The Abdus Salam
International Centre for Theoretical Physics

United Nations
Educational, Scientific and
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IAEA
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1951-31

Workshop on the original of P, CP and T Violation

2 - 5 July 2008

Experimental searches for mirror matter

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Experimental searches for mirror matter

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Workshop on origin of P, CP and T violation
July 2-5, 2008
Trieste, Italy

Plan:

- mirror matter model

- searches at low energies
  - Ps - Ps` oscillations (focus of the talk)
  - n-n` transitions (Berezhani, this workshop)

- searches at LHC
  - H-H`mixing (Chacko, this workshop)

- Summary

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)

mirror matter (mm) model

- 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 mm model -

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

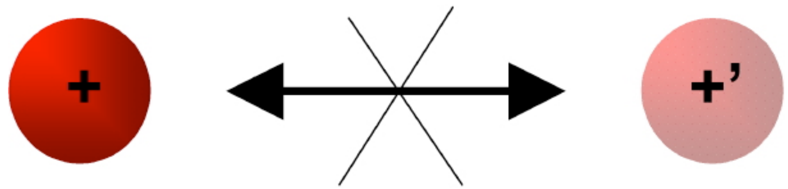
- mm must have different cosmology,
- is a good candidate for dark matter
- can be linked to string theory, extra dimen., …

Foot, Volkas'91 Berezhiani, Mohapatra'95, Berezhiani et al.'00-08, Akhmedov, Senjanovic'92, …..

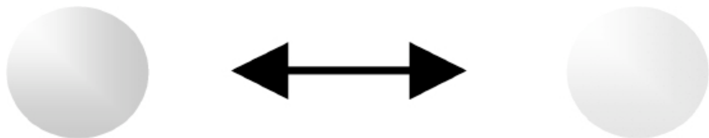
For review see: L.Okun hep-ph/0606202

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)



possible mm effects:

- Higgs mixing

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

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

- dark matter

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 particles

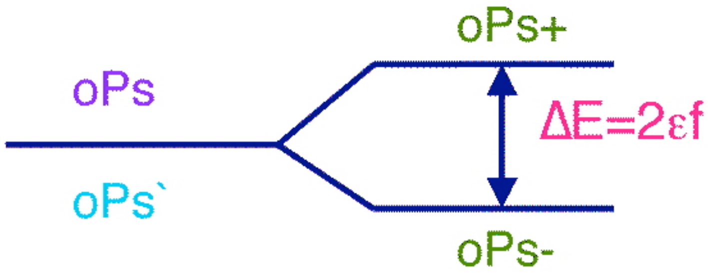
Holdom '85; Ignatiev '91; Gninenko et al.'07….

- anomalous events, ……

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

γ-γ` kinetic mixing

- interaction: $\varepsilon F^{\mu\nu} F`_{\mu\nu}$



- new mass eigenstates: oPs± = (oPs±oPs`)/√2

- energy splitting: $\Delta E = 2\varepsilon f$, $f = 8.4 \times 10^4$ MHz from oPs-pPs splitting

- oscillation probability: $P(\text{oPs-oPs}`)(t) = \sin^2(2\pi\varepsilon f t)$

Holdom'86, Glashow '86

Experimental signatures for oPs-oPs' oscillations

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

- oPs\`-> 3γ' -> invisible decay - more convenient: 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):

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

Suppression factor

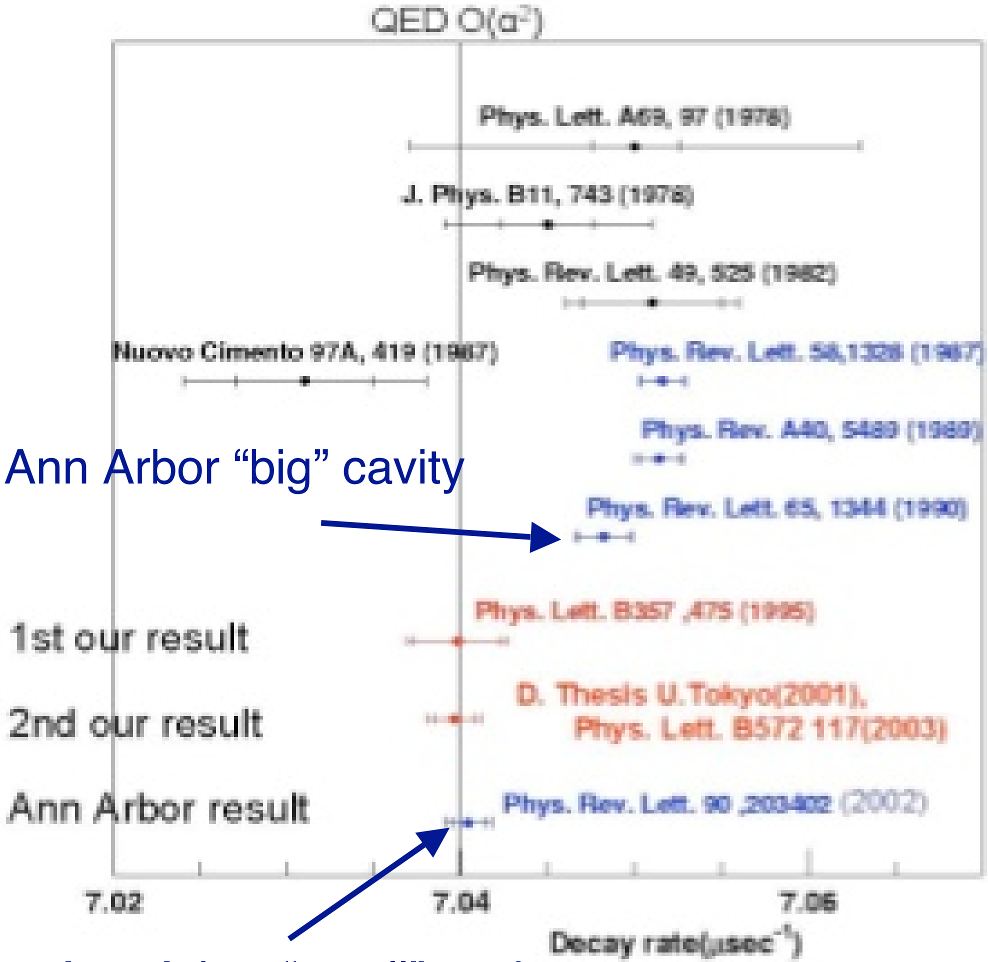
SG'95, Foot and SG '00

Positronium decays in the SM

- 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
- only ~~0~~, ~~1~~, 2 , 3 , ~~4~~, ..gamma in the final state.
  for Br(oPs--> anything)>~10^{-5}

o-Ps decay rate puzzle (1982-2002)

History of oPs decay rate measurements



Ann Arbor "big" cavity

Ann Arbor "small" cavity

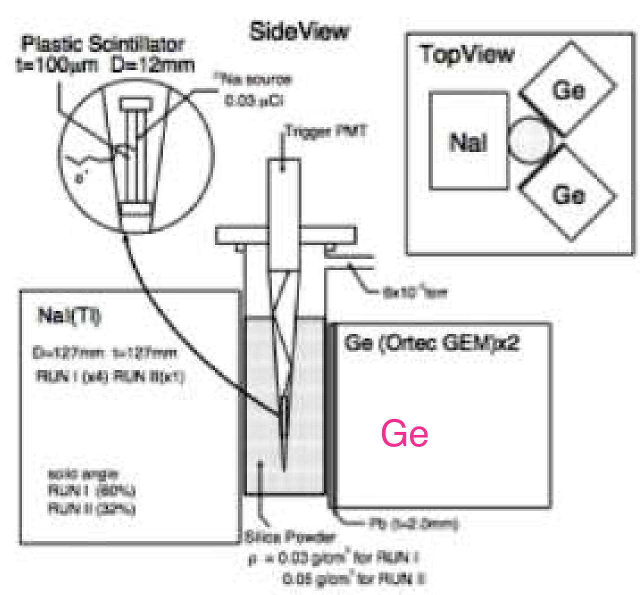
Discrepancy $\Gamma_{\exp} > \Gamma_{SM}$:
-unknow contribution at the level Br(oPs->X)~10^{-3} or
- experimental problems

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

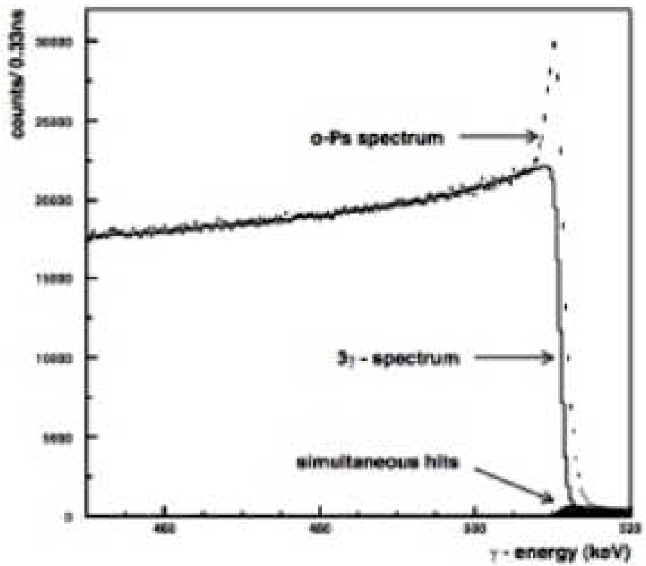
Tokyo experiment with silica target

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

511-keV line
from 2γ annihilation



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} Γ_{oPs}

and suppression of oPs-oPs’ transitions

Asai et al.’08

o-Ps decay rate vs mirror effect

Discrepancy triggers searches for new physics.

all exotic modes oPs-> wrong number of photons : 0,1, 2, 4….
are excluded at the level Br< $\sim 10^{-5}$. However, measurements are performed whith oPs formation in a target, i.e. oscillations oPs-oPs' are suppressed and cannot contribute through oPs-> invisible, hence no constraint on oPs->invisible through mirror oscillations.

Experiments that agree with QED predictions,

-Tokyo measurements are not sensitive to mirror effect: oscillations oPs-oPs' are suppressed and cannot contribute to the decay rate
- Ann Arbor vacuum experiment: small cavity size is used and oPs collisions with the cavity walls may dump oscillations.

