A NEW EXPERIMENT TO STUDY HYPERON CP VIOLATION AND THE CHARMONIUM SYSTEM

DANIEL M. KAPLAN

Physics Division, Illinois Institute of Technology
Chicago, Illinois 60616, USA
kaplan@iit.edu

Fermilab operates the world's most intense antiproton source, now exclusively dedicated to serving the needs of the Tevatron Collider. The anticipated 2009 shutdown of the Tevatron presents the opportunity for a world-leading low- and medium-energy antiproton program. We summarize the status of the Fermilab antiproton facility and review physics topics for which a future experiment could make the world's best measurements.

Keywords: antiproton; hyperon; charmonium.

1. Introduction

An international collaboration is proposing[1] to revive the experimental program at the Fermilab Antiproton Accumulator. We summarize the goals of this effort in the context of other efforts world-wide.

1.1. *Antiproton sources*

The world's highest-energy and highest-intensity antiproton source is at Fermilab. Having previously supported medium-energy antiproton fixed-target experiments (including the charmonium experiments E760 and E835), it is now 100% dedicated to providing luminosity for the Tevatron Collider. At CERN, the LEAR antiproton storage ring was decommissioned in 1996; its successor facility, the Antiproton Decelerator (AD), provides antiproton beams at momenta of 100 and $300\,\mathrm{MeV}/c$, at intensities up to $\approx 2 \times 10^7$ per minute.[2] These are the only operating facilities. Germany has embarked on a ≈billion-Euro upgrade for the GSI-Darmstadt nuclear-physics laboratory, with planned construction by ≈ 2014 of 30 and $90\,\mathrm{GeV}$ rapid-cycling synchrotrons and low- and medium-energy antiproton storage rings.[3]

1.2. *Physics with antiproton sources*

Many interesting topics can be addressed with such a facility, including

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- precision $\bar{p}p \to$ charmonium studies, begun by Fermilab E760 and E835;
- open-charm studies, including searches for $D^0/\overline{D}^0$ mixing and CP violation;
- studies of $\bar{p}p \to$ hyperons, including hyperon CP violation and rare decays;
- the search for glueballs and gluonic hybrid states predicted by QCD; and
- trapped-$\bar{p}$ and antihydrogen studies.

Needed beam energy or intensity makes only the last of these possible at the CERN AD. All have been discussed as program components of the GSI-FAIR (Facility for Antiproton and Ion Research) project[3] and its general-purpose PANDA detector.[4] However, GSI-FAIR construction has yet to begin, and PANDA data taking is not expected before 2014. Table 1 gives some relevant mass and momentum thresholds.

Table 1.   Thresholds for some processes of interest in $\sqrt{s}$ and $\bar{p}$ momentum in the lab frame for $\bar{p}p$ fixed-target.

Process	Threshold	
	$\sqrt{s}$ (GeV)	$p_{\bar{p}}$ (GeV/c)
$\bar{p}p \to \overline{\Lambda}\Lambda$	2.231	1.437
$\bar{p}p \to \overline{\Sigma}^-\Sigma^+$	2.379	1.854
$\bar{p}p \to \overline{\Xi}^+\Xi^-$	2.642	2.620
$\bar{p}p \to \overline{\Omega}^+\Omega^-$	3.345	4.938
$\bar{p}p \to \eta_c$	2.980	3.678
$\bar{p}p \to \psi(3770)$	3.771	6.572
$\bar{p}p \to X(3872)$	3.871	6.991
$\bar{p}p \to X$ or $Y(3940)$	3.940	7.277
$\bar{p}p \to Y(4260)$	4.260	8.685

A number of intriguing recent discoveries can be elucidated at such a facility: the states provisionally named $X(3872)$, $X(3940)$, $Y(3940)$, $Y(4260)$, and $Z(3930)$ in the charmonium region,[5] as well as the observation of apparent flavor-changing neutral currents (FCNC) in hyperon decay;[6] indeed, high sensitivity can be achieved to symmetry-violating or rare hyperon decays generally. In addition, the h_c mass and width, χ_c radiative-decay angular distributions, and $\eta'_c(2S)$ full and radiative widths, important parameters of the charmonium system that remain to be precisely determined, are well suited to the $\bar{p}p$ technique.[7,8]

1.3. Quarkonium physics

Heavy-quark–antiquark bound states ("quarkonia") offer a unique testing ground for QCD. Both potential models and lattice-gauge Monte Carlo successfully predict aspects of heavy-quark systems. Quenched-approximation lattice-QCD predictions of the masses of low-lying charmonium states agree qualitatively with the experimental values;[9] this agreement is expected to improve once dynamical quarks on the
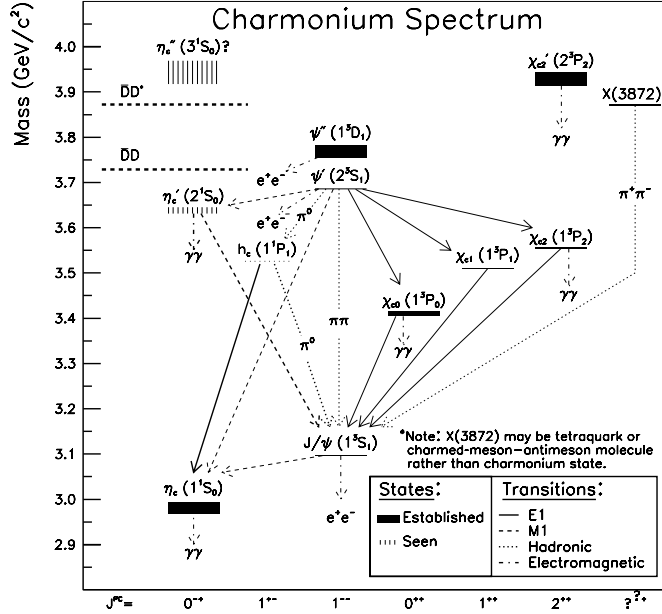
Fig. 1.   Spectrum of the charmonium system. Shown are masses, widths (or for those not yet measured, 90% confidence level upper limits on widths), and quantum numbers of observed charmonium states, with some of the important transitions also indicated.[10,5]

lattice (now being implemented by various groups) are successfully incorporated.[11] Charmonium (Fig. 1) is an important proving ground for QCD: the c and $\bar{c}$ quarks are slow enough that relativistic effects are significant but not dominant, and are sufficiently massive that non-perturbative effects are small but not negligible. Once certified by experiment, these calculational techniques can then be confidently applied in interpreting such physics results as *CP* asymmetries in the beauty system.

