Positronium:
from Fundamental Researches
to
Industrial Applications

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ИЯИ РАН, Москва
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Plan:

- Introduction to Ps
- Search for new physics with Ps:

  rare decays, C, CP, CPT violation,
- Invisible decay of oPs.
  - millicharged fermions and PVLAS anomaly, extra dimensions, mirror dark,

  recent results and plans
- New techniques and its challenges
  - high efficiency pulsed slow positron beam
  - secondary electron emission spectrometer
- Hbar program at CERN: Free gravity fall of antihydrogen and CPT tests
  - ultra-cold Ps formation
- Material Researches and Industrial Applications:
  - PALS and other techniques
  - characterization and metrology of nanoporous films for microelectronics etc….
- Summary

Introduction to Positronium

Positronium (Ps) is the bound state of an e+ and e-

- An atom without a nucleus (no Strong Interaction)
  No nuclear structrure effects on atomic spectrum
  (Nuclear charge, magnetization distributions, sructure functions)
- Weak Interaction effects: Really, really small!

$$\Gamma\left(e^+e^- \to \nu_e\bar{\nu}_e\right) \sim (10^5\ \text{years})^{-1}$$

Z exchange: opposite parity levels mix at $10^{-(10\text{-}11)}$

A purely leptonic system described entirely by QED (almost)
Extremely rich in symmetries

States $\psi(1,x)$ are $^3S_1$ = Orthopositronium (o-Ps) mean lifetime ~ 140 ns
State $\psi(0,0)$ is $^1S_0$ = Parapositronium (p-Ps) mean lifetime ~ 125 ps

$$C\left|\mathrm{Ps}\left(^{2S+1}L_J\right)\right\rangle = (-1)^{L+S}\left|\mathrm{Ps}\left(^{2S+1}L_J\right)\right\rangle$$

$$\left|^1S_0\right\rangle \to 2\gamma, 4\gamma, \ldots \qquad \left|^3S_1\right\rangle \to 3\gamma, 5\gamma, \ldots$$

$^3S_1$ (O-Ps) cannot decay to two photons --
angular momentum of photons
Wheeler, Ann. N.Y. Acad. Sci. **48**, 219 (1946).
P symmetry requires $^1S_0$ two photon decay to have photons w/perpendicular lin. polarization, Yang, Phys. Rev. **77**, 242 (1950).

$$R_4^{\not{C}} = \frac{\Gamma(\mathrm{O-Ps} \to 4\gamma)}{\Gamma(\mathrm{O-Ps} \to 3\gamma)}$$

$$R_{3,5}^{\not{C}} = \frac{\Gamma(\mathrm{P-Ps} \to 3,5\gamma)}{\Gamma(\mathrm{P-Ps} \to 2\gamma)}$$

Search for New Physics with Ps

Proceedings, International Workshop, Zurich, Switzerland, May 30-31, 2003.
M. Felcini, (ed.), S.N. Gninenko, (ed.), A. Nyffeler, (ed.), A. Rubbia, (ed.) (Zurich, ETH & Moscow, INR) . 2004. 217pp. Published in Int. J. Mod. Phys. A19 (2004) 3769-3985

Recent review: Gninenko, Krasnikov, Matveev, Rubbia, Phys.Part.Nucl. 37(2006)

- Search for exotic decays: gamma +X(axions, light bosons, taxions, …)
- Search for C violating modes of decay to 4, 5 photons
- Lorentz violation search
- Search for CP violation in o-Ps decay
- Search for CPT violation in o-Ps decay
- Search for “Invisible Decay” (missing energy) -- new result + plans
- Motivation for o-Ps invisible decay experiment
- Previous experiments on invisible decays of o-Ps

Limits on exotic o-Ps decay modes

Decay mode	Upper limit, ppm (90%C.L.)	Comments	Group
γ+X		Axion, Long-lived X boson	
	5-1	m_X~~100-800 keV	CERN
	1.1	$m_X < 800$ keV	Tokyo U.
	340	$m_X < 30$ keV	INR Moscow
γ+X -> γ + 2γ		Short-lived X boson	
	300	$m_X < 500$ keV	Tokyo U.
	28	$m_X < 100$ keV	INR Moscow
2γ	350	Space isotropy	Tokyo U.
	230		Michigan U.
4γ	2.6	C-parity violation	Tokyo U.
	3.8		Berkeley
γ+X +Y	44	$m_X + m_Y < 900$ keV	ETH-INR Moscow
invisible	540		INR Moscow
	2.6		Tokyo U.
	0.47		ETH-INR Moscow

Search for Invisible Decay of Orthopositronium

Motivations

What is the mechanism by which e^+e^- annihilates to an invisible final state?

1. Mirror matter

$$e^+ + e^- \to \gamma\,(\text{virtual}) \to \gamma^*\,(\text{mirror analog}) = \text{invisible}$$

o-Ps should be formed and decay in vacuum . Br(o-Ps ->nothing) ~ below BBN limit (~1e-6)
Is Interesting

2. Millicharged particles

Could generate (o-Ps $\to$ nothing) anywhere from 1e-7 and lower…
Strongly motivated by the PVLAS-CAST discrepancy

3. Neutrino magnetic moment

$$e^+ + e^- \to \nu\,\nu\,,$$

Could result in 1e-8 - 1e -10

4. Infinite extra dimensions (RS2)

Could be 1e-8 and lower .

5. Light X-boson

$e^+ + e^- \to XX$, e.g. from g-2 (S.G., Krasnikov, PLB (2001))

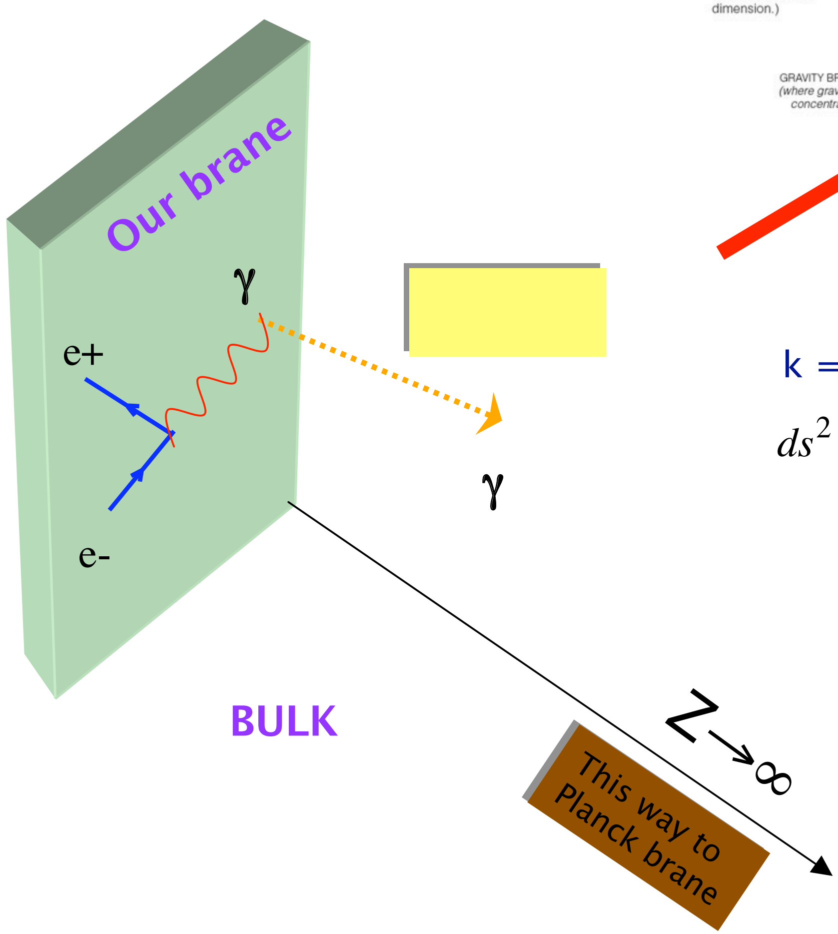
6. Standard Model background

$e^+ + e^- \to \nu\,\nu$

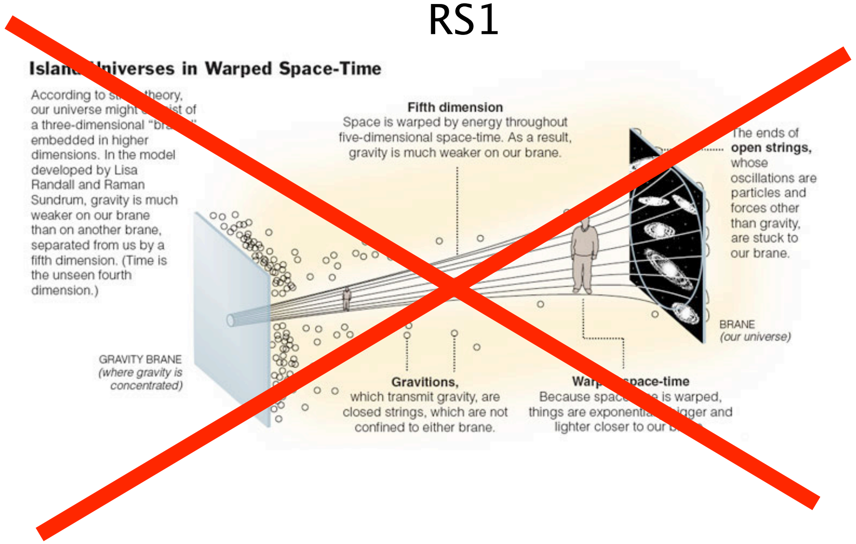
Branching ratio is about 1e-18, depending on neutrino mass.

Dubovsky , Rubakov, Tinaykov PRD **62**, 105011;
Rubakov UFN 171(2001)

$e^+ + e^- \to \gamma\,(\text{virtual}) \to \gamma\,(\text{bulk mode}) \to z=\infty$



RS1



k = warp factor parameter

$$ds^2 = e^{-(kz)^2}\eta_{\mu\nu}dx^\mu dx^\nu - dz^2$$

Fermions themselves are quite stable by virtue of their gauge couplings.
Very stuck to the brane.

What size signal from escape to extra dimensions in o-Ps?

Gninenko, Krasnikov, Rubbia Phys. Rev. D **67**, 075012 (2003).

Estimates the decay rate of o-Ps into extra dimensions, expressed as a branching ratio

For n = 2 extra dimensions

$$\Gamma\left(\gamma^{*} \to \text{X Dim's.}\right) = \frac{\pi m_{\gamma^*}}{4}\left(\frac{m_{\gamma^*}}{k}\right)^2$$

k = energy scale of new physics

upper bound from (Z -> nothing) search $k \geq 17$ TeV

lower bound from hypothesis that extra dimensions fix gauge hierarchy : $k \leq O(10 \text{ TeV})$

$$1\times10^{-10} < \frac{\Gamma(\text{O}-\text{Ps} \to \text{nothing})}{\Gamma(\text{O}-\text{Ps} \to 3\gamma)} < 4\times10^{-9}$$

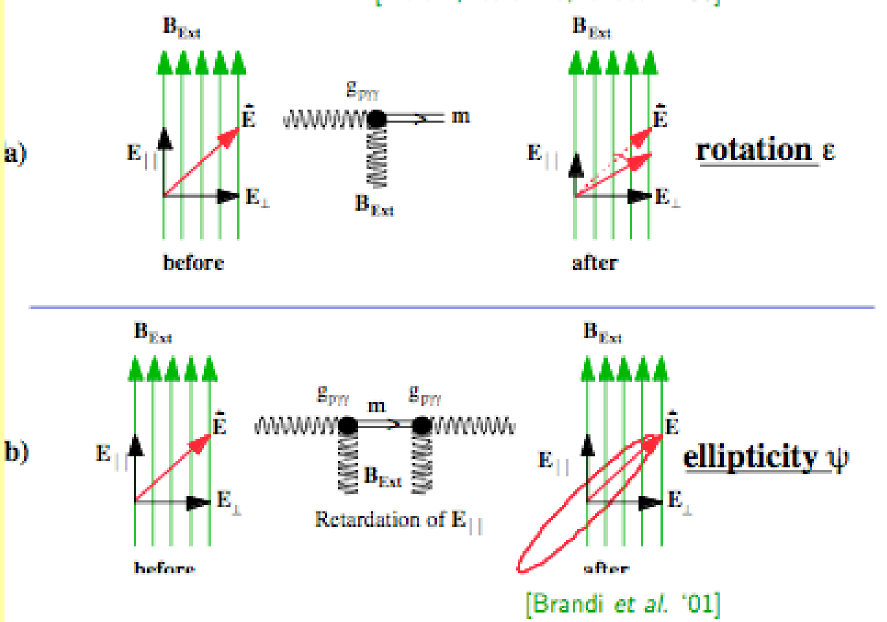
Invisible decays could also be caused by :

- Fractional charged particles (q ~ 10^{-3} e appear in some GUT's)
- New light electroweak vector boson? SSM candidate in (g-2)
- Non-zero neutrino magnetic moment (really small!)

PVLAS anomaly

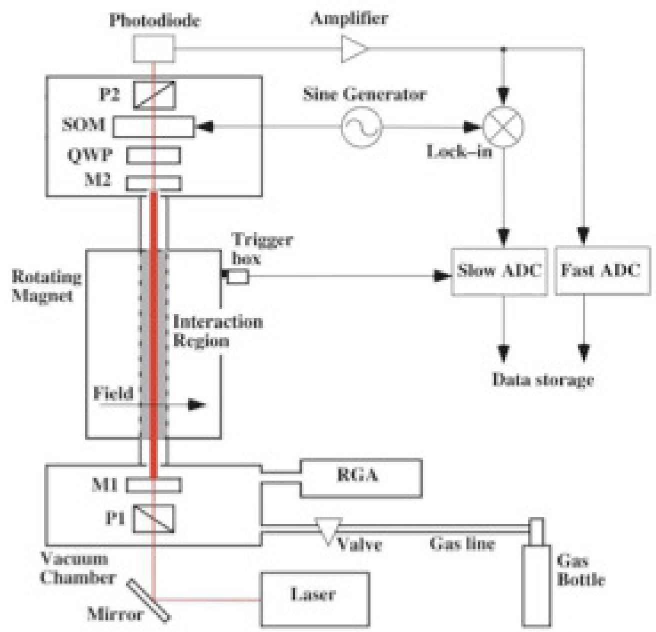
New axion-like particle coulpled to 2 photons: $L \approx g_{a\gamma\gamma}(EB)a$

Effects of Nearly Massless, Spin Zero Particles on Light Propagation in a Magnetic Field



PVLAS experiment: [Zavattini,... PRL '06]

$B = 5\ \mathrm{T}, \ell = 1\ \mathrm{m}, \omega = 1.2\ \mathrm{eV}, N_r = 44000$



$m_a < 1.e\text{-}3$ eV, $g_{a\gamma\gamma} \sim 10^{-6}$ 1/GeV

Search for light (pseudo)scalars at CERN

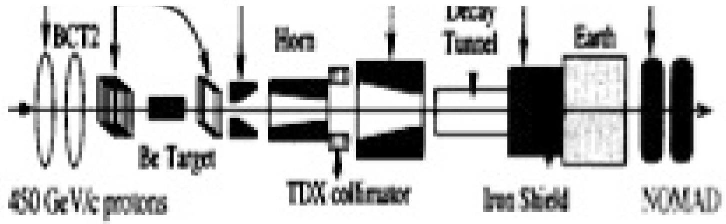
NOMAD, 2000

Search for eV (pseudo)scalar penetrating particles in the SPS neutrino beam

S.N. Gninenko[a*]

[a]EP Division, CERN,
CH 1211, Geneva 23, The Switzerland

(for the NOMAD Collaboration)



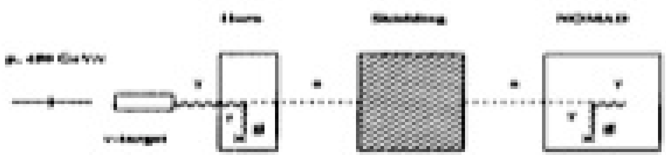
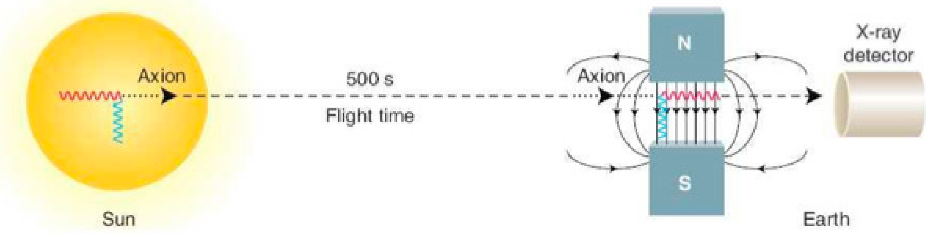


Figure 1. Schematic layouts of the WANF beam line (top) and WANF-NOMAD high energy photon-regeneration experiment (bottom).

