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Orthopositronium as a probe for new physics

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Symmetries

Symmetry: the beauty of nature

- Symmetries play an extremely important role in Physics, and in particular in the physics of elementary particles.
- Invariance under given <u>continuous</u> or <u>discrete</u> transformations provide a unique mean to understand physics through the associated conserved quantities (Noether's theorem)
  - Space-time-translation invariance → energy-momentum conservation
  - Rotation invariance → angular momentum conservation
  - Gauge invariance → charge conservation, gauge field theories
  - Flavor symmetries (isospin, strangeness, …) → hadrons classification ("Eight-fold way")
- In particular, the invariance properties under the Lorentz group are a fundamental component of modern theories
  1. Proper Lorentz transformation
     → Rotation
     → Boost → Conserved current is rest mass
  2. Improper Lorentz transformation
     → Space reflection (parity operation)
     → Time reflection

Lorentz transformation

- The properties under Lorentz transformation are the schoolbook example of the importance of symmetry in physics

$$(x^\mu)' = \Lambda^\mu{}_\nu x^\nu \qquad x^\mu \equiv (t, x, y, z)$$

Boost
e.g. along x

$$\Lambda^\mu{}_\nu = \begin{pmatrix} \gamma & -\beta\gamma & 0 & 0 \\ -\beta\gamma & \gamma & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

Proper L.T.

Reflection,
e.g. space

$$\Lambda^\mu{}_\nu = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & -1 \end{pmatrix}$$

Improper L.T.

$$P: \begin{cases} \vec{x} \to -\vec{x} \\ t \to t \end{cases} \qquad P^2 = 1$$

Parity

Symmetry of the Lorentz group

- A modern theory would never be taken seriously if it was not "relativistic"
  - ➥ Proper Lorentz transformations have a special place in our minds
  - ➥ Without them we could not categorize particles by their rest masses
  - ➥ What about improper Lorentz transformations?
- In contrast, parity is violated by the fundamental weak interaction!

T.D. Lee and C.N. Yang, Phys. Rev. 104 (1956) 4
C.S. Wu et al., Phys. Rev. 105 (1957) 1413
R.L. Garwin, L.M. Lederman, M. Weinrich, Phys. Rev. 105 (1957) 1415
J.I. Friedman, V.L. Telegdi, Phys. Rev. 105 (1957) 1681.

- ➥ A big issue at the time.
- ➥ e.g. W. Pauli (Letter to R. Davis, 1956)
  - ☛"I believe in reflection invariance in contrast to Yang and Lee… Between believing and knowing is a difference and in the last end such questions must be decided experimentally".
- ➥ Now everybody accepts it.

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Left-right asymmetry of the Standard Model

- Indeed, in the modern Standard Model, the left-right asymmetry of Nature is introduced “from the beginning” in the assignment of the particle fields:

$$\begin{pmatrix} \nu_l \\ l^- \end{pmatrix}_L , \quad l^-_R , \quad \begin{pmatrix} u \\ d \end{pmatrix}_L , \quad u_R , \; d_R$$

  which implies specific quantum numbers and accordingly specific “couplings” to the weak currents.

- The left-handed and the right-handed chiral projections of the elementary fermions are intrinsically different, since they belong to different representations of the fundamental symmetry group of the theory (they do not mix under the symmetry group transformation).
- Right-handed projection of neutrino field does not yield a physical state (neutrino is said to be purely left-handed, even after symmetry breaking & generation of masses and mixings)

  ➥ Neutrino masses and oscillations?

Left-right asymmetry of Nature ?

- Is the left-right-asymmetry a fundamental property of nature, or do we happen to “live” in the universe dominated by particles with such properties?
- Two possibilities:
  1) Left-right symmetric models: symmetry restored at high energy
     - ☛ V+A interaction suppressed by gauge boson W_R heavy mass
     - ☛ E.g. $SU(2)_L \otimes SU(2)_R \otimes U(1)_{B-L}$
     - ☛ $M_R > 715$ GeV, $Z_{LR} > 860$ GeV (95%C.L.)

     Pati and Salam, Phys. Rev. D10 (1974) 275; Mohapatra and Pati, Phys. Rev. D11 (1975) 566, 2558; Senjanovic and Mohapatra, Phys. Rev. D12 (1975) 1502.

  2) Mirror world

     Lee & Yang, Phys. Rev. 104 (1956) 256; Kobzarev, Okun, Pomeranchuk, Sov. J. Nucl. Phys. 3 (1966) 837; Pavsic Int. J. Theor. Phys. 9 (1974) 229

     - ☛ E.g. matter-antimatter:
       - ★ Nature is CPT invariant
       - ★ Both types of particles exist, but our Universe is dominated by what we call matter
     - ☛ Matter-mirror matter:
       - ★ Mirror-fermions are similar to fermions but with left- and right-properties exchanged
       - ★ With matter and mirror-matter, Nature is intrinsically L-R symmetric. But we happen to live in a Universe dominated by matter
       - ★ Mirror stars? Mirror galaxies? Mirror matter behaves as dark matter!
- They are phenomenogically different.

Parity violation and the mirror world

- While the original 1956 paper of Lee&Yang was devoted to arguing that parity is violated (and left-right symmetry is broken) by the weak interaction, the last two paragraphs suggested that it could be unbroken if mirror matter existed:
  - "As is well known, parity violation implies the existence of a right-left asymmetry. We have seen in the above some possible experimental tests of this asymmetry. These experiments test whether the present elementary particles exhibit asymmetrical behaviour with respect to the right and the left. **If such asymmetry is indeed found, the question could still be raised whether there could not exist corresponding elementary particles exhibiting opposite asymmetry such that in the broader sense there will still be over-all right-left symmetry.** If this is the case, it should be pointed out, there must exist two kinds of protons p_R and p_L, the right-handed one and the left-handed one. Furthermore, at the present time the protons in the laboratory must be predominately of one kind in order to produce the supposedly observed asymmetry"
  - "In such a picture the supposedly **observed right and left asymmetry is therefore ascribed not to a basic non-invariance under inversion, but to a cosmologically local preponderance of say p_L over p_R, a situation not unlike that of the preponderance of the positive proton over the negative**."

Photon-mirror-photon mixing

Holdom, Phys. Lett. B166 (1986) 196

- Ordinary and mirror matter interacts through (1) gravitation and (2) possible mixing between mirror partners
- **Photon-mirror-photon kinetic mixing** (Holdom's model, 1986)

$$\mathcal{L}_{\mathrm{int}} = \varepsilon F_{\mu\nu} F'^{\mu\nu}$$

$F^{\mu\nu} \equiv$ *field-tensor for ordinary electromagnetism*

$F'^{\mu\nu} \equiv$ *field-tensor for mirror electromagnetism*

$\varepsilon \equiv$ *free parameter*

- This gauge-invariant and renormalizable term describes the kinetic mixing between the ordinary and the mirror photons.

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Ordinary and mirror quantum electrodynamics

e.g. Foot, Ignatiev, Volkas, Phys. Lett. B503 (2001) 355

- One can consider the gauge-field theory of ordinary+mirror quantum electrodynamics generated by the group U(1) $\otimes$ U'(1)
  - Ordinary electron ψ, photon A^{μ} and mirror-electron ψ' and mirror photon A'^{μ}

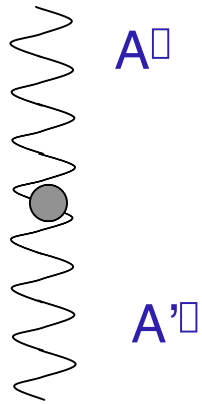
$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} + \bar{\psi}\left(i\gamma^{\mu}\partial_{\mu} - m\right)\psi + \bar{\psi}'\left(i\gamma^{\mu}\partial_{\mu} - m\right)\psi' +$$

$$+e\bar{\psi}\gamma^{\mu}A_{\mu}\psi + e\bar{\psi}'\gamma^{\mu}A'_{\mu}\psi' +$$

$$+\epsilon F_{\mu\nu}F'^{\mu\nu}$$

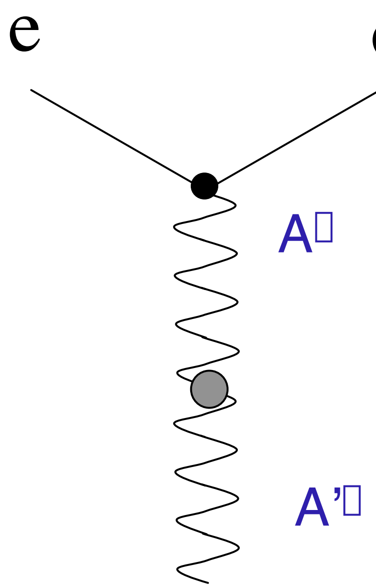
- Feynman-rules: usual QED + an extra A-A' mixing vertex

$$-i\frac{2\pi\epsilon}{q^2}\left(g^{\mu\nu} - \frac{q^{\mu}q^{\nu}}{q^2}\right) \equiv$$



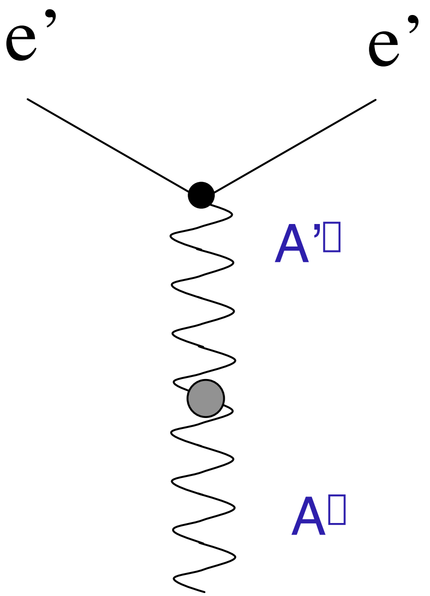
Coupling to matter-mirror-matter

- The kinetic mixing term introduces an interaction between the ordinary electron and the mirror-photon (to first order in ϵ)



$$Vertex\ \ factor = 2\epsilon e \gamma^\mu$$

- Similarly,



Mirror electrons are coupled to ordinary electrons with an effective charge $2\epsilon e$

Positronium

What is positronium ? (history)

- Dirac (1930): prediction of e^+, Andersen (1933): discovery
- Mohorovicic (1934): postulate existence e^+e^- bound state
- Ruark (1945): name “positronium”, qualitative discussion of spectroscopic structure of Ps
  - ➥ Ps is complete structure analog of Hydrogen-atom
  - ➥ Reduced mass: $M_{Ps} = m_e/2 = M_H/2$
  - ➥ Levels energy $E_n = e^4 M Z^2 / 2\hbar n^2$
    - ☛ Ionization potential (n=1) W=6.8 eV
  - ➥ Bohr radius $r_B = \hbar^2 n^2 / e^2 M Z^2$
    - ☛ $r_{PS}(n=1) = 2r_B \approx 1$ Å
  - ➥ Two ground states:
    - ☛ Singlet: para-positronium n=1, $^1S_0$
    - ☛ Triplet: ortho-positronium n=1, $^3S_0$

$$\chi_S(m=0) = \frac{1}{\sqrt{2}}\left(\uparrow\downarrow - \downarrow\uparrow\right)$$

$$\chi_T(m=+1) = \uparrow\uparrow$$

$$\chi_T(m=0) = \frac{1}{\sqrt{2}}\left(\uparrow\downarrow + \downarrow\uparrow\right)$$

$$\chi_T(m=-1) = \downarrow\downarrow$$

- McGervey and de Benedetti (1959): labels p-Ps and o-Ps
- Deutsch (1951): Experimental detection
  - ➥ First production (in gas) and measurement of lifetime of o-Ps to ±10%

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Positronium: main features

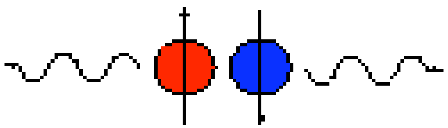
- A particularly simple particle-antiparticle system determined by QED: purely leptonic, no weak or strong contributions at present level of experimental and theoretical precision
- Ps is bound and self-annihilates through the same interaction: unique feature not present in any other bound system
- Test ground for bound state treatment in QFT (e.g. $c\bar{c}$, $b\bar{b}$, …)
- Simple selection rules:
  - ➥ Eigenstate of the charge-conjugation operator (*Wolfenstein, Ravenhall 1952*)

$$C\psi(n,l,s) = (-1)^{l+s}\psi(n,l,s)$$

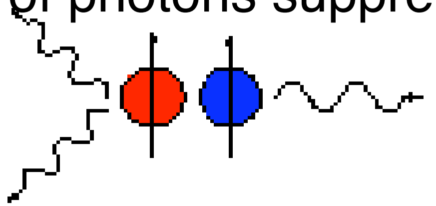
  - ➥ Discrete C-conservation in decay:

$$p-Ps \to 2\gamma, 4\gamma, \ldots \qquad o-Ps \to 3\gamma, 5\gamma, \ldots$$

  - ➥ Implication for decay rate (lifetime): addition of photons suppressed by α



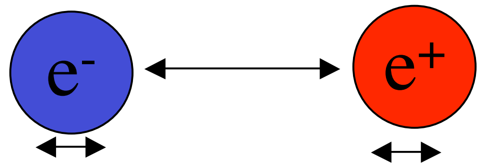
$\tau \approx 125$ps



$\tau \approx 142$ns

Positronium formation and decay

- Formation: e⁺ slow down, capture of e⁻, migration through vacuum (neutral)
- Decay:
  - ➥ Annihilation region (Compton wavelength): $r_e \approx \lambdabar_e = \dfrac{\hbar}{m_e c} = 4 \times 10^{-10}\, cm$
  - ➥ Bohr radius $r \approx 2 r_B = 2\dfrac{4\pi\varepsilon_0 \hbar^2}{m_e e^2} \approx 10^{-8}\, cm$



- Decay rates: $\Gamma_{2\gamma} \propto \left(\dfrac{r_e}{c}\right)^{-1}\left(\dfrac{r_e}{r}\right)^{3} \propto \alpha^2 \quad \Rightarrow \quad \tau \approx 10^{-10}\, s$

  $\Gamma_{3\gamma} \propto \left(\dfrac{r_e}{c}\right)^{-1}\left(\dfrac{r_e}{r}\right)^{3} \propto \alpha^3 \; oPS \quad \Rightarrow \quad \tau \approx 10^{-7}\, s$

- Higher orders: (highly suppressed) $\dfrac{\Gamma(p - Ps \to 4\gamma)}{\Gamma(p - Ps \to 2\gamma)} \approx 10^{-6}, \qquad \dfrac{\Gamma(o - Ps \to 5\gamma)}{\Gamma(o - Ps \to 3\gamma)} \approx 10^{-6}$

Decay rate

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Successes of QED

- QED is the textbook example of the success of Quantum Field Theories
- Basic concepts and capability to compute observable with high level of precision
  - ➥ Anomalous electron magnetic moment:

    $$a_e = \left(g_e - 2\right)/2, \quad \delta a_e \approx 10^{-9}$$

  - ➥ Anomalous muon magnetic moment:

    $$a_\mu = \left(g_\mu - 2\right)/2, \quad \delta a_\mu \approx 10^{-10}$$

  - ➥ Hydrogen, muonium, positronium hyperfine splitting: $\approx 10^{-6}$
  - ➥ Lamb shift: $\approx 10^{-5}$
  - ➥ Positronium decay rate: $\approx 10^{-4}$

o-Ps decay rate in the Standard Model (QED)

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- The three photon decay width in vacuum is

$$\Gamma(o-Ps \rightarrow \gamma\gamma\gamma) = \frac{2(\pi^2-9)\alpha^6 m_e}{9\pi}[1 - 10.28661(1)\frac{\alpha}{\pi} - \frac{\alpha^3}{3}ln(\frac{1}{\alpha}) + B_0(\frac{\alpha}{\pi})^2 - \frac{3\alpha^3}{2\pi}ln^2\frac{1}{\alpha} + O(\alpha^3 ln(\alpha))]$$

$$\approx (7.03824 + 3.9 \times 10^{-5} B_0) \quad \mu s^{-1}$$

- The B_0 term parameterizes the non-logarithmic two-loop effects (a complicated calculation)
- Weak processes are negligible

$$\Gamma(o-Ps \rightarrow \nu_e\bar{\nu}_e) = \frac{G_F^2\alpha^3 m_e^2}{24\pi^2}(1 + 4\sin^2\theta_W)^2 \approx 6.2 \times 10^{-18}\Gamma(o-Ps)$$

$$\Gamma(o-Ps \underset{l=\mu,\tau}{\rightarrow} \nu_l\bar{\nu}_l) = \frac{G_F^2\alpha^3 m_e^2}{24\pi^2}(1 - 4\sin^2\theta_W)^2 \approx 9.5 \times 10^{-21}\Gamma(o-Ps)$$

Recent theoretical progress

Adkins, Fell and Sapirstein, Phys.Rev.Lett. 84 (2000) 5086.

