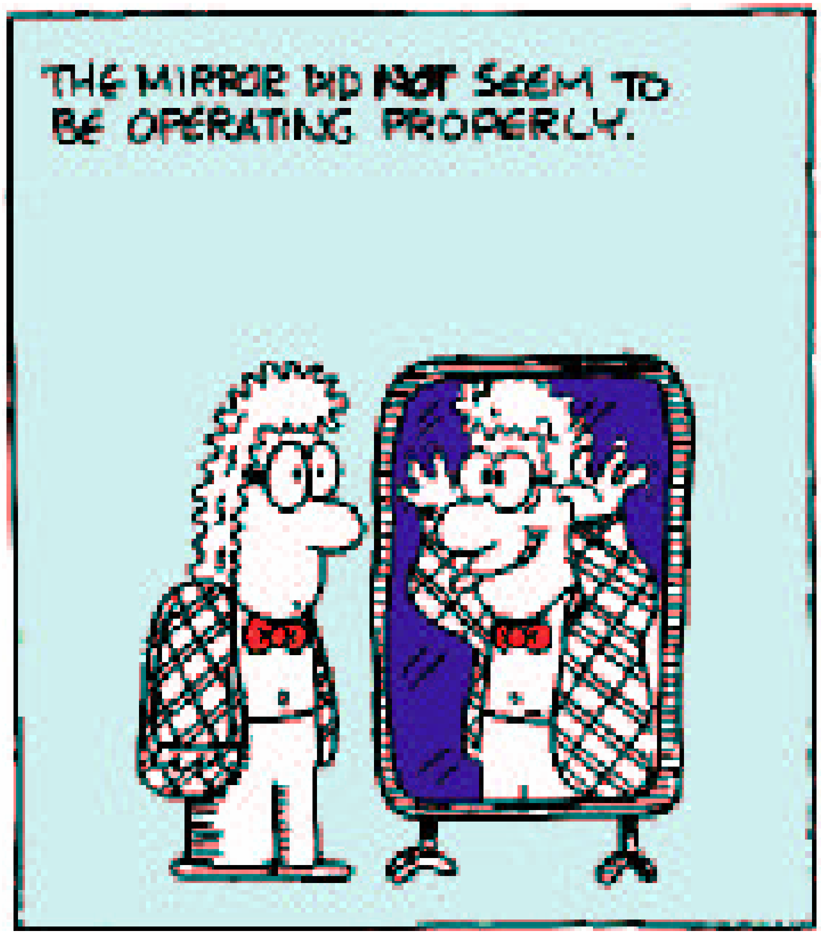
Experimental test of CP symmetry in positronium

Motivation

Previous search

Possibilities for a new experiment

Summary and outlook



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Motivation

One of the many questions…

why are there so many types of quarks and leptons and what explain their pattern of mixing and CP violation?

Theory does not answer yet
Look for new sources of CP violation, eg in the leptons, neutrinos, but also charged leptons…

Positronium can be another place where to look…

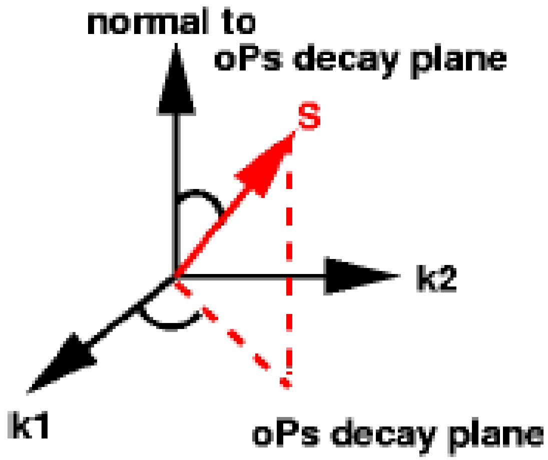
Experimental considerations

What can we measure?

Angular correlations between the ortho-positronium (oPs) spin (=1) and the momenta of the (3) photons from the oPs decay, proportional to the CP violating term in the Lagrangian

$$(\hat{S} \cdot \hat{k}_1)(\hat{S} \cdot \hat{k}_1 \times \hat{k}_2)$$

$$N(\cos\theta) = N_0(1 + C_{CP}\cos\theta)$$



$$\cos\theta \equiv \cos\theta_1 \cos\theta_2$$

How precisely?

