Future CPT Tests at Fermilab
Proposed Antiproton Experiments at Fermilab

Daniel M. Kaplan

ILLINOIS INSTITUTE OF TECHNOLOGY
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Outline

Varied menu!

• Symmetry violation tests with antiprotons
• Hyperon CP violation & rare decays
• A new experiment
• Charm & charmonium
• Antihydrogen measurements
• Competing proposals for the facility
• Summary
Symmetry Violation Tests with Antiprotons

- 3 proposed experimental programs:
  - medium-energy $\bar{p}$ annihilation
  - antihydrogen production in flight
  - slow antihydrogen

- Can search for
  - CP violation in charm and hyperons
  - CPT/Lorentz violation in charm and antihydrogen
  - CPT/Lorentz violation in antimatter gravity
Hyperon CP Violation

- Example Feynman diagrams (SM):

  \[ \text{Hyp} \text{ron Di} \text{rect CP Violation} \]

- “New physics” (SUSY, etc.) could also contribute!
Hyperon CP Violation

- CP-odd observables include $A = \Delta \alpha / \alpha$, $\Delta = \Delta \Gamma / \Gamma$.
- (anti)matter parity-violation or branching-ratio differences.
- Standard Model predicts small hyperon CP asymmetries.
- New physics can amplify them by orders of magnitude.

Table 5: Summary of predicted hyperon CP asymmetries.

<table>
<thead>
<tr>
<th>Asymmetry</th>
<th>Mode</th>
<th>SM</th>
<th>NP</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A_\Lambda$</td>
<td>$\Lambda \to p\pi$</td>
<td>$\lesssim 10^{-5}$</td>
<td>$\lesssim 6 \times 10^{-4}$</td>
<td>[68]</td>
</tr>
<tr>
<td>$A_{\Xi\Lambda}$</td>
<td>$\Xi^{+} \to \Lambda \pi$, $\Lambda \to p\pi$</td>
<td>$\lesssim 5 \times 10^{-5}$</td>
<td>$\leq 1.9 \times 10^{-3}$</td>
<td>[69]</td>
</tr>
<tr>
<td>$A_{\Omega\Lambda}$</td>
<td>$\Omega \to \Lambda K$, $\Lambda \to p\pi$</td>
<td>$\leq 4 \times 10^{-5}$</td>
<td>$\leq 8 \times 10^{-3}$</td>
<td>[36]</td>
</tr>
<tr>
<td>$\Delta_{\Xi\pi}$</td>
<td>$\Omega \to \Xi^0 \pi$</td>
<td>$2 \times 10^{-5}$</td>
<td>$\leq 2 \times 10^{-4}$ *</td>
<td>[35]</td>
</tr>
<tr>
<td>$\Delta_{\Lambda K}$</td>
<td>$\Omega \to \Lambda K$</td>
<td>$\leq 1 \times 10^{-5}$</td>
<td>$\leq 1 \times 10^{-3}$</td>
<td>[36]</td>
</tr>
</tbody>
</table>

*Once they are taken into account, large final-state interactions may increase this prediction [56].

Small sizes of $(A,\Delta)_{SM}$ favorable for NP CPV search!
The Hyperon CP Violation

- **Measurement history:**

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Decay Mode</th>
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<tr>
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<td></td>
<td>$(-6 \pm 2 \pm 2) \times 10^{-4}$ [BEACH08 preliminary]</td>
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Hyperon CP Violation

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- Previous Measurements:
  - None of the pre-HyperCP experiments had the sensitivity to test theory HyperCP probes well into regions where BSM theories predict nonzero asymmetries.
The HyperCP Collaboration has observed three events for the decay $\Sigma^+ \rightarrow p\mu^+\mu^-$ which may be interpreted as a new particle of mass 214.3 MeV. However, existing data from kaon and $B$-meson decays provide stringent constraints on the construction of models that support this interpretation. In this Letter we show that the “HyperCP particle” can be identified with the light pseudoscalar Higgs boson in the next-to-minimal supersymmetric standard model, the $A^0_1$. In this model there are regions of parameter space where the $A^0_1$ can satisfy all the existing constraints from kaon and $B$-meson decays and mediate $\Sigma^+ \rightarrow p\mu^+\mu^-$ at a level consistent with the HyperCP observation.
## Beyond HyperCP?