Fermilab experiments E760 and E835 made the world's most precise measurements of charmonium masses and widths.[7,8] This precision ($\lesssim 100\,\mathrm{keV}$) reflects the narrow energy spread of the stochastically cooled antiproton beam and the absence of Fermi motion and negligible energy loss in hydrogen cluster-jet targets. The other key advantage of $\bar{p}p$ annihilation is its ability to produce charmonium states of all quantum numbers, whereas e^+e^- machines produce primarily 1^{--} states.

1.4. *Our proposal*

We are proposing a focused experimental program aimed at those measurements for which the Antiproton Source is best suited: (1) precision studies of states in the charmonium region and (2) the search for new physics in hyperon decay. These measurements can be performed with a common apparatus using existing technologies. Depending on available resources, existing detector components might be recycled for these purposes; alternatively, modest expenditures for new equipment could yield

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improved performance. The opportunity for such studies will soon arrive, with the planned 2009 shutdown of the Tevatron. The importance of these measurements justifies the resumption of such a program at Fermilab.

2. Capabilities of the Fermilab Antiproton Source

The Antiproton Source maximum stacking rate is now $\approx 20\,\mathrm{mA/hr}$ (or $2\times10^{11}\,\overline{p}/\mathrm{hr}$), five times that in E835.[7] We propose to run with up to ten times the typical E835 luminosity[7] ($\mathcal{L} \lesssim 2 \times 10^{32}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$), via increased store intensity or target density. Since stochastic cooling works best with small stacks, more intense stores seem nonoptimal. The E835 cluster-jet target (an upgrade of the E760 one) produced[7] up to $\approx 2.5\times10^{14}\,\mathrm{atoms/cm}^2$. Higher cluster-jet density is proposed for the PANDA program (also planned for $\mathcal{L} = 2\times10^{32}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$).[4] Other options include a plastic or metal wire or pellet in the beam halo,[12] a solid-H_2 target on the tip of a cold finger, or a stream of H_2 pellets. A non-H_2 target, while suitable for hyperon running, would destroy the superb energy resolution needed for the charmonium studies. We favor simultaneous charmonium and hyperon running with an H_2 target.

3. Physics Goals

To clarify issues for a future antiproton facility, we consider representative physics examples: studying the $X(3872)$, improved measurement of the parameters of the h_c, searching for hyperon CP violation, and studying a recently discovered rare hyperon-decay mode. (This list is not exhaustive; see Sec. 3.5 for additional topics.)

3.1. $X(3872)$

The $X(3872)$ was discovered[13] in 2003 by the Belle Collaboration via $B^{\pm} \rightarrow K^{\pm}X(3872)$, $X(3872) \rightarrow \pi^+\pi^- J/\psi$, and quickly confirmed by CDF,[14] DØ,[15] and BaBar.[16] Now seen (Table 2) in $\gamma J/\psi$,[17] $\pi^+\pi^-\pi^0 J/\psi$,[18] and $D^0\overline{D}^0\pi^0$ modes[19] as well, it does not appear to fit within the charmonium spectrum. Although well above open-charm threshold, its width[10] ($< 2.3\,\mathrm{MeV}$ at 90% C.L.) implies that decays to $D\overline{D}$ are forbidden, suggesting unnatural parity,[9] $P = (-1)^{J+1}$. It is a poor candidate for $\psi_2\,(1\,^3D_2)$ or $\psi_3\,(1\,^3D_3)$[5,18,9] due to nonobservation of radiative transitions to χ_c. The observation of $X(3872) \rightarrow \gamma J/\psi$ implies positive C-parity, and additional observations essentially rule out all possibilities other than $J^{PC} = 1^{++}$.[20,21] The available charmonium assignment with those quantum numbers, $\chi'_{c1}\,(2\,^3P_1)$, is highly disfavored[5,9] by the observed rate of $X(3872) \rightarrow \gamma J/\psi$. Moreover, the plausible identification of $Z(3930)$ as the $\chi'_{c2}\,(2\,^3P_2)$ suggests[5] that the $2\,^3P_1$ should lie some $49\,\mathrm{MeV}/c^2$ higher than the observed[10] $m_X = 3871.2 \pm 0.5\,\mathrm{MeV}/c^2$.

The coincidence of the $X(3872)$ with $D^0\overline{D}^{*0}$ threshold suggests various solutions to this puzzle, including an S-wave cusp[22] or a tetraquark state.[23] An intriguing possibility is that the $X(3872)$ represents the first clear-cut observation of a meson-

Table 2.   Experimental observations of $X(3872)$.

Experiment	Year	Mode	Events	Ref.
Belle	2003	$\pi^+\pi^- J/\psi$	35.7 ± 6.8	13
CDF	2004	$\pi^+\pi^- J/\psi$	730 ± 90	14
D0	2004	$\pi^+\pi^- J/\psi$	522 ± 100	15
Belle	2004	$\omega(\pi^+\pi^-\pi^0) J/\psi$	10.6 ± 3.6	18
BaBar	2005	$\pi^+\pi^- J/\psi$	25.4 ± 8.7	16
Belle	2005	$\gamma J/\psi$	13.6 ± 4.4	17
Belle	2006	$D^0 \overline{D}{}^{*0}$	23.4 ± 5.6	19

antimeson molecule: a bound state of $D^0\overline{D}{}^{*0} + D^{*0}\overline{D}{}^0$.[24] [a] A key measurement is the precise mass difference between the X and that threshold, which should be slightly negative, in accord with the small molecular binding energy:[21]

$$0 < E_X = (m_{D^0} + m_{D^{*0}} - m_X)c^2 \ll 10 \, \text{MeV} \,. \tag{1}$$

A measurement of the width is also highly desirable.

With the latest CLEO measurement,[25] $M_{D^0} = 1864.847 \pm 0.150 \pm 0.095 \, \text{MeV}/c^2$, and the world-average[10] $m_{D^{*0}} - m_{D^0} = 142.12 \pm 0.07 \, \text{MeV}/c^2$, we have $E_X = 0.6 \pm 0.6 \, \text{MeV}/c^2$, with the uncertainty dominated by that of m_X. When our precision measurement is made, it will still dominate, assuming the total uncertainty on m_{D^0} improves roughly as $1/\sqrt{N}$ as the statistics of the CLEO analyzed sample increase by an order of magnitude.[26] Additional important measurements include $\mathcal{B}[X(3872) \to \pi^0\pi^0 J/\psi]$ to confirm the C-parity assignment[27] and $\mathcal{B}[X(3872) \to \gamma\psi']$ to further tighten the constraints with respect to the $2\,^3P_1$ assignment.[5]

3.1.1. $X(3872)$ *sensitivity estimate*

The $\bar{p}p \to X(3872)$ cross section is unmeasured but estimated to be similar in magnitude to those for χ_c.[28] This estimate is supported by the observed rates and distributions of $\bar{p}p \to X(3872) +$ anything at the Tevatron[15] and of $B^\pm \to K^\pm X(3872)$,[10] which resemble those for charmonium states. E760 detected $\chi_{c1}, \chi_{c2} \to \gamma J/\psi$ (branching ratios of 36% and 20%, respectively[10]) with $44 \pm 2\%$ acceptance $\times$ efficiency and ≈ 500 observed events per pb^{-1} at each resonance.[29] At $10^{32}\,\text{cm}^{-2}\text{s}^{-1}$, the 90%-C.L. limit[30] $\mathcal{B}[X(3872) \to \pi^+\pi^- J/\psi] > 0.042$ then implies $\gtrsim 4 \times 10^3$ events in that mode per nominal month $(1.0 \times 10^6\,\text{s})$ of running. Current sample sizes (Table 2) are likely to increase by not much more than an order of magnitude as experiments complete during the current decade.[b]

Given the uncertainties in the cross section and branching ratios, the above may well be an under- or overestimate of the $\bar{p}p$ formation and observation rates,

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[a]The mass coincidence may be accidental, and the $X(3872)$ a $c\bar{c}$-gluon hybrid state; however, the mass and 1^{++} quantum numbers make it a poor match to lattice-QCD predictions for such states.[5]
[b]The $\bar{p}p \to X(3872)$ sensitivity will be competitive even with that of the proposed SuperKEKB upgrade,[31] should that project go forward.

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perhaps by as much as an order of magnitude. Nevertheless, it appears that a new experiment at the Antiproton Accumulator could obtain the world's largest clean samples of $X(3872)$, in perhaps as little as a month of running. The high statistics, event cleanliness, and unique precision available in the $\bar{p}p$ formation technique could enable the world's smallest systematics. Such an experiment could thus provide a definitive test of the nature of the $X(3872)$.

3.2. h_c

Observing the $h_c\,(1\,^1P_1)$ charmonium state and measuring its parameters were high-priority goals of E760, E835, and their predecessor experiment, CERN R704. As a narrow state with suppressed couplings both to e^+e^- and to the states that are easily produced in e^+e^- annihilation, the h_c is a difficult state to study experimentally.

The pioneering charmonium experiment R704 was one of the last experiments at the Intersecting Storage Rings (ISR). With a stochastically cooled $\bar{p}$ beam, a hydrogen cluster-jet target, and a nonmagnetic spectrometer of limited angular coverage, it searched for final states including $J/\psi \to e^+e^-$ decay. A claimed 2.3σ signal of 5 $\bar{p}p \to J/\psi + X$ events near the χ_c center of gravity was interpreted as evidence for the (isospin-violating) $h_c \to J/\psi\,\pi^0$ mode, with h_c mass $3525.4 \pm 0.8 \pm 0.5\,\mathrm{MeV}$.[32] The R704 signal implies an on-resonance cross section of $\approx 2\,\mathrm{nb}$ and $\Gamma_{h_c} \times \mathcal{B}(h_c \to p\bar{p}) \times \mathcal{B}(h_c \to J/\psi\,X) \times \mathcal{B}(J/\psi \to e^+e^-) = 0.135^{+0.150}_{-0.060}\,\mathrm{eV}$.[33]

Following the ISR shutdown, these studies continued with Fermilab E760. Also nonmagnetic but with $\approx 3\pi$ coverage, E760 found in a $\approx 17\,\mathrm{pb}^{-1}$ sample an enhancement in $J/\psi\,\pi^0$ at $3526.2 \pm 0.15 \pm 0.2\,\mathrm{MeV}$,[34] with a 1-in-400 estimated probability of the 59 candidate events arising at random. The E760 measurements of on-resonance cross-section, $\approx 0.3\,\mathrm{nb}$, and $\Gamma_{h_c} \times \mathcal{B}(h_c \to p\bar{p}) \times \mathcal{B}(h_c \to J/\psi\,X) \times \mathcal{B}(J/\psi \to e^+e^-) = 0.010 \pm 0.003\,\mathrm{eV}$ appear to rule out the R704 events as being signal.[33]