-In addition……

more interesting observation:

- two Ann Arbor vacuum experiments with big and small cavities disagree: oPs decay rate for big cavity measurements is higher $\sim 10^{-3}$

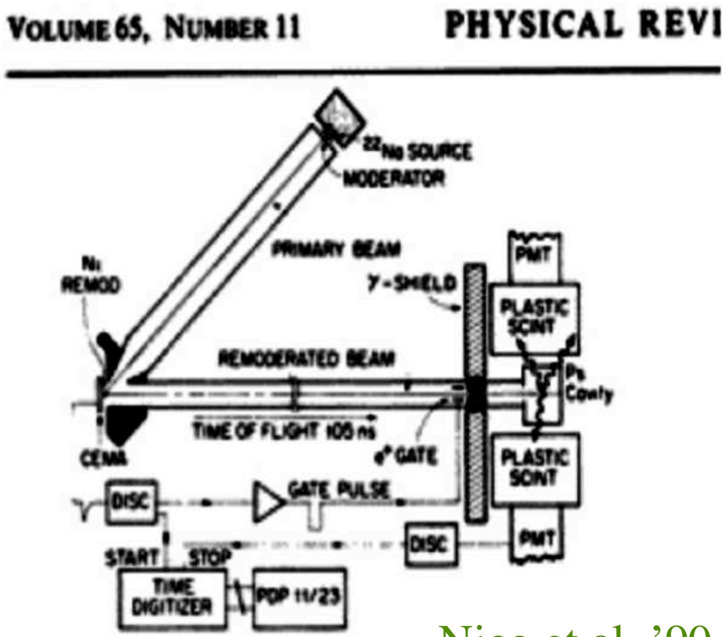
- if "acceleration" of oPs decay is due to a SM process, e.g. due to oPs positron annihilation with wrong electron (pick off process) or due to oPs-pPs mixing,

then

- 2γ (511 keV line) must be seen in the final state in the big cavity experiment in addition to the main spectrum from oPs-> 3 γ !

Two Ann Arbor experiments on oPs decay rate in vacuum

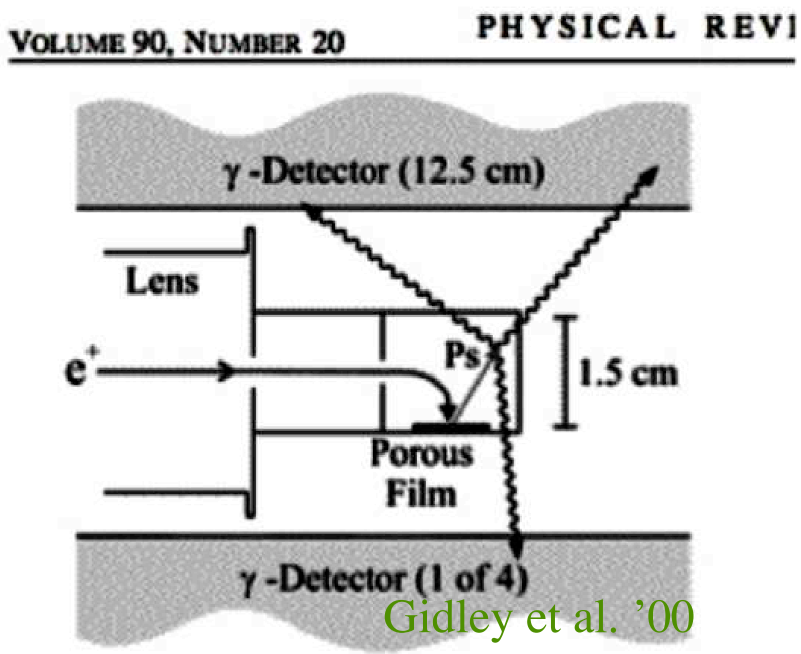
$\Gamma_{\exp} > \Gamma_{SM}$



Nico et al. '90

big cavity

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



Gidley et al. '00

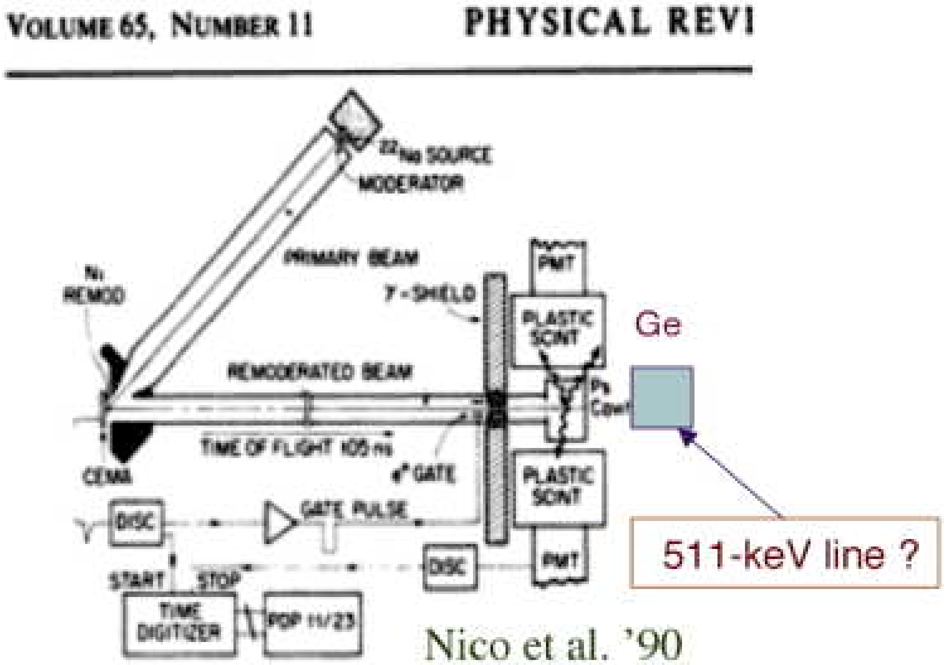
small cavity

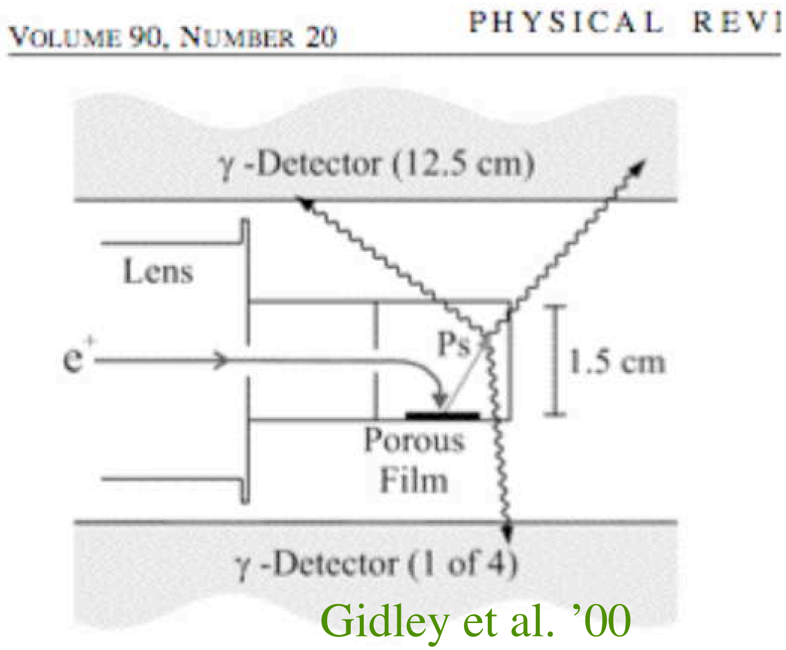
in the SM oPs can decay faster only due to additional SM 2γ annihilation process, i.e.

- pick-off annihilation, or
- oPs-pPs mixing (external fields)

Search for 511 keV line.

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





check presence of 2γ (511 keV line) with intensity ~10^{-3} of the total rate

No 511 keV line - hint for mirror matter ?

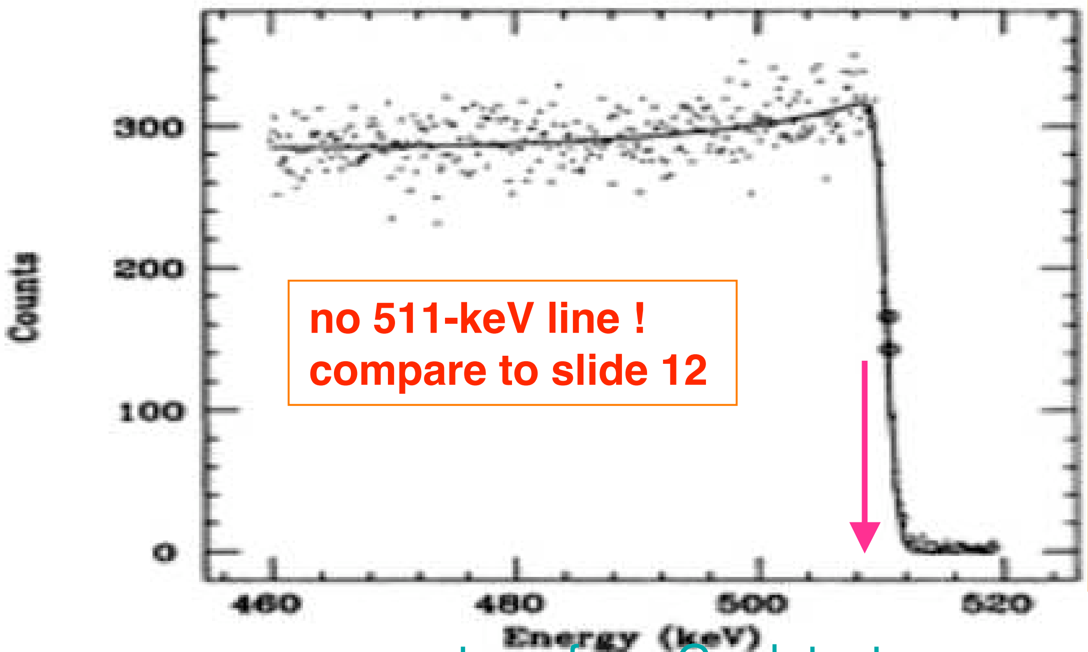
VOLUME 66, NUMBER 10 PHYSICAL REVIEW LETTERS 11 MARCH 1991

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 $\to 2\gamma$ 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.Fs



no 511-keV line !
compare to slide 12

spectrum from Ge detector

In measurements'90
oPs-oPs' oscillations contribute to the oPs decay rate because of less collision rate (large cavity size)

In measurements'00
oPs-oPs' oscillations could be suppressed,e.g by a higher collisional rate (much smaller cavity size)

What size ε, if oPs escapes to mirror world?

$$\Delta\Gamma(oPs \rightarrow invisible) = \Gamma_{EXP} - \Gamma_{SM}$$

$$\Delta\Gamma(oPs \rightarrow invisible) \simeq 10^{-3}$$

$$\Delta\Gamma(oPs \rightarrow invisible) = \frac{2(2\pi\varepsilon f)^2}{\Gamma_{SM}\Gamma_{COLL}}$$

$$\Gamma_{COLL} \simeq 3\,\Gamma_{SM}$$

$$\varepsilon \simeq (5 \pm 1) \times 10^{-7}$$

Existing limits on ε

- $\varepsilon < \sim 10^{-5}$ from milli-charged particle searches

  SLAC'01

- $\varepsilon < 10^{-8}$ Tokyo group claim. However, suppression due to collisions are not considered.

