中国科学技术大学大一新生《科学与社会》研讨课

第三讲 关于反物质若干问题

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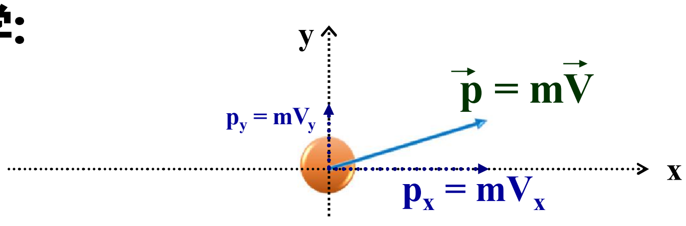
一、狄拉克是如何预言反物质的？

经典力学:



$$E = \frac{1}{2}mv^2 = \frac{p^2}{2m}$$

p_x 可以 + 或 -

E 总是+

量子力学

particles behave like waves

λ=h/p **ν=E/h**

wavelength **frequency**

Prerelativity:

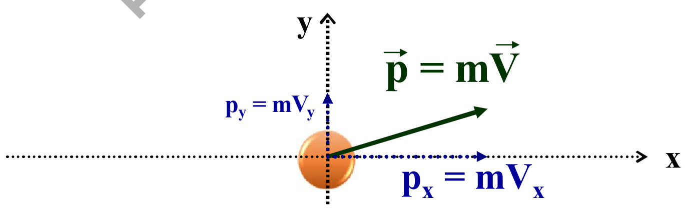
$p = m_0 v \quad (v = p/m_0)$

$E = \frac{1}{2} m_0 v^2 = p^2/2m_0$

λ= h/p ← can be + or –

$\nu = p^2/2m_0 h$ ← always +

相对论力学



$$E^2 = p^2c^2 + (mc^2)^2$$

$$E = \pm\sqrt{p^2c^2 + (mc^2)^2}$$

p_x (or p_y or p_z) can be + or -

E also can be + or -

相对论量子力学

$p = \gamma\, m_0\, v \qquad (v = p/m_0)$

$E = \pm\sqrt{p^2c^2 + (mc^2)^2}$

$\lambda = h/p$ ← can be + or –

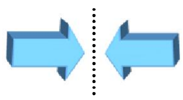
$\nu = \dfrac{\pm\sqrt{p^2c^2+(mc^2)^2}}{h}$ ← can be + or –

二、对称性

Parity, *P*

Parity reflects a system through the origin. Converts right-handed coordinate systems to left-handed ones. Vectors change sign but axial vectors remain unchanged

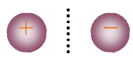
$\vec{x} \to -\vec{x}\ ,\ \vec{p} \to -\vec{p},$ but $\vec{L} = \vec{x} \times \vec{p} \to \vec{L}$



Charge Conjugation, *C*

Charge conjugation turns a particle into its anti-particle

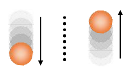
$e^+ \to e^-\ ,\ K^- \to K^+$

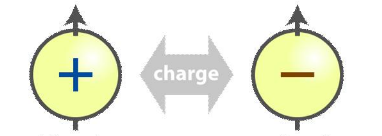


Time Reversal, *T*

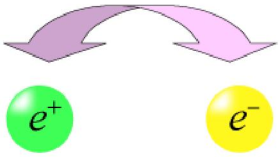
Changes, for example, the direction of motion of particles

$t \to -t$



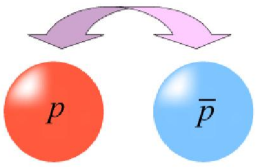


$\mathcal{C}$: changes particle into antiparticle



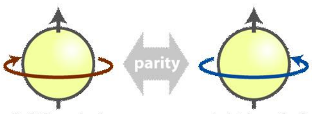
$$C\ |e^-\rangle = |e^+\rangle$$

$$C\ |e^+\rangle = |e^-\rangle$$

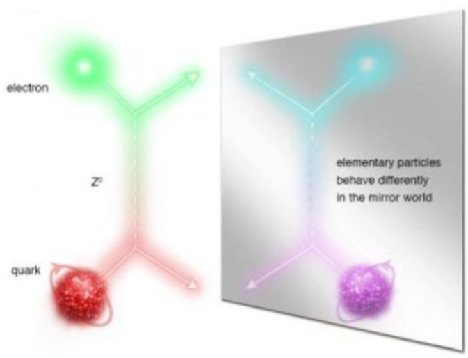


Also: proton ←→ antiproton   neutron ←→ antineutron etc

$$C\ |p\rangle = |\overline{p}\rangle \qquad C\ |n\rangle = |\overline{n}\rangle$$



$\mathcal{P}$: not well defined for an electron, can be ±1 but must be opposite for antielectron



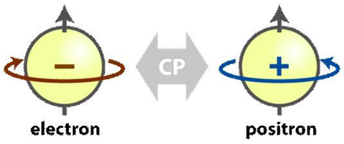
$$\mathcal{P}\ |e^-\rangle = \pm|e^-\rangle$$

must be opposite

$$\mathcal{P}\ |e^+\rangle = \mp|e^+\rangle$$

$$\mathcal{P}\ |e^-\rangle|e^+\rangle = -|e^-\rangle|e^+\rangle$$

must be -1



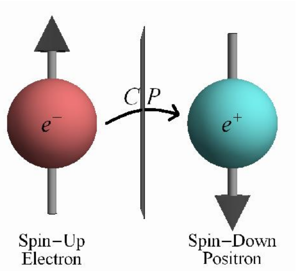
CP变换

$$C(\ |e^+\uparrow\rangle|e^-\downarrow\rangle \pm |e^+\downarrow\rangle|e^-\uparrow\rangle\ ) = |e^-\uparrow\rangle|e^+\downarrow\rangle \pm |e^-\downarrow\rangle|e^+\uparrow\rangle$$

$$= \pm 1 \times (|e^+\uparrow\rangle|e^-\downarrow\rangle \pm |e^+\downarrow\rangle|e^-\downarrow\rangle)$$

$$P|e^+\rangle|e^-\rangle = -1\times|e^+\rangle|e^-\rangle$$

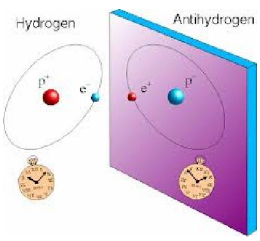
$$P(\ |e^+\rangle|e^-\rangle \pm |e^-\rangle|e^+\rangle\ ) = -1\times(\ |e^-\rangle|e^+\rangle \pm |e^+\rangle|e^-\rangle\ )$$



$$CP(\ \frac{1}{\sqrt{2}}(|e^+\uparrow\rangle|e^-\downarrow\rangle \pm |e^+\downarrow\rangle|e^-\uparrow\rangle)\ )$$
$$= \mp\frac{1}{\sqrt{2}}(|e^+\uparrow\rangle|e^-\downarrow\rangle \pm |e^+\downarrow\rangle|e^-\uparrow\rangle)$$