E835 spent considerable running time in the h_c region, finding no signal in $J/\psi\,\pi^0$ at the E760 mass value, but (in an $\approx 80\,\mathrm{pb}^{-1}$ sample) a 13-event enhancement in $\eta_c\gamma$ (with $\eta_c \to \gamma\gamma$) at $3525.8 \pm 0.2 \pm 0.2\,\mathrm{MeV}$.[35] The estimated significance, in the range $1\text{--}3 \times 10^{-3}$, was comparable to that of the E760 h_c signal. More recently, CLEO's study[36] of $\psi(2S) \to \pi^0 h_c \to (\gamma\gamma)(\gamma\eta_c)$ has established the existence of the h_c at $> 4\sigma$: based on 168 ± 40 signal events, they find $m(h_c) = 3524.4 \pm 0.6 \pm 0.4\,\mathrm{MeV}$, not inconsistent with the E835 measurement. Neither experiment was able to measure the width of the h_c, but E835 set a 90%-C.L. upper limit of $1\,\mathrm{MeV}$.

A key prediction of QCD and perturbation theory is that the charmonium spin-zero hyperfine splitting, as measured by the mass difference Δm_{hf} between the h_c and the spin-weighted average of the χ_c states, should be close to zero.[37] Using the current PDG-average values,[10] $\langle m(^3P_J) \rangle = 3525.36 \pm 0.06\,\mathrm{MeV}$ and $m(h_c) = 3525.93 \pm 0.27\,\mathrm{MeV}$, we find $\Delta m_{\mathrm{hf}} = -0.57 \pm 0.28\,\mathrm{MeV}$, nonzero at 2σ but within the QCD expected range. The PDG error on $m(h_c)$ includes a scale factor of 1.5 due to the tension among the four most precise measurements (Fig. 2). Moreover, the two most precise (E760 and E835) are based on statistically marginal signals,
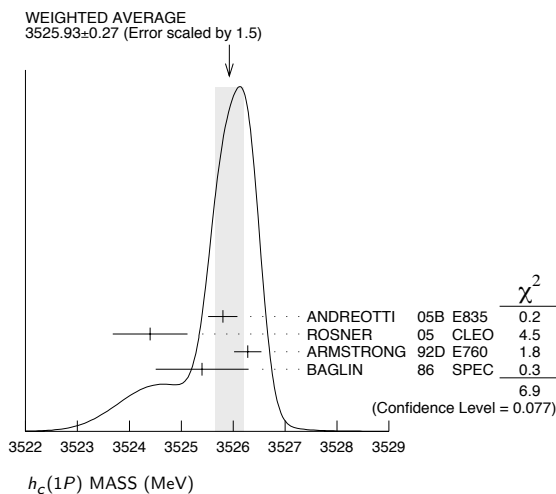
Fig. 2.   PDG ideogram of the four most precise measurements of the h_c mass (from Ref. 10).

and the reliability of the E760 result is called into question by the negative results of the E835 search. The R704 result is on even weaker ground: a $\bar{p}p \to h_c \to J/\psi\, X$ signal at the level implied by Baglin *et al.*[32] is most likely ruled out by E760[33] (as discussed above) as well as by E835. Thus of the four results used by the PDG in Fig. 2, only one is clearly reliable, and the claimed precision on $m(h_c)$ is far from established. This motivates an improved experimental search. Also of interest are the width and branching ratios of the h_c, for which QCD makes clear predictions; the decay modes also bear on the question of isospin conservation in such decays.

E835's $h_c \to \eta_c\gamma \to (\gamma\gamma)\gamma$ sensitivity was limited by the $(2.8 \pm 0.9) \times 10^{-4}$ $\eta_c \to \gamma\gamma$ branching ratio, and their acceptance $\times$ efficiency was only $\approx 3\%$ due to cuts against the substantial π^0 background.[35] With a magnetic spectrometer, likely η_c modes include $\phi\phi$, ϕK^+K^-, K^*K^*, and $\eta'\pi^+\pi^-$. These have branching ratios up to two orders of magnitude larger, as well as more-distinctive decay kinematics, than $\gamma\gamma$, probably allowing looser cuts and thus higher efficiency. For example, the $\phi\phi \to K^+K^-K^+K^-$ final state has no quarks in common with the initial $\bar{p}p$ state and so should contain little background. E835 searched for $\eta_c \to \phi\phi$ but without a magnet it was barely feasible. Assessing the degree of improvement will require detailed simulation work, but at least an order of magnitude in statistics seems likely. Additional improvement will come from the higher luminosity we propose.

Provided detailed simulation studies bear out these ideas, we will soon have the opportunity to resolve this 20-year-old experimental controversy.

3.3. *Hyperon CP violation*

Besides the well-known *CP* violation in *K*- and *B*-meson mixing and decay,[10] the standard model (SM) predicts slight hyperon-decay asymmetries.[38–40] Standard-model processes dominate *K* and *B CP* asymmetries, thus it behooves us to study

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hyperons (and charm; Sec. 3.5), in which new physics might stand out more sharply.

More than one hyperon CP asymmetry may be measurable in $\overline{p}p$ annihilation. Hyperon CP violation would of course be of the direct type, so as to conserve baryon number. Accessible signals include angular-distribution differences of polarized-hyperon and antihyperon decay products;[39] partial-rate asymmetries, possibly at detectable levels, are also expected.[41,42] To compete with previous Ξ and Λ CP studies would require $\sim 10^{33}$ luminosity. While summarizing the state of hyperon CP violation generally, we therefore emphasize in particular the $\Omega^-/\overline{\Omega}^+$ partial-rate asymmetry, for which there is no previous measurement.