  $\varepsilon < \sim 10^{-6}$ after correction. ⇒ $Br(oPs\text{->}inv) < \sim 10^{-2}$

  Mitsui et al. '93; SG '95;

- $\varepsilon < 3\text{x}10^{-8}$ from BBN ⇒ $Br(oPs\text{->}inv) < \sim 10^{-6}$

  Glashow, Carlson'87;

- $\varepsilon \sim 4\text{x}10^{-9}$ from DAMA, DAMA/LIBRA observation of modulation ⇒ $Br(oPs\text{->}inv) \sim 10^{-7}\text{-}10^{-8}$

  Foot'01-08;

Program of experiments

1. search for oPs escape into extra dimensions
   - sensitivity in Br~ 10^{-8} - 10^{-9}

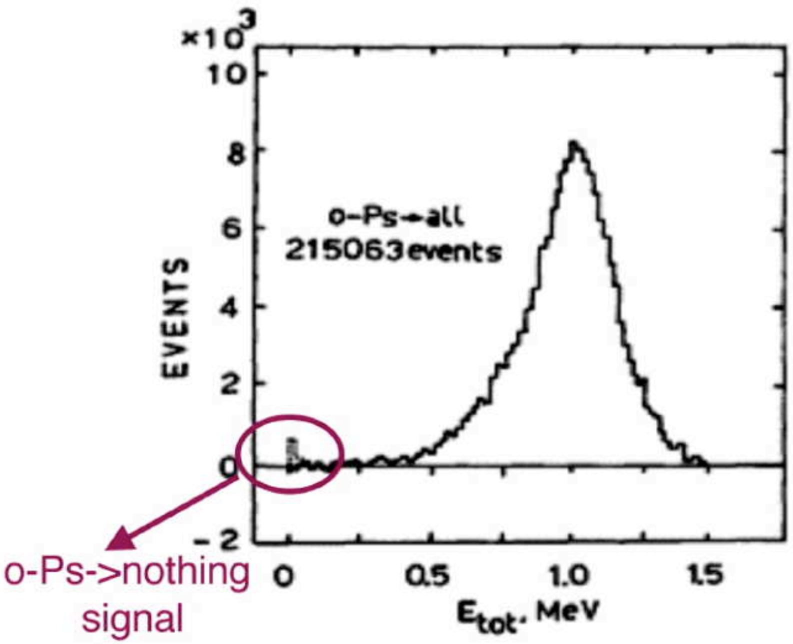
2. measurements of free gravity fall of antihydrigen (and positronium) , very cold < 10 mK Rydberg oPs formation is required

tests of mirror matter effect in oPs decays well fit into this program

Moscow experiment on o-Ps->invisible

"A search for photonless annihilation of orthopositronium,"
Atoyan, SG, Razin, Ryabov , Phys. Lett. B 220, 317 (1989).
LEP *Z->invisible*

- 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



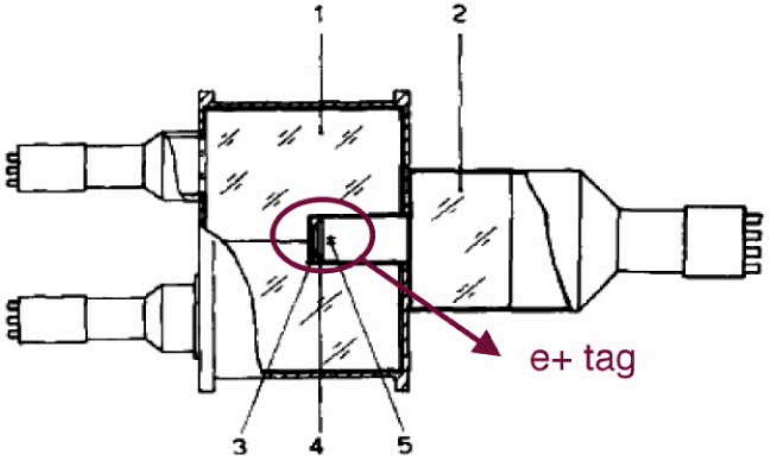


Fig. 1. Schematic view of the set-up: (1): NaI calorimeter; (2): NaI counter (3): target; (4): proportional counter; (5): the positron source ^{22}Na.

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

Cannot be resnonsible for
o-Ps decay rate anomaly.

Tokyo experiment on o-Ps -> invisible

- 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).

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

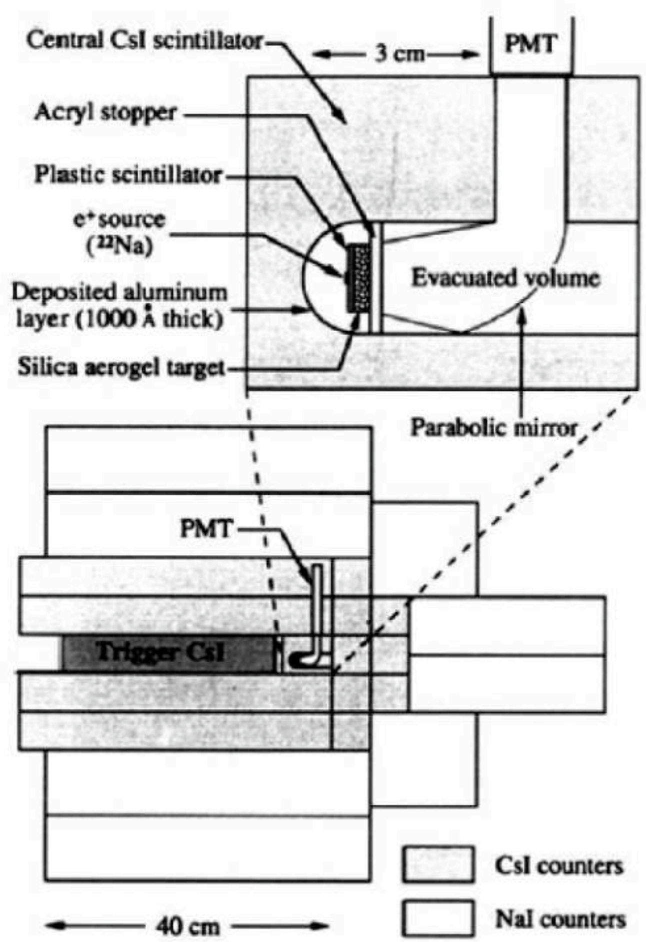
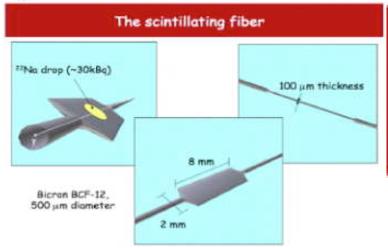


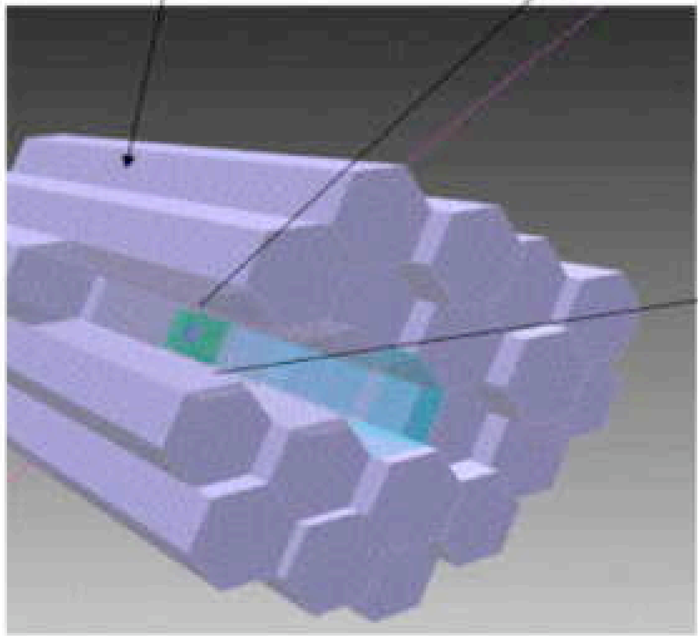
FIG. 1. Schematic of the experimental setup.

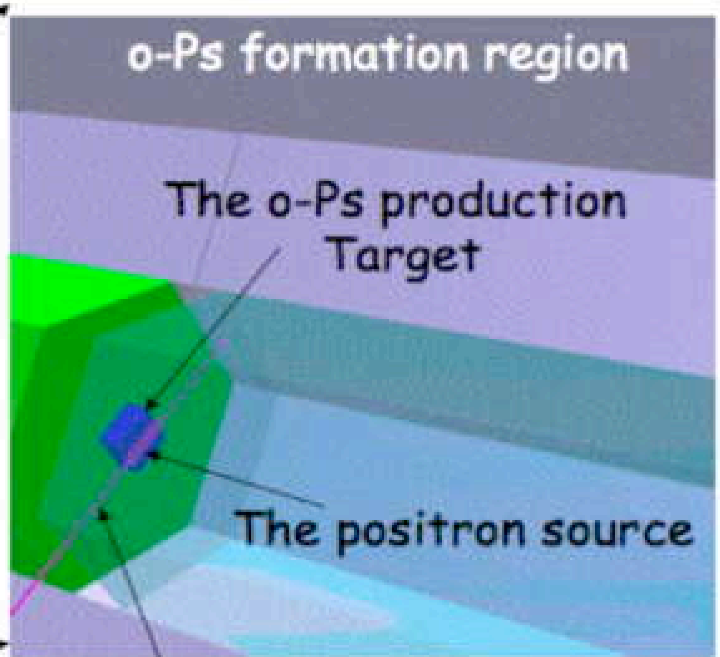
ETH-INR-LAPP experiment on o-Ps -> invisible



The o-Ps formation region

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

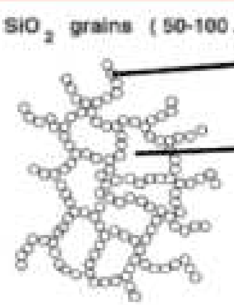




The scintillating fiber to tag the positron

oPs target

SiO_2 aerogel target (0.1 g/cm³)