CAST, 2006

Principle of the Axion helioscope Sikivie, Phys. Rev. Lett 51 (1983)



Sun: a thermal photon converts into an axion in the Coulomb fields of nuclei and electrons in the solar plasma (Primakoff process)

Earth: an axion converts into a photon in a strong transverse magnetic field

$m_a < 0.02$ eV, $g_{a\gamma\gamma} < 10^{-10}$ 1/GeV

Possible explanation of the PVLAS-CAST discrepancy: millicharged fermions

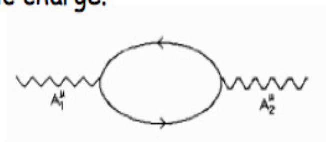
m≈0.1 eV, q ≈ 3x10^{-6} e , Motivated by string theory.

Paraphotons: L.B.Okun, Zh.Eksp.Teor.Fiz 83,892(1982), JETP 56, 502 (1982).

Positronium and charge quantisation

B. Holdom, *Phys. Lett.* **B166**, 196 (1986)

- By adding a second, unobserved photon (the "shadow" photon) one can construct in a natural way grand unified models with a small electric charge.



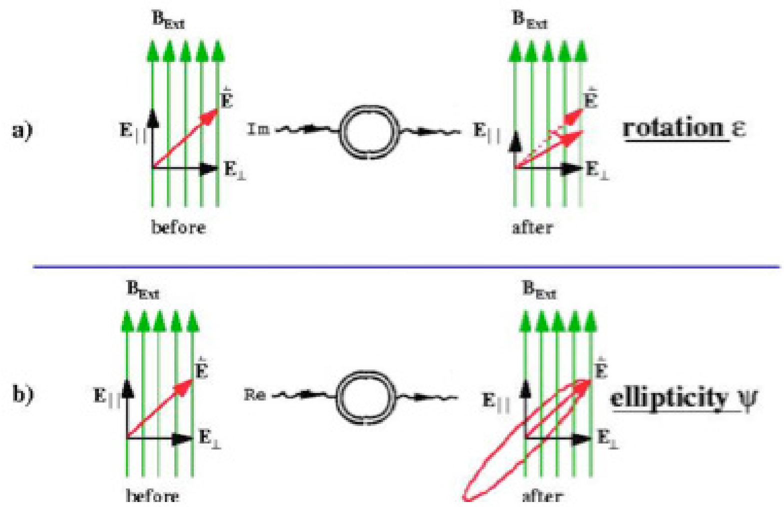
- If milli-charged particles exist o-Ps could decay apparently invisibly since such particles would mostly penetrate any type of calorimeter without interaction

$$Br(o-Ps \to X\bar{X}) = \frac{3\pi\varepsilon^2}{4\alpha(\pi^2-9)}\left[1-\left(\frac{m_x}{m_e}\right)^2\right]^{1/2}\left[1-\frac{1}{2}\left(\frac{m_x}{m_e}\right)^2\right]$$

$$\approx 370\varepsilon^2 \quad for \quad m_x << m_e$$

- Stimulation of new experimental tests (recent SLAC search).

Polarized Light Propagating in a Magnetic Field as a Probe for Millicharged Fermions [Gies,Jaeckel,AR '06]



In analogy to theoretically well-studied e^+e^- real and virtual production

[...;Toll '52;...;Adler '71;...;Tsai,Erber '74,'75;...]

Direct Tests of mQ`s

Search for mQ`s in Reactor Experiments

- Nuclear power reactors with $P > 2$ GW emit more than 10^{20} γ/s
- These γs may convert within reactor into $\epsilon^+\epsilon^-$ pairs
- A small fraction of these particles could lead to an observable excess of electrons from $\epsilon^\pm e^-$ scattering in a detector
- Recent results from the TEXONO experiment set up at the Kuo-Sheng Nuclear Power Station (2.8 GW) in Taiwan probing for $\mu_{\overline{\nu}_e}$ by searching for an excess of events from νe^- magnetic scattering [TEXONO Coll. '03]

⇒ Bound on fractional electric charge,

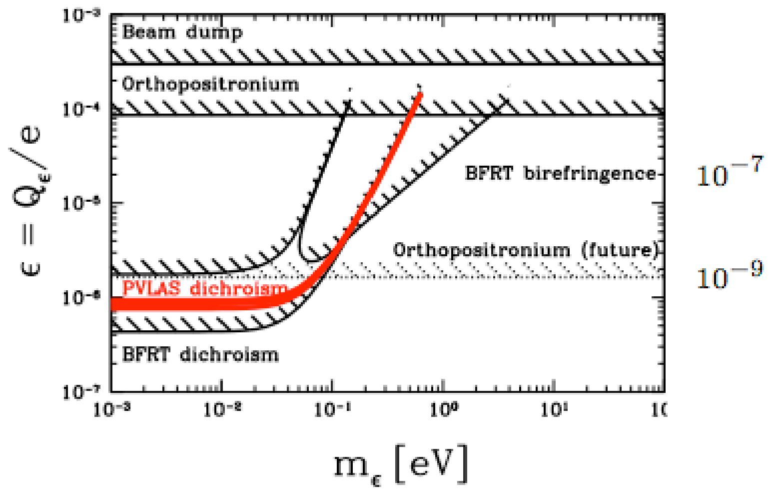
$$\epsilon \lesssim 10^{-5}, \text{ for } m_\epsilon \lesssim 1 \text{ keV}$$

- May be improved in near future with massive liquid argon detector

[Gninenko,Krasnikov,A.Rubbia '06] PRD,2007

"Search for Invisible Orthopositronium Decay" [Dobroliubov,Ignatiev '89] Gninenko `89

$$\mathrm{BR}(\mathrm{OP} \to \epsilon^+\epsilon^-) \simeq \frac{3\pi\epsilon^2}{4\alpha(\pi^2-9)} \simeq 371\,\epsilon^2$$



[Mitsui *et al.* '93]: $\mathrm{BR}(\mathrm{OP} \to \mathrm{inv.}) < 2.8 \times 10^{-6}$

[Badertscher *et al.* '06]: $\mathrm{BR}(\mathrm{OP} \to \mathrm{inv.}) < 4.2 \times 10^{-7}$

INR: First experiment on o-Ps -> nothing

"A search for photonless annihilation of orthopositronium,"
Atoyan, Gninenko, Razin, Ryabov , Phys. Lett. B 220, 317 (1989).

Motivated by : LEP1 Z->*invisible* , and mostly by Dobroliubov, Ignatiev, Matveev: *π-> 2 photino*, **Sov.J.Nucl.Phys.47:296,1988, Yad.Fiz.47:468,1988**.

- Radioisotope Ps source (^{22}Na)
- Generate trigger on ^{22}Na decay (positron + 1.2 MeV photon)
- Detect energy of all e+ annihilations
- Subtract p-Ps -> 2γ events in NaI spectrum
- "Difference of two large numbers" problem
- Statistics, background limited

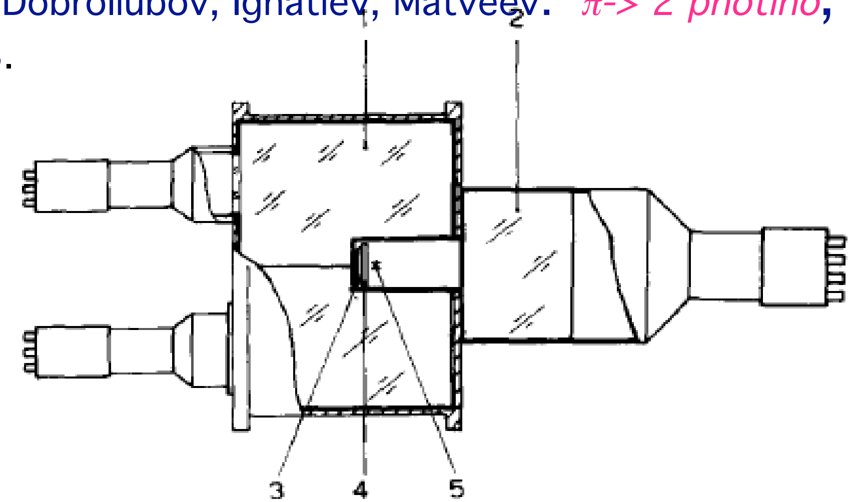
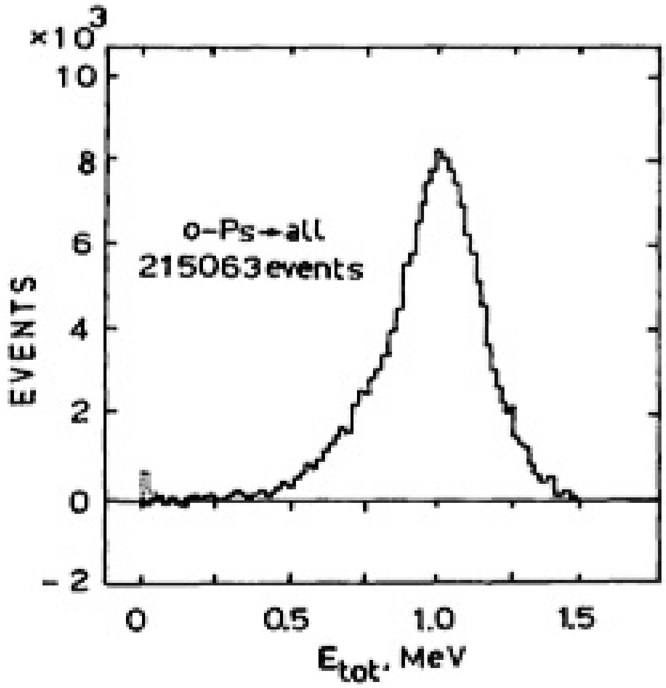


Fig. 1. Schematic view of the set-up: (1): NaI calorimeter; (2): NaI counter (3): target; (4): proportional counter; (5): the positron source ^{22}Na.



$$\frac{\Gamma(O-Ps \to \text{nothing})}{\Gamma(O-Ps \to 3\gamma)} < 5.8\times10^{-4}$$

Cannot be resnonsible for o-Ps decay rate anomaly.

Tokyo experiment on o-Ps -> nothing

- Radioisotope source: 22Na
- Composite trigger: (e+) & (1275 keV)
- 840 kg calorimeter mass
- “High resolution” 1275 keV trigger
- Statistics, PMT noise limited

T. Mitsui *et al.*, PRL **70**, 2265 (1993).

$$\frac{\Gamma(\mathrm{O-Ps} \to \mathrm{nothing})}{\Gamma(\mathrm{O-Ps} \to 3\gamma)} < 2.8 \times 10^{-6}$$

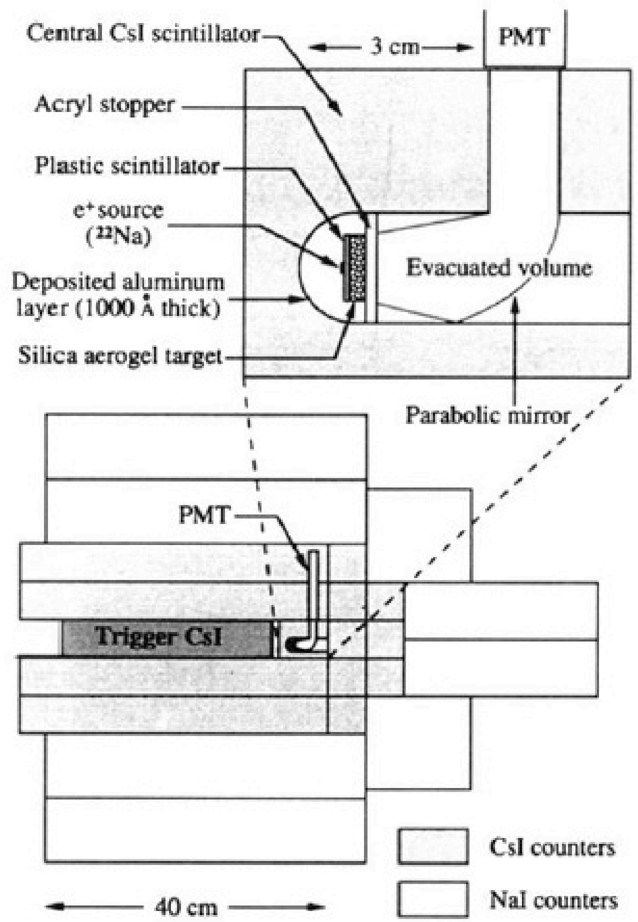
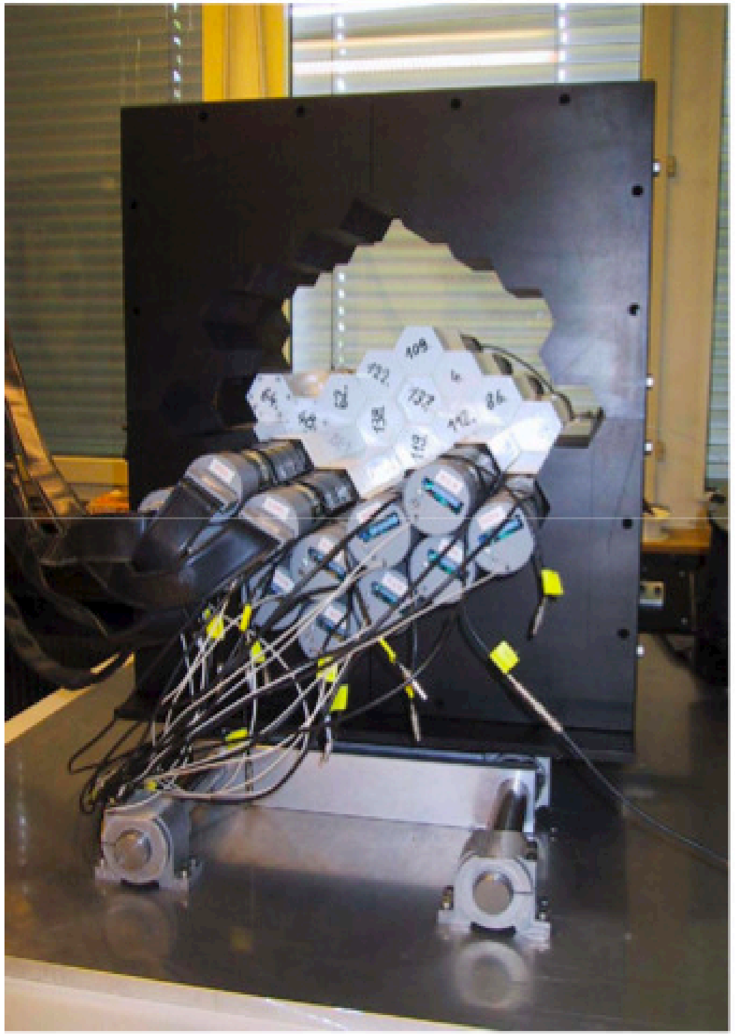
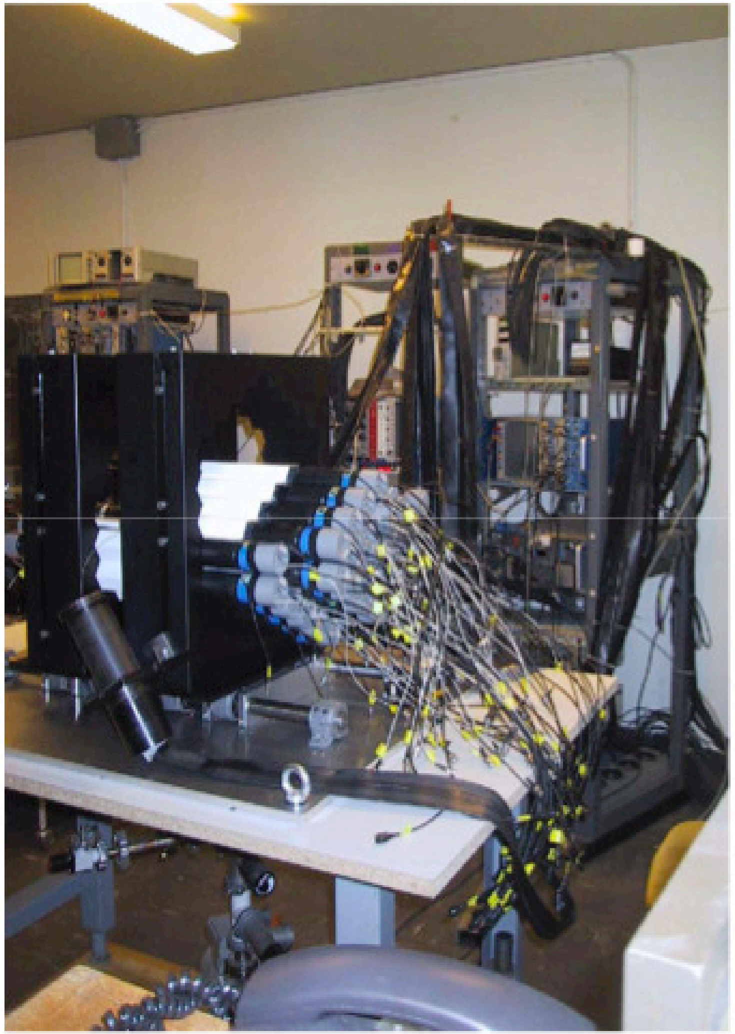


