Experimental Tests of CPT with B Decays

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Outline:

- Why study CPT symmetry with B Decays?
- Quantities sensitive to CPT symmetry violation
- Current bounds from B Decays
- Aside: CPT in charm decay
- Conclusions
Why Search for CPT Violations in B Decays?

- CPT is preserved by local, relativistic, point-like particle theories (such as the standard model)

- Violations could result from fundamental theories

  - string theory

  - spontaneous breaking of Lorentz symmetry and CPT  
    Kostelecky, Potting ‘91

  - Standard Model extensions  
    Kostelecky, Potting ‘95  
    Colladay, Kostelecky ‘97 ‘98

  - experimental tests
Experimental Tests

- Tests in QED
  - Penning traps
  - Spectroscopy of hydrogen/antihydrogen

- Neutral Meson sensitivities
  - K decay: \[ \left| \frac{M_{K^0} - M_{\bar{K}^0}}{M_{K^0}} \right| \leq 10^{-18} \]
  - B decay: \[ \left| \frac{M_{B^0} - M_{\bar{B}^0}}{M_{B^0}} \right| \leq 10^{-16} \]
  - D decay: (?)
CP Violation in B Decay

- Physical states given by:

\[ |B_1\rangle \propto (1 + \varepsilon_b + \delta_b) |B^0\rangle + (1 - \varepsilon_b - \delta_b) |\bar{B}^0\rangle \]

\[ |B_1\rangle \propto (1 + \varepsilon_b - \delta_b) |B^0\rangle - (1 - \varepsilon_b + \delta_b) |\bar{B}^0\rangle \]

where \(\varepsilon_b, \delta_b\) are small complex parameters describing CP violation

\[ \varepsilon_b \propto -i(\Lambda_{12} - \Lambda_{21}) \quad \text{T violated} \]

\[ \varepsilon_b \propto -i(\Lambda_{11} - \Lambda_{22}) \quad \text{CPT preserved} \]

\[ \delta_b \propto -i(\Lambda_{12} - \Lambda_{21}) \quad \text{CPT violated} \]

\[ \delta_b \propto -i(\Lambda_{11} - \Lambda_{22}) \quad \text{T preserved} \]

* note: in SM, \(\delta = 0\)
δ in SM Extension

- It is a derivable quantity
- Depends on a single coupling of the form:

  \[-a_\mu^q \bar{q} \gamma^\mu q\]

  \(q\) valence quark field
  \(a_\mu^q\) spacetime constant, but depends on quark flavor

- Thus δ can be different for K,B,D
- Also, Lorentz symmetry is broken, so δ depends on boost and orientation of meson 4-velocity relative to frame in which couplings are specified
Semileptonic B Decay Rates

- Time dependent decay probabilities

\[ B_d^0 \rightarrow B_d^0 : \quad \frac{e^{-t/\tau}}{\tau} \cdot \frac{1 + \cos \Delta m_d t - 4 \text{Im} \delta_B \sin \Delta m_d t}{2k} \]

\[ B_d^0 \rightarrow \bar{B}_d^0 : \quad \frac{e^{-t/\tau}}{\tau} \cdot \frac{1 - \cos \Delta m_d t}{2k} \cdot \frac{1 - 4 \text{Re} \epsilon_B}{k} \]

\[ \bar{B}_d^0 \rightarrow \bar{B}_d^0 : \quad \frac{e^{-t/\tau}}{\tau} \cdot \frac{1 + \cos \Delta m_d t + 4 \text{Im} \delta_B \sin \Delta m_d t}{2k} \]

\[ \bar{B}_d^0 \rightarrow B_d^0 : \quad \frac{e^{-t/\tau}}{\tau} \cdot \frac{1 - \cos \Delta m_d t}{2k} \cdot \frac{1 + 4 \text{Re} \epsilon_B}{k} \]

- Mass difference $\Delta m_d$ determines oscillation frequency
A key quantity sensitive to CP and CPT violating parameters is the difference in decay rate asymmetries:

\[
D(t) = \frac{\Gamma(\bar{B} \to f) - \Gamma(\bar{B} \to f)}{\Gamma(\bar{B} \to f) - \Gamma(\bar{B} \to f)} - \frac{\Gamma(B \to f) - \Gamma(B \to \bar{f})}{\Gamma(B \to f) + \Gamma(B \to \bar{f})}
\approx -\Re\epsilon_B \cdot (1 - \cos \Delta m_d t) + 4 \Im\delta_B \sin \Delta m_d t
\]

\[
\Delta m = 0.5 \text{ ps}^{-1}
\]

\[
\Re\epsilon = 0.045
\]

\[
\Im \delta = 0.01
\]

\[
\Im \delta = 0.0
\]
CPT Limits on B Decay from LEP

- OPAL first to try this out with inclusive leptons. $Q_1$ tags flavor at decay
- $b$-hadron flavor at production using a jet charge technique incorporating information from both same-side and away-side jets: $Q_{2\text{jet}}$
- Product $Q_1 Q_{2\text{jet}}$ estimates mix or not

![Graph showing $1/N dN/d(Q_1 Q_{2\text{jet}})$ distribution]

OPAL Monte Carlo
**B Decay CPT limit (OPAL)**

\[ Q_1 Q_{2\text{jet}} > 0 \]

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**Q_1 Q_{2\text{jet}} < 0**

\[ |Q_{2\text{jet}}| > 2 \]

\[ |Q_{2\text{jet}}| < 2 \]

\[ \text{Fit result: } \operatorname{Re} \varepsilon_B = -0.006 \pm 0.010 \pm 0.006 \]

\[ \text{Im} \delta_B = -0.020 \pm 0.016 \pm 0.006 \]
Testing CPT with BTeV

- **Consider:**
  - 10,000 “effective” reconstructed semileptonic B decays
  - proper time resolution of 50 fs
  - use a jet charge technique which yields a mistag probability of 25%

- **Result:**

![Graph showing D(t) vs. proper time (ps) with data points and a fit line. The graph includes the following details:

- $\Delta m = 0.44$ ps$^{-1}$
- Re $\epsilon = 0.01$
- Im $\delta = 0.02$
- 10K signal]
Testing CPT with BTeV

- Same, but with 100K semileptonic decays

\[ \Delta m = 0.44 \text{ ps}^{-1} \]
\[ \text{Re} \, \epsilon = 0.01 \]
\[ \text{Im} \, \delta = 0.02 \]

100K signal
Aside: CPT in Charm Decay

- $D^*$ is an excellent production tag

\[ D^{*+} \rightarrow D^0 \pi^+ \quad \text{Soft } \pi^+ \text{ tags initial state} \]
\[ \downarrow \]
\[ D^0 \rightarrow K^- \pi^+ \quad (\text{right sign}) \]
\[ D^0 \rightarrow K^+ \pi^- \quad (\text{wrong sign}) \]

eg: 2% mistag prob:

\[ \Delta m = 0.5 \ \text{ps}^{-1} \]
\[ \Re \epsilon = 0.00 \]
\[ \Im \delta = 0.02 \]
\[ 100K \text{ signal} \]
Conclusions

- Fundamental theories in which Lorentz symmetry is spontaneously broken result in spontaneous CPT breaking.

- SM extensions incorporating string theory have been developed and can be tested experimentally.

- CPT symmetry tests at LEP using B decays have been surprisingly sensitive $\sim 10^{-16}$

- Data from Run II and beyond should significantly improve these constraints. This should be pursued along with other CP, mixing studies.