P and C on positronium

$$CP(\ \frac{1}{\sqrt{2}}(|e^+\uparrow\rangle|e^-\downarrow\rangle \pm |e^+\downarrow\rangle|e^-\updownarrow\rangle)\ )$$
$$= \mp\frac{1}{\sqrt{2}}(|e^+\uparrow\rangle|e^-\downarrow\rangle \pm |e^+\downarrow\rangle|e^-\uparrow\rangle)$$



$$CP(\ F(r)\ Y_{\ell m}\ (\theta,\phi)) = (-1)^{\ell}$$

$$CP\psi = (-1)^{S+1}\frac{1}{\sqrt{2}}(|e^+\uparrow\rangle|e^-\downarrow\rangle \pm |e^+\downarrow\rangle|e^-\uparrow\rangle)\times(-1)^{\ell}F(r)Y_{\ell m}$$

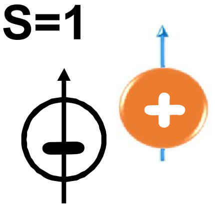
$$= (-1)^{S+\ell+1}\psi$$

$\mathcal{C}$ and $\mathcal{P}$ & $\mathcal{CP}$ on positronium

$$CP\psi = (-1)^{S+\ell+1}\psi$$

For ℓ=0 (S-wave):

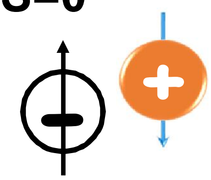
S=1



量子数
$\mathcal{P}$=-1
$\mathcal{C}$=-1
$\mathcal{CP}$=+1

"Ortho-positronium"

S=0



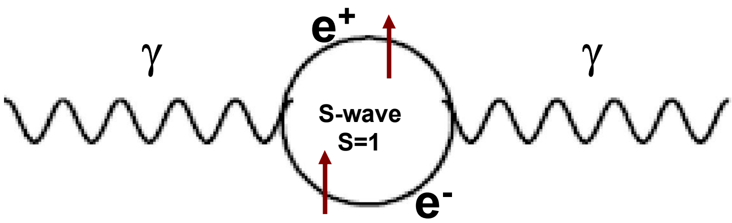
量子数
$\mathcal{P}$= -1
$\mathcal{C}$=+1
$\mathcal{CP}$=-1

"Para-positronium"

$\mathcal{C}$ and $\mathcal{P}$ for a photon

In QED

- **photon has J=S=1.**
- **it can convert into a virtual S-wave e^+e^- pair for short times**



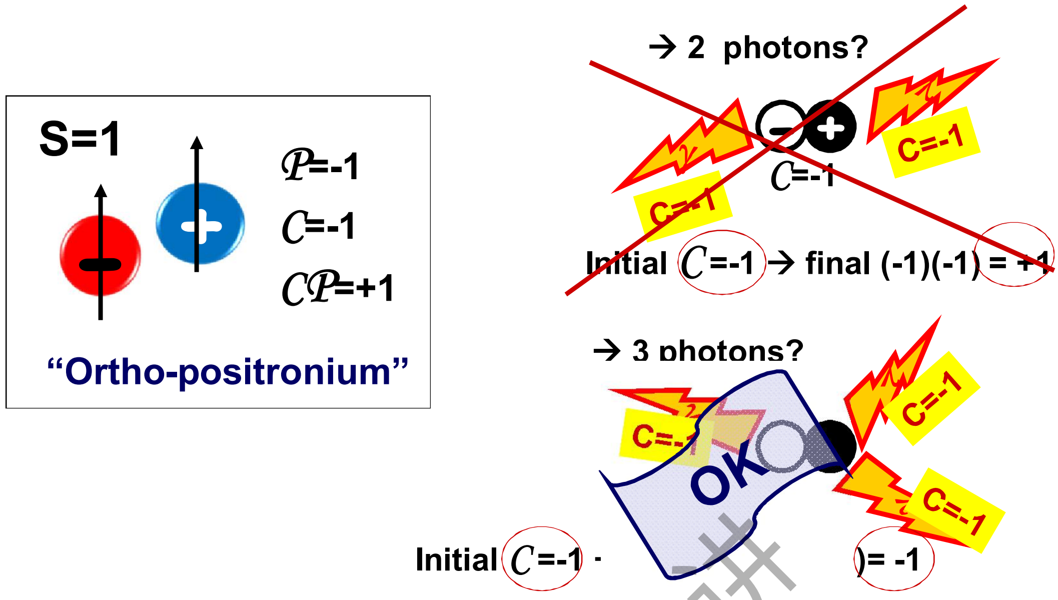
量子数

➔ **photon has same $\mathcal{C}$ & $\mathcal{P}$ quantum numbers as an S=1 positronium**

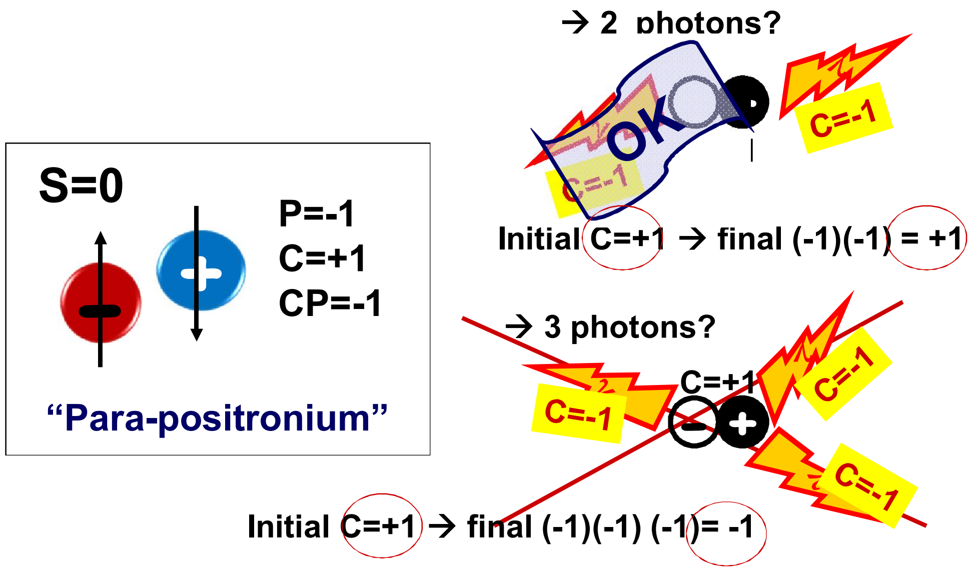
$\mathcal{P}_\gamma$=-1
$\mathcal{C}_\gamma$=-1