- Just recently: new calculations to O(□^{2}) corrections

$$B_0 = 44.52 \pm 0.26$$

$$\square(o \,\square\, Ps) = 7.039934 \pm 0.00001 \;\square s^{\square 1}$$

$$(\square\square/\square)_{theo} \;\square\, 10^{\square 6}$$

- Previous estimation: 7.03824±0.00007 μs^{-1}

How to produce and study positronium?

- The positrons are generally taken from a radioactive source
- Different techniques are then used to produce positronium

1. Gas
   - ☛ e^+ is slowed down by the gas and eventually picks up an electron
   - ☛ Typ. p≈1 atm, 25-50% of positrons form Ps within 10^{-10} s
2. Porous materials (e.g. small grained powder, aerogel)
   - ☛ Paulin and Ambrosino (1968): positrons from a source on a variety of small-grained (70-90 Å), low density (0.5 g/cm^3) powders of MgO, Al_2O_3, SiO_2, … then up to 30% of positrons from Ps
   - ☛ Once the Ps is formed it diffuses out of the grain and collide with grains without reentering them (≈vacuum).
   - ☛ Advantage: experiment is smaller than with gas
3. Vacuum-surface interface
   - ☛ Requires slow (moderated) ≈eV positrons
   - ☛ Canter, Mills and Berko (1974): slow 1eV beam of positrons is incident on various surfaces (Au, Ti, Cu, ..), up to 80% of positrons can form Ps which subsequently leaves the target and enters the surrounding vacuum region

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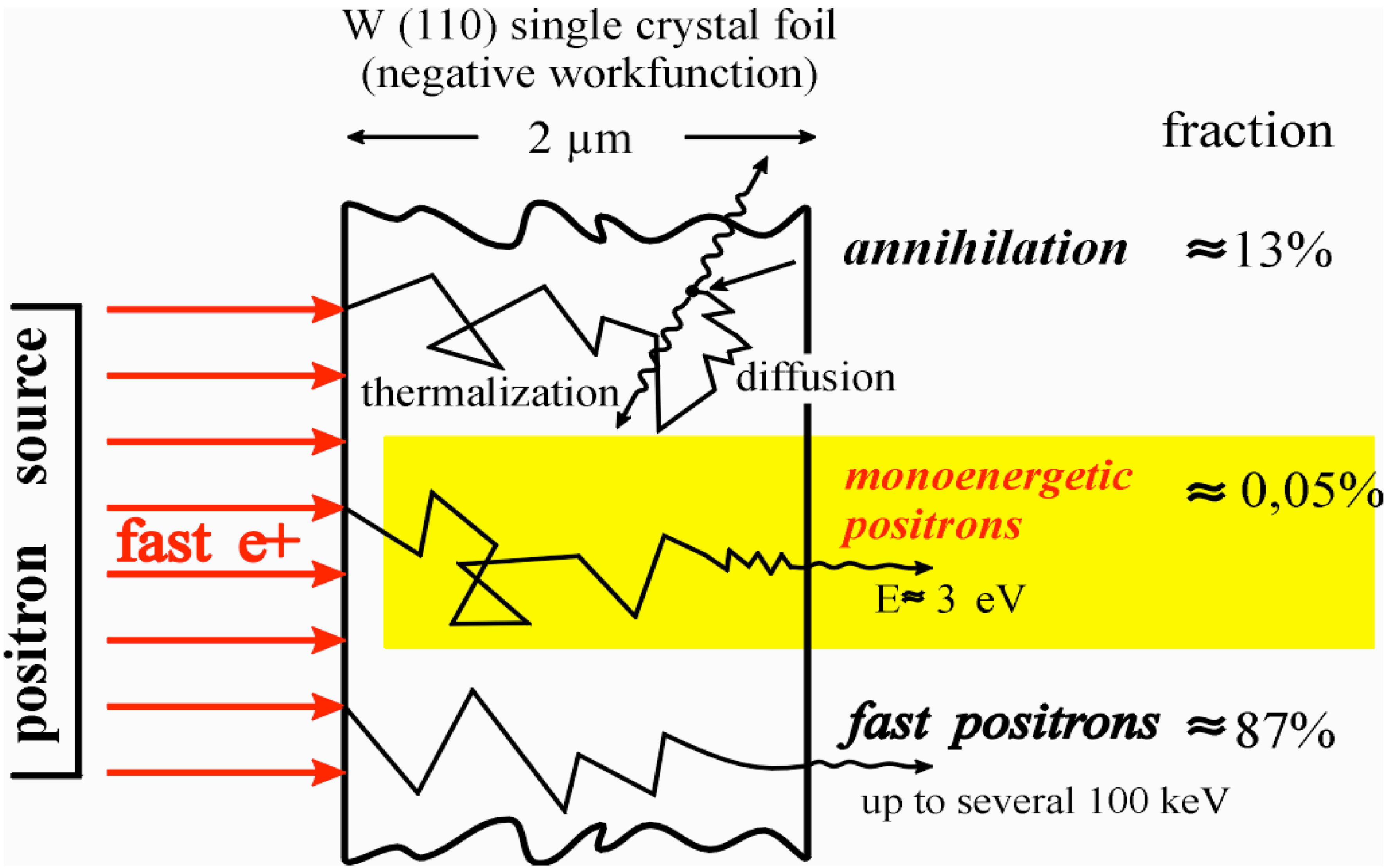
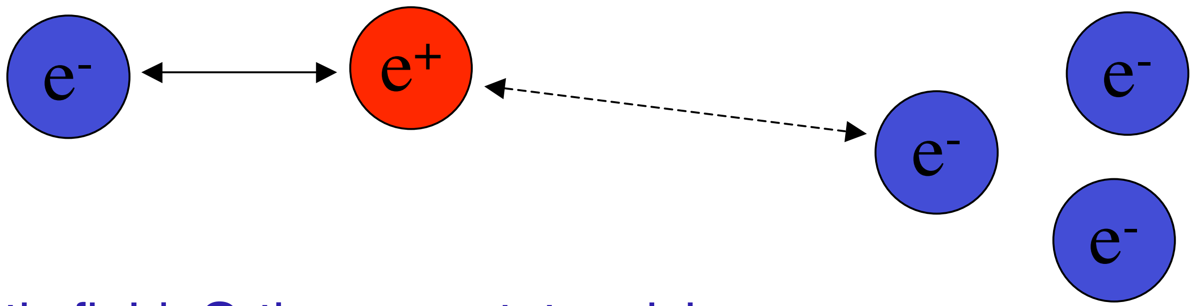
Principle of positron moderation



Mechanisms for changing o-Ps lifetime

- The 10^3 suppression of o-Ps decay rate versus p-Ps is driven by the conservation of the C-parity of the system
  - ➥ **System must remain unperturbed: if other ways become available (i.e. it is "quenched"), o-Ps will decay rapidly**
- Direct pick-off annihilation (collisional quenching):
  - ➥ In matter there is the probability that the bounded positron annihilates **<u>in 2γ</u>** with an electron which is not the partner electron



- External magnetic field: Ortho-para state mixing
- Other sources: Chemical reaction, Stark effect (in matter)

$$\lambda_{Obs}(t) = \lambda_{3\gamma} + \lambda_{pick-off}(t) + \lambda_{other}(t)$$

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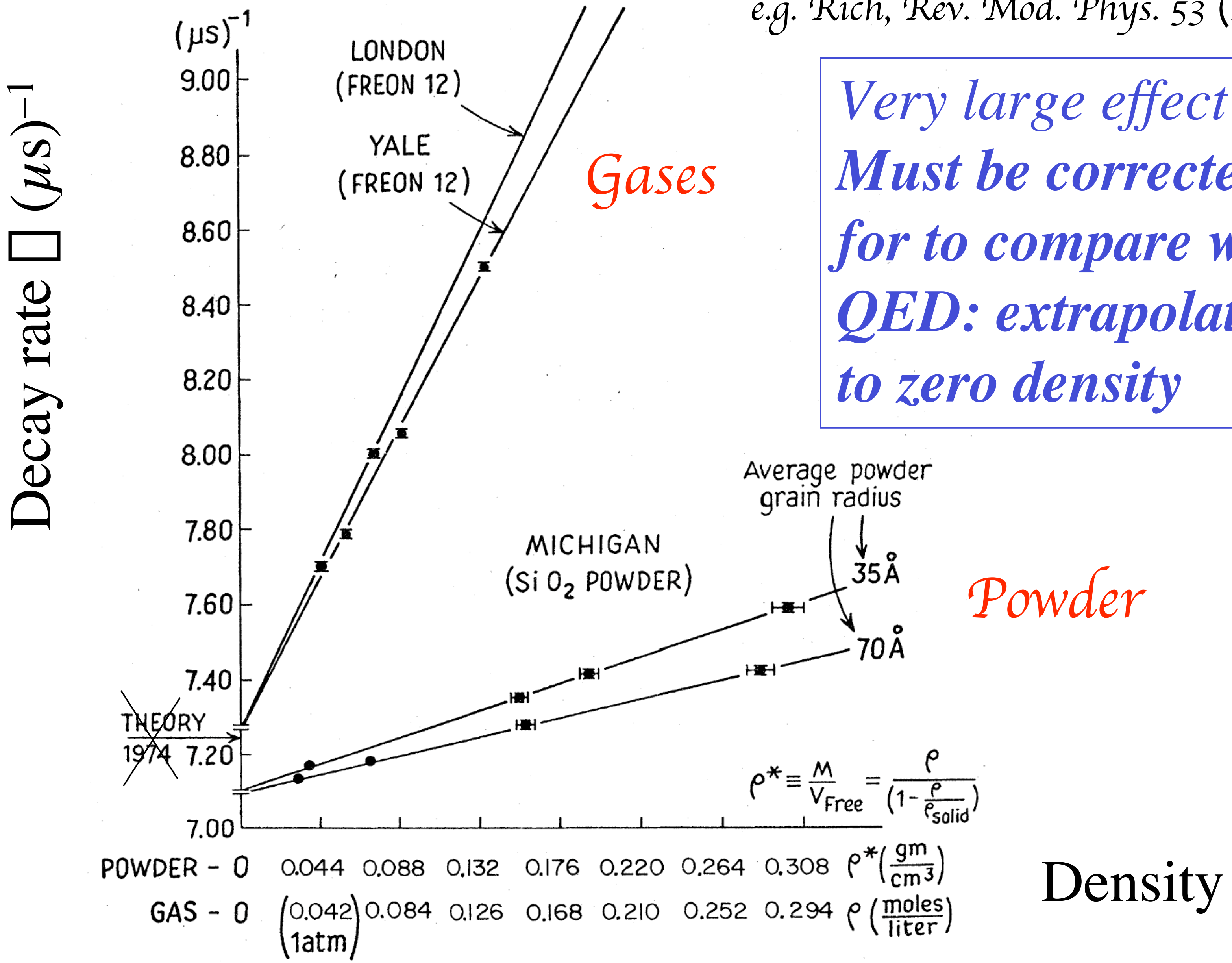
Extrapolation of o-Ps lifetime to zero-density

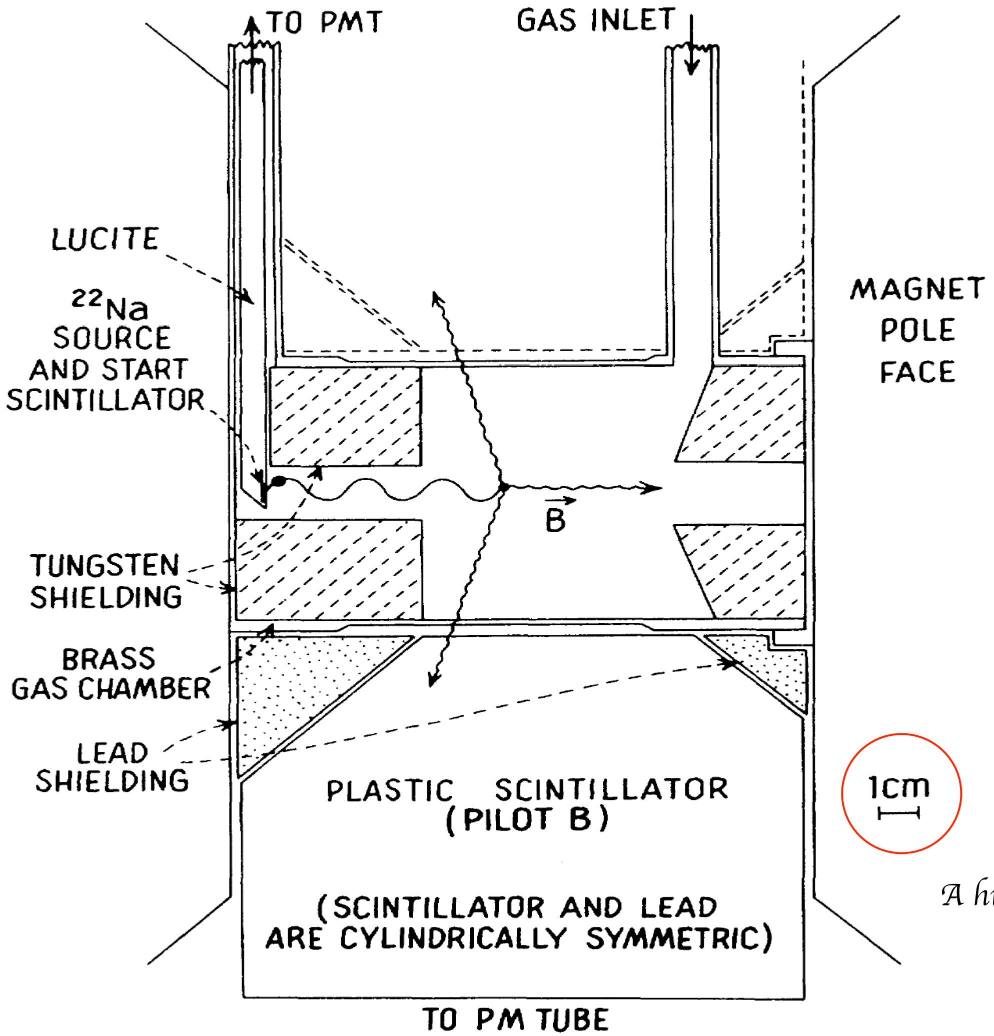
e.g. Rich, Rev. Mod. Phys. 53 (1981) 27.



Very large effect !
Must be corrected for to compare with QED: extrapolation to zero density

Ann-Arbor gas λ_T experiment (I)

Westbrook, Gidley, Conti, Rich, Phys.Rev. A40 (1989) 5489.