Since the effect we want to detect is probably very small, the precision of the experiment defines our capability to detect Ccp … or not

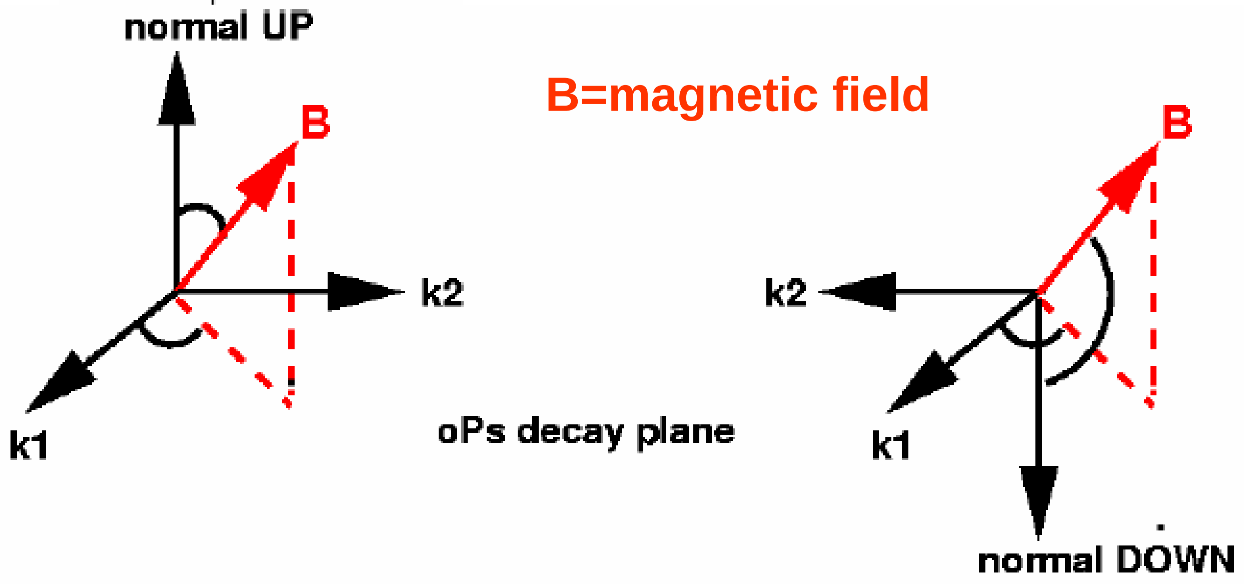
Experimental method

$$N_+ = N(\cos\theta_+)$$

$$N_- = N(\cos\theta_-)$$

$$\cos\theta_+ = \cos\theta$$

$$\cos\theta_- = -\cos\theta$$



$$N(\cos\theta_+) - N(\cos\theta_-) = 2N_0 C_{CP}\cos\theta = N_+ - N_-$$

Asymmetry

$$A = \frac{(N_+ - N_-)}{(N_+ + N_-)} = C_{CP}\cos\theta$$

Experimental method

Use an external magnetic field B to ALIGN the Ps SPIN

Recall: Ps states: singlet S=0, m= 0

triplet S=1, m= 1, 0, –1

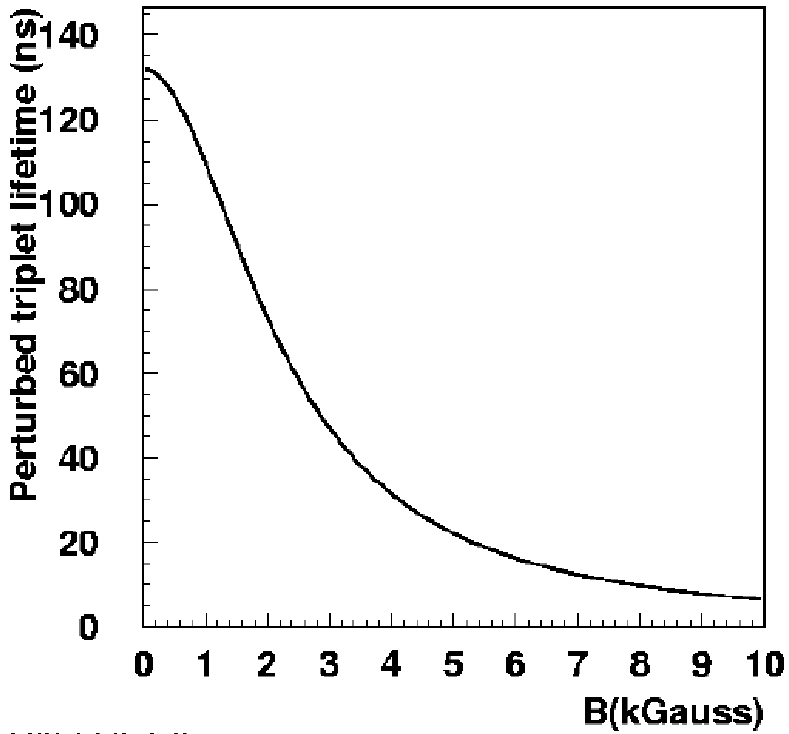
---> spin parallel, perpendicular,antiparallel to magnetic field vector

But an external magnetic field also perturbs and mix the m=0 states.

