Позитроний:
Фундаментальные и Прикладные Исследования

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15 Февраля 2011

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ПЛАН

- Введение
- Поиск новой физики в распадах позитрония
- Разработка новой экспериментальной техники: пульсирующий пучок медленных позитронов и временной спектрометр на электронах вторичной эмиссии
- Эксперимент по измерению свободного гравитационного падения антиводорода
- Дефектоскопия наноструктурных материалов
- Заключение

High and Low energy approaches to Search for New Physics

SM is not a complete theory, many q`s: what is the origin of masses? how massive are neutrinos? where is and what is dark matter? … why parity is violated?

• High energy physics -Probe unknown physics in direct way in high energy collisions of particles: new scale $\Lambda_{NP} \sim E >> m$, probe of short distances, resolution : $r \sim hc/\Delta q \sim 1/E \sim 10^{-17}$cm/E(TeV)

• Low energy physics - New results could be expected from precision measurements at low energies: $\Delta q < m$ Large distances and large amount of space involved in the interaction. Typically precision requied $\sim (m/\Lambda_{NP})^n$

New Physics: high-energy vs low-energy experiments

Н.В. Красников, В.А. Матвеев
“Новая Физика на Большом
Адронном Колайдере“ (2010).

- Higgs
- SUSY
- Extra Dimensions
- Hidden valley
- ……………

- H-H’ , Ps-Ps’ mixing
- g-2, mu-e, …
- Newton low, Ps->invisible
- Ps -> invisible (vacuum)
- ……………

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 $10^{-(10-11)}$

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

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

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

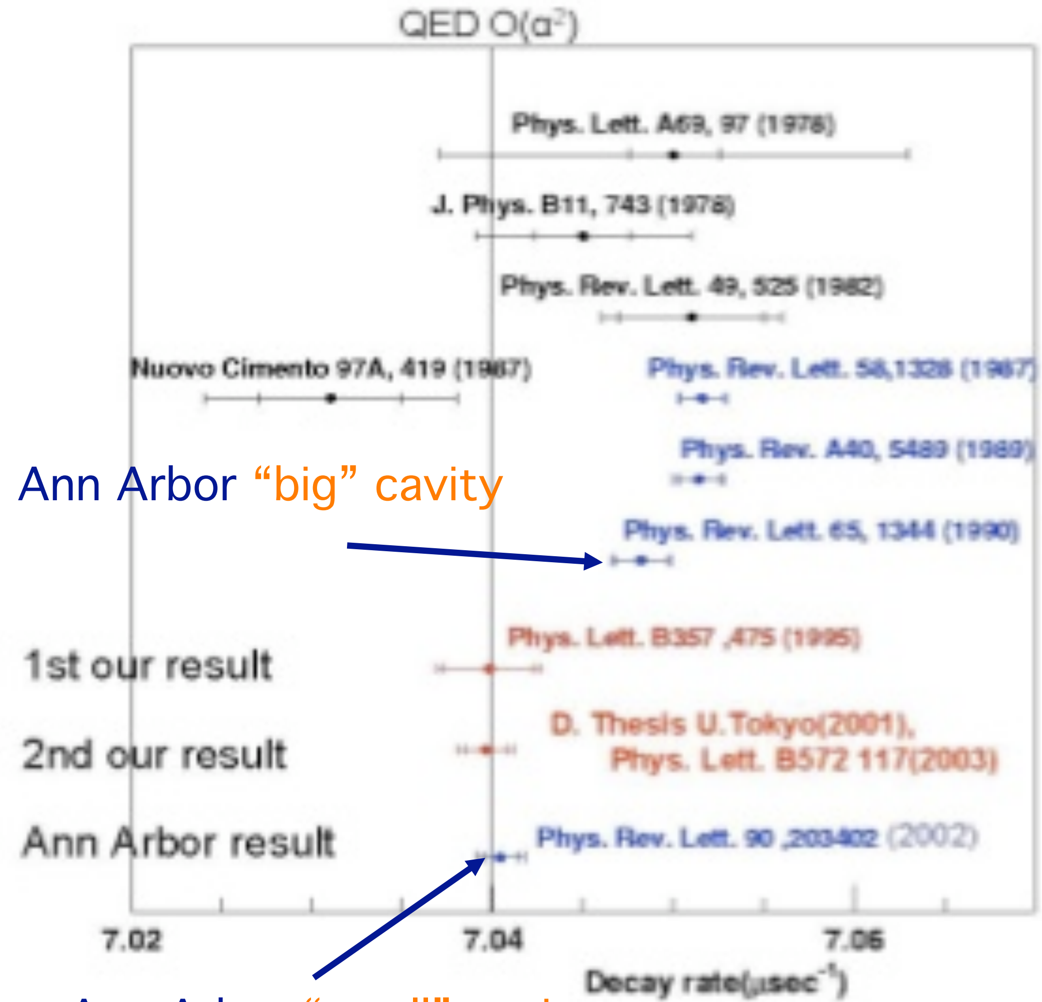
$^3S_1$ (o-Ps) cannot decay to two photons —
angular momentum of photons
Wheeler, Ann. N.Y. Acad. Sci. **48**, 219 (1946).
P symmetry requires $^1S_0$ two photon decay to have photons w/perpendicular lin. polarization, Yang, Phys. Rev. **77**, 242 (1950).

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

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

o-Ps decay rate puzzle

Review: Dobroliubov, Gninenko, Ignatiev, Matveev, IJMP A8 (1993) 2859



Ann Arbor “big” cavity

Ann Arbor “small” cavity

$$\Gamma_{3\gamma} = \Gamma_0\left(1 + A\frac{\alpha}{\pi} + B\left(\frac{\alpha}{\pi}\right)^2 + \ldots\right)$$

Discrepancy $\Gamma_{\exp} > \Gamma_{SM}$:

- new unknow contribution
- Br(oPs->X)$\sim 10^{-3}$
- experimental problems
- B is anomalously big

Tokyo measurements
(oPs formation in target)

Ann Arbor experiment
(oPs formation in vacuum,)
agree to each other and also
agree with QED predictions

Today: agreement within 1sigma, but theoretical accuracy is a factor 100 better!

Поиск новой физики в распадах позитрония

Что можно искать в экспериментах с 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: S.G., Krasnikov, Matveev, Rubbia, Phys.Part.Nucl. 37(2006)

- **новые частицы**
- **новые силы или взаимодействия**
- **новые законы сохранения**

Topics:

- 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

Positronium decays in the standard model

- parapositronium g.s.: L=0, S=0, pPs-> 2, 4, .. γ, $\tau \sim 10^{-10}$ s
- orthopositronium g.s.: L=0, S=1, oPs-> 3, 5, .. γ, $\tau \sim 10^{-7}$ s
- oPs—>2γ forbidden
- Br (pPs—>4γ)~ Br(oPs—>5γ)~10^{-6}
- $e^+ + e^- + M \to \gamma + M$ or $e^+ + e^- + M \to M^*$ are small
- Br(oPs—> invisible)<~10^{-18} is extremely small

Important Conclusion:

only $\cancel{0}$, $\cancel{1}$, 2 , 3 , $\cancel{4}$, ..gamma in the final state.

for Br(oPs—> anything)>~10^{-5}

Bounds on rare o-Ps decay modes

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

Multi-Photon Branching Ratio Results

C Symmetry Tests
(90% Confidence level limits)

$(\text{O-Ps} \to 4\gamma)/(\text{O-Ps} \to 3\gamma) < 3.7 \times 10^{-6}$ (90% C.L.)

Previous limit (1996) $< 2.6 \times 10^{-6}$ (90% C.L.)
[Yang *et al.*, Phys. Rev. A **54**, 1952 (1996)]

$(\text{P-Ps} \to 5\gamma)/(\text{P-Ps} \to 2\gamma) < 2.7 \times 10^{-7}$ (90% C.L.)
(no previous limit)

QED Tests (1 σ errors)

$(\text{O-Ps} \to 5\gamma)/(\text{O-Ps} \to 3\gamma) = 1.67(99)(37) \times 10^{-6}$

QED value(tree) $= 0.9591 \times 10^{-6}$
Previous mmt.(1 event, '95) $= 2.2(2.2) \times 10^{-6}$
[Matsumoto *et al.*, Phys. Rev. A **54**, 1947(1996)]

$(\text{P-Ps} \to 4\gamma)/(\text{O-Ps} \to 2\gamma) = 1.14(33)(21) \times 10^{-6}$

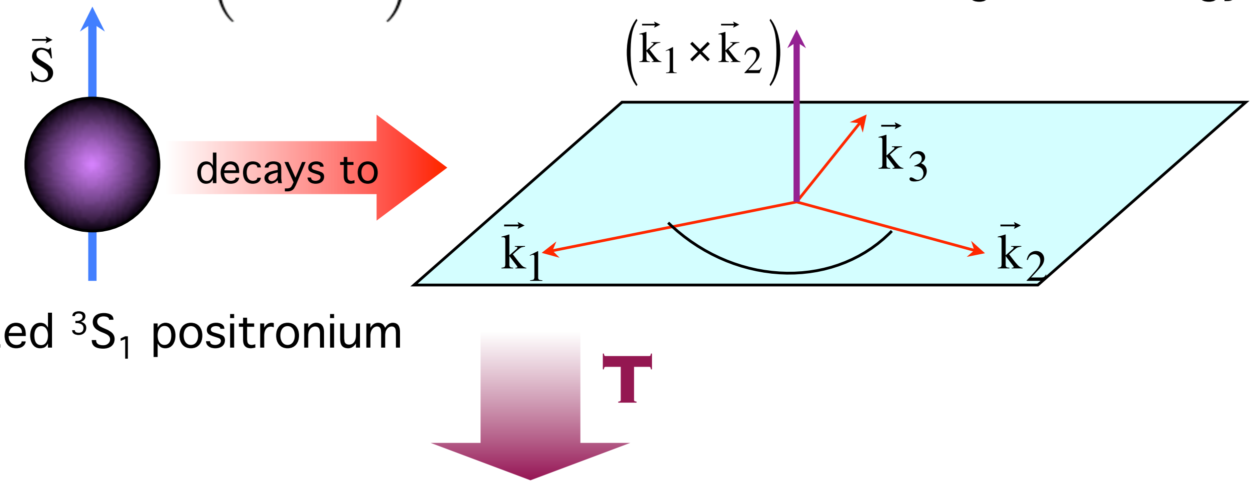
QED value(one-loop) $= 1.4388 \times 10^{-6}$
Previous mmt. (1994) $= 1.50(11) \times 10^{-6}$
[von Busch *et al.*, Phys. Lett. B **325**, 300 (1994)]

Time Reversal Symmetry in o-Ps Decay

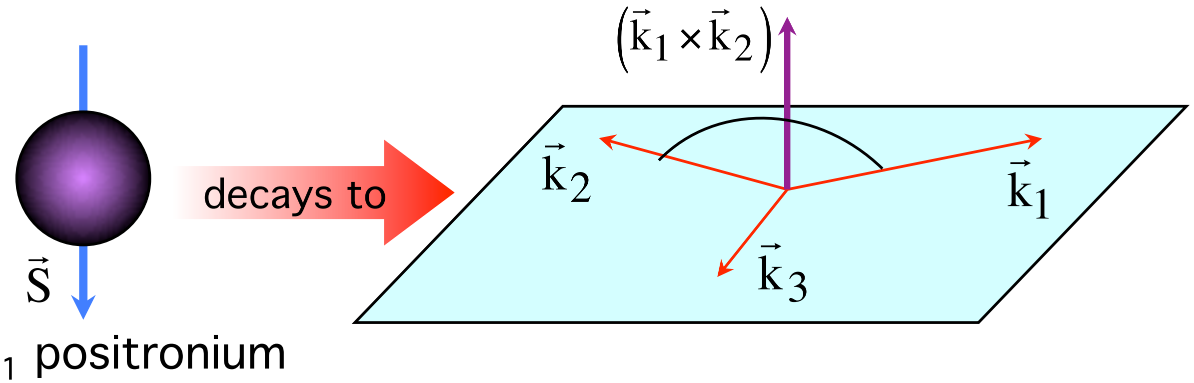
{C, P, T, CP, CPT and positronium
Krasnikov, IJMP, A19,2004}

In the decay (o-Ps -> 3γ), the photon momenta all lie in a plane.

Decay plane normal vec$\vec{n} = \left(\vec{k}_1 \times \vec{k}_2\right)$, where 1 and 2 are the highest energy photons.



photon momenta and spin reverse does not reverse.



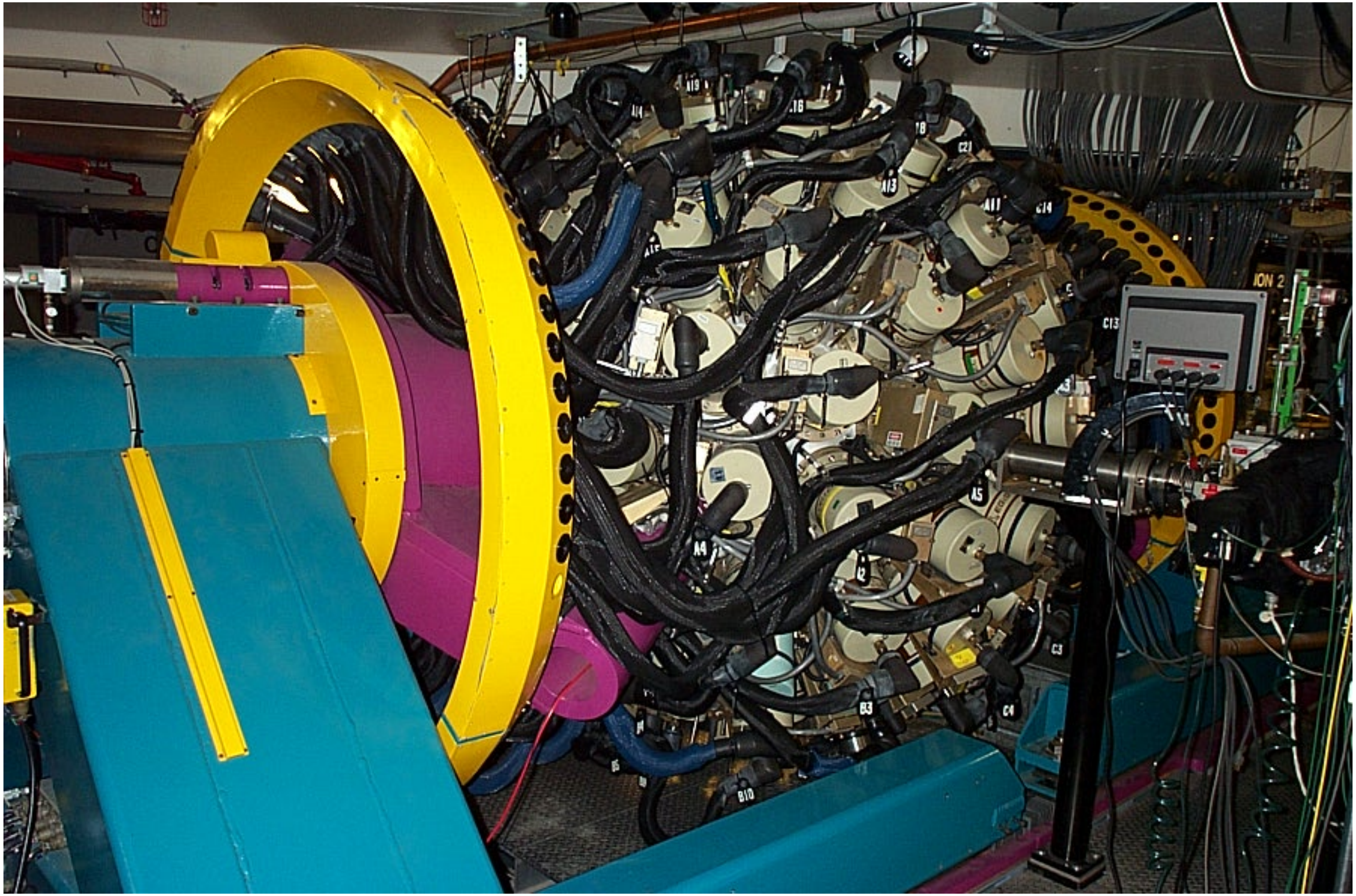
$\boxed{\vec{s} \cdot \left(\vec{k}_1 \times \vec{k}_2\right)}$ is a T-odd observable.

o-Ps is CP even, so $\boxed{\vec{s} \cdot \left(\vec{k}_1 \times \vec{k}_2\right)}$ is CPT- odd

*(caveat)

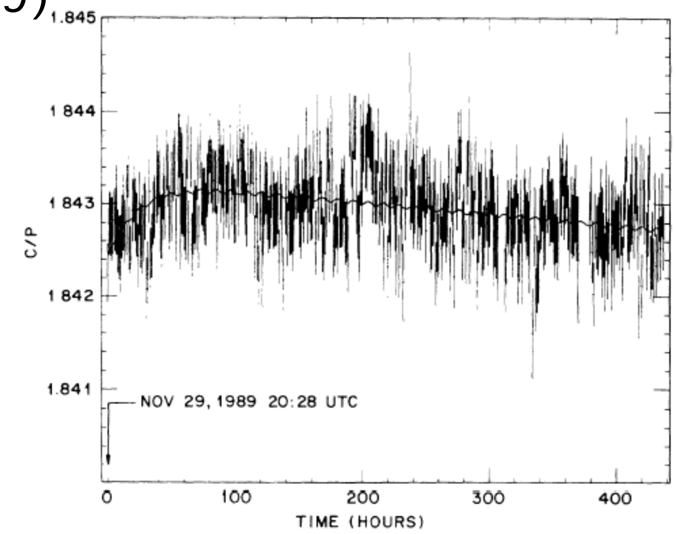
The Gammasphere Detector Array -- LBNL/ANL

110 High-Purity Germanium detectors



Lorentz Violation

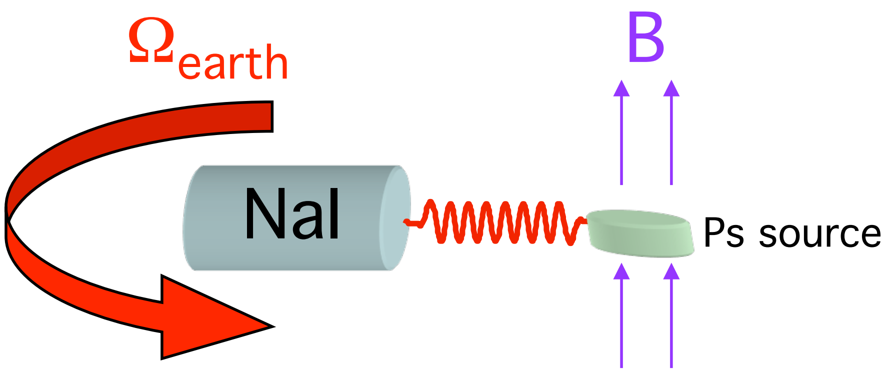
"Search for Spatial Anisotropy in Orthopositronium Annihilation,"
A.P. Mills and D.M. Zuckerman, PRL **64**, 2637 (1989)

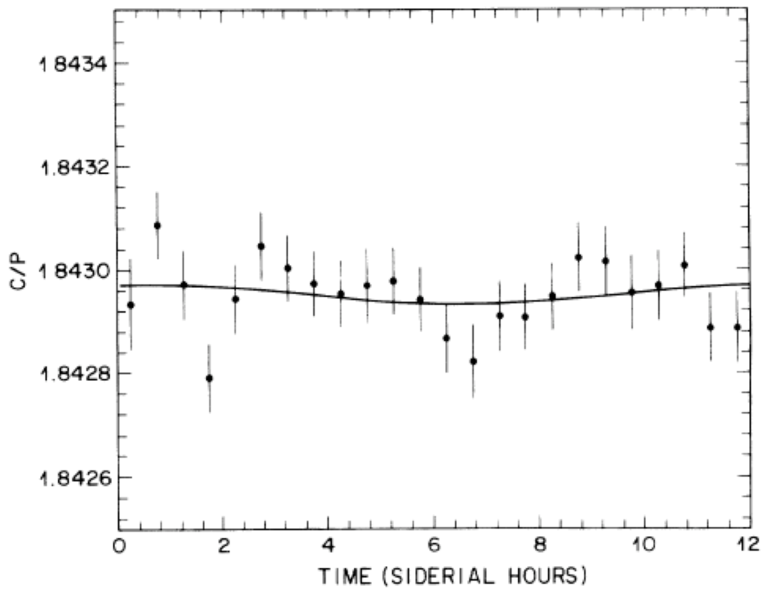


Effectively a search for (o-Ps -> 2γ)
(not allowed in naive non-commuting QED...)

Magnetic field quences m = 0 state of o-Ps
Lorentz violation would quench m = +/-1
Time dependence Ω (12 h)

Measure 3γ/2γ yield





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.

7. Unparticles (H. Georgi (2007))

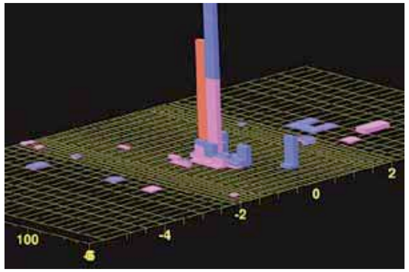
8. ………………

Extra dimensions models

among GUT, technicolor, SUSY , string, Little Higgs.. models .. Extra Dimensions models probably are the most intriguing. First proposal for ED: Kaluza and Klein in 1920 unification of gravity and e-m in 5D theory

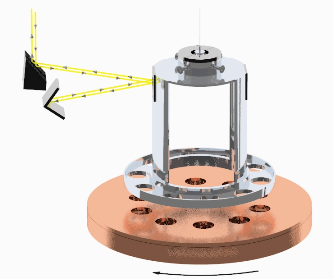
Modern ED theories(>3D) has shifted towards ``brane world'' picture, which assumes that ordinary matter (with possible exceptions of gravitons) is trapped to a 3D submanifold --- brane --- embedded in fundamental multi-dimensional space. In the brane world scenario, ED may be large, infinite, warped; they may have effects, directly observable in current or fothcoming experiments.

How might extra dimensions be detected?

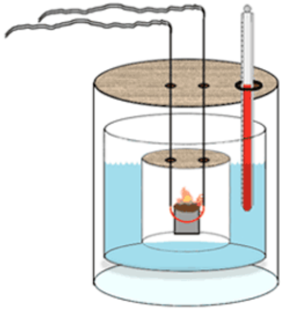


Discover massive KK modes at particle accelerators
- heavy bosons (new particle signature)
- heavy gravitons (missing energy signature)
  (Substantial Std. Model background)

Maybe the KK modes are stable particles and are dark matter
- dark matter, WIMP searches



Gravity behaves differently at short range
- fancy Cavendish balances



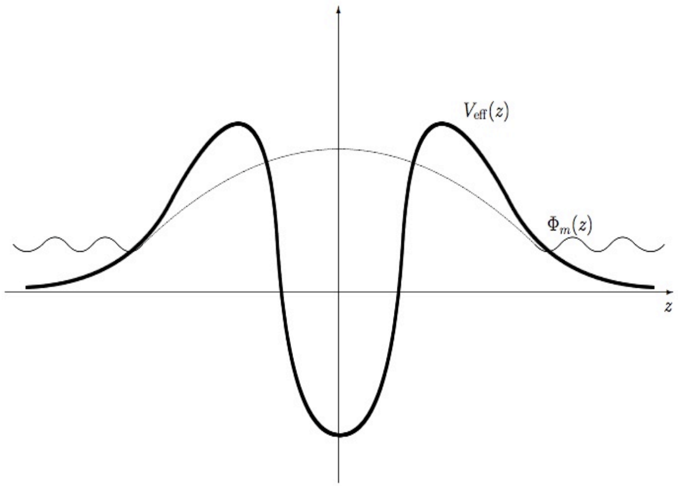
Mass-energy itself is unstable in some scenarios
bulk modes of particles allow tunneling off our brane
- Total calorimetry experiment to search for energy disappearance

Disappearing massive matter

Literature-

V.A. Rubakov: Physics of extra dimensions, Lectures at CERN, Feb 2004
V.A. Rubakov et al., PRD 62(2000)105011; JHEP 08(2000)041; Phys.Usp. 44(2001)871.
Dubovsky , Rubakov, Tinaykov PRD **62**, 105011
Rubakov UFN 171(2001) 913-938

"Our world is a brane embedded into a higher-dimensional space-time.Particles initially locate on our brane may leave the brane and tunnel into extra dimensions. These transitions have b found to be generic in a class of models of localization of particles on a brane".



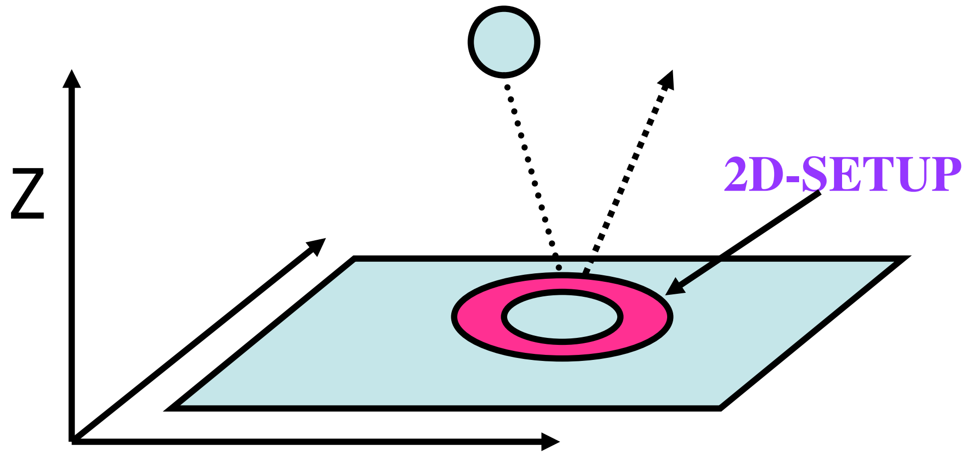
N.Arkani-Hamed et al., PLB 429(1998)263; Phys.Today, Febr.(2002)36.
S.Dubovsky JHEP,01(2002)012.

"The presence and properties of the extra dimensions will be investigated by looking for any loss of energy from our 3D-brane into the bulk"

Tunneling to Extra Dimensions

Mass-energy initially located at our brane is unstable in some scenarios. Particles allow tunneling off our brane and escaping to ED

Experimental signature:
disappearance of a particle
in our world , i.e.
particle → invisible decay



Recall:

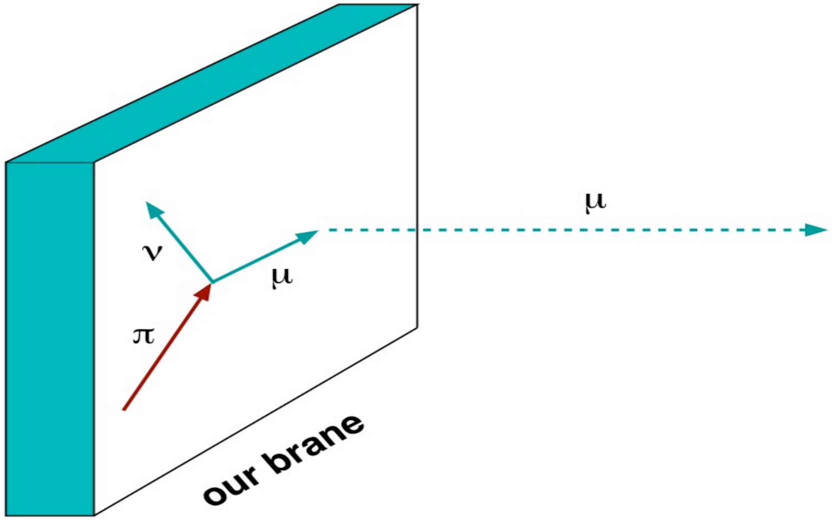
Properties of *Z—>invisible decay* plays fundamental role in determination of lepton families number in the Standard Model

Motivation to search for $\mu^+ \to invisible$

Is the electric charge conserved in brane world?

S.L. Dubovsky, V.A. Rubakov, P.G. Tinyakov JHEP 0008:041,2000.

S.G. , Phys.Rev. D 76, 055004 (2007)



charged lepton escaping rate from the brane- strong mass dependence. Too many paramters to make even an order-of-magnitude prediction

Putting this result first to Eq. (5) and then to Eqs. (4) and (3) and taking the integral over the masses of bulk modes one gets

$$\Gamma = \beta k \left(\frac{m_e}{M_W}\right)^4 \left(\frac{m_e}{k}\right)^{2\nu-1}$$

where the numerical coefficient β is equal to

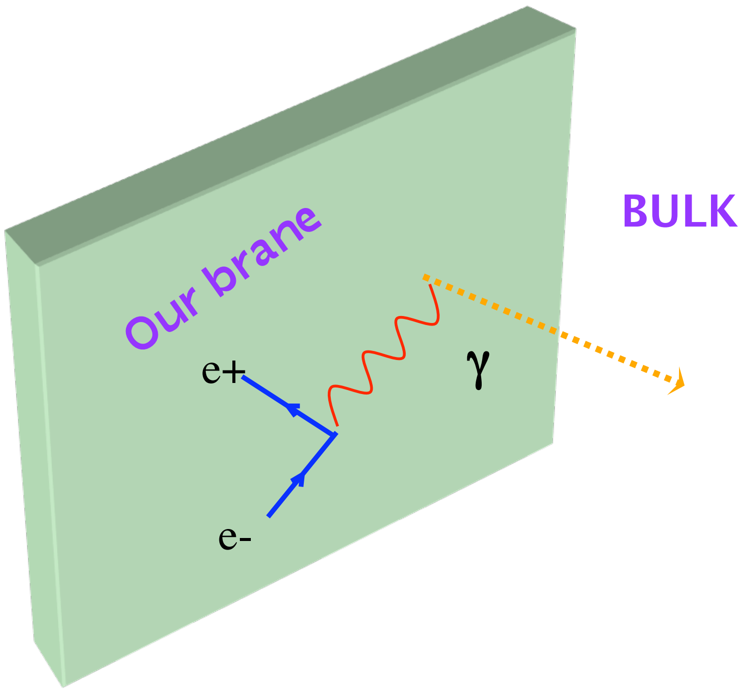
$$\beta = \frac{cg_2^2}{16\pi n\nu(\nu+2)(\nu+3)}$$

S.L. Dubovsky`05

Some generic property of a class of models with large ED may lead to low energy effects: Electric charge is not conserved in our brane (even for $m_\gamma=0$!), but conserved in multi-D space

What size signal from oPs escape to extra dimensions ?

SG, Krasnikov, Rubbia Phys. Rev. D **67**, 075012 (2003).
Positronium physics.Int. Workshop, ETH, May 30, 2003, Int. J. Mod. Phys. A19(2004)



Escaping rate of oPs
(for n=2 extra dimensions)

$$\Gamma(\gamma^* \to ext.\dim.) = \frac{\pi m_{\gamma^*}}{4}\left(\frac{m_{\gamma^*}}{k}\right)^2$$

k – *scale of new physics*

prediction for ortho – positronium:

$$\boxed{10^{-10} \lesssim \frac{\Gamma(oPs \to invisible)}{\Gamma(oPs \to 3\gamma)} \lesssim 10^{-8}}$$

In the SM oPs-> inv rate is very small:

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

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]

$\Rightarrow$ Bound on fractional electric charge,

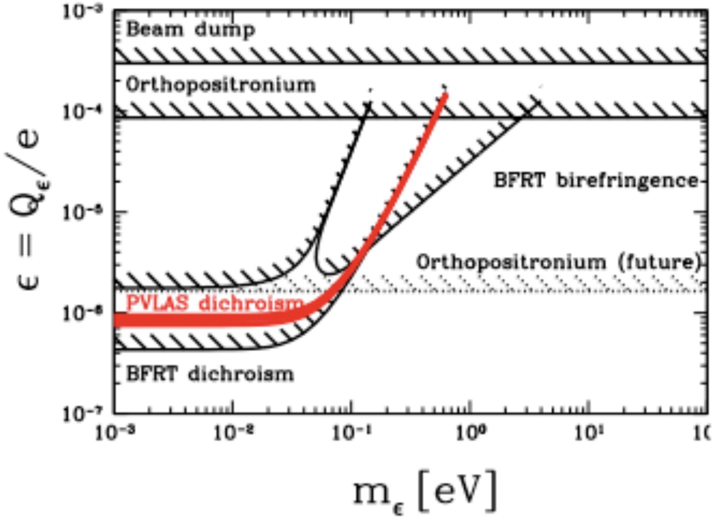
$$\epsilon \lesssim 10^{-5}, \text{ for } m_\epsilon \lesssim 1 \text{ keV}$$

- 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

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



10^{-7}

10^{-9}

[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 group: 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

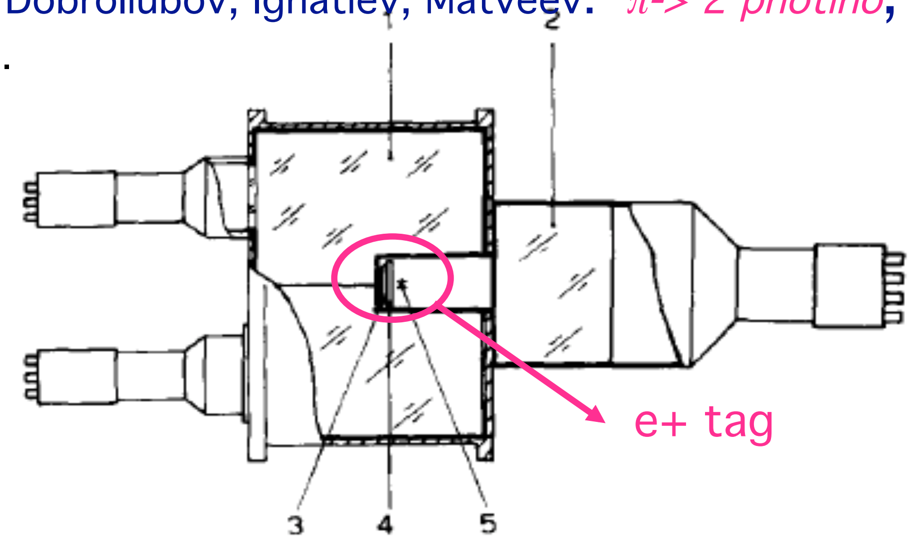
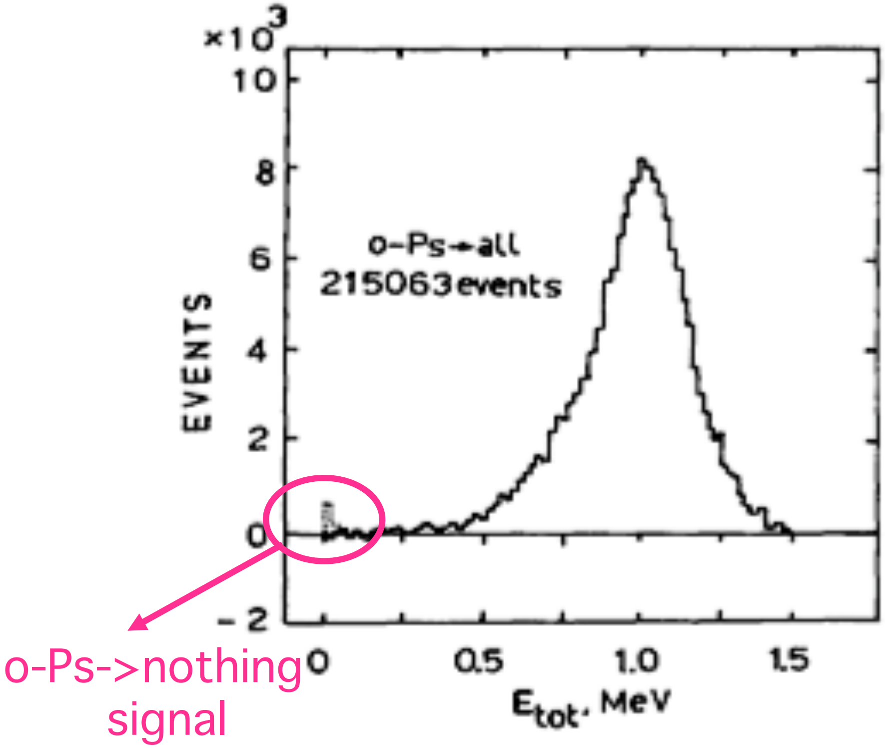


Fig. 1. Schematic view of the set-up: (1): NaI calorimeter; (2): NaI counter (3): target; (4): proportional counter; (5): the positron source ^{22}Na.



$$\frac{\Gamma(\mathrm{O-Ps} \to \mathrm{nothing})}{\Gamma(\mathrm{O-Ps} \to 3\gamma)} < 5.8 \times 10^{-4}$$

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).