$\mathcal{CP}_\gamma$=+1

Ortho-positronium annihilation



Para-positronium annihilation



Rule for all-photon decays

偶数

C=+1 ➔ only even number of photons

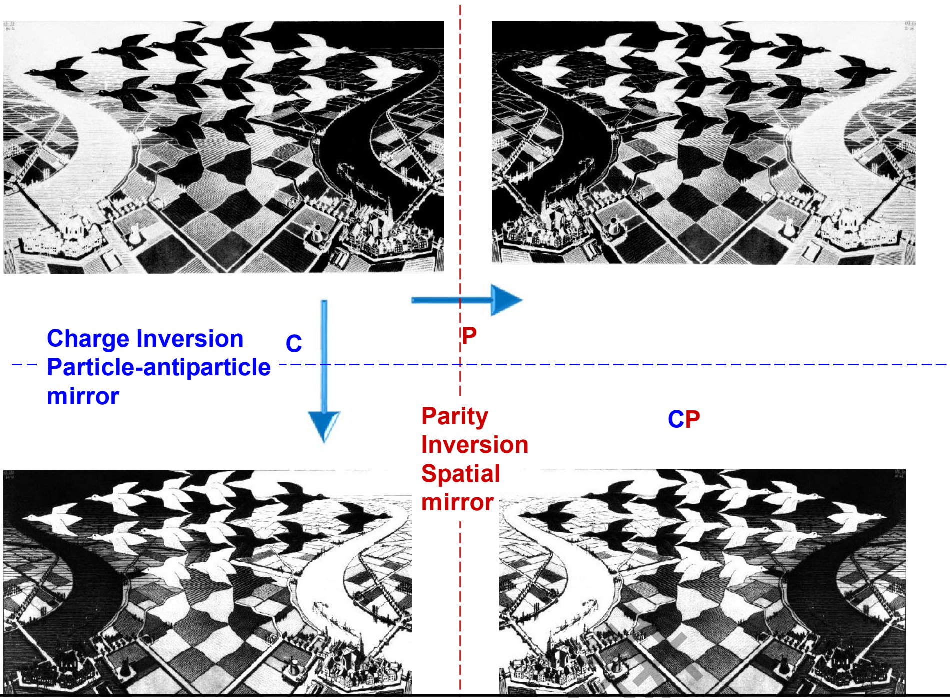
奇数

C=-1 ➔ only odd number of photons

三、CP Violation:
Why is it interesting ?

Fundamental: The Martian test

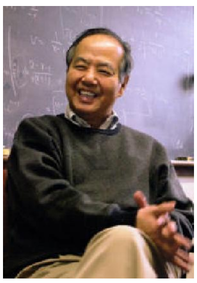
- C violation does not distinguish between matter/anti-matter. LH/RH are conventions
- CP distinguishes matter from anti-matter
- CP says preferred decay $K_L \rightarrow e^+ \nu_e \pi^-$



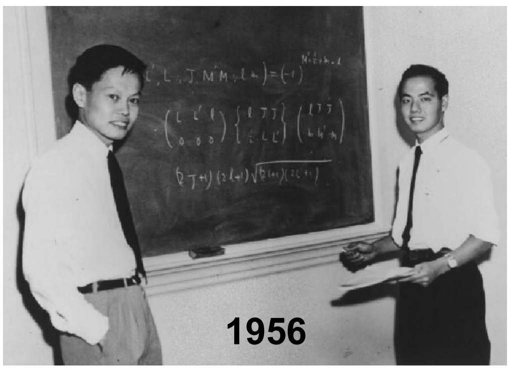
Is nature left-right symmetric?

1956: The force that is responsible for radioactive decay may not be symmetric under Parity transformation

Yang, Chen-Ning



Lee, Tsung-Dao



Parity violation discovered

WU, Chien Shiung

1912-1997

1956:
studied radioactive β-decay of polarized Co^{60} nuclei:

$$Co^{60} \rightarrow Ni^{60} \; e^{-} \; \nu$$

She found an asymmetry: more electrons are emitted opposite to the nuclear spin direction than along it

Violation of left-right symmetry

In the "real electrons are emitted opposite to the J direction

$\mathcal{P}$ is not conserved

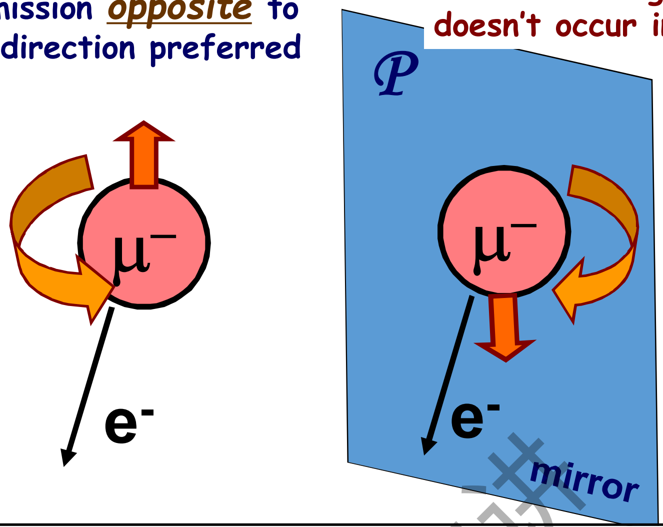
the "mirror" d electrons mitted along J direction

Mirror world & real world are different L-R symmetry is violated.

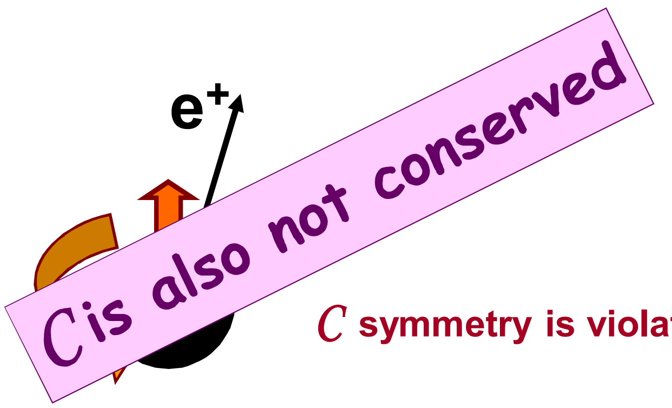
Parity violation in μ^- decay

e⁻ emission *opposite* to Spin direction preferred

Mirror image case doesn't occur in Nature



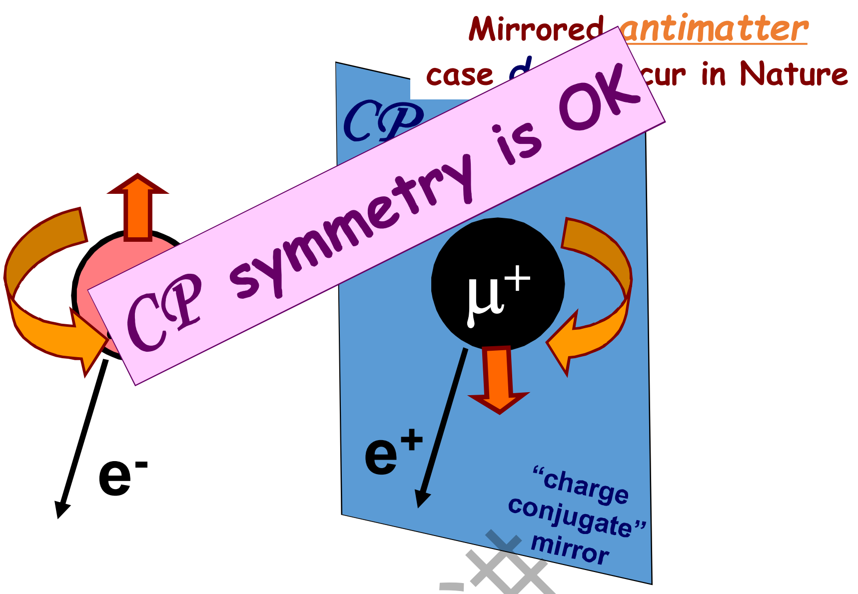
μ^+ asymmetry is opposite



C symmetry is violated

e⁺ emission *parallel* to Spin direction preferred

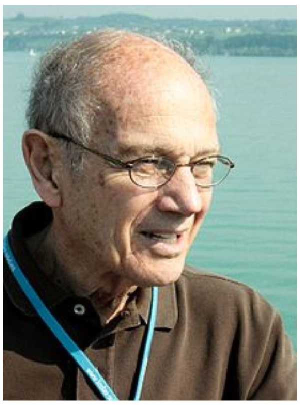
$\mathcal{C}$ x $\mathcal{P}$ in μ decay