### Measurement history:

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### Note: until ~2000, LEAR (CERN AD predecessor) had world’s best sensitivity

- $p\bar{p}$ annihilation capable of further advance?
Antiprotons

- Fermilab Antiproton Source is world’s highest-energy and most intense

Table 1: Antiproton energies and intensities at existing and future facilities.

<table>
<thead>
<tr>
<th>Facility</th>
<th>Kinetic Energy (GeV)</th>
<th>Stacking: Rate (10^{10}/hr)</th>
<th>Duty Factor</th>
<th>Operation: Hours /Yr</th>
<th>( \bar{p} / \text{Yr} ) (10^{13})</th>
</tr>
</thead>
<tbody>
<tr>
<td>CERN AD</td>
<td>0.005</td>
<td>–</td>
<td>–</td>
<td>3800</td>
<td>0.4</td>
</tr>
<tr>
<td></td>
<td>0.047</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fermilab Accumulator:</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>now</td>
<td>8</td>
<td>20</td>
<td>90%</td>
<td>5550</td>
<td>100</td>
</tr>
<tr>
<td>proposed</td>
<td>( \approx 3.5-8 )</td>
<td>20</td>
<td>15%</td>
<td>5550</td>
<td>17</td>
</tr>
<tr>
<td>FAIR (( \gtrsim 2018 ))</td>
<td>2–15</td>
<td>3.5</td>
<td>90%</td>
<td>2780*</td>
<td>9</td>
</tr>
</tbody>
</table>

...even after FAIR@Darmstadt turns on

\( \Rightarrow \) exceeds LEAR \( \bar{p} \) intensity (<1 MHz) by 10 orders of magnitude!
A Possible Approach

One possibility:

- Once Tevatron shuts down (≈2011?),
  - Reinstall E760 EM spectrometer
  - Add small magnetic spectrometer
  - Add precision TOF system
  - Add wire or pellet target
  - and fast DAQ system

- Run \( p\bar{p} = 5.4 \text{ GeV/c} \) \( (2m_{\Omega} < \sqrt{s} < 2m_{\Omega} + m_{\Xi^0}) \)
  @ \( \mathcal{L} \sim 10^{32} \text{ cm}^{-2} \text{ s}^{-1} \) (10 × E835)

\[ \sim \text{few} \times 10^8 \Omega^- \Xi^+ / \text{yr} + \sim 10^{12} \text{ inclusive hyperon events!} \]
What Can This Do?

• Observe many more $\Sigma^+ \rightarrow p\mu^+\mu^-$ events and confirm or refute SUSY interpretation

• Discover or limit $\Omega^- \rightarrow \Xi^- \mu^+\mu^-$ and confirm or refute SUSY interpretation

• Discover or limit CP violation in $\Omega^- \rightarrow \Lambda K^-$ and $\Omega^- \rightarrow \Xi^0 \pi^-$ via partial-rate asymmetries

Predicted $\mathcal{B} \sim 10^{-6}$ if $P^0$ real

Predicted $\Delta \mathcal{B} \sim 10^{-5}$ in SM, $\leq 10^{-3}$ if NP
Also good for "charmonium" (\(c\bar{c}\) QCD "hydrogen atom"):

- Fermilab E760/835 used Antiproton Accumulator for precise (\(\lesssim 100\) keV) measurements of charmonium parameters, e.g.:
  - best measurements of \(\eta_c, \chi_c, h_c\) masses, widths, branching ratios,...

\(p\bar{p}\) produces all quantum states (not just \(1^{--}\), unlike \(e^+e^-\))
• Much interest in mysterious states recently discovered in charmonium region: $X(3872)$, $X(3940)$, $Y(3940)$, $Y(4260)$, $Z(3930)$, ...