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

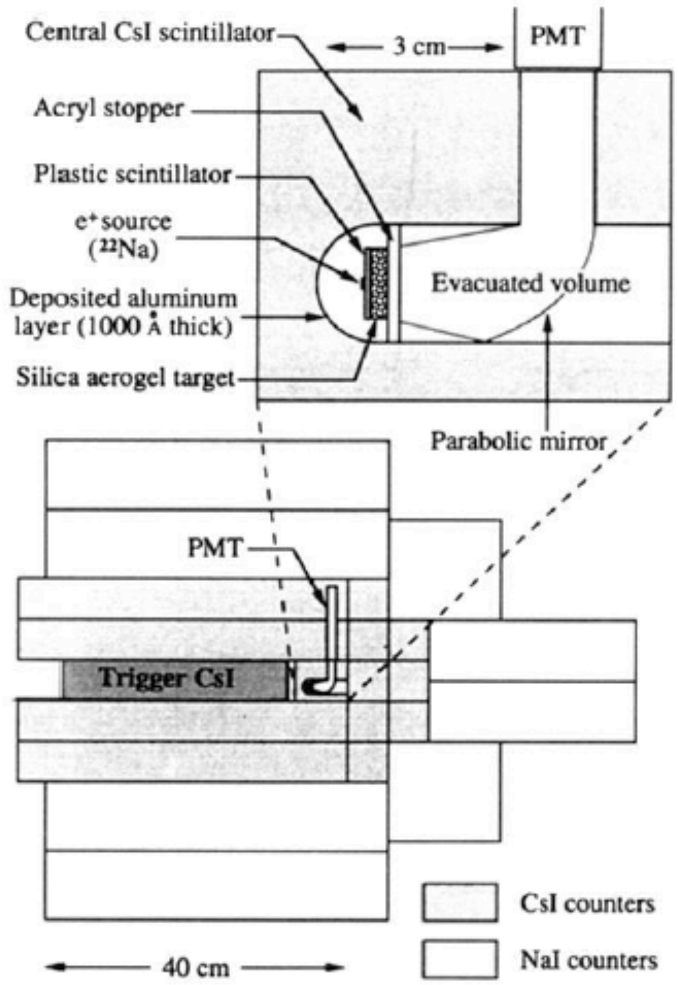
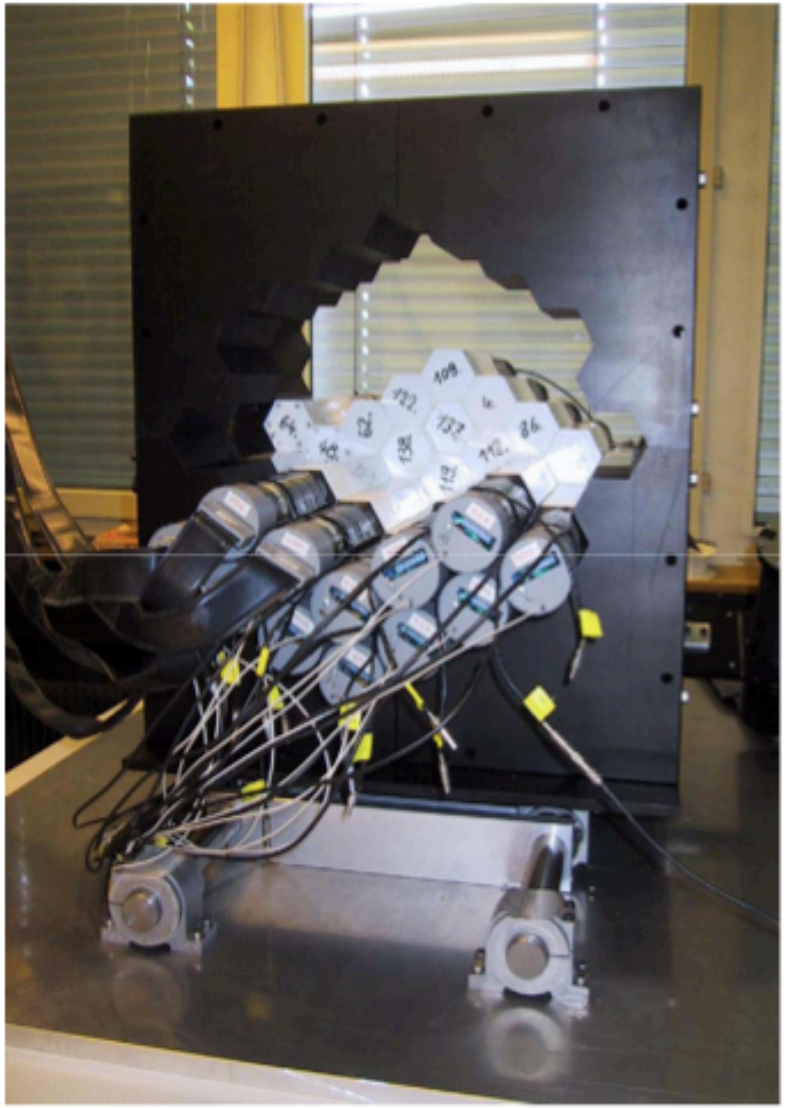


FIG. 1. Schematic of the experimental setup.

ETH-INR experiment on o-Ps -> nothing

Photograph of the calorimeter (assembling phase)



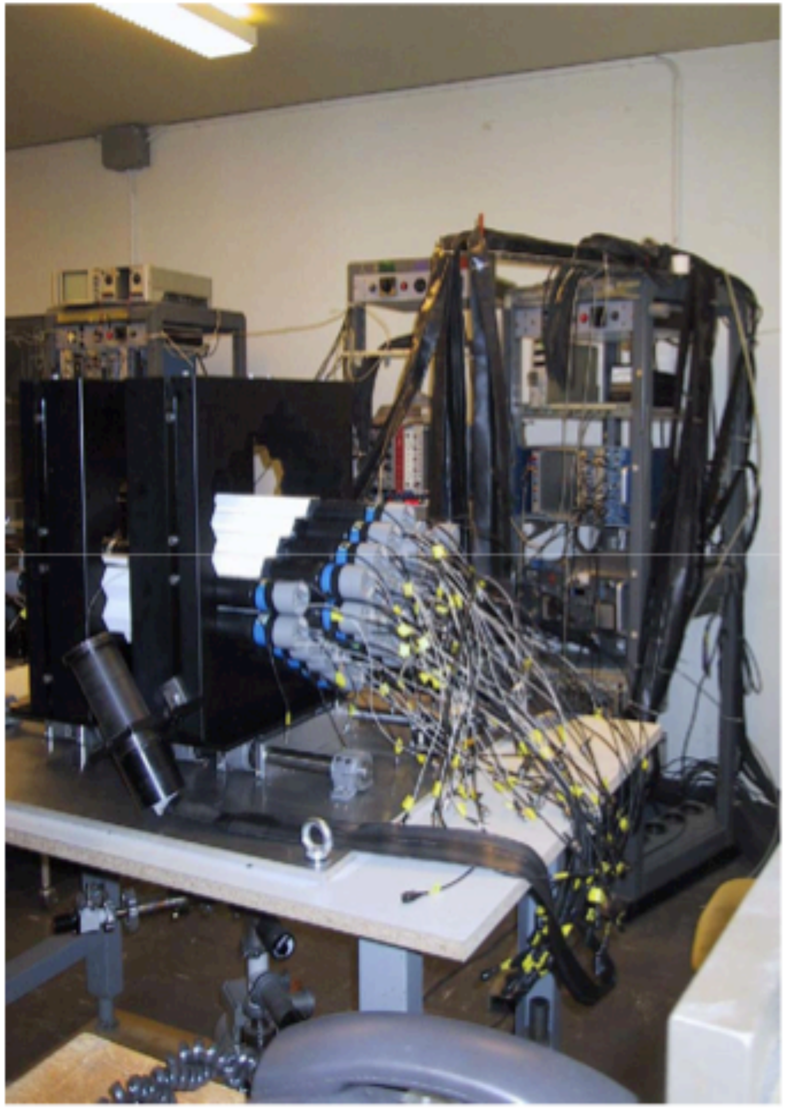
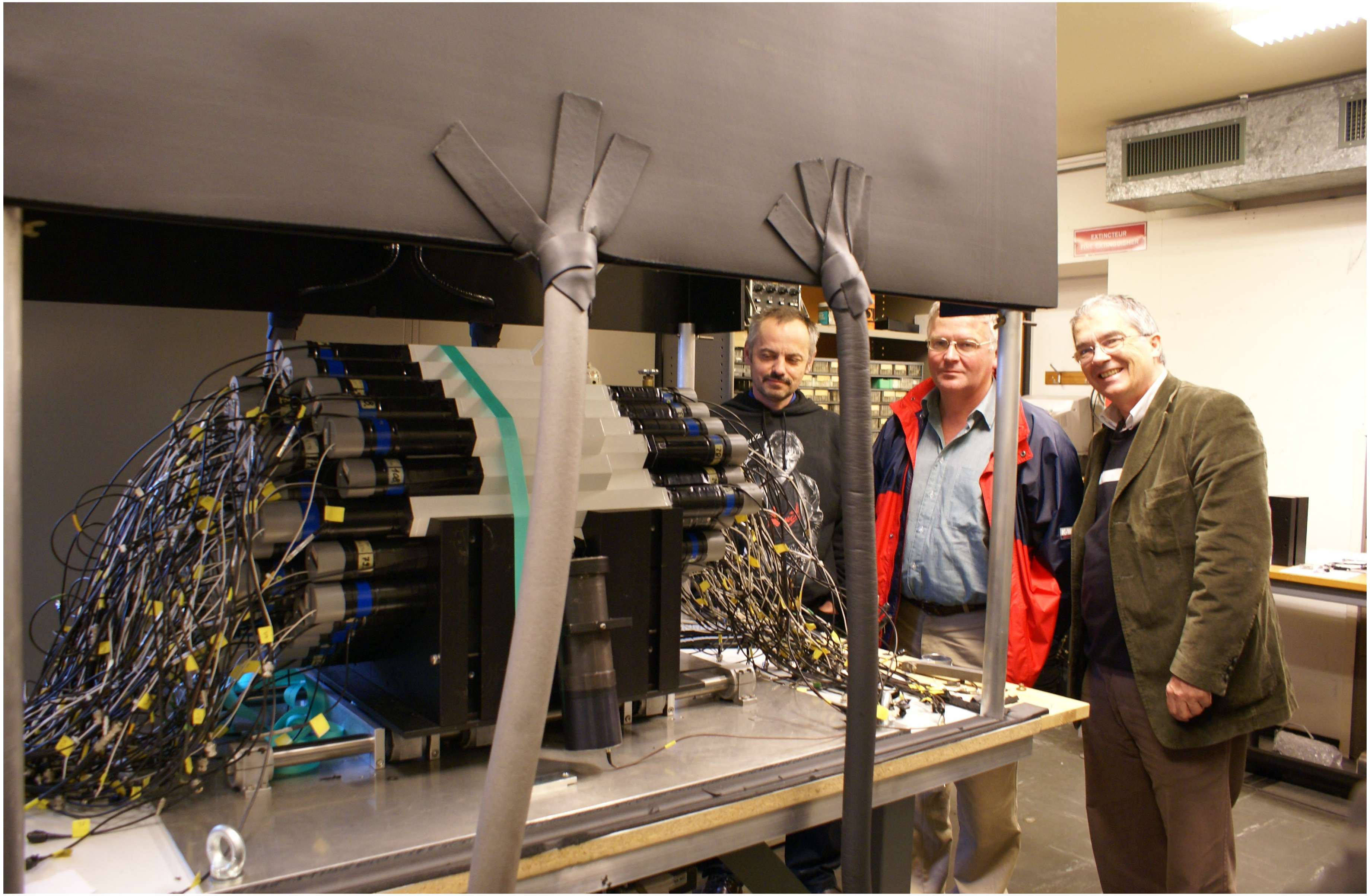
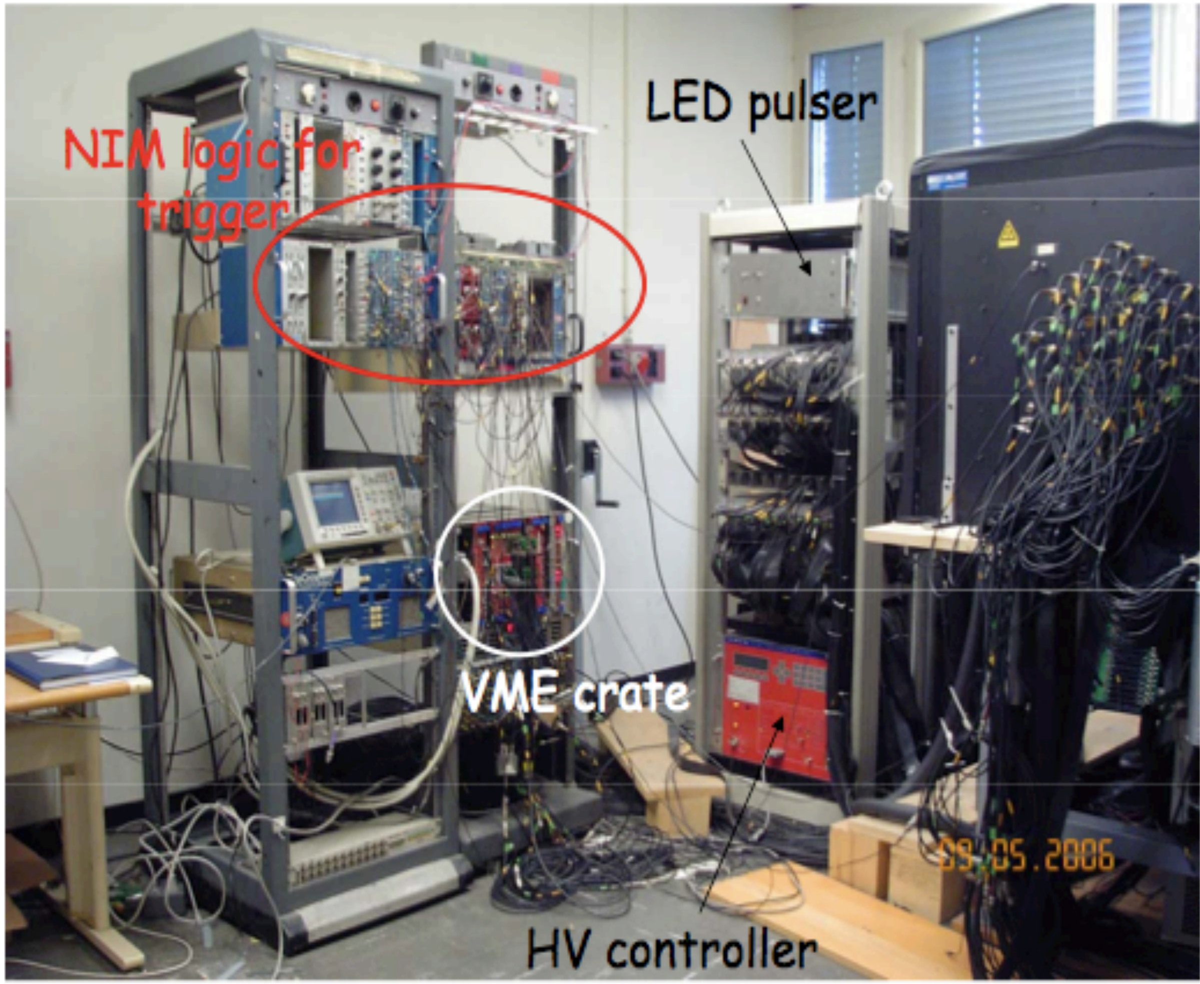


Фото 2



Picture of the lab

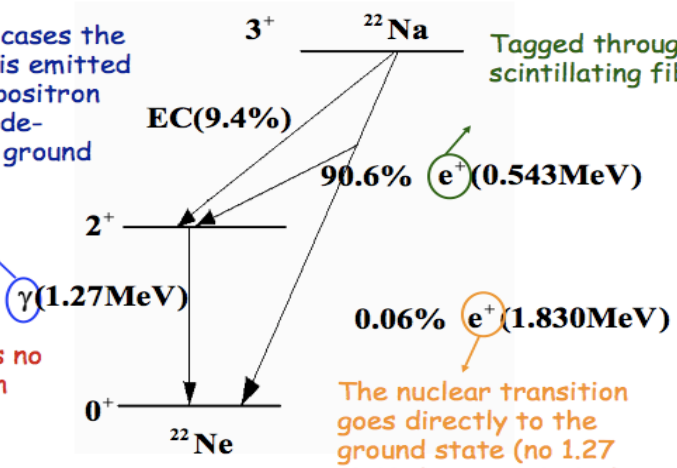


Components

Description of the source

In 90.6 % of the cases the 1.27 MeV gamma is emitted 3.7 ps after the positron because of Neon de-excitation to the ground state.

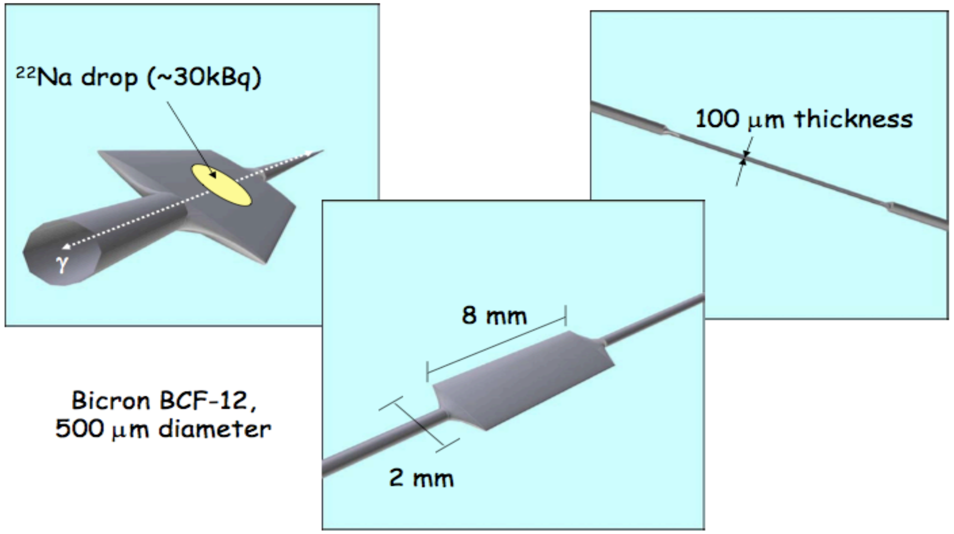
In 9.4 % there is no positron emission because of EC.



Tagged through scintillating fiber.

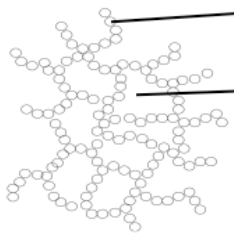
The nuclear transition goes directly to the ground state (no 1.27 MeV photon emission)

The scintillating fiber



SiO_2 aerogel target (0.1 g/cm³)

SiO_2 grains (50-100 Å)



Positronium can form inside the grain

It can migrate in the pores where it decays almost freely (it undergoes about 10^4 collisions per lifetime)

In vacuum: $\tau_{vacuum} \cong 142ns$

Collisional quenching

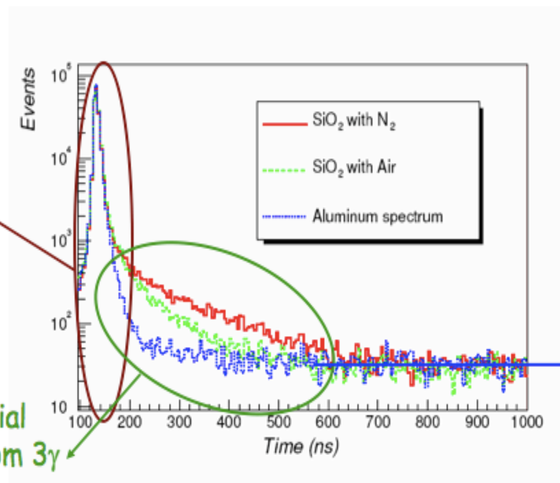
In Aerogel pores filled with Nitrogen: $\tau_{Nitrogen} \cong 132ns$

$\tau_{Air} < \tau_{Nitrogen}$ ⇨ With N_2 bigger fraction of o-Ps than with Air

In Air spin-exchange: $o-Ps+O(\uparrow\uparrow) \rightarrow p-Ps+O(\uparrow\downarrow)$

Time spectra between tagged positron and photon detected in the calorimeter

Peak from 2γ annihilation

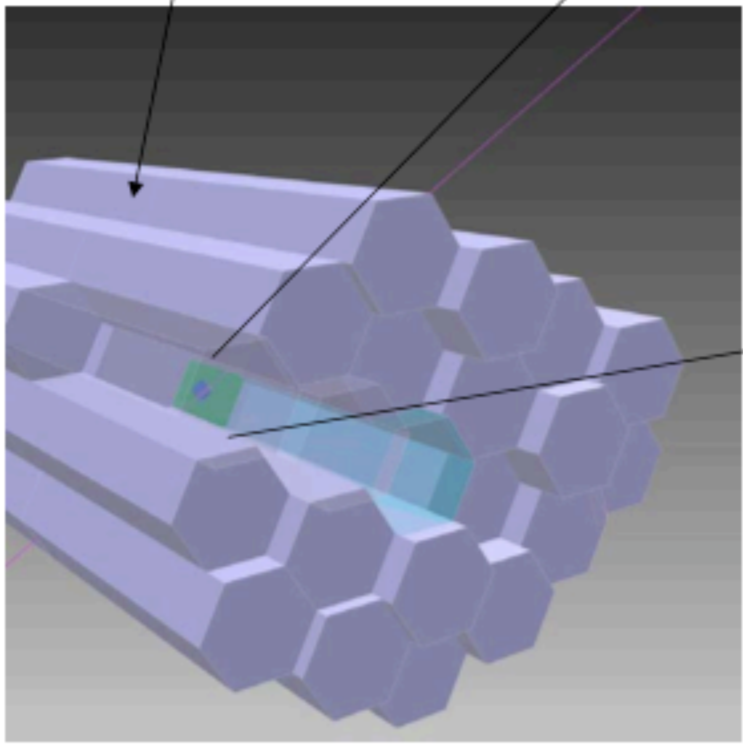


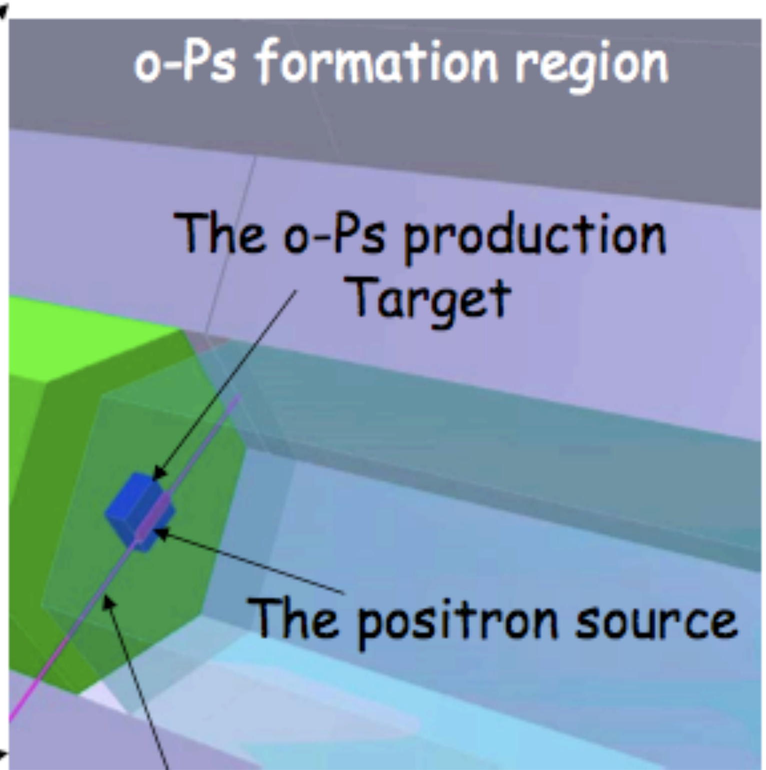
Constant background

Exponential decay from 3γ

The o-Ps formation region

The 4π BGO calorimeter surrounding the o-Ps formation region

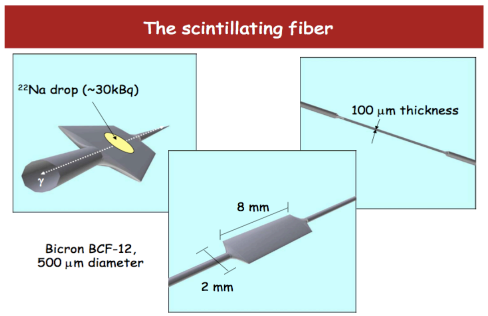




The o-Ps production Target

The positron source

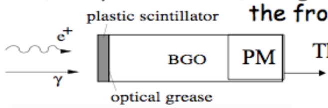
The scintillating fiber to tag the positron



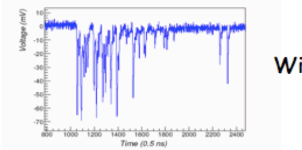
Improvements

Charged particle VETO

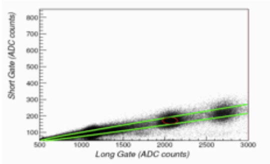
Discrimination between charged particle and photons in the trigger BGO (decay time 300ns) using a plastic scintillator (decay time 2.7 ns) on the front face of the crystal.

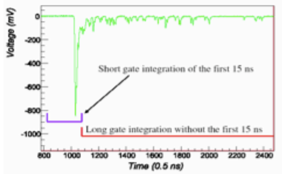


The same to read the light from the BGO and the one of the scintillator

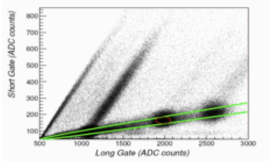


Without scintillator



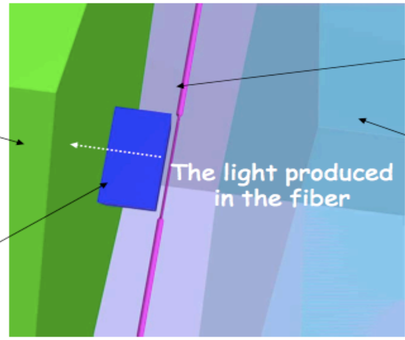


With scintillator



Fiber energy spectroscopy

The energy is read with the FBGO through the aerogel and a hole in the wrapping using the BGO as a light guide.

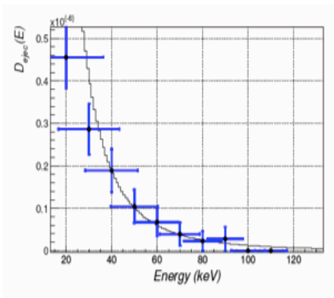


13 photoelectrons instead of 1.2 compared to the fiber, cut meaningful.

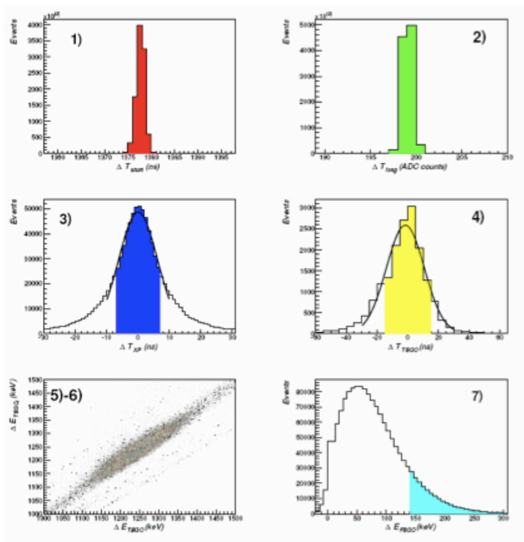
Rejection of shake-off electrons

The atomic shell electrons ejected in the EC process are a source of background. The ejection probability decreases strongly with the energy of the ejected electrons thus a cut on the energy deposited in the fiber can suppress this background to the required level of 10^{-8}.

The probability for the atomic shell electrons to be ejected in the EC process was measured as a function of the energy deposited in the fiber.



Data selection



1)-2) Checking of the electronics

3)-4) Reduction of accidentals

5)-6) Charged particle veto

7) Suppression of shake-off electrons

Background estimation

The table summarizes the expected background for the experiment estimated from the simulation and the measurement of the shake-off probability

BACKGROUND SOURCE	EXPECTED LEVEL
Hermiticity Dead Material Resolution	$< 10^{-9}$
Absorption in trigger Energy window	$< 10^{-9}$
MS positron 546 keV	$< 10^{-9}$
MS positron 1.83 MeV	$< 10^{-9}$
Compton EC photon	$< 10^{-9}$
Accidental noise and EC photon	3.2×10^{-11}
Source contamination and EC photon	$< 1.6 \times 10^{-10}$
Shake–off electrons in EC process	$\simeq 10^{-8}$ (for 140 keV threshold)
Physical backgrounds	10^{-10}
Total	$\simeq 10^{-8}$

Most dangerous!

Results

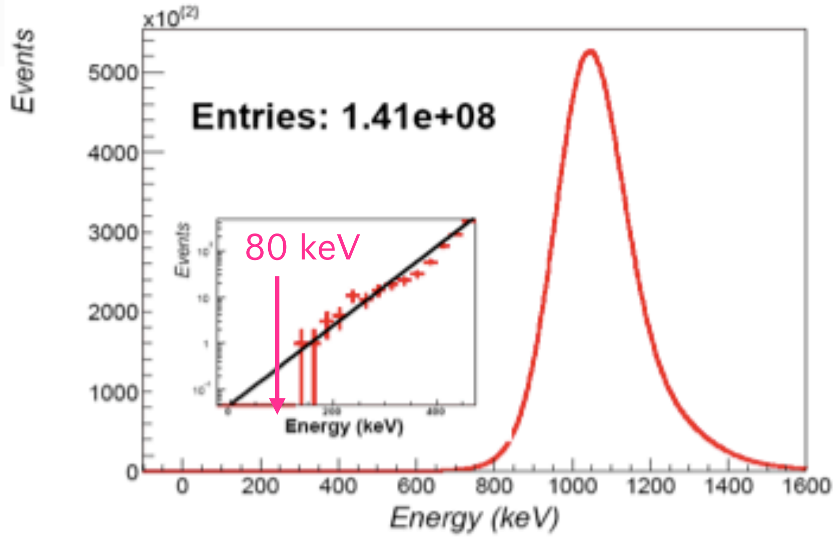
A.Baderscher et al., PRD(2007)

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

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

factor ~7 better than Tokyo

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

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

Interpretation of the result -1

1) Limit on photon mirror-photon mixing strenght:

$$\epsilon = \frac{1}{2\pi f}\sqrt{\frac{Br_{o-Ps\rightarrow invisible}\Gamma_{SM}\Gamma_{coll}}{2(1-Br_{o-Ps\rightarrow invisible})}} \leq 1.55\times10^{-7}$$

for $\Gamma_{coll} = 5\times10^{4}\ s^{-1}$

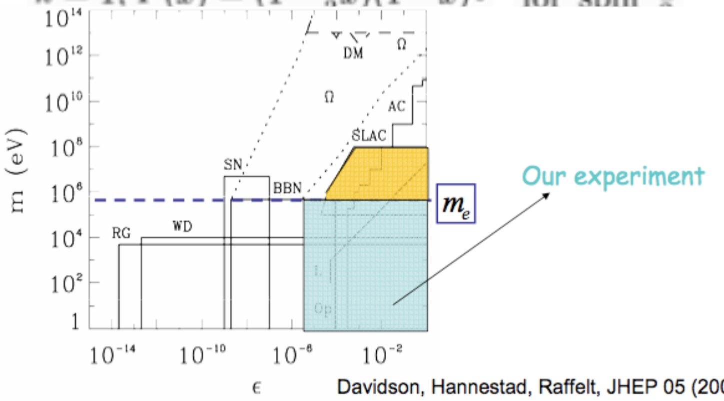
BBN limit of $\epsilon < 3 \times 10^{-8}$

2) Upper limit for milli-charged particle with $m_x < m_e$:

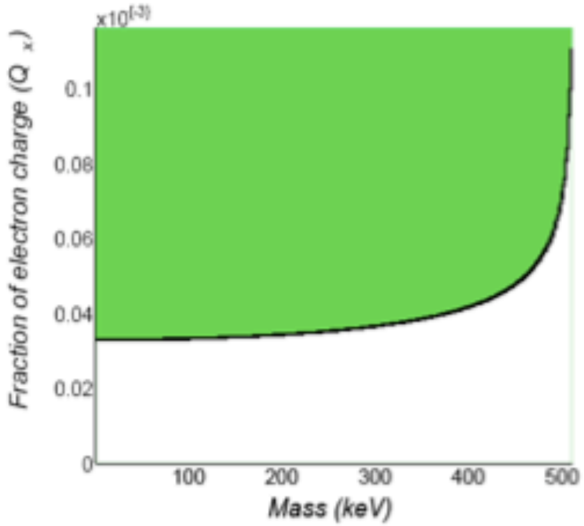
$$\Gamma(o-Ps\rightarrow X\bar{X}) = \frac{\alpha^5 Q_X^2 m_e}{6}\cdot k\cdot F(\frac{m_X^2}{m_e^2})$$

where Q_X is the electric charge of the X-particle ($Q_e \equiv 1$),

$k = 1$, $F(x) = (1-\frac{1}{4}x)(1-x)^{\frac{1}{2}}$ for spin $\frac{1}{2}$



Davidson, Hannestad, Raffelt, JHEP 05 (2000) 003



Interpretation of the result -2

3) Upper bound on magnetic moment of the tau neutrino:

$$\Gamma_{\text{o-Ps}\to\nu\bar{\nu}} = \frac{\alpha^3}{12}\frac{m_e c^2}{\hbar}\sum_{l=e,\mu,\tau}\left(\alpha\frac{\mu_{\nu_l}}{\mu_B}\right)^2\sqrt{1-\frac{m_{\nu_l}^2}{m_e^2}}\left(1+2\frac{m_{\nu_l}^2}{m_e^2}\right)$$

$$\mu_\tau \le 4.66\times 10^{-5}\sqrt{1-\frac{m_{\nu_\tau^2}}{m_e^2}}\left(1+2\frac{m_{\nu_\tau}^2}{m_e^2}\right)$$

$\mu_{\nu_e}, \mu_{\nu_\mu} \ll \mu_{\nu_\tau}$ and $m_{\nu_e}, m_{\nu_\mu} \ll m_{\nu_\tau}$

4) Upper limit on p-Ps->invisible and e$^+$e$^-$->invisible

$$Br(p-Ps\to invisible) = 2.3/(N_{p-Ps}\cdot\epsilon) \le 4.3\times 10^{-7}\ (90\%\ \text{C.L.})$$

$$Br(e^+e^-\to invisible) = 2.3/(N_{e^+e^-}\cdot\epsilon) \le 2.1\times 10^{-8}\ (90\%\ \text{C.L.})$$

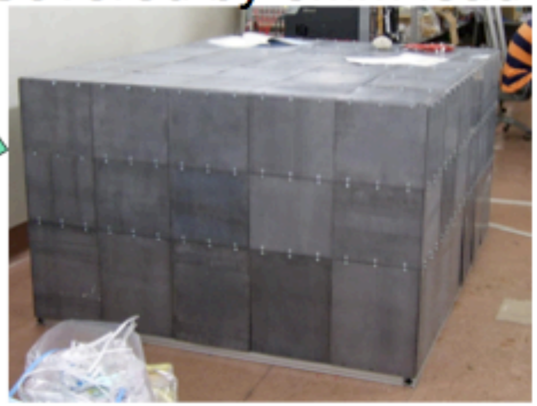
New Tokyo experiment on o-Ps -> invisible

Detector overview

All scintillators arranged

Bottom half

Covered by 5mm lead



Tokyo results`08 on o-Ps -> invisible

まとめ

- 余剰次元の理論から予言されている、o-Psの不可視崩壊を探索するため、高感度の検出器を設計、製作し実験を行った。

- 約半年間の実験の測定を行い、4.76×10^6イベントのo-Psイベントが得られ、この中で不可視崩壊は発見されなかった。
  - 得られたリミット:
    - $Br(\text{o-Ps} \rightarrow \text{invisible}) < 6.9 \times 10^{-7}$
    - $k > 0.42\,\text{TeV}\ (n=2)$

(Not published)

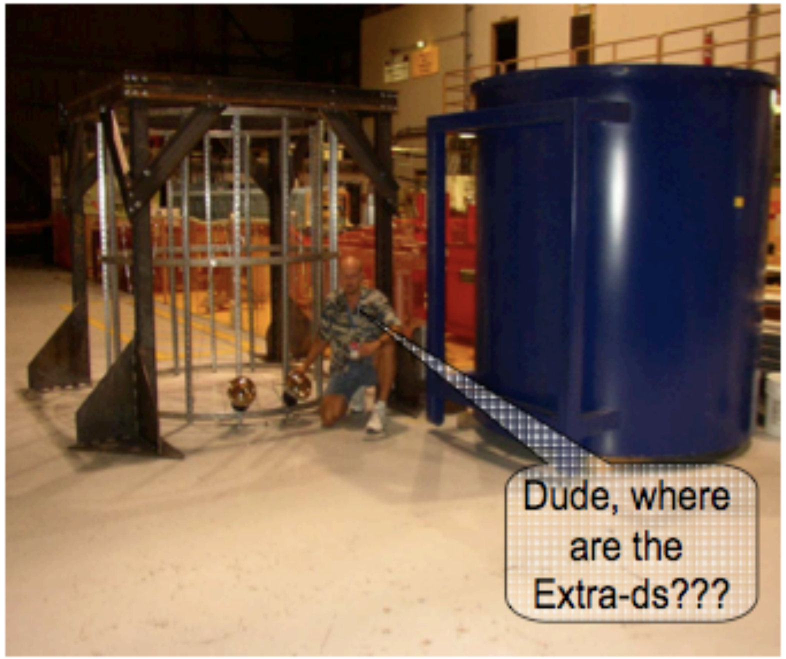
Summary

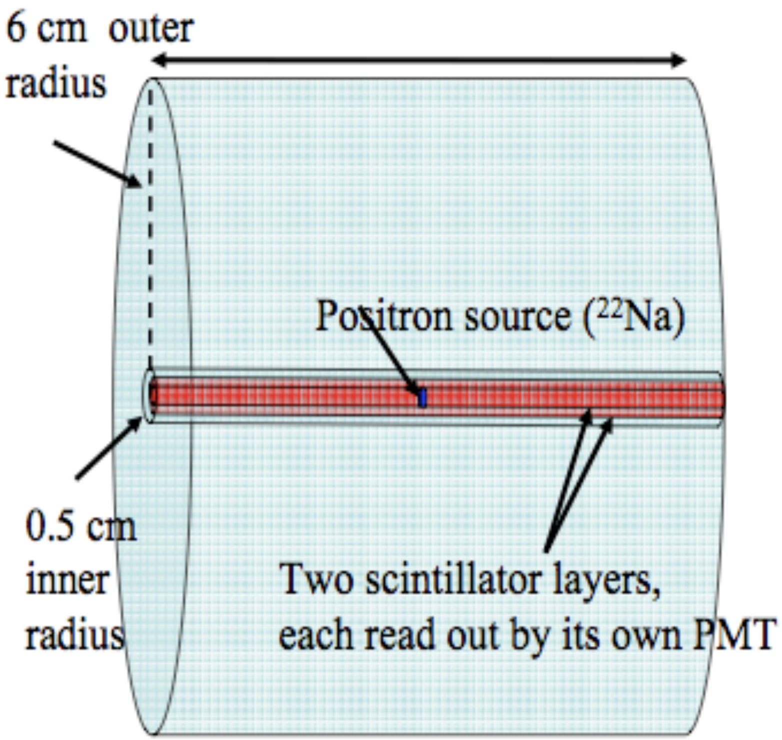
- Search for invisible decay of o-Ps
- Designed and constructed a new detector whose sensitivity is 10^{-8}
- Now we are almost ready for the data taking, and some basic plots show the detector design is OK
- All data taking will be finished in 4 months, and its result will be reported in the next JPS meeting