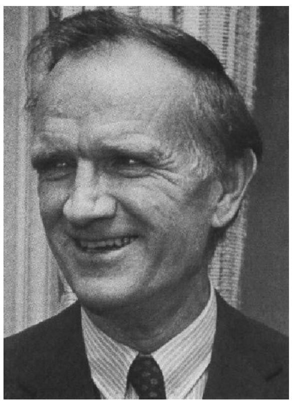
R L Garwin, L M Lederman and M Weinrich

CP-symmetry states that the laws of physics should be the same if a particle is interchanged with its antiparticle.

The discovery of CP violation in 1964 in the decays of neutral kaons



James Watson Cronin

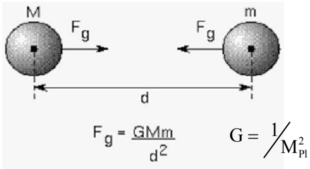


Val Logsdon Fitch

Nobel Prize in Physics in 1980

Gravitational Force

Attractive force between 2 massive objects:



Proportional to product of masses
Assumes interaction over a distance d

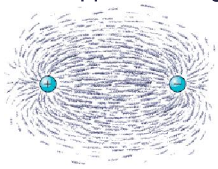
==> comes from properties of space and time

Is very weak unless one of the masses is huge, like the earth

Electromagnetic Force

Attracts particles of opposite charge

$$F = \frac{k\, e_1 e_2}{d^2}$$

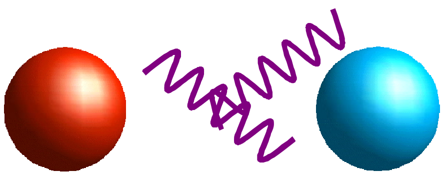


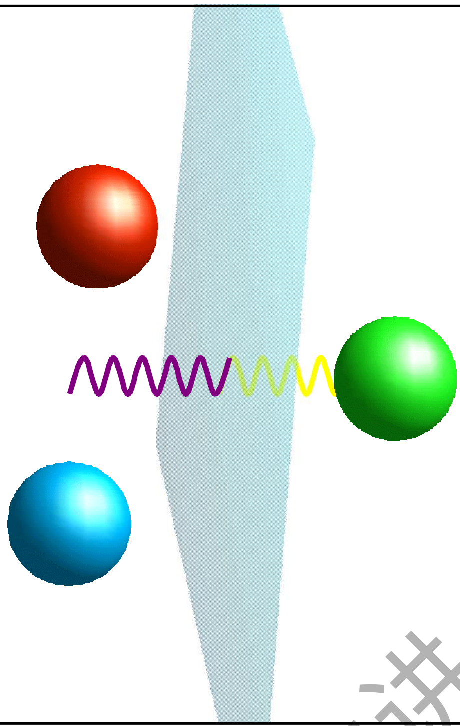
Forces within atoms and between atoms

+ and - charges bind together and screen each other

➔ $s_\lambda = 1$ $m_\gamma = 0$

Modeled by a theory based on U(1) gauge symmetry





四、New Physics?

- **Antimatter**
- **Mixing** $\gamma \leftrightarrow \bar{\gamma}$
- **Mirror Universe**
- **Extra-dimensions?**

A.Salam; I.Kobzarev, L.Okun, Y.Pomeranchuk (1966)

1. Positronium and the Mirror Universe

S.Glashow (1986)

- **Hyperfine splitting** $\delta(\Delta\nu) \propto \varepsilon\alpha^4 m_e \sim \varepsilon\Delta\nu^{\mathrm{LO}}$

$$\varepsilon \sim \alpha^3 \sim 10^{-7}$$

- **Decay rate** $\delta\Gamma_o \propto \varepsilon^2\alpha^2 m_e \sim \frac{\varepsilon^2}{\alpha^4}\Gamma_o^{\mathrm{LO}}$

$$\varepsilon \sim \alpha^{7/2} \sim 10^{-8}$$

Glashow (1986): Ps system is a good probe to test existence of mirror matter

Volume 125B, number 2,3 PHYSICS LETTERS 26 May 1983

Do we live inside a domain wall?

V.A. RUBAKOV and M.E. SHAPOSHNIKOV
Institute for Nuclear Research of the Academy of Sciences of the USSR, 60th October Anniversary Prospect 7a, Moscow 117312, USSR

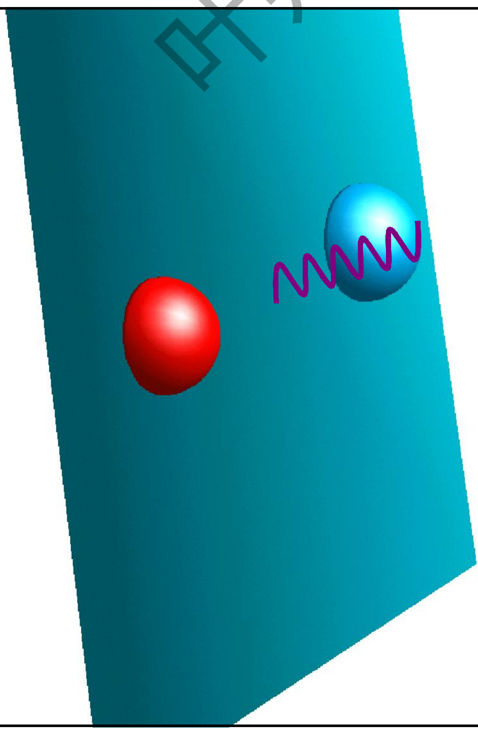
Received 7 February 1983

We discuss the possibility that space–time has (3 + *N*) + 1 dimensions, but ordinary (light) particles are confined in a potential well which is narrow along *N* spatial directions and flat along three others. A five-dimensional model is considered in which this picture arises naturally. In a universe of this type, processes looking like $e^+e^- \to$ nothing are possible at high energies.

2. The Extra Dimensions

- Compact extra dimensions T.Kaluza (1921); O.Klein (1926)
  - Invisible at low energies
- Infinite extra dimensions L.Randall, R.Sundrum (1999)
  - Matter can escape into the extra dimensions!