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

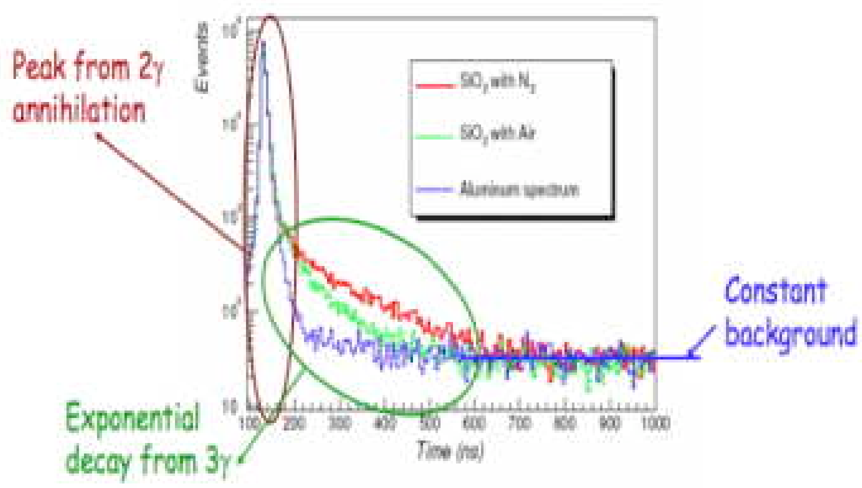
Collisional quenching

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

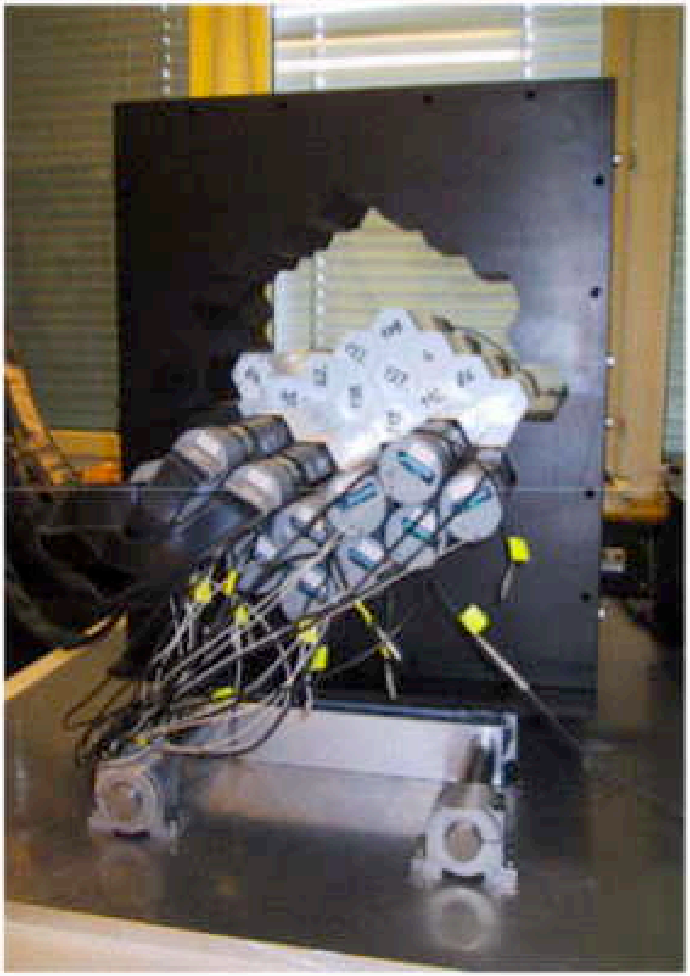
$\tau_{Air} < \tau_{Nitrogen}$ ⇨ With N_2 bigger fraction of o-Ps than with Air

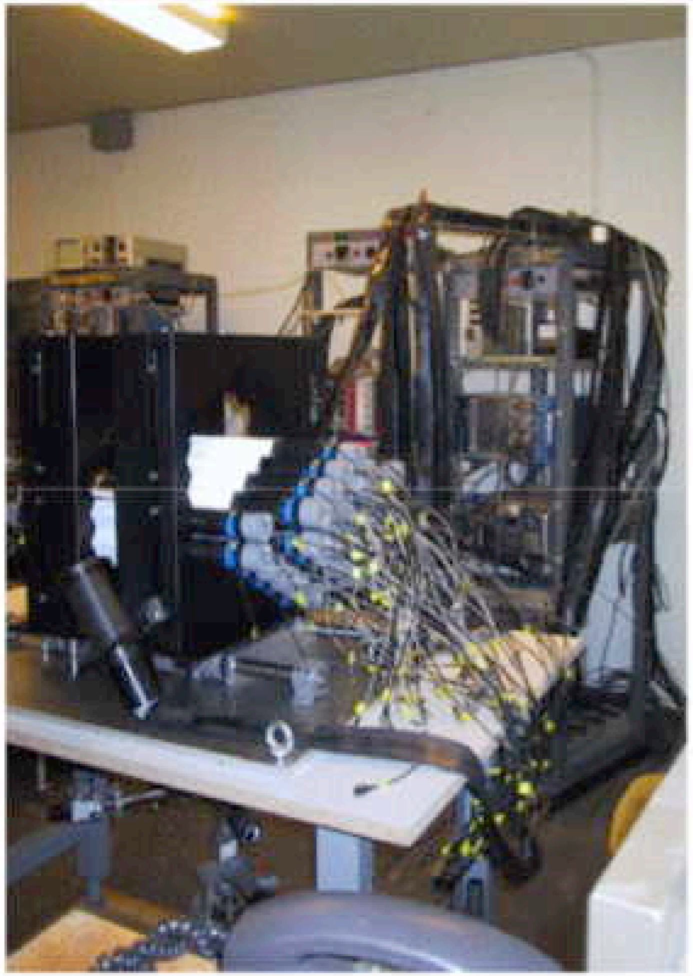
In Air spin-exchange: $o-Ps+O(\uparrow\uparrow) \rightarrow p-Ps+O(\uparrow\downarrow)$

Time spectra between tagged positron and photon detected in the calorimeter

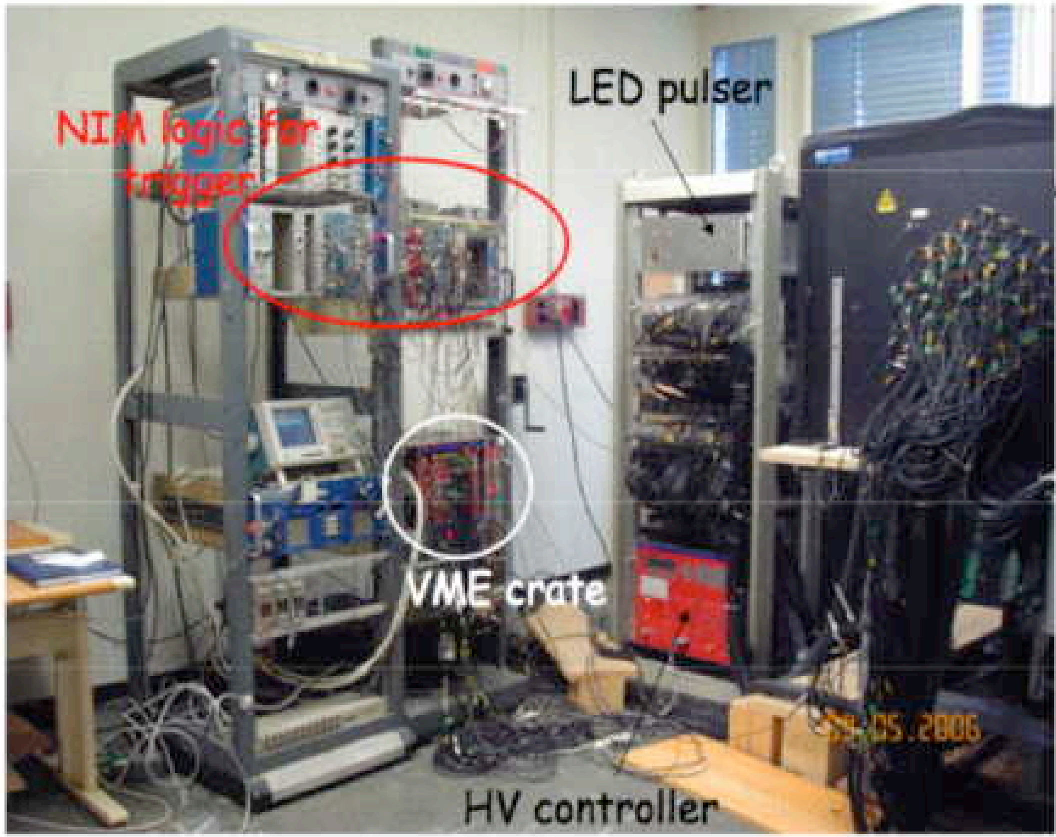


Photograph of the calorimeter (assembling phase)





Picture of the lab



Light tight Box

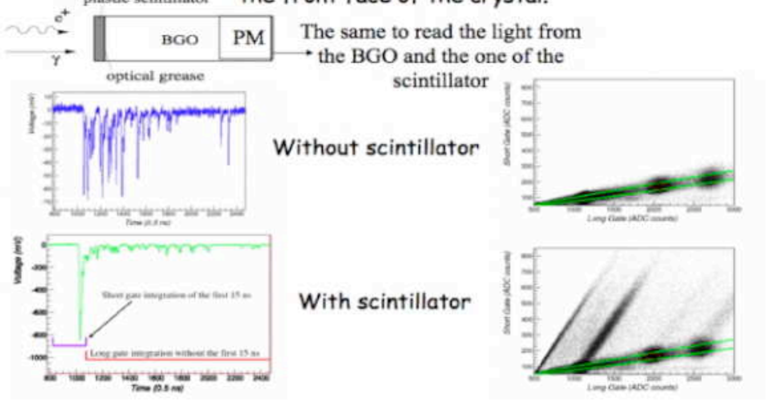
ETH - INR Experiment

photo 2

Signal selection

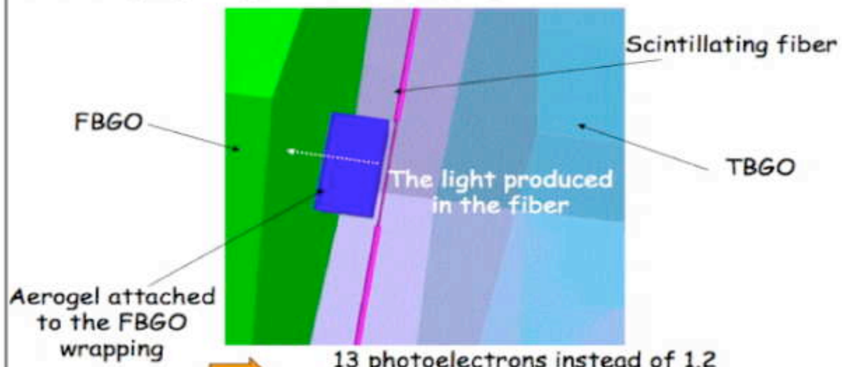
Charged particle VETO

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.



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.

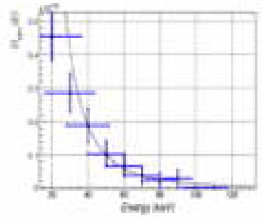


13 photoelectrons instead of 1.2 compared to the fiber, cut meaningful.