  (sorry for APS people)

VLADD
VLAnd extra Dimensions Detector
http://home.fnal.gov/~hray/

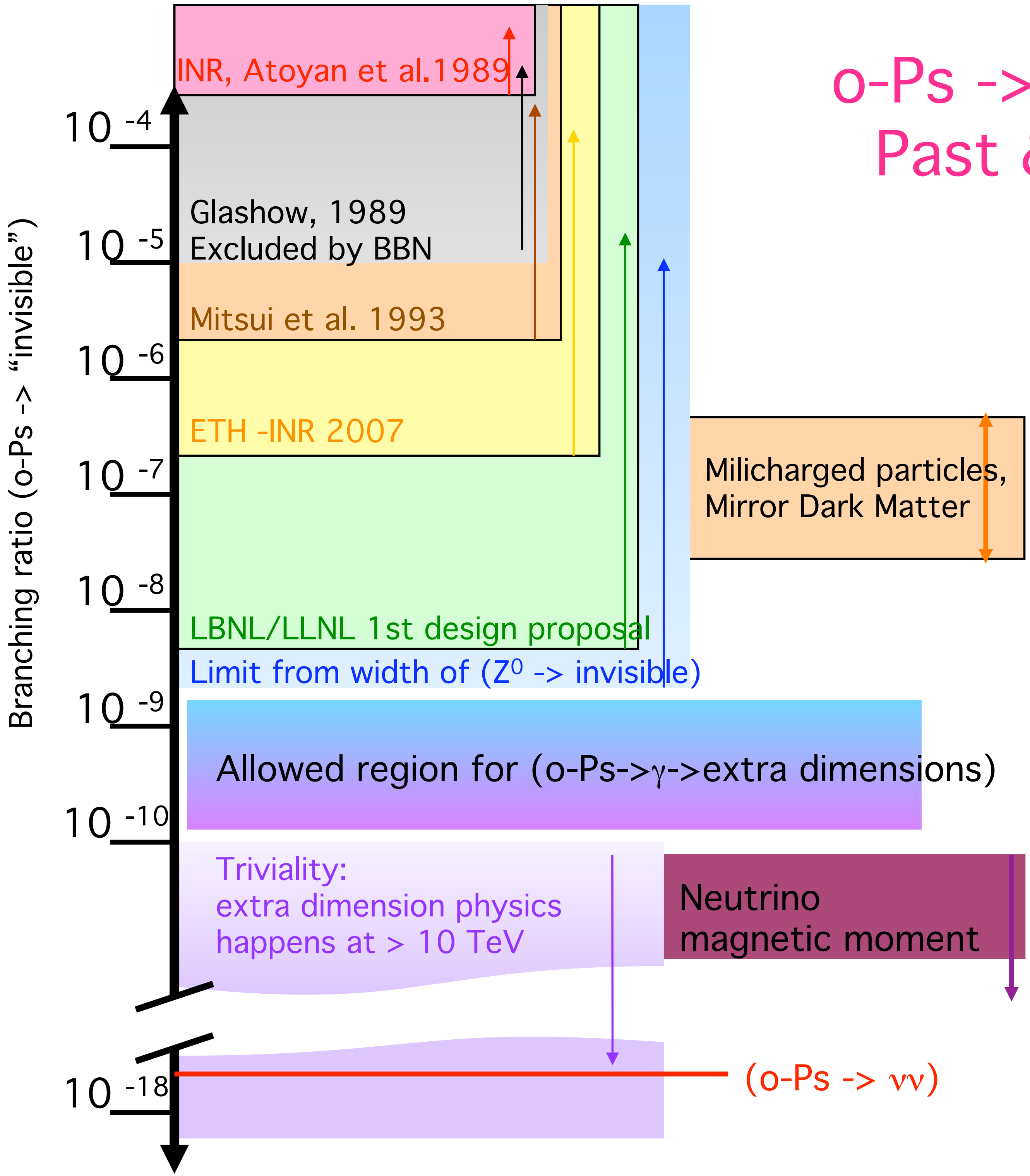
Authors	Heather Ray (LANL)
	Richard Van de Water (LANL)
	Paul Vetter (LBL)
	Janet Conrad (Columbia)
	Mike Shaevitz (Columbia)





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

o-Ps -> nothing: Past &Future



P. Vetter
LBNL, 2006

Поиск темной материи в распадах позитрония

P violation: two classes of models

Great mistery: why only left-handed fermions feel week interactions?

Wu et al.'56: decays of polarized $^{60}Co \to ^{60}Ni\ e^- \nu$.

❑Left-right symmetric models-

Parity restoration at high energy scale > 1 TeV,

New heavy right handed W_R

LHC can probe W_R mass up to 3 TeV, (N.V.Krasnikov, this Workshop)

however, already high limits on $M(W_R)$:

> 2.5 TeV from $\Delta M_{K/B}$ and

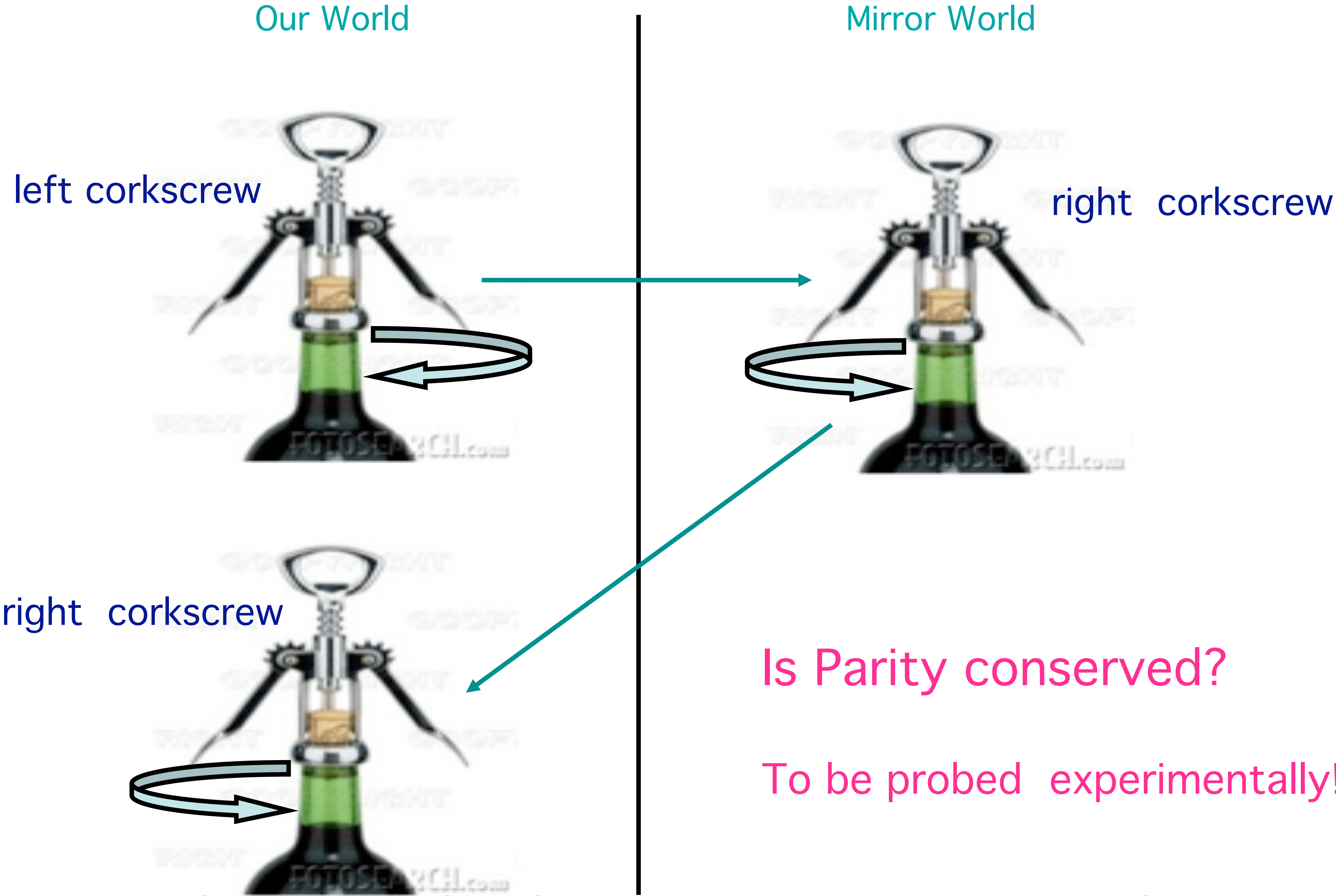
> 4 TeV from K0-decays (R.Mohapatra,X.Ji, this Workshop)

❑ Mirror matter model -

So far no data confronting the model

Effects of parity restoration can be directly observed at low energies in a table top experiment (a'la Wu)

Left-Right (Mirror) Symmetry



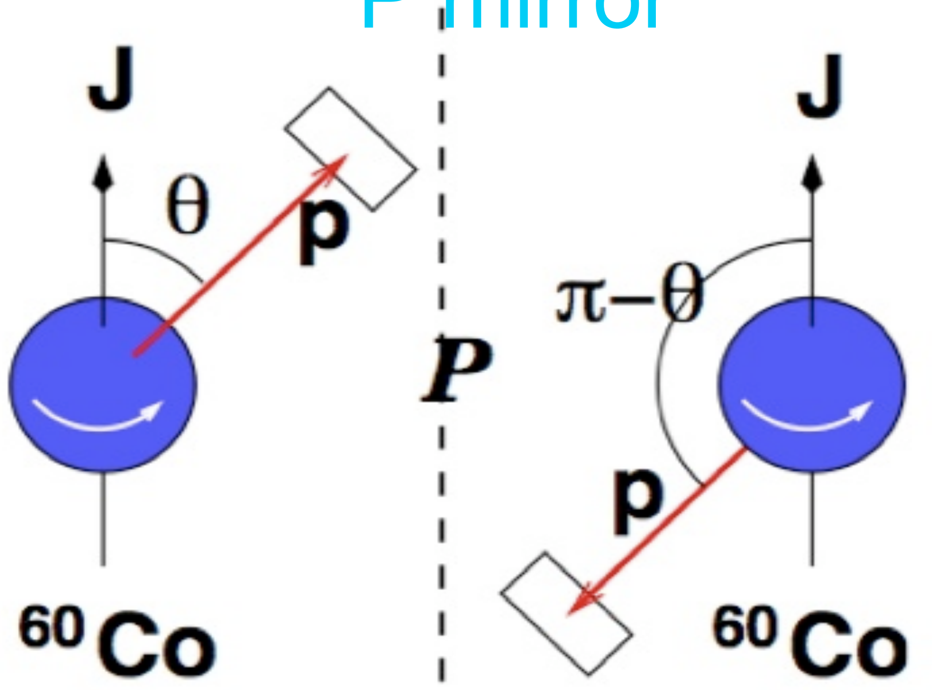
Is Parity conserved?

To be probed experimentally!


Our World
...we need more measurements ...
Mirror World

Parity Violation

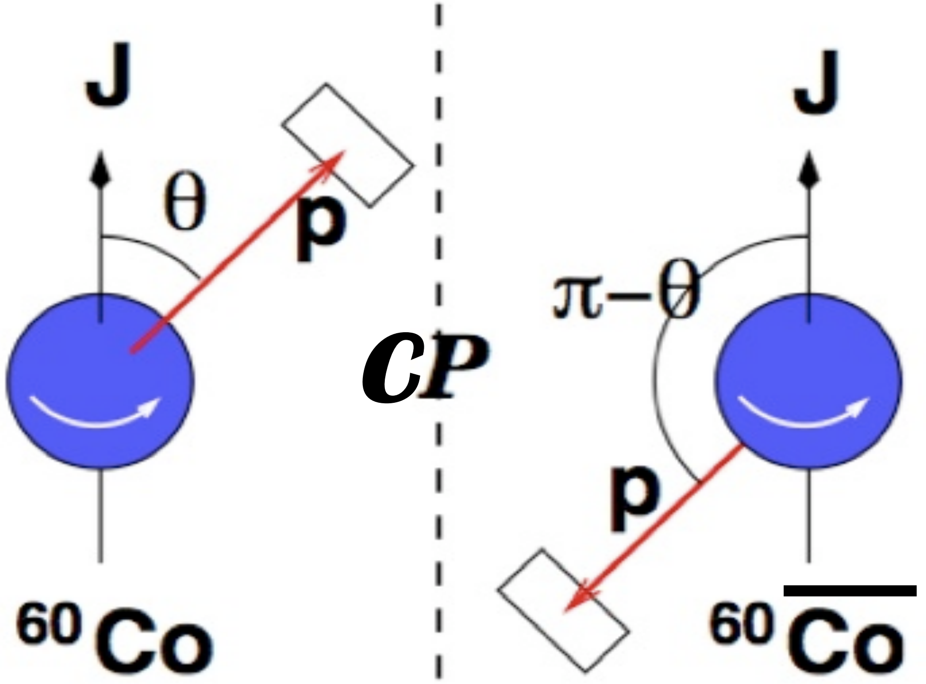
P mirror



Experiment: $I(\Theta)d\Theta = C(1+\alpha\cos\Theta)\sin\Theta d\Theta$!

CP invariance

CP mirror

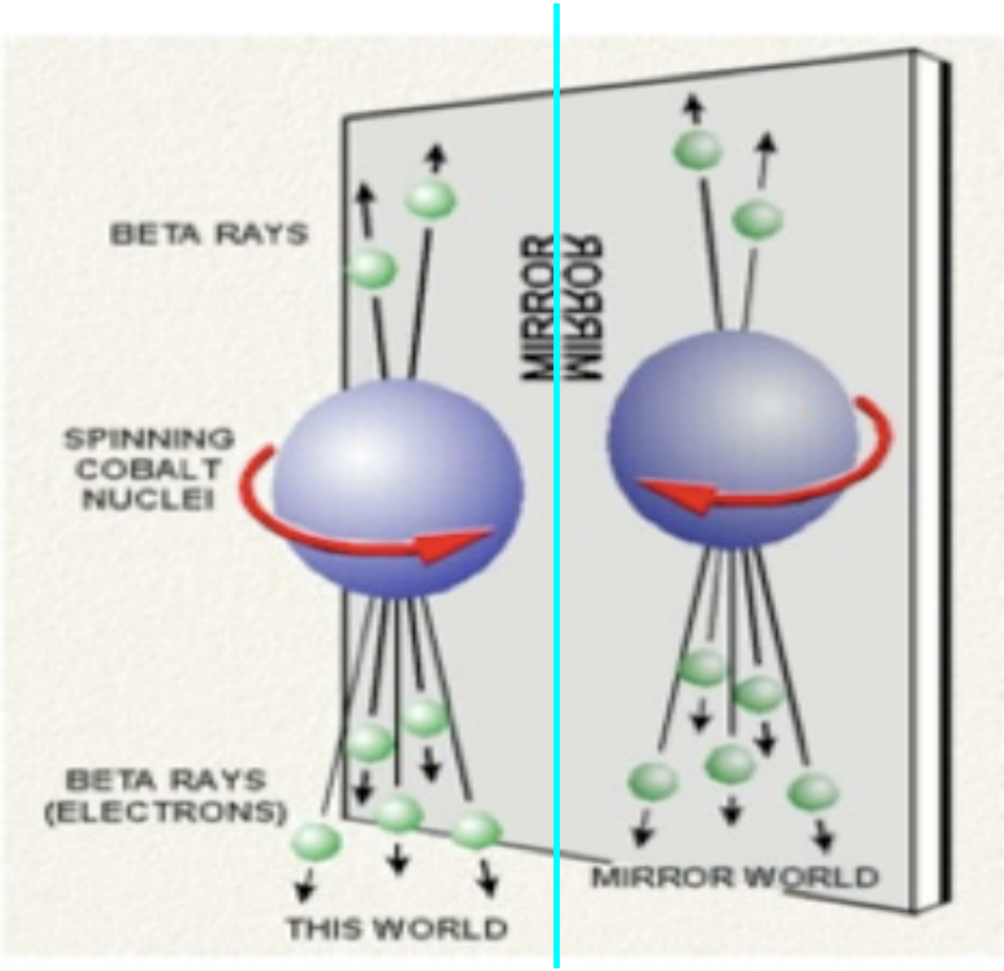


Our world and CP-world are the same: e- -> e+, p -> $\bar{p}$, ...

Experiment: CP violation in K meson decays !

Hidden (Mirror) World

CPA mirror



Our world and CPA-world are not the same: e- -> e’,...

Must be hidden!

Mirror Matter Model/ Hidden Valely@LHC

- old idea: P -> CP -> CPA symmetry

  Nature is intrinsically L-R symmetric with L-R particle properties exchanged: V-A->V+A

  New CPA-sector must be hidden; connected to our world by gravity

  Kobzarev, Okun, Pomeranchuk'65; Lee, Yang'56; Pavsic'74; Blinnikov, Khlopov'83.

- Modern MMM is based on minimal symmetry:

  $(SU(3)_C \times SU(2)_L \times U(1)_Y) \times (SU(3)_{CM} \times SU(2)_R \times U(1)_{YM})$

  SM fermions and gauge bosons are accompanied by identical mirror partners. MM is a good candidate for DM, can be linked to string theory, extra dimensins.

  no data confronting the model

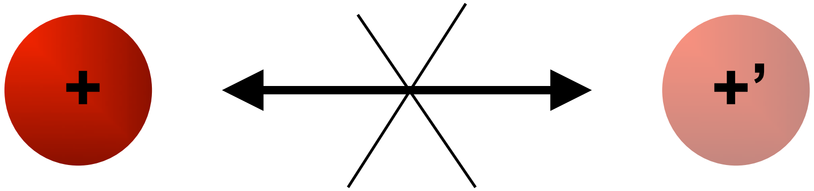
- Ordinary-Mirror particles renormalizible interactions

  - mixing of Higgs
  - kinetic mixing of photons

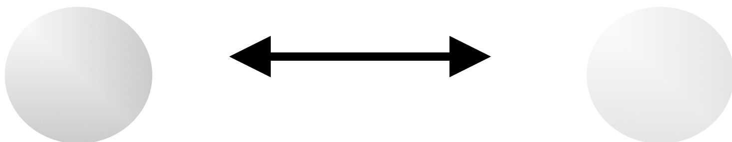
  Foot, Volkas'91 Berezhiani, Mohapatra'95, Berezhiani et al.'00-08,
  .For review see: L.Okun hep-ph/0606202

Ordinary -mirror particle interaction

Conservation laws for ordinary matter and mirror matter prevent particles with colour and charge from interacting between two sectors.



But, interaction between colourless neutral particles is allowed: ordinary and hidden sectors can communicate trough
mixing of H-H`, kinetic mixing of photons, mass mixing between neutrinos, neutrons, etc…(Z.Berezhiani, this Workshop)



How our and hidden world could communicate?

- through gravity
- through photon-hidden photon mixing
- through mixing of Higgs particles
- and , in principle, through mixing of other particles

What are the observational consequenses?

Possible MM effects:

- **Higgs mixing (LHC)**

  Ignatiev, Volkas '01; Barbieri et al. '05, Wilczek' 07, Li et al. '07…..

- **Ps-Ps` oscillations**

  Glashow '86, SG '95, Foot, SG '01; Atoyan et al. '89, Mitsui et al. '95, Badertsher et al. 07

- **n-n` mixing (PSI)**

  Berezhiani, Bento '05; Pokotilovski '06, Ben et al.(PSI) '07, Serebrov et al. (PNPI) '07, Mohapatra et al. '05.

- **dark matter(Gr.Sasso)**

  DAMA '05; DAMA/LIBRA '07, Foot '01-07; Ignatiev,Volkas'03, Mitra'03-06,…

- **ν-ν` mixing**

  Berezhiani, Mohapatra '95, Foot, Volkas '00; Mohapatra, Nasri '05

- **cosmology**

  Blinnikov, Khlopov'82,83, Khlopov'91,00, Berezhiani'95-08, Ciarcelluti'03-05,….

- **millicharged part. (SLAC,DESY)**

  Holdom '85; Ignatiev '91; Gninenko et al.'07….

- **anomalous events, ……**

  Foot, Silagadze'01-05, Foot,Mitra'02-03,…

Mirror Matter at LHC (F. Wilczek`s Colloqium at CERN)

Higgs Portal Into Hidden Sectors

Frank Wilczek
CERN Colloqium
May 3 2007

Might the LHC See Nothing?

The usual answer is:

A Higgs particle must show up, at least.

But that is not guaranteed. In fact, there are quite simple, phenomenologically unobjectionable models in which the Higgs particle becomes effectively invisible.

Example 2: Mirror World Model

$$V(\phi,\eta) = -\mu_1^2\,\phi^\dagger\phi + \lambda_1(\phi^\dagger\phi)^2 - \mu_2^2\,\eta^2 + \lambda_2\,\eta^4 - \kappa\,\phi^\dagger\phi\,\eta^2$$

The upshot is that the two mass eigenstates (=particles) are created by mixtures of the conventional Higgs field and the phantom field.

Thus the same overall production rate of Higgs particles is now divided between two lines.

Rather than one channel with S/N = 2, for the same exposure you'll get two channels with S/N=1.

Of course, it's easy to generalize this model. With more phantom fields, one has more division.

$5 \times 1\,\sigma \neq 5\,\sigma$.

Search for neutron-mirror neutron ocsillations

Z. Berezhiani and L.Bento, PRL 96(2006) 081801

the small mass mixing between the ordinary neutron n and its mirror partner n' could have direct astrophysical consequences, in particular, for the propagation of ultra-high energy cosmic rays at cosmological distances The experimental possibilities to test the n-n' oscillation were discussed by Yu.N. Pokotilovski PL B639(2006)214

PSI (2007)

A Direct experimental limit on neutron-mirror neutron oscillations.

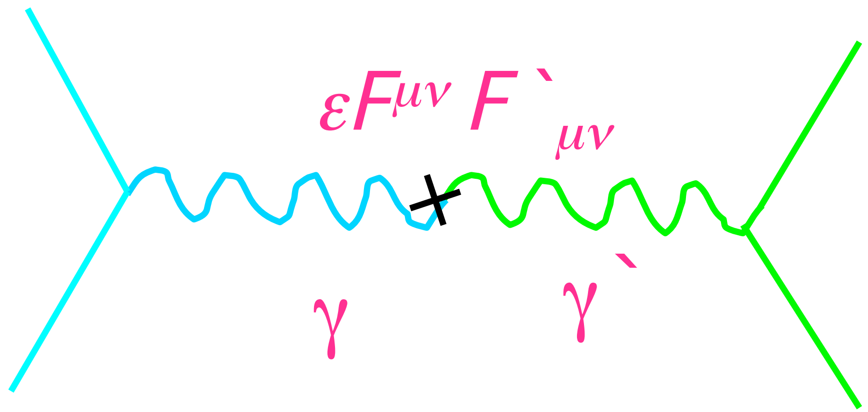
G. Ban *et al.* **arXiv:0705.2336** [nucl-ex]

PNPI (2007)

Experimental search for neutron-mirror neutron oscillations using storage of ultracold neutrons.

A.P. Serebrov *et al.***arXiv:0706.3600** [nucl-ex]

Effects from γ-γ` <u>kinetic</u> mixing



- γ-γ` oscillations (if γ` not massless) Okun'82
- millicharged particles: q=2εe Holdom'86
- oPs - oPs` oscillations Glashow'86, Foot,S.G.'2000
- mirror matter scattering off our matter Foot'04-08

DAMA/LIBRA effect

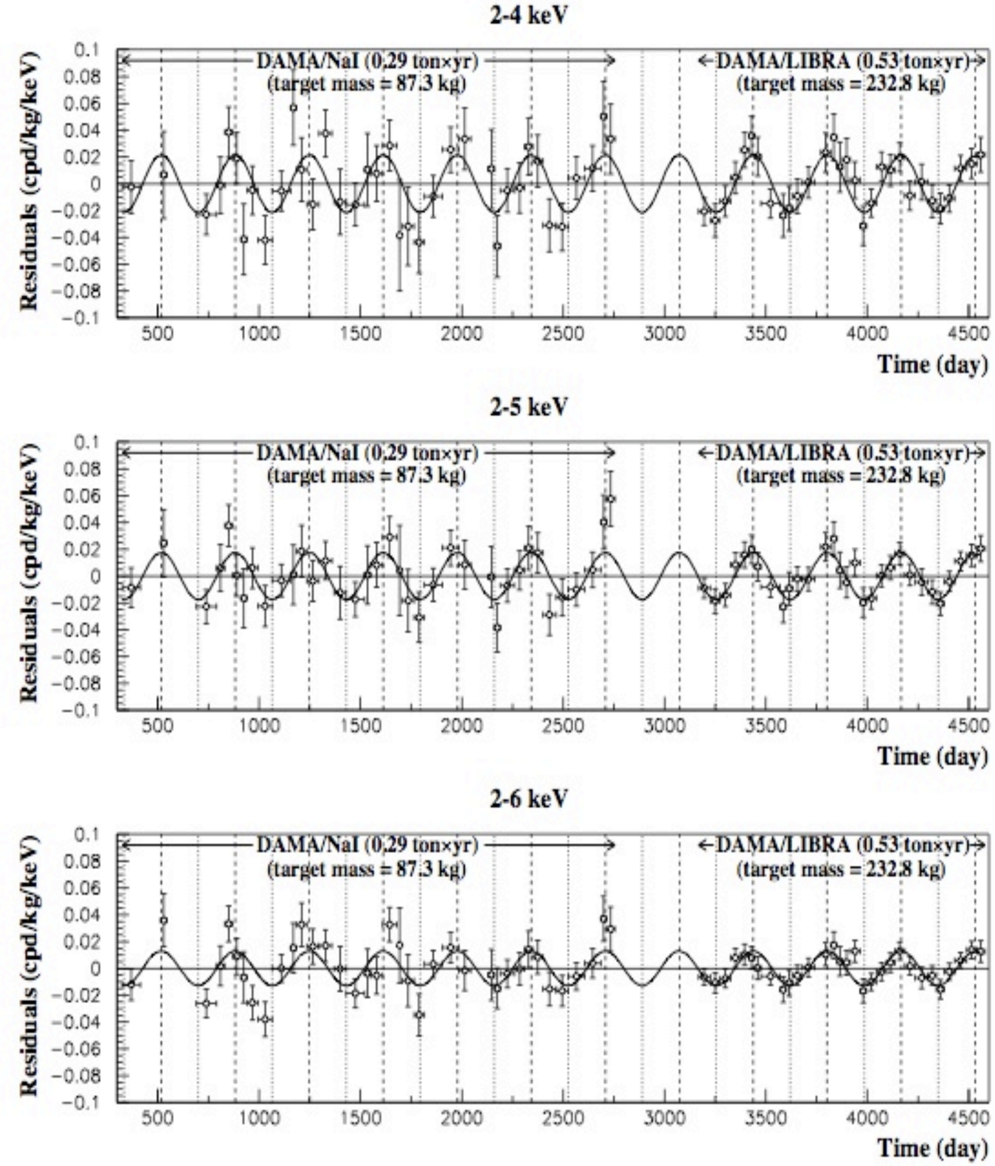
Dark matter signal annual modulation?

~250 kg NaI(Tl),
0.53 ton x y
Signal in 2-6 keV region

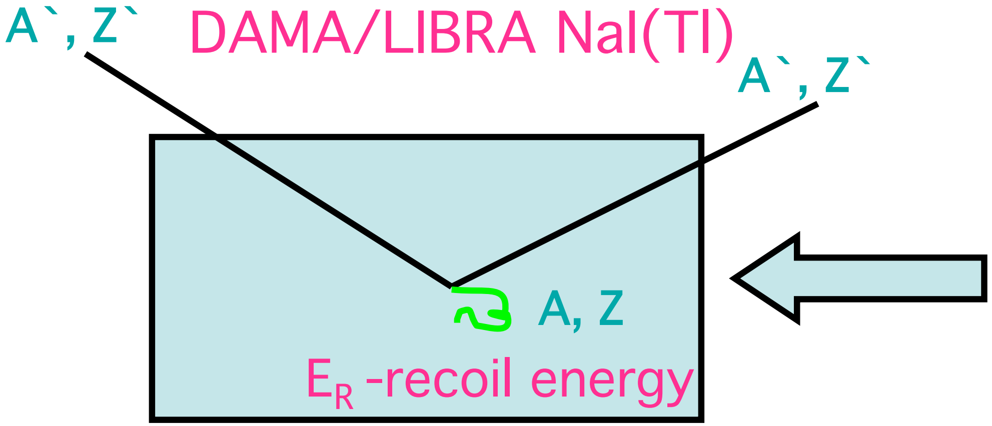
$S = A\cos(2\pi(t-t_0)/T)$
$A = (0.013 +- 0.0016)$ cpd/kg/keV
significance 8 sigma
$T/y = 0.998 +- .003$
t_0 /day=144+-8

If Dark matter:
$T/y = 1.0$, t_0 /day=152.5

R. Bernabei et al.
Eur.Phys.J.C56:333-355,2008.
e-Print: arXiv:0804.2741 [astro-ph]



DAMA/LIBRA: Mirror Dark Matter scattering?



If mirror matter is identified with the nonbaryonic DM - mirror atoms could be a large component of galactic DM halo

Counting rate due to γ-γ` interaction :

$dR/dE_R \sim \varepsilon^2 n`/(vE_R)^2$

v - Earth velocity around the Sun is modulated
170 km/s < v < 270 km/s

n` - halo number density for
A` = H`, He`, O`, etc.

⇒ **Prediction: $\varepsilon \sim 10^{-9}$**

R. Foot, PRD 78(2008)043529

Mixing strength $\varepsilon \sim 10^{-9}$

- Consistent with BBN $\varepsilon < 3\ 10^{-8}$ and all experimental limits

- Consistent with null results of

-CDMS/Ge

-CDMS/Si

-XENON10

due to lower DAMA energy threshold and lighter target

- Other WIMP interpretations : are they disfavoured ?

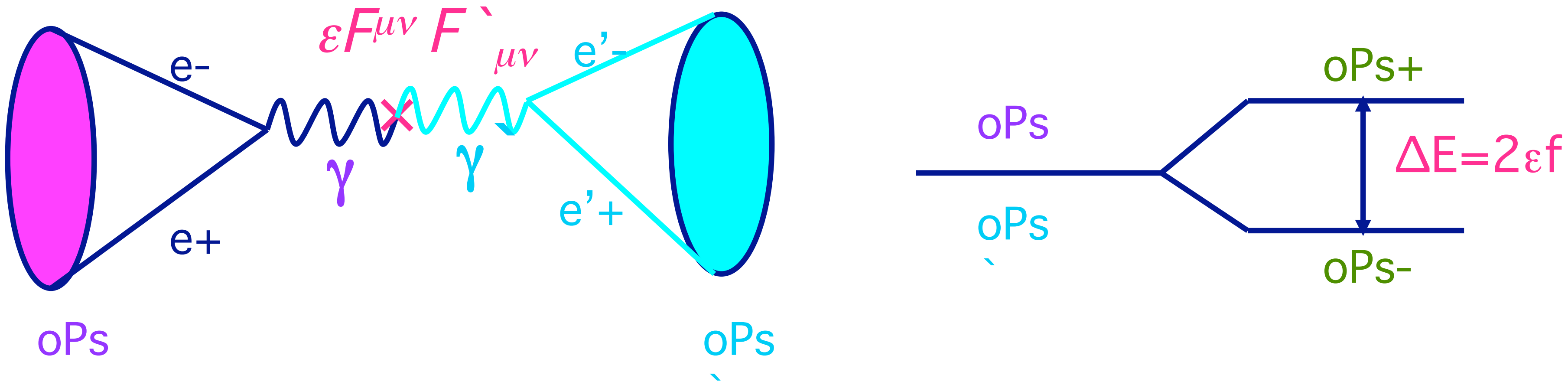
How to check DAMA/LIBRA Mirror DM interpretation?

-Directly: Massive ~ 1 ton, low Z detector with a low ~ 1 keV recoil energy threshold - very challenging task.

-Indirectly: oPs-oPs` oscilaltions

Orthopositronium oscillations

Glashow '86; SG`91; Foot and SG`00



- new mass eigenstates: oPs± = (oPs±oPs`)/√2
- energy splitting: $\Delta E=2\varepsilon f$, $f=8.4\times10^4$ MHz from oPs-pPs splitting
- oscillation probability: $P(\mathrm{oPs}\text{-}\mathrm{oPs}`)(t)=\sin^2(2\pi\varepsilon f t)$

Experimental signatures for oPs-oPs' oscillations

- modification of oPs decay curve -
  very difficult to measure, high statistics required

- oPs->oPs`-> 3γ' -> invisible decay -
  more convinient: few events need to be observed

Branchnig ratio in vacuum:

$$Br(oPs \rightarrow invisible) = \frac{2(2\pi\varepsilon f)^2}{\Gamma^2_{SM} + 4(2\pi\varepsilon f)^2}; \ t >> \frac{1}{\Gamma_{SM}}$$

in a target (in presence of collisions):

$$Br(oPs \rightarrow invisible) \simeq \frac{2(2\pi\varepsilon f)^2}{\Gamma_{SM}\Gamma_{COLL}}; \ t >> \frac{1}{\Gamma_{COLL}}$$

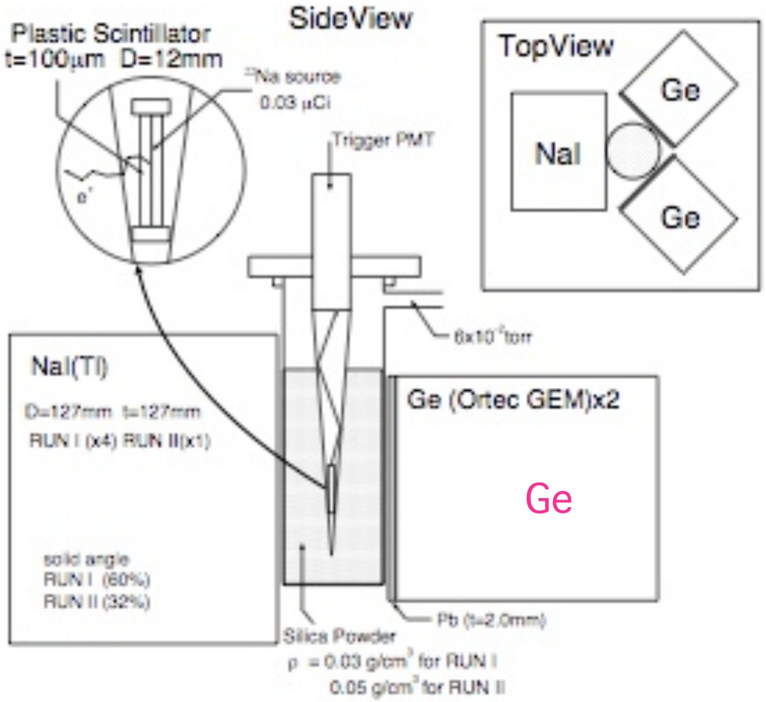
SG'95, Foot and SG '00

Suppression factor

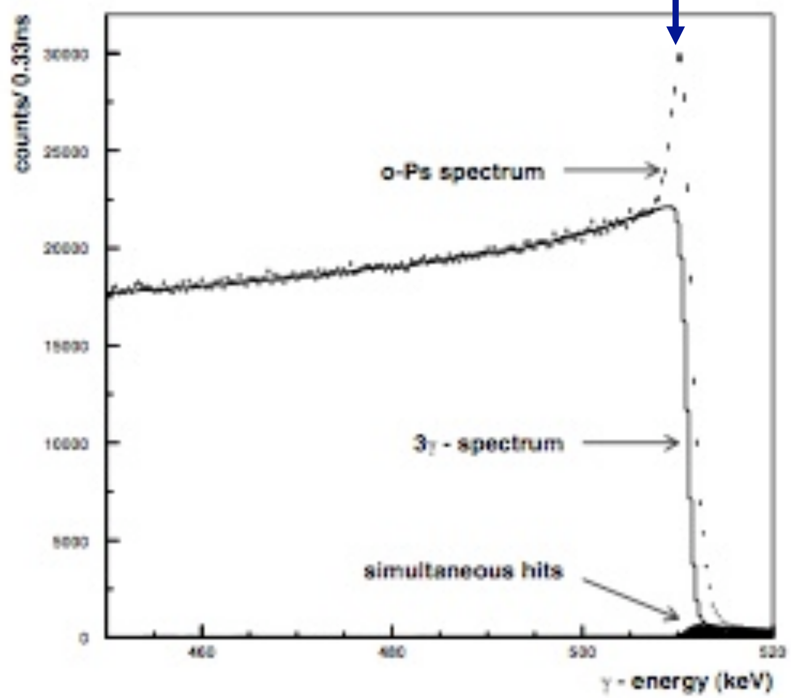
Tokyo experiment with silica target

511-keV line
from 2γ annihilation

$$\Gamma_{oPs} = \Gamma_{exp} - \Gamma_{pick\text{-}off}$$



Experimental setup



spectrum from Ge detector

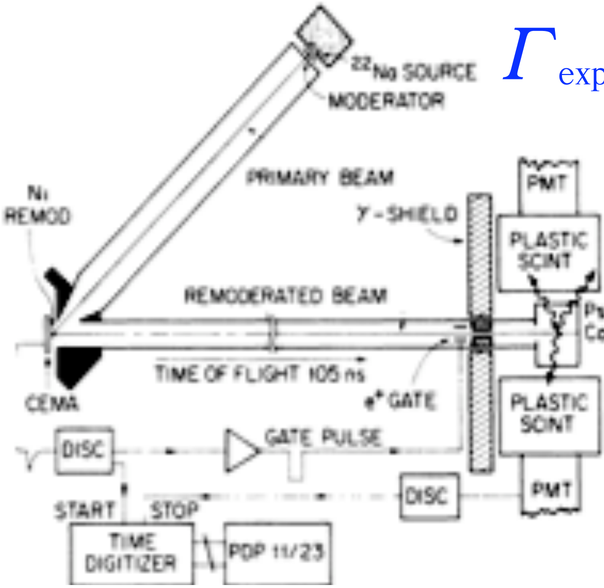
oPs formation and decay in a 0.1 g/cm^3 dense target
~10^4 collisions/lifetime results in pick off rate:
e+e- + (e-M)-> e- + (e+e- -> 2γ)+ M ~$10^{-2}\ \Gamma_{oPs}$

Asai et al.'08

Ann Arbor Paradox: but no 511 keV line?!