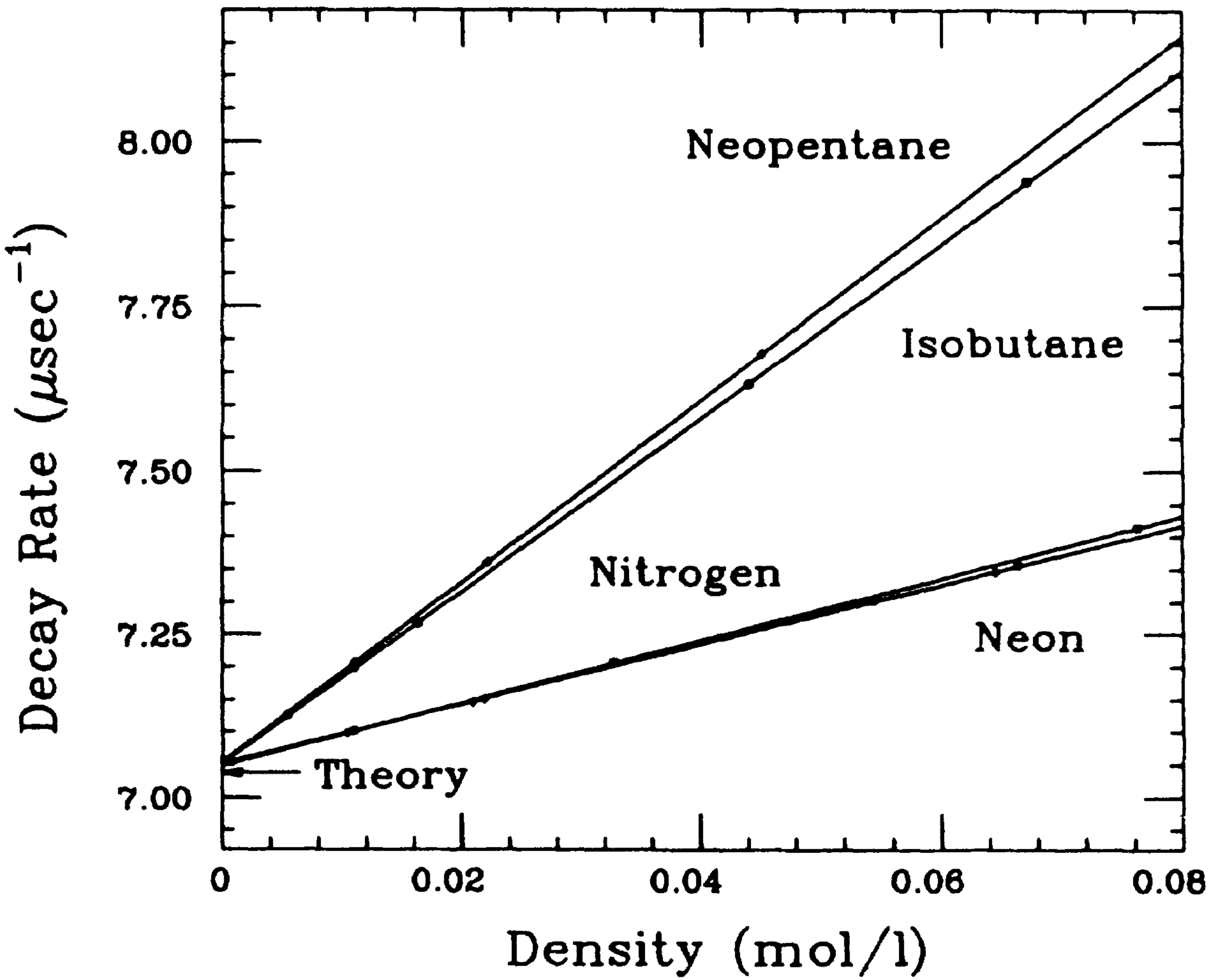


A human scale experiment

- Measurement of time spectrum
- Correction for pickoff:
  - ➥ (linear) extrapolation to zero density
  - ➥ Check for different gases
- **λ_T = 7.0514±0.0014 μs^{-1} (230 ppm)**
- **Large discrepancy with theory**

Ann-Arbor gas λ_T experiment (II)

Westbrook, Gidley, Conti, Rich, Phys.Rev. A40 (1989) 5489.



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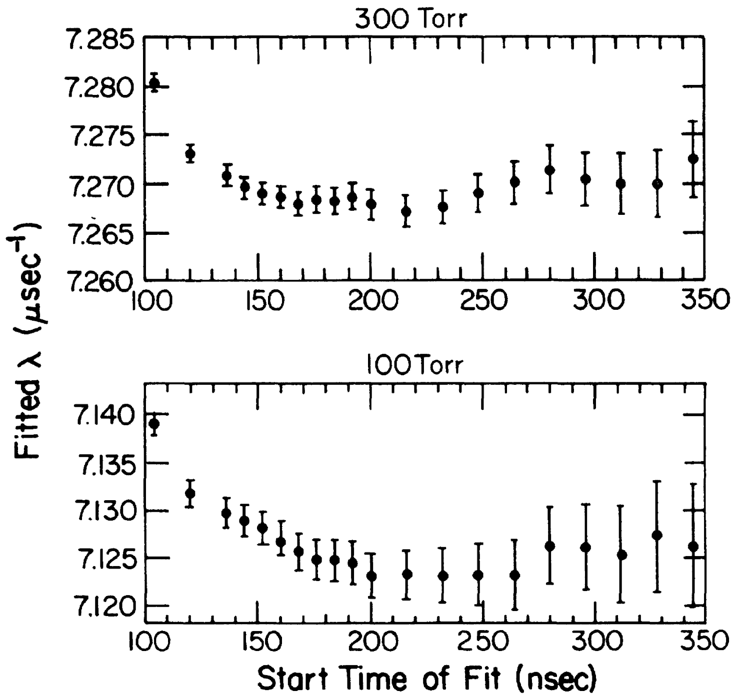
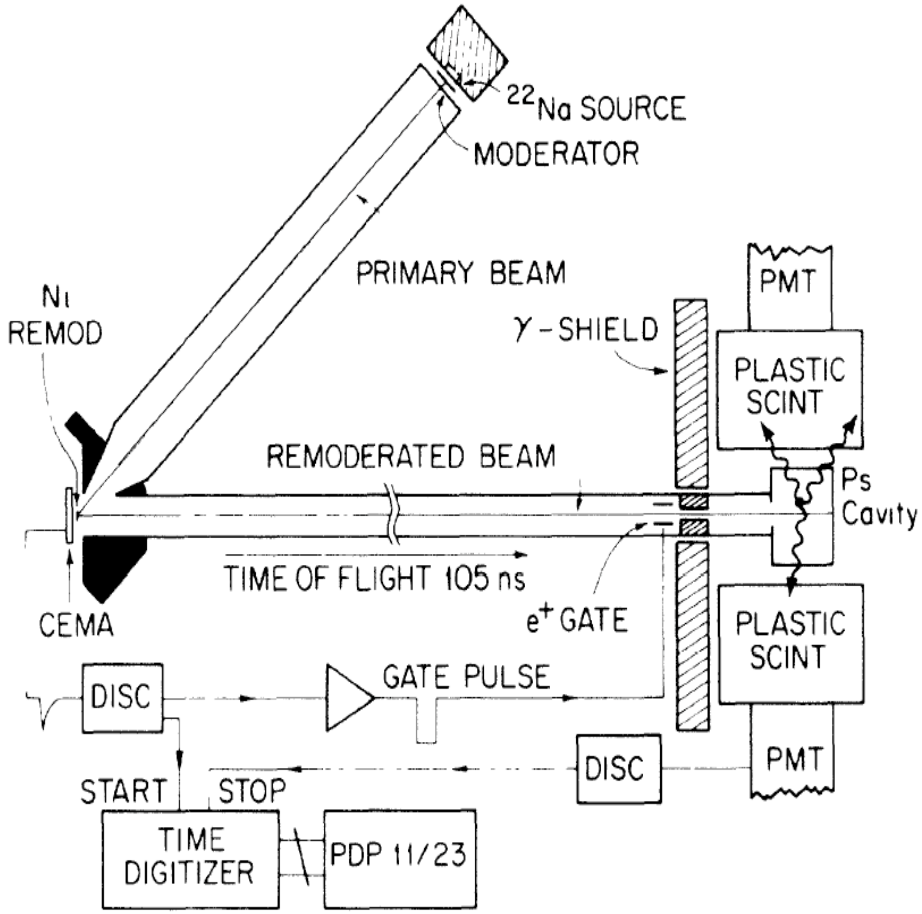
Comments to Ann-Arbor gas λ_T experiment

- Pickoff rate is proportional to the rate at which the o-Ps collides with material:
  - ➥ Proportional to the density of the target
  - ➥ But also depends on the velocity of o-Ps
- Energy after formation typ. 1 eV being thermalized to ≈0.03 eV
  - ➥ Pickoff rate changes with time
  - ➥ Evidence found by changing fitting time-window
- This cannot be corrected by the extrapolation to zero densities
- Furthermore the exact linear dependence with density of the target is not proven since the collision processes between o-Ps and gas are a priori complicated phenomena
  - ➥ The extrapolation toward zero densities might be a non-negligible source of error



Ann-Arbor vacuum λ_T experiment

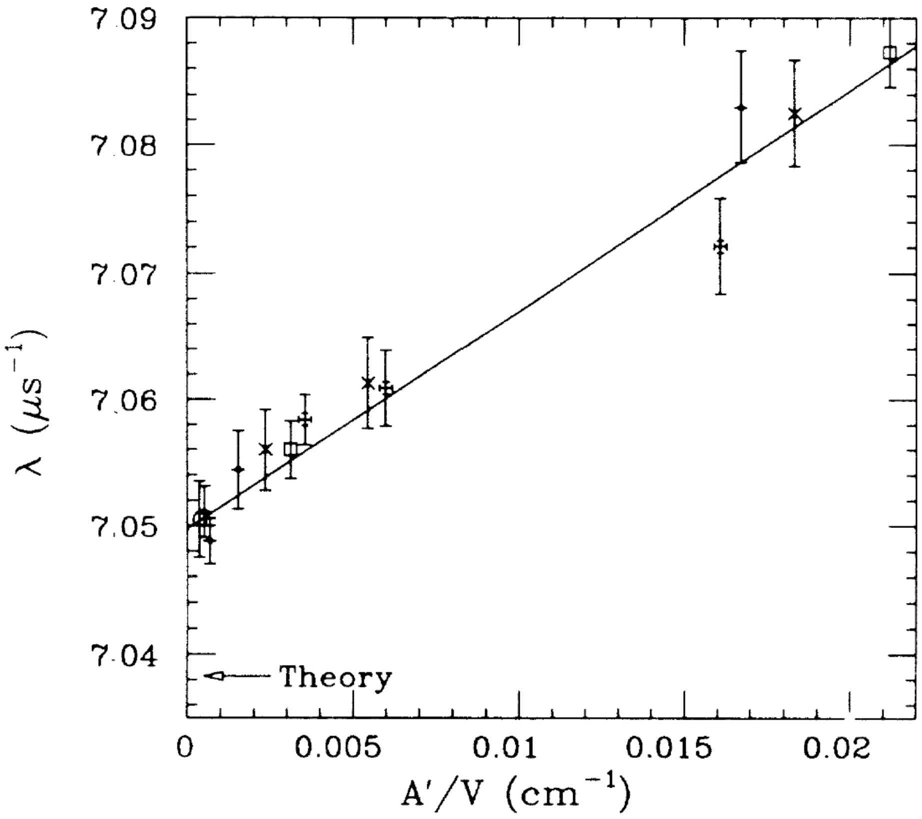
Nico, Gidley, Rich, Zitzewitz, Phys.Rev.Lett. 65 (1990) 1344.



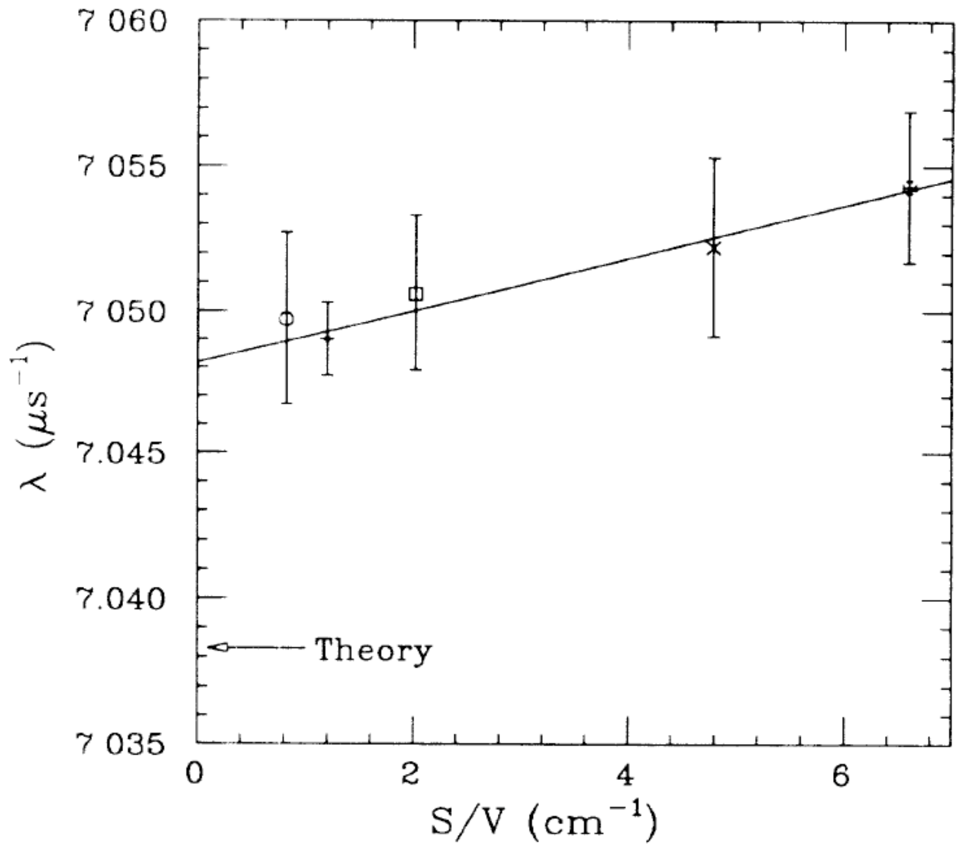
- Bunched positron beam is sent into evacuated cavity (10^{-9} Torr)
- Formation of o-Ps on cavity-surface+vacuum interface
- Source of pickoff is limited to collisions of o-Ps against the walls of the cavity
  - ➥ Pickoff rate is typ. 10^2-10^4 times smaller than in gas or powder target
- **λ_T = 7.0482±0.0016 μs^{-1} (230 ppm)**
- **Dominant error is statistical (200 ppm)**
- **Large discrepancy with theory**

Vacuum λ_T experiment: extrapolation to infinite cavity

Nico, Gidley, Rich, Zitzewitz, Phys.Rev.Lett. 65 (1990) 1344.



Extrapolation of cavity aperture (o-Ps escape through the cavity hole)

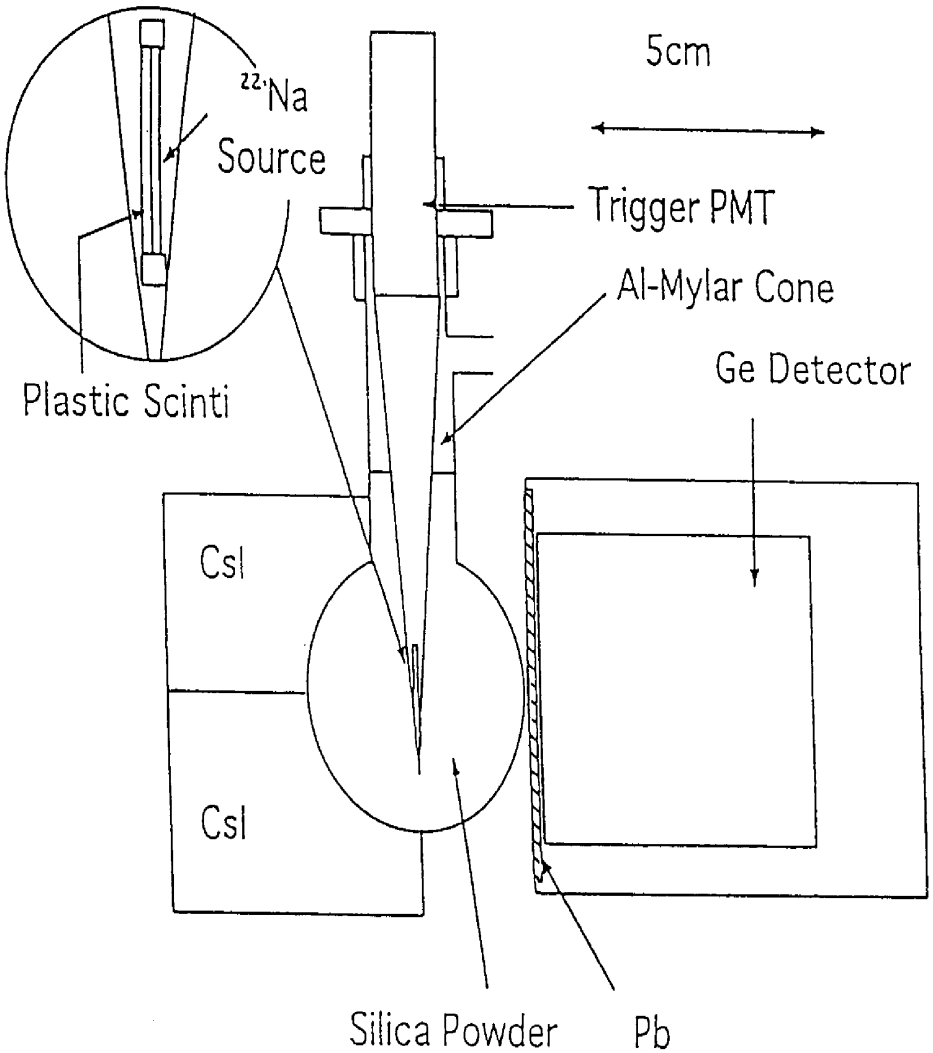


Extrapolation of cavity surface (o-Ps pickoff with walls)