By angular-momentum conservation, in the decay of a spin-1/2 hyperon to a spin-1/2 baryon plus a pion, the final state must be either S-wave or P-wave.[c] Interference between the S- and P-wave decay amplitudes causes parity violation, described by Lee and Yang[43] in terms of two independent parameters α and β, proportional to the real and imaginary parts (respectively) of the interference term. Hyperon CP-violation signatures include differences in $|\alpha|$ or $|\beta|$ between a hyperon decay and its CP-conjugate antihyperon decay, as well as particle–antiparticle decay partial-width differences between a mode and its CP conjugate.[39,44] Precision angular-distribution asymmetry measurement requires accurate knowledge of the relative polarizations of the initial hyperons and antihyperons.

3.3.1. *Angular-distribution asymmetries*

Table 3 summarizes the experimental situation. The first three experiments cited studied Λ decay only,[45−47] setting limits on the CP-asymmetry parameter[39,44]

$$A_\Lambda \equiv \frac{\alpha_\Lambda + \overline{\alpha}_\Lambda}{\alpha_\Lambda - \overline{\alpha}_\Lambda}\,, \tag{2}$$

where α_Λ ($\overline{\alpha}_\Lambda$) characterizes the Λ ($\overline{\Lambda}$) decay to (anti)proton plus charged pion. If CP is a good symmetry in hyperon decay, $\alpha_\Lambda = -\overline{\alpha}_\Lambda$.

Fermilab fixed-target experiment E756[48] and CLEO[49] used the decay of charged Ξ hyperons to produce polarized Λ's, in whose subsequent decay the slope of the (anti)proton angular distribution in the "helicity" frame measures the product of α_Ξ and α_Λ. If CP is a good symmetry in hyperon decay this product should be identical for Ξ^- and $\overline{\Xi}^+$ events. The CP-asymmetry parameter measured is thus

$$A_{\Xi\Lambda} \equiv \frac{\alpha_\Xi\alpha_\Lambda - \overline{\alpha}_\Xi\overline{\alpha}_\Lambda}{\alpha_\Xi\alpha_\Lambda + \overline{\alpha}_\Xi\overline{\alpha}_\Lambda} \approx A_\Xi + A_\Lambda\,. \tag{3}$$

The power of this technique derives from the relatively large $|\alpha|$ value for the $\Xi^- \to \Lambda\pi^-$ decay ($\alpha_\Xi = -0.458 \pm 0.012$).[10] A further advantage in the fixed-target case is that within a given $\overset{(-)}{\Xi}$ momentum bin the acceptances and efficiencies for Ξ^- and $\overline{\Xi}^+$ decays are very similar, since the switch from detecting Ξ to detecting $\overline{\Xi}$ is made by reversing the polarities of the magnets, making the spatial distributions

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[c]A similar argument holds for a spin-3/2 hyperon, but involving P and D waves.

of decay products across the detector apertures almost identical for Ξ and for $\overline{\Xi}$. (There are still residual systematic uncertainties arising from the differing momentum dependences of the Ξ and $\overline{\Xi}$ cross sections and of the cross sections for the p and $\overline{p}$ and π^+ and π^- to interact in the material of the spectrometer.)

Subsequent to E756, this technique was used in the "HyperCP" experiment (Fermilab E871),[50,51] which ran during 1996–99 and has set the world's best limits on hyperon CP violation, based so far on about 5% of the recorded $\overset{(-)}{\Xi}{}^{\mp} \to \overset{(-)}{\Lambda}\pi^{\mp}$ data sample. (The systematics of the full data sample is still under study.) Like E756, HyperCP used a secondary charged beam produced by $800\,\mathrm{GeV}$ primary protons interacting in a metal target. The secondary beam was momentum- and sign-selected by means of a curved collimator installed within a 6-m-long dipole magnet. Particle trajectories were measured downstream of a 13-m-long (evacuated) decay region. HyperCP recorded the world's largest samples of hyperon and antihyperon decays, including 2.0×10^9 and 0.46×10^9 Ξ^- and $\overline{\Xi}^+$ events, respectively. When the analysis is complete, these should determine $A_{\Xi\Lambda}$ with a statistical uncertainty

$$\delta A = \frac{1}{2\alpha_\Xi\alpha_\Lambda}\sqrt{\frac{3}{N_{\Xi^-}}+\frac{3}{N_{\overline{\Xi}^+}}} \lesssim 2\times10^{-4}\,. \tag{4}$$

The standard model predicts[39] this asymmetry to be of order 10^{-5}. Thus any significant effect seen in HyperCP will be evidence for new sources of CP violation in the baryon sector. (A number of standard-model extensions, e.g., nonminimal SUSY, predict effects as large as $\mathcal{O}(10^{-3})$.[52]) Such an observation could be of relevance to the mysterious mechanism that gave rise to the cosmic baryon asymmetry.

HyperCP has also set the world's first limit on CP violation in $\overset{(-)}{\Omega}{}^{\mp}$ decay, using a sample of 5.46 (1.89) million $\Omega^- \to \Lambda K^-$ $(\overline{\Omega}^+ \to \overline{\Lambda}K^+)$ events.[53] Here, as shown by HyperCP,[54,55] parity is only slightly violated: $\alpha = (1.75\pm0.24)\times10^{-2}$.[10] Hence the measured magnitude and uncertainty of the asymmetry parameter $A_{\Omega\Lambda}$ (inversely proportional to α as in Eq. 4) are rather large: $[-0.4\pm9.1\,(\mathrm{stat})\pm8.5\,(\mathrm{syst})]\times10^{-2}$.[53] This asymmetry is predicted to be $\leq 4\times10^{-5}$ in the standard model but can be as large as 8×10^{-3} if new physics contributes.[42]