• $X(3872)$ of particular interest – may be the first meson-antimeson ($D^0 \overline{D}^{*0} + \text{c.c.}$) molecule

$\Rightarrow$ need very precise mass & width measurement to confirm or refute

$\Rightarrow \overline{p}p \rightarrow X(3872)$ formation ideal for this
E. Braaten estimate of $\bar{p}p$ $X(3872)$ coupling assuming $X$ is $D^*D$ molecule
- extrapolates from $K^*K$ data

By-product is $D^{*0}\bar{D}^0$ cross section
D*D cross-section estimate (after E. Braaten, PRD 77, 034019)

(Expect good to factor ~3)

- E. Braaten estimate of \( \bar{p}p \) \( X(3872) \) coupling assuming \( X \) is \( D^*D \) molecule
  - extrapolates from \( K^*K \) data
- By-product is \( D^{*0}\bar{D}^{0} \) cross section
  - 1.3 \( \mu b \) → 5 \( \times 10^9 \)/year
- Expect efficiency as at \( B \) factories
Charm!

- What’s so exciting about charm?

> $D^0$’s mix! (c is only up-type quark that can)

- **Big question:** New Physics or old?

  - Key is CP Violation!

- $B$ factories have $\sim 10^9$ open-charm events

- Can $\bar{p}p$ produce $\sim 10^{10}$/y?
Charm!

- What’s so exciting about charm?

- $D^0$’s mix! (c is only up-type quark that can)
  
  Singly Cabibbo-suppressed (CS) $D$ decays have 2 competing diagrams:
  
  a)
  
  Singly Cabibbo-suppressed (CS) $D$ decays have 2 competing diagrams:
  
  a)
  
  b)

- Big question: New Physics or old?
  
  - key is CP Violation!

- $B$ factories have $\sim 10^9$ open-charm events
  
  - can $\bar{p}p$ produce $\sim 10^{10}/\gamma$?

- world’s best sensitivity to charm CPV
Charm!

- Ballpark sensitivity estimate based on Braaten formula:

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Running time</td>
<td>$2 \times 10^7$</td>
<td>s/y</td>
</tr>
<tr>
<td>Duty factor</td>
<td>0.8*</td>
<td></td>
</tr>
<tr>
<td>$\mathcal{L}$</td>
<td>$2 \times 10^{32}$</td>
<td>cm$^{-2}$s$^{-1}$</td>
</tr>
<tr>
<td>Target $A$ (Al)</td>
<td>27</td>
<td></td>
</tr>
<tr>
<td>$A^{0.29}$</td>
<td>2.6</td>
<td></td>
</tr>
<tr>
<td>$\sigma(p\bar{p} \rightarrow D^{*+}X)$</td>
<td>1.25</td>
<td>µb</td>
</tr>
<tr>
<td># $D^{*\pm}$ produced</td>
<td>$2.1 \times 10^{10}$</td>
<td>events/y</td>
</tr>
<tr>
<td>$B(D^{*+} \rightarrow D^0\pi^+)$</td>
<td>0.677</td>
<td></td>
</tr>
<tr>
<td>$B(D^0 \rightarrow K^-\pi^+)$</td>
<td>0.0389</td>
<td></td>
</tr>
<tr>
<td>Acceptance</td>
<td>0.5</td>
<td></td>
</tr>
<tr>
<td>Efficiency</td>
<td>0.1</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>$2.7 \times 10^6$</td>
<td>events/y</td>
</tr>
</tbody>
</table>

- Compare with $1.22 \times 10^6$ total tagged evts at Belle [M. Staric et al., PRL 98, 211803 (2007)]

(LHCb will have comparable statistics but diff’t systematics)
Testing CPT/LV with Charm

- SME limits from FNAL FOCUS Expt. [J.M. Link et al., PLB 556 (2003) 7]:
  
  \(-2.8 < N(x, y, \delta)(\Delta a_0 + 0.6 \Delta a_Z) < 4.8 \times 10^{-16} \) GeV
  
  \((-7.0 < N(x, y, \delta)\Delta a_X < 3.8 \times 10^{-16} \) GeV
  
  \((-7.0 < N(x, y, \delta)\Delta a_Y < 3.8 \times 10^{-16} \) GeV

  - based on \(\approx 2 \times 10^4\) right-sign \(D^0\) and \(\bar{D}^0\) decays

- We hope for \(\times 10^3\) increase in sample size

- But effects \(\propto \gamma \approx 2, 20 \times\) smaller than in FOCUS

  \(\Rightarrow\) sensitivities likely comparable

(but we can do better now that mixing measured)
Charm?