S.Dubovsky, V.Rubakov, P.Tinyakov (2000)



In the Standard Model o-Ps can decay invisibly in a neutrino-antineutrino pair:

$$BR(o-Ps \to \nu_e \bar{\nu}_e) \approx 6.2 \cdot 10^{-18} \Gamma(o-Ps \to 3\gamma)$$

$$BR(o-Ps \to \nu_l \bar{\nu}_l) \approx 9.5 \cdot 10^{-21} \Gamma(o-Ps \to 3\gamma) \qquad l \neq e$$

The observation of an invisible o-Ps decay (by invisible is meant photonless) at a higher level would unambiguously signal the presence of new physics.

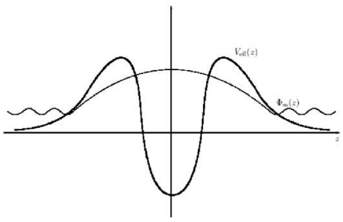
Ortho-positronium and extradimension

- **Presently there is a big interest in models with additional dimensions which might provide solution to the gauge hierarchy problem. In Randall-Sundrum model typeII particles can be trapped on the brane, where they are expected to be metastable, they decay into continuum Kaluza-Klein modes. From the point of view of an observer in 3d-"brane" the particle disappear into the bulk of the additional dimension.**

In a recent paper it was pointed out that this mechanism could result in a disappearing of ortho-positronium into the bulk of additional dimensions. The probability was calculated to be:

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

10^{-9}<Br(o-Ps extradim)<10^{-8}



Tunneling of a particle through extra-dimension (V. A. Rubakov)

Existing limit on the o-Ps invisible (not in vacuum)

The first experiment:

$$BR(o-Ps \rightarrow invisible) \leq 5.8 \cdot 10^{-4}$$

Ayotan et al. (Phys. Lett. **B** 220, 317 (1989))

The present limit is:

$$BR(o-Ps \rightarrow invisible) \leq 2.8 \cdot 10^{-6}$$

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

Invisible decay search of orthopositronium with the source experiment

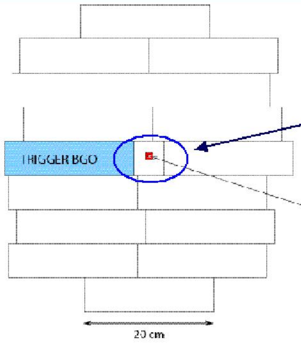
Fundamental Physics, ETHZ, Switzerland:

- This experiment was motivated by the long standing discrepancy between theory and experiment in the lifetime of ortho-positronium. A possible contribution of an exotic channel could have explained what at that time was still considered a puzzle (the new measurements of the Michigan and Tokyo groups in 2003 are now agreement).
- **Exotic decays have been searched extensively, one of the remaining possibilities which was not yet excluded was the possibility of a decay of o-Ps in a photon and two weakly interacting particles. The goal of our experiment was to search for it with the sensitivity necessary to exclude [...] discrepancy.**

Mod. Phys. Lett. A Vol. 17, No. 26 (2002) 1713

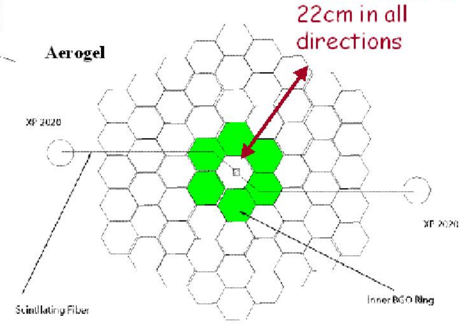
Badertscher et al., Phys Lett. B543:29-34, 2002

Side and front view of the calorimeter



Region of positronium formation

Thickness of 20-22cm in all directions



About 400Kg: to have at least 20λ @ 511keV
→ Probability of one escaping photon <10^{-9}

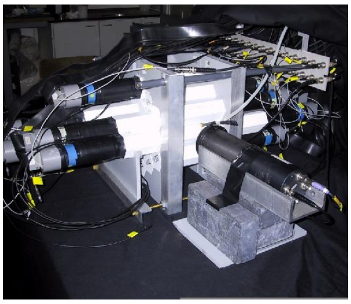
100 BGO

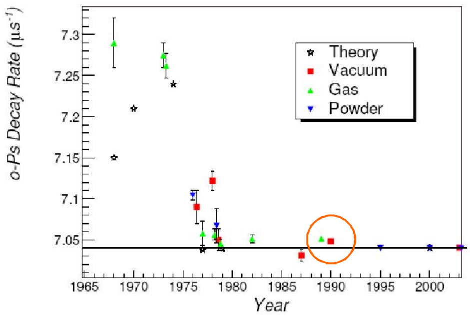
2002: Exotic three body decay search

Badertscher et al., Phys. Lett. B542, (2002) 29-34

From our search for an exotic three body decay of o-Ps

$$BR(o-Ps \rightarrow \gamma + X_1 + X_2) \leq \quad 4.4\text{x}10^{-5} \text{ at } 90\% \text{ CL}$$





Theory (2000)

We excluded this decay channel as a possible source of the o-Ps lifetime discrepancy

2003: Workshop on Positronium at ETHZ

Proceedings, Int. J. Mod. Phys. A19 (2004) No23

1. **o-Ps is an ideal probe for new physics, i.e. to search for hidden-sectors: extra-dimension, dark matter of mirror particle type or milli-charged particles predicted in GUT**
2. **Precision of the lifetime measurement 200 times worse than the recent theoretical calculations -> need of a new experiment with a higher precision to check the QED corrections**

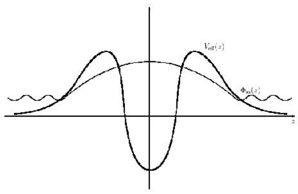
Positronium = interesting for research

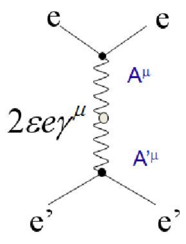
2003: Orthopositronium and new physics

Gninenko, Krasnikov, Rubbia, Phys.Rev.D67:075012,2003

New physics could be signaled by an o-Ps -> invisible decay with an experimentally interesting branching ratio of the order of 10^{-8} .

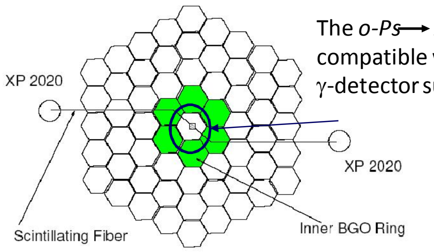
The models that predict such a decay are:



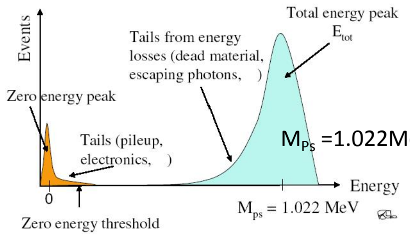


The search for o-Ps->invisible decays

P. Crivelli, PhD Thesis, No. 16117, ETHZ, Switzerland (2006)



The *o-Ps*→ *invisible* decay would appear as an event compatible with zero-energy deposition in a hermetic γ-detector surrounding the o-Ps formation region.