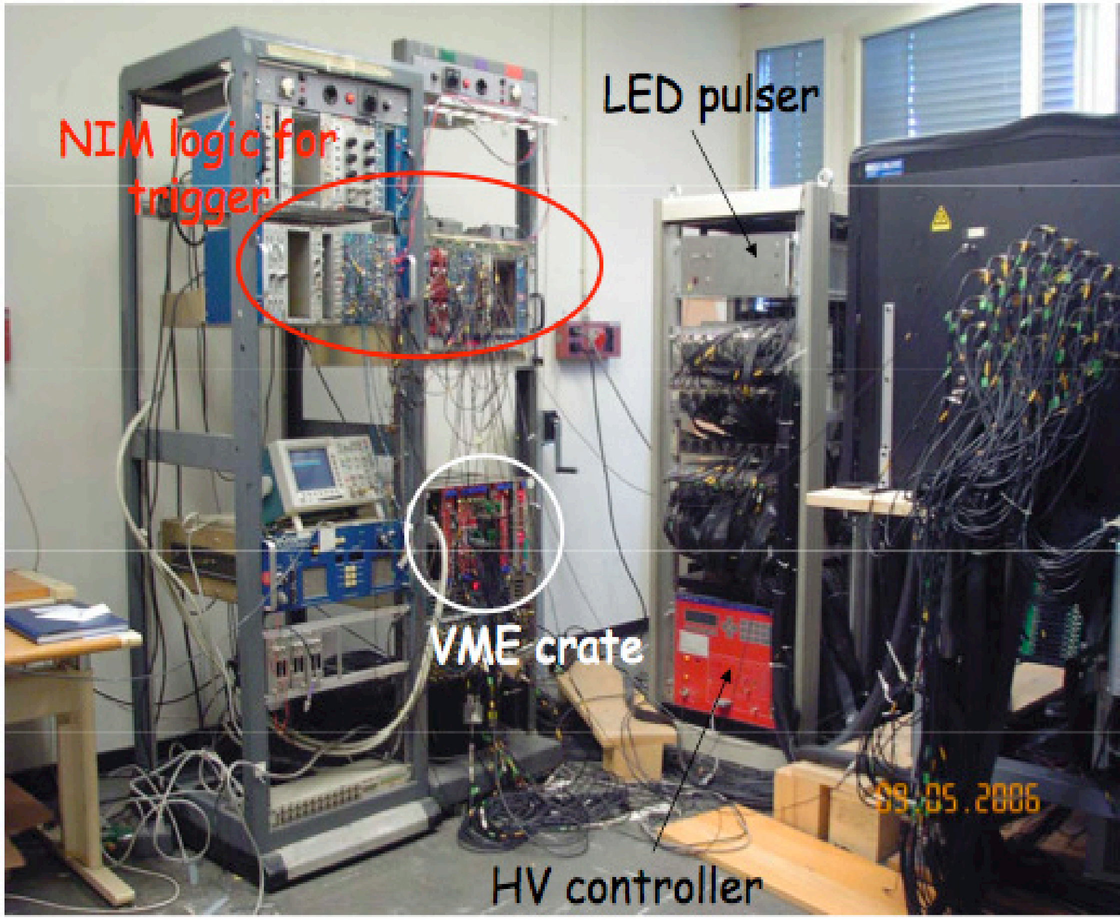
FIG. 1. Schematic of the experimental setup.

Photograph of the calorimeter (assembling phase)

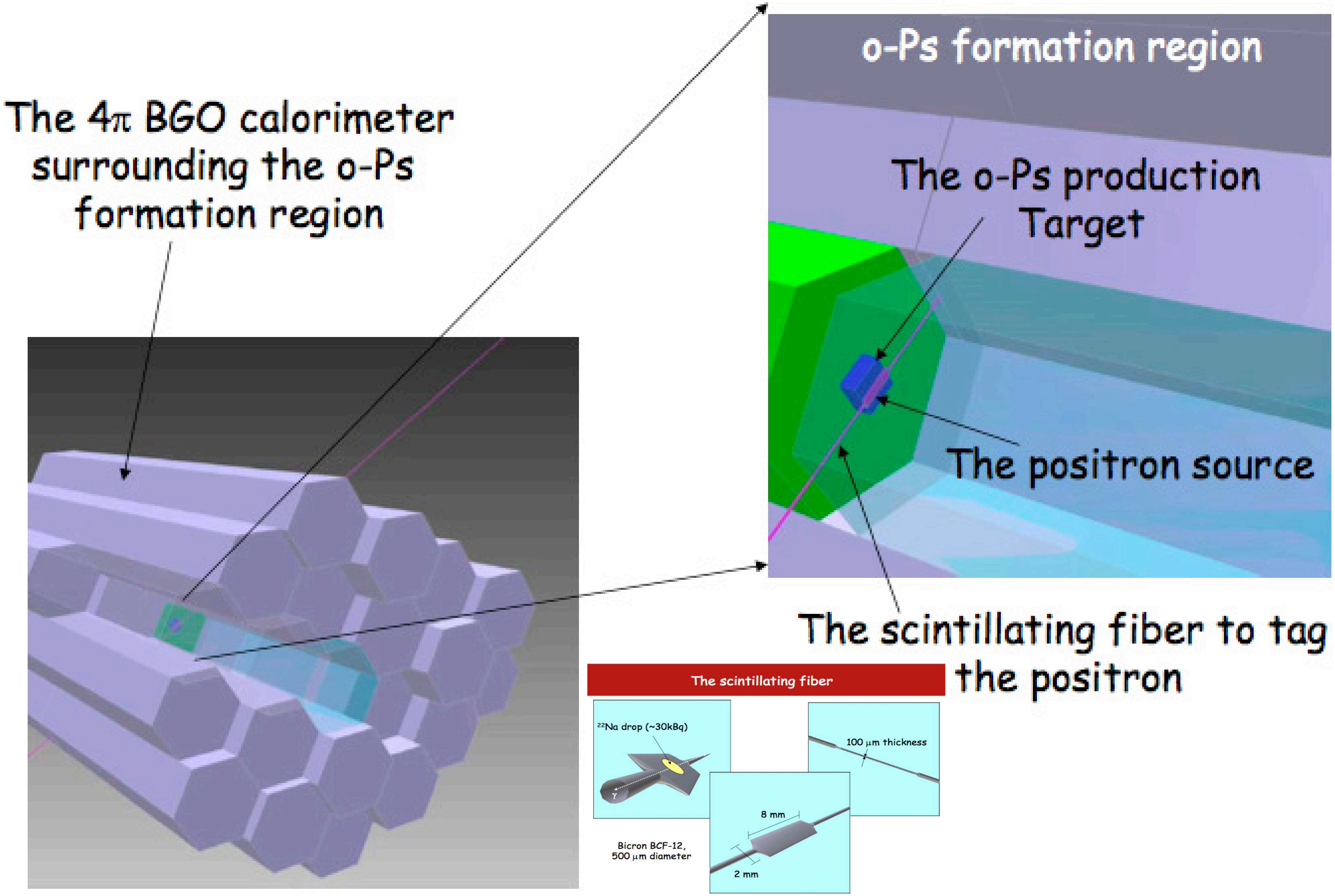




Picture of the lab



The o-Ps formation region



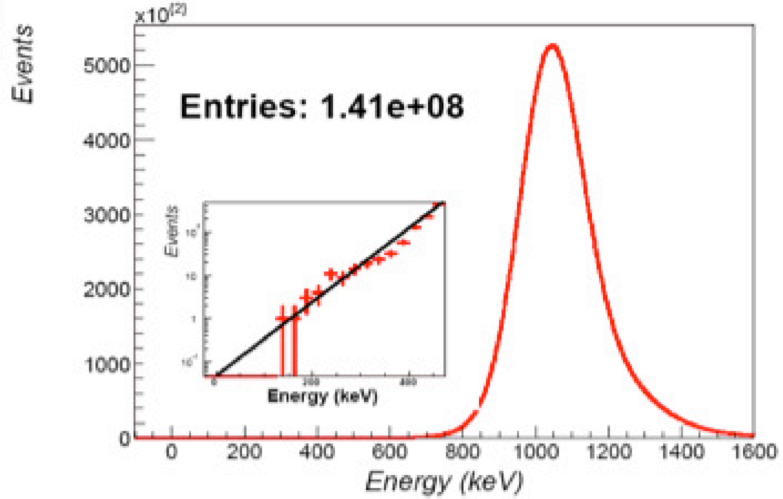
Results

A.Baderscher et al., PRD(2007)

DATA	Air	Nitrogen	Combined
Fiber triggers	0.6×10^{10}	0.79×10^{10}	1.39×10^{10}
Selected events	0.61×10^{8}	0.8×10^{8}	1.41×10^{8}
o-Ps fraction	3.41 %	5.29 %	4.48 %
Number of o-Ps	2.08×10^{6}	4.23×10^{6}	6.31×10^{6}

Data taking period: 4.5 months

1.39×10^{10} triggers



After the selection cut one can perform the sum of the total energy in the calorimeter

$$E_{tot} = \sum_{i}^{all} E_i - E_{TBGO}$$

Since no event is observed in the signal region, this result provides an upper limit on the o-Ps -> invisible

$$Br(o-Ps \to invisible) = 2.3/(N_{o-Ps}\cdot\epsilon) \le 4.2\times10^{-7}$$

factor ~7 better than Tokyo

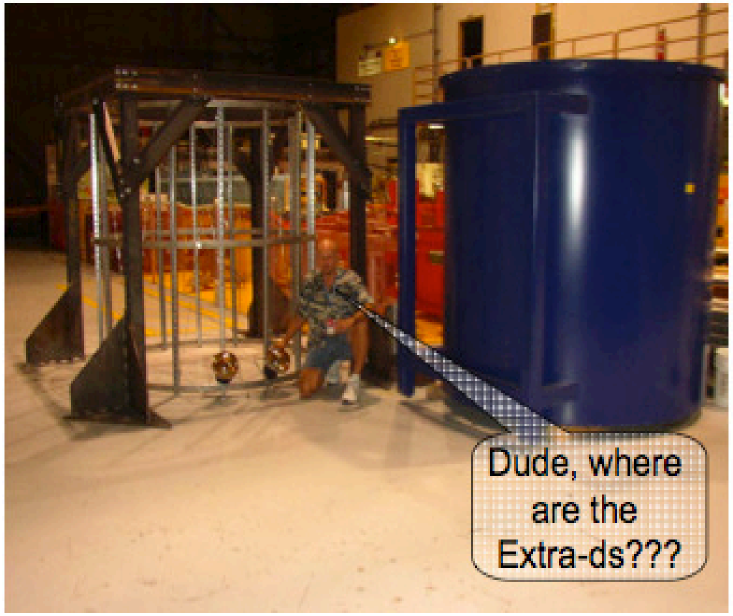
$$Br(p-Ps \to invisible) = 2.3/(N_{p-Ps}\cdot\epsilon) \le 4.3\times10^{-7} \text{ (90\% C.L.)}$$

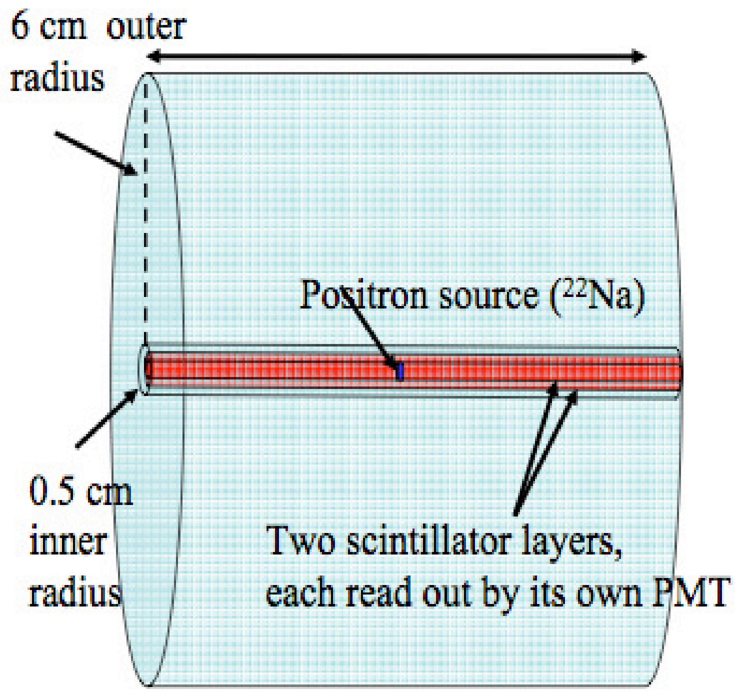
$$Br(e^+e^- \to invisible) = 2.3/(N_{e^+e^-}\cdot\epsilon) \le 2.1\times10^{-8} \text{ (90\% C.L.)}$$

VLADD
VLAnd extra Dimensions Detector

http://home.fnal.gov/~hray/

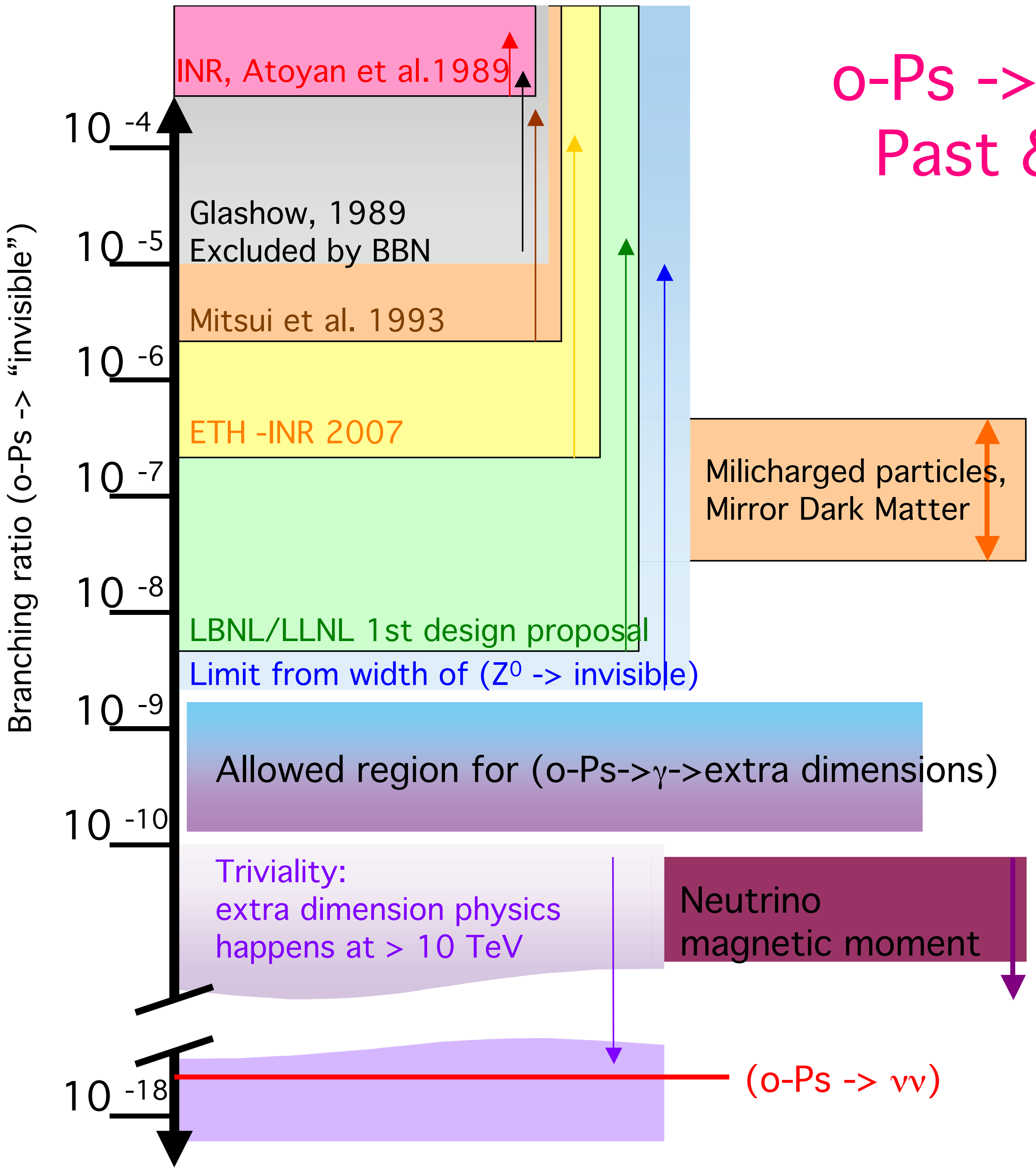
Authors	Heather Ray (LANL)
	Richard Van de Water (LANL)
	Paul Vetter (LBL)
	Janet Conrad (Columbia)
	Mike Shaevitz (Columbia)





Goal: Br(oPs->nothing) ~10^{-9}

o-Ps -> nothing: Past &Future



P. Vetter
LBNL, 2006

Hidden Sector: Mirror Matter

Kobzarev, Okun, Pomeranchuk (1966)

Recent rewiew: Okun, hep-ph/0606202; UFN 177, 397(2007)

P -> CP -> CPA -> oPs-> nothing decay in vacuum

Could well be at the level 10^{-4} - 10^{-6}

Mixing strenght

- Tokyo group claimed $\varepsilon<10^{-8}$, however this resulted to be wrong due to high collision rate of o-Ps in their target, suppression factor is proportional $1/N_{coll} \approx 10^{-4}$. Taking this into account one get $\varepsilon < 10^{-6}$

  Gninenko, Phys. Lett. B326, 317(1994)

- BBN limit $\varepsilon<3x10^{-8}$

  E.D. Carlson and S.L. Glashow, Phys. Lett. B 193 (1987) 168.