3.3.2. *Partial-rate asymmetries*

While CPT symmetry requires identical lifetimes for particle and antiparticle, partial-rate asymmetries violate only CP. For most hyperon decays, these are expected to be undetectably small.[40] However, for the decays $\Omega^- \to \Lambda K^-$ and $\Omega^- \to \Xi^0\pi^-$, the particle/antiparticle partial-rate asymmetries could be as large as 2×10^{-5} in the standard model and one to two orders of magnitude larger if non-SM contributions dominate.[41,42] The quantities to be measured are

$$\Delta_{\Lambda K} \equiv \frac{\Gamma(\Omega^- \to \Lambda K^-) - \Gamma(\overline{\Omega}^+ \to \overline{\Lambda}K^+)}{\Gamma(\Omega^- \to \Lambda K^-) + \Gamma(\overline{\Omega}^+ \to \overline{\Lambda}K^+)}$$

$$\approx \frac{1}{2\Gamma}(\Gamma - \overline{\Gamma}) \approx 0.5\,(1 - N/\overline{N}) \tag{5}$$

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Table 3.   Summary of experimental limits on *CP* violation in hyperon decay; the hyperons studied are indicated by *, †, and ‡.

Exp't	Facility	Year	Ref.	Modes	$^*A_\Lambda \, / \, ^\dagger A_{\Xi\Lambda} \, / \, ^\ddagger A_{\Omega\Lambda}$
R608	ISR	1985	45	$pp \to \Lambda X, pp \to \overline{\Lambda} X$	$-0.02 \pm 0.14^*$
DM2	Orsay	1988	46	$e^+e^- \to J/\psi \to \Lambda\overline{\Lambda}$	$0.01 \pm 0.10^*$
PS185	LEAR	1997	47	$\overline{p}p \to \overline{\Lambda}\Lambda$	$0.006 \pm 0.015^*$
CLEO	CESR	2000	49	$e^+e^- \to \Xi^- X, \Xi^- \to \Lambda\pi^-,$ $e^+e^- \to \overline{\Xi}^+ X, \overline{\Xi}^+ \to \overline{\Lambda}\pi^+$	$-0.057 \pm 0.064 \pm 0.039^\dagger$
E756	FNAL	2000	48	$pN \to \Xi^- X, \Xi^- \to \Lambda\pi^-,$ $pN \to \overline{\Xi}^+ X, \overline{\Xi}^+ \to \overline{\Lambda}\pi^+$	$0.012 \pm 0.014^\dagger$
HyperCP	FNAL	2004	50	$pN \to \Xi^- X, \Xi^- \to \Lambda\pi^-,$ $pN \to \overline{\Xi}^+ X, \overline{\Xi}^+ \to \overline{\Lambda}\pi^+$	$(0.0 \pm 6.7) \times 10^{-4 \, \dagger, \S}$
HyperCP	FNAL	2006	53	$pN \to \Omega^- X, \Omega^- \to \Lambda K^-,$ $pN \to \overline{\Omega}^+ X, \overline{\Omega}^+ \to \overline{\Lambda}K^+$	$-0.004 \pm 0.12^\ddagger$

§ Based on $\approx 5\%$ of the HyperCP data sample; analysis of the full sample is still in progress.

(and similarly for $\Delta_{\Xi\pi}$), where in the last step we have assumed nearly equal numbers (N) of Ω and ($\overline{N}$) of $\overline{\Omega}$ events, as would be the case in $\overline{p}p$ annihilation. Sensitivity at the 10^{-4} level then requires $\mathcal{O}(10^7)$ reconstructed events. Measuring such a small branching-ratio difference reliably will require the clean exclusive $\overline{\Omega}^+\Omega^-$ event sample produced less than a π^0 mass above threshold, or $4.938 < p_{\overline{p}} < 5.437 \, \text{GeV}/c$.

3.3.3. *Hyperon sensitivity estimates*

There have been a number of measurements of hyperon production by low-energy antiprotons. Johansson *et al.*[56] report cross sections measured by PS185 at LEAR, but the maximum LEAR $\overline{p}$ momentum ($2 \, \text{GeV}/c$) was insufficient to produce Ξ's or Ω's. Chien *et al.*[57] report measurements of a variety of hyperon final states performed with the BNL 80-inch liquid-hydrogen bubble chamber in a 6.935 "BeV/c" electrostatically separated antiproton beam at the AGS; Baltay *et al.*[58] summarize data taken at lower momenta. In 80,000 pictures Chien *et al.* observed some 1,868 hyperon or antihyperon events, corresponding to a total hyperon-production cross section of $1.310 \pm 0.105 \, \text{mb}$.[57] The corresponding cross section measured at $3.7 \, \text{GeV}/c$ was $720 \pm 30 \, \mu\text{b}$, and $438 \pm 52 \, \mu\text{b}$ at $3.25 \, \text{GeV}/c$.[58] The inclusive hyperon-production cross section at $5.4 \, \text{GeV}/c$ is thus about 1 mb. At $2 \times 10^{32} \, \text{cm}^{-2}\text{s}^{-1}$ this amounts to some 2×10^5 hyperon events produced per second, or 2×10^{12} per year. (Experience suggests that a data-acquisition system that can cope with such a high event rate is both feasible and reasonable in cost. For example, the $\overline{p}p$ interaction rate is comparable to that in BTeV, yet the charged-particle multiplicity per event is only $\approx 1/10$ as large.)