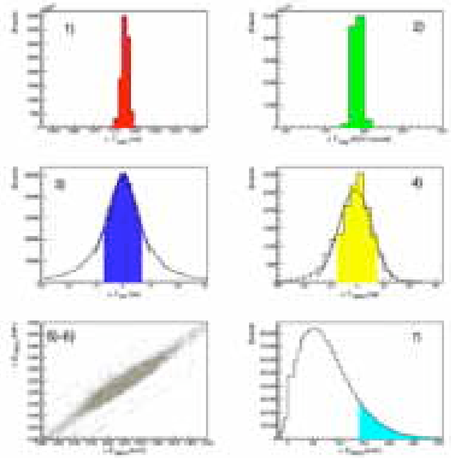
Rejection of shake-off electrons

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 background

Results

A.Baderscher et al., PRD(2007)

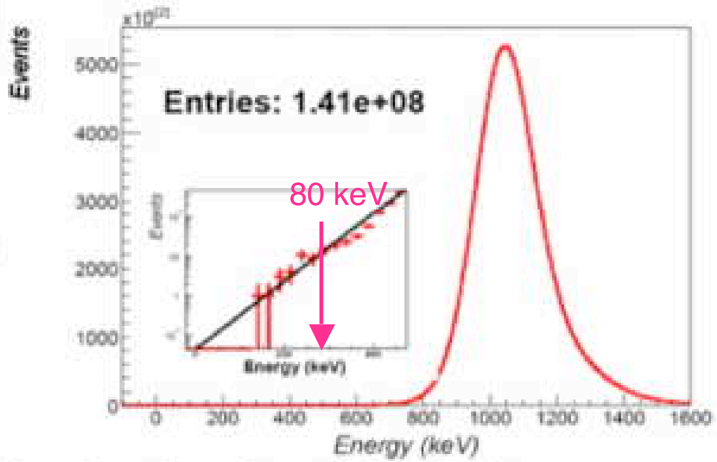
DATA	Air	Nitrogen	Combined
Fiber triggers	0.6×10^{10}	0.79×10^{10}	1.39×10^{10}
Selected events	0.61×10^{8}	0.8×10^{8}	1.41×10^{8}
o-Ps fraction	3.41 %	5.29 %	4.48 %
Number of o-Ps	2.08×10^{6}	4.23×10^{6}	6.31×10^{6}

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 result

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

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

New limit on ε

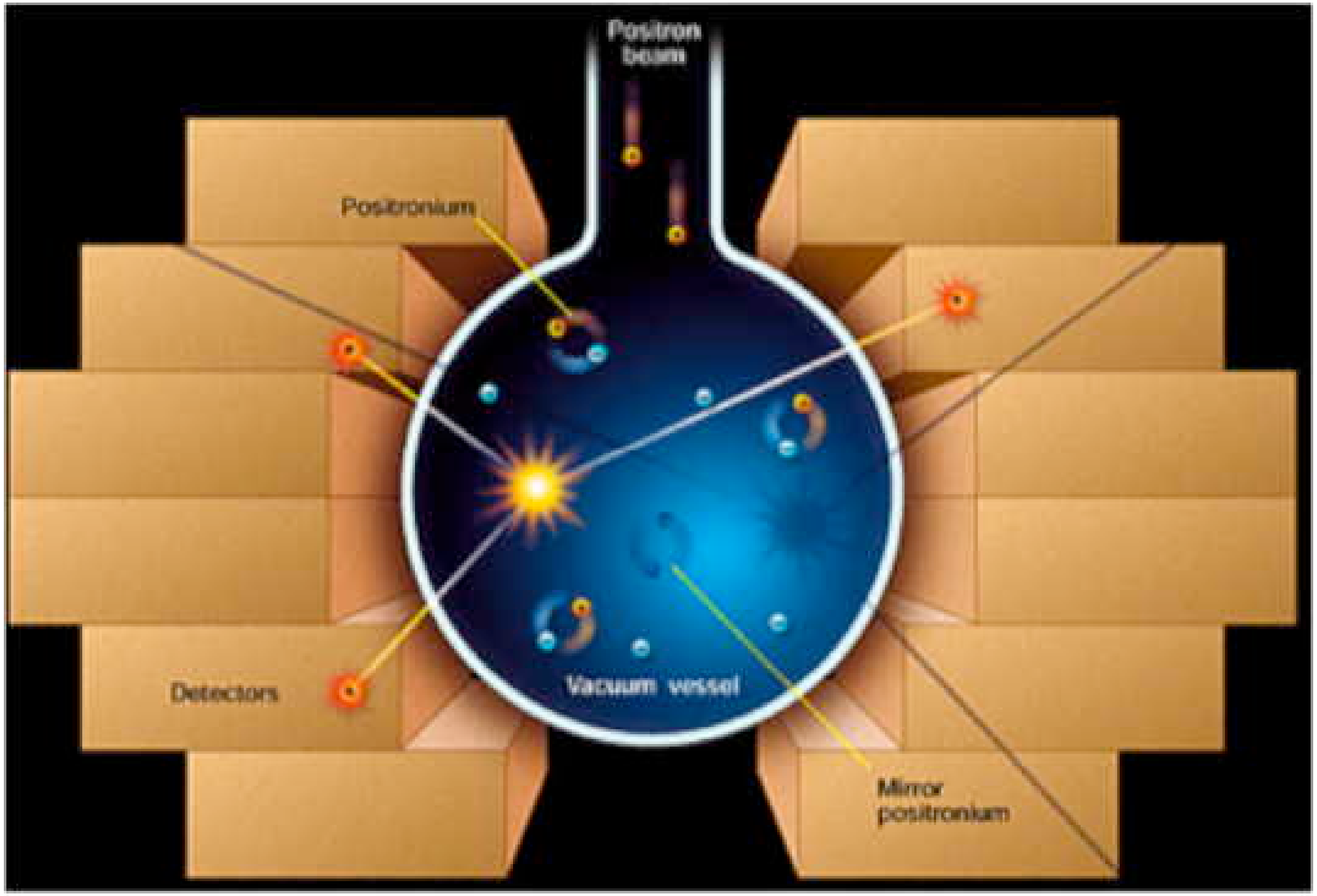
- $\varepsilon < (1.6 - 3)\times10^{-7}$

Main uncertainty from collision rate of oPs in the aerogel target: $\varepsilon \sim (5 \pm 1)\times 10^{-7}$ cannot be reliably excluded.
still could be Br(oPs->inv)~ 10^{-3}

Badertsher et al.'07;

- vacuum experiment is needed

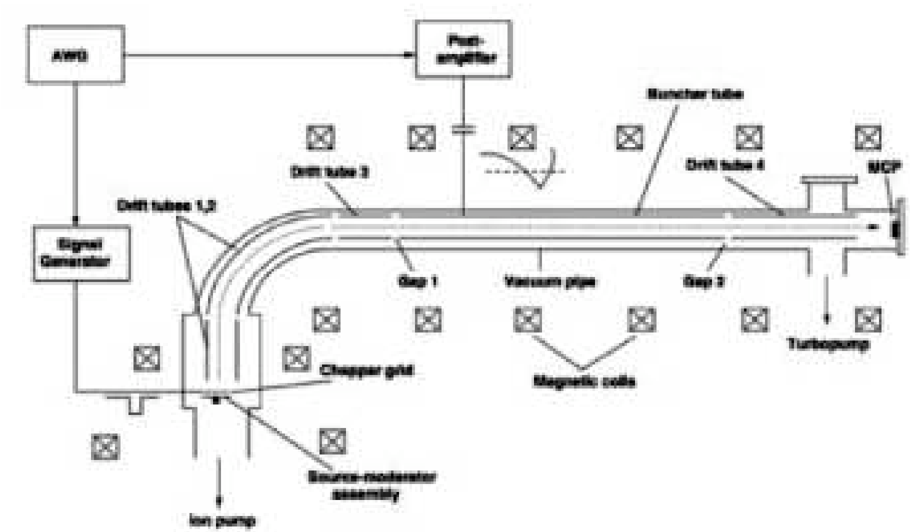
How to search for hidden world with oPs?

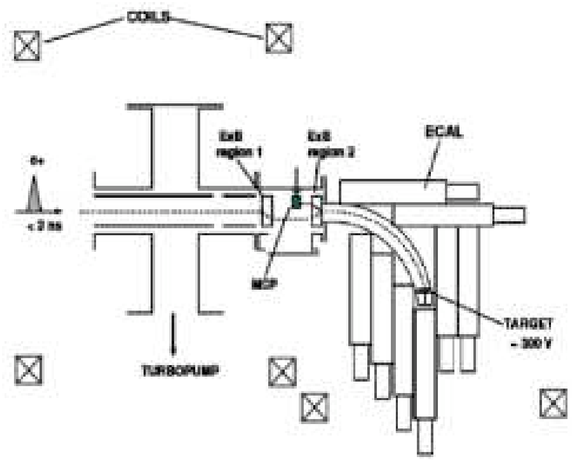


Cortesy New Scientists, 2004.

Search for mirror matter via o-Ps->invisible decays in vacuum

"An apparatus to search for mirror dark matter via the invisible decay of orthopositronium in vacuum,"
SG'03, Badertscher *et al.'03*





- cold oPs formation in vacuum: minimum collisions, enough time for oscillations, minimize leak through entrance window
- e+ tagging system: timing coincidence of e+ bunch and MCP signal from secondary e-'s emission , inefficiency < 1.e-8
- pulsed slow positron beam: high efficiency & compression factor
- hermetic calorimeter in magnetic field
- very thin vacuum pipe
- expected sensitivity in Br(oPs->inv) $\sim 10^{-8}$

cold Ps formation target

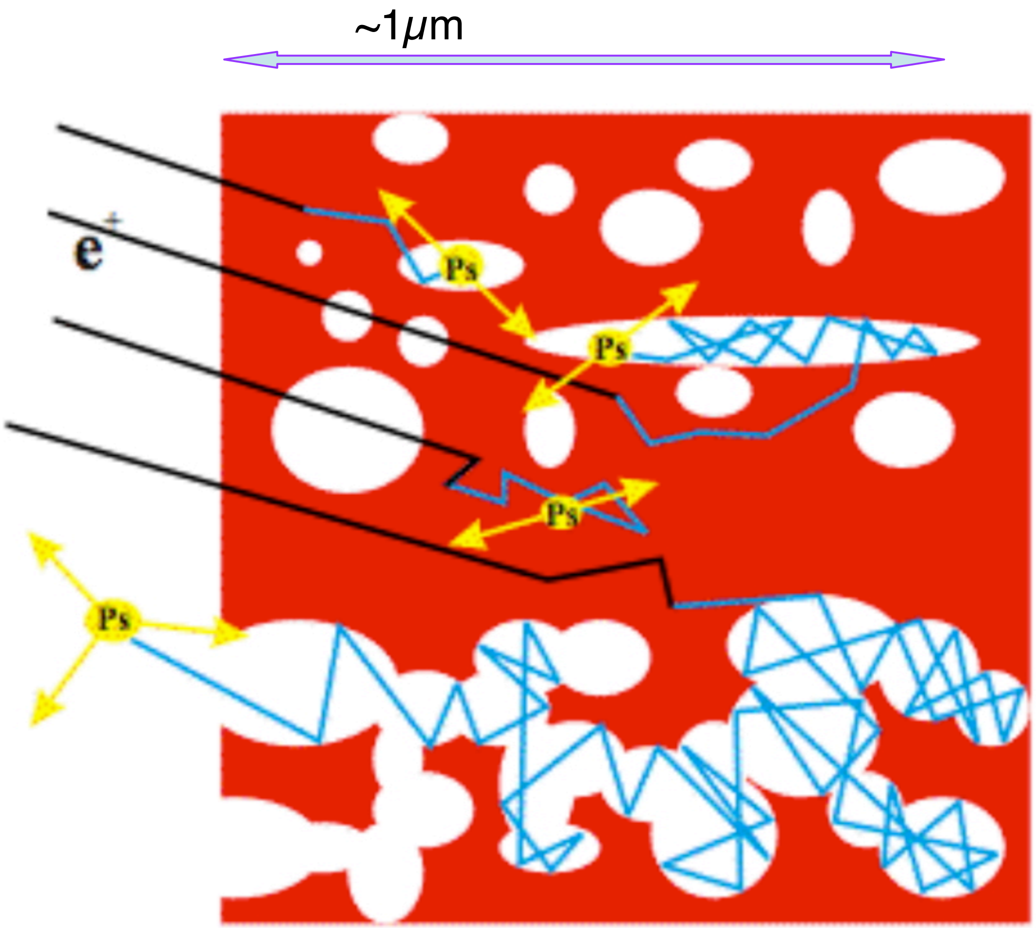


Figure 1 Positronium formation in porous materials.