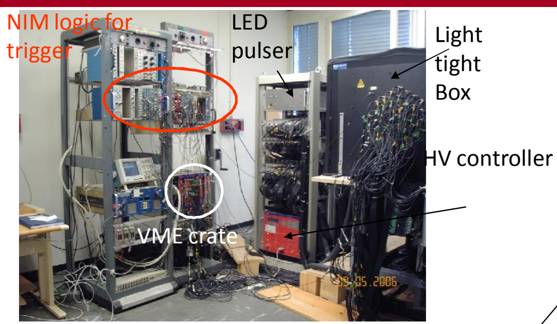


Design criteria:

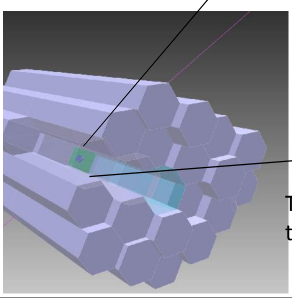
1. Hermetic calorimeter: Escaping probability for annihilation photons <10^9
2. Region around the target with less dead material as possible
3. High fraction of produced o-Ps-> high statistics and background from gammas suppression
4. Efficient positron tagging system to provide a clean trigger
5. Veto of charged particle in the crystal used to identify the 1.27 MeV from the ^{22}Na source emitted with the positron and used as a requirement for the trigger.

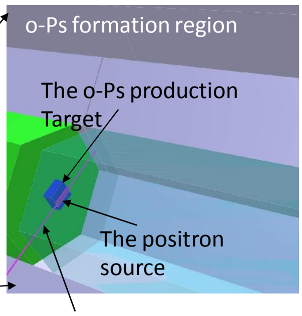
The calorimeter the o-Ps->invisible search

P. Crivelli, PhD Thesis, No. 16117, ETHZ, Switzerland (2006)



The 4π BGO calorimeter surrounding the o-Ps formation region (100 BGO crystals kindly lend us from PSI)





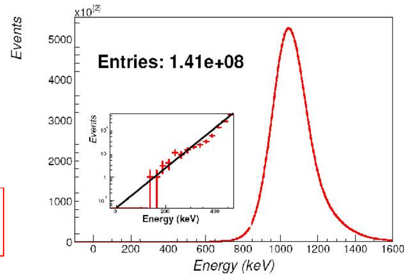
The scintillating fiber to tag the positron

Results of the o-Ps -> invisible search

A. Badertscher et al., hep-ex/ 0609059

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: 5 months
$1.39\text{x}10^{10}$ triggers



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

$$Br(o-Ps \rightarrow invisible) = 2.3/(N_{o-Ps} \cdot \epsilon) \leq 4.2 \times 10^{-7}$$

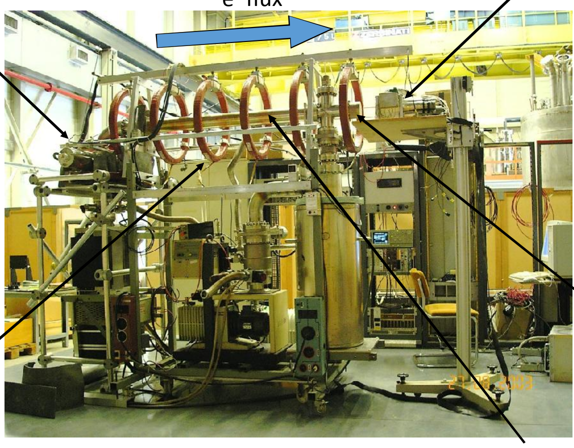
This limit is 7 times more stringent than what was previously reported by the Tokyo group.
Simulations and an extrapolation of the data show that performing some improvements in the trigger rate with this experimental setup one could gain a factor 5 in the sensitivity.

The slow positron Beam

1 Mbq ^{22}Na source of positron (prepared at PSI) &Tungsten moderator chamber

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)

The goal of the slow positron beam

Fundamental Physics:

1. A new lifetime measurement of o-Ps with an improved precision to check the QED corrections (the present result are 200 times worse than the recent theoretical calculations).
2. A search for dark matter of mirror particle type.
3. Positronium spectroscopy measurements.
4. Efficient anti-hydrogen production using the reaction: Ps*+pbar->Hbar+e- with the goal of measuring gravity fall for antimatter

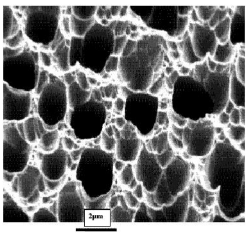
Applied Physics:

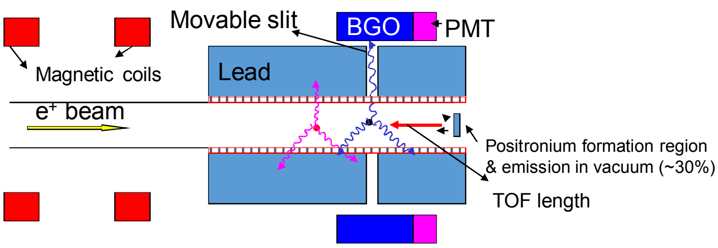
1. Characterization of nano-porous materials using the positron annihilation spectroscopy technique (PALS)

Therefore, the final beam construction had to compromise several design criteria.

2006-2007: Positronium formation Study

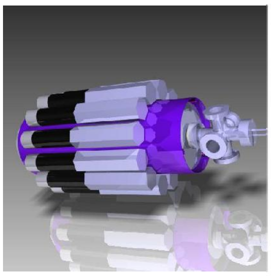
The nearest goal: controlled production of o-Ps to be used for future experiments, new lifetime measurement, invisible decay search of o-Ps in vacuum, positronium spectroscopy measurement, very efficient anti-hydrogen formation.

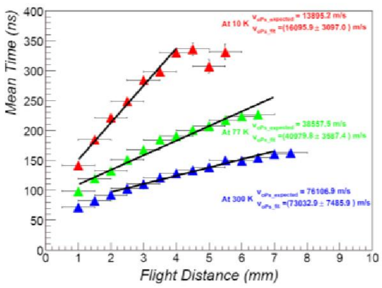


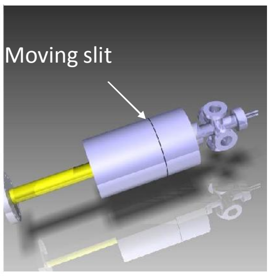


Design of the TOF and PALS experiment

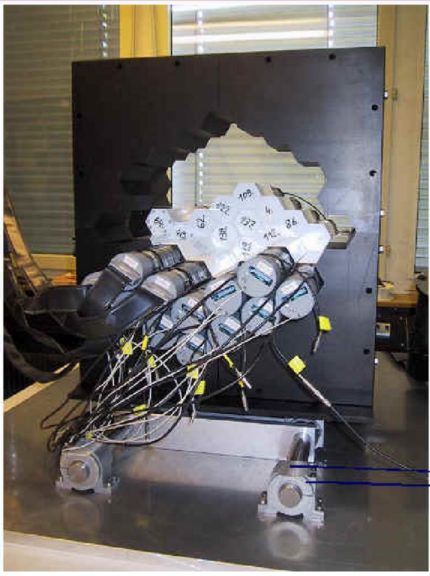
The designed detector will serve for both, TOF and PALS spectroscopy of the thin SiO_2 films is finished.

