ps (minimum energy)
- tunneling between pores
  → Ps escape model
  (L. Liszkay et al, APL 95, 124103 (2009))

Status of the positron-positronium converter: technical aspects

what we have:

- converter material with 30 % efficiency and ~50 meV mean o-Ps energy
- reproducible growth method for the converter film
- stable up to 2×10^7 positron pulse intensity (1.5 mm diam. beam)
- scheme for the antiproton target (tube)

what we need still:

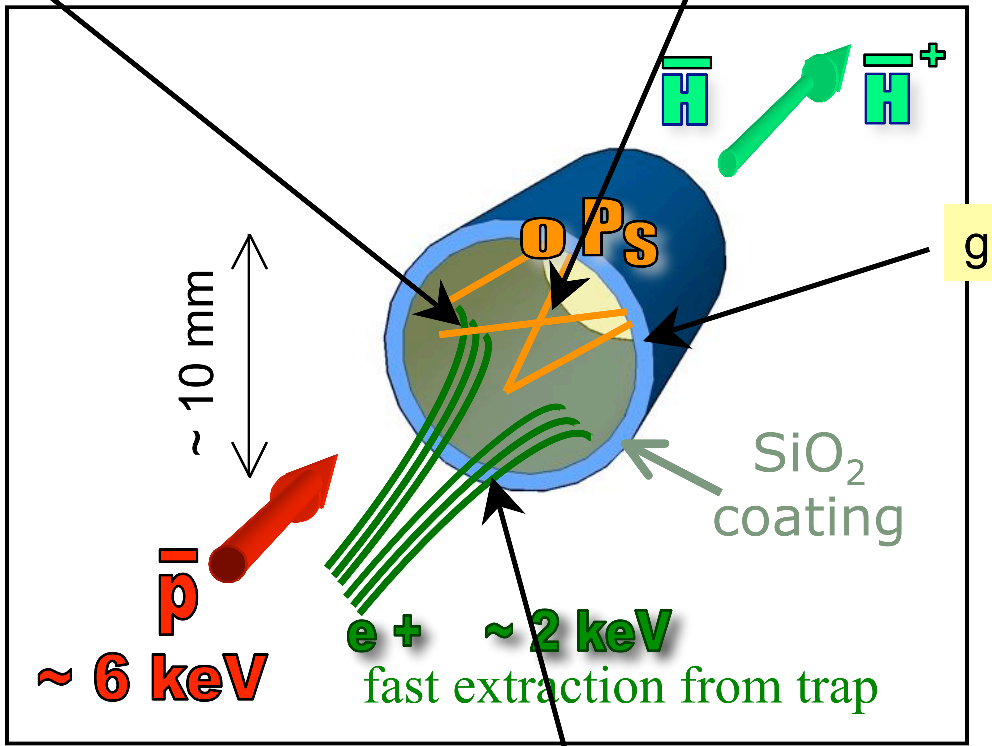
- stability up to 10^{10}-10^{11} positron / pulse (but possibly larger surface)
  (measurement will be feasible with the high field trap from Japan)
- o-Ps reflection in the internal surfaces of the tube
- possibly lower o-Ps energy (not essential)

+ understanding of physical processes of o-Ps birth, cooling and escape (→ efficiency and energy)

A possible geometry of the converter

e^+ - o-Ps conversion in reflection geometry

multiple refection of o-Ps from the walls



glass tube (substrate)

deviation of e^+ by electric field

Conclusions

- positron / positronium conversion efficiency is not reduced at 10^{11} times higher positron beam current density
- mean positronium energy is below 50 meV
- no complete termalization of o-Ps
- o-Ps emission energy is possibly determined by quantum confinement of o-Ps in the pores

Outlook

- full QM description of the o-Ps localization / emission is needed
- porous materials with smaller (~ 1 nm) and larger (> 10 nm) have to be tested to check effect of quantum confinement (possibility of lower o-Ps energy)
- test with even higher positron current density is needed to check possible Ps-Ps interaction and defect creation (but: lack of facilities)