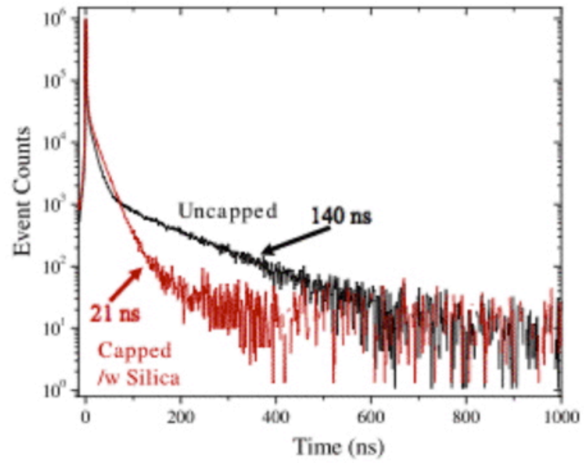


Figure 4 Typical Ps lifetime spectra for a film with open porous network (*black*) and after capping (*red*).

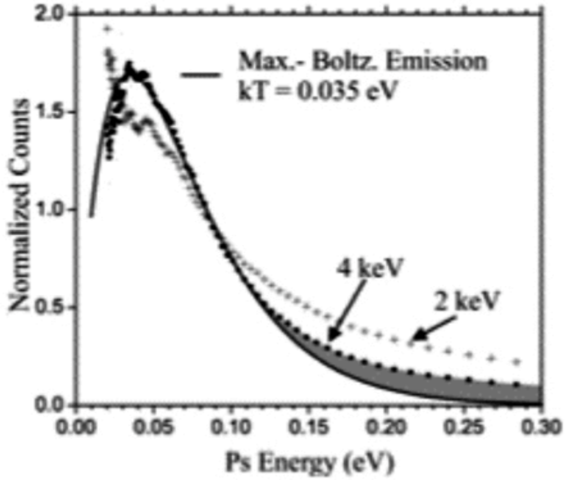
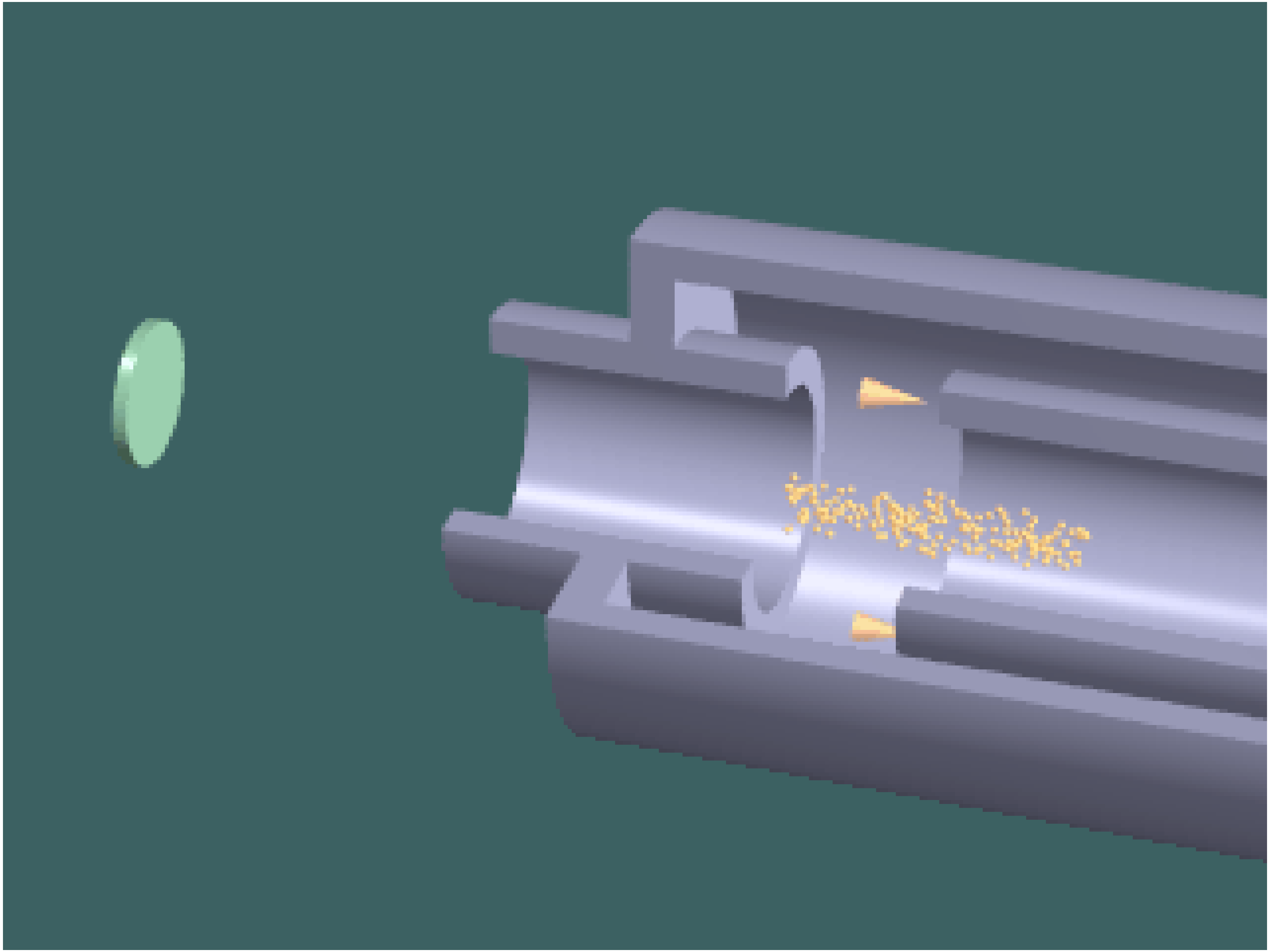


FIG. 2. The energy distribution of *o*-Ps emitted from a typical porous silica film. Note that higher energy positrons implanted more deeply (solid circles) in the film produce more thermalized *o*-Ps with fewer events in the epithermal tail.

Ps formation in porous Si films
to minimize the leak.

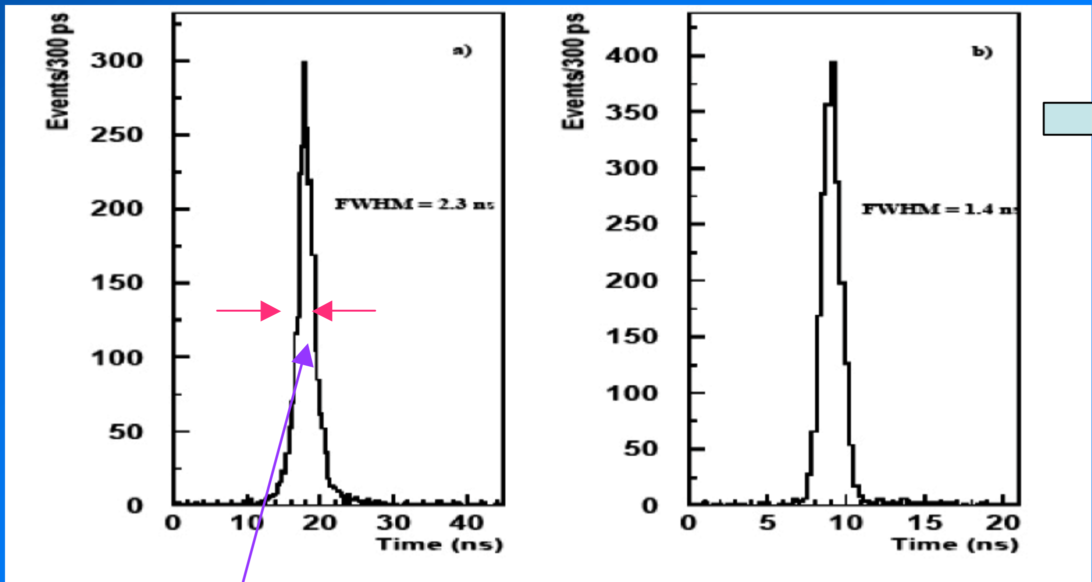


Results on positron pulse width

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

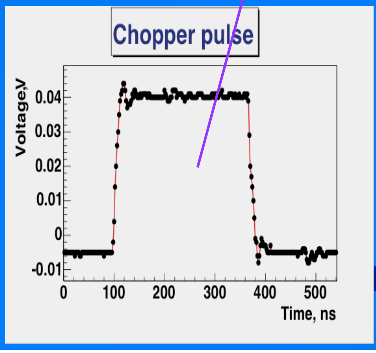
~ 2.3 ns (FWHM)
for an Initial pulse
of 300ns