To estimate the exclusive $\overline{p}p \to \overline{\Omega}\Omega$ cross section requires some extrapolation, since it has yet to be measured (moreover, even for $\overline{p}p \to \overline{\Xi}^+\Xi^-$ only a few events have been seen). A rule of thumb is that each strange quark "costs" between one and two orders of magnitude in cross section, reflecting the effect of the strange-

quark mass on the hadronization process. This is borne out e.g. by HyperCP, in which 2.1×10^9 $\Xi^- \to \Lambda\pi^-$ and 1.5×10^7 $\Omega^- \to \Lambda K^-$ decays were reconstructed;[51] given the $160\,\mathrm{GeV}/c$ hyperon momentum and $6.3\,\mathrm{m}$ distance from HyperCP target to decay pipe, this corresponds to ≈ 30 Ξ^-'s per Ω^- produced at the target. A similar ratio is observed in HERA-B.[59] In exclusive $\overline{p}p \to \overline{Y}Y$ production (where Y signifies a hyperon) there may be additional effects, since as one proceeds from Λ to Ξ to Ω fewer and fewer valence quarks are in common between the initial and final states. Nevertheless, the cross section for $\overline{\Xi}^+\Xi^-$ somewhat above threshold ($p_{\overline{p}} \approx 3.5\,\mathrm{GeV}/c$) is $\approx 2\,\mu\mathrm{b}$,[60,58,61] or about $1/30$ of the corresponding cross section for $\overline{\Lambda}\Lambda$. Thus the $\approx 65\,\mu\mathrm{b}$ cross section measured for $\overline{p}p \to \overline{\Lambda}\Lambda$ at $p_{\overline{p}} = 1.642\,\mathrm{GeV}/c$ at LEAR[56] implies $\sigma(\overline{p}p \to \overline{\Omega}\Omega) \sim 60\,\mathrm{nb}$ at $5.4\,\mathrm{GeV}/c$.

For purposes of discussion we take this as the exclusive production cross section.[d] At $2.0 \times 10^{32}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ luminosity, some 1.2×10^8 $\overline{\Omega}\Omega$ events are then produced in a nominal 1-year run ($1.0 \times 10^7\,\mathrm{s}$). Assuming 50% acceptance times efficiency (comparable to that for χ_c events in E760), we estimate $\overset{(-)}{N}_{\Xi\pi} = 1.4 \times 10^7$ events each in $\Omega^- \to \Xi^0\pi^-$ and $\overline{\Omega}^+ \to \overline{\Xi}^0\pi^+$, and $\overset{(-)}{N}_{\Lambda K} = 4.1 \times 10^7$ events each in $\Omega^- \to \Lambda K^-$ and $\overline{\Omega}^+ \to \overline{\Lambda}K^+$, implying the partial-rate-asymmetry statistical sensitivities

$$\delta\Delta_{\Xi\pi} \approx \frac{0.5}{\sqrt{N_{\Xi\pi}}} \approx 1.3 \times 10^{-4}\,, \quad \delta\Delta_{\Lambda K} \approx \frac{0.5}{\sqrt{N_{\Lambda K}}} \approx 7.8 \times 10^{-5}\,. \tag{6}$$

Tandean and Valencia[41] have estimated $\Delta_{\Xi\pi} \approx 2 \times 10^{-5}$ in the standard model but possibly an order of magnitude larger with new-physics contributions. Tandean[42] has estimated $\Delta_{\Lambda K}$ to be $\leq 1 \times 10^{-5}$ in the standard model but possibly as large as 1×10^{-3} if new physics contributes. (The large sensitivity of $\Delta_{\Lambda K}$ to new physics in this analysis arises from chromomagnetic penguin operators and final-state interactions via $\Omega \to \Xi\pi \to \Lambda K$.[42 e]) It is worth noting that these potentially large asymmetries arise from parity-conserving interactions and hence are limited by constraints from ϵ_K;[41,42] they are independent of A_Λ and A_Ξ, which arise from the interference of parity-violating and parity-conserving processes.[62]

Of course, the experimental sensitivities will include systematic components whose estimation will require careful and detailed simulation studies yet to be done. Nevertheless, the potential power of the technique is apparent: the experiment discussed here may be capable of observing the effects of new physics in Omega *CP* violation via partial-rate asymmetries, and it will represent a substantial improvement over current sensitivity to Omega angular-distribution asymmetries.

3.4. *Study of FCNC hyperon decays*

Behind its charged-particle spectrometer, HyperCP had muon detectors for rare-decay studies.[51,6] Using them HyperCP has observed[6] the rarest hyperon decay ever,

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[d]This estimate will be testable in the upgraded MIPP experiment.[63]
[e]Large final-state interactions should also affect $\Delta_{\Xi\pi}$ but were not included in that prediction.[41,62]
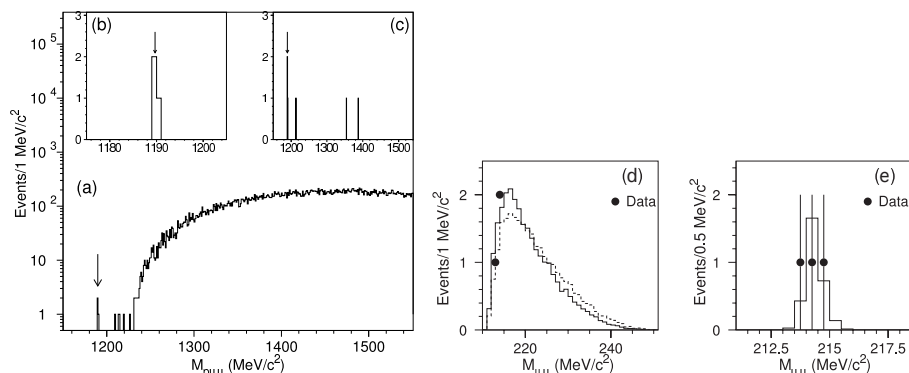
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Fig. 3.   Mass spectra for candidate single-vertex $p\mu^+\mu^-$ events in HyperCP positive-beam data sample: (a) wide mass range (semilog scale); (b) narrow range around Σ^+ mass; (c) after application of additional cuts as described in Ref. 6 (arrows indicate mass of Σ^+); dimuon mass spectrum of the candidate events compared with Monte Carlo spectrum assuming (d) standard-model virtual-photon form factor (solid) or isotropic decay (dashed), or (e) decay via a narrow resonance X^0.