- ε =4x10^{-9} from the DAMA observation

  R.Foot, astro-ph/0407623

- $10^{-9}<\varepsilon<10^{-8}$ motivated by Grand Unification models

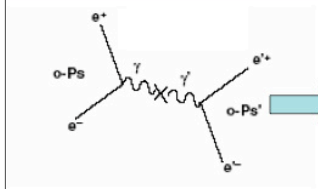
  Berezhiani (hep-ph/0312335)

- All this implies that the sensitivity in *BR(o-Ps→ invisible)* has to be of the order of 10^{-6} for an experiment performed in vacuum

  Experimentally feasible!

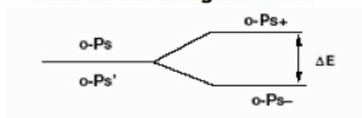
Positronium and the mirror Universe

Glashow, Phys. Lett. B167 (1986) 35



•<u>Breaking of degeneracy</u>: o-Ps is connected via a one-photon annihilation diagram to its mirror version, giving rise to ordinary-mirror oscillations with characteristic frequency εf where f=8.7×10^4 Mhz (contribution of (o-Ps)-(p-Ps) splitting from one-photon annihilation)

- Vacuum mass eigenstates



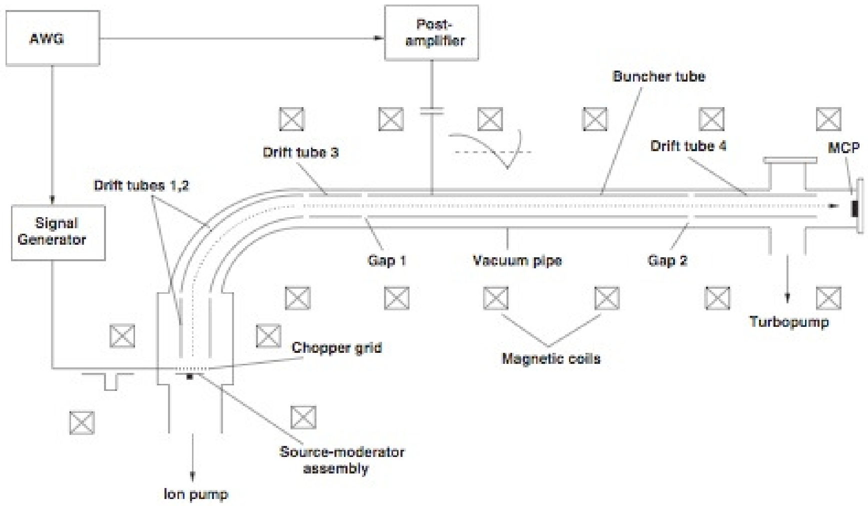
$$\begin{cases}(o-Ps+o-Ps')/\sqrt{2} \\ (o-Ps-o-Ps')/\sqrt{2}\end{cases}$$

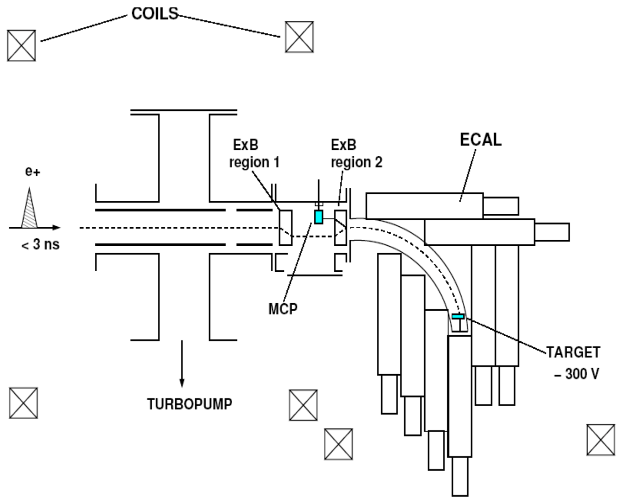
•Energy splitting: $\boxed{\Delta E = 2h\varepsilon f}$

•Oscillation probability:

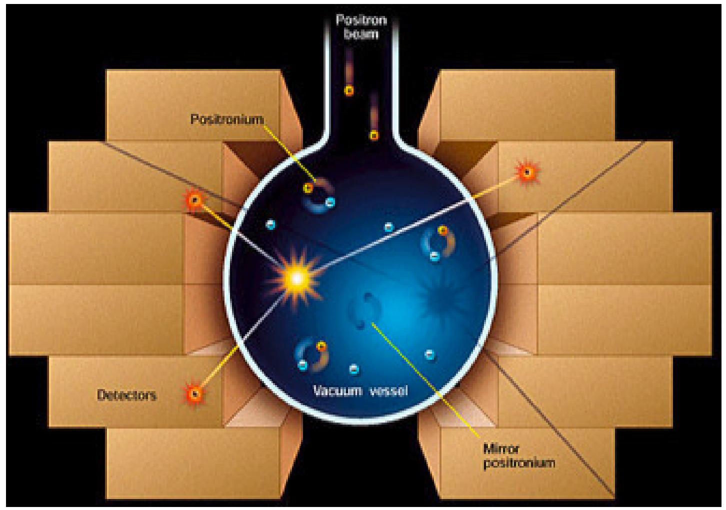
$$\boxed{P(o-Ps \rightarrow o-Ps') = \sin^2(2\pi\varepsilon f t)}$$

"An apparatus to search for mirror dark matter via the invisible decay of orthopositronium in vacuum,"
A. Badertscher *et al*. hep-ex/0311031



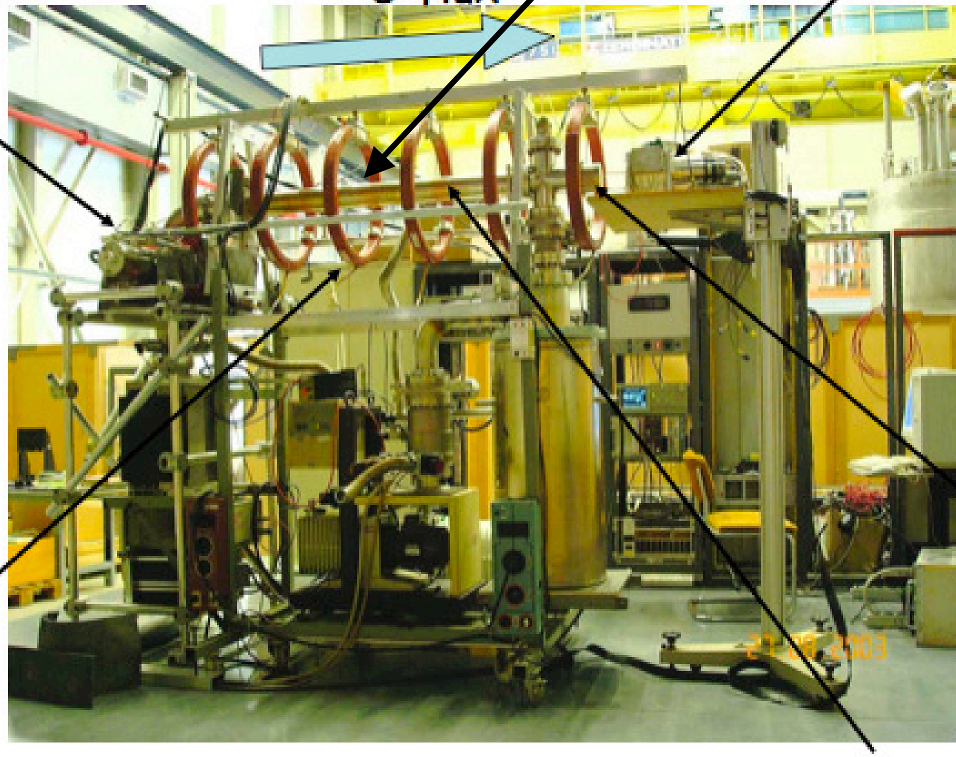


- e+ tagging system: timing coincidence of e+ bunch and MCP signal from secondary electron emission , inefficiency < 1.e-8
- pulsed slow positron beam, high efficiency & compression factor
- cold oPs to minimize leak through entrance window
- hermetic calorimeter in magnetic field
- very thin vacuum pipe



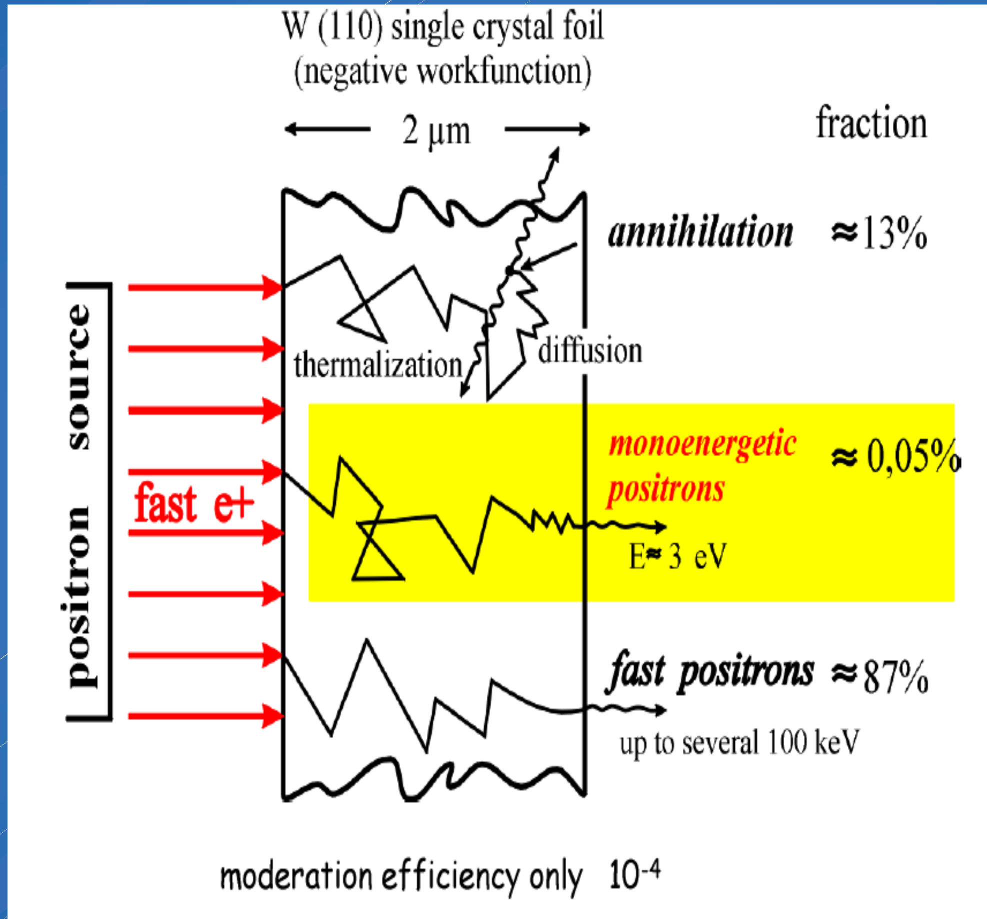
New Scientists, 2004.

The slow positron Beam



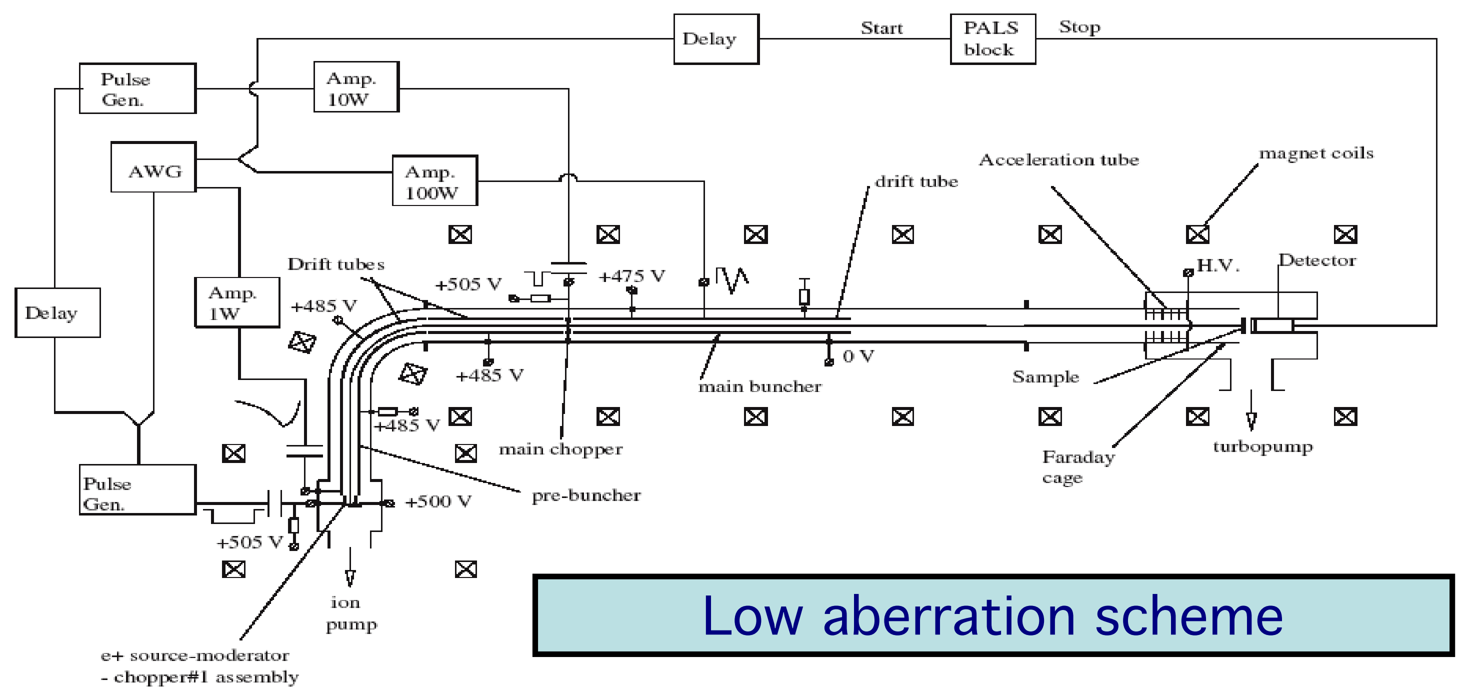
Positron moderation

- e^{+}s strike a W single crystal foil
- Slow to epithermal energies in ~10^{-12} s
- Diffuse ~ 500 nm. Either annihilate, or
- Escape through a surface with E ~3 eV. Efficiency ~10^{-4}
- Difficulties:
  - annealing at 2000 C to remove deffects
  - UHV for lifetime of the surface