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



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

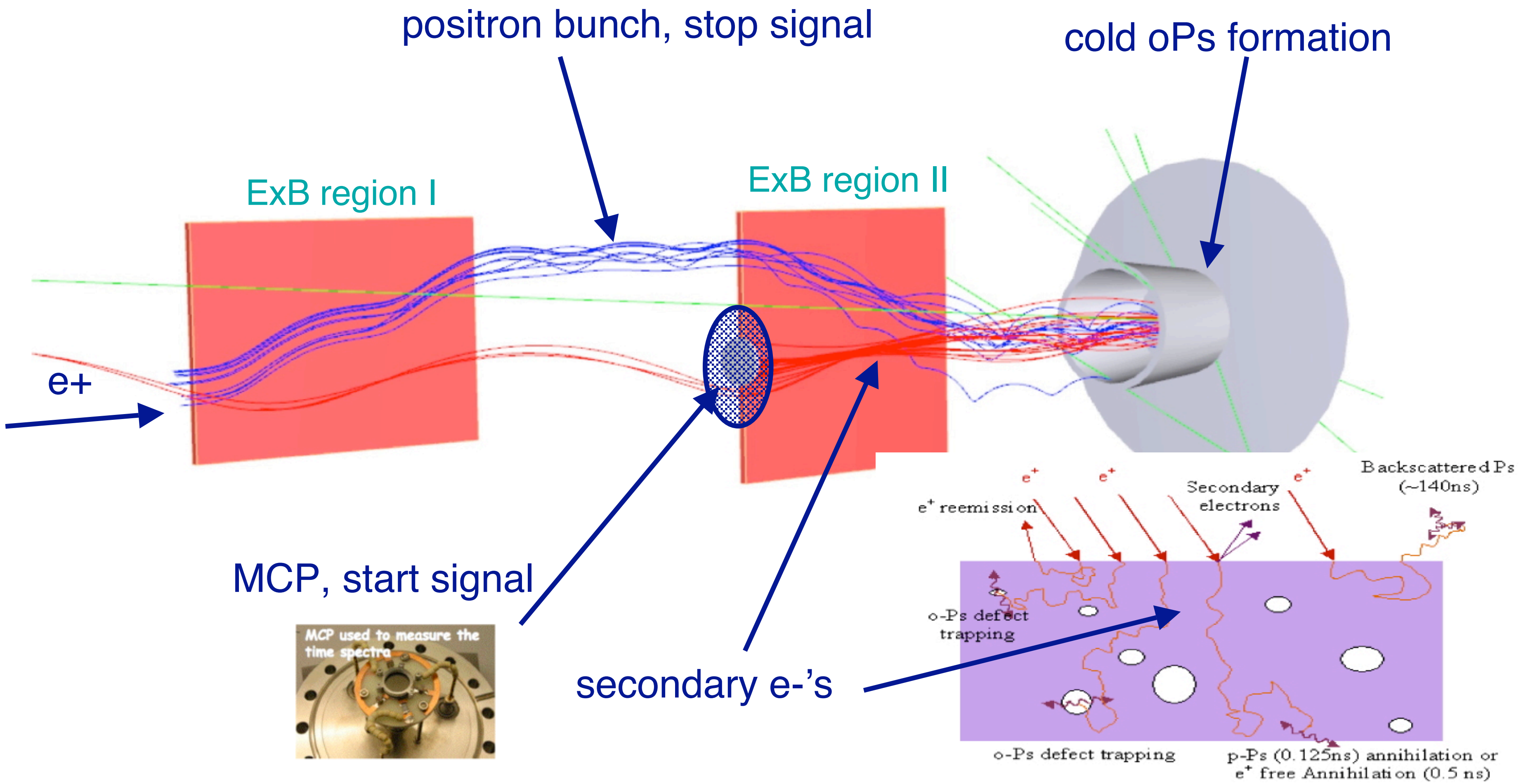
Repetition period ~ 1 μs



Tokyo Univ. group, H. Iijima et al.
NIM A483 (2002) 641: Compression of
~ 60 ns → ~ 2 ns (FWHM)

positron tagging system

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



The slow positron Beam

4Mbq ^{22}Na source of positron & Tungsten moderator chamber

Double Gap Buncher

Calorimeter

e^+ flux

Positronium formation region

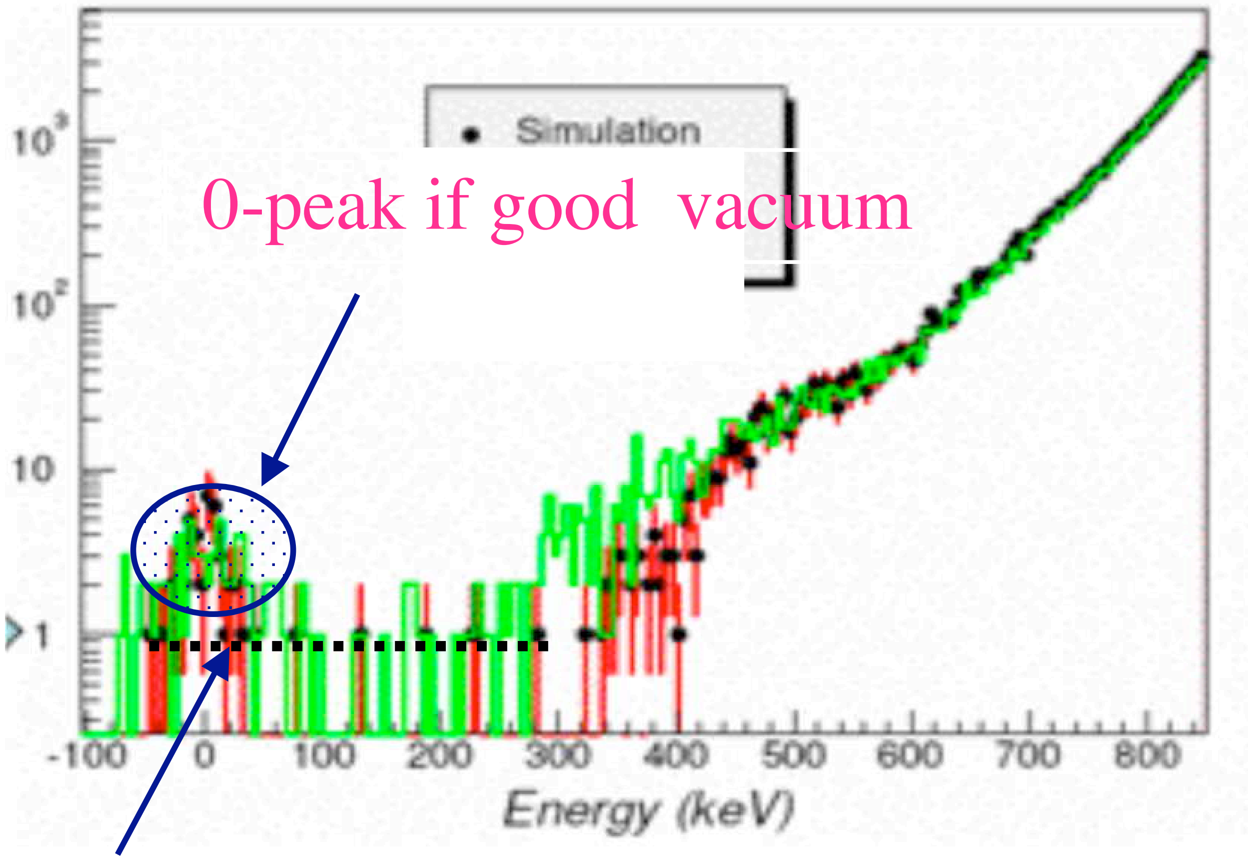
Magnetic coils for positron transportation (quasi-uniform longitudinal field of 70 Gauss)

Beam pipe (10^{-8}-10^{-9} mBar)

photo 3

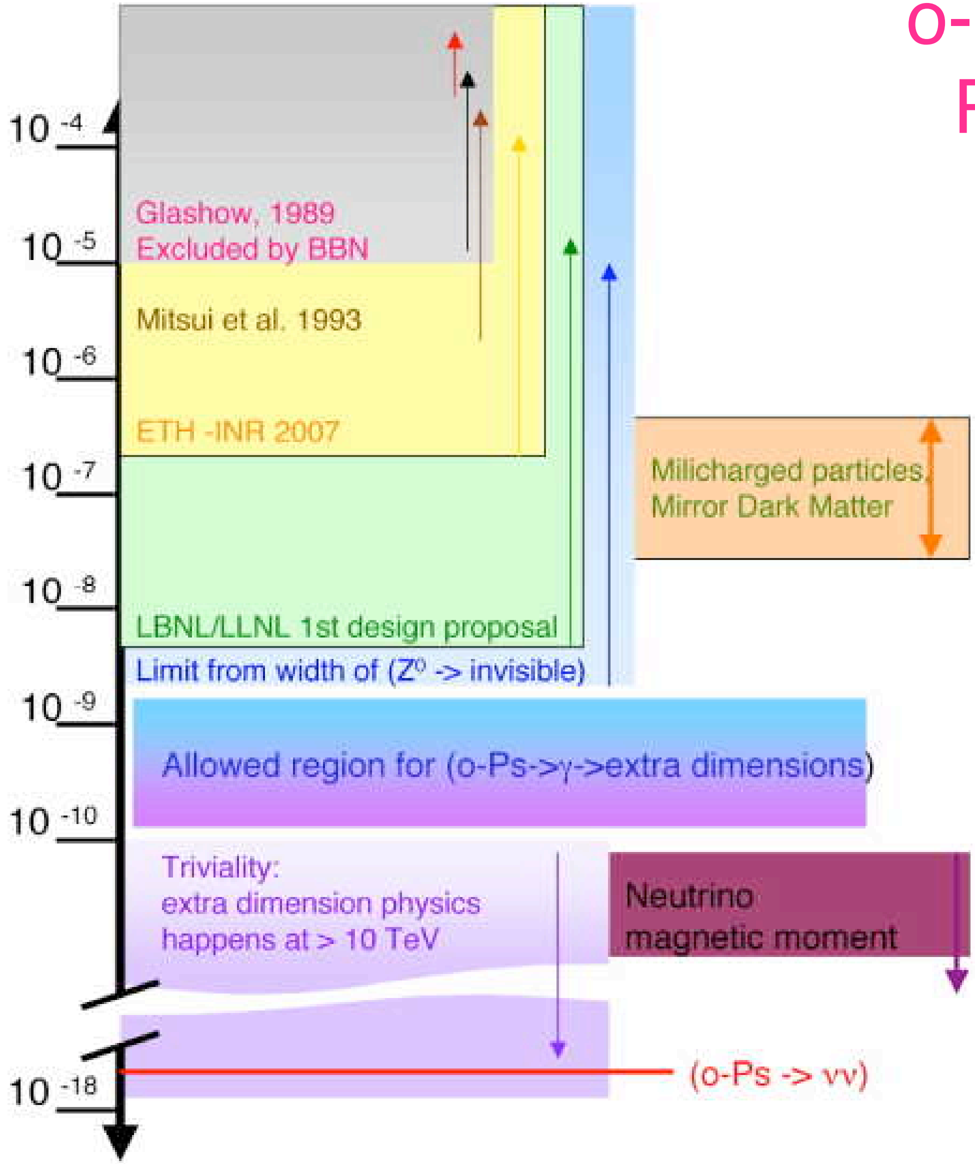
Cross-check of oPs disappearance

$$\Delta n = n_{p1}(E < E_{thr}) - n_{p2}(E < E_{thr})$$



no 0-peak if "bad" vacuum

o-Ps -> nothing: Past &Future



expected before 2011

Search for n-n` oscillations

- effective interaction: e.g. $(udc)(u`d`c`)$

- the small mass n-n`mixing could have direct consequences for the propagation of ultra-high energy cosmic rays at cosmological distances (GZK cut off) Oscillations could be fast $\tau \sim 1$ sec