Two new states: perturbed singlet and perturbed triplet––> perturbed lifetimes

Perturbed singlet lifetime still < 1 ns

Perturbed triplet lifetime varies as a function of the B field

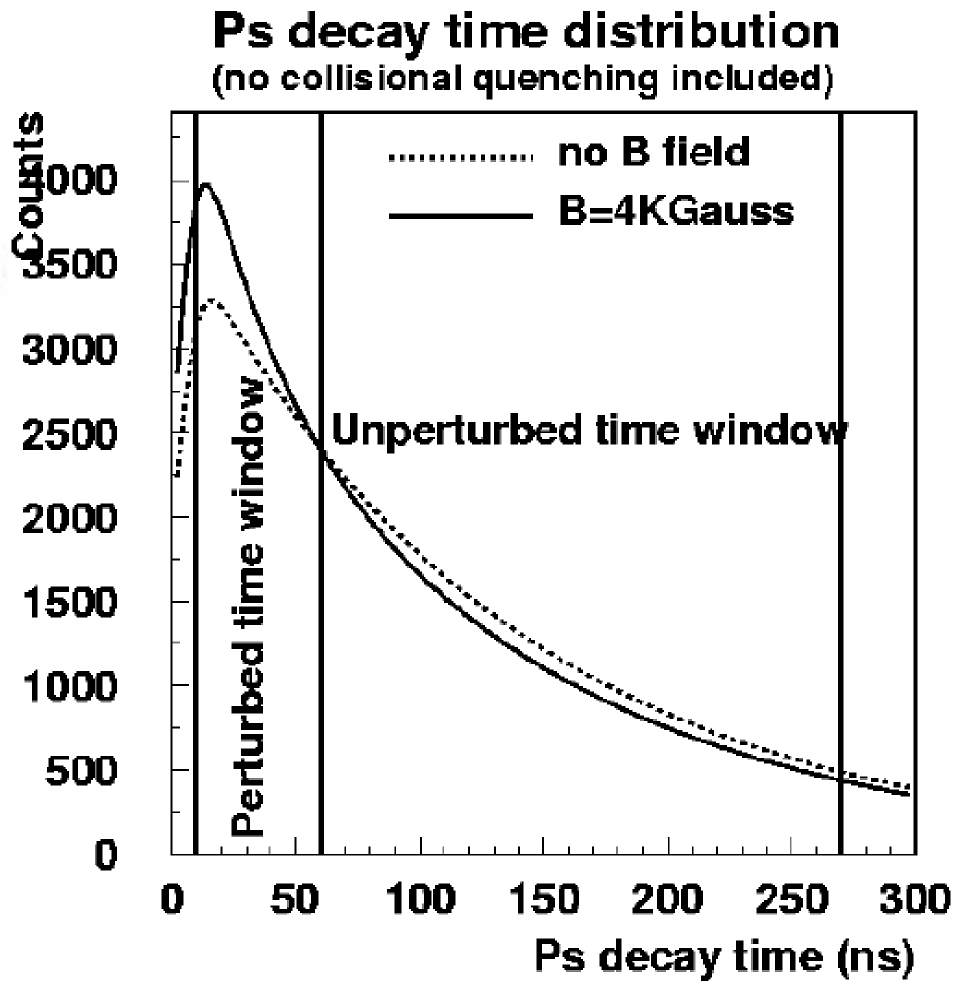


Experimental method

Exploit the perturbed triplet lifetime to possibly measure the CP violating angular correlation

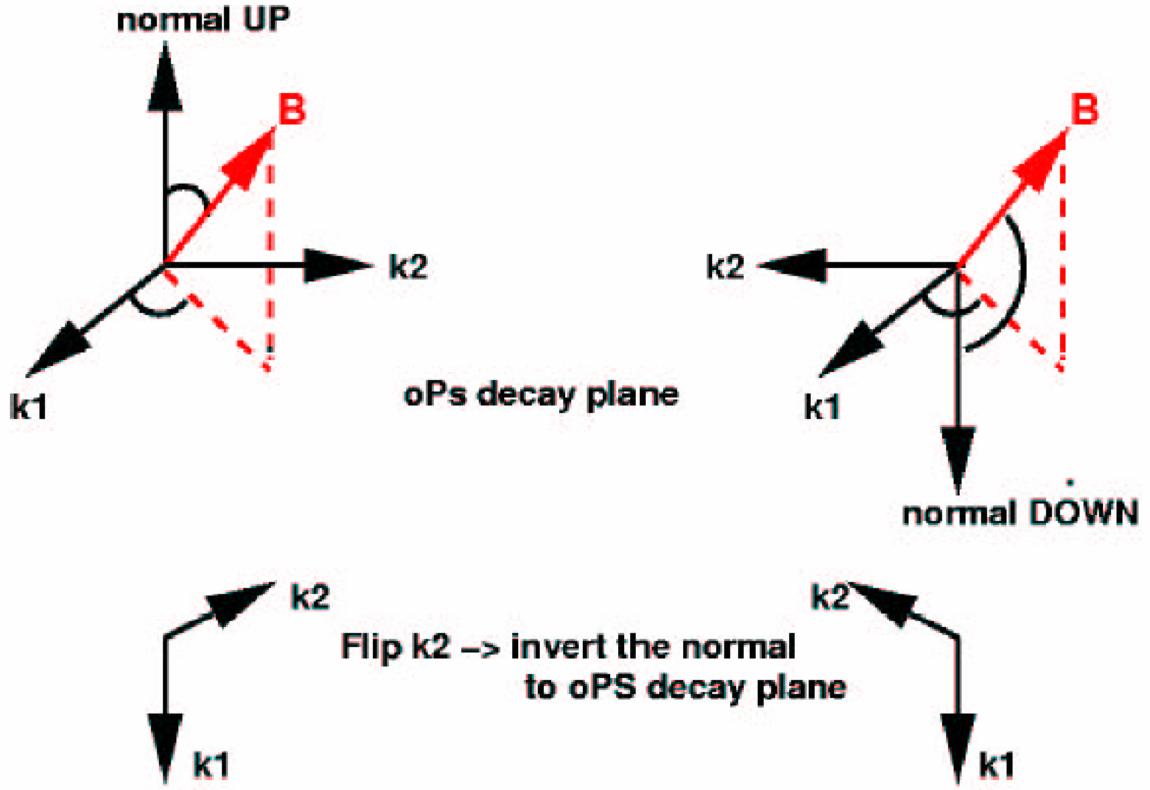
Choose a value of the perturbed triplet lifetime, so to have the best separation between perturbed and unperturbed states:
an optimal separation is obtained for

perturbed triplet lifetime ~30 ns
choose B~4KGauss



Experimental method

Record Ps decay time distribution in magnetic field
for two event configurations:
for events with normal UP and with normal DOWN
(i.e with k2 pointing in the two directions symmetric wrt k1, see fig.)



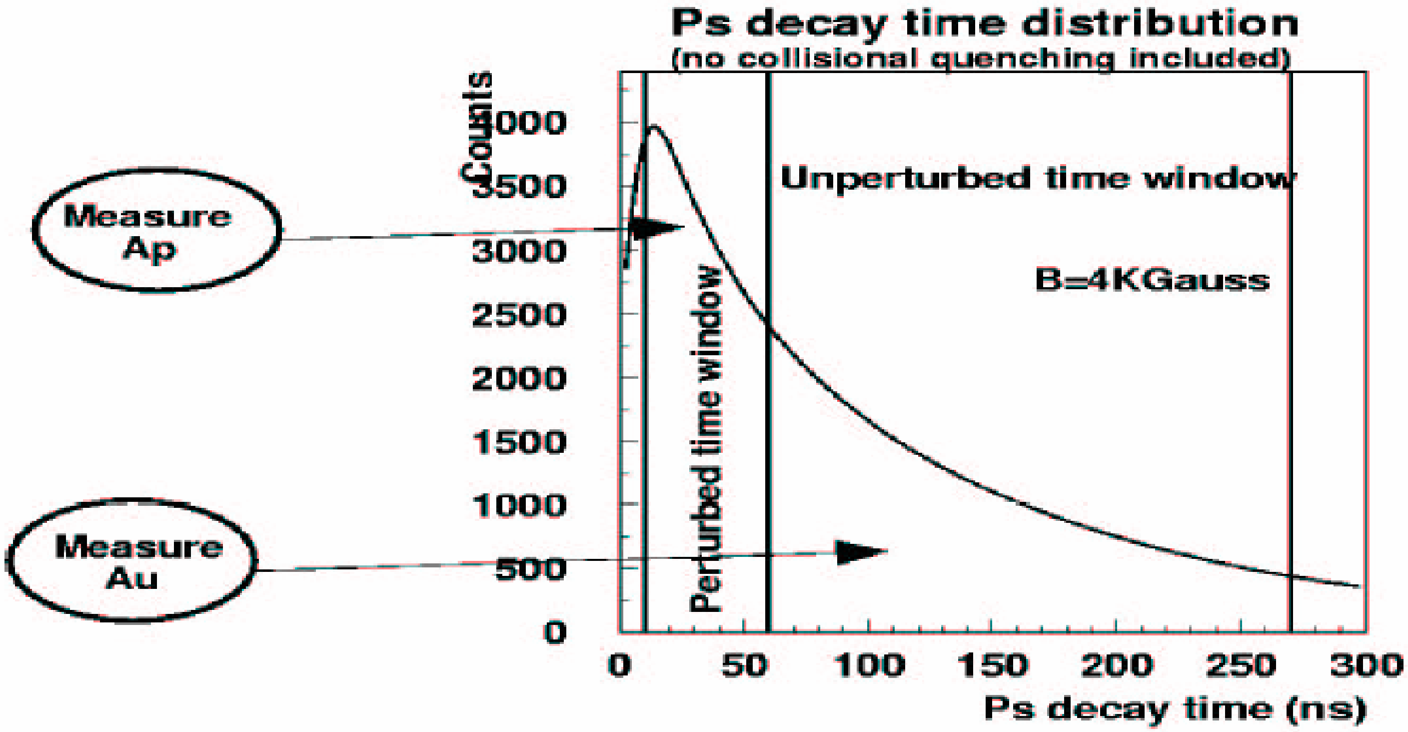
Experimental method

Measure the asymmetries Ap and Au for the perturbed and unperturbed time windows

$$A = \frac{N^{+} - N^{-}}{N^{+} + N^{-}}$$

N+ = number of events normal UP

N– = number of events normal DOWN



Experimental method

The difference: $\bar{A} = (A_u - A_p)/2$

gives a ~ systematic free measurement of the asymmetry A

dominant error on A is statistical

A is related to Ccp, the CP violation amplitude parameter, by:

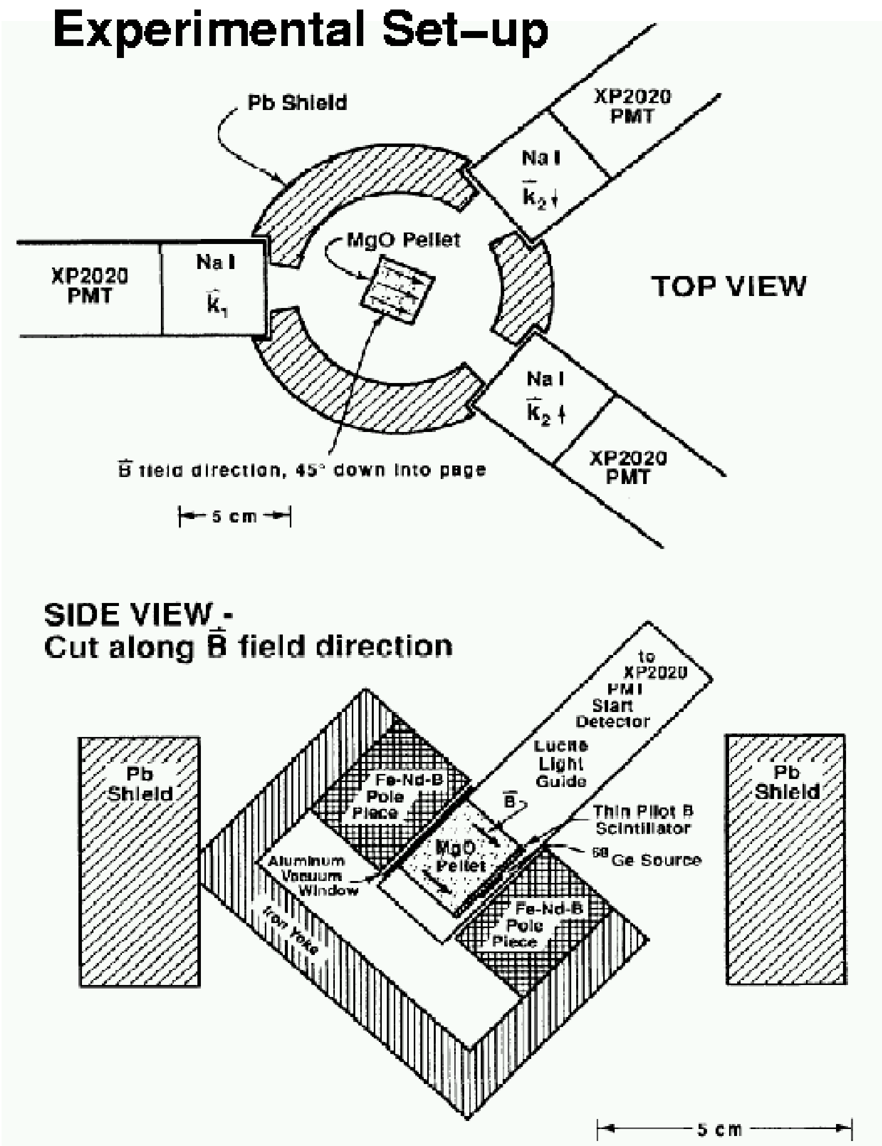
A = Ccp Q Ccp = CP violation amplitude parameter
Q = analysing power to be determined
by simulation/tests **Q < 1 for a real expt**

The sensitivity of the experiment to Ccp is determined by the error on Ccp

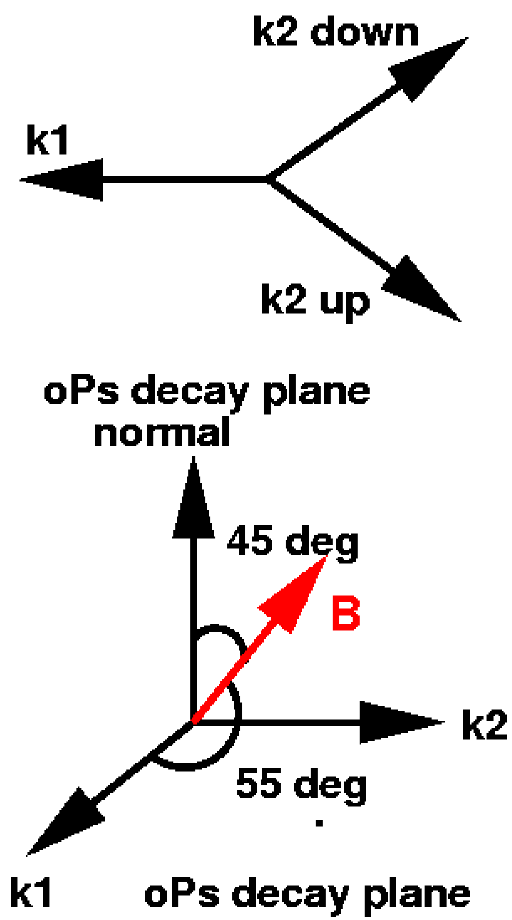
How do the errors on A and Q affect the error on Ccp?

Previous CP search with oPs

Skalsey,
Van House 91



For this experiment:



Previous CP search: results

$A_{stat} = -0.0004 \pm 0.0010$ $A_{final} = -0.0004 \pm 0.0011$

TABLE I. Measured asymmetries under differing conditions.

Test Conditions	Asymmetry A
Initial configuration	-0.0040 ± 0.0020
Interchanged $\hat{\mathbf{k}}_2$ detectors	-0.0002 ± 0.0019
Reversed $\mathbf{B}$	$+0.0011 \pm 0.0020$
Inverted Pb shield	$+0.0022 \pm 0.0024$
Wt. average	-0.0004 ± 0.0011

Relation between measured A and Ccp A = Ccp Q

$$Q = 0.072 \pm 0.0154$$

$$C_{CP} = -0.0056 \pm 0.0154$$

Previous CP search: systematics

Main systematics from
1. Shadowing of the crystals by the magnet coils
2. Identification of B direction
3. Identification of the oPs decay plane
4. Identification of backgrounds

1 and 2 can be improved by INCREASED B FIELD VOLUME

3 and 4 can be improved **BETTER DETECTOR SPATIAL (ANGULAR) RESOLUTION and IMPROVED BKGD REJECTION (SPATIAL AND ENERGY RESOL.)**

How to improve on this measurement?

Ccp = A/Q —-> How does the error on Ccp depends on the errors on the measured asymmetry A and on the analysing power Q?

Define: Δ Ccp = error on Ccp

ΔA = error on the asymmetry

ΔQ = error on the analysing power

$$\left|\frac{\Delta Ccp}{Ccp}\right|^2 = \left|\frac{\Delta A}{A}\right|^2 + \left|\frac{\Delta Q}{Q}\right|^2$$

$$\left|\frac{\Delta Ccp}{Ccp}\right|^2 \approx \frac{1}{Ccp^2}\left|\frac{\Delta A}{Q}\right|^2 + \left|\frac{\Delta Q}{Q}\right|^2 = \frac{1}{Q^2}\left[\left|\frac{\Delta A}{Ccp}\right|^2 + \Delta Q^2\right]$$

$$\Delta Ccp = \frac{1}{Q}\left[\Delta A^2 + Ccp^2\,\Delta Q^2\right]^{1/2} \approx \frac{\Delta A}{Q}$$

for Ccp<<1

An improved experiment

$$\Delta C_{cp} = \frac{1}{Q}\left[\Delta A^2 + C_{cp}^2\, \Delta Q^2\right]^{1/2} \approx \frac{\Delta A}{Q}$$

for $C_{cp} << 1$

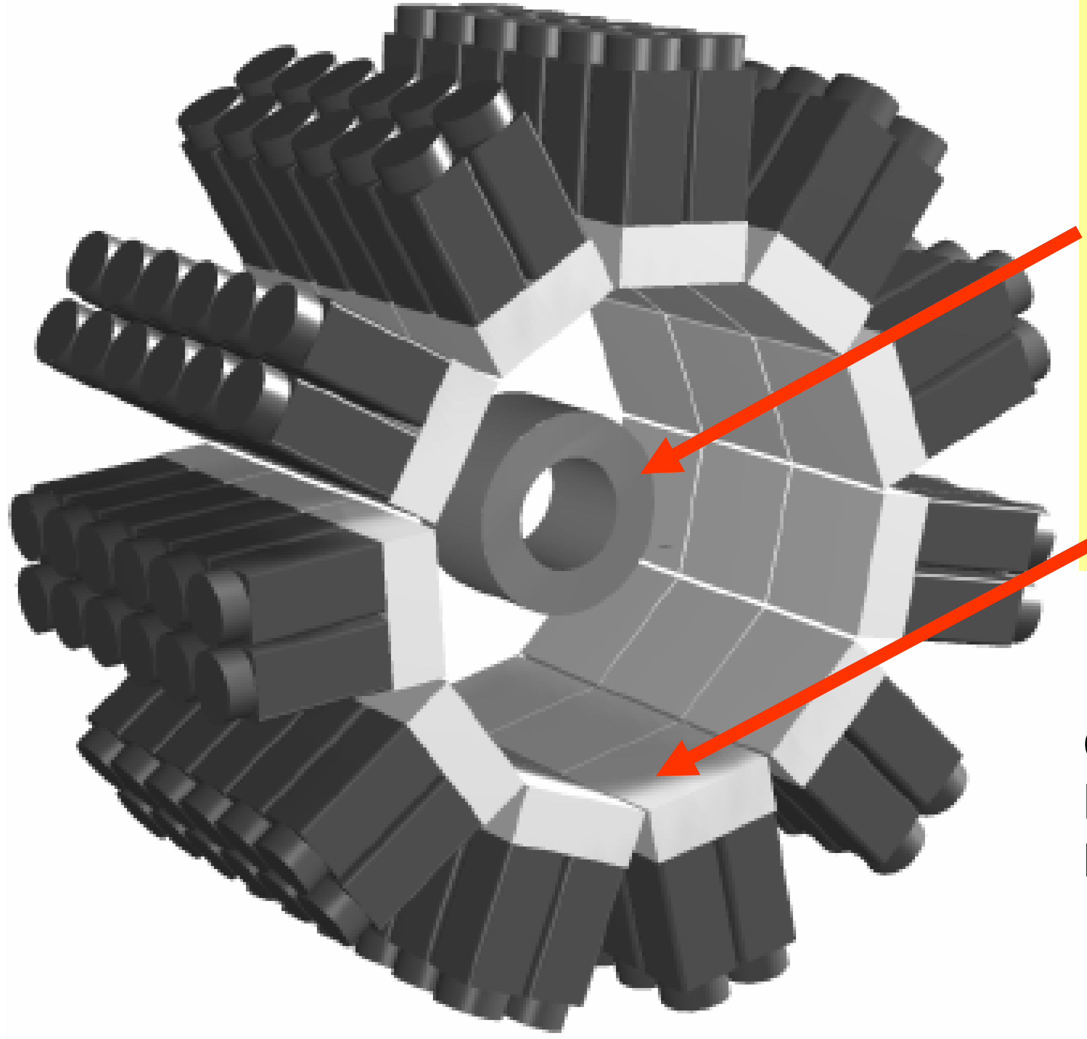
ΔA **decreases with increased event statistics,**
decreased background rate
improved angular resolution

Q **increases with improved angular and energy resolution**

Use high spatial and energy resolution detector, for precise angular measurements and improved background rejection

An improved experiment

http://www.cima-collaboration.org/



High spatial and energy resolution detector including

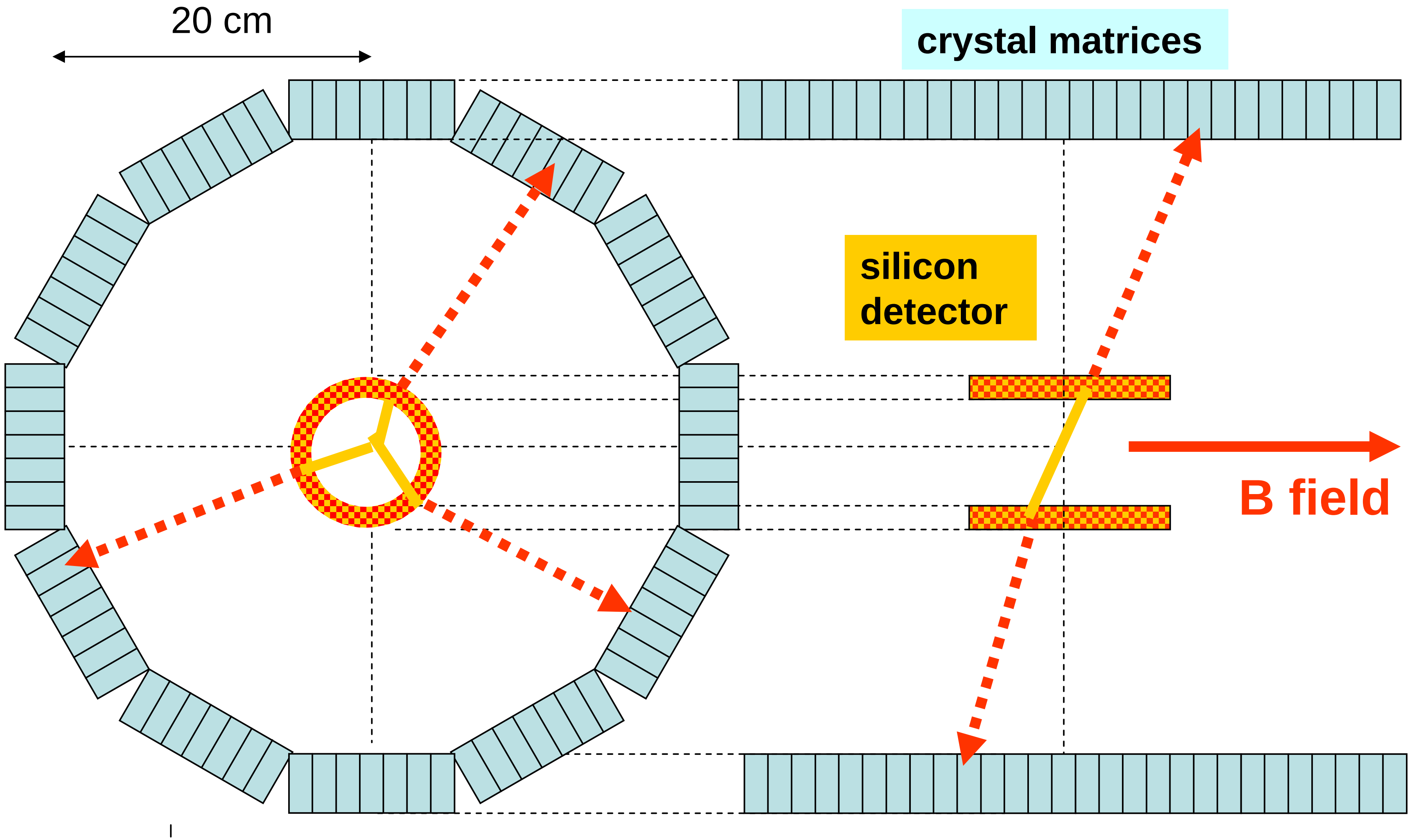
an inner ring of 3-D position-sensitive solid-state detectors

surrounded by

a ring of scintillation detectors.

Concept being developed for high-resolution Positron Emission Tomography detector

An improved experiment



Expected improved results

Using silicon pixel lateral size of 200 μm, BGO crystal energy resolution function,
and high event statistics (10^{12} events)
(similar analysis as in M.F., Int.J.Mod.Phys.A19:3853,2004)
preliminary simulation studies give

ΔA **(stat. + syst.) ~ 2 x 10^{-6}** **Q ~ 0.4**

$\Delta Ccp \approx 5 \times 10^{-6}$

Summary and outlook

Experimental observation of CP violation in positronium would be sign of physics beyond the Standard Model
Present precision on Ccp at 1% level

An experimental set-up has been proposed with the potential of reaching a precision

$$\Delta Ccp \approx 5 \times 10^{-6}$$

Is this experiment interesting?
we do not have a theory who can answer but
major discoveries have been made even if the theory did not predict them…