VOLUME 65, NUMBER 11 PHYSICAL REVI

$\Gamma_{exp} > \Gamma_{SM}$

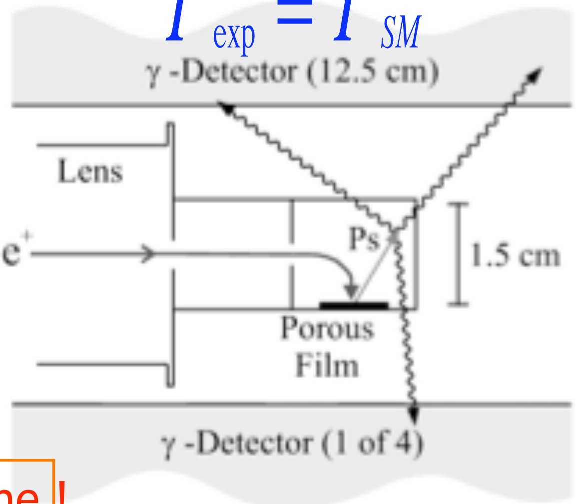


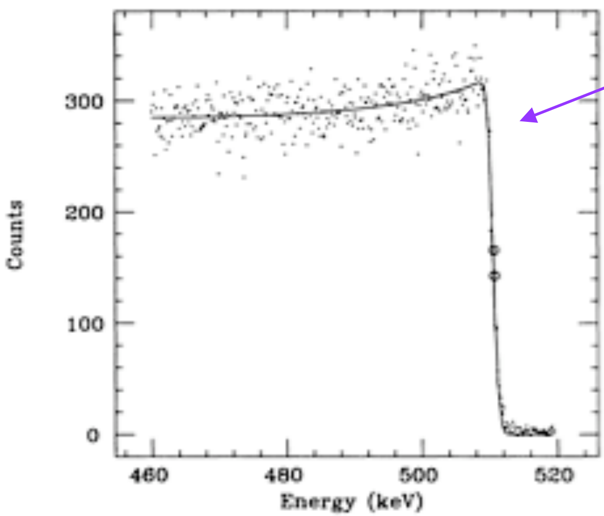
Ge

no 511-keV line !

VOLUME 90, NUMBER 20 PHYSICAL REVI

$\Gamma_{exp} = \Gamma_{SM}$





ME 66, NUMBER 10 PHYSICAL REVIEW LETTERS 11 MARCH 1991

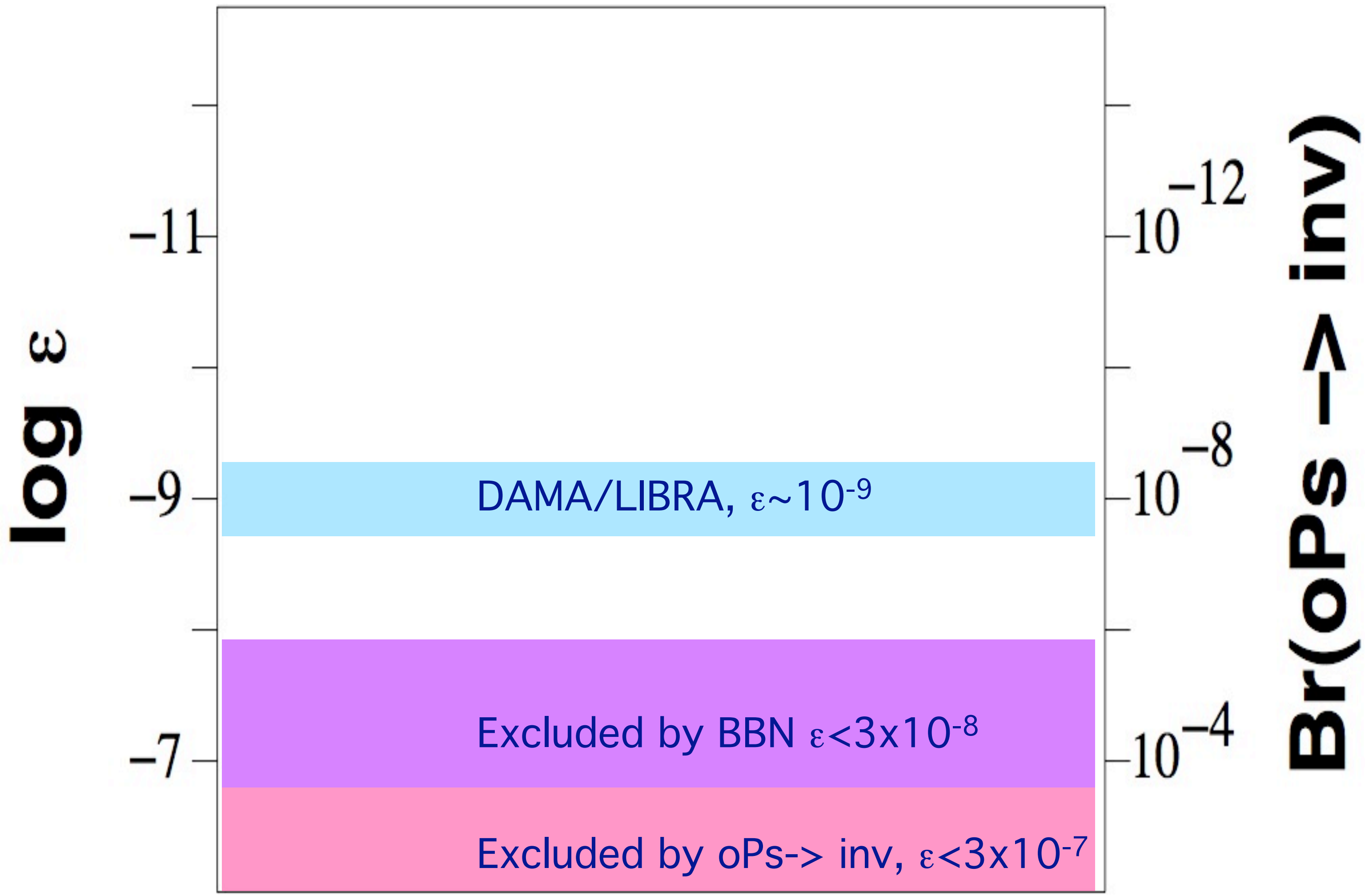
Direct Search for Two-Photon Decay Modes of Orthopositronium

D. W. Gidley, J. S. Nico, and M. Skalsey
Department of Physics, University of Michigan, Ann Arbor, Michigan 48109
(Received 13 December 1990)

A direct search for γ rays from the forbidden decay o-Ps → 2γ has been performed using the same apparatus that recently measured an anomalously high o-Ps decay rate. Using a high-resolution Ge γ-ray detector, a 233-ppm limit is set on the branching ratio to a pair of 511-keV γ rays, and a 200-ppm limit is set on the branching ratio to a pair of unequal-energy γ rays that sum to 1022 keV. Hence, these 2γ modes cannot be responsible for the o-Ps decay-rate discrepancy between theory and experiment of 1400 ± 230 ppm.

PACS numbers: 36.10.Dr, 11.30.−j, 12.20.Fv

Limits on ε



Vacuum experiment with a sensitivity in Br(oPs->inv)~10^{-8} would be very important to check DAMA/LIBRA and BBN

Preprint typeset in JINST style - HYPER VERSION

Positronium Portal into Hidden Sector: A new Experiment to Search for Mirror Dark Matter

Paolo Crivelli[a], **Alexander Belov**[b], **Ulisse Gendotti**[c], **Sergei Gninenko**[b], **André Rubbia**[c]

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Rio de Janeiro, Brazil
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Moscow, Russia
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101 Raemistrasse 8093 Zurich, Switzerland
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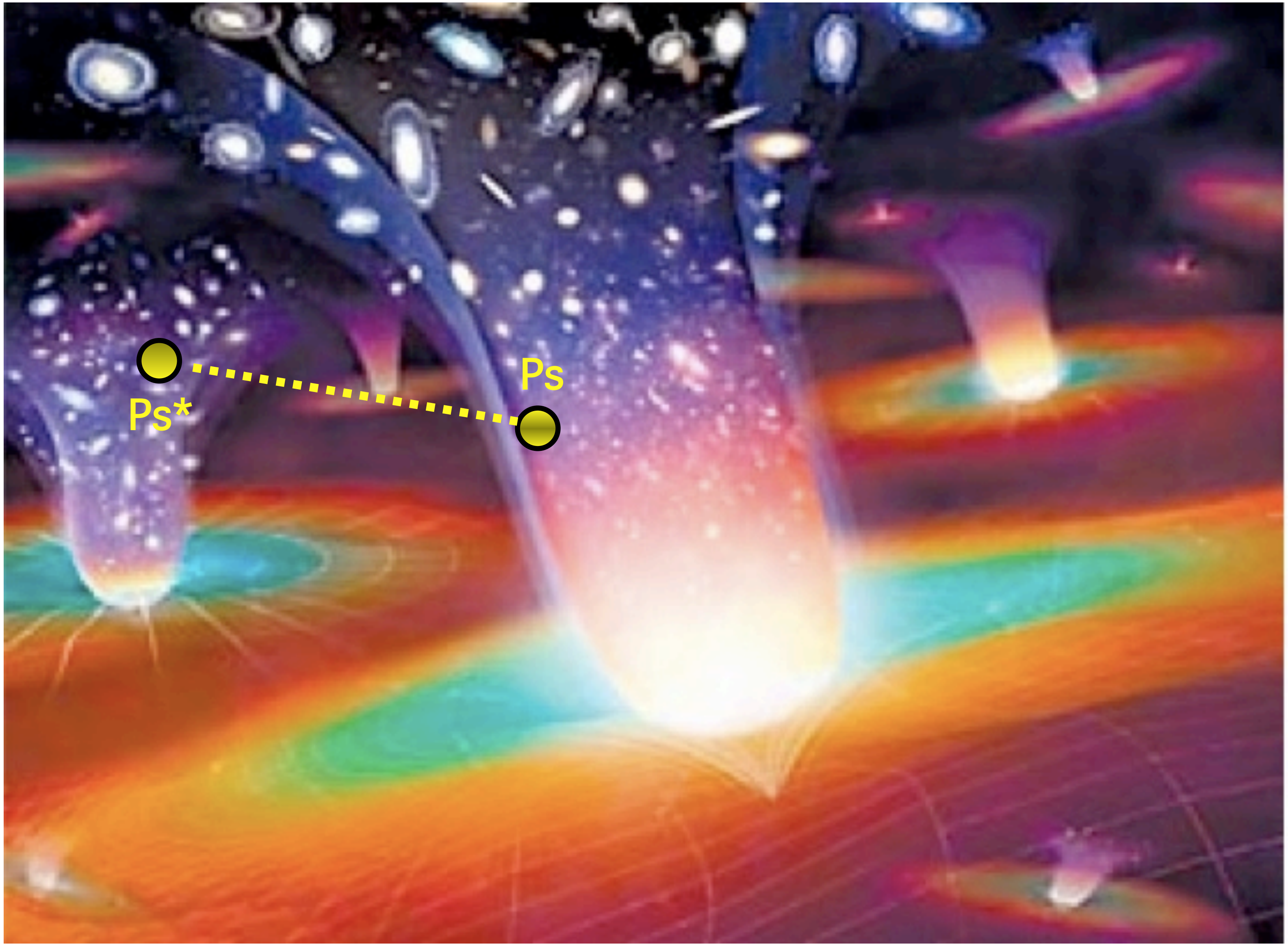
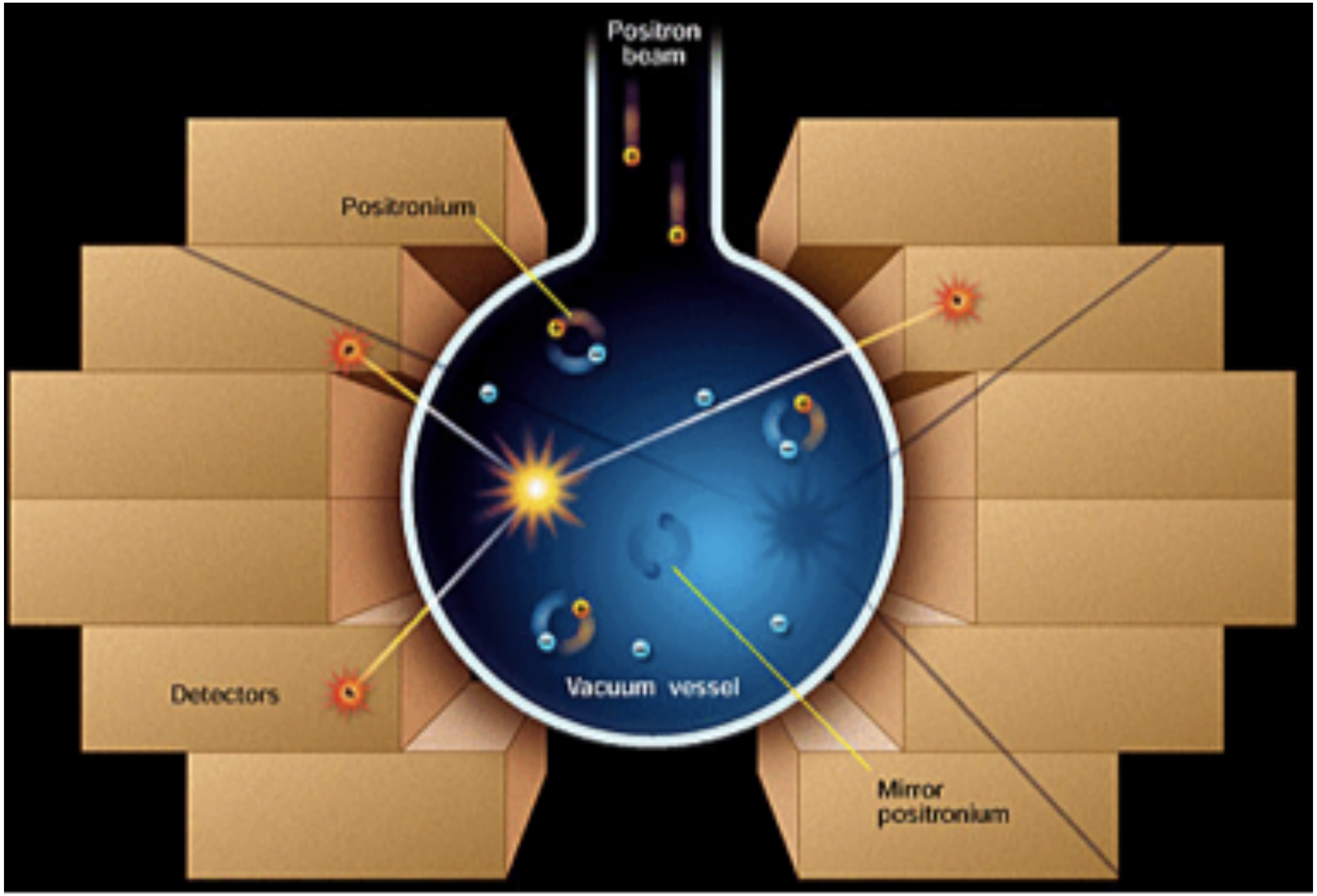
ABSTRACT: The understanding of the origin of dark matter has great importance for cosmology and particle physics. Several interesting extensions of the standard model dealing with solution of this problem motivate the concept of hidden sectors consisting of $SU(3)_C \times SU(2)_L \times U(1)_Y$ singlet fields. Among these models, the mirror matter model is certainly one of the most interesting. The model explains the origin of parity violation in weak interactions, it could also explain the baryon asymmetry of the Universe and provide a natural ground for the explanation of dark matter. The mirror matter could have a portal to our world through photon-mirror photon mixing (ε). This mixing would lead to orthopositronium ($o-Ps$) to mirror orthopositronium oscillations, the experimental signature of which is the apparently invisible decay of $o-Ps$. In this paper, we describe an experiment to search for the decay $o-Ps \rightarrow invisible$ in vacuum by using a pulsed slow positron beam and a massive 4π BGO crystal calorimeter. The developed high efficiency positron tagging system, the low calorimeter energy threshold and high hermiticity allow the expected sensitivity in mixing strength to be $\varepsilon \simeq 10^{-9}$, which is more than one order of magnitude below the current Big Bang Nucleosynthesis limit and in a region of parameter space of great theoretical and phenomenological interest. The vacuum experiment with such sensitivity is particularly timely in light of the recent DAMA/LIBRA observations of the annual modulation signal consistent with a mirror type dark matter interpretation.

KEYWORDS: Positronium; Dark matter; Hidden sectors.

Поиск темной материи



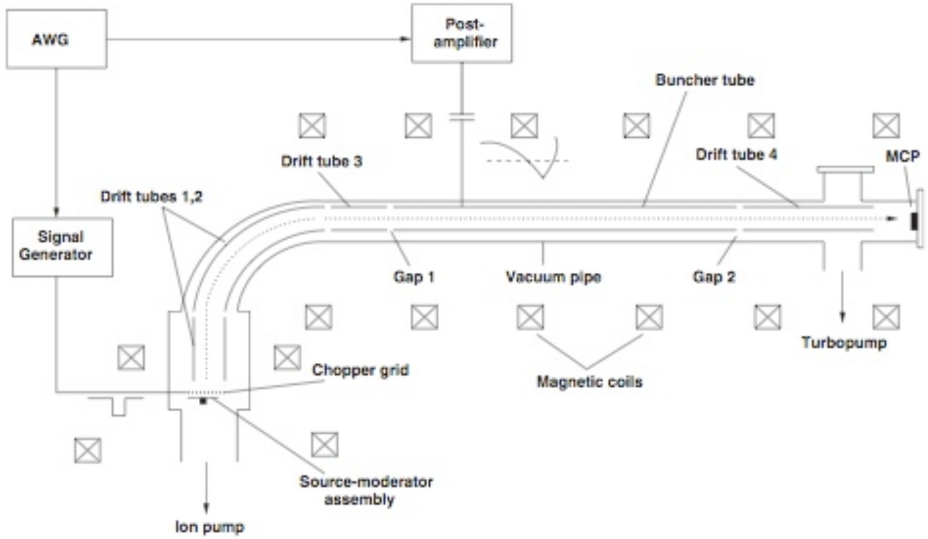
How to search for hidden world with oPs?

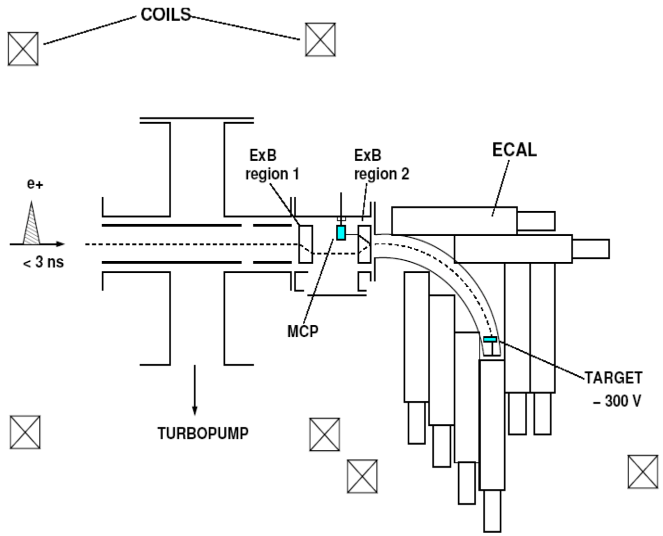


Cortesy New Scientists, 2004.

Search for mirror dark matter via o-Ps->invisible

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

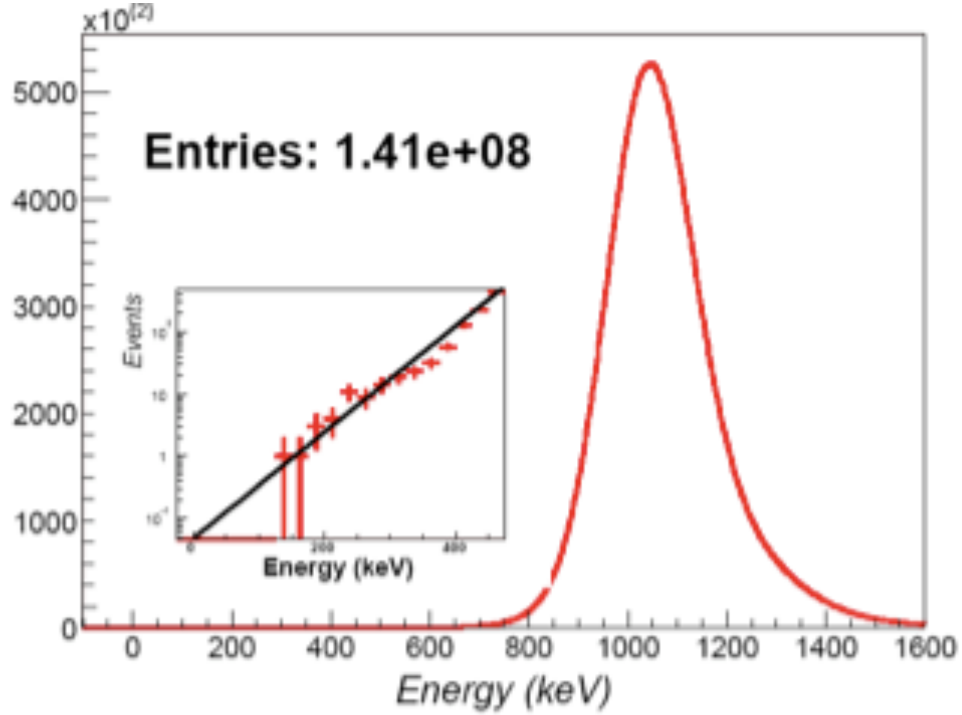




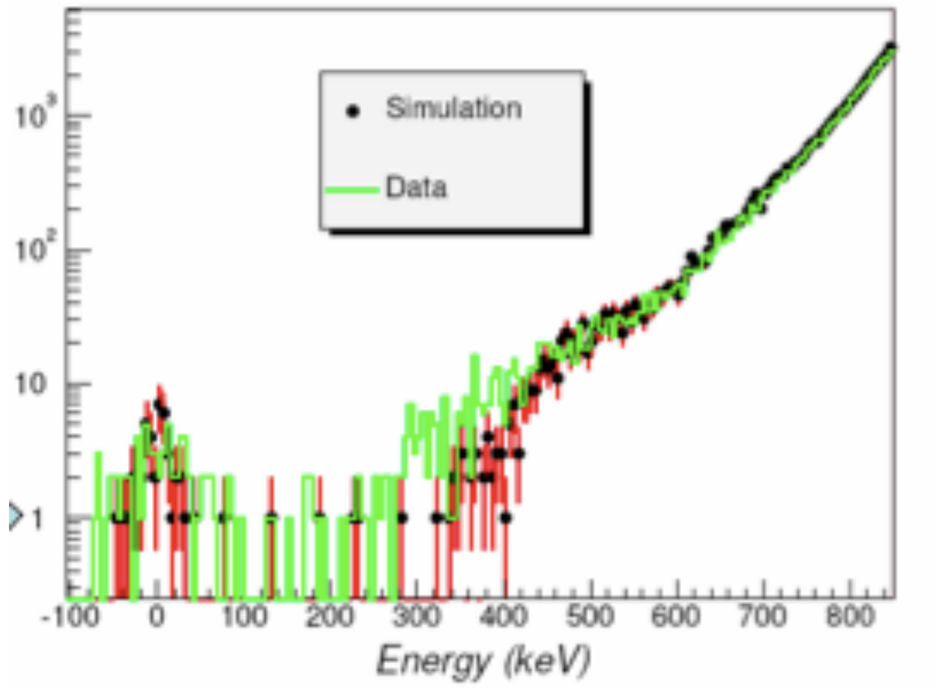
- e+ tagging system: timing coincidence of e+ bunch and MCP signal from secondar electron emission , inefficiency < 1.e-8
- pulsed slow positron beam, high efficiency & compression factor
- cold oPs to minimize leak through entrance window
- hermetic calorimeter in magnetic field
- very thin vacuum pipe

Cross-check of oPs disappearance

No Coherence due to collisional quenching of oPs-oPs`transitions



Coherent oPs-oPs`transitions

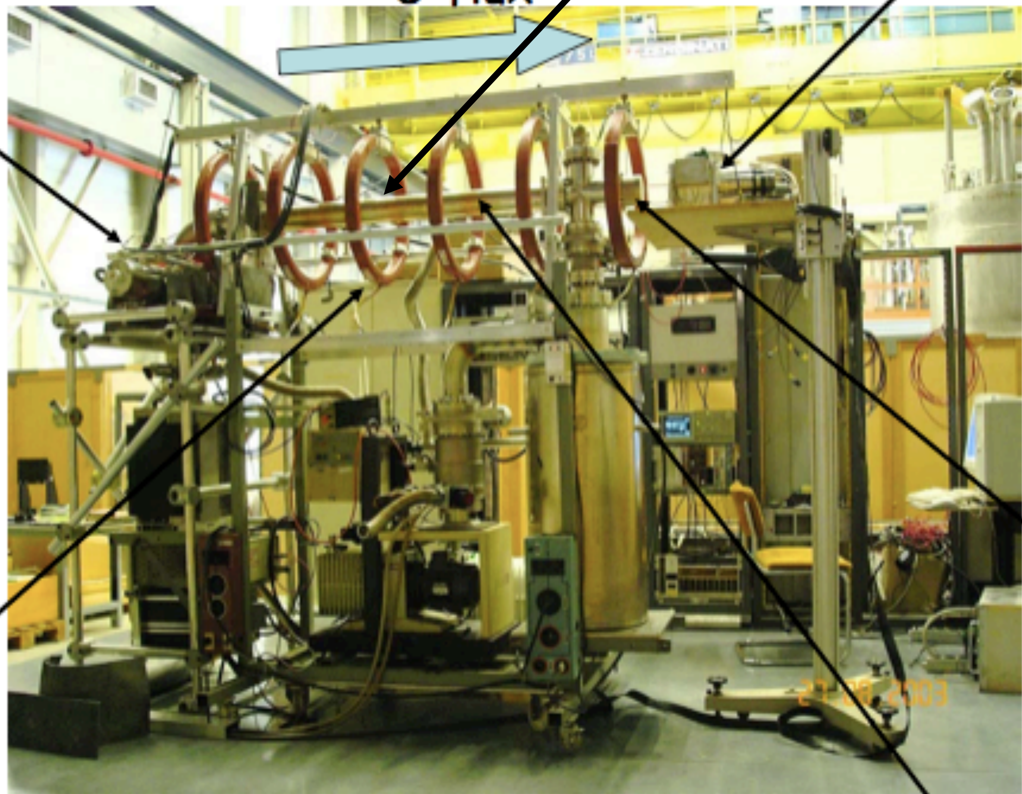


Different from the LEPTA approach to search for modulations of the o-Ps decay curve, e.g. I.N. Meshkov et al. NIM B214 (2004) 186

Comparison of two independent experiments would be very Intersting and important!

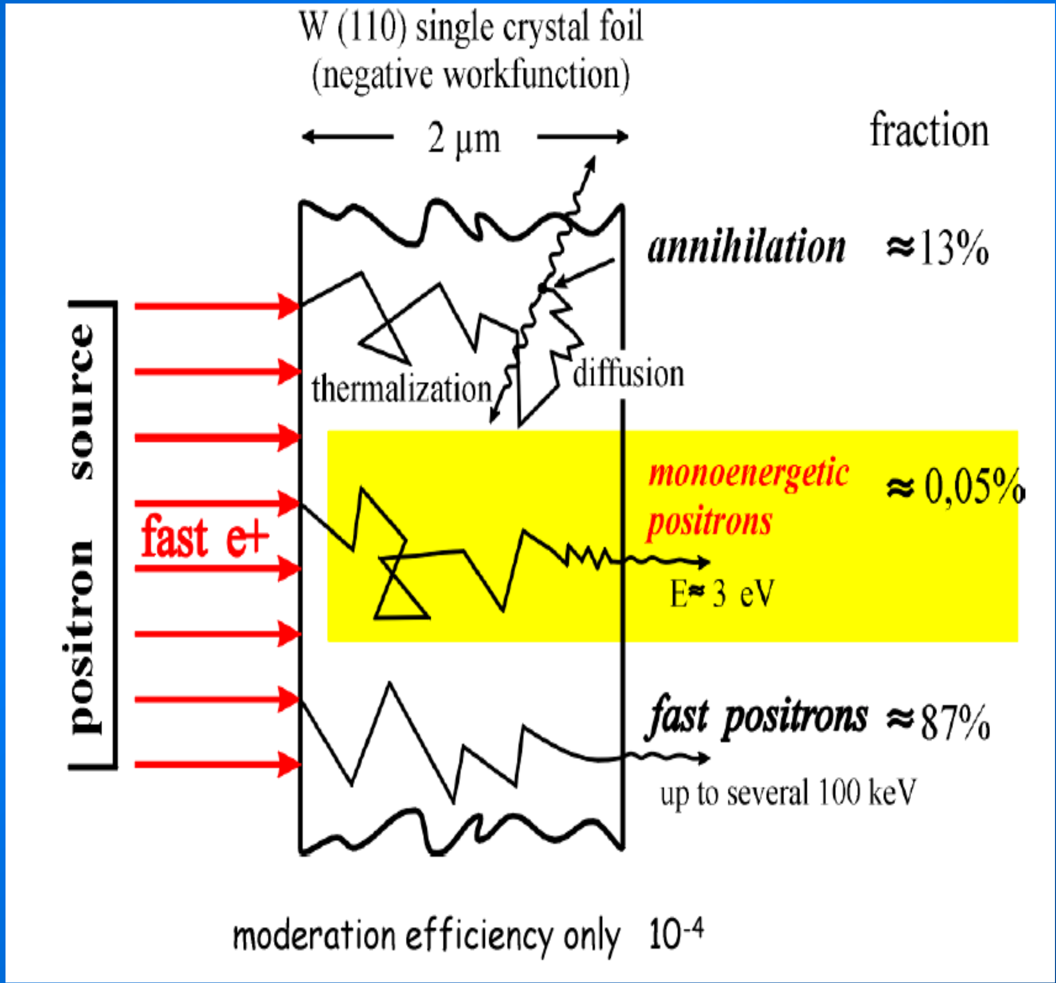
Пульсирующий пучок, система мечения, и вакуумная мишень позитронов

The slow positron Beam



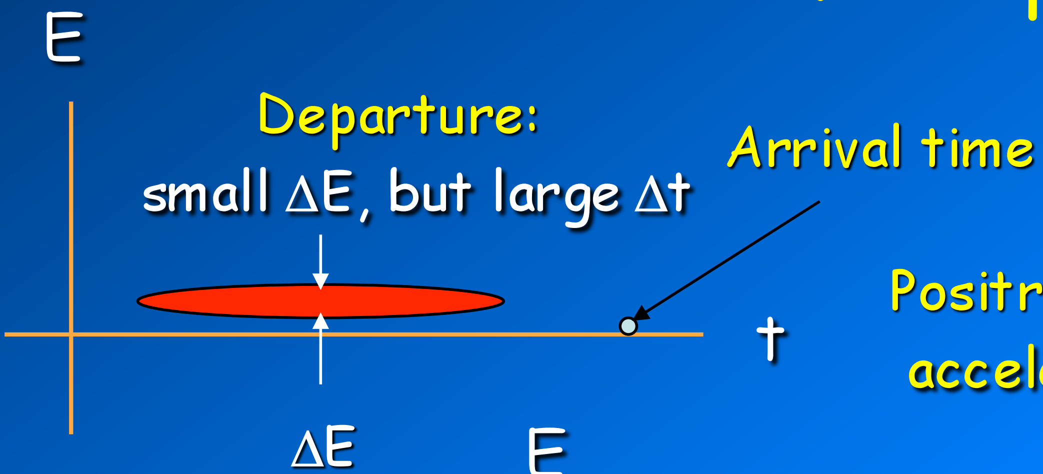
Positron moderation

- 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

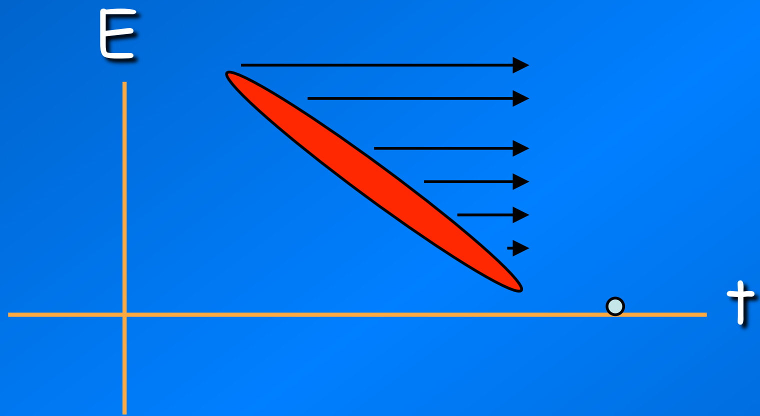


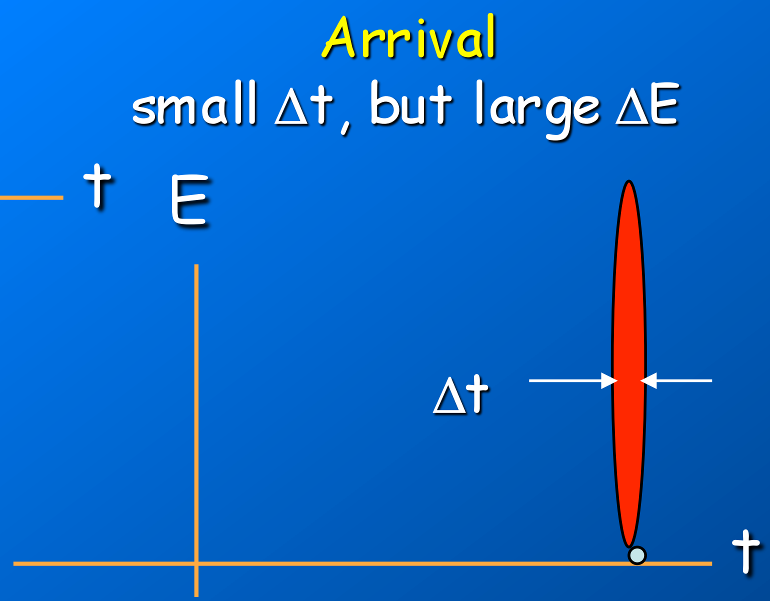
http://positron.physik.uni-halle.de

How to make pulsed beam?