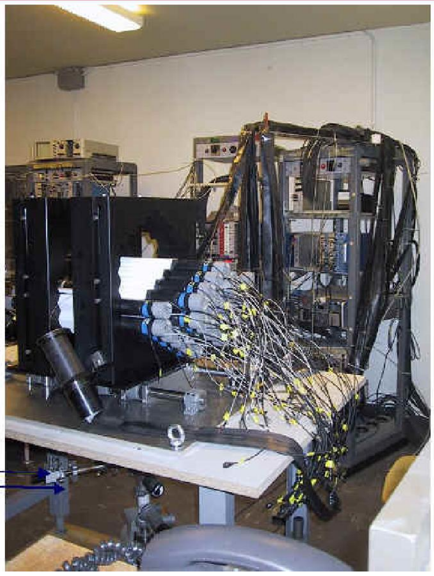




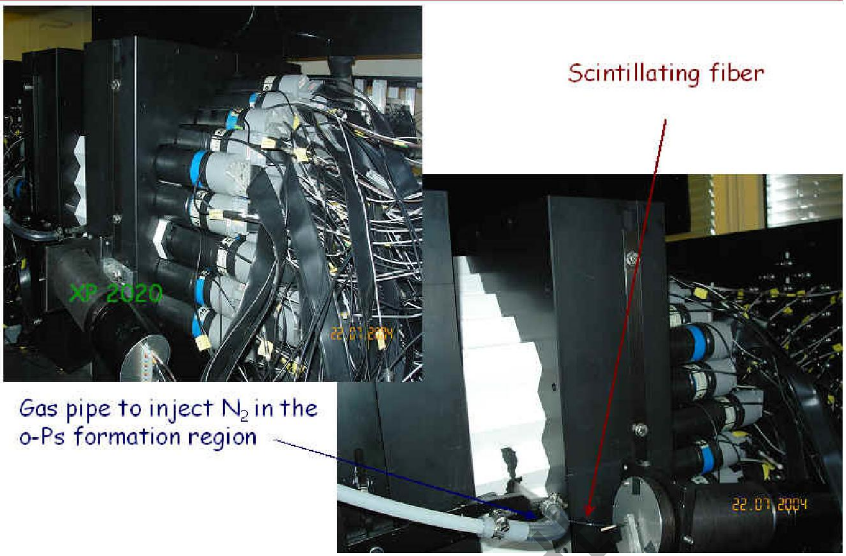


Photograph of the calorimeter (assembling phase)





Photograph of the assembled calorimeter



If :

1) **Locality** (no action at a distance)
2) **Lorentz invariance** (all inertial frames are equivalent)
3) **Causality** (no interaction between two space-time points outside each other's light cone)
4) **Vacuum = lowest energy** (spin-statistics connection)

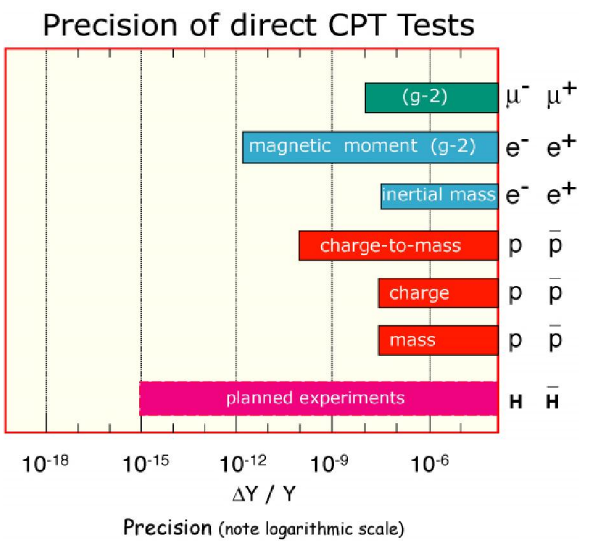
Then :

Particles and antiparticles must have **exactly equal**

- mass
- lifetime
- charge (magnitude)
- energy levels of bound states

*1955 - Proof of CPT theorem by Pauli (following work by Schwinger and Lüders)

Direct comparison of stable particles and antiparticles



- DIRECT TESTS CONFIRM CPT ~ 10^{-12} LEVEL
- THERE IS NO "THEORY" OF CPT VIOLATION

$\mathcal{C}\,\mathcal{P}$ and the forces of Nature

Force	$\mathcal{C}$	$\mathcal{P}$	$\mathcal{CP}$
Gravity	√	√	√
Electro-magnetic	√	√	√
Strong-nuclear	√	√	√
Weak-Interaction	×	×	OK?

$\tau - \theta$ puzzle revisited

$\theta^+ \rightarrow \pi^+ \pi^0$

$\mathcal{P}$ = (-1)x(-1) = +1

same mass
same lifetime

But opposite parity

$\tau^+ \rightarrow \pi^+ \pi^+ \pi^-$

$\mathcal{P}$ = (-1)x(-1)x(-1) = -1

θ^+ and τ^+ are the same particle, the K^+ meson.
K+ meson decays do not conserve parity

3. Antimatter Gravitation

Argument in favour of weak equivalence principle:

The masses of particles and antiparticles obey $E = mc^2$. Since it is this energy that curves space, antimatter must have the same gravitational interaction as matter

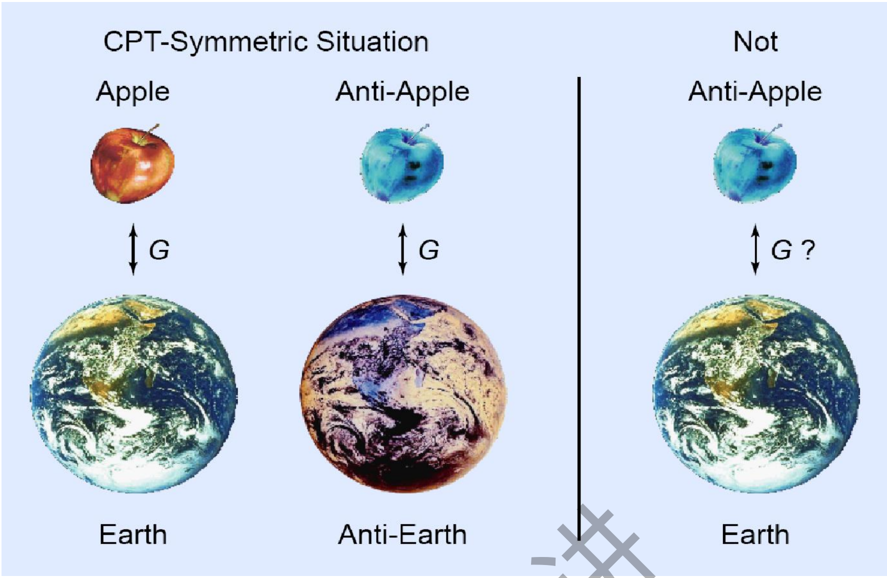
But:

There could be (yet) unknown additional (vector) components of gravity

These may have finite range and change sign for antimatter

What about experiments??