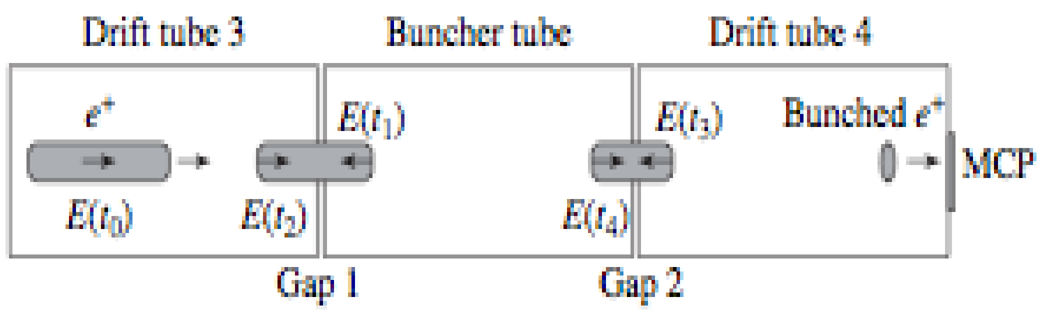
http://positron.physik.uni-halle.de

Pulsing System

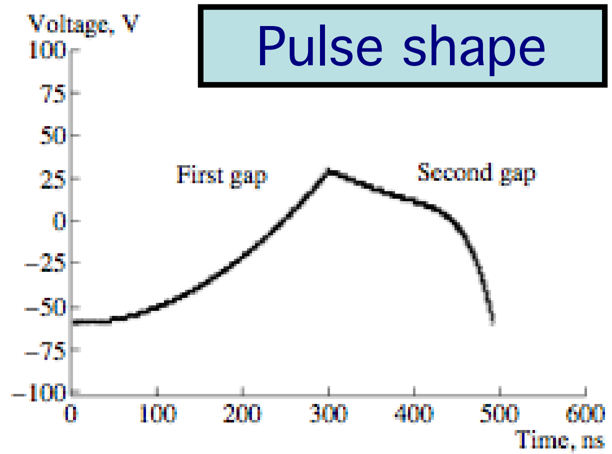


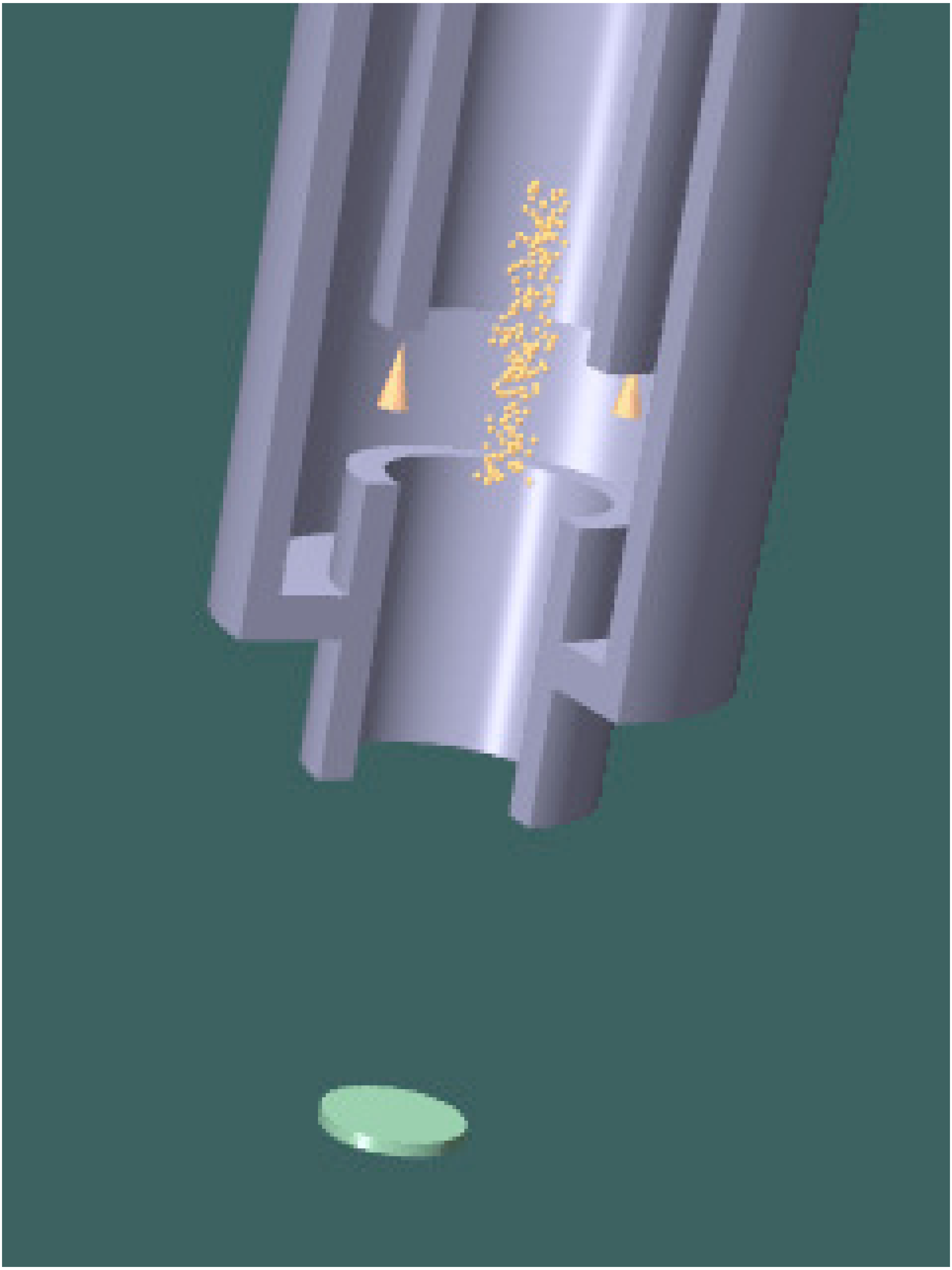
Low aberration scheme

Double gap buncher

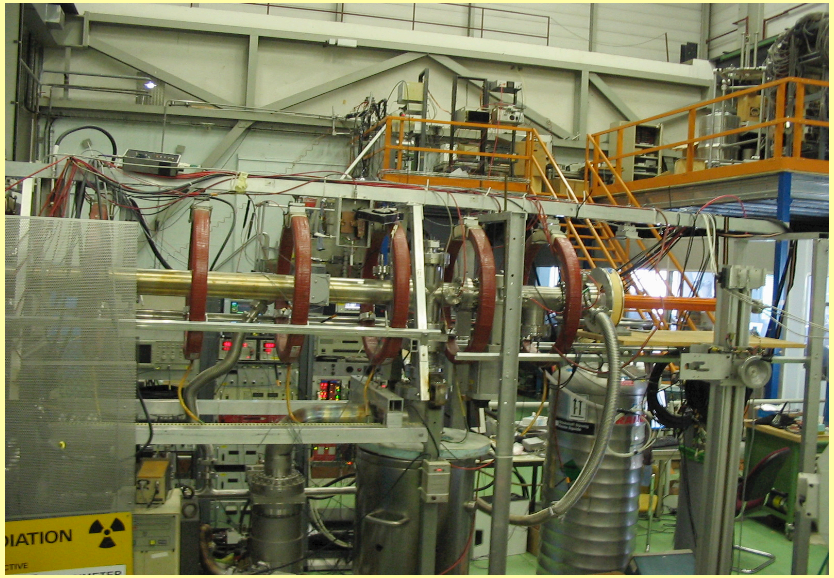


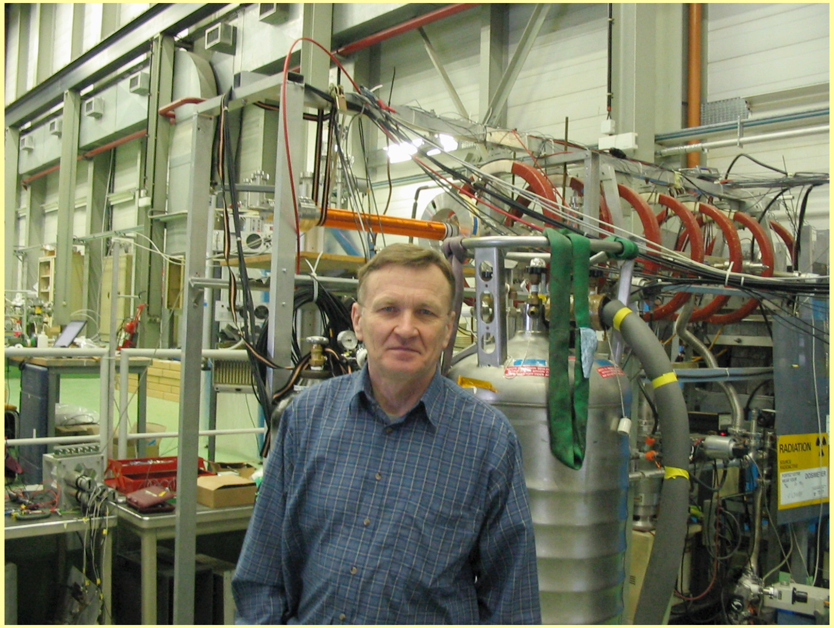
Pulse shape

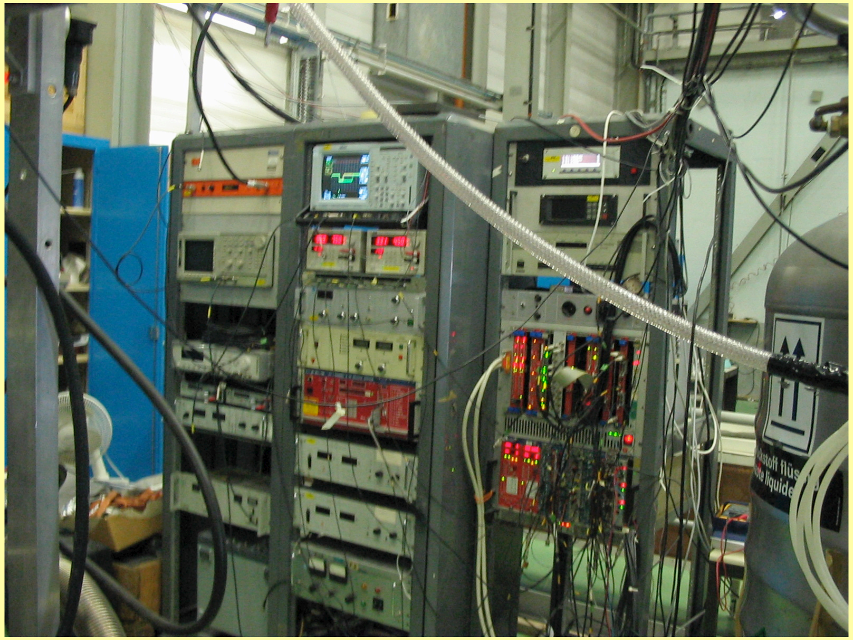




Beam Photos





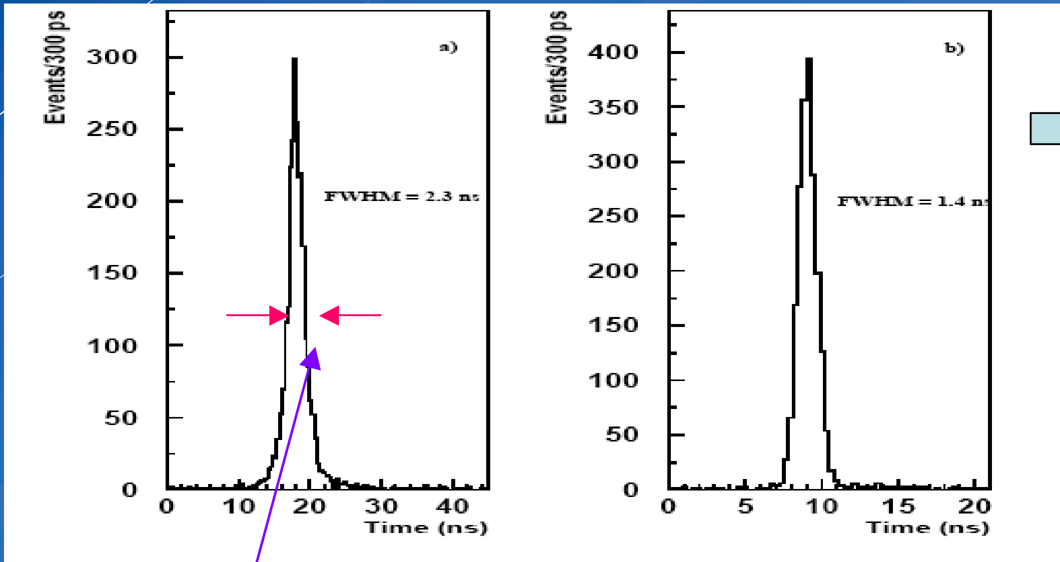


Results on positron pulse width

Alberola et al., Nucl. Instr. Method A 560 (2006) 224-232

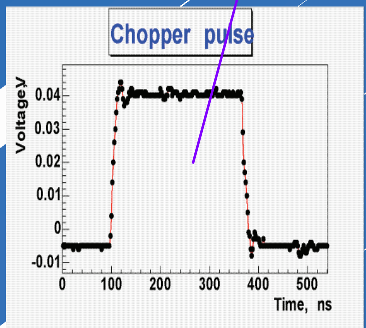
~ 2.3 ns (FWHM) for an Initial pulse of 300ns

~1.4 ns (FWHM) for an initial pulse of 120ns



Compression factor 100!
5 times better than reported previously by two groups in Japan

Repetition period ~ 1 μs



Tokyo Univ. group, H. Iijima et al.
NIM A483 (2002) 641: Compression of

~ 60 ns → ~ 2 ns (FWHM)

Cold Ps formation target

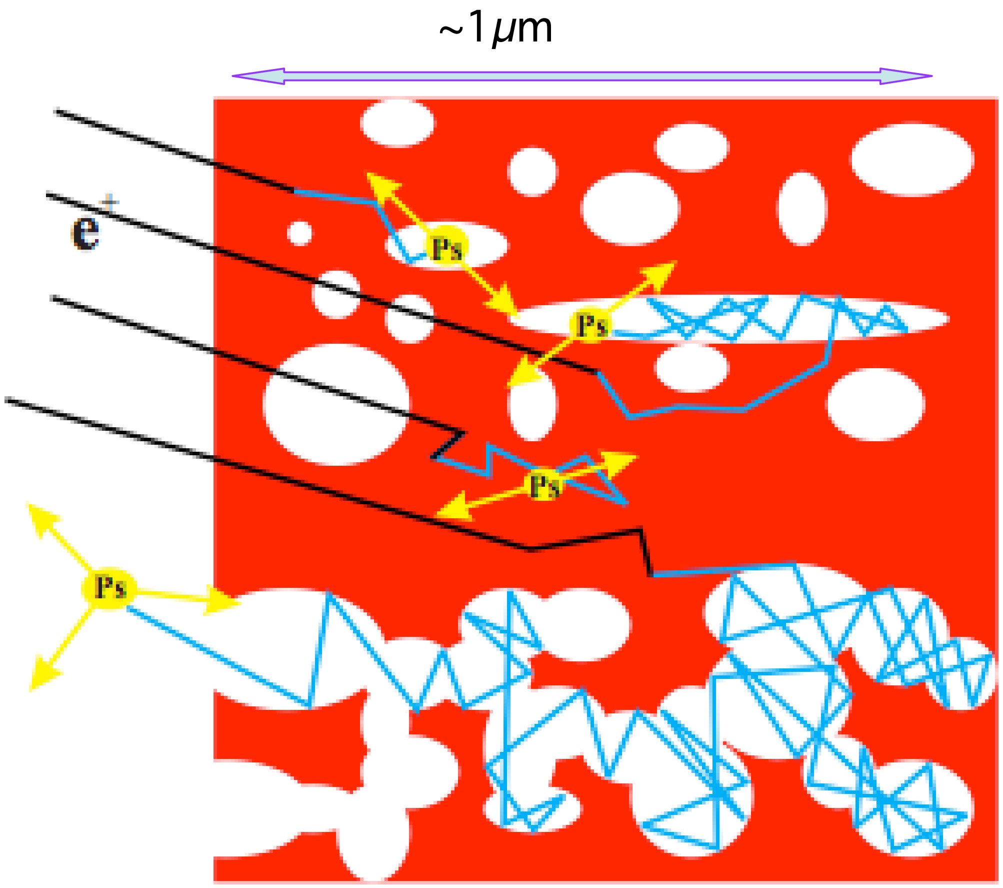


Figure 1 Positronium formation in porous materials.

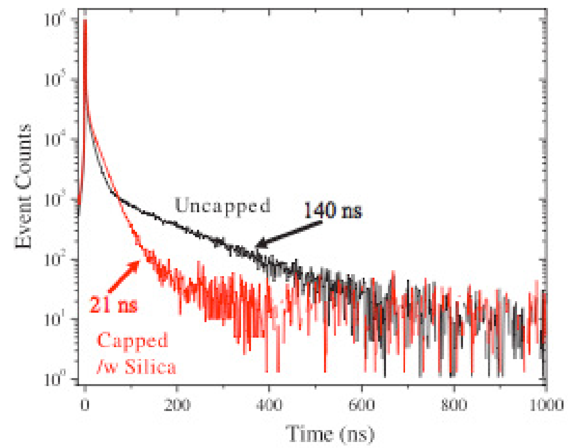


Figure 4 Typical Ps lifetime spectra for a film with open porous network (*black*) and after capping (*red*).