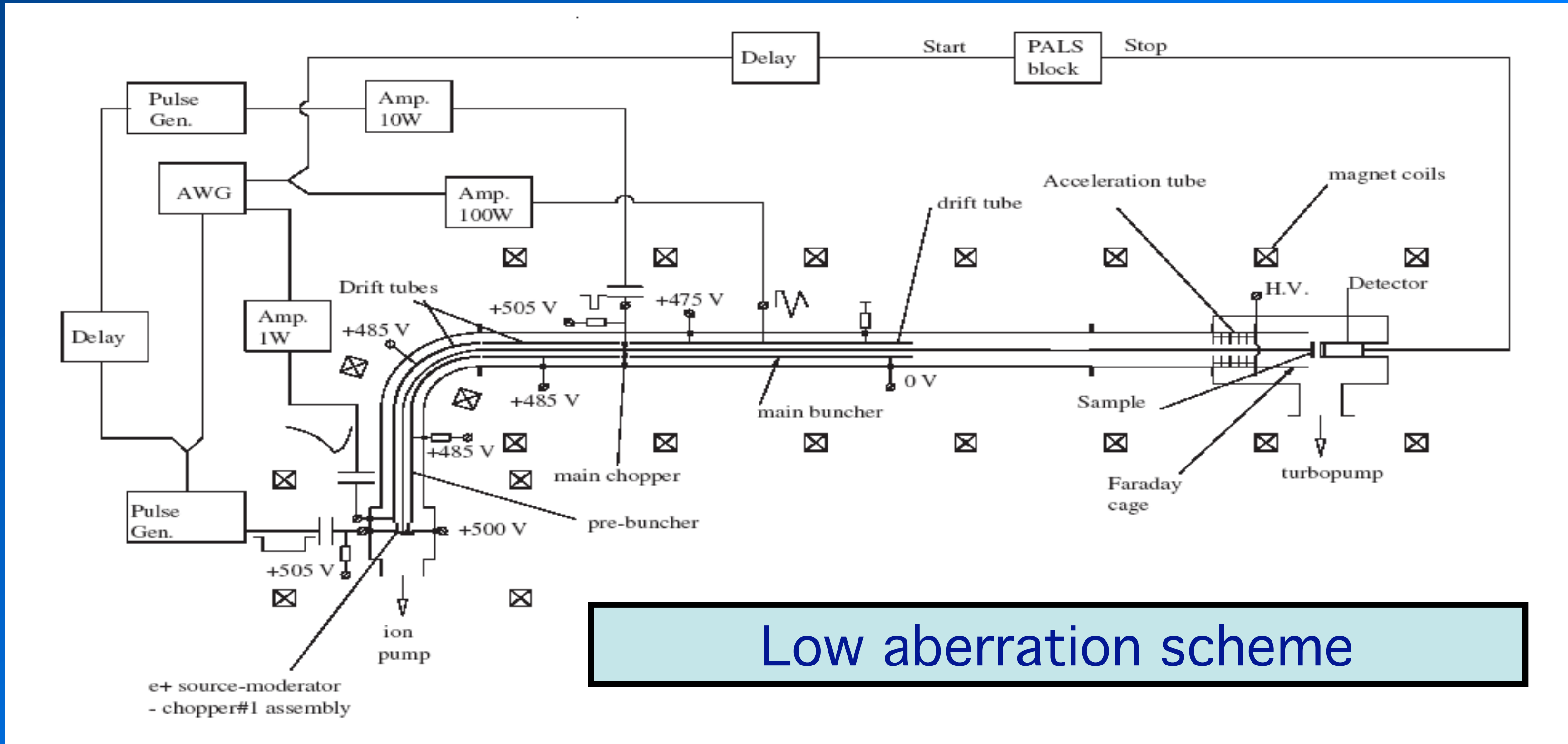
Positron velocity modulation:
accelerate those who are late

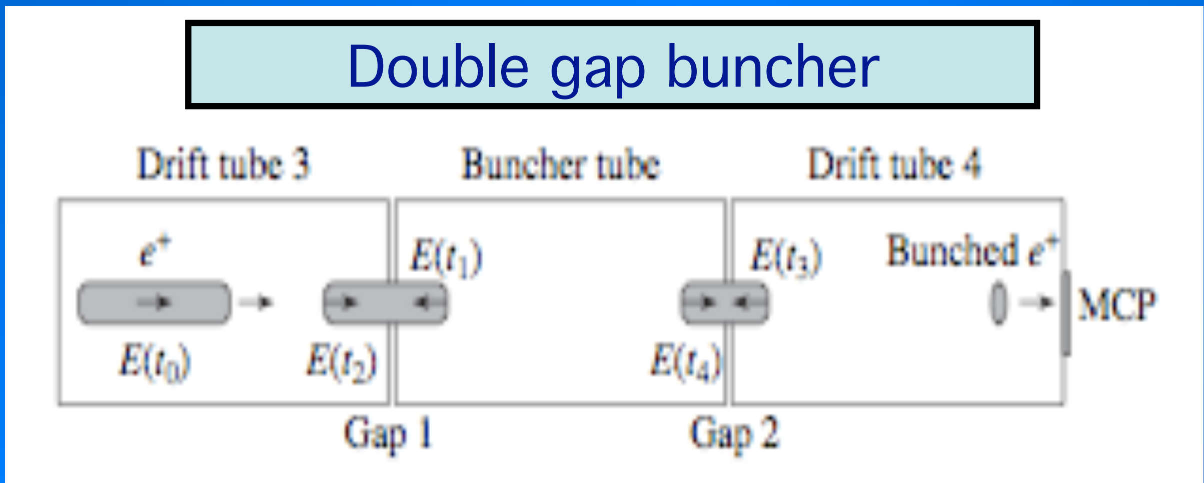


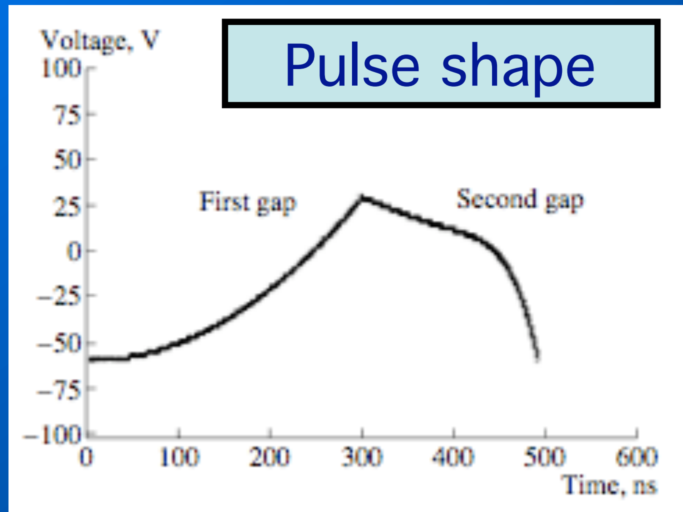


Problems for large Δt
- fast switch on-off of high voltage
- possible aberrations
- intensity is limited by rad. safety

Pulsing System







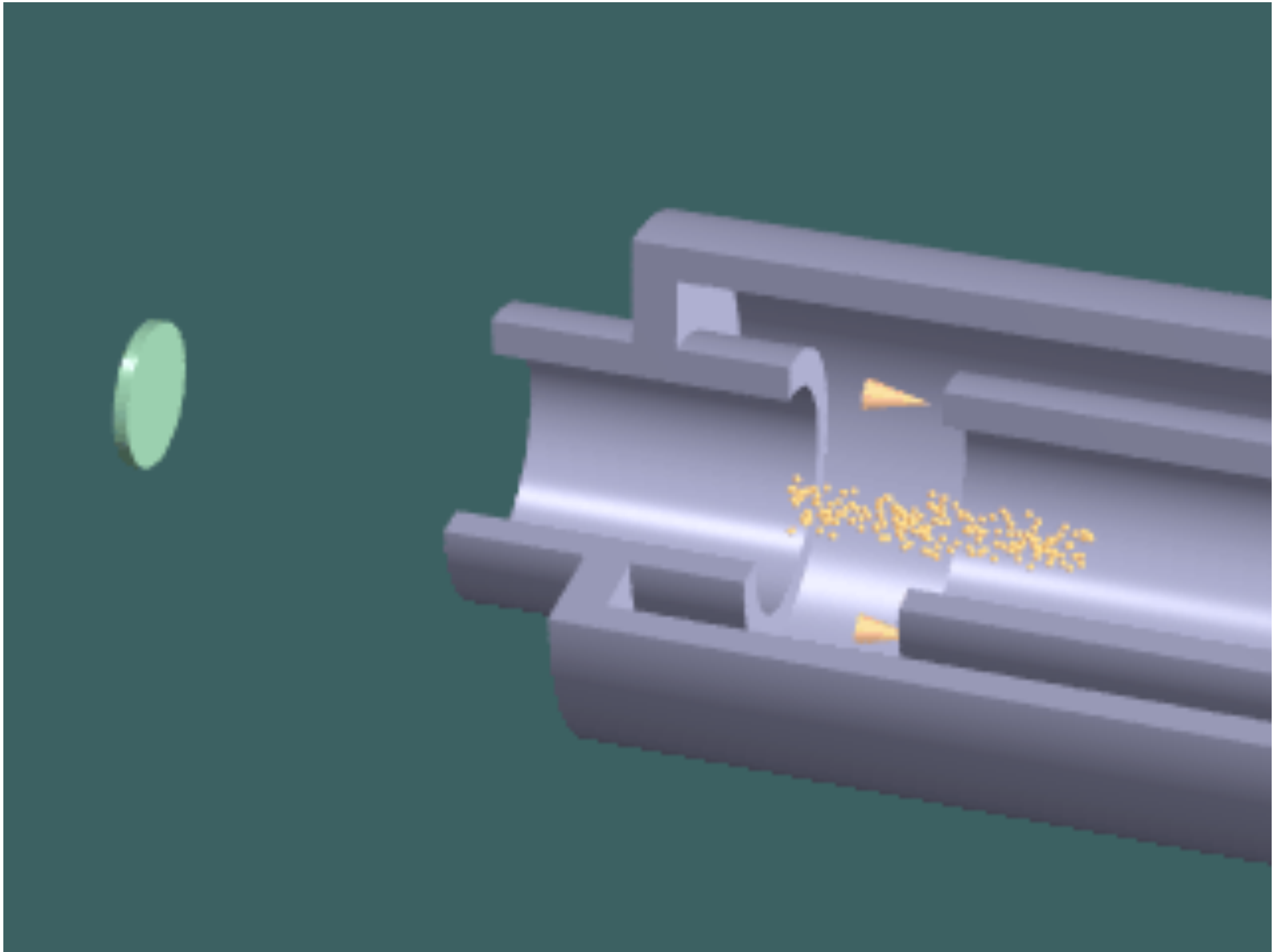
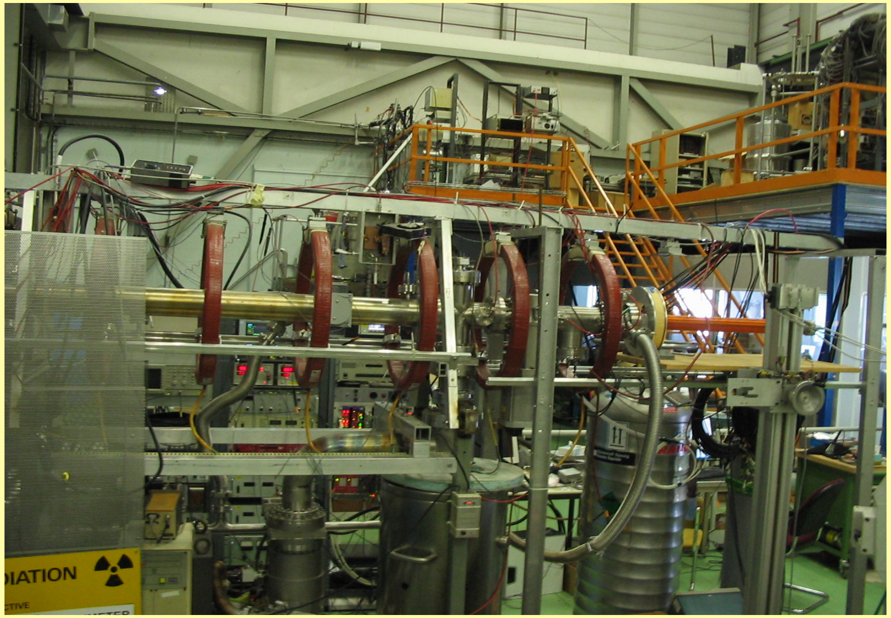
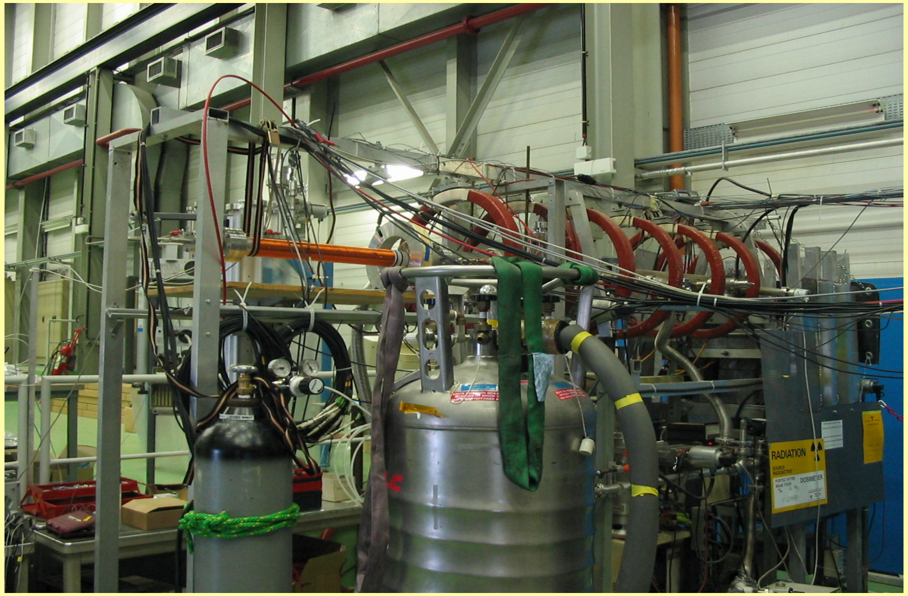
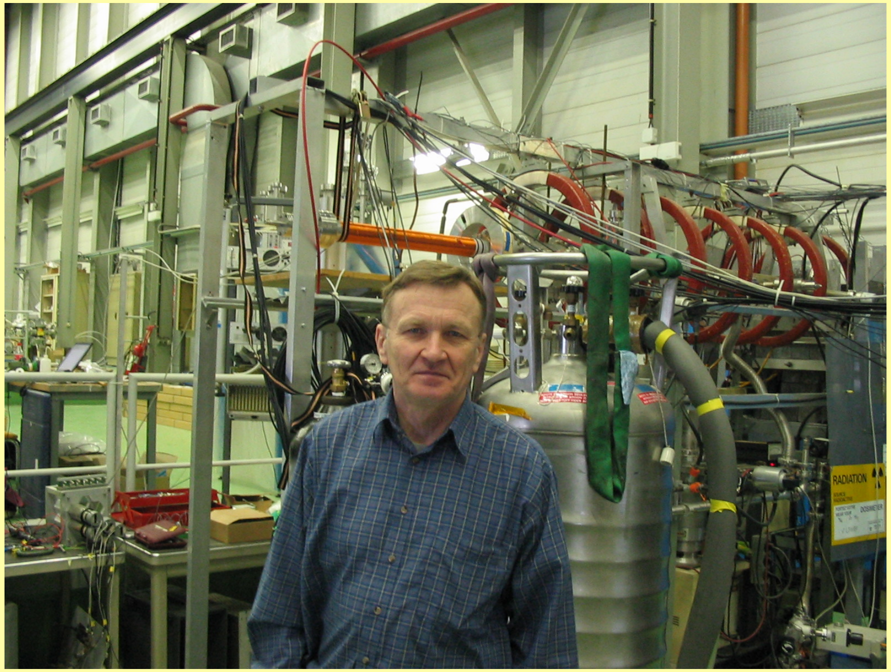


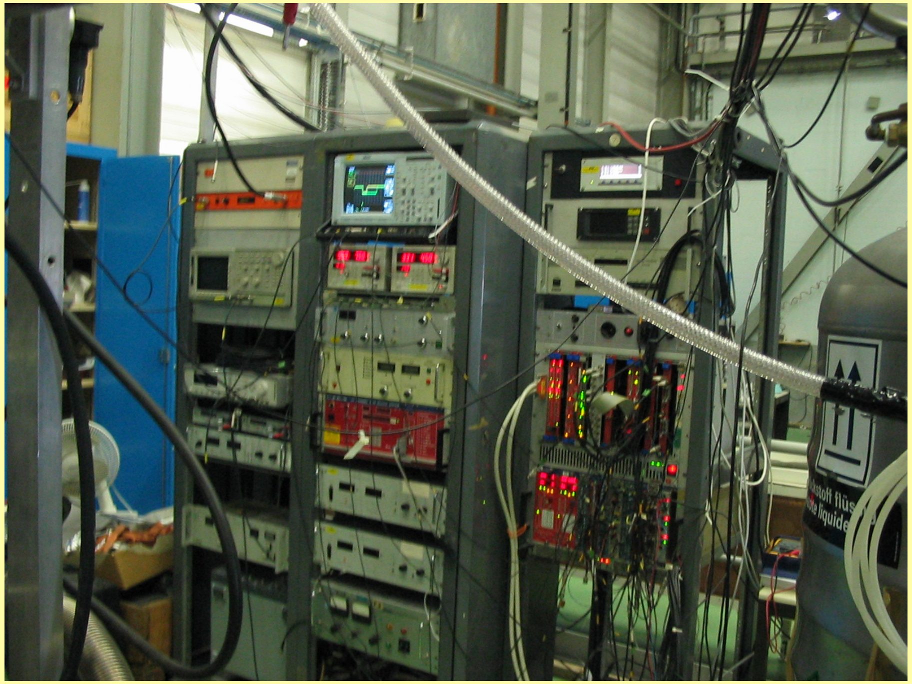
Фото пучка (+топ модель)

Beam Photos







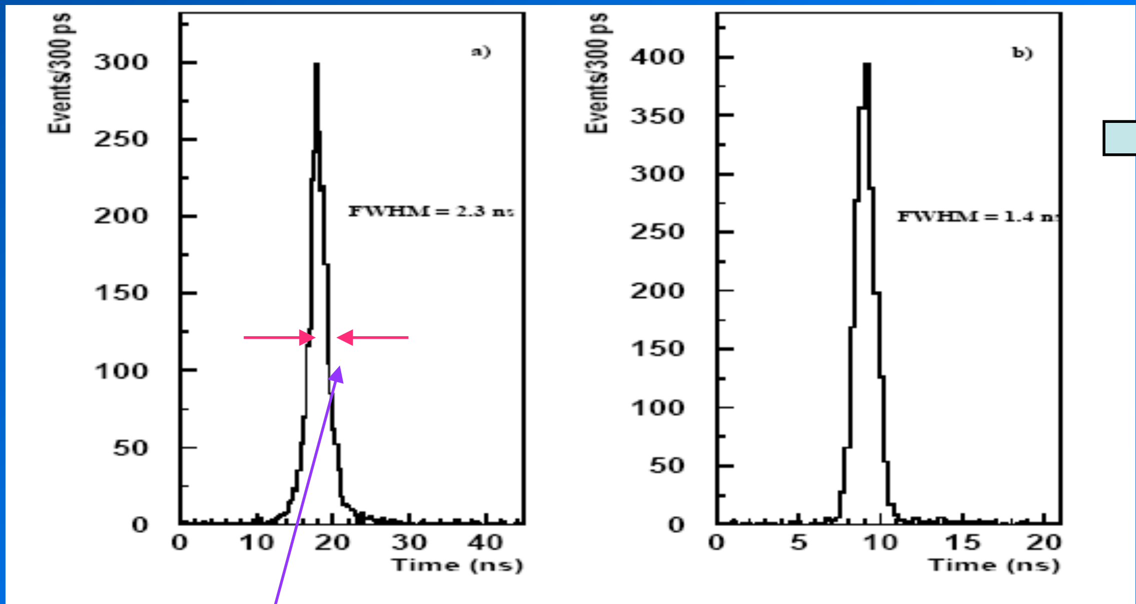


Results on positron pulse width

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

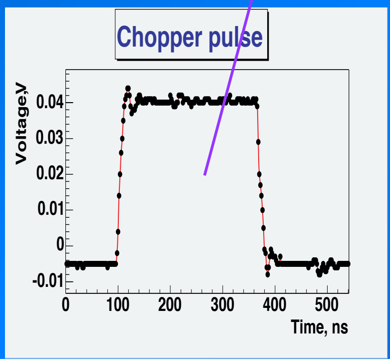
~ 2.3 ns (FWHM)
for an Initial pulse
of 300ns

~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)

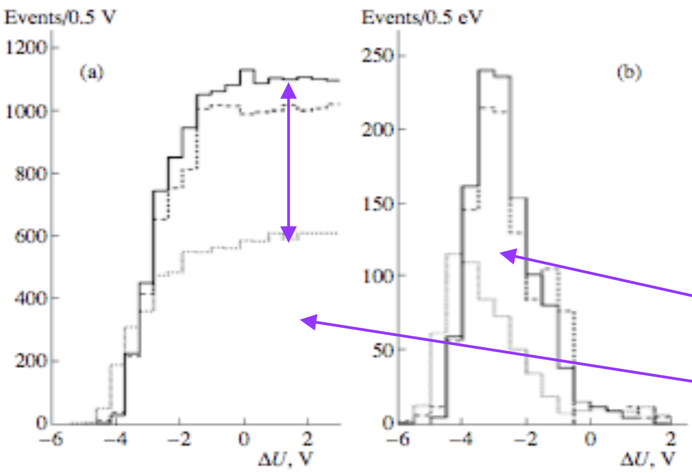


Fig. 13. (a) Positron yield as a function of the potential difference between the moderator and chopper grid; (b) longitudinal kinetic energy distribution of moderated positrons for the W(100) single crystal, moderated before (dotted), ~1 h after (solid), and 2 days after (dashed) in situ annealing.

Spectra of moderated e+ before and after annealing at ~2000 C:

improved monochromaticity and e+ yield

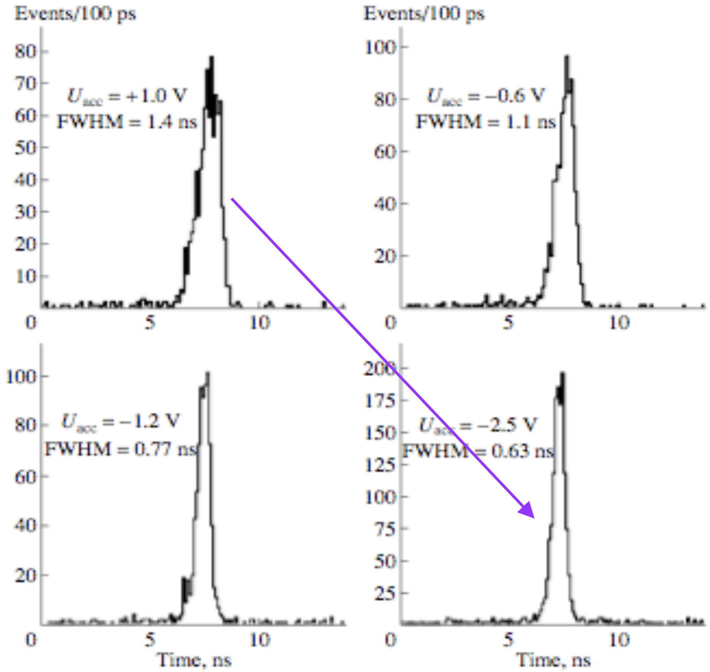


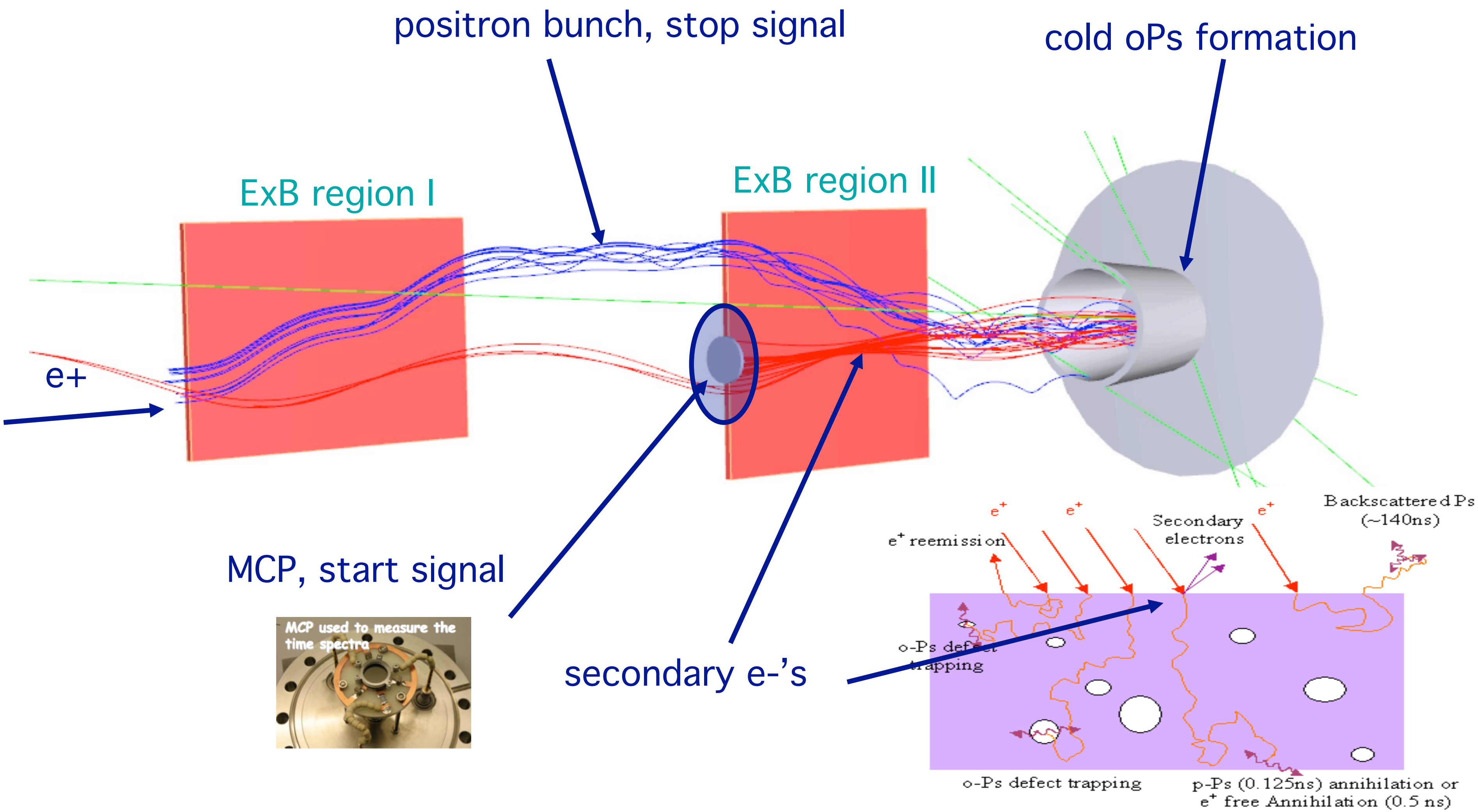
Fig. 14. Time distributions of pulsed positrons at the target position, measured for an initial positron pulse of 90 ns and for different potential difference U_{acc} between the moderator and the grid indicated on the plots.

e+ bunch shape vs V(mod):

FWHM from 1.4 ns to 0.6 ns

positron tagging system

expected inefficency < 10^{-8}, Δt=start-stop~ 10^{-9} sec



Cold Ps formation target

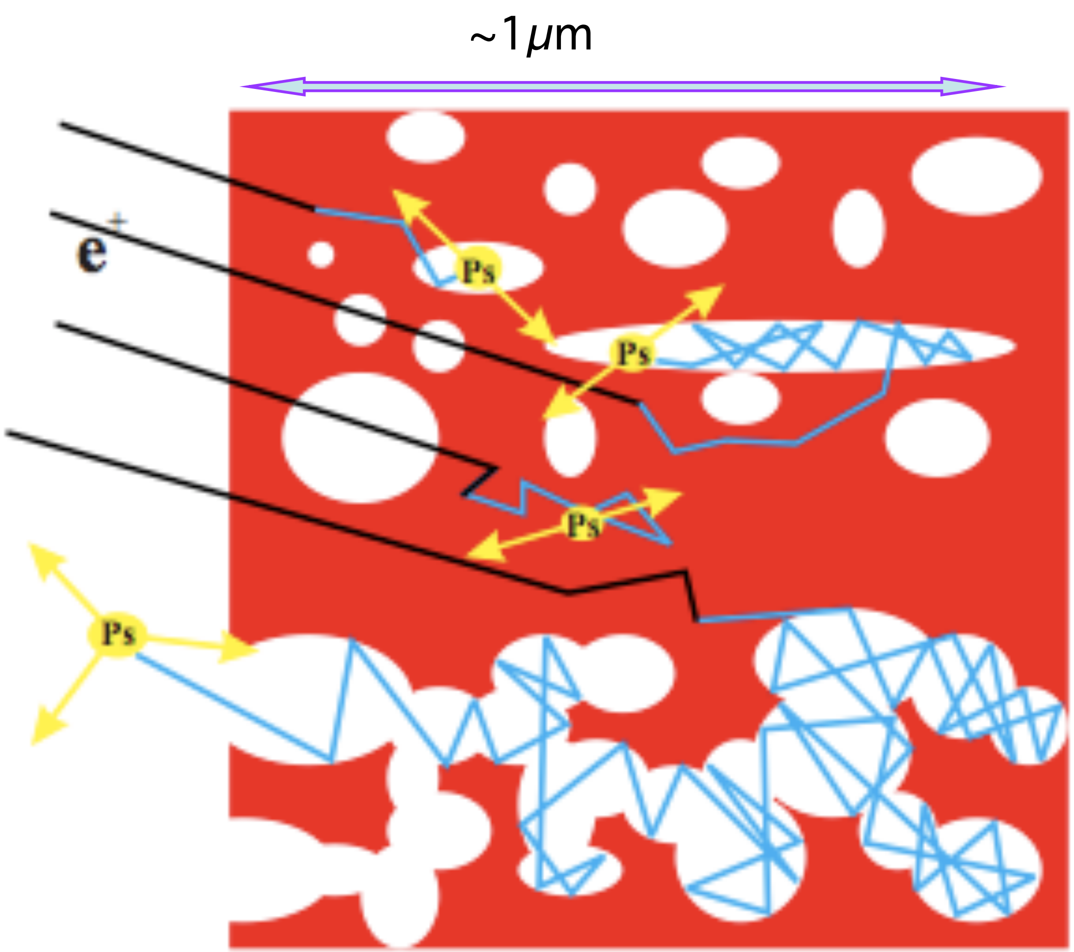


Figure 1 Positronium formation in porous materials.

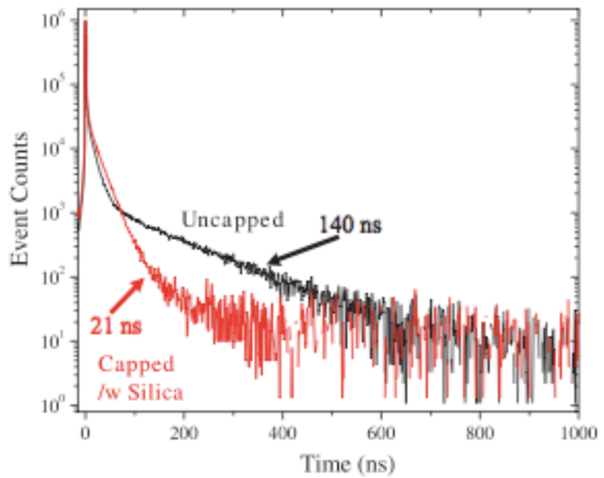


Figure 4 Typical Ps lifetime spectra for a film with open porous network (*black*) and after capping (*red*).

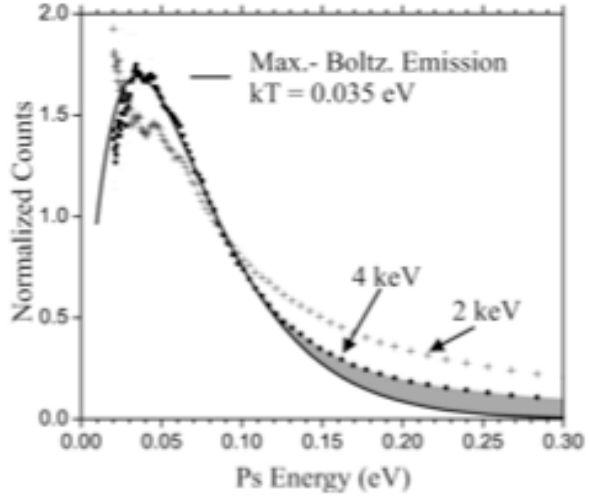
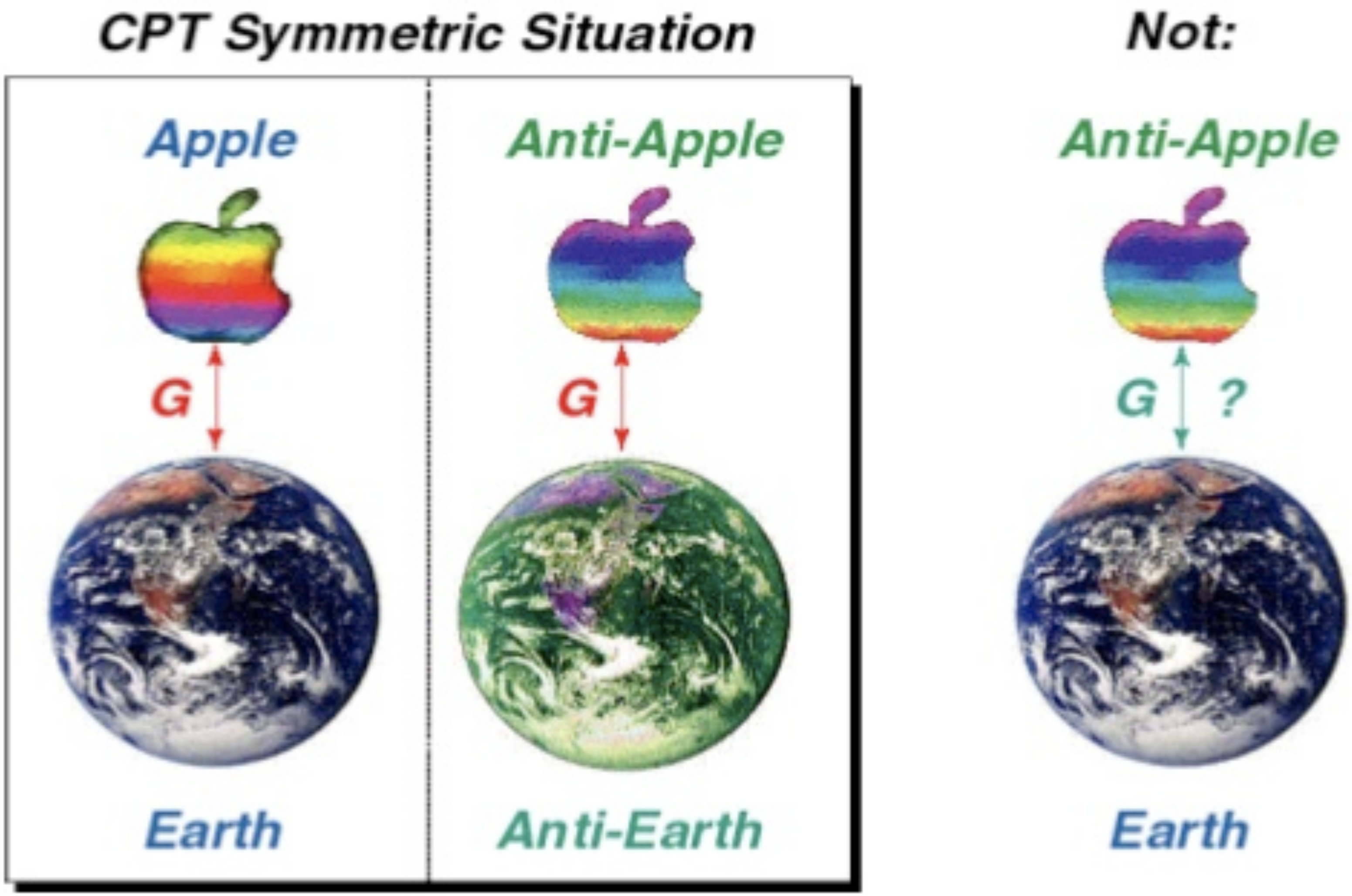


FIG. 2. The energy distribution of *o*-Ps emitted from a typical porous silica film. Note that higher energy positrons implanted more deeply (solid circles) in the film produce more thermalized *o*-Ps with fewer events in the epithermal tail.