Two-variable extrapolation yields "infinite vacuum" result

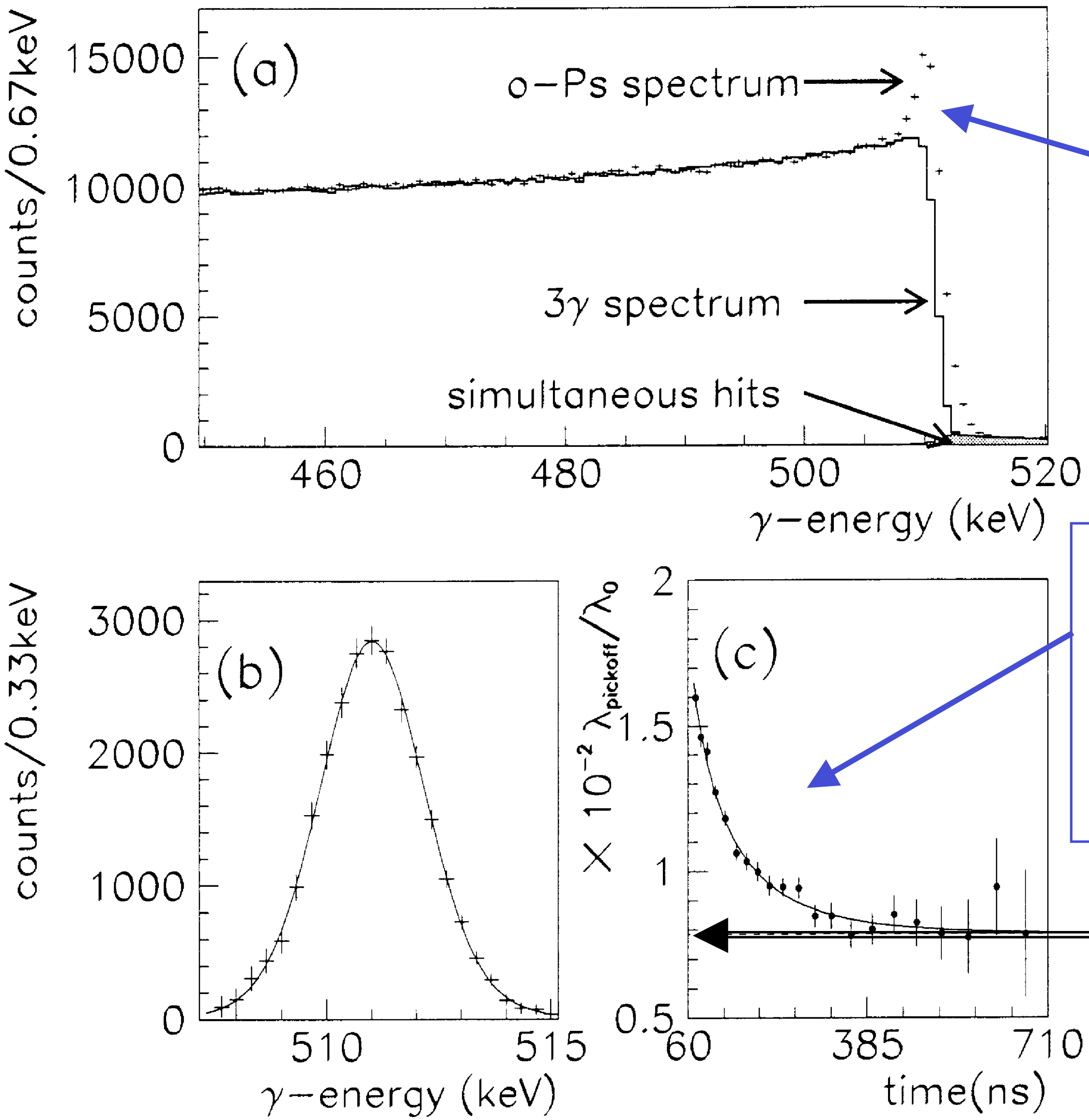
Tokyo powder λ_T experiment

Asai, Orito, Shinohara, Phys. Lett. B 357 (1995) 475.



- Formation of o-Ps in powder
- Source of pickoff is very large but is measured directly with the help of high precision germanium detector
- λ_T = **7.0398 ±0.0029 μs^{-1} (410 ppm)**
- **Error is statistical (355 ppm) and systematical (210 ppm)**
- **NO discrepancy with theory !**

Tokyo powder λ_T experiment: pickoff correction



Excess at 511 KeV peak interpreted at 2γ pickoff decay

Observed time dependence (thermalization) of pickoff rate

$$\lambda_{pickoff} \approx 10^{-2}\lambda_0 \approx (10^4\ ppm)\lambda_0$$

Tokyo powder λ_T experiment: systematic error

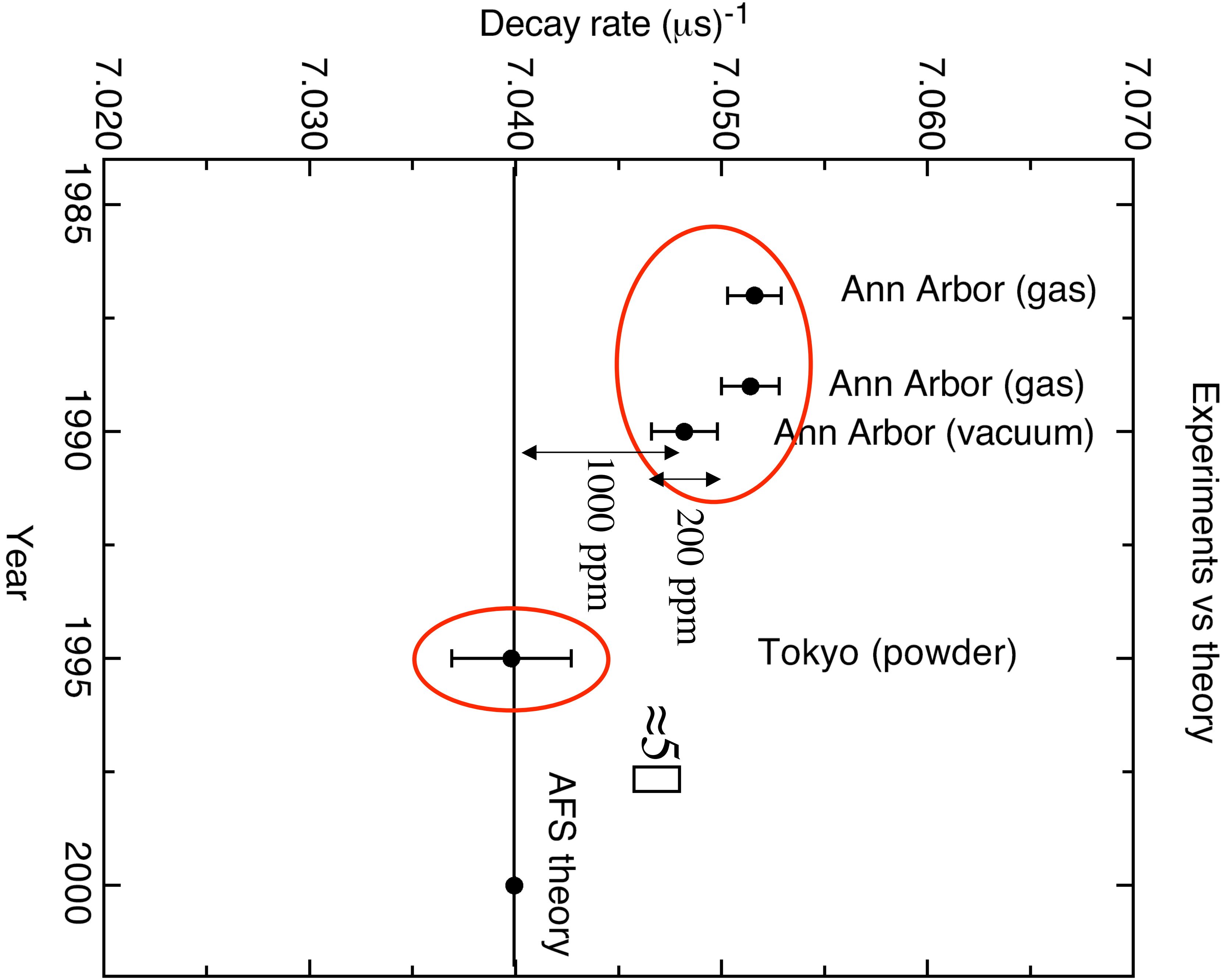
Source	Error (ppm)
Accuracy of the time calibrator	±50
Stability of TDC	±60
Relative efficiency of the Ge detector	-80 and +50
Monte Carlo simulation of the 3γ decay	-150 and +190
Calculation of $\lambda_{pickoff}/\lambda_0$	±50
Dependence on the BASE-ADC selection	-70
Energy correction of the CsI scintillator	±60
Non-uniformity of the SiO_2 powder	±30
Total	-220 and +230

Table 1 Summary of the systematic errors

However corrections for pickoff is large: $\lambda_{pickoff} \approx \left(10^4\ ppm\right)\lambda_0$

Theoretical & experimental values of o-Ps decay rate

Ref.	Year	□ $(\mu s)^{-1}$	Precision (ppm)	Difference from AFS $(ms)^{-1}$ (ppm)
		Theory		
AFS	2000	**7.039934(10)**	1.4	
Lepage, Adkins	1992	7.03824(7)	10	
		Experiments		
Gas, Ann Arbor	1987	**7.0516(13)**	190	11.66±1.3 (1600±190ppm)
Gas, Ann Arbor	1989	**7.0514(14)**	227	11.46±1.4 (1600±227ppm)
Vacuum, Ann Arbor	1990	**7.0482(16)**	230	8.3±1.6 (1170±230ppm)
Powder, Tokyo	1995	**7.0398(29)**	355(stat),210(syst)	–0.13±3.0 (–20±400ppm !)


Decay rate (μs)$^{-1}$
7.020
7.030
7.040
7.050
7.060
7.070
Year
1985
1990
1995
2000
Ann Arbor (gas)
Ann Arbor (gas)
Ann Arbor (vacuum)
1000 ppm
200 ppm
Tokyo (powder)
≈5
AFS theory
Experiments vs theory

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Short summary

- The o-Ps decay rate in vacuum has been recently improved by the new calculations of AFS including all the corrections to order α^2 (theoretical error << experimental error)
- The discrepancy of the o-Ps lifetime measured in gas
  - ➥ Has been confirmed in vacuum
  - ➥ However not in powder (spectacular agreement with QED given exp. errors)
- Different experiments have different systematic problems
- Conclusion from AFS paper:
  - ➥ *"…obviously, no conclusion can be drawn until the experimental situation is clarified"*
- The ball is in the experimental camp: two approaches
  - ➥ New measurements of λ_T
    - ☛ In vacuum with direct measurement of pickoff ! (see later)
  - ➥ Direct search for other (exotic) decay modes that would increase the observed decay rate of o-Ps

Exotic decays

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Exotic decays of o-Ps

For recent review, see Gninenko, Krasnikov, Rubbia, Mod. Phys. Lett. A17 (2002) 1713.

- Due to C-parity, the o-Ps decays predominantly to 3. As compared to p-Ps, the factor $\approx 10^3$ enhancement makes o-Ps more sensitive to an admixture of new interactions which are not accommodated in the Standard Model.
- QED alone cannot accommodate a difference of 1000 ppm (i.e. $B_0 \approx 200$, whereas AFS finds $B_0 = 44.52 \pm 0.26$)
- Originally it was hoped that an exotic o-Ps decay mode at the level of $Br \approx 10^{-3}$ would solve the problem
  - ➥ *One of the first sensitive searches motivated by the discrepancy was performed at CERN by U. Amaldi et al. more than 15 years ago!*
- One can distinguish
  - ➥ Visible exotic decays
  - ➥ Invisible exotic decays

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Limits on exotic decays

Two body

Decay mode	90 % upper limit	Comments	Group
□+X	1.1ppm	X long-lived boson m_X<800 keV	CERN, Moscow, Tokyo, Heidelberg
□+X□ □+2 □	400 ppm	Short-lived boson m_X<900 keV	Moscow, Tokyo
□□	3.5 ppm	Forbidden by angular momentum conservation	Ann Arbor, Tokyo
□□□	2.8 ppm	Vector boson	Tokyo
□□□□	2.6 ppm	Forbidden by C-parity	
□+X_1+X_2	44 ppm	$m_{X1}+m_{X2}$<900 keV	ETHZ-Moscow (this talk)
Invisible	2.8 ppm	Not in vacuum	Moscow, Tokyo

None of the exotic modes can explain discrepancy

ELSEVIER

Physics Letters B 542 (2002) 29–34

PHYSICS LETTERS B

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Search for an exotic three-body decay of orthopositronium

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Editor: L. Montanet

Abstract

We report on a direct search for a three-body decay of the orthopositronium into a photon and two penetrating particles, o-Ps $\to \gamma + X_1 + X_2$. The existence of this decay could explain the discrepancy between the measured and the predicted values of the orthopositronium decay rate. From the analysis of the collected data a single candidate event is found, consistent with the expected background. This allows to set an upper limit on the branching ratio $B(\text{o-Ps} \to \gamma + X_1 + X_2) < 4.4 \times 10^{-5}$ (at the 90% confidence level), for the photon energy in the range from 40 keV $< E_\gamma <$ 400 keV and for mass values in the kinematical range $0 \leqslant m_{X_1} + m_{X_2} \leqslant 900$ keV. This result unambiguously excludes the o-Ps $\to \gamma + X_1 + X_2$ decay mode as the origin of the discrepancy.

Keywords: Orthopositronium decay; New particles; Experimental tests

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Search for an exotic decay of o-Ps

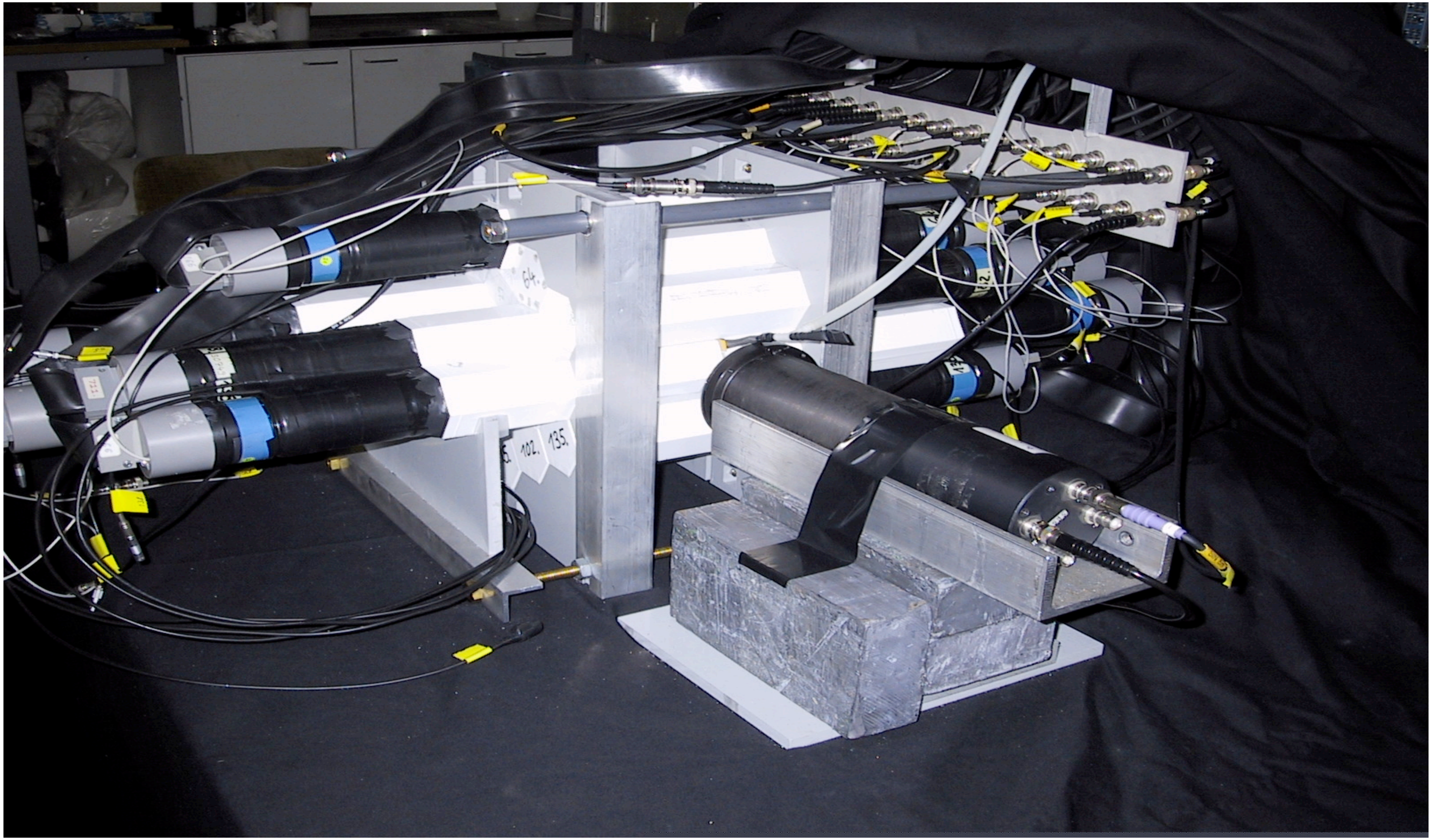
Badertscher et al., Phys. Lett. B542 (2002) 29