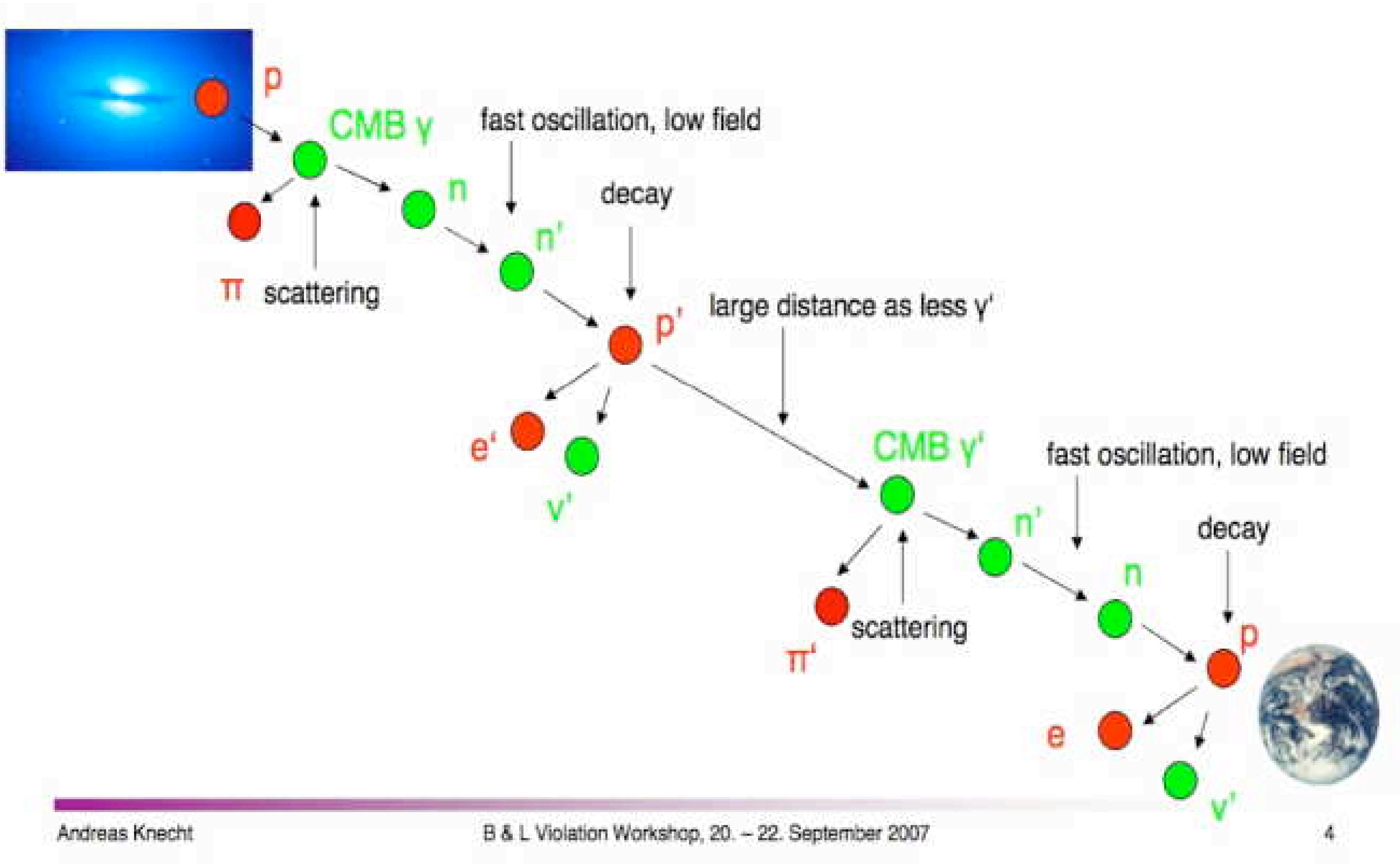
  Berezhiani, Bento '05;

- experimental technique: n decays in a trap:
  - no magnetic field
  - as less as posible collisions

  Pokotilovski'06

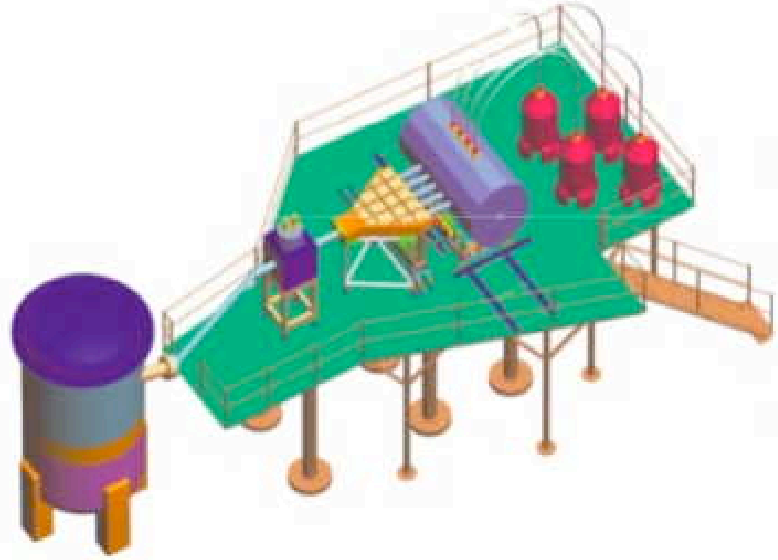
GZK cut off

Explanation with fast ($\tau_{osc} << \tau_n$) neutron – mirror neutron oscillations



Proposal of PNPI for $n \to n'$ experiment

Experiment for $n \to n'$ oscillations
can be realized using PNPI EDM spectrometer



$\tau_{storage\ H=0}$ (without magnetic field)

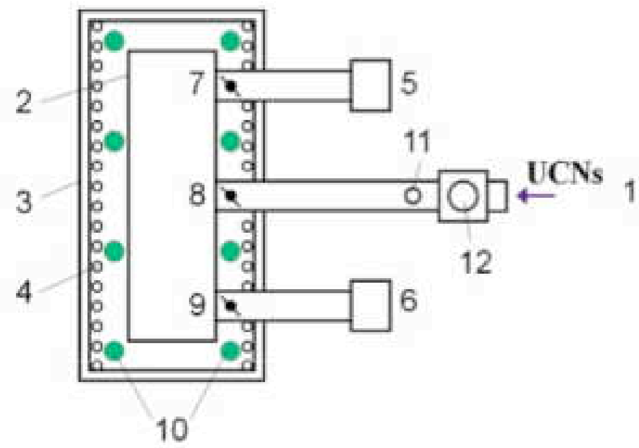
$\tau_{storage\ H\neq 0}$ (with magnetic field)

$\Delta\tau = \tau_{storage\ H\neq 0} - \tau_{storage\ H=0} = (\neq)0$

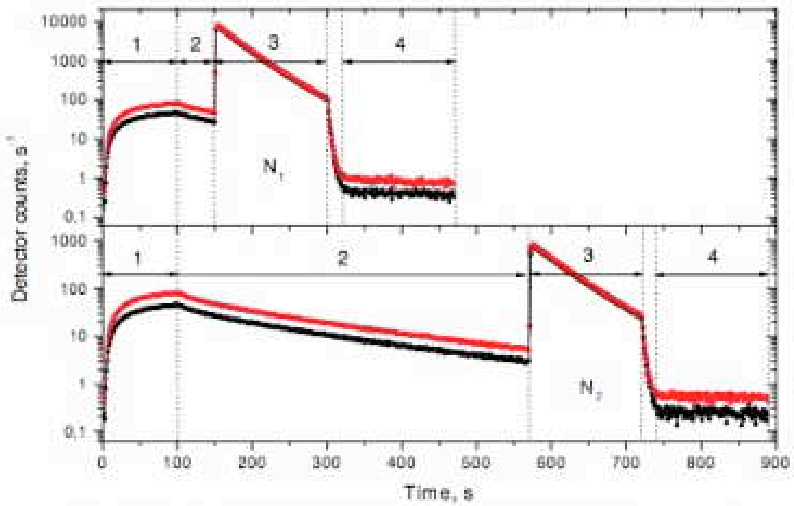
It is the main question

A.Serebrov Talk at B-L Workshop'07

Scheme of experimental installation to search for n-n' transitions



1: UCN input guide; 2: UCN storage chamber; 3: magnetic shielding; 4: solenoid; 5-6: UCN detectors; 7-9: valves; 10: Cs-magnetometers, 11: monitor detector, 12: entrance valve.



Count rates of UCN detectors (5 and 6) in log scale during measurements. The filling time is 100 s. Holding times were t_1 = 50 s and t_2 = 470 s. Empting time is 150 s. The time of background measurement is 150 s. The region 3 in these plots is used to deduce the numbers N_1 and N_2 required for the determination of the storage time, respectively the ratio *R* (after background subtraction). This picture was obtained after 130 cycles. τ_{fill} = 35 s, τ_{emp} = 30 s after holding time 50 s, τ_{emp} = 38 s after holding time 470 s.

17

A.Serebrov Talk at B-L Workshop'07

Present experimental status of n-n` mixing

- U. Shmidt et al'07 (UFRM II, Munchen) $\tau_{osc} > 2$ s
- G. Ban et al.'07 (ILL, Grenoble) $\tau_{osc} > 103$ s
- A.Serebrov et al. (ILL, Grenoble) $\tau_{osc} > 414$ s

Further improvement $\tau_{osc} > 10^4$ sec

Higgs:

<u>Higgs Boson</u>

Ordinary matter Higgs: $\Phi_O \sim (1,2,1)(1,1,0)$

Mirror matter Higgs: $\Phi` \sim (1,1,0)(1,2,1)$

The Z_2 symmetry implies an operator which transforms the two kinds of matter between each other, $\Phi_O \leftrightarrow \Phi`$

.

interaction: $L_{H-H'} = \eta \phi^+ \phi \phi'^+ \phi'$

two mass eigenstates are created by mixture of our Higgs field and the mirror field

$$\Phi_\pm = \frac{1}{\sqrt{2}} (\Phi_O \pm \Phi`)$$

Search for H-H`mixing

overall Higgs production rate now is devided between two channels instead of one channel with significance S (=Siganl/Noise) for the same running time one will get significance S/2

Higgs signal at LHC might be much weaker.

Foot, Lew, Volkas'Ignatiev, Volkas '95; Barbieri et al. '05; Wilczek '06, Zhu et al. '07

SUMMARY

- what is the origin of parity violation?
  50 years old question

- experiments results
  - on H-H` at LHC
  - on n-n` and Ps-Ps` at low energies

  might give an answer to this question in the near future