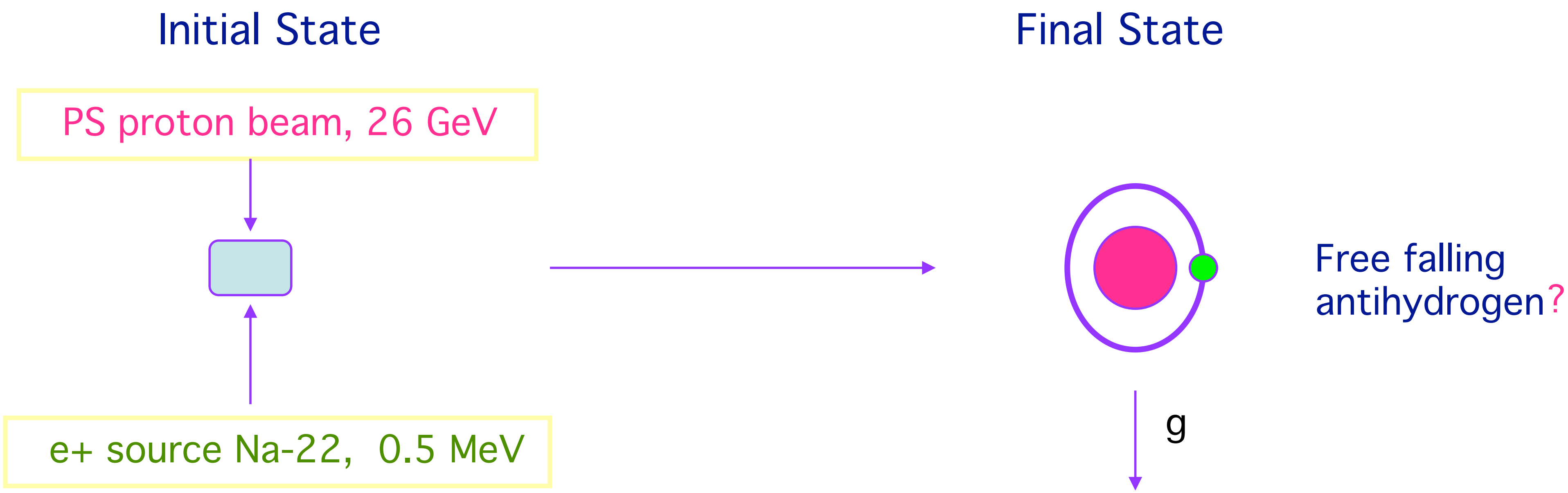
Ps formation in porous Si films
to minimize the leak.
Could be crutial for Hbar formation!

Измерение свободного гравитационного падения антиводорода

Гравитация или…Антигравитация?



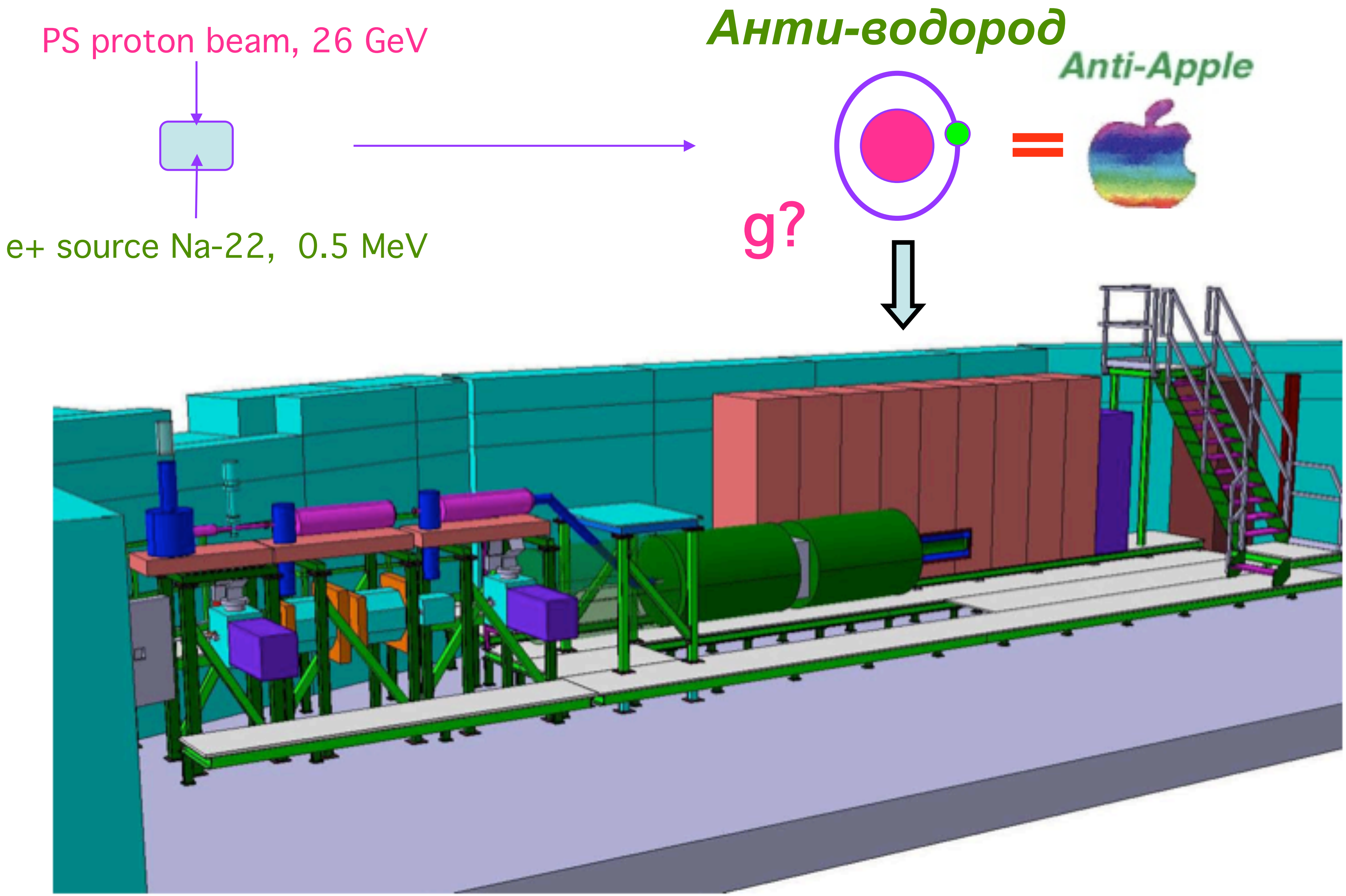
Antihydrogen study at CERN:
AEGIS



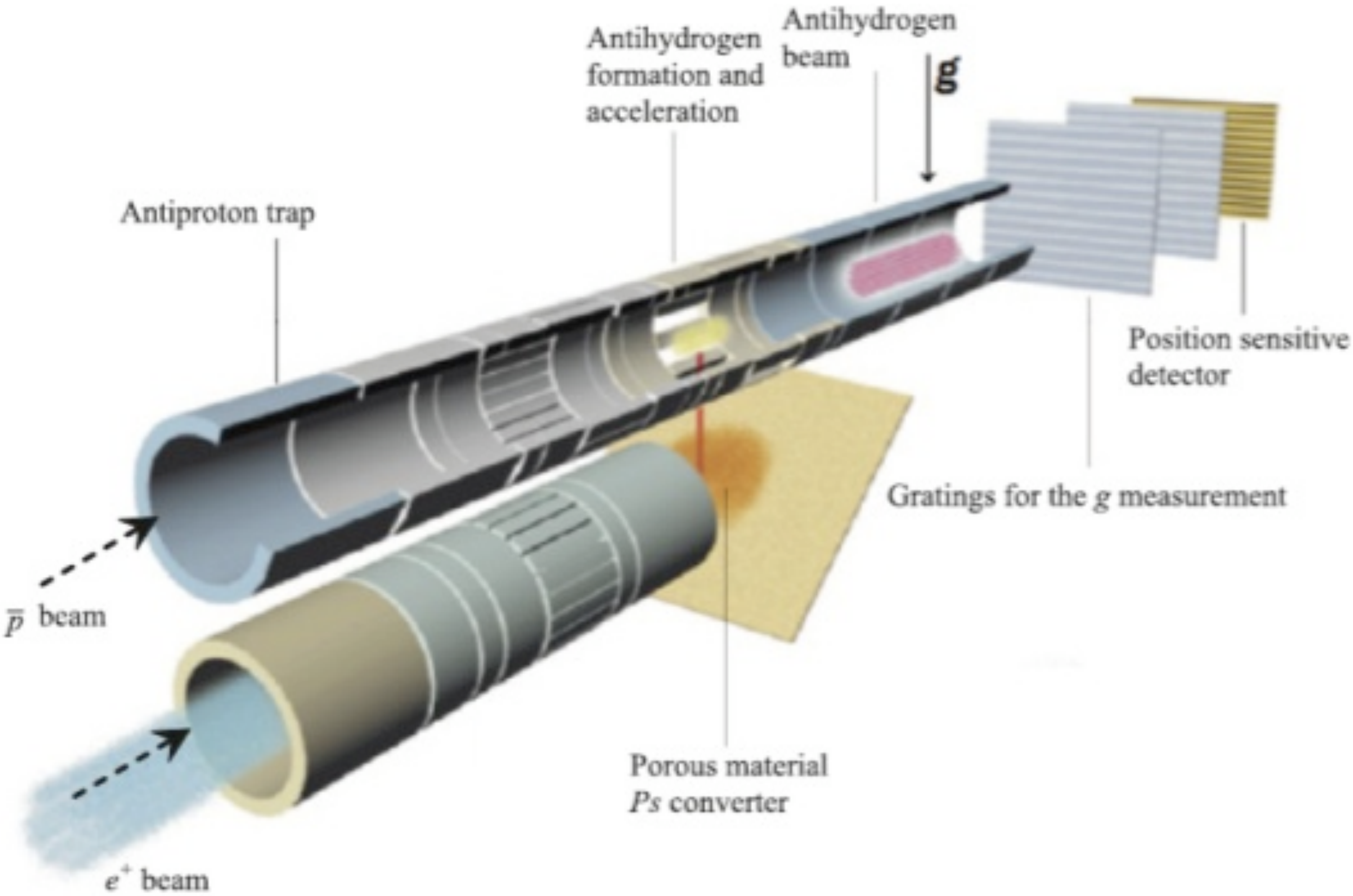
goals

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

Свободное падение Антиводорода: AEGIS



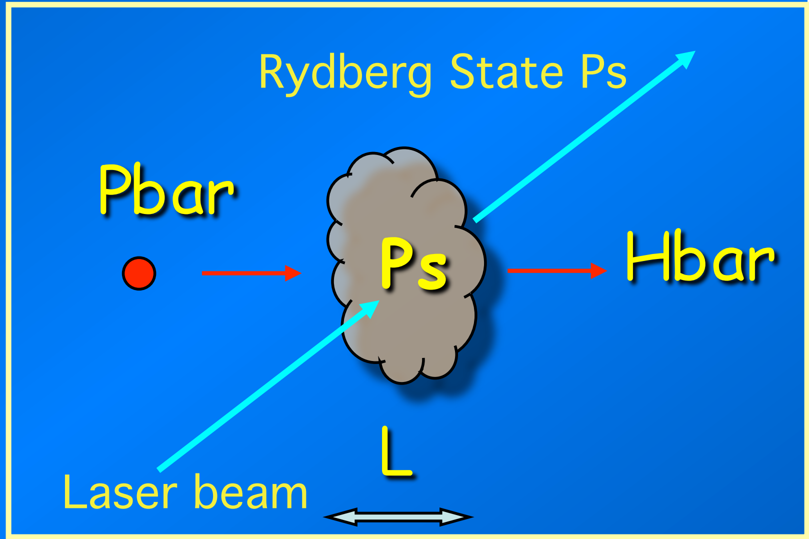
AEGIS@CERN



Antihydrogen formation and acceleration
Antihydrogen beam
g
Antiproton trap
Position sensitive detector
Gratings for the g measurement
$\bar{p}$ beam
Porous material
Ps converter
e^+ beam

Hbar formation: Why cold Ps ?

antihydrogen production rate:
$R = N(p)\, n(Ps)\, \sigma(p+Ps^* \rightarrow Hbar)\, L\, \varepsilon\, \Omega$



Ps density: $n(Ps)=N(Ps)]/Vol$

$n(Ps) \sim 1/Vol \sim (1/L)^3 \sim (1/v_{Ps})^3$
$\sim (1/T)^{3/2}$

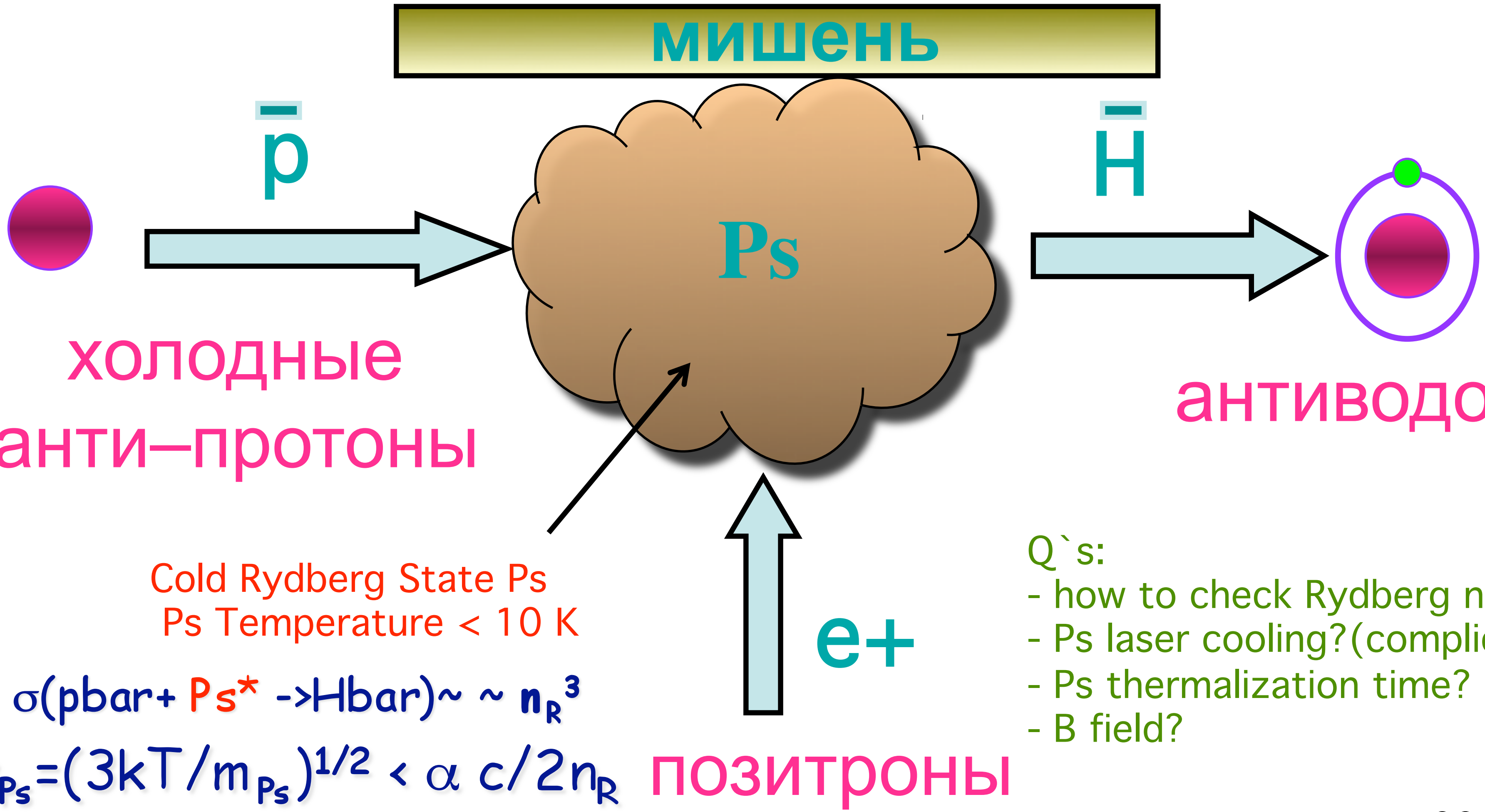
for charge exchange $\sigma(p+Ps^* \rightarrow H)$ is enhanced
if $v_{Ps}=(3kT/m_{Ps})^{1/2} < \alpha\, c/2n_R$ (velocity in Rydberg state n)

for $n_R \sim 40$ $v_{Ps} \sim 25$ km/s and $T \sim 10$ K

Can we create and manipulate cold Ps's in a vacuum under controlled conditions?

Формирование холодного антиводорода

$$\bar{p} + Ps(e^+ e^-) \to \bar{H}(\bar{p}e^+) + e^-$$



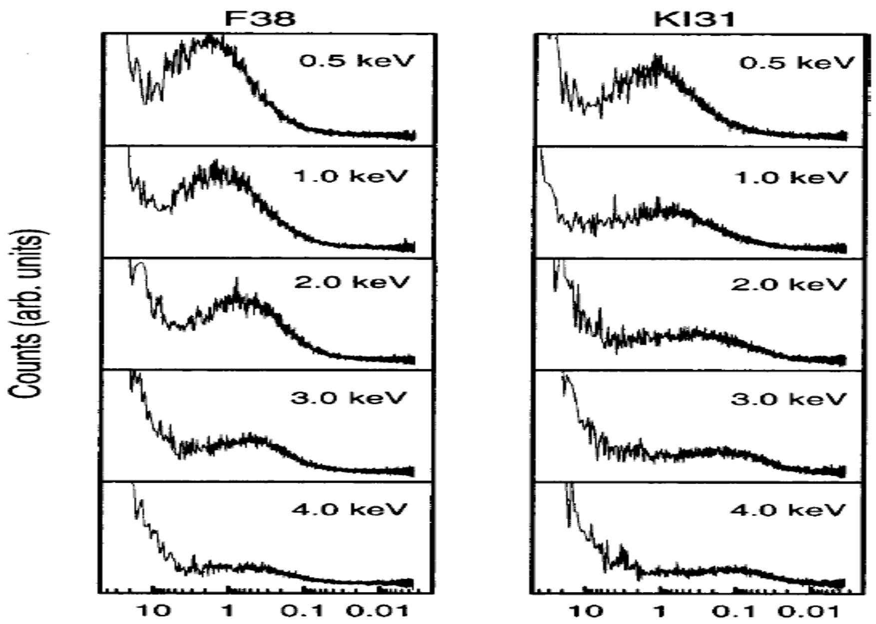
Cold Rydberg State Ps
Ps Temperature < 10 K

$\sigma(\text{pbar}+ Ps^* \to \text{Hbar}) \sim \sim n_R^3$

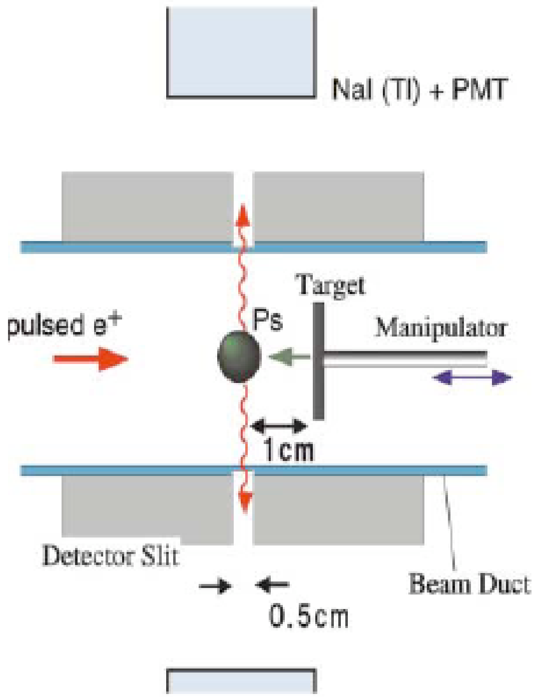
$v_{Ps} = (3kT/m_{Ps})^{1/2} < \alpha\, c/2n_R$

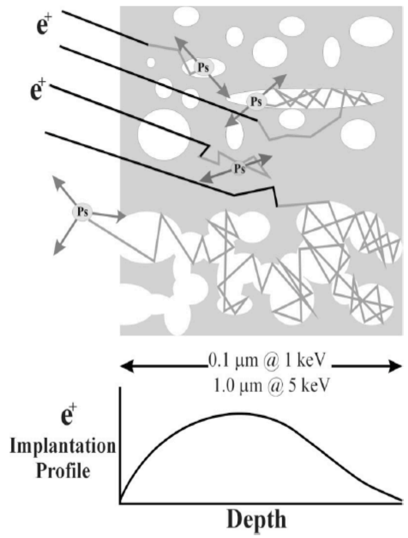
Q`s:
- how to check Rydberg n?
- Ps laser cooling?(complicated)
- Ps thermalization time?
- B field?

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 << t (o-Ps)
- E = 40 meV, V=1.2 10^7 cm/s,
  R ~ 1 cm/lifetime





Диагностика Наноструктурных Материалов. Новый PALS спектрометр на вторичной электронной эмиссии.

(How to make money out of theory like QED!?)

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…``   T. Hyodo

- 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)

Defect types and sizes

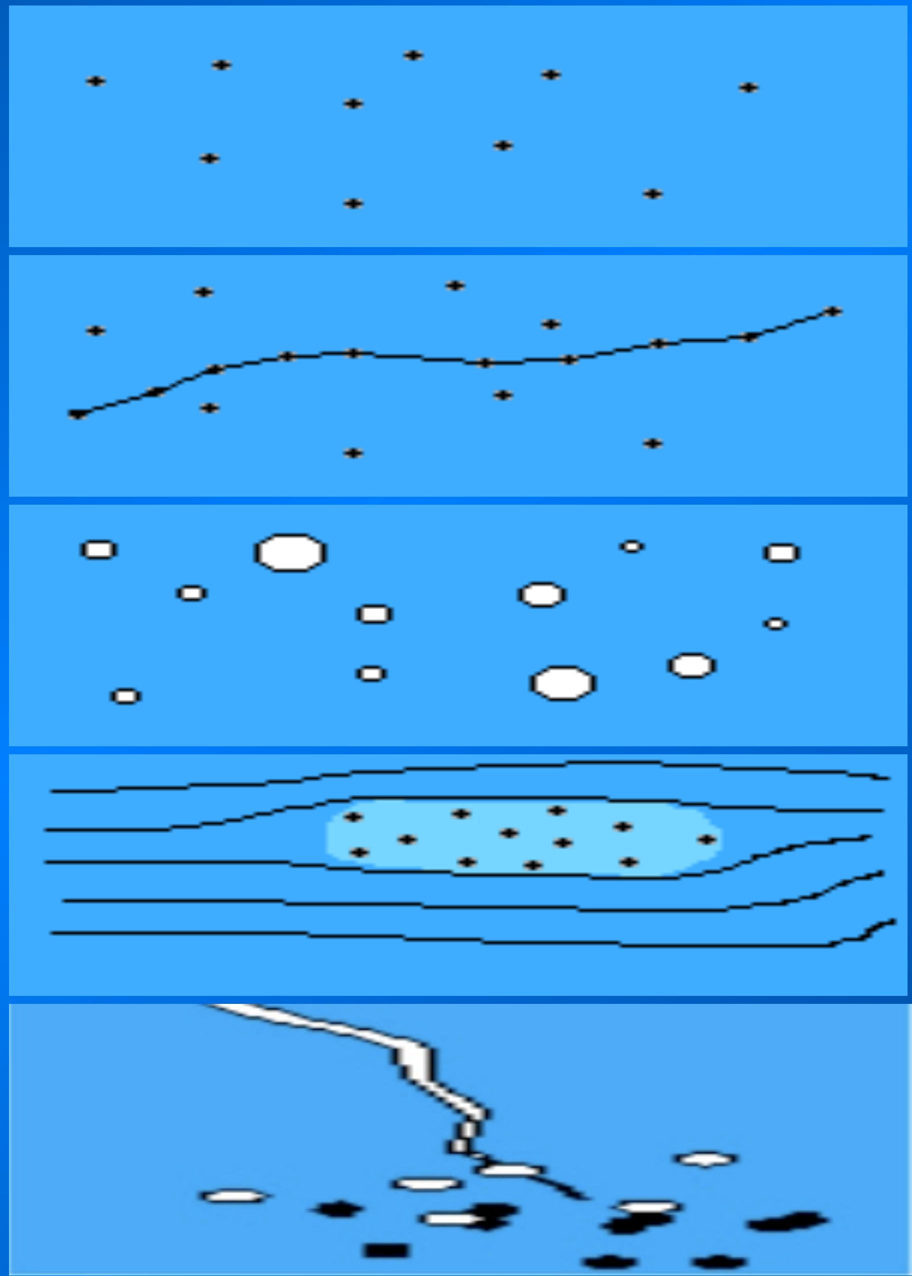
Atomic vacancies, 0.1 nm

Dislocations, 1 nm -10 mkm

Voids, 0.1 nm - 1 mkm

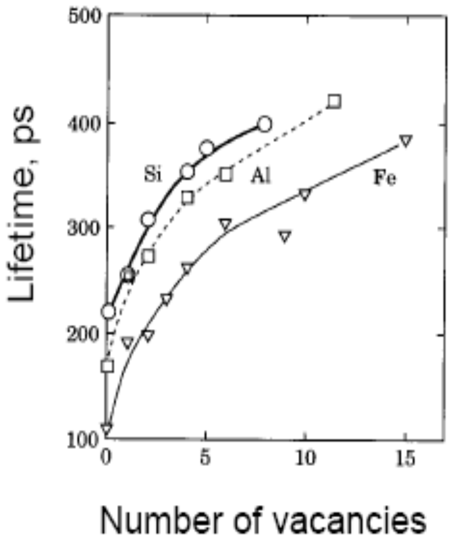
Holes, 0.1 nm - 10 mkm

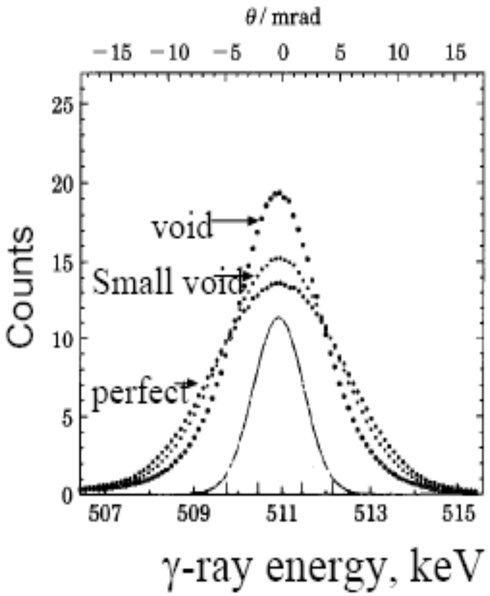
Cracks, 0.1 - 10 mkm

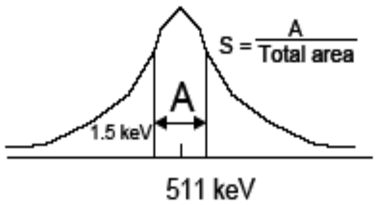


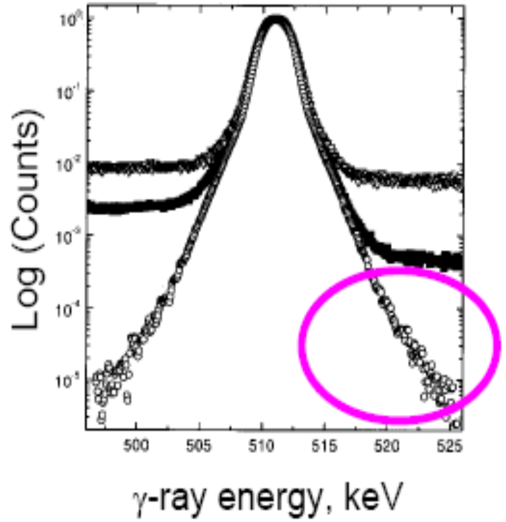
PAS: unique tools for Defect Characterization in Material Researches

Lifetime	Doppler broadening	CDB
Electron density	Low electron momentum	High electron momentum
Defect size	Amount of defects	Chemical analysis of defects

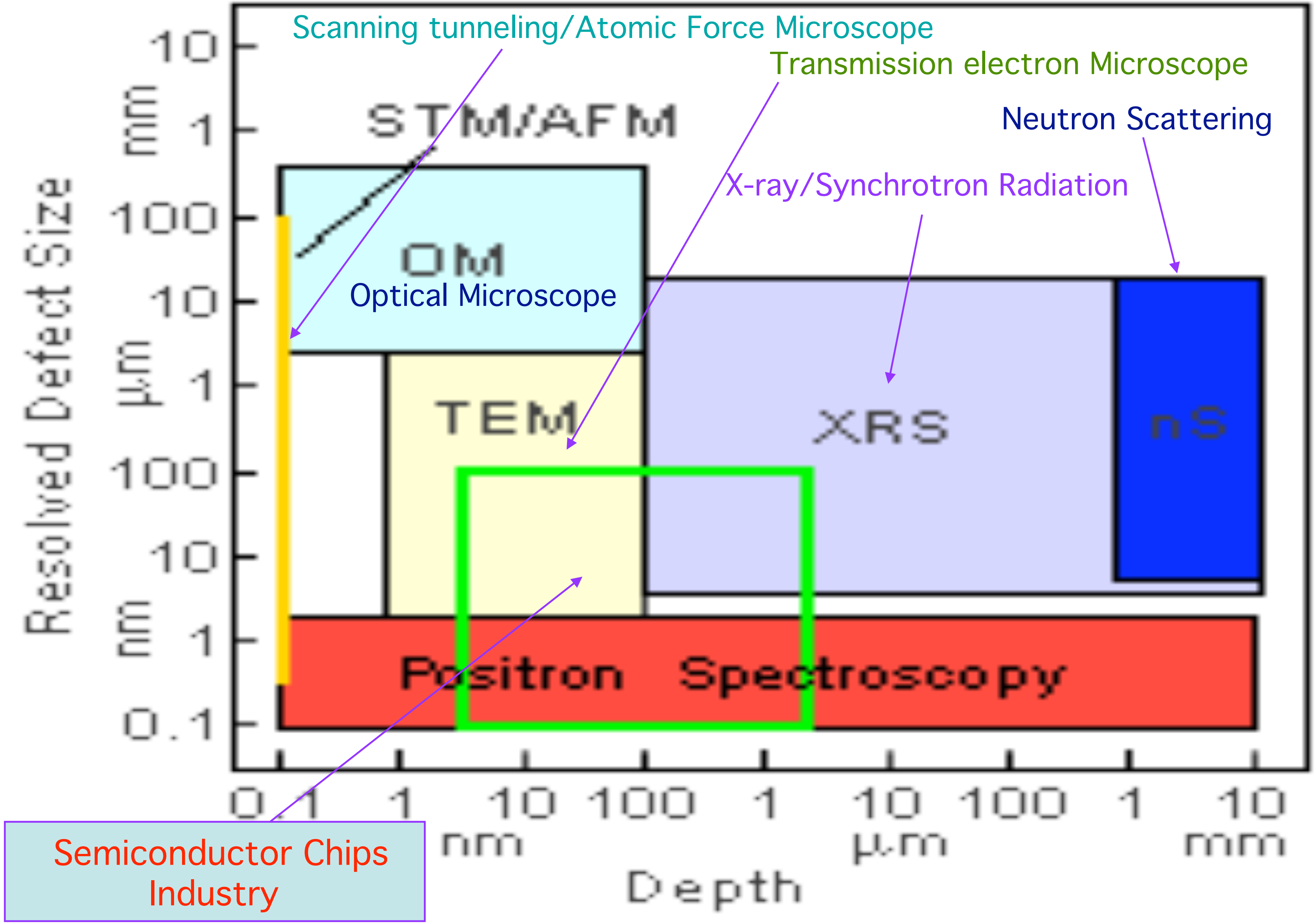




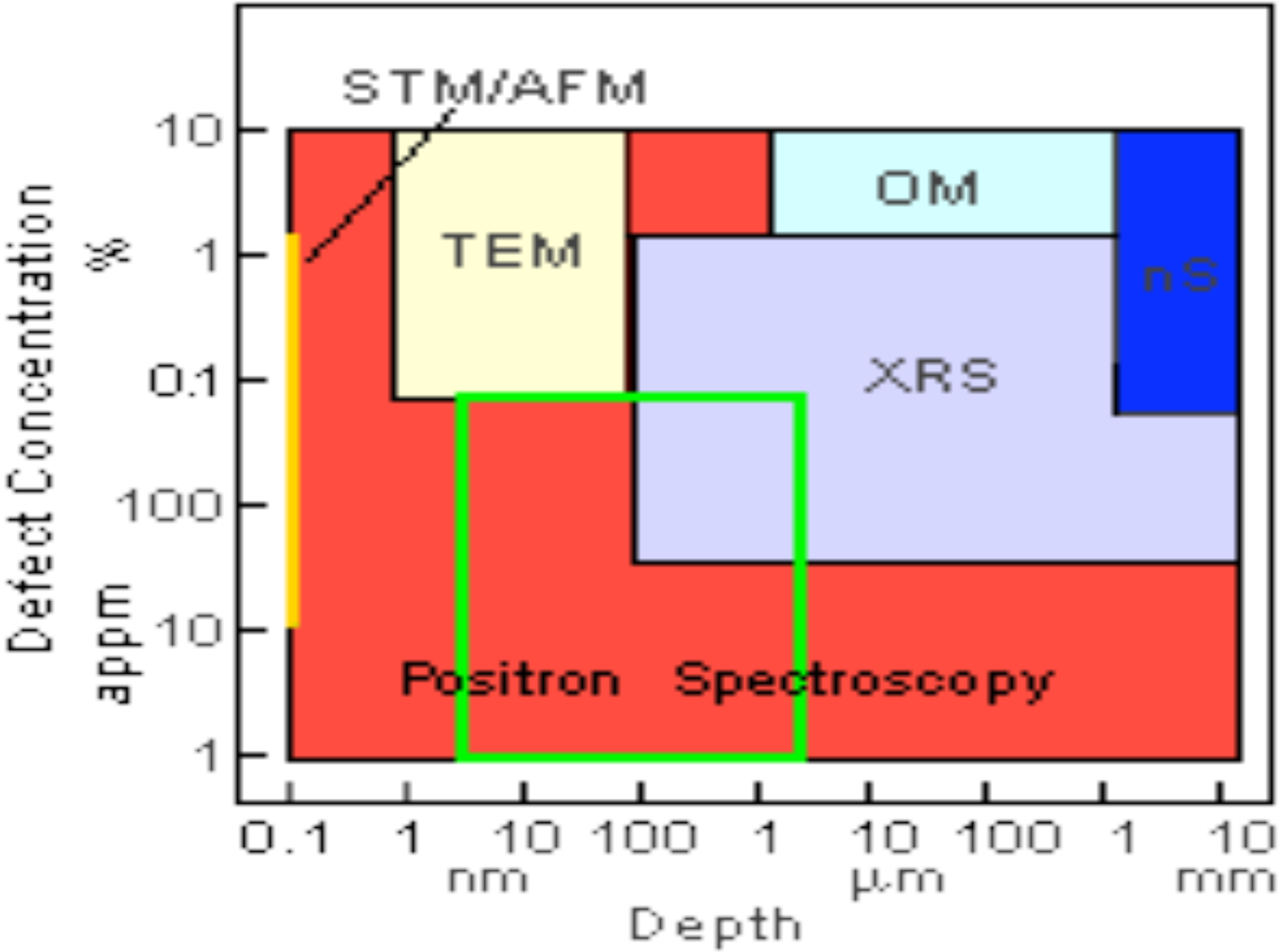




Comparison of Different Techniques for ID of Defects



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 Beam Facilities

- **NEPOMUC at FRM-II** / *Garching @ Munich*
  - 5 beamlines under construction; 4 already in use; new remoderator
  - Good news: PLEPS is running now; very fast!
- **Argonne Project APosS**
  - 15.5 MeV, 0.1 μA, 60 Hz
  - First positrons detected – up to 3×10^{9} e^{+}/s expected
- **Helsinki Pulsed Positron Beam at HUT**
  - Timing problems solved, isolation problems considered – first lifetime results to be expected soon
- **SOPHI Project in Saclay** – Mini LINAC for Gravity Experiment with Anti-H
  - Tabletop commercial accelerator: 6 MeV, 300 Hz, 0.2 ma; 10 kW
  - Under construction (solid Ne moderator possible)
  - Aim 10^{8} e^{+}/s

Positron Beam Facilities

- **Positron Microbeam for Transmission Positron Microscope** at KEK (large Japanese Collaboration)
    - 60 μm diameter after remoderation
    - Amazing results for Ni transmission moderator (up to 20% efficiency)
- **Positron Beam at IHEP Beijing China**
    - Many promising activities: lifetime, AMOC, CDBS
    - Isotope and LINAC-based bunched slow positron beams
- **Positron Probe Micro Analyser (PPMA) at AIST** (Tsukuba)
    - 100 μm beam (10μm expected); lifetime; 200…300 s/ pixel; 200ps FMHM expected
- **Australian Positron beam Facility**
    - 2 beam lines: materials science & atomic/bio/molecular
    - AMO beam line: Pulsed; rare gas moderator; 25 meV energy resolution expected
    - Materials beam line under construction; aim: bunched 200ps FWHM; 10^7 e^+/s
- News from **ATHENA / ALPHA** at CERN: trapped neutral Anti-H; special trap

Positron Beam Facilities

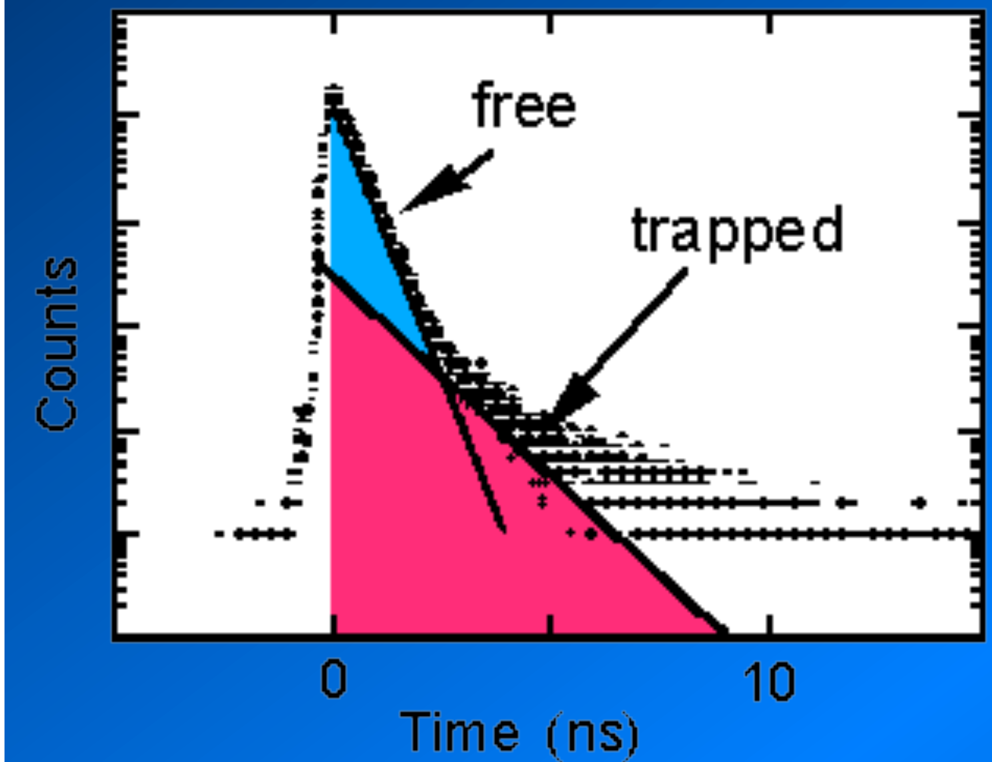
- **EPOS: ELBE Positron Source** @ Rossendorf / Dresden
  - 40 MeV, 1 mA, 13 MHz repetition time in cw mode
  - Retain original time structure for simplicity and best time resolution
  - Test in Halle; almost ready for setup in Rossendorf
- News from **Washington State University** Positron facilities; how to store positrons?
- Poster BP1: **e^+-Microbeam JAEA** in Takasaki (3,4 μm using aperture); similar to Bonn system; soon pulsing system
- New magnetically guided slow positron **beam in Taiwan** (Chung Yuan Christian Univ.)