$$e^+e^-(o-Ps) \to \gamma + X_1 + X_2$$

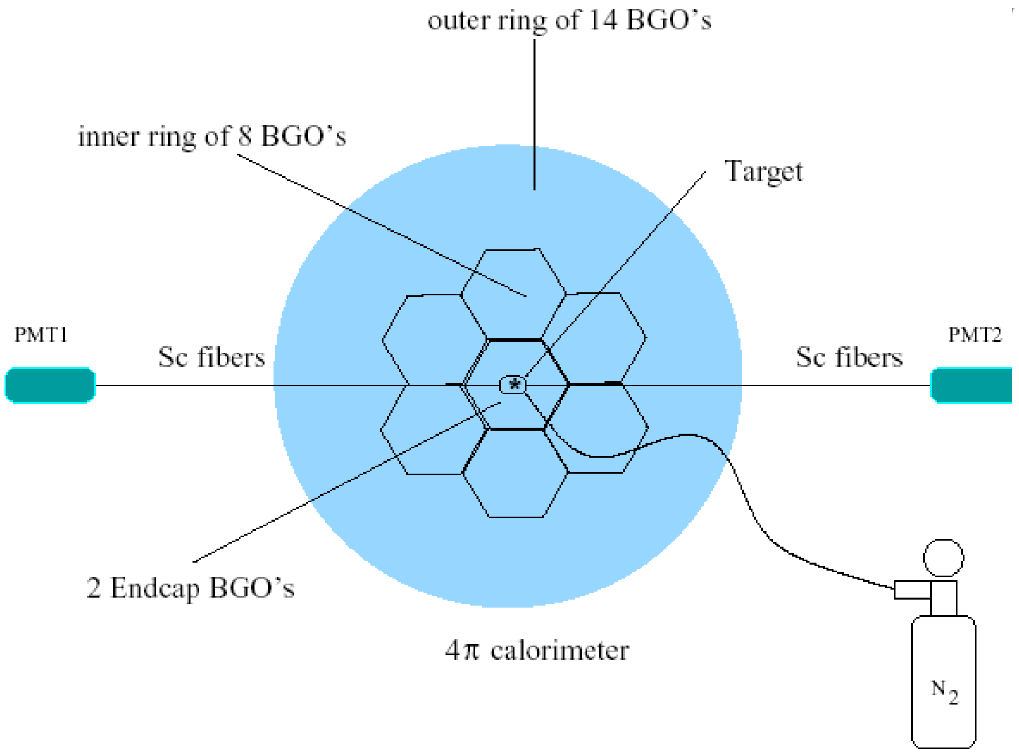
Two weak interacting massive particles

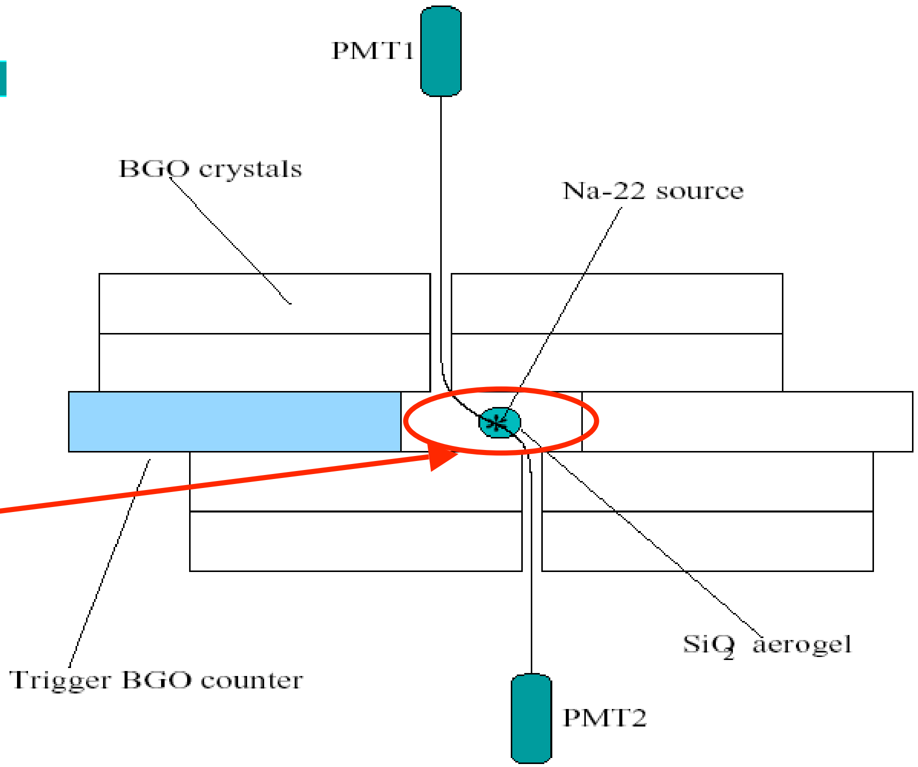
- If at the level of Br≈10^{-3}, this decay could solve the o-Ps lifetime problem.
- The signature of such an event is a single photon detected in an hermetic calorimeter accompanied by no other energy deposition.
- In this exotic decay the photon has a continuum of energy, thus this search is more difficult than the previous ones which were based on the peak detection arising from the 2 body decay.
- The second goal was to optimize calorimeter for the next steps of the experiment (hermeticity based on MC simulation cross-checked with the acquired data)

The experiment



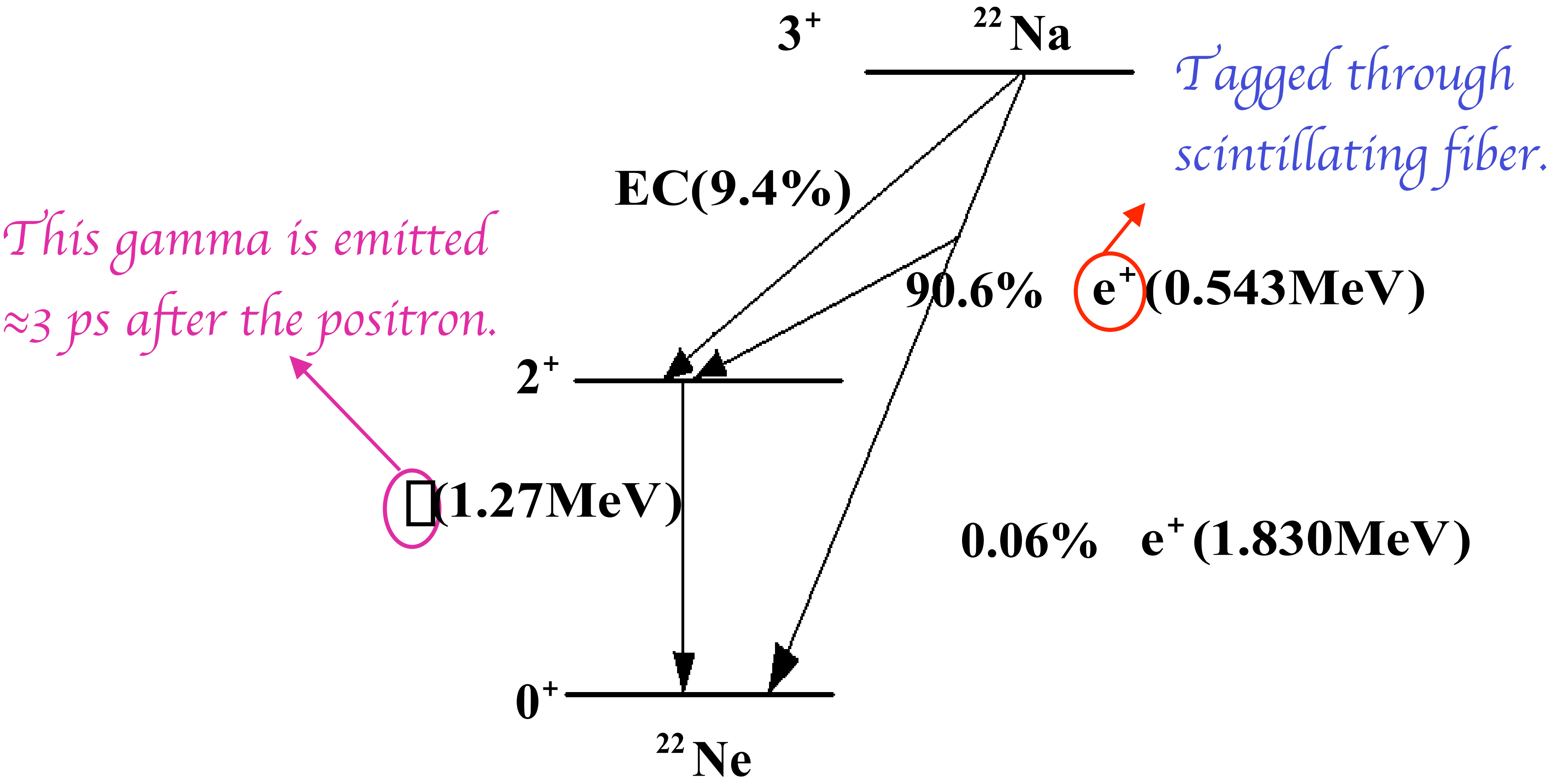
Schematic view of the experiment



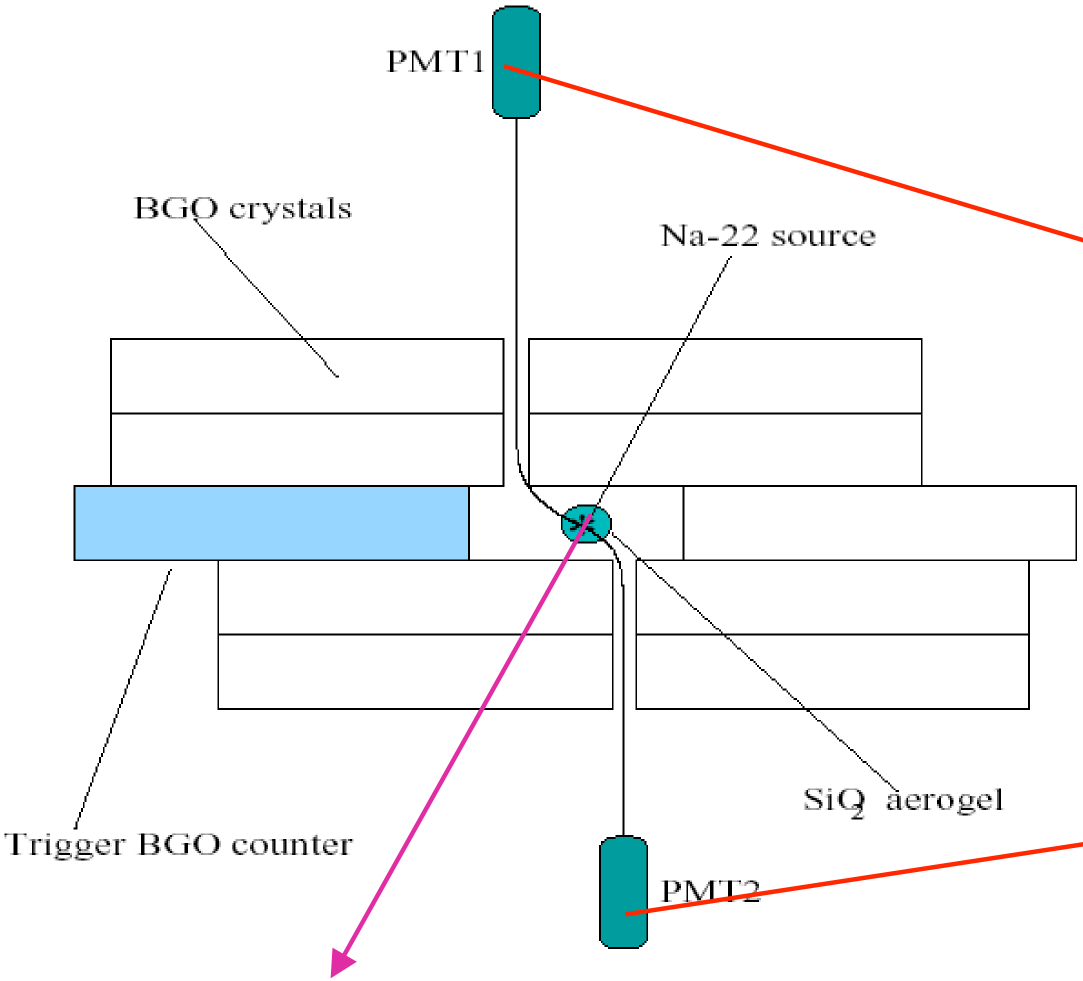


Region of positronium formation

Na source tagging



Emitted positron detection



The positrons are tagged when the signals from the 2PMT's are in coincidence, then the gate opens (START).

^{22}Na source
3.6kBq

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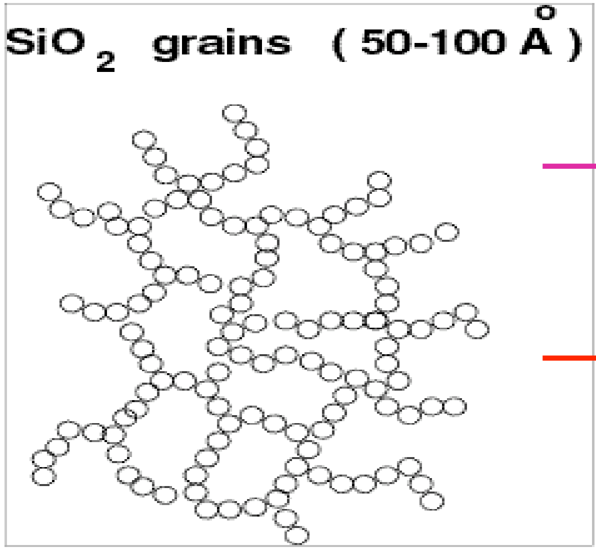
Target



After the fiber the positrons enter the Aerogel

Positronium can form inside the grain

It can migrates in the inter granular space where it decay almost freely

$e^+e^-(\text{singlet}) \to \gamma\gamma \quad \tau \approx 125\text{ps}$ (in vacuum)

or

$e^+e^-(\text{triplet}) \to \gamma\gamma\gamma \quad \tau \approx 142\text{ns}$ (in vacuum)

Collisional quenching

In Aerogel pores filled with nitrogen: $\tau \approx 132\text{ns}$

Time spectra between tagged positron and photon detected in the calorimeter (with aerogel)