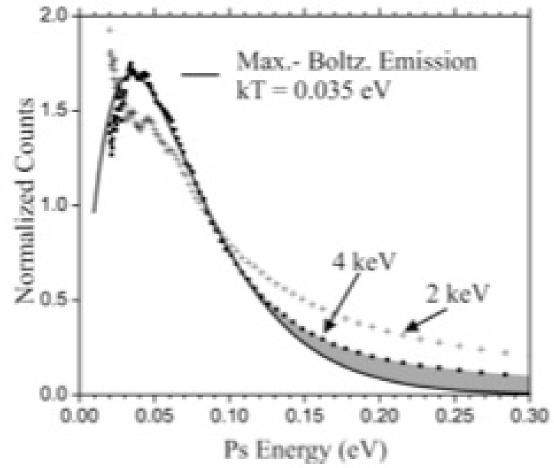


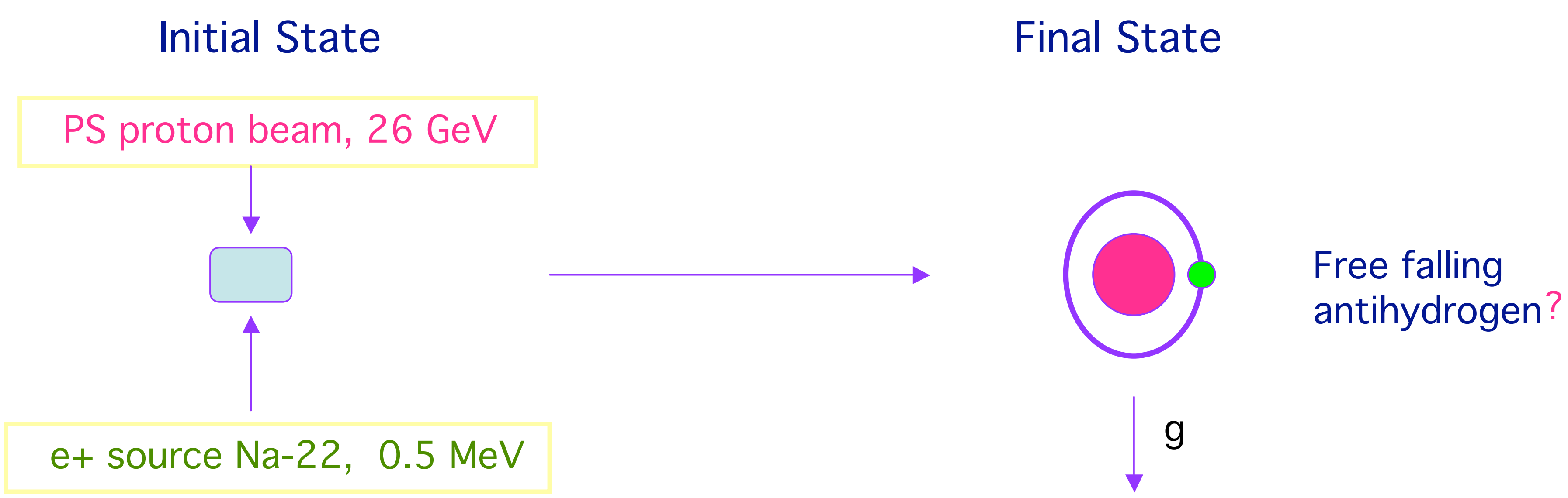
FIG. 2. The energy distribution of *o*-Ps emitted from a typical porous silica film. Note that higher energy positrons implanted more deeply (solid circles) in the film produce more thermalized *o*-Ps with fewer events in the epithermal tail.

Ps formation in porous Si films

to minimize the leak.

Could be crutial for Hbar formation!

Antihydrogen study at CERN: AEGIS

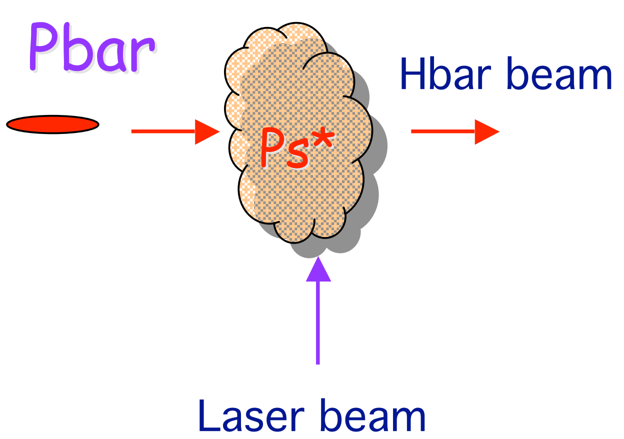


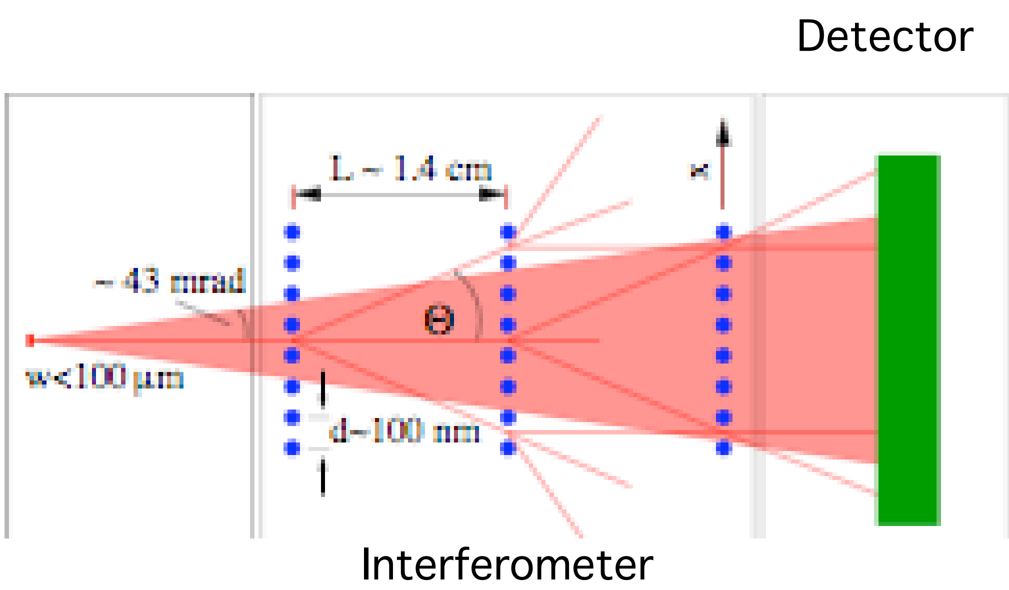
goals

- CPT in Hbar
- free gravity fall of Hbar
- Ps physics

Experimental setup for Hbar gravity fall

Cold Rydberg State Ps
Ps Temperature < 10 K



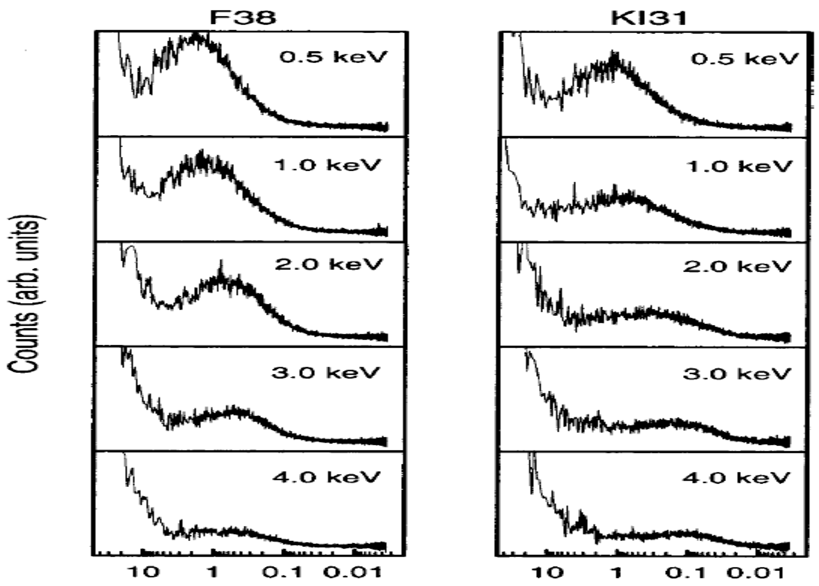


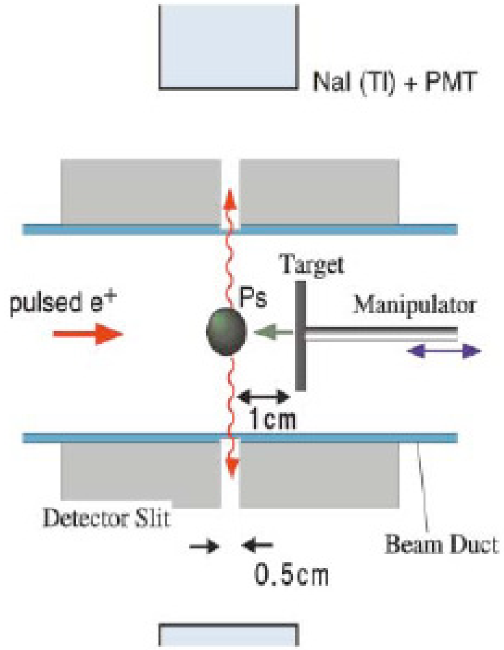
$$\sigma(\bar{p} + Ps^* \to \bar{H}) \sim n_R^3$$

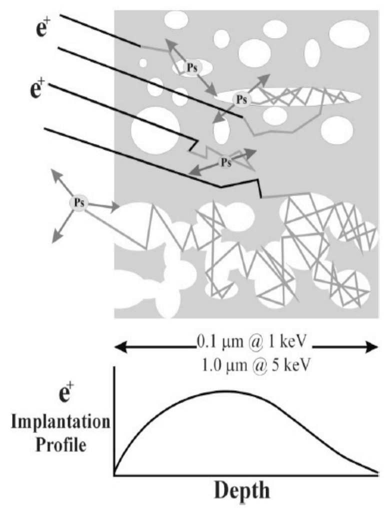
$$v_{Ps} = (3kT/m_{Ps})^{1/2} < \alpha\, c/2n_R$$

Q`s:
- how to check Rydberg n?
- Ps laser cooling? (too complicated)
- Ps thermalization time?
- B field?

Cold Ps: TOF-study of yield and temperature







- e+'s stop, thermalized, form o-Ps
- o-Ps yield:~30-40% emitted into vacuum
- mean free path ~ 3 nm, diffusion length L>> film thickness
- number of collisions with pore walls 10^4 - 10^6 (depending on implantation depth/energy)
- well thermalized E(o-Ps) ~ kT
- thermalization time t~R/V n
  t~1 ns << τ (o-Ps)
- E = 40 meV, V=1.2 10^7 cm/s,
  R ~ 1 cm/lifetime

Slow Positron Beams and Positronium :

Material Researches and Industrial Applications

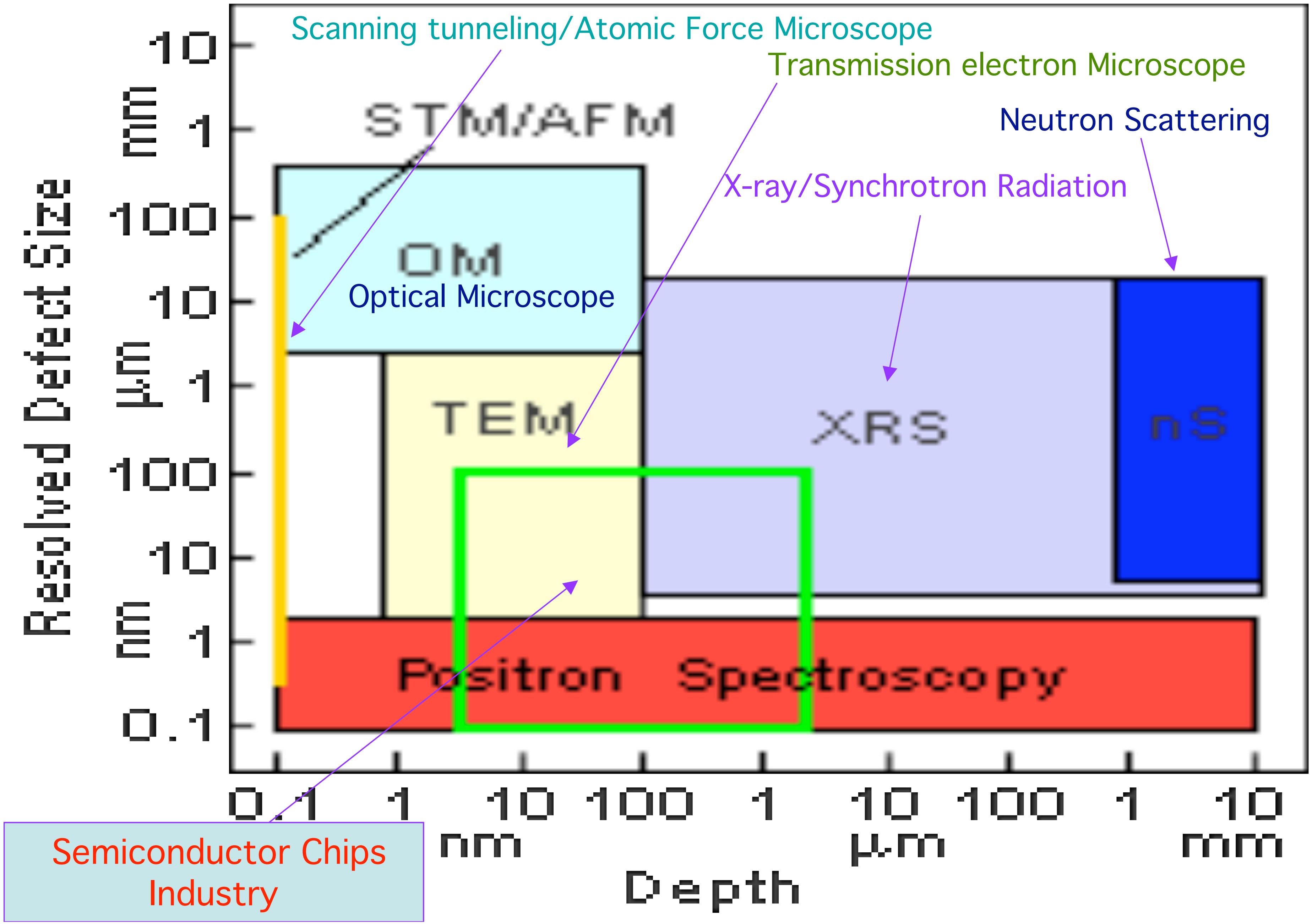
Materials science forum, ICPA-13, JAPAN

There is no doubt that, when it comes to the study of the structures and defects of nano-materials, there is presently no technique that rivals positron annihilation.

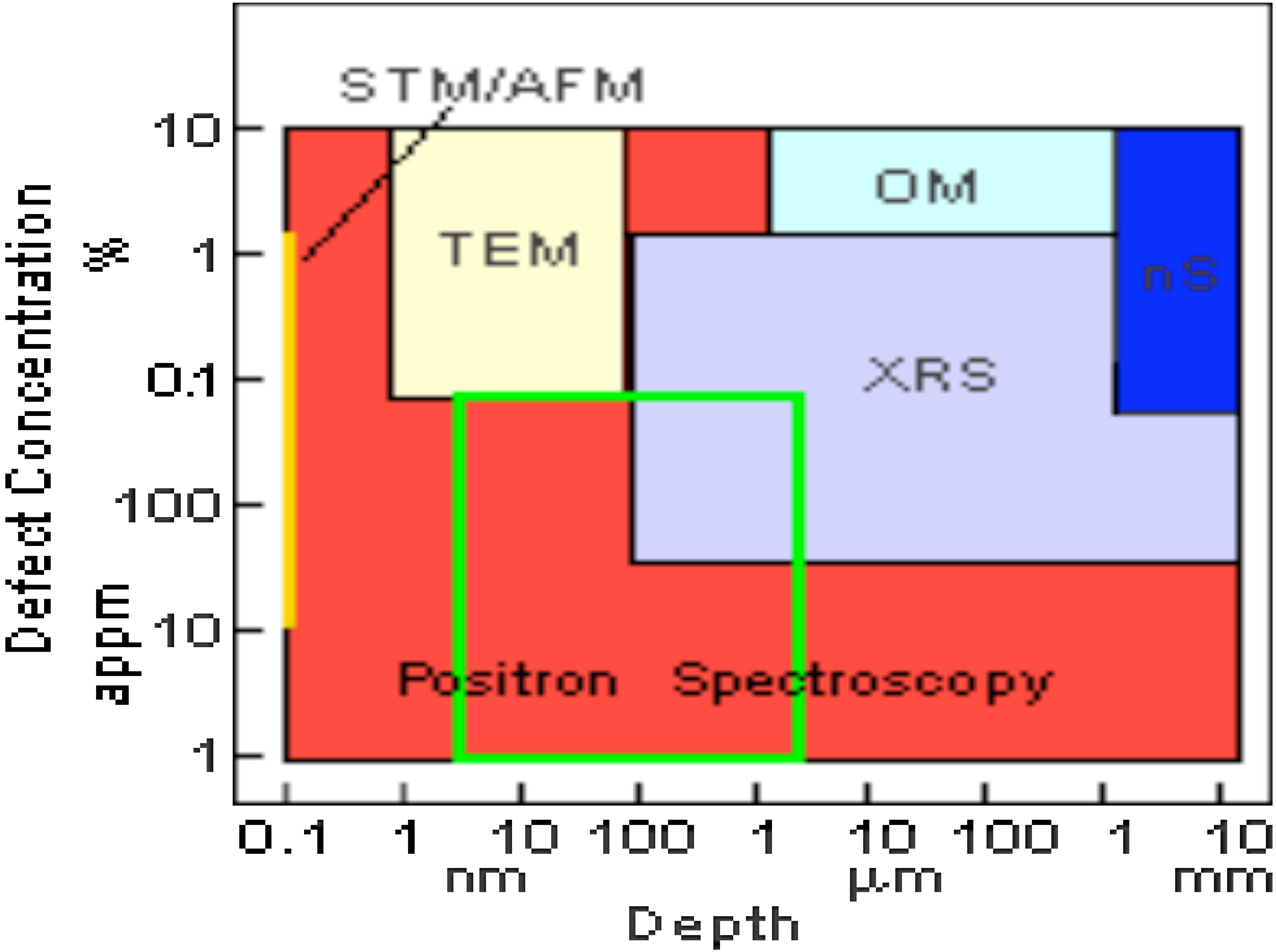
- Slow positron beam application to: Polymers, Drug-delivery and Cancer Researches
- PAS study of Radiation ebrittlement of Nuclear Reactor Steels
- Slow positron study of corrosion defects in Metallurgy iron and Al alloy.
- Application of PAS technique for monitoring of Semiconductors
- Pulse slow-positron beam for Polymer films
- PAS for nanocavities and nanoclusters in Si
- Durability of polymeric coatings for Aircraft Industry
- Application of PAS for biological objects
- …………
- Energy Storage
- POSITRON Bomb