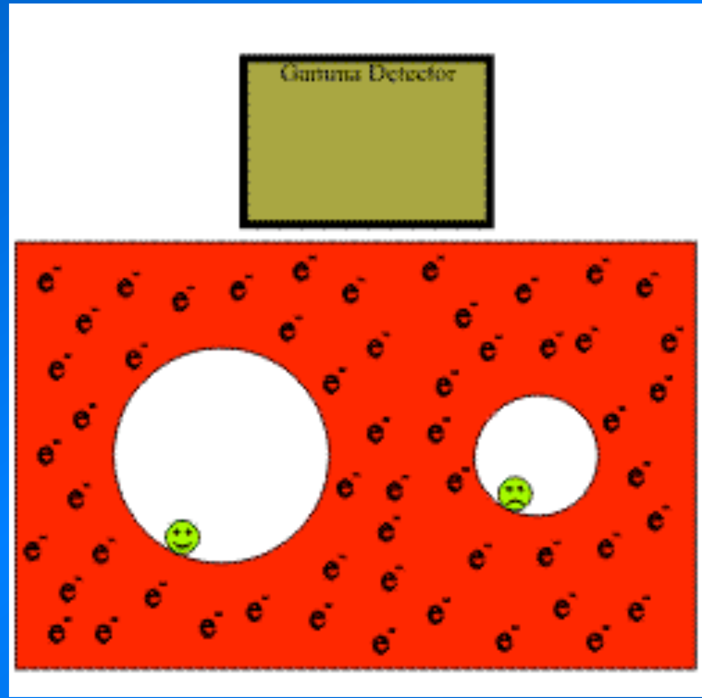
Russia

Отсутствуют пучки медленных позитронов,
сильная школа “позитронщиков“.

- ИФХ
- ИТЭФ
- ФИАН
- ОИЯИ (LEPTA)

Positron Annihilation Lifetime Spectroscopy(PALS)



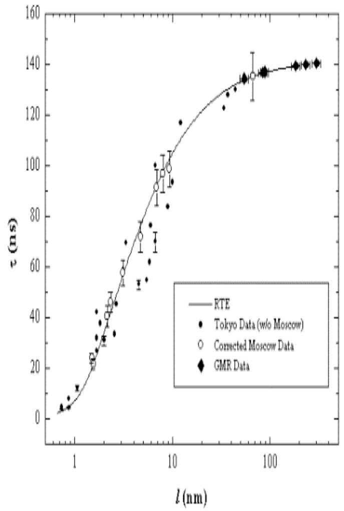


- positron lifetime spectra consist of exponential decay components
- positron trapping in open-volume defects leads to long-lived components
- longer lifetime due to lower electron density
- analysis by non-linear fitting: lifetimes τ_i and intensities I_i
- positron lifetime spectrum: $$N(t) = \sum_{i=1}^{k+1} \frac{I_i}{\tau_i} \exp\left(-\frac{t}{\tau_i}\right)$$

trapping coefficient

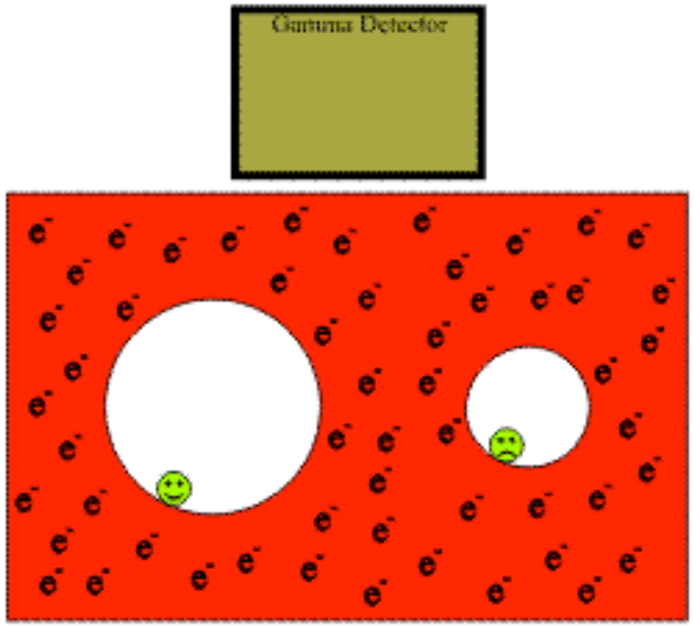
- $$\boxed{\kappa_d = \mu C_d} = \frac{I_2}{I_1}\left(\frac{1}{\tau_b} - \frac{1}{\tau_d}\right)$$

trapping rate defect concentration



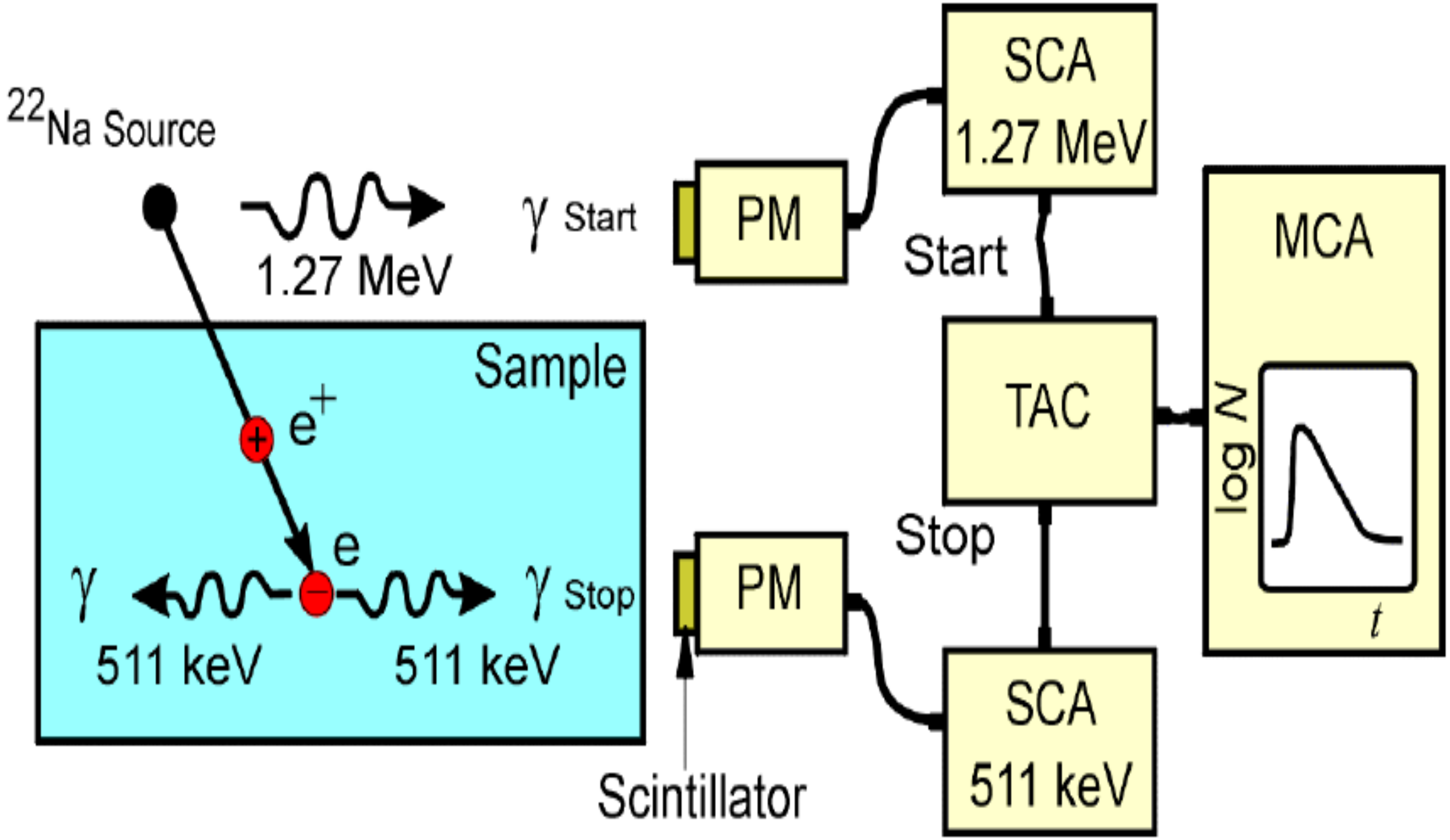
Main Experimental Problems :

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



Gamma Detector

Схема измерений



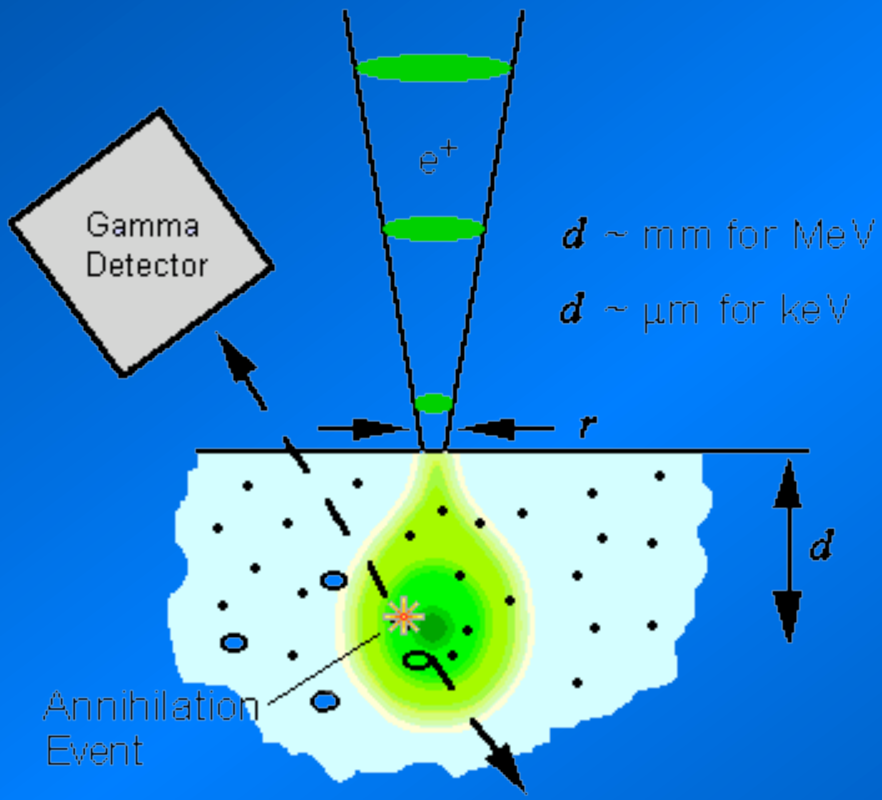
Проблема

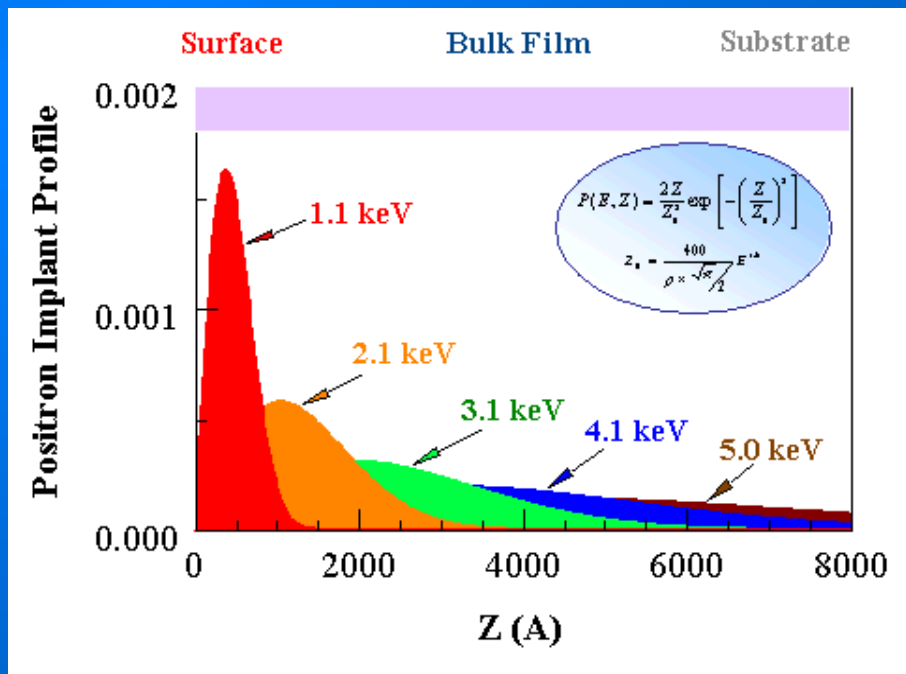
как измерять очень тонкие (100-1000 Å) образцы нано–материалов?

Позитроны от радиоактивного источника обладают слишком высокой энергией, Ē >200 кэВ, проходят через образец и не формируют позитроний

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 electronics, STOP: annihilation gammas

Osaka Univ., 2002

ETH-INR, 2006–2007

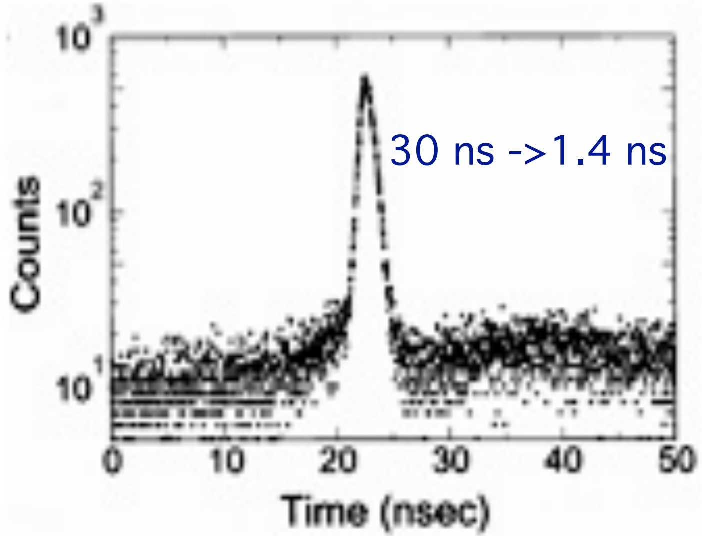


Fig. 7. Positron annihilation lifetime spectrum of the bunched slow positron beam. A copper plate is used as sample.

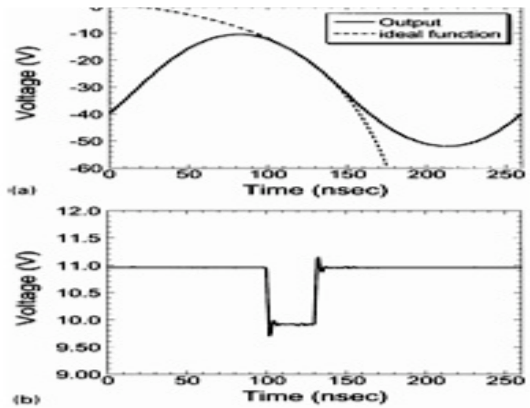
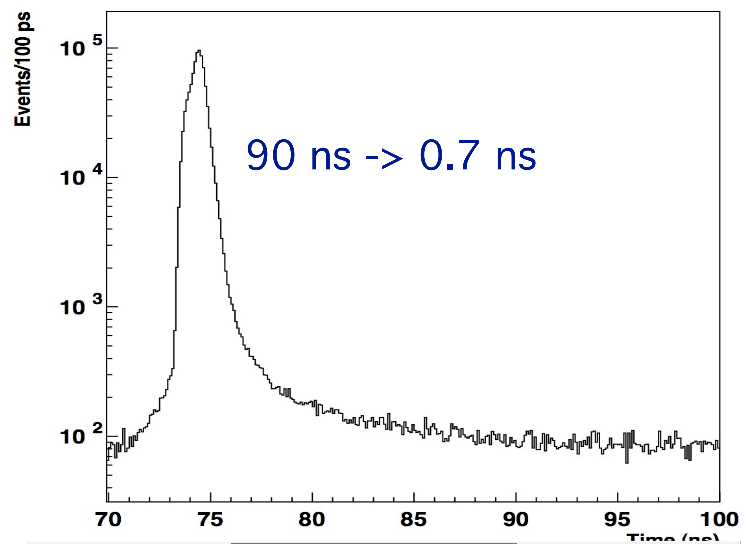
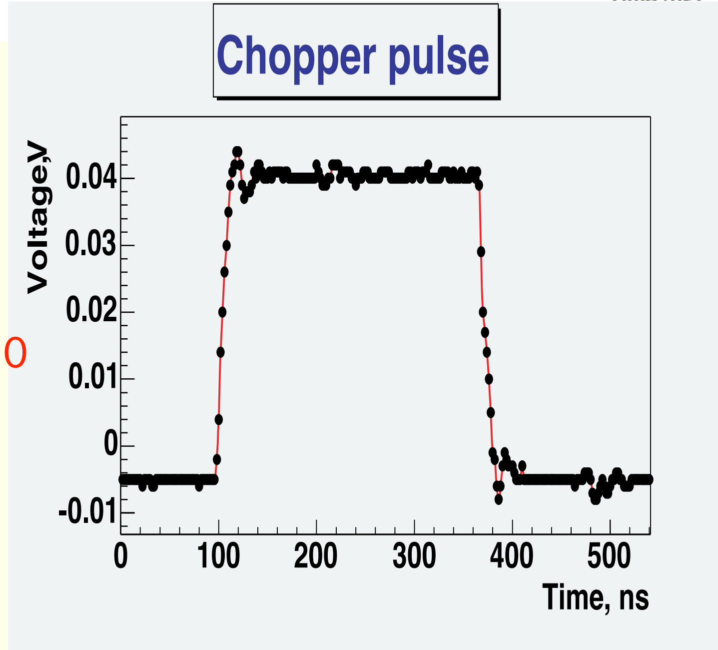


Fig. 6. (a) Optimized waveform generated by AWG and amplified. Dashed line indicates the ideal function. (b) Waveform at the chopper electrode.

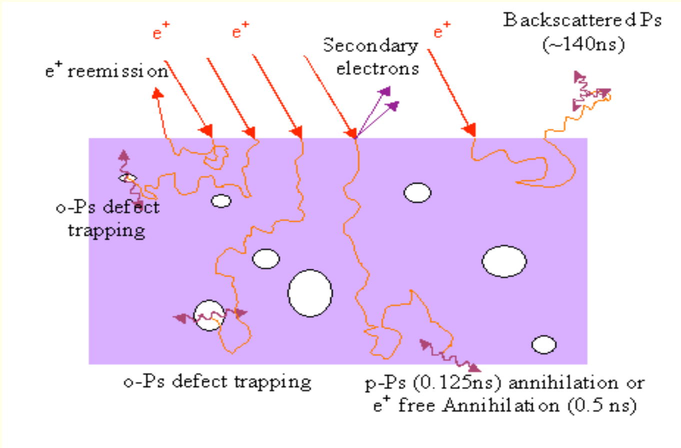
width better ~ 2
Compression ~ 3
Peak/background ~10



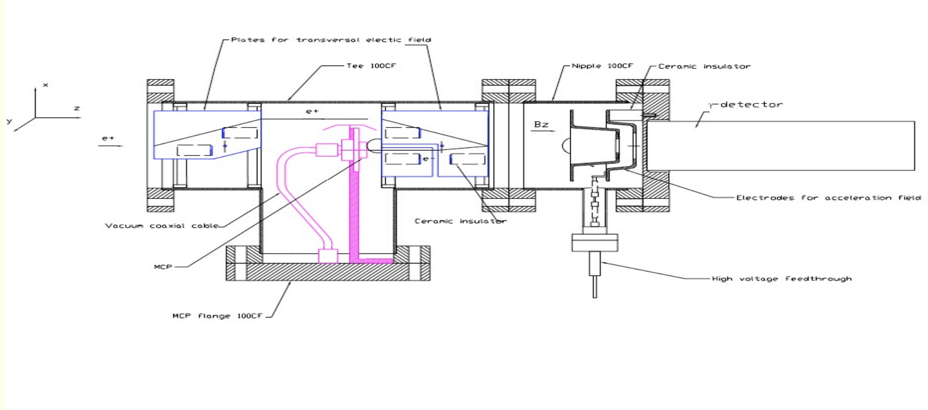


PALS technique 2: Secondary Electron Emission Detector

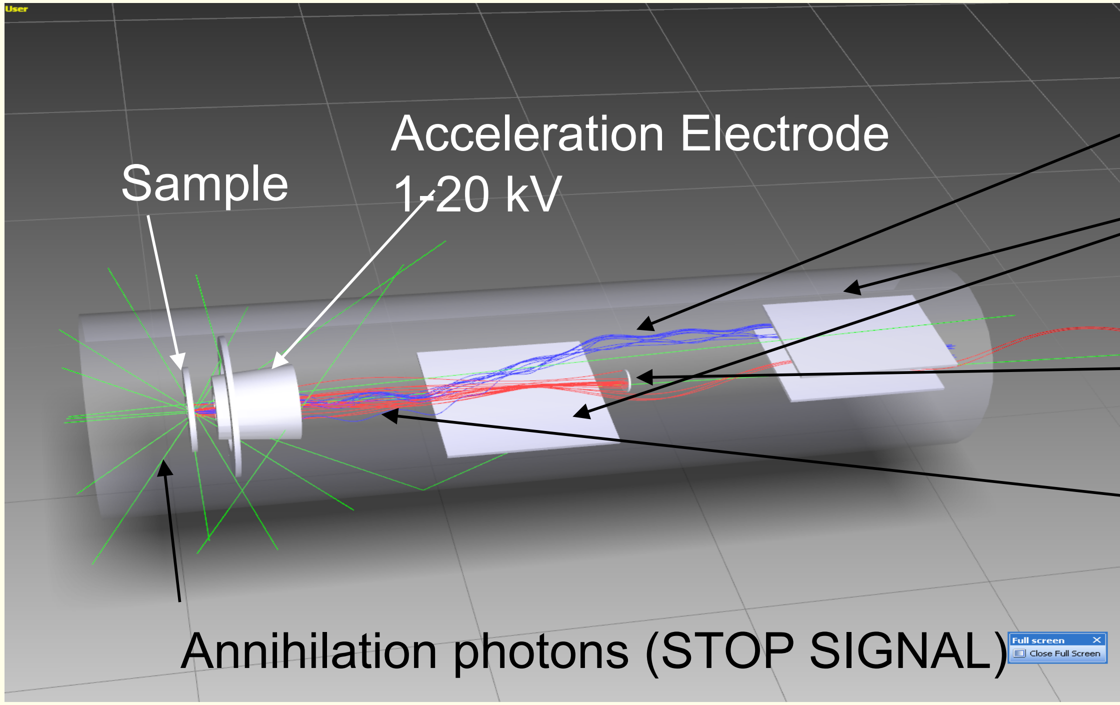
START: secondary electrons, STOP: annihilation gammas



BaF$_2$



Simulation of SEED extraction optics:



Slow Positrons ~200 eV

Deflection Plates

MCP (START SIGNAL)

Secondary electrons

Application to Nanoporous films

The International Roadmap for the Next Generation of Microelectronics

- Today's Microelectronics needs:

-smaller and faster devices ,

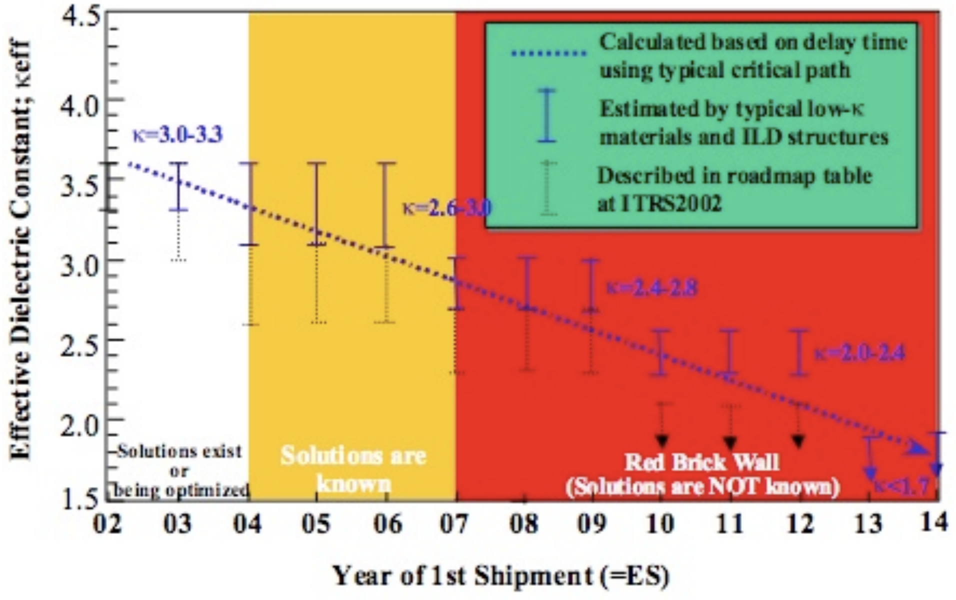
-reduction of transistor gate delays.

- The signal propagation delay:

- RC delay , R interconnect resistance

- C interlayer dielectric capacitance

- Industry: replacement traditional Si with lower-dielectric constant (low-k) materials

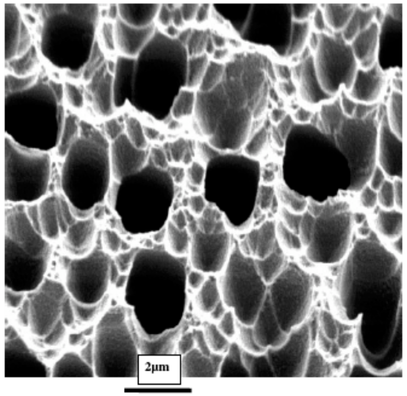


- Candidates for k=2.0-3.5:

- organic and inorganic polymers,

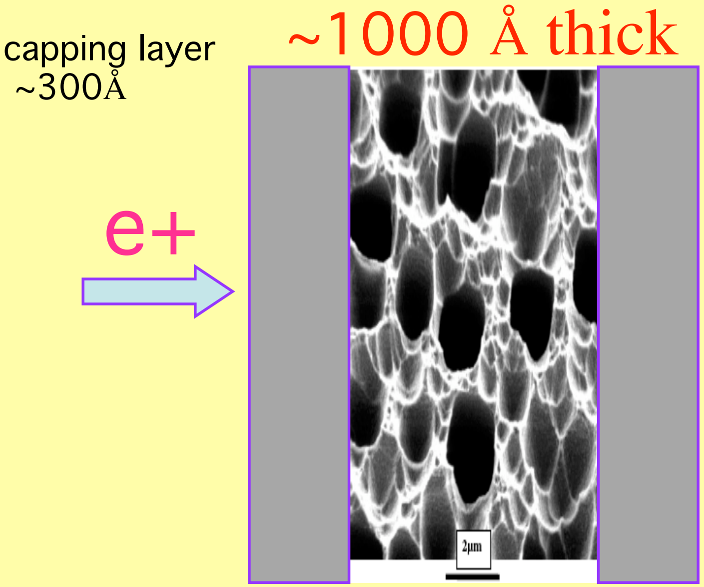
- nanoporous SiO2, etc.

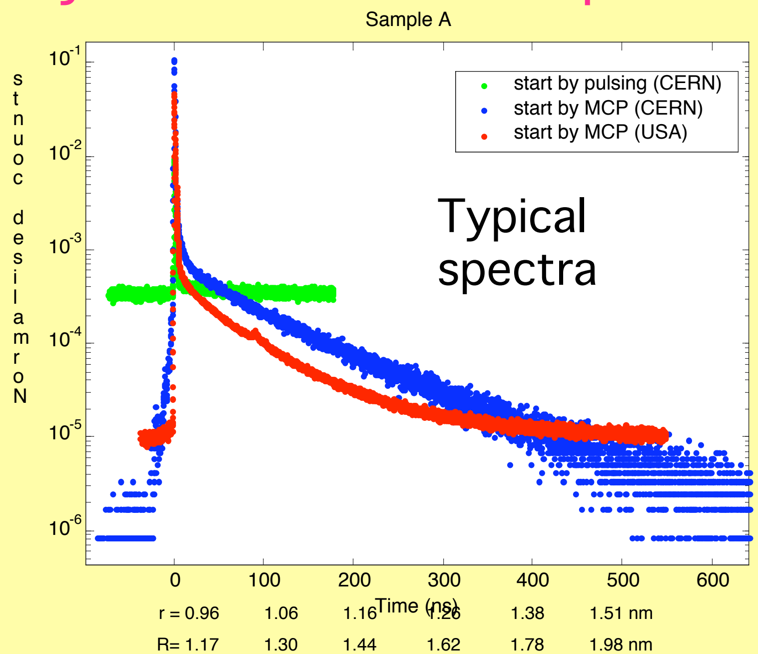
Large pores will be necessary to go down to k~1.0 (air)

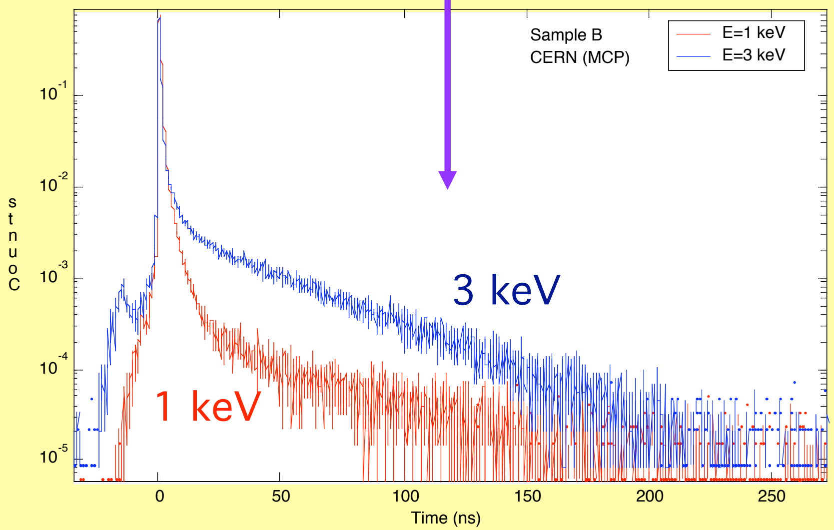


First Results with SEED

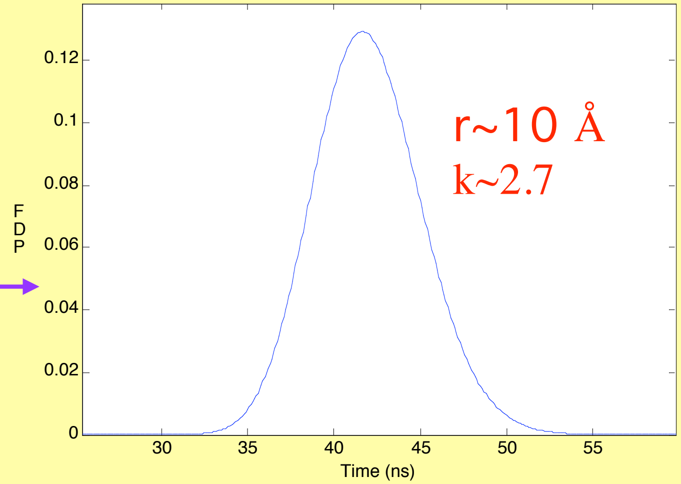
on nanoporous low – k dielectrics films from Microelectronics: thickness and structure of the internal layer are difficult to probe







PALS spectra at different energies

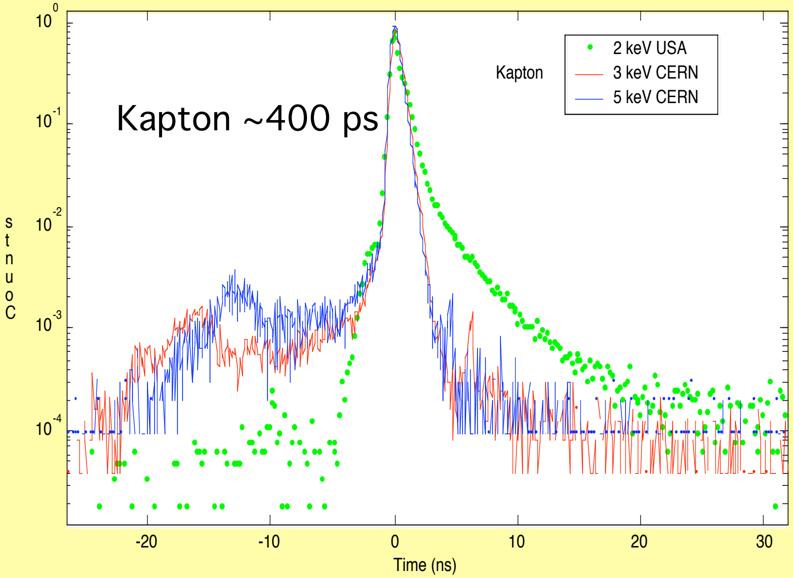


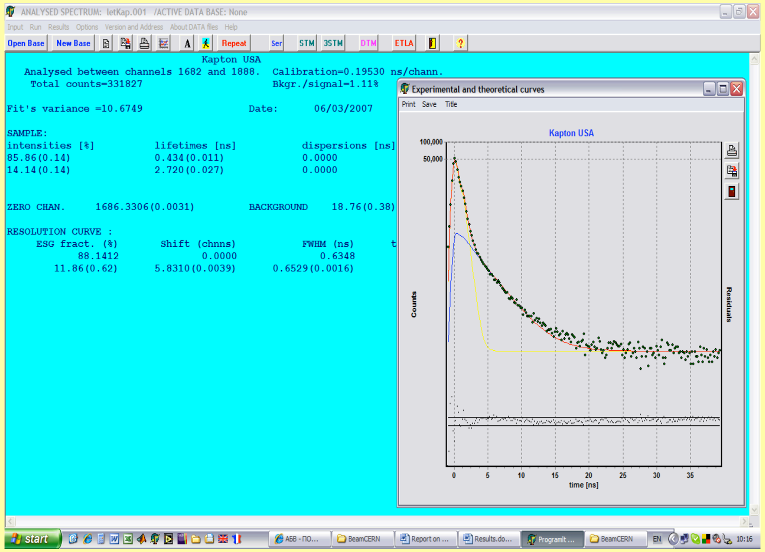
Pore size distribution

Comparison of PALS spectra

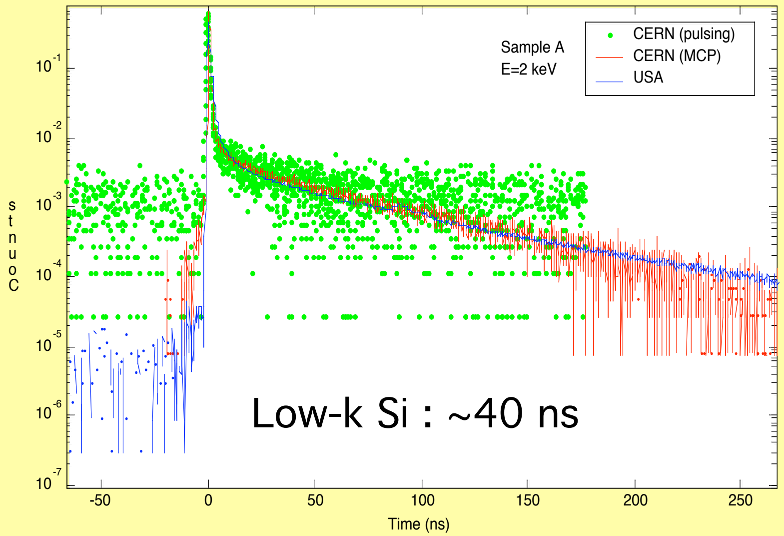
Washington Center of Materials Researches (Prof.K.Lynn,Lab)