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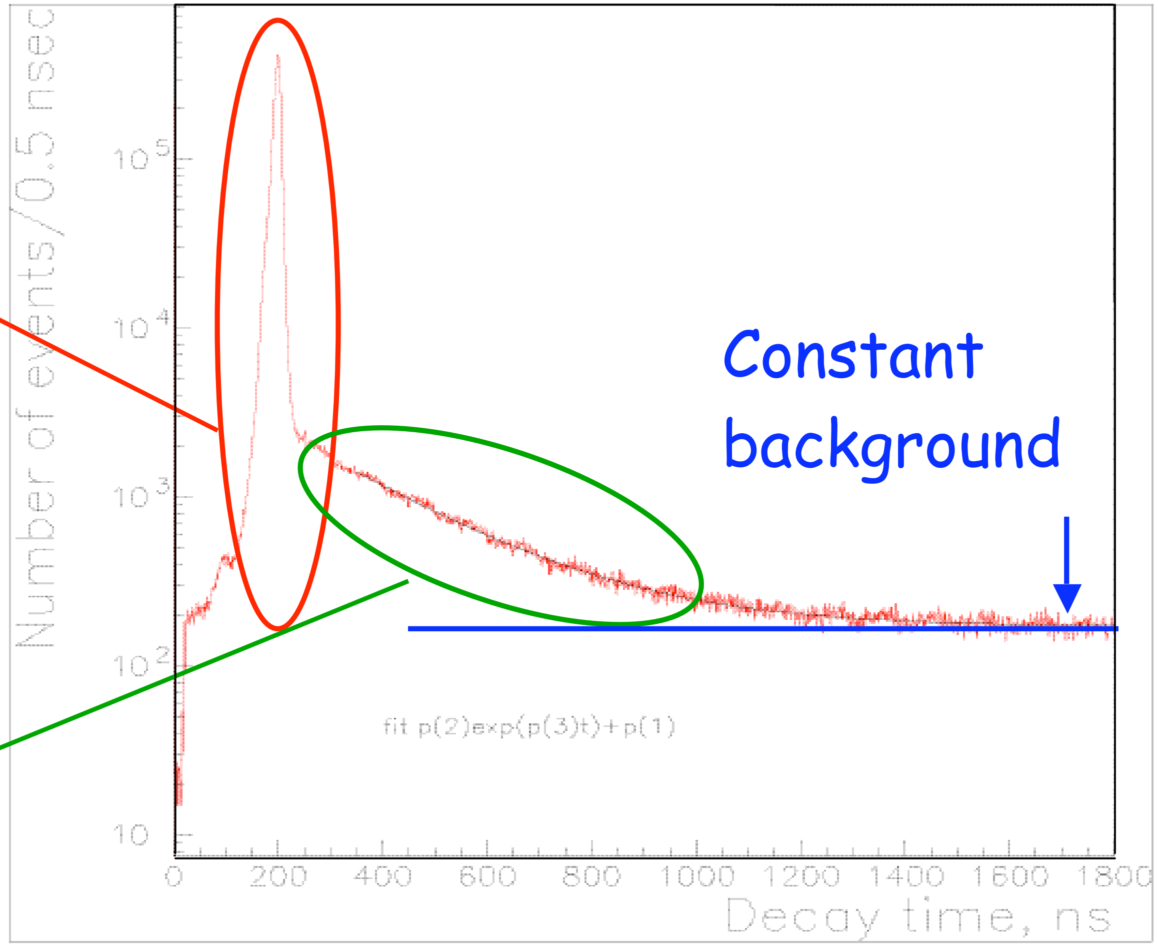
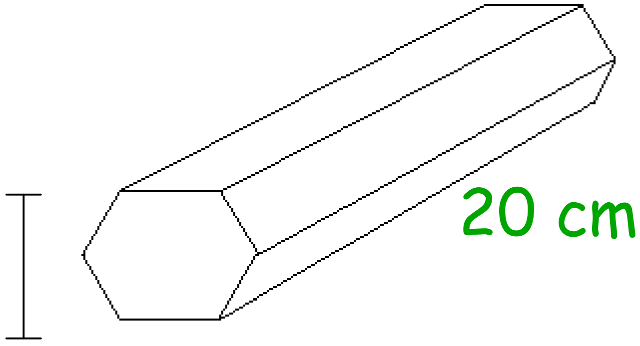
Peak from p-Ps annihilation

Exponential decay from o-Ps

Constant background



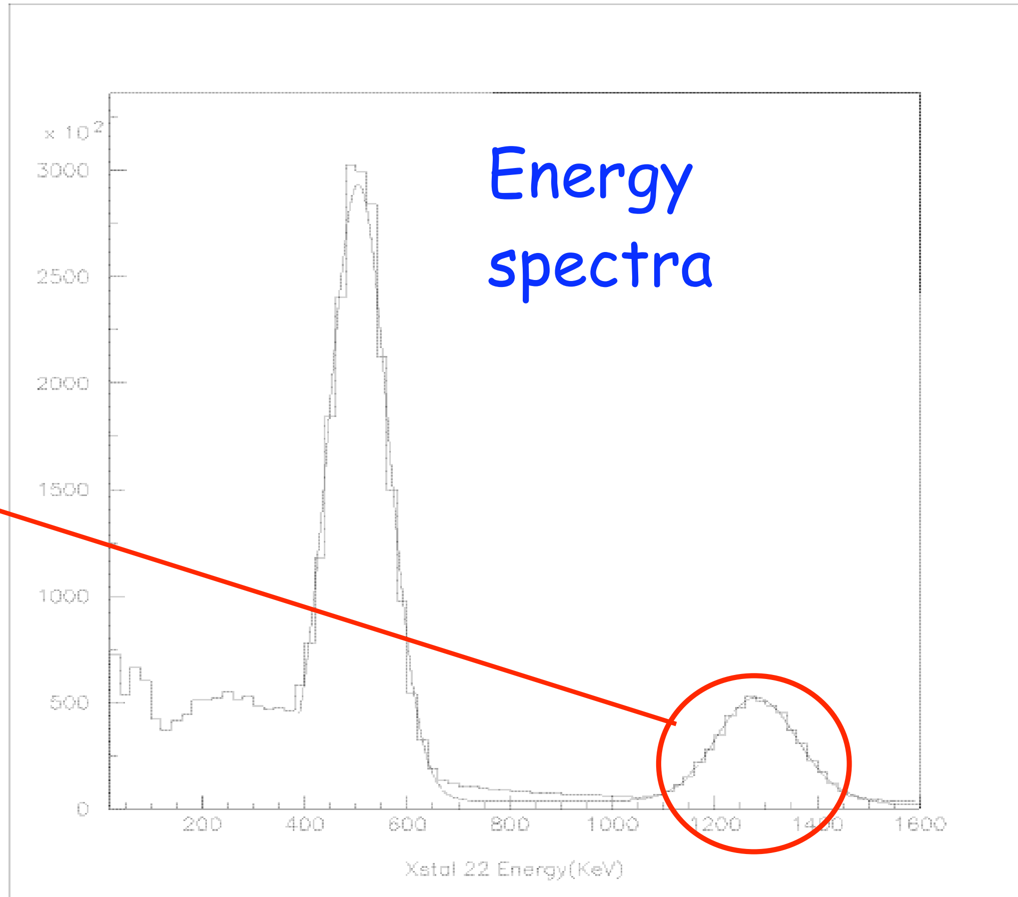
Calorimeter



24 x BGO (from PSI)

20 cm length

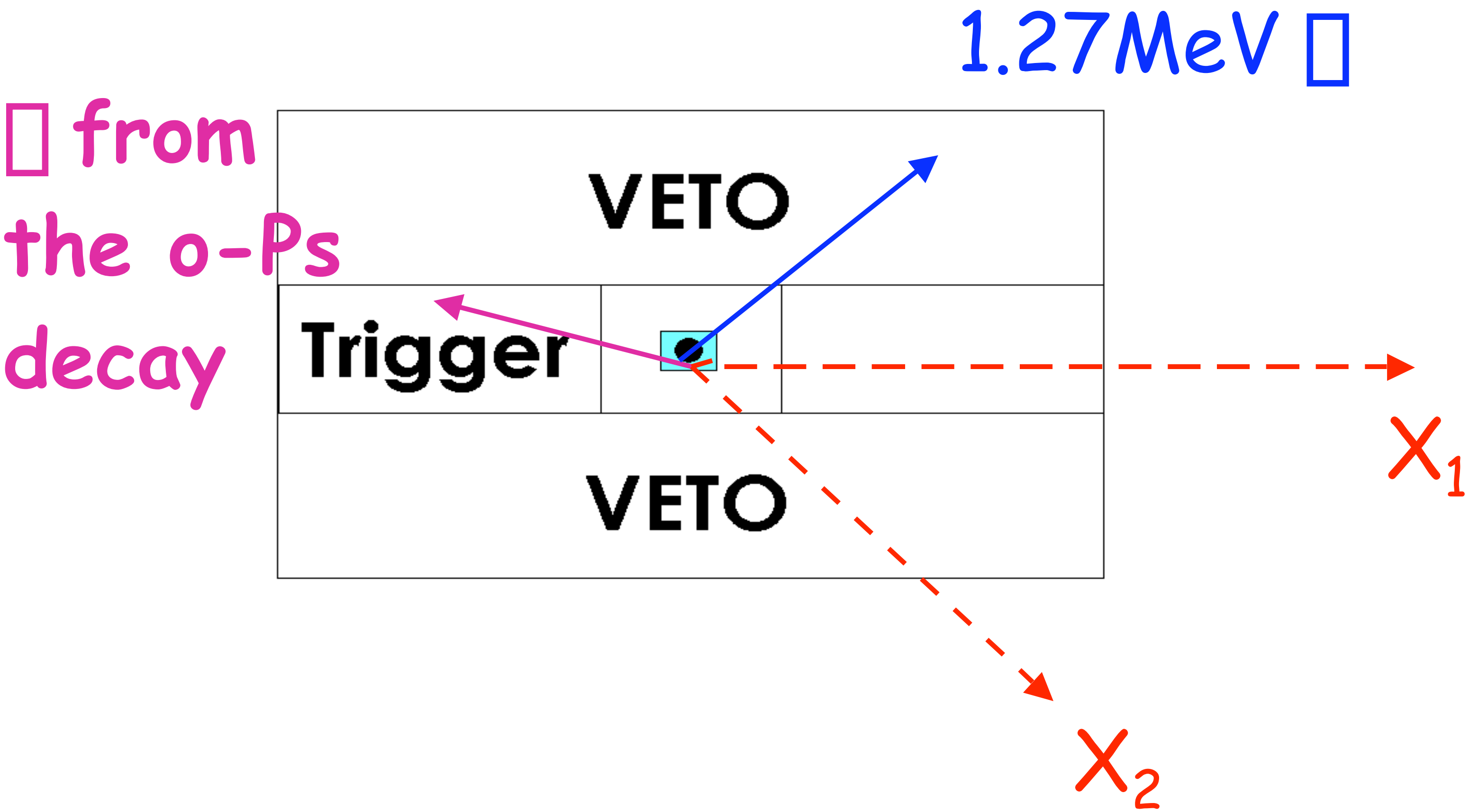
5,2 cm thickness



The resolution of the crystals determined with a fit is about 16% at 1.27MeV (FWHM)

Example of exotic signal signature

- We look for a single photon (in the trigger crystal) in addition to the 1.27 MeV from the source

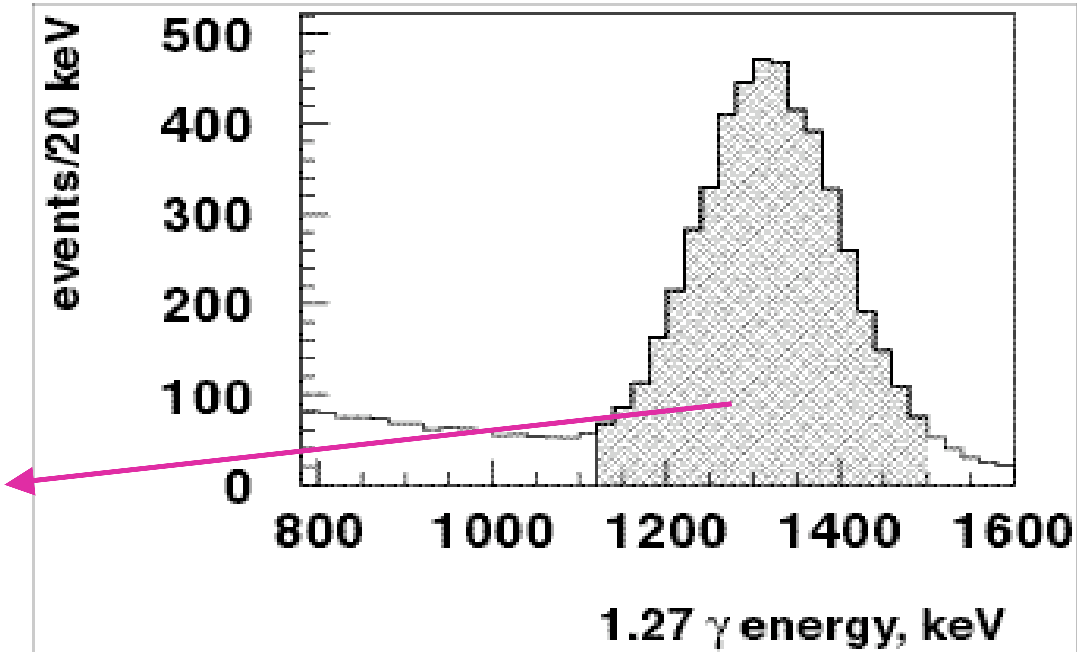


Event selection

- One of the photons with energy between 40 and 700 keV from the decay is asked to be in the trigger BGO.

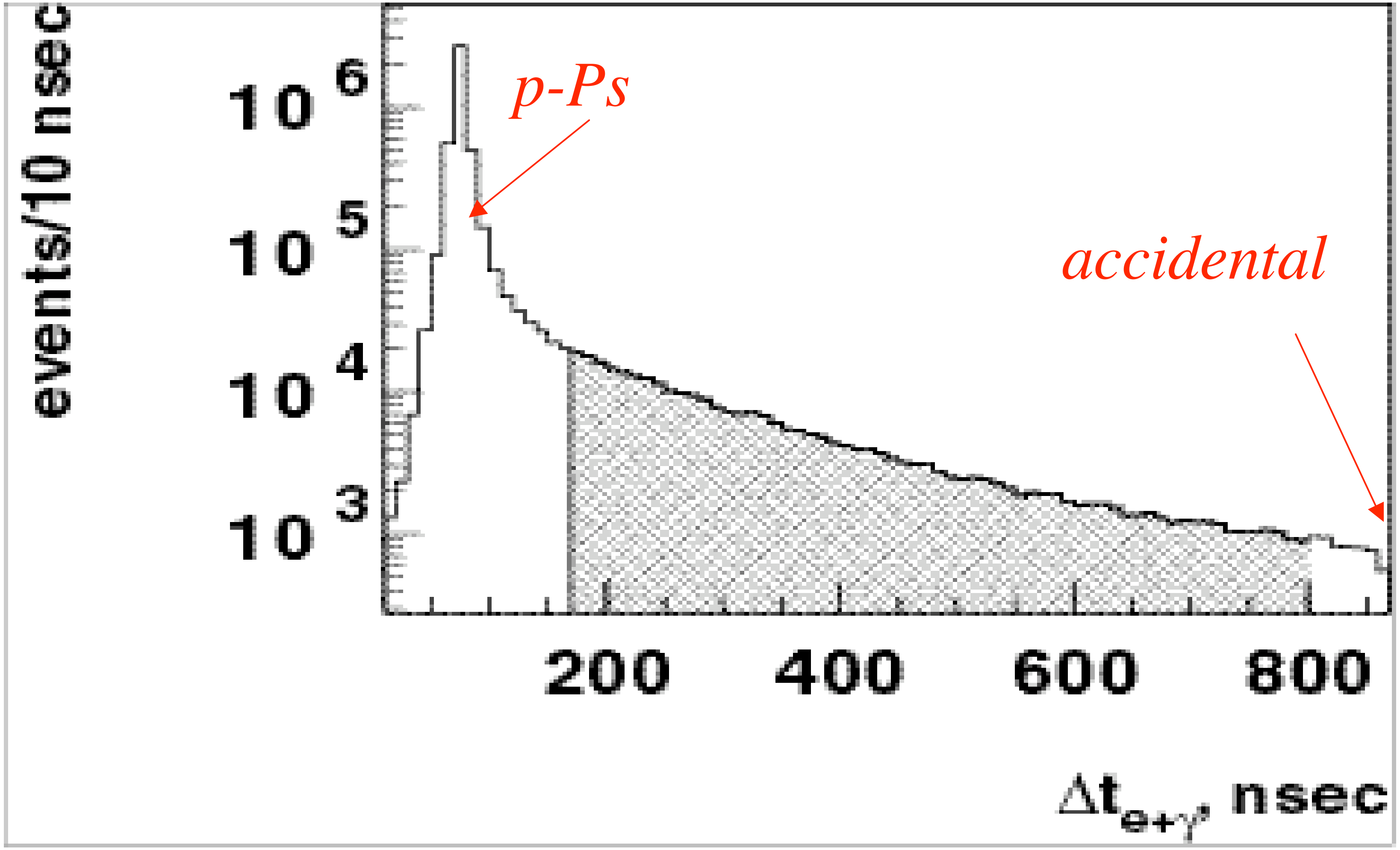
- For the same event the 1.27MeV (not more then one) should be present in one of the other crystals.

Selection of the 1.27 MeV



o-Ps decays selection

- In order to decrease the background from p-Ps, apply a cut on the STOP-START time delay.

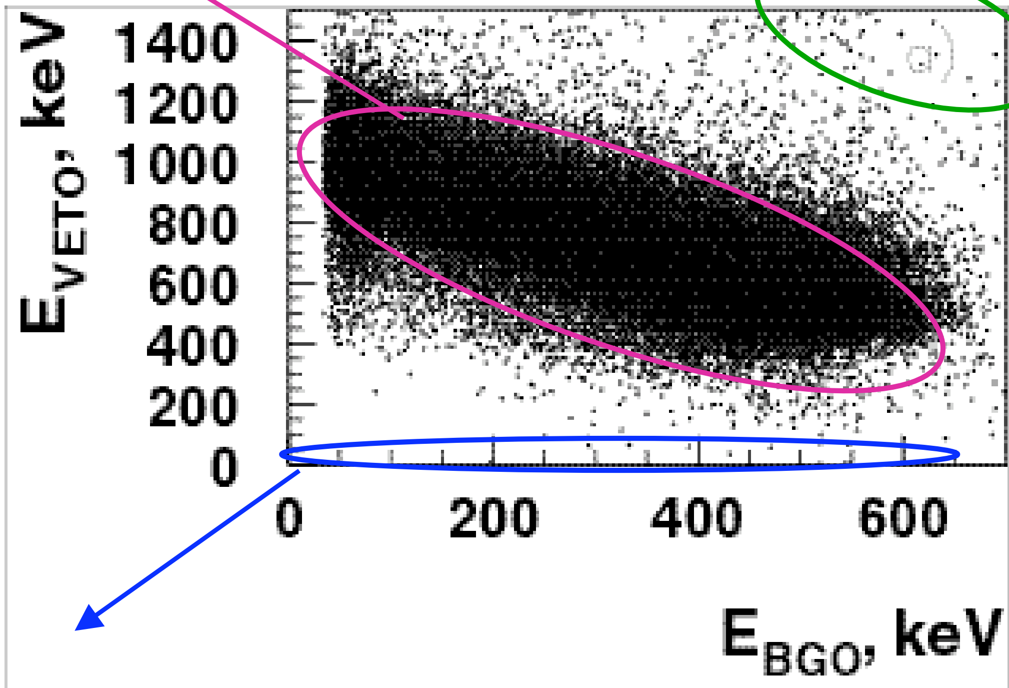


Result

After selection, the sum is calculated.

$$E_{VETO} = \sum_{all} E - E_{1.27} - E_{TriggerBGO}$$

The sum $E_{VETO} + E_{TriggerBGO} \approx 1 MeV$



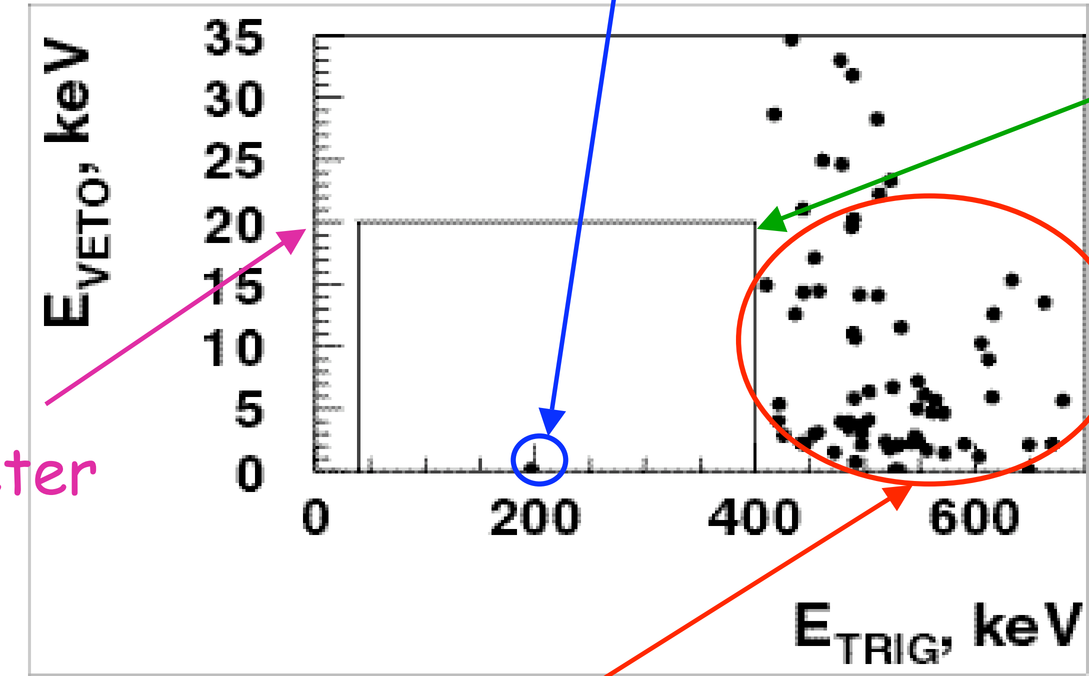
Pile up

Signal region

Signal region

$40\text{keV} \leq E_{\gamma} \leq 400\text{keV}$ and $E_{VETO} \leq 20\text{keV}$

One event has been observed



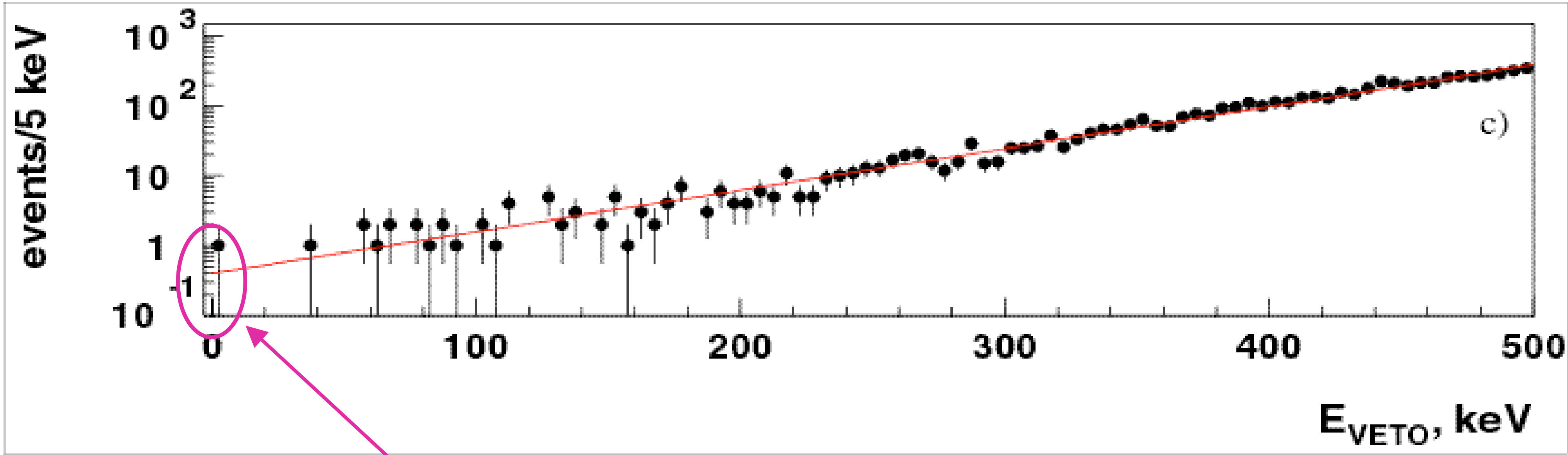
The single photon maximal energy depends on the mass of the two exotic particles.

Sensivity of the calorimeter 20keV

For the 511 keV photons from the 2 photons decay the non-hermeticity of the calorimeter is in the order of 10^{-3}.

Background estimation

The expected background is extrapolated assuming a linear fit (in log scale) of the projected energy in the VETO.



For E_{VETO} 20keV, 1.6 event (± 0.8) is expected, which is consistent with the measurements.

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Calculation of upper limit

$$BR(o\text{-}Ps \rightarrow \gamma + X_1 + X_2) \leq \frac{\varepsilon_{3\gamma}}{\varepsilon_{1\gamma}} \frac{N^{up}_{o\text{-}Ps \rightarrow \gamma + X_1 + X_2}}{N_{o\text{-}Ps \rightarrow 3\gamma}}$$

$N^{up}_{o\text{-}Ps \rightarrow \gamma + X_1 + X_2} = 3.8$ has been calculated with Poisson statistic for 1 event observed and 0-background expected (conservative).

Using a Monte-Carlo simulation (assuming phase space) we estimate the different detection efficiencies for a photon from the three photon and from the single photon decay:

$3.0 < \varepsilon_{3\gamma} / \varepsilon_{1\gamma} < 3.7$ for: $0 \leq M_{X_1} + M_{X_2} \leq 900 keV$

The number of o-Ps decays in the target is measured from the decay curve, the measured lifetime is 6.6% less than in vacuum, it follows that $N_{o\text{-}Ps \rightarrow 3\gamma} \approx 3.2x10^5$

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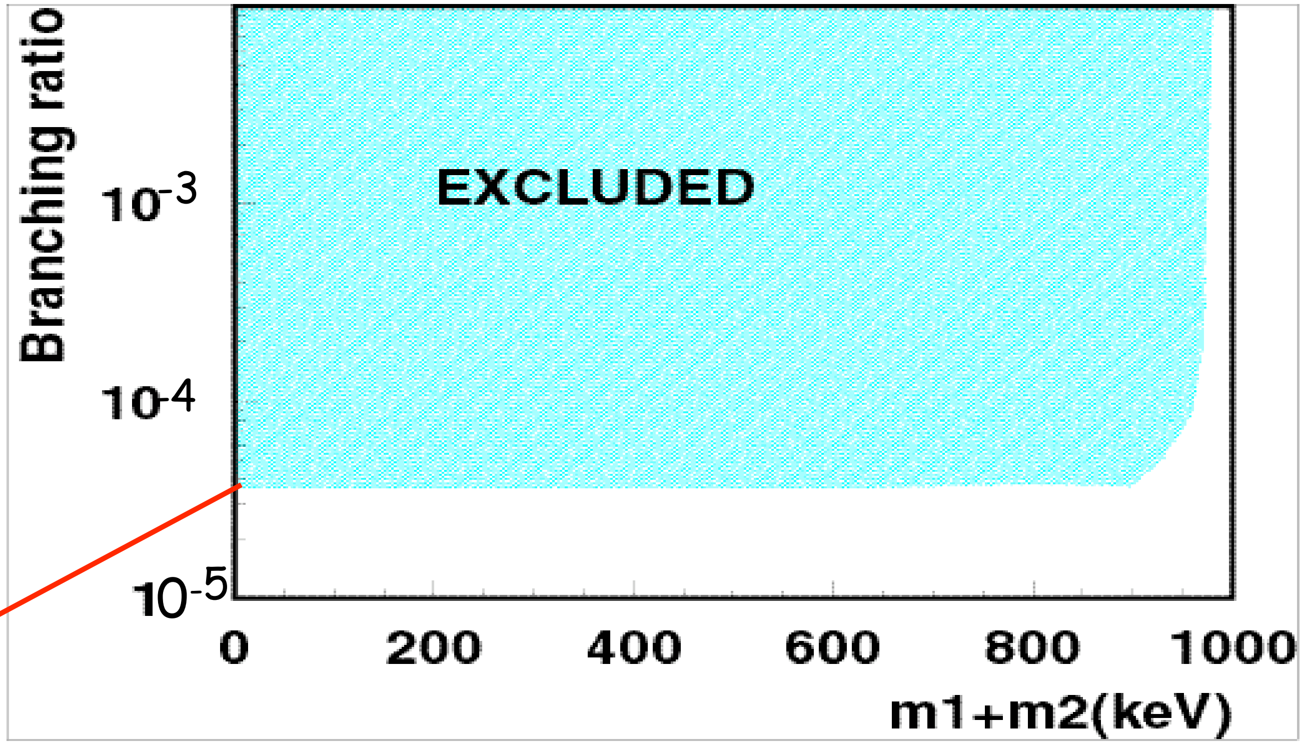
Exclusion region



$\mathbf{BR(e^+e^-(o-Ps) \rightarrow \gamma + X_1 + X_2) < }$ 4.4x10^{-5} at 90% CL

This exotic decay mode can not explain the discrepancy (the limit is ≈20 times smaller)!

What's next?

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Positronium and the mirror Universe (I)

Glashow, Phys. Lett. B167 (1986) 35

- Glashow pointed out that positronium was an excellent system to constrain the existence of the mirror universe
- Consider the effect upon Ps system of the existence of a degenerate mirror-system o-Ps'.
  - ➥ Use Holdom's kinetic term which mixes photon-mirror-photon (free parameter ε)
- Breaking of degeneracy: o-Ps is connected via a one-photon annihilation diagram to its mirror version, giving rise to ordinary-mirror oscillations with characteristic frequency εf, where $f=8.7\times10^4$ Mhz (contribution of (o-Ps)-(p-Ps) splitting from one-photon annihilation)
- Vacuum mass eigenstates

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

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

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

In absence of E- or B-field

Positronium and the mirror Universe (II)

- The oscillation between ordinary and mirror o-Ps introduces an invisible decay occuring during a long enough observation

Mitsui et al., Phys. Rev. Lett. 70 (1993) 2265

$$Br(o\text{-}Ps \rightarrow invisible) = \frac{2(2\pi\delta f)^2}{\Gamma^2 + 4(2\pi\delta f)^2}$$

- However, it was pointed out that the collision rate of o-Ps in experiments is larger than the decay rate and loss of coherence due to collisions must be included

Some measurements of the orthopositronium lifetime. The last column is an estimate of the mean scattering length of the orthopositronium in the experiment

Reference	$\Gamma_{\text{o-Ps}}(\mu s^{-1})$	Method	Γ_{coll}
Ann Arbor [7]	7.0482 ± 0.0016	Vacuum Cavity	$\sim(3\text{–}10)\Gamma_{\text{o-Ps}}$
Ann Arbor [8]	7.0514 ± 0.0014	Gas	$\sim 10^3\Gamma_{\text{o-Ps}}$
Tokyo [9]	7.0398 ± 0.0029	Powder	$\sim 10^4\Gamma_{\text{o-Ps}}$

Foot and Gninenko, Phys. Lett. B480 (2000) 171

$$\Gamma_{obs} \simeq \Gamma^0\left[1 + \frac{2(2\pi\delta f)^2}{\Gamma^0\Gamma_{coll}}\right]$$

$$\epsilon \simeq 10^{-7} \quad \textit{could explain o-Ps lifetime discrepancy !}$$

Positronium and milli-charged particles

- Related to the problem of quantization of electric charge
  - ➥ Where does it come from ?
  - ➥ Speculation about existence of milli-charged particles
- o-Ps could decay apparently invisibly since such particles would mostly penetrate any type of calorimeter without interaction

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

$$\approx 370\epsilon^2 \qquad for \quad m_x << m_e$$

- Result on Br(o–Ps→ inv) < 2.8 ppm (taking into account collisions): $\epsilon <\approx 10^{-6}$
- Recent SLAC search sets: $\epsilon <\approx 10^{-5}$
- To improve experimental limits requires a sensitivity:

$$Br(o-Ps \to invisible) < 10^{-8}$$

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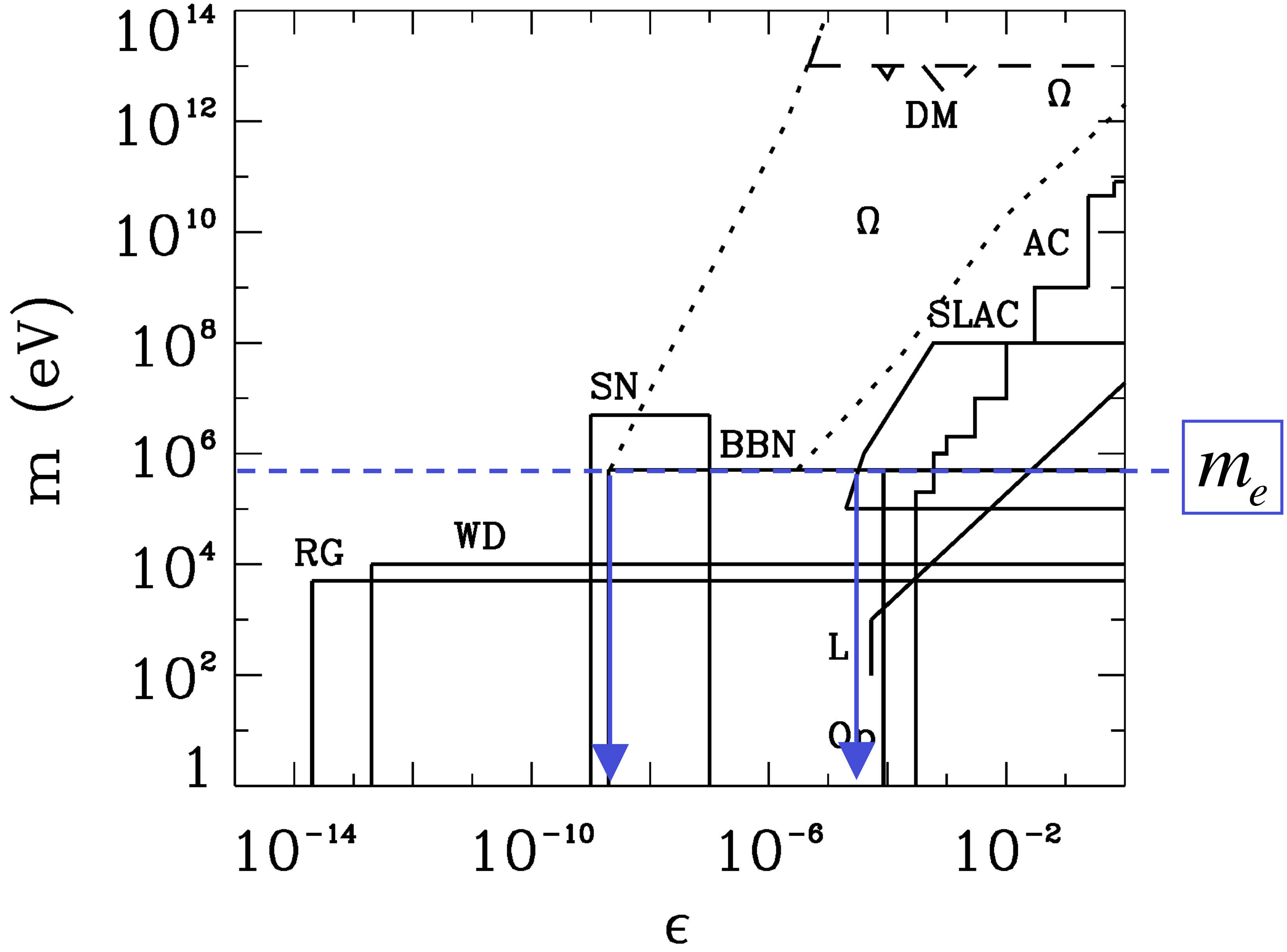
Mass-charge parameter space

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



Orthopositronium and extra-dimensions

Gninenko, Krasnikov, Rubbia, Mod. Phys. Lett. A17 (2002) 1713

- Recently we have contemplated the behavior of o-Ps within the context of extra-dimensions
  - ➥ Generally speaking o-Ps can migrate to extra-dimensions
- E.g. Randall-Sundrum model *Phys. Rev. Lett 83 (1990) 3370 & 4690*

$$Br(o\text{-}Ps \to \ extra\ \ \text{dimensions}) \simeq 3 \times 10^{-4}\left(\frac{m_{Ps}}{k}\right)^2$$

k=parameter of the theory

Gravitational potential: $$V(r) = G\frac{m_1 m_2}{r}\left(1 + \frac{1}{r^2 k^2}\right)$$

- Collider constraint (Z-decays) and theory ≈3 TeV < k < ≈10 TeV

$$\approx 10^{-10} < Br(o\text{-}Ps \to \ extra\ \ \text{dim}) < \approx 5 \times 10^{-9}$$

- Required sensitivity

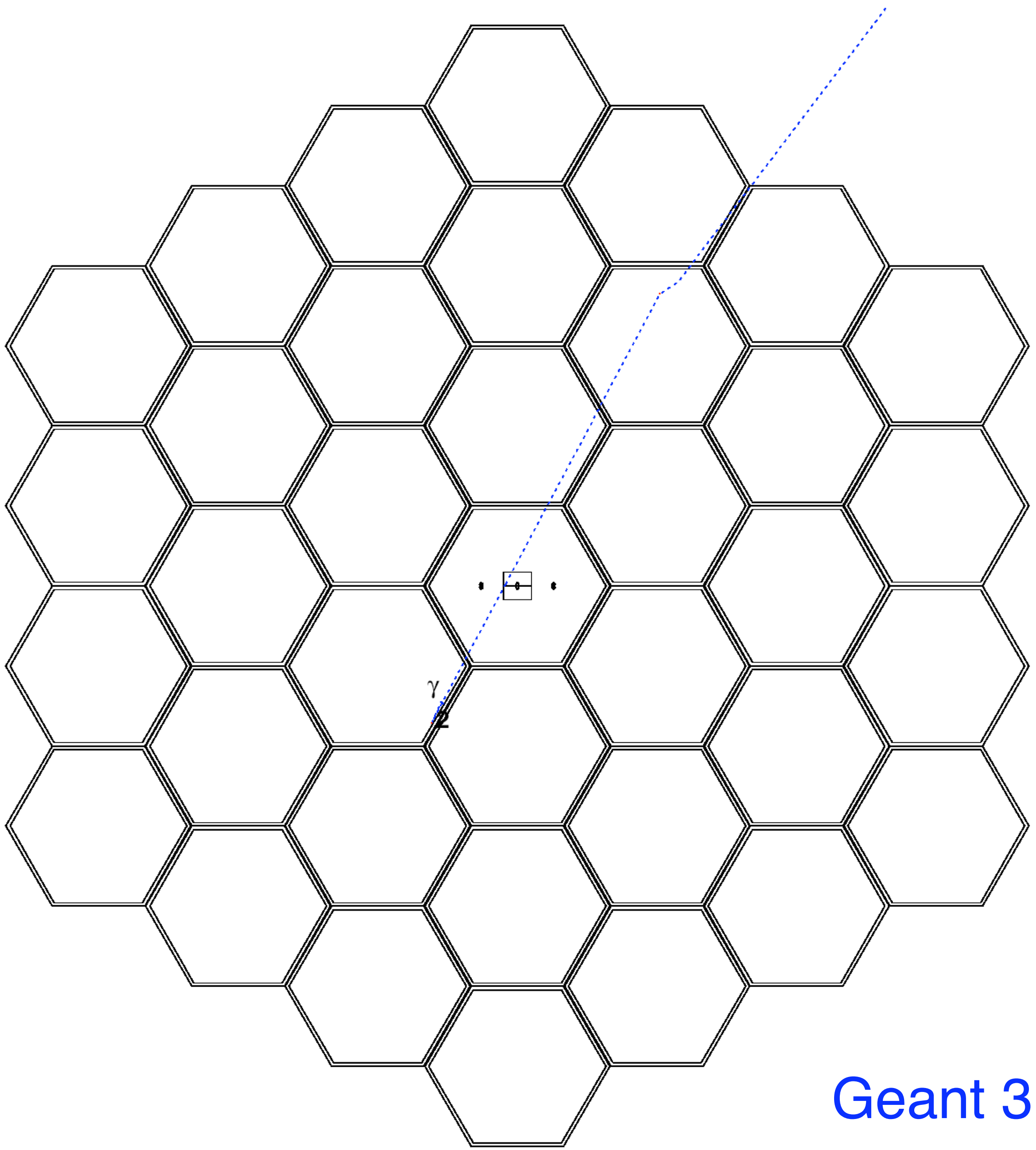
$$Br(o\text{-}Ps \to \ invisible) < 10^{-9}$$

Search for invisible decay with improved sensitivity

Status of the aerogel experiment:

Based on a Monte-Carlo simulation (tuned with the first phase of the experiment) we could reach the sensitivity **BR < ≈10^{-8}-10^{-9}**, if we could increase the size of the detector. The geometry should have 98 crystals!

	Background from 2□escaping detection
24 crystals (present)	2×10^{-5}
56 crystals	3.3×10^{-8}
98 crystals	10^{-10}



Geant 3

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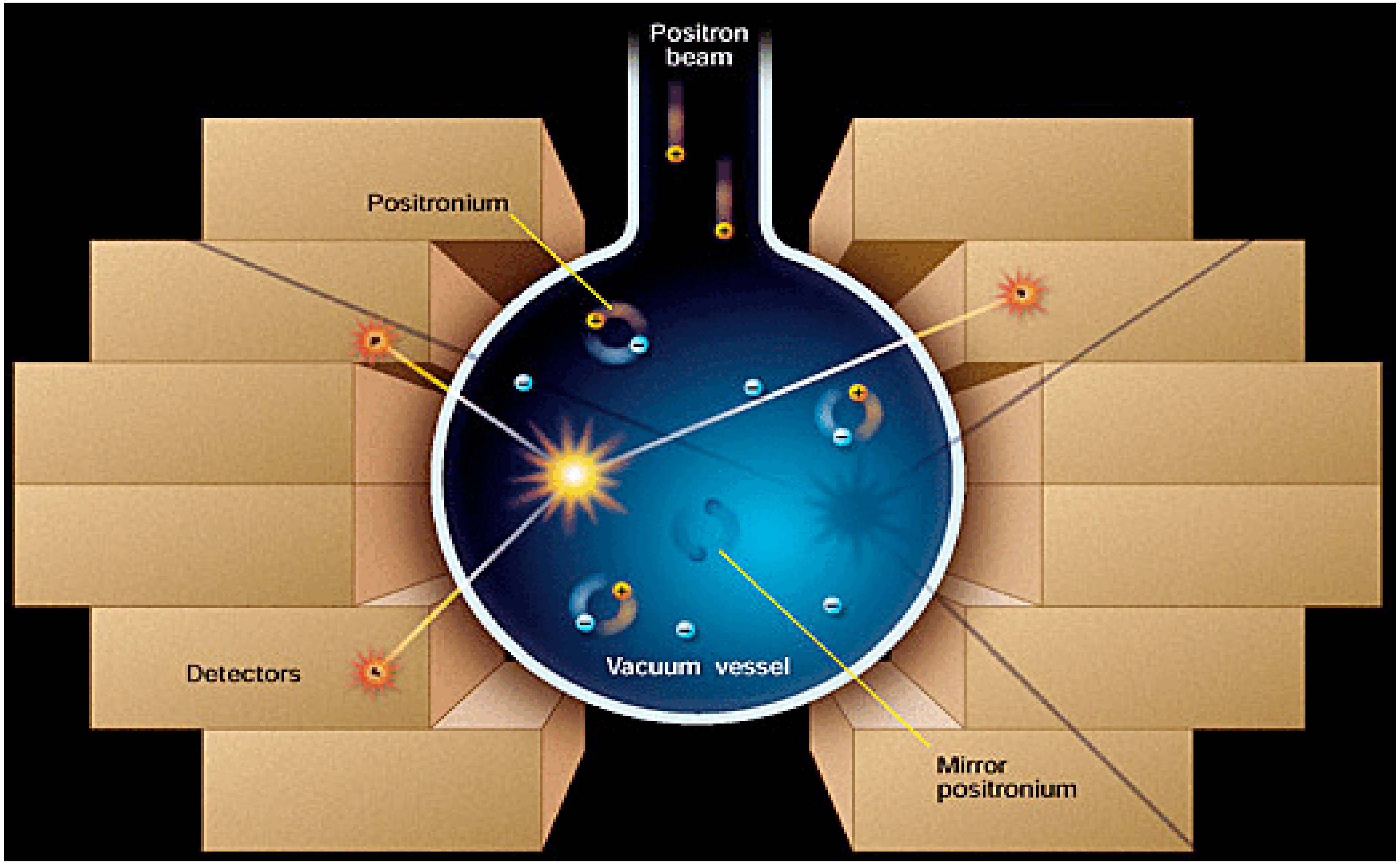
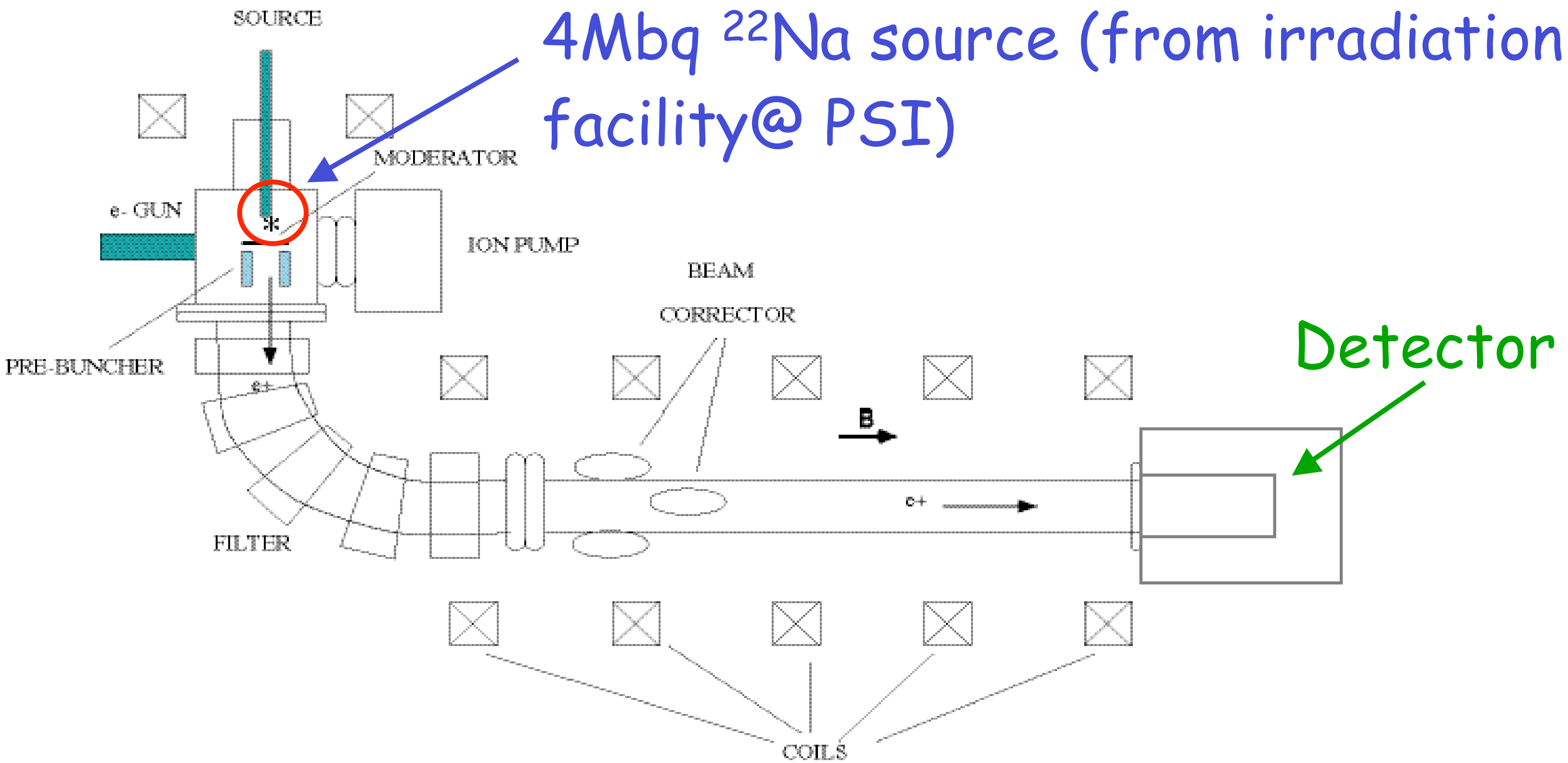
Measurement of o-Ps lifetime and search for invisible decay in vacuum

ETHZ, INR (Moscow), LAPP

- Combine the vacuum lifetime measurement with direct measurement of pick-off rate (&different systematics from Michigan) and direct search for invisible decays in vacuum: cavity surrounded by hermetic calorimeter



Phase 1: Prototype of the pulsed slow positron beam (2002-2003)



Corollary: Submission of a proposal for the development of a pulsed slow positron beam for applied material science physics (EOI to the EU submitted as Collabration ETHZ and LMOPS (Bourget-le-Lac)) “Pulsed Slow Positron Beam For Nanoscale Investigation Of Materials For Nanotechnology Industries”

Prototype pulsed slow positron beam (Dec 2002)

coils

source

UHV ≈ 10^{-8} mbar

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Conclusion

- The o-Ps decay rate puzzle is a long-standing problem
  - ➥ The 5s discrepancy between QED and experiment has been recently confirmed by updated higher-order calculations
  - ➥ The ball is in the experimental camp
- Solving the puzzle of the ortho-positronium lifetime in vacuum is a "must do" of particle physics. The situation is currently unsatisfactory.
- If the anomaly persists, it will certainly have important implications.
  - ➥ A failure of QED expansion in □ ? Treatment bound-states ?… Sharp constrast with other very precise QED observables (anomalous magnetic moment, Lamb shift, …)
  - ➥ It could signal presence of new physics beyond the SM
- If the anomaly disappears, it will help further constrain physics beyond the SM.
- In any case, we are convinced that in addition to a new measurement of the o-Ps decay rate, a very sensitive search for invisible decays in vacuum in the range of $10^{-8} \approx 10^{-9}$ would be an extremely valuable result
  - ➥ We have started a new activity in 2002 along those lines.