- Another possibility (E. Braaten): use the $X(3872)$ as a pure source of correlated $D^*{}^0\overline{D}^0$ events
  
  - the $\overline{p}p$ equivalent of the $\psi(3770)$!? 
  - assuming current Antiproton Accumulator parameters ($\Delta p/p$) & Braaten estimate, produce $\sim 10^8$ events/year 
  - comparable to BES-III statistics 
  - could gain factor $\sim 5$ via AA $e^- \text{ cooling}$?

- Proposed expt will establish feasibility & reach
Antihydrogen

CPT test using relativistic antihydrogen

[D. Christian, FNAL]

- Antihydrogen is produced in the gas-jet target - exits the Accumulator in the ground state.
  - 99 antihydrogen atoms were observed by E862 with 0 background.
- The atoms enter a 7kG magnet and a large fraction are excited to N=2 long-lived Stark state by laser light.
- Atoms exit magnet & pass through a field-free region, then enter a second magnet with field 6-8 kG. The mixture of N=2 Stark states in the second magnet depends on the time spent in the field-free region, the fine structure, and the Lamb shift.
- Distribution of field ionization in the second magnet reflects probability of being in each of the three N=2 Stark states.

Monte Carlo ---+ an experiment in which 100 atoms exit the first magnet in N=2,L will yield a 1% measurement of the fine structure and a 5% measurement of the Lamb shift. Assuming that only the 2S level is shifted by a CPT violating force, the 1σ sensitivity is 50 parts per billion of the 2S binding energy.
Antihydrogen

• Parasitic running appears feasible
  ➞ need not wait for end of Tevatron program

• High-Z foil installed, operable in Antiproton Accumulator beam halo

• Next need to install thin exit window (this shutdown)

• Could subsequently assemble spectroscopy apparatus (magnets, laser, detectors) and begin shakedown and operation

• Hope for few-per-$10^9$ precision with respect to $2S$ binding energy
Antimatter Gravity

- Experimentally, unknown whether antimatter falls up or down! Or whether $g - \bar{g} = 0$ or $\varepsilon$. Or (IPM) $0.5g$? [AK&JT]
  - In principle a simple interferometric measurement with slow $\bar{H}$ beam [T. Phillips, Hyp. Int. 109 (1997) 357]:

  - Not nutty!
  
  $\bar{g} = -g$ gives natural explanations for baryon asymmetry & dark energy
  $\bar{g} = g + \varepsilon$ natural in quantum gravity due to scalar & vector terms

  $\Rightarrow$ tests for possible "5th forces"

- $\sim 10^{-4}$ feasible with matter gratings
- $\sim 10^{-9}$ with laser interferometer
With end of Tevatron Collider in sight, many are viewing Antiproton Source as generic resource:

- 2 large-acceptance 8 GeV rings
  ➤ can they be reconfigured to enable $\mu 2e$, $g - 2$, etc.?

This ignores large, unique value for $\bar{p}$ physics!

- with >1 G€ expenditure in progress on FAIR, can cannibalizing FNAL pbar source truly be sensible?!

Nevertheless, $\mu 2e$ may eliminate FNAL pbar option starting around 2017

- leaves at least 4–5-year window of opportunity during which FNAL $\bar{p}$ capabilities are unique in the world
Letters of Intent

- Initial Letters of Intent prepared in ’08, revised ’09
- Physics Advisory C’tee & Director Oddone:
  1. Interesting physics!
  2. Antimatter Gravity: need $10^{-9}$ matter demonstration before FNAL can provide support
     - Techniques for $10^{-9}$ matter demonstration under development (M. Raizen et al., UT Austin)
  3. Antiproton Annihilation: can be considered further at this time only if cost to Lab is minimal
     - Proposal in development – Lab funding not essential
Summary

• Best experiment yet on hyperons, charm, and charmonia may soon be feasible at Fermilab
  - including world’s most sensitive charm CPV study

• Unique tests of CPT symmetry & antimatter gravity may be starting up soon

• pbar Source offers simplest way for Fermilab to have broad program in post-Tevatron era

👉 Please help spread the word! (Want to join?)

(See http://capp.iit.edu/hep/pbar/)