

Prospects for Low-Energy Antiproton Physics at Fermilab

Daniel M. Kaplan

Illinois Institute of Technology, Chicago, Illinois 60616, USA

Abstract. Fermilab has long had the world's most intense antiproton source. Despite this, opportunities for low-energy antiproton physics at Fermilab have in the past been limited and — with the antiproton source now exclusively dedicated to serving the needs of the Tevatron Collider — are currently nonexistent. While the future of antiproton physics at Fermilab is uncertain, the anticipated shutdown of the Tevatron in about 2009 presents the opportunity for a world-leading low-energy antiproton program. We summarize the current status of the Fermilab antiproton facility and review some current topics in hyperon physics as examples of what might be achievable.

Fermilab has the world's highest-intensity antiproton source, and (thanks to the ongoing efforts of the Antiproton Source Dept.) the beam intensity it can provide continues to increase. With the planned shutdown of the Tevatron starting in 2009, the antiproton facility might then once again become available for low-energy studies. There is an extensive list of interesting particle-physics topics that can be addressed with such a facility [1], including “unfinished business” from the former LEAR and Fermilab low-energy antiproton programs. These include

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

Due to their requirements for beam energy (see Table 1) or intensity, all but the last of these cannot be done at the CERN Antiproton Decelerator. Many of them have been discussed in the context of the GSI FLAIR (Facility for Low-Energy Antiproton and Ion Research) project [2] and its general-purpose PANDA detector [1]. However, that facility is expected to have insufficient luminosity for the hyperon-physics topics just mentioned.

CAPABILITIES OF THE FERMILAB ANTIPROTON SOURCE

Fermilab's Antiproton Source (which includes the Debuncher ring and the Antiproton Accumulator ring, in which stochastic cooling is performed) now cools and accumulates

TABLE 1. