Experimental test of CP symmetry in positronium

Motivation

Previous search

Possibilities for a new experiment

Summary and outlook
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

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

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

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

\[ N_+ = N(\cos \theta_+) \quad N_- = N(\cos \theta_-) \]

\[ \cos \theta_+ = \cos \theta \quad \cos \theta_- = - \cos \theta \]

B=magnetic field

Asymmetry

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

\[ A = \frac{(N_+ - N_-)}{(N_+ + N_-)} = C_{CP} \cos \theta \]
Experimental method

Use an external magnetic field $B$ to ALIGN the Ps SPIN
Recall: Ps states: singlet $S=0$, $m=0$
triplet $S=1$, $m=1,0,-1$

$\rightarrow$ 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 $\rightarrow$ 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 $\sim 30$ ns
choose $B \sim 4 \text{K Gauss}$
Experimental method

Record $\Psi$s decay time distribution in magnetic field
for two event configurations:
for events with normal UP and with normal DOWN
(i.e with $k_2$ pointing in the two directions symmetric wrt $k_1$, see fig.)
Experimental method

Measure the asymmetries $A_p$ and $A_u$ 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

Ps decay time distribution
(no collisional quenching included)

Measure $A_p$

Measure $A_u$

Counts

Unperturbed time window

Perturbed time window

$B=4$K Gauss

Ps decay time (ns)
Experimental method

The difference:

$$\mathcal{A} = (A_u - A_p) / 2$$

gives a ~ systematic free measurement of the asymmetry $A$

and dominant error on $A$ is statistical

$A$ is related to $C_{cp}$, the CP violation amplitude parameter, by:

$$A = C_{cp} \cdot Q$$

$C_{cp} = \text{CP violation amplitude parameter}$

$Q = \text{analysing power to be determined by simulation/tests}$

$Q < 1$ for a real expt

The sensitivity of the experiment to $C_{cp}$ is determined by the error on $C_{cp}$

How do the errors on $A$ and $Q$ affect the error on $C_{cp}$?
Previous CP search with oPs

Skalsey, Van House 91

For this experiment:

- k1
- k2 down
- k2 up
- oPs decay plane normal
- 45 deg
- 55 deg
- k1
- oPs decay plane

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Previous CP search: results

\[ A_{\text{stat}} = -0.0004 \pm 0.0010 \quad A_{\text{final}} = -0.0004 \pm 0.0011 \]

**Table I.** Measured asymmetries under differing conditions.

<table>
<thead>
<tr>
<th>Test Conditions</th>
<th>Asymmetry ( A )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial configuration</td>
<td>(-0.0040 \pm 0.0020)</td>
</tr>
<tr>
<td>Interchanged ( \hat{K}_2 ) detectors</td>
<td>(-0.0002 \pm 0.0019)</td>
</tr>
<tr>
<td>Reversed B</td>
<td>(+0.0011 \pm 0.0020)</td>
</tr>
<tr>
<td>Inverted Pb shield</td>
<td>(+0.0022 \pm 0.0024)</td>
</tr>
<tr>
<td>Wt. average</td>
<td>(-0.0004 \pm 0.0011)</td>
</tr>
</tbody>
</table>

Relation between measured \( A \) and \( C_{CP} \):

\[ A = C_{CP} \quad Q \]

\[ Q = 0.072 \pm 0.0154 \]

\[ C_{CP} = -0.0056 \pm 0.0154 \]
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?

\[ C_{cp} = \frac{A}{Q} \quad \text{---→ How does the error on } C_{cp} \text{ depend on the errors on the measured asymmetry } A \text{ and on the analysing power } Q? \]

Define:
- \( \Delta C_{cp} = \text{error on } C_{cp} \)
- \( \Delta A = \text{error on the asymmetry} \)
- \( \Delta Q = \text{error on the analysing power} \)

\[ \left| \frac{\Delta C_{cp}}{C_{cp}} \right|^2 = \left| \frac{\Delta A}{A} \right|^2 + \left| \frac{\Delta Q}{Q} \right|^2 \]

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

\[ \Delta C_{cp} = \frac{1}{Q} \left[ \Delta A^2 + C_{cp}^2 \Delta Q^2 \right]^{1/2} \approx \frac{\Delta A}{Q} \quad \text{for } C_{cp} \ll 1 \]
An improved experiment

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

for \( C_{cp} << 1 \)

\[ \Delta A \]

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

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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

20 cm

crystal matrices

silicon detector

B field
Expected improved results

Using silicon pixel lateral size of 200 $\mu$m, 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

$$\Delta A^{(\text{stat.} + \text{syst.})} \approx 2 \times 10^{-6}$$

$$Q \approx 0.4$$

$$\Delta C_{cp} \approx 5 \times 10^{-6}$$
Summary and outlook

Experimental observation of CP violation in positronium would be sign of physics beyond the Standard Model. Present precision on $C_{\text{cp}}$ at 1% level.

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

$$\Delta C_{\text{cp}} \approx 5 \times 10^{-6}$$

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…