Gravitation is not constrained by CPT



Antiparticle gravitation experiments have been attempted, but ...

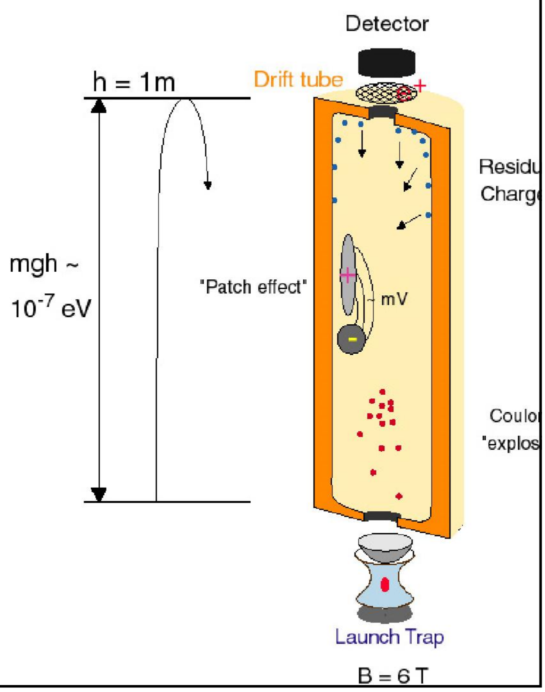
No measurement of gravitational effects on (charged) antiparticles has yet succeeded ..

- controversial result for positrons, 1967
- failed attempt with antiprotons at LEAR, 1996

Problems:

- Coulomb explosion
- Patch effect (mV/cm)
- Residual charges

(10^{-7} eV ~ 1 electron at 1 m distance)

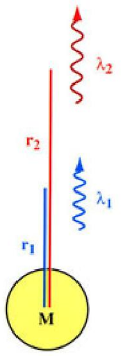


Conclusion: Antimatter Gravity

Weak equivalence principle is well tested with ordinary matter*, but not at all with antimatter

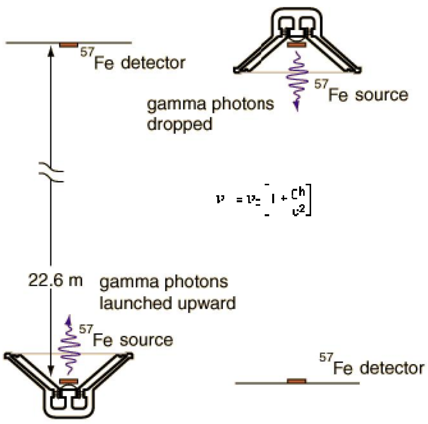
* Overview: B.R. Heckel et al., Adv. Space Res. 25 (2000) 1125

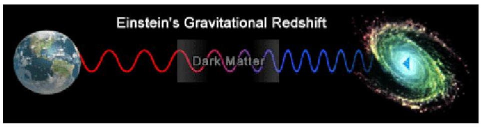
Gravitational redshift



$$\frac{hc}{\lambda_1} - \frac{GMh}{r_1 c \lambda_1} = \frac{hc}{\lambda_2} - \frac{GMh}{r_2 c \lambda_2}$$

$$\frac{\lambda_2}{\lambda_1} = \frac{\left[1 - \frac{GM}{r_2 c^2}\right]}{\left[1 - \frac{GM}{r_1 c^2}\right]}$$





$$\Delta E = mgh = \frac{E}{c^2} gh = \frac{14.4keV}{c^2} g \cdot 22.6m$$

$$\Delta E = 3.5x10^{-11} eV$$

$$\left(\frac{\Delta E}{E}\right)_{down} - \left(\frac{\Delta E}{E}\right)_{up} = \frac{2(3.5x10^{-11}eV)}{(14.4keV)} = 4.9x10^{-15}$$

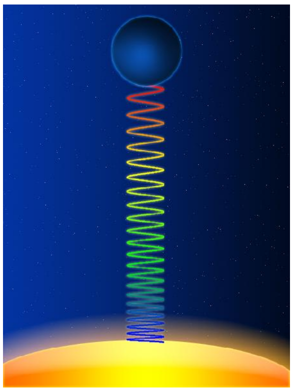
The measured difference was $\left(\frac{\Delta E}{E}\right)_{down} - \left(\frac{\Delta E}{E}\right)_{up} = (5.1 \pm 0.5)x10^{-15}$

$$1/2\ (g_{matter} + g_{antimatter}) = g_{photon}$$

$$E = hf = 2mc^2$$

Suppose that we now take these photons and send them to someone at the bottom of the tower. If that person measures the energy of the photons, they will measure a different energy that we did at the top of the tower, because the photons will be blueshifted. The photons will gain energy as they fall in a gravitational field.

$$E = hf' = 2mc^2\ (1 + g_{photon}L / c^2) = 2mc^2 + 2m\ g_{photon}\ L \qquad g_{matter} = 9.8\ m/s^2$$

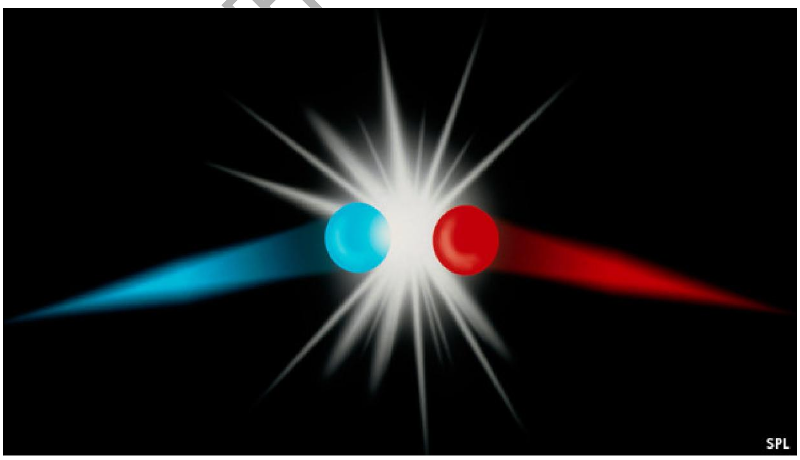


As explained above, when this equation is coupled with gravitational redshift experiments, it shows that antimatter must fall down with an acceleration within 0.04% of that of ordinary matter.

$$m\ g_{matter}\ L + m\ g_{antimatter}\ L = 2m\ g_{photon}\ L \qquad 1/2\ (g_{matter} + g_{antimatter}) = g_{photon}$$

$$g_{antimatter} = 2\ g_{photon} - g_{matter} \qquad g_{antimatter} = 2\ g_{photon} - g_{matter}$$

$$g_{antimatter} = g_{matter}\ (2 \pm 0.04) - g_{matter} = g_{matter}\ (1 \pm 0.04)$$



Thank you!