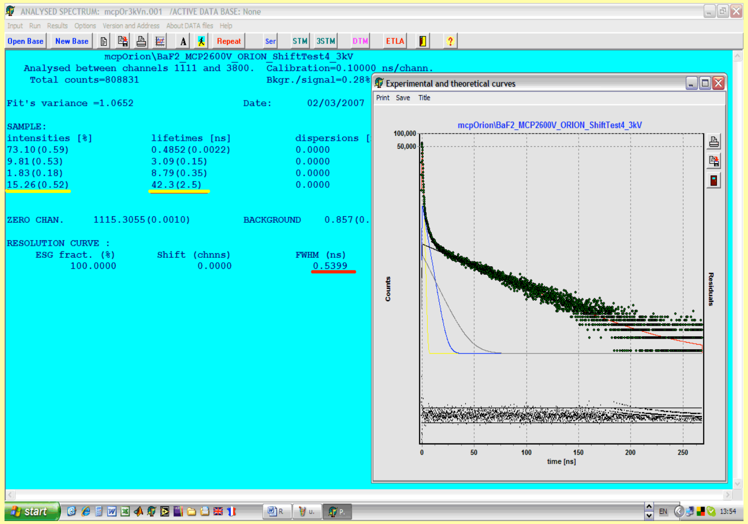
dense





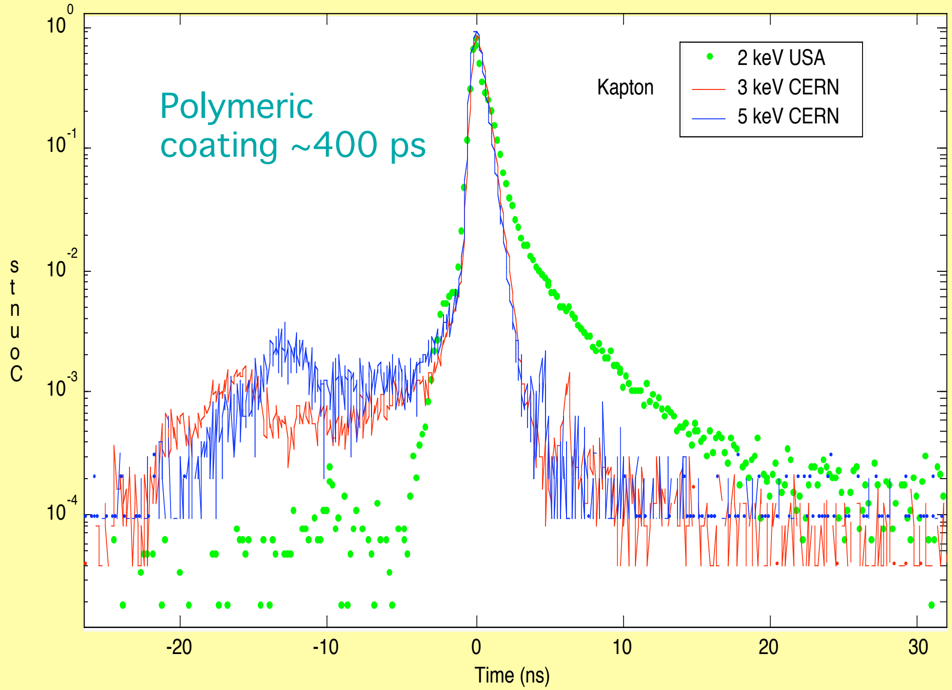
porous

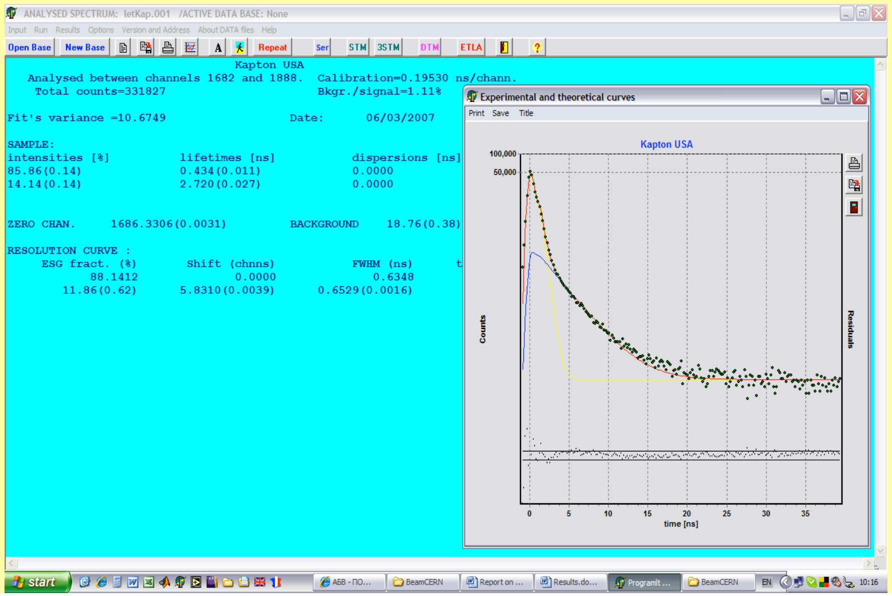


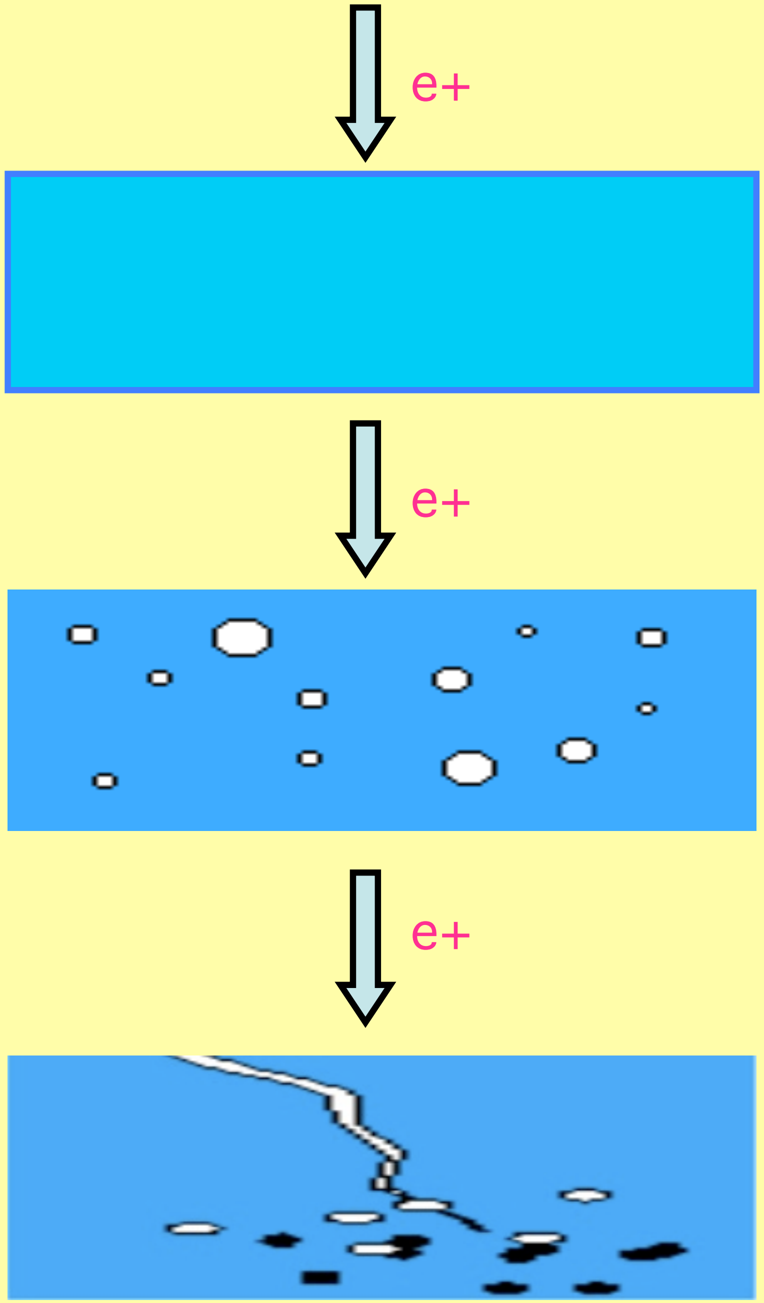


Excellent agreement for wide range of positron lifetimes

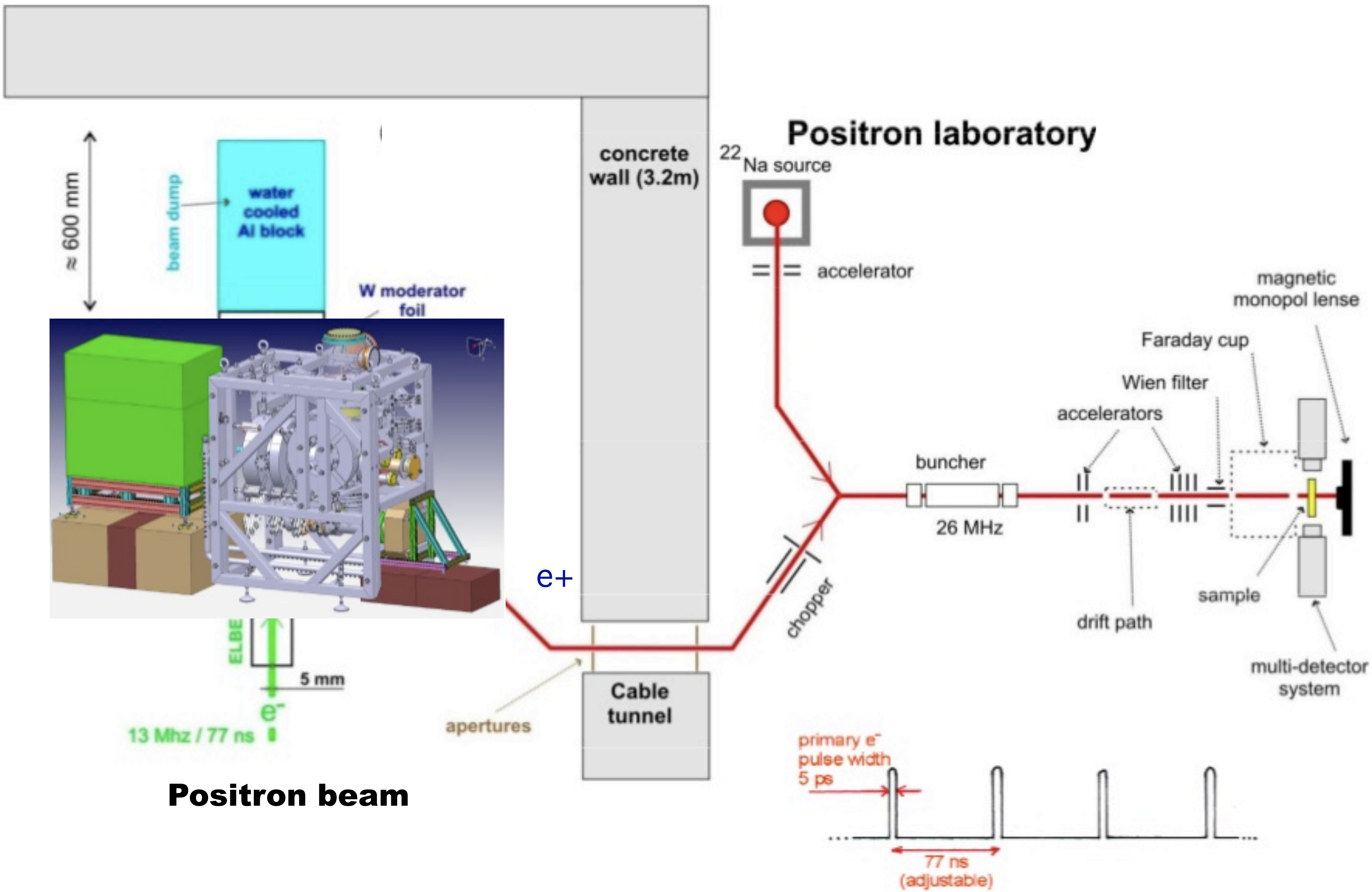
PALS spectra for degraded polymeric coating







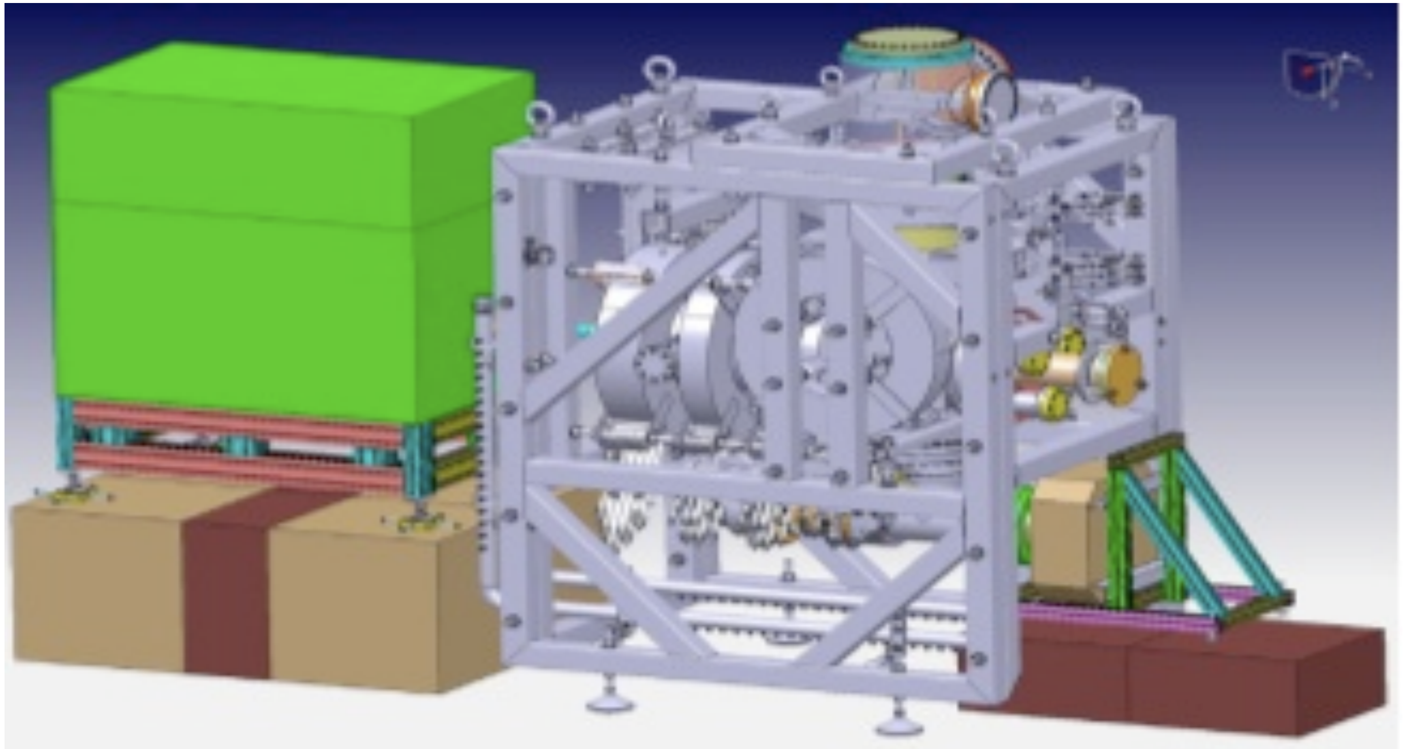
Экспериментальный комплекс для позитронных исследований



Linac Technologies (FRANCE)


Small Industrial Linac

- ~10 MeV, ~ 2 mA, ~10 kW
- pulse mode: 1 – 4 mks, 200 Hz
- intensity: ~ 5 10^{11} fast e+/s
- flux: ~ 3 10^{7} slow e+/s, eff.~10^{-4}
- cost ~ 300 kEuro



NC STATE UNIVERSITY

COLLEGE OF ENGINEERING

ENGINEERING NEWS

SHARE

August 17, 2005

NC State to Receive $1 Million NSF Grant to Establish Intense Anti-Matter Beam

— Facility will be only one in U.S.

The Department of Nuclear Engineering at North Carolina State University, in collaboration with researchers from Oak Ridge National Laboratory (ORNL) and the University of Michigan, has received a $1 million major research instrumentation (MRI) grant from the National Science Foundation (NSF). The funding will support the establishment of an intense positron (anti-matter) beam at the NCSU PULSTAR nuclear reactor and the development of an intense positron annihilation spectrometry system for nanophase characterization. The facility will be the only one of its kind at a university research reactor in the U.S.

The unique facility will provide two different spectrometers for the nondestructive probe of matter, giving next-generation materials researchers a new way to “see” the structure inside nanomaterials. One spectrometer, a positronium PALS spectrometer, will be able to study nanoporous thin films and patterned microelectronic devices. The other instrument, a time-bunched positron PALS spectrometer, will be used for studying metals and semiconductors.

“These probes are essential for the further development of nanotechnology,” said Dr. Ayman Hawari, associate professor of nuclear engineering and director of the Nuclear Reactor Program at NC State. “Intense positron annihilation spectrometry will give researchers a more powerful tool — by several orders of magnitude — for studying the structure of newly developed materials.”

The NC State, ORNL and Michigan team built a prototype instrument that demonstrated the ability to produce and extract positrons near the core of the PULSTAR reactor. Once completed the new facility, complemented by PULSTAR facilities for neutron scattering, will form the centerpiece for North Carolina National Center for Nanophase Characterization $(NC)^3$. It will be available to academic researchers at no cost under the US Department of Energy University Reactor Sharing Program.

The positron beam project grew out of the Multi-University Southeast INIE Consortium (MUSIC) that is led by the Department of Nuclear Engineering at NC State and funded through the Innovations in Nuclear Infrastructure and Education (INIE) program. The INIE program provides funding for developing ways for university research reactors to perform unique fundamental and applied research.

— weston —

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

Phenomenology:

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

New Experimental Techniques:

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

Experiments:

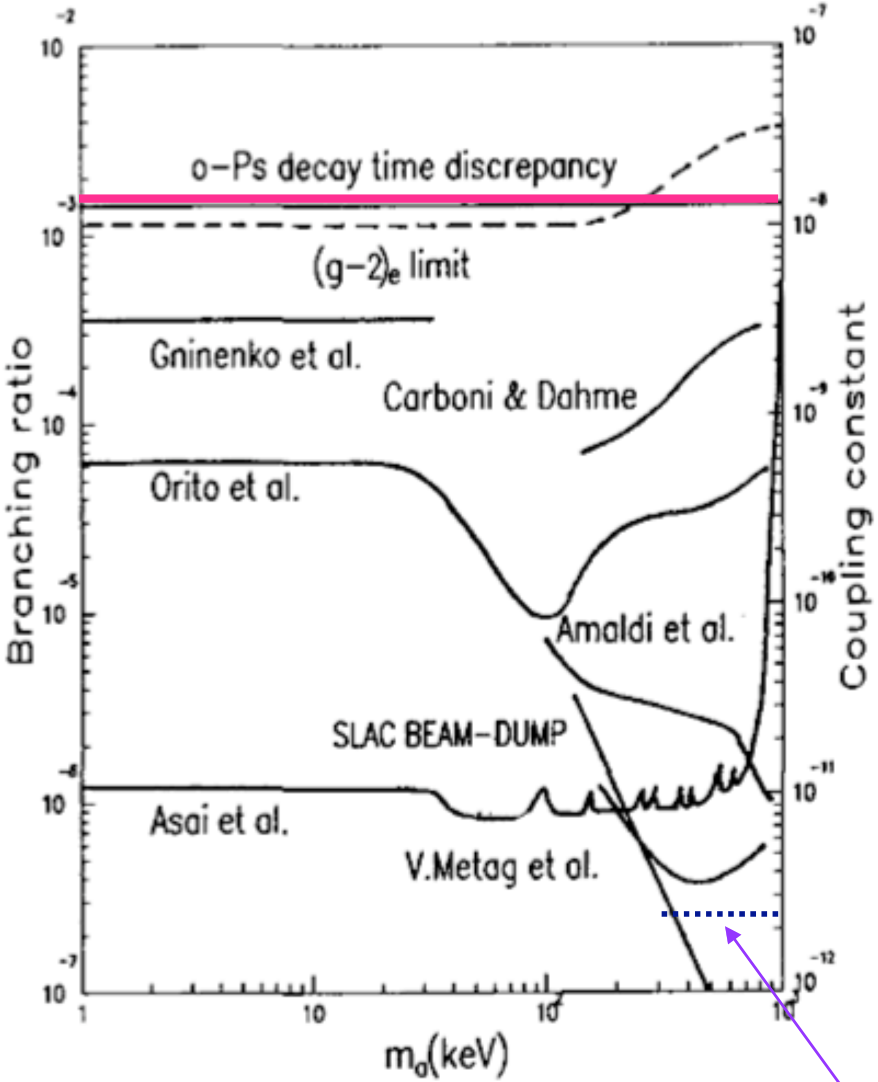
- precision measurements with oPs
- searches for exotic Ps decays
- search for hidden sectors (extra D, mirror type matter), best limit on oPs->nothing
- Hbar gravity fall

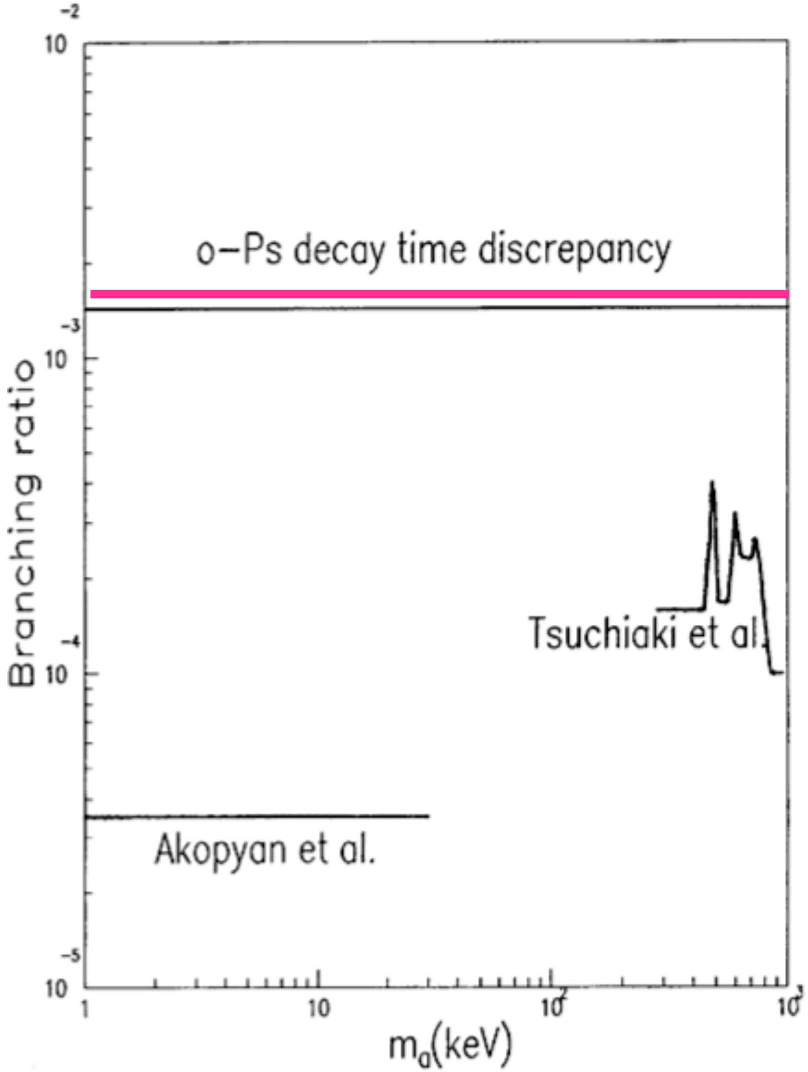
Nanoscience and Technology

- 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, ...

Backup Slides

o-Ps -> gamma + X decay





S.G.,Krasnikov(preliminary)

LEPTA approach

The purpose of the project LEPTA (Low Energy Particle Toroidal Accumulator) is to create in the JINR new basic installation for investigations in the field of positronium physics.

The precision measurement of the ortho- and parapositronium characteristics is one of the fundamental problems of the modern quantum electrodynamics. With positronium fluxes in vacuum one can to perform new original setting up the experiments without the distortion caused by medium in the traditional methods of the positronium generation in a target. The accuracy of the measurement of the positronium life time, the probability of decays with momentum conservation and charge invariant infringement (CPT violation), fine structure of the positronium spectrum, Lamb shift measurements can be much higher than in traditional methods.

So, in the positronium physics the following problems can be addressed as important subjects for experimental studies:

- the positronium life time (in ortho- and para-states),

- search for hypothetical short-lived bosons,

- the hypotheses of so called "mirror universe",

- the parameters of the positronium atomic structure,

- the comparison of electron and positron electric charges, measuring a deflection of positronium in strong magnetic field.

The experiments with antihydrogen-in-flight can be performed by comparison of antihydrogen and hydrogen atoms characteristics under the same conditions. This brings great advantage for high precision and high-resolution measurements. Among these experiments the most promising are the following:

- the comparison of antiproton and positron electric charges, measuring a deflection of antihydrogen in strong magnetic field; repeating the same for hydrogen and using very precise knowledge of electron and positron charge values, one can "close the chain" for all 4 particles and compare also proton/antiproton masses, using very precise knowledge of their charge to mass ratio,

- microwave spectroscopy of antihydrogen;

- laser spectroscopy of antihydrogen;

- comparison of antiproton and proton magnetic moments from data of antihydrogen spectroscopy.

- The design of the storage ring and elaboration of the technology of the magnetic system manufacturing were performed
- under support of the RFBR (project “Creation of low energy positron storage ring and positronium fluxes generation”,
- grant N96-02-17211) and Fermilab, USA (Accord on Modified Betatron Prototype).

- The works in the frame of the project are supported by RFBR (project “Positronium flux generator”) and INTAS
- (“Generation and experimental studies of antihydrogen and positronium in-flight”, grant N96-0966) and are provided
- in collaboration with Institut fur Kernphysics, Juelich, Germany, University College London, UK and ITEP, Moscow.
-

Testing CPT in Ps Annihilation

Polarized O-Ps has a distribution of decay planes with respect to $\vec{s}$.

$$\frac{d\Gamma}{d\Omega} = \Gamma_0 \frac{9}{16\pi}\left[\underbrace{\left(1-\frac{1}{3}\cos^2\theta\right)}_{\text{T-even}} + \underbrace{P_z C_n \cos\theta}_{\text{T-odd}}\right]$$

Search for a cos(θ) distribution of decay planes with respect to spin $\vec{s}\cdot\left(\vec{k}_1\times\vec{k}_2\right)$
Determine polarization from $\cos^2(\theta)$ distribution of decay planes

Previous Results on this signature: $C_n \cdot\left[\vec{s}\cdot\left(\vec{k}_1\times\vec{k}_2\right)\right]$

$$C_n = +0.020 \pm 0.023$$

B.K. Arbic *et al*., Phys. Rev. A **37**,3189(1988).

$$C_n = +0.014 \pm 0.019$$

S.K. Andrukhovich *et al*., Inst. and Exp. Techniques **43**, 453 (2000).

Factor of 10 improvement
with Gammasphere

LBNL Gammasphere Result
$C_n = -0.0026(31)$
P.A. Vetter and S.J. Freedman, PRL **91**, 263401 (2003).

Methods of Positron Annihilation Spectroscopy (PAS)

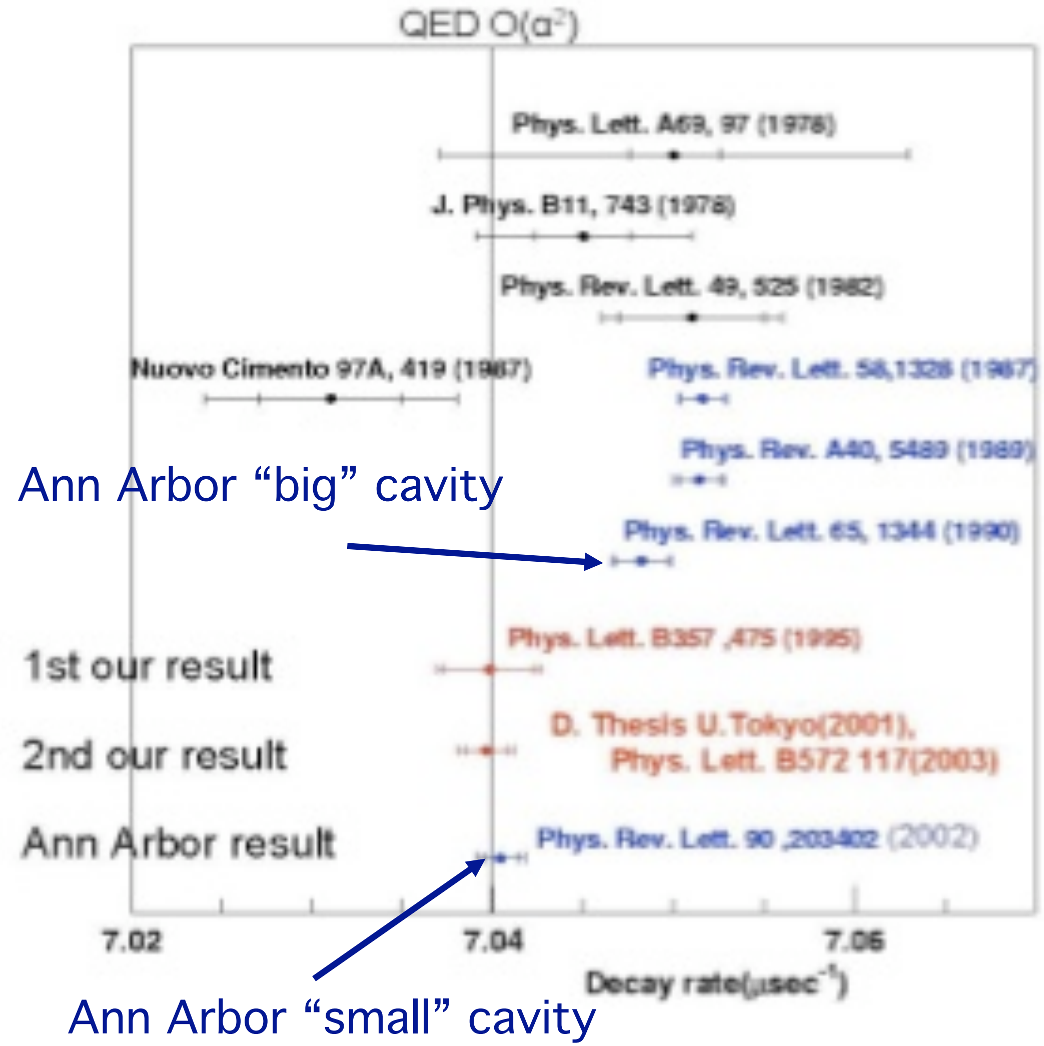
When positron stops in a matter it finally annihilates with an electron into photons

What one can measure?:

- Time of photons emission relative to positron injection time to the target (PALS - positron annihilation lifetime spectroscopy)
- Angular correlations between emitted photons (ACAR - angular correlatiuon of annihilation radiation)
- Energy spread of emitted photons (DB-Doppler broadenning)

o-Ps decay rate puzzle (1982–2002)

History of oPs decay rate measurements



Discrepancy $\Gamma_{\exp} > \Gamma_{SM}$:

-unknow contribution at the level

Br(oPs->X)~10^{-3} or

- experimental problems

Tokyo measurements (oPs formation in target) and Ann Arbor experiment (oPs formation in vacuum,) agree to each other and also agree with QED predictions

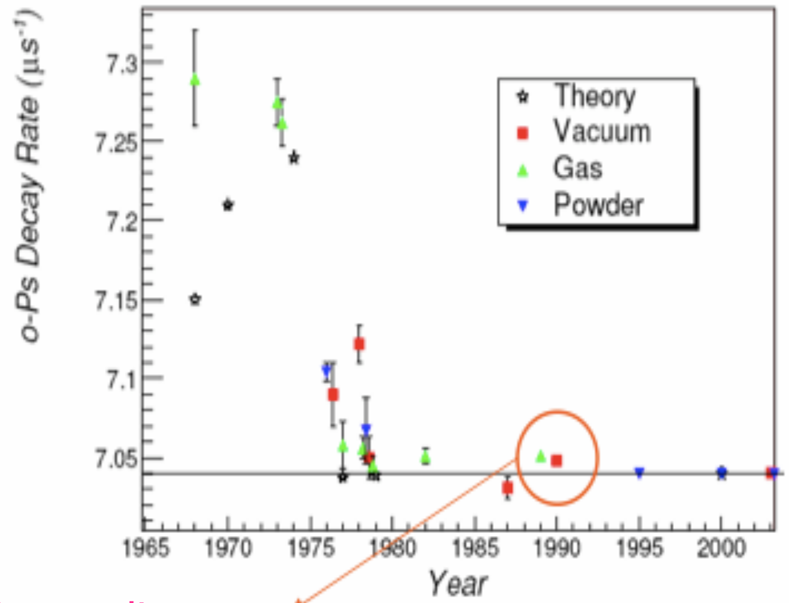
o-Ps decay rate puzzle (1980–2000)

Discrepancy beween measured and predicted oPs dacay rate in vacuum

Review: Dobroliubov, Gninenko, Ignatiev, Matveev, IJMP A8 (1993) 2859

- systematics ?
- QED rate is not reliably calculated ?
- new physics ?

$$\Gamma_{3\gamma} = \left[1 + A\frac{\alpha}{\pi} + \frac{\alpha^2}{3}ln(\alpha) + B\left(\frac{\alpha}{\pi}\right)^2 - \frac{3\alpha^2}{2\pi}ln^2(\alpha) + C\frac{\alpha^3}{\pi}ln(\alpha) + D\left(\frac{\alpha}{\pi}\right)^3 + ...\right]\Gamma^0_{3\gamma}$$



B calculated
G. Adkins et al., 2000

Theory
(2000)

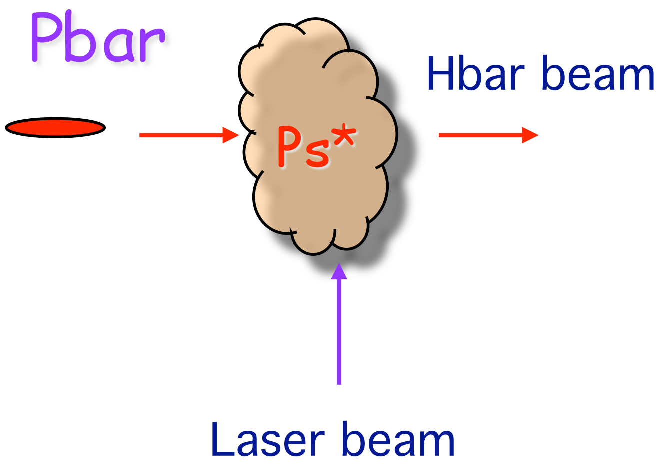
~10 sigma discrepancy
unknown B

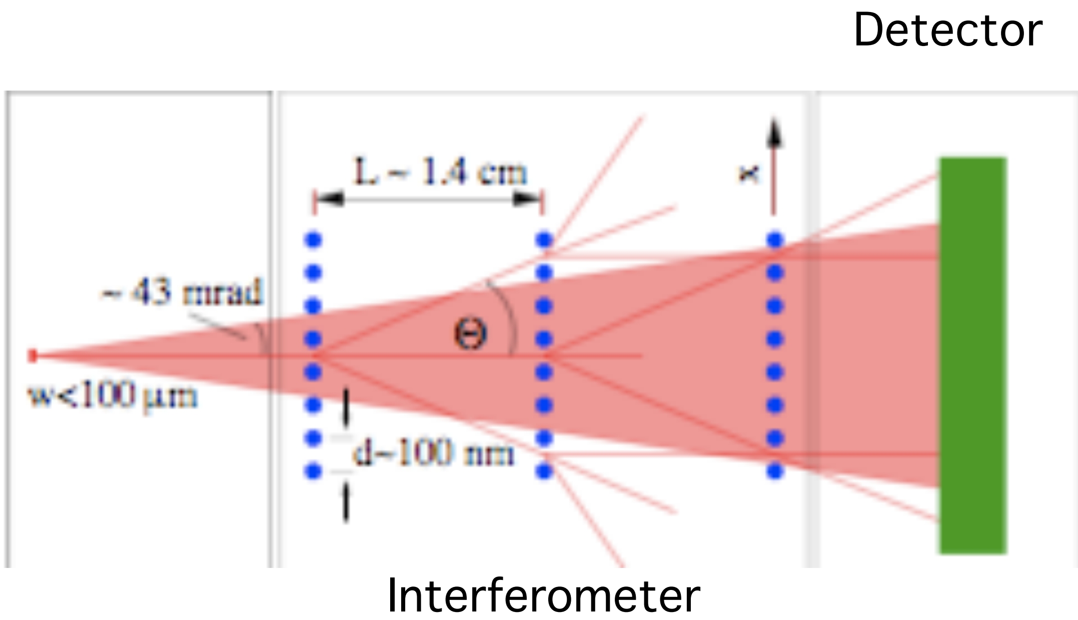
Today: agreement within 1sigma, but theoretical accuracy is a factor 100 better!

Experimental setup for Hbar gravity fall

Cold Rydberg State Ps

Ps Temperature < 10 K





$\sigma(\text{pbar}+\text{Ps}^* \to \text{Hbar}) \sim n_R^3$

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

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