$\Sigma^+ \to p\mu^+\mu^-$. Surprisingly (Fig. 3), the 3 observed events are consistent with a two-body decay, $\Sigma^+ \to pX^0$, $X^0 \to \mu^+\mu^-$, with X^0 mass $m_{X^0} = 214.3 \pm 0.5 \,\mathrm{MeV}/c^2$. This interpretation is of course not definitive, with the confidence level for the form-factor decay spectrum of Fig. 3d estimated at 0.8%. The measured branching ratio is $[3.1 \pm 2.4\,(\mathrm{stat}) \pm 1.5\,(\mathrm{syst})] \times 10^{-8}$ assuming two-body, or $[8.6^{+6.6}_{-5.4}\,(\mathrm{stat}) \pm 5.5\,(\mathrm{syst})] \times 10^{-8}$ assuming three-body Σ^+ decay.

This result is intriguing in view of Gorbunov's proposal[64] that certain nonminimal supersymmetric models include a pair of "sgoldstinos" (supersymmetric partners of Goldstone fermions), which can be scalar or pseudoscalar and low in mass. A light scalar particle coupling to hadrons and muon pairs at the required level is ruled out by its nonobservation in kaon decays; however, a pseudoscalar sgoldstino with $\approx 214\,\mathrm{MeV}/c^2$ mass would be consistent with all available data.[65−67] Alternatively, He, Tandean, and Valencia suggest[68] the X^0 is the light pseudoscalar Higgs boson (A_1^0) in the next-to-minimal supersymmetric standard model.

Studying this with exclusive $\overline{\Sigma}^-\Sigma^+$ events just above threshold would require $\overline{p}$ momentum (see Table 1) well below that previously achieved by deceleration in the Antiproton Accumulator, as well as very high luminosity to access the $\mathcal{O}(10^{-8})$ branching ratio. An experimentally less challenging but equally interesting objective is the corresponding FCNC decay of the Ω^-, with $\mathcal{O}(10^{-6})$ predicted branching ratio[65] if the X^0 is real.[f] (The larger branching ratio reflects the additional phase space available compared to that in $\Sigma^+ \to p\mu^+\mu^-$.) As above, assuming 2×10^{32} luminosity and 50% acceptance times efficiency, 120 or 44 events are predicted in

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[f]The standard-model prediction is[69] $\mathcal{B}(\Omega^- \to \Xi^-\mu^+\mu^-) = 6.6 \times 10^{-8}$.

the two cases (pseudoscalar or axial-vector X^0) that appear to be viable:[65,66]

$$\mathcal{B}(\Omega^- \to \Xi^- X_P \to \Xi^- \mu^+ \mu^-) = (2.0^{+1.6}_{-1.2} \pm 1.0) \times 10^{-6}, \tag{7}$$

$$\mathcal{B}(\Omega^- \to \Xi^- X_A \to \Xi^- \mu^+ \mu^-) = (0.73^{+0.56}_{-0.45} \pm 0.35) \times 10^{-6}. \tag{8}$$

Given the large inclusive hyperon rates at $\sqrt{s} \approx 3.5\,\mathrm{GeV}$, sufficient sensitivity might also be available at that setting to confirm the HyperCP $\Sigma^+ \to p\mu^+\mu^-$ results. Alternatively, it is possible that a dedicated run just above $\overline{\Sigma}^-\Sigma^+$ threshold may have competitive sensitivity; evaluating this will require a detailed simulation study.

3.5. *Additional physics*

Besides the $X(3872)$, the experiment would be competitive for the charmonium and related states mentioned in Sec. 1.2. The large hyperon samples could enable precise measurement of hyperon semileptonic and other rare decays. The APEX experiment[70] vacuum tank and pumping system could be reinstalled, enabling substantially increased sensitivity for $\bar{p}$ lifetime and decay modes. There is interest in decelerating further (e.g., at the ends of stores) for trapped-antiproton and antihydrogen experiments.[71,72] This capability could make Fermilab the premiere facility for such research. The $\bar{p}$ intensity available at Fermilab could enable studies not feasible at the AD, such as a measurement of the gravitational force on antimatter.[72] A complementary approach is the study of antihydrogen atoms in flight,[73] which may overcome some of the difficulties encountered in the trapping experiments.

The PANDA TPR[4] claims competitive sensitivity for open charm, estimating the rate of D-pair production at about 100/s for $\sqrt{s}$ near the $\psi(4040)$. This could lead to a sample of $\sim 10^9$ events/year produced and $\sim 10^8$/year reconstructed, roughly an order of magnitude beyond the statistics accumulated by the B Factories so far. Whether this sensitivity can be realized in practice will depend on details of trigger and analysis efficiency whose estimation will require detailed simulation studies. Nevertheless, there does appear to be the potential for competitive measurements, e.g., of D^0 mixing and possible *CP* violation in charm decay.

The bottomonium system has not benefited from $\bar{p}p$ formation studies but is potentially accessible if the Antiproton Accumulator (or perhaps a new replacement storage ring) can be configured for colliding beams. The $\bar{p}p$ widths of bottomonium states are unknown. If they can be shown to be sufficiently large, $\bar{p}p$ formation could lead to the discovery of bottomonium singlet states, which have so far eluded observation, as well as precise measurements of the many states already observed.

4. A New Experiment

We see two approaches to implementing low-cost apparatus to perform the measurements here described:[1] one based on existing equipment from E835, and the other on the DØ superconducting solenoid (available once the Tevatron Collider program ends). Should sufficient resources be available, a new spectrometer, free

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of constraints from existing apparatus, may give better performance than either of these. The possibility of building a new storage ring has also been mentioned. We hope to study these options in detail in the coming months.

Acknowledgments

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