} Simposium on Production and Storage of Macro-quantities of e+`s (US Air Force)

Comparison of Different Techniques for ID of Defects



Comparison of Different Techniques for ID of Atomic Defects



Facilities and Labs
for Positrons Nanoscience and Technology

USA: 25

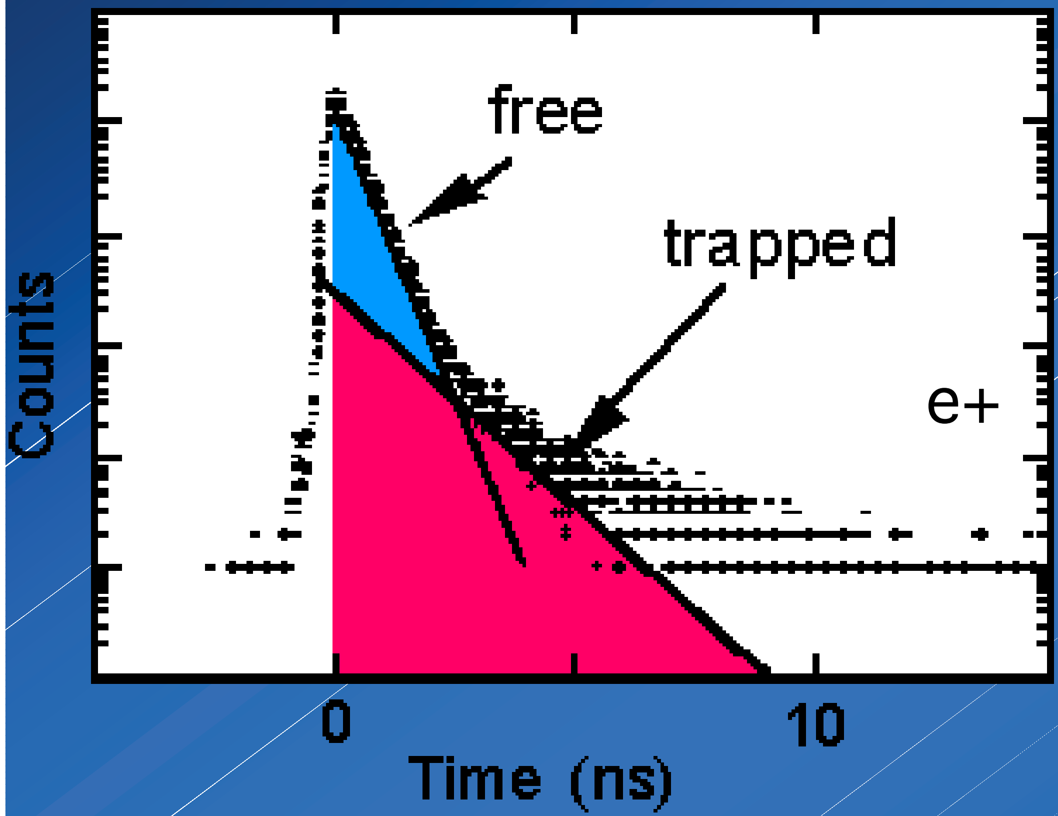
Japan: 10

EU: 30

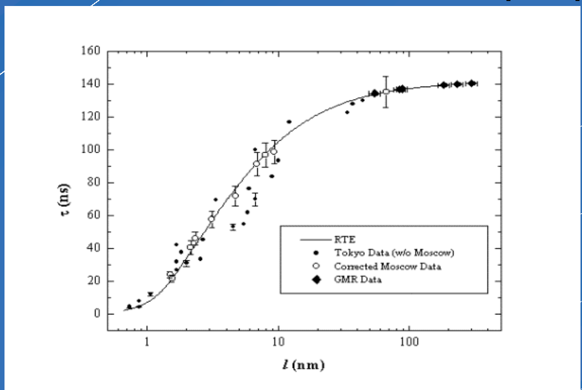
- Washington Center of Material Researches, USA
- EPOS , Research Center , Rossendorf, Germany
- National Inst. of Advanced Industrial Science and Technology, Japan
- e.g. no PALS beam in France, Switzerland, . . .

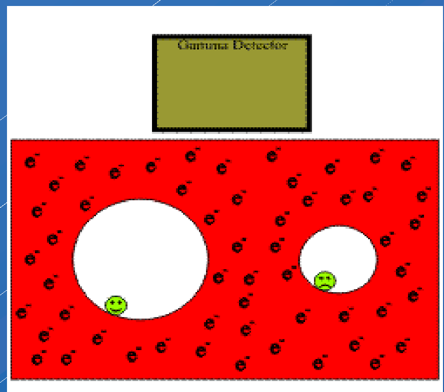
Positron Annihilation Lifetime Spectroscopy(PALS)

Sensitive Probe of Electron Density in Materials



- positron lifetime spectra consist of exponential decay components
- positron trapping in open-volume defects leads to long-lived components
- longer lifetime due to lower electron density
- analysis by non-linear fitting: lifetimes τ_i and intensities I_i
- positron lifetime spectrum: $N(t) = \sum_{i=1}^{k+1} \frac{I_i}{\tau_i} \exp\left(-\frac{t}{\tau_i}\right)$
- $\kappa_d = \mu C_d = \frac{I_2}{I_1}\left(\frac{1}{\tau_b} - \frac{1}{\tau_d}\right)$ (trapping rate κ_d, trapping coefficient μ, defect concentration C_d)





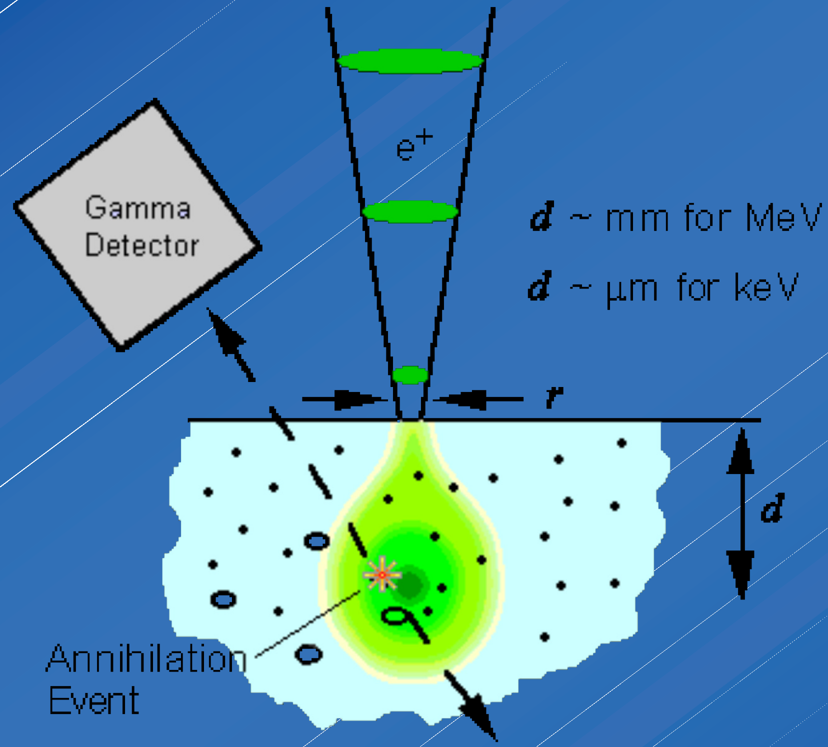
Main Experimental Problems :

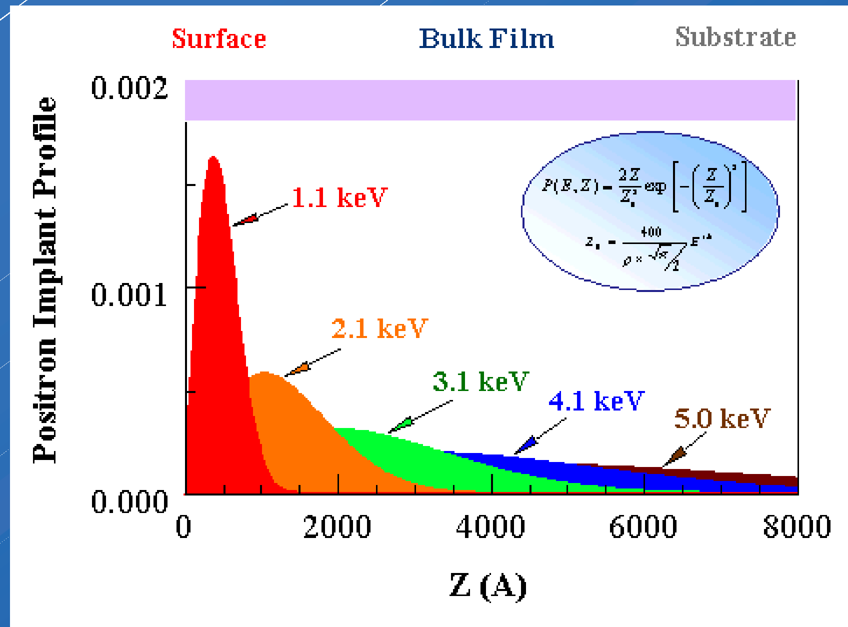
- Time resolution < 0.5ns
- resolution function shape
- peak/background > 1.e3
- wide range of lifetimes from 0.3 to 100 ns

Beam PALS : Depth Profiling of defects

The major advantage of e+ beams is ability to control positron implantation depth by varying the beam energy

Critical feature for analysis of surfaces and thin films





Mokhov`s Implantation Profiles

PALS technique 1: Pulsed slow-positron beam

START: pulsing system, STOP: annihilation gammas

Osaka Univ., 2002

ETH-INR, 2006-2007

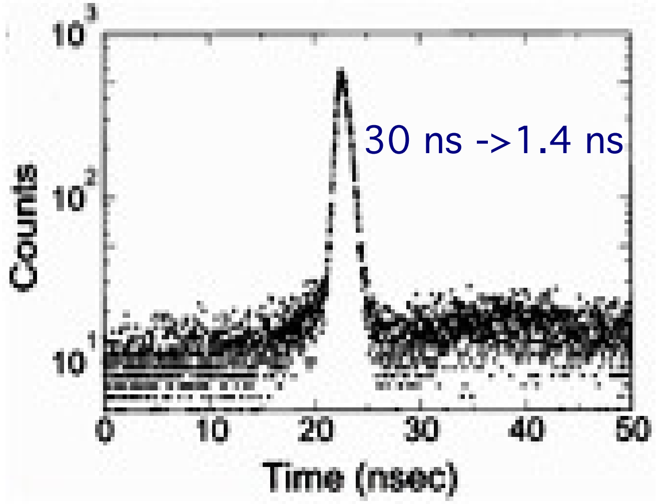


Fig. 7. Positron annihilation lifetime spectrum of the bunched slow positron beam. A copper plate is used as sample.

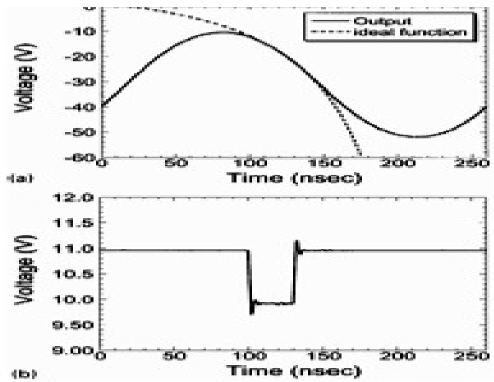
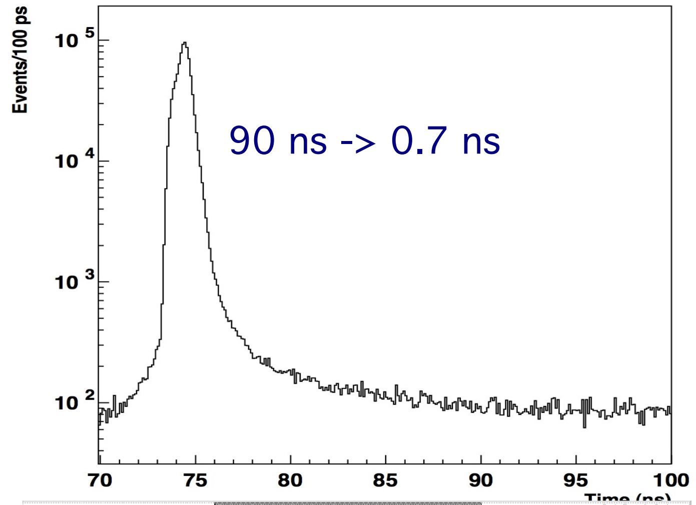
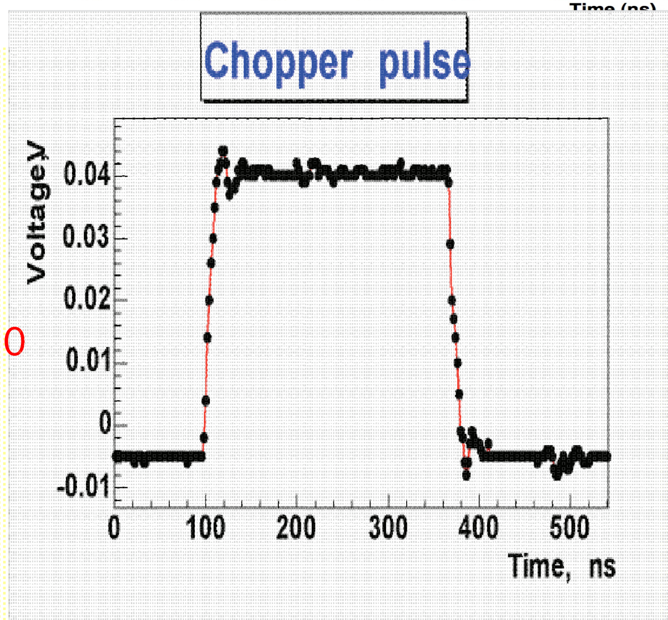


Fig. 6. (a) Optimized waveform generated by AWG and amplified. Dashed line indicates the ideal function. (b) Waveform at the chopper electrode.

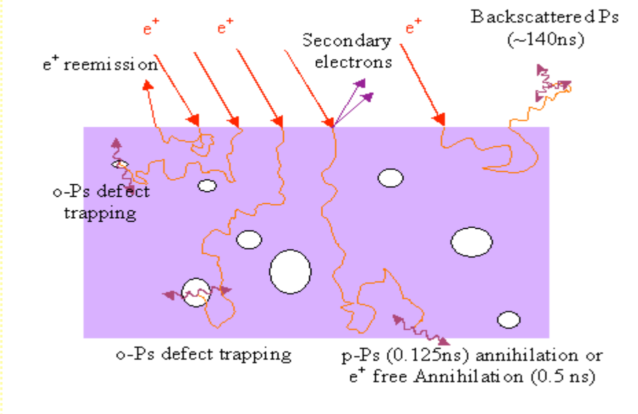
width better ~ 2
Compression ~ 3
Peak/background ~10

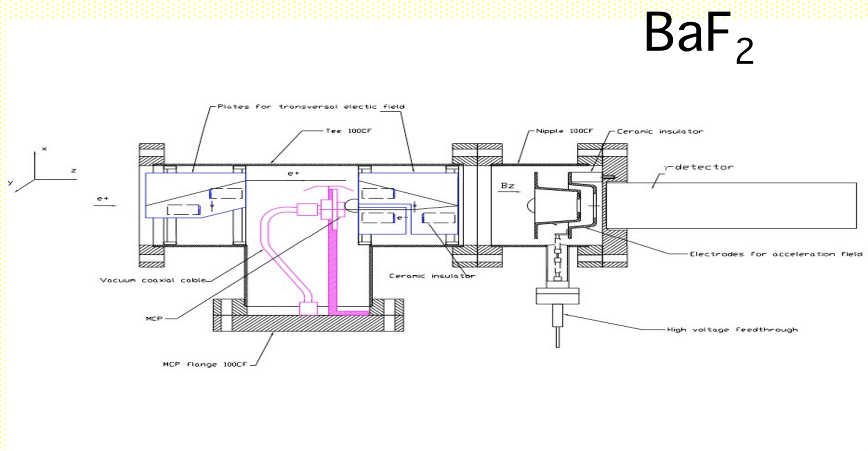




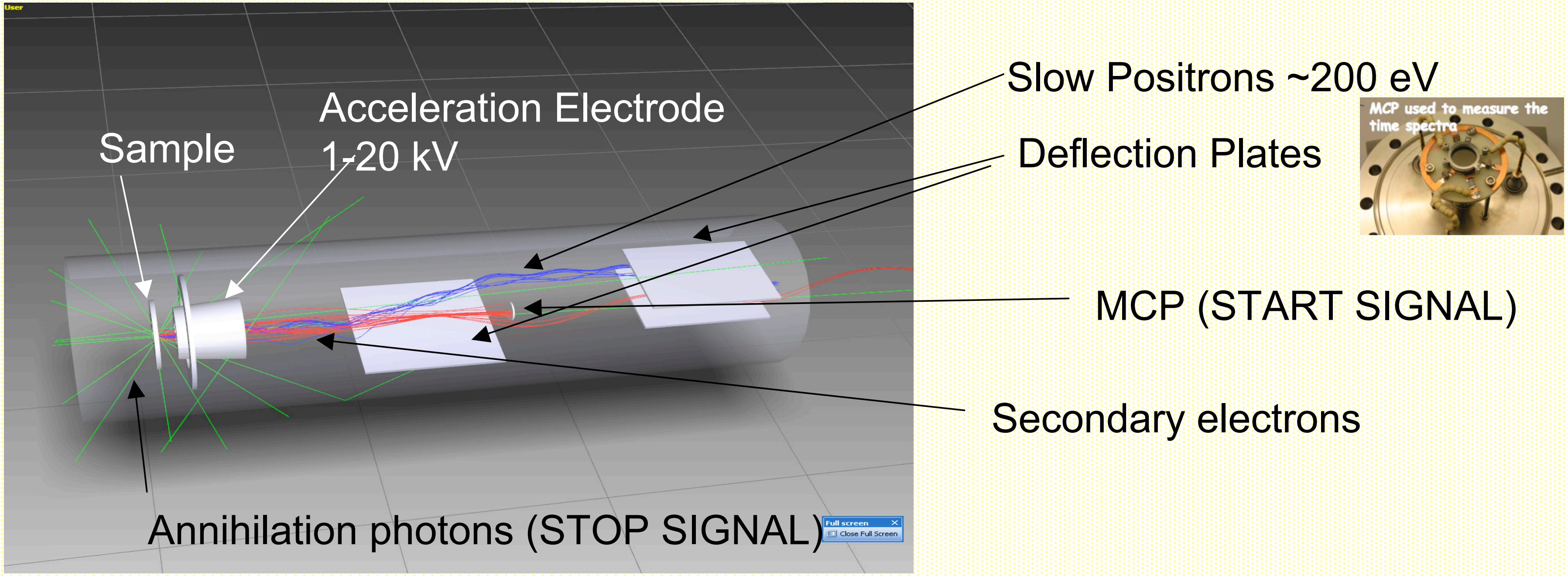
PALS technique 2: Secondary Electron Emission Detector

START: secondary electrons, STOP: annihilation gammas



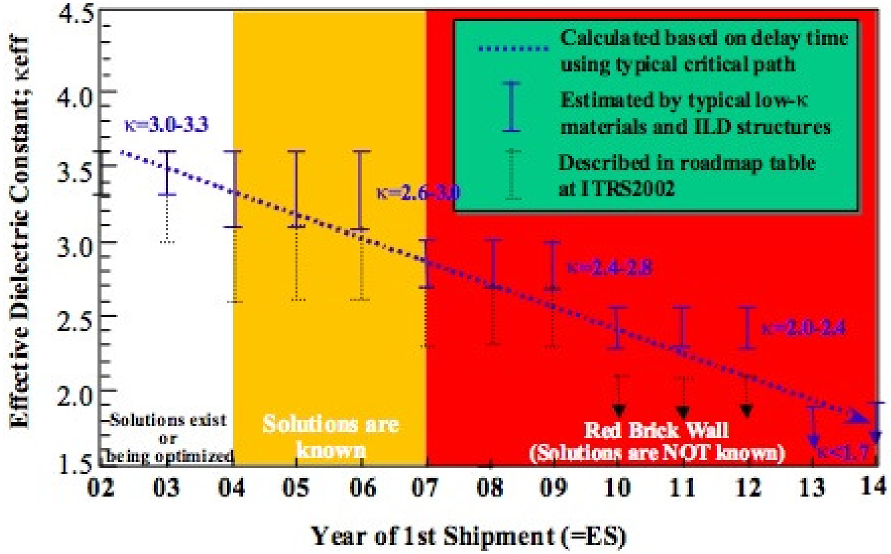


Simulation of SEED extraction optics:



Application to Nanoporous films

The International Roadmap for the Next Generation of Microelectronics



- Today's Microelectronics needs:

-smaller and faster devices ,

-reduction of transistor gate delays.

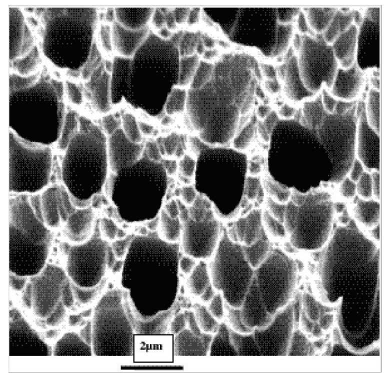
- The signal propagation delay:

- RC delay , R interconnect resistance

- C interlayer dielectric capacitance

- Industry: replacement traditional SiO2 dielectrics(k=4)

  with lower-dielectric constant (low-k) materials



- Candidates for k=2.0-3.5:

- organic and inorganic polymers,

- nanoporous SiO2, etc.

Large pores will be necessary to go down to k~1.0 (air)

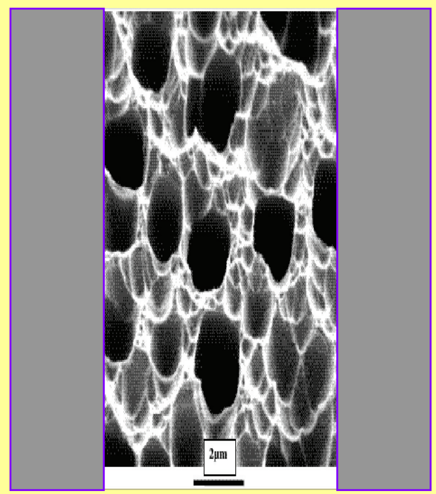
First Results with SEED

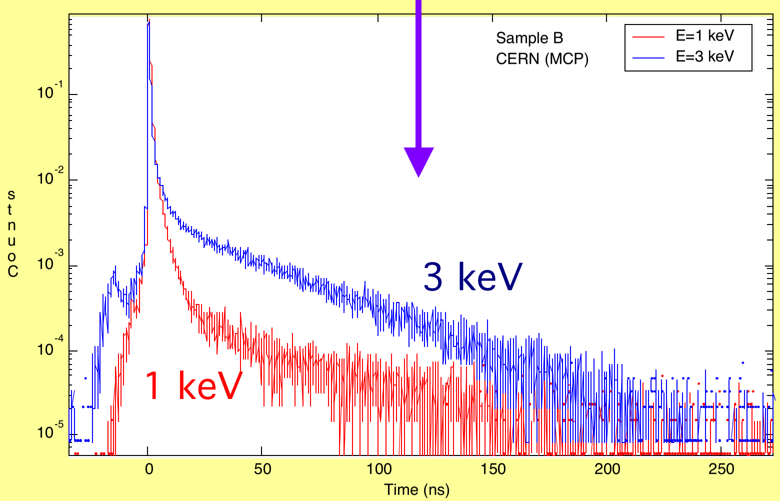
on nanoporous low - k dielectrics films from Microelectronics: thickness and structure of the internal layer are difficult to probe

capping layer
~300Å

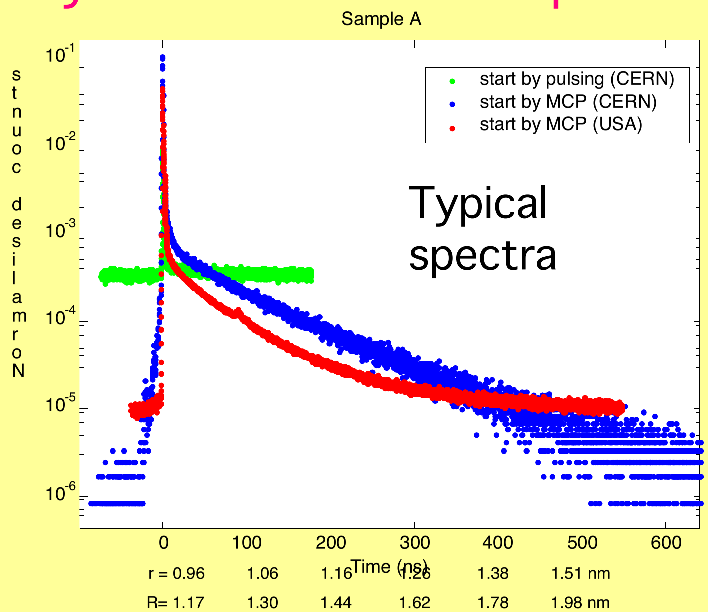
~1000 Å thick

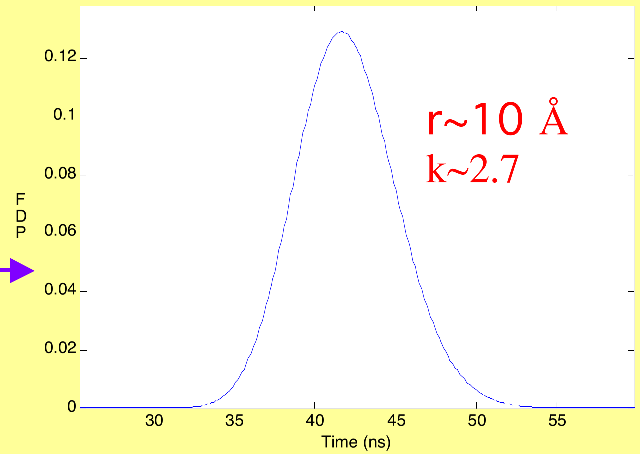
e+





PALS spectra at different energies



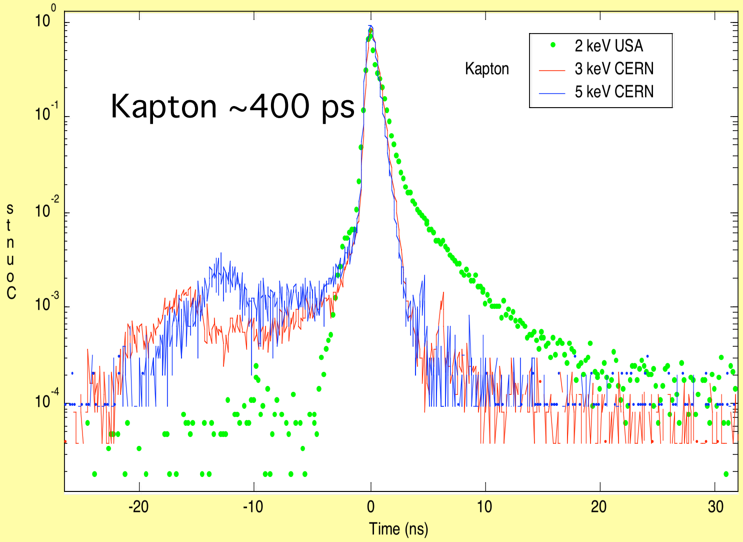


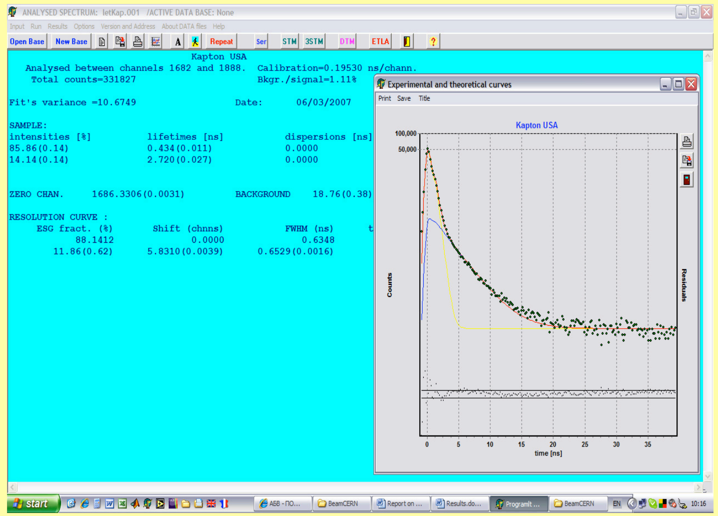
Pore size distribution

Comparison of PALS spectra

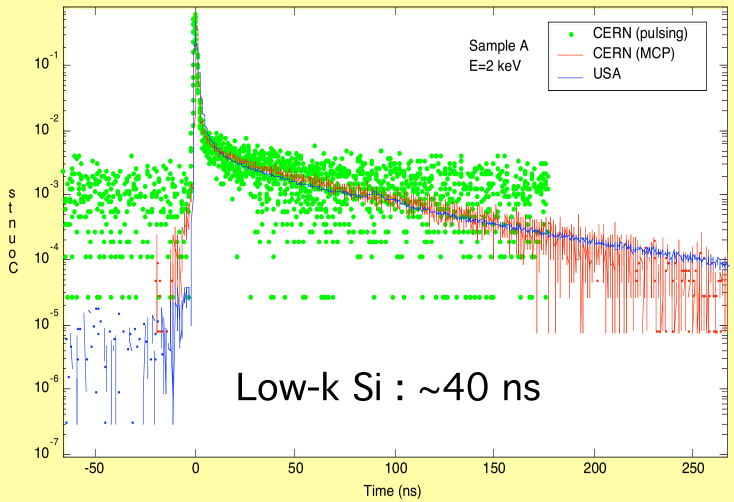
Washington Center of Materials Researches (Prof.K.Lynn,Lab)

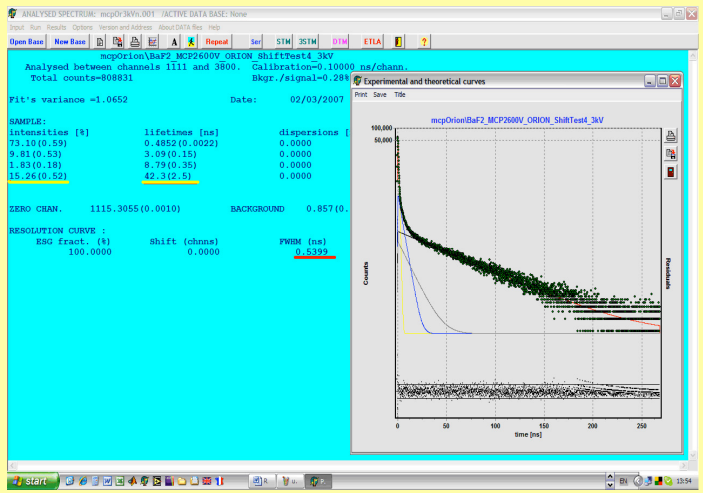
dense





porous





Excellent agreement for wide range of positron lifetimes

SUMMARY

New Multidisciplinary Research Direction on Positron and Ps Physics, including

- precision tests of the SM and searches for New Physics beyond the SM
- developing of new experimental techniques for fundamental and applied researches
- use of developed techniques as an unique tool for Material Researches, in particular for characterizations of nanomaterials and for Industrial Applications

INR Contributions:

Phenomenology:

- millicharged particles
- new light bosons
- extra dimensions
- mirror type matter
- C, CP, CPT tests

Experiments:

- precision measurements with oPs
- searches for exotic Ps decays
- search for hidden sectors (extra D, mirror type matter), best limit on oPs->nothing
- test of PVLAS anomaly
- Hbar

New Experimental Techniques:

- high efficiency slow positron beam
- secondary electron emission lifetime spectrometer
- cold Ps formation
- Simulation tools: SIMION, 3d-B, Geant 4, ..

Positronium Nanoscience and Technology

- low-k dielectric nanoporous films for 3d generation of microelectronics
- surface defects and coatings
- free volumes in polymers
- defects in semiconductors, ...
- Analysis tools: PALFIT, MELT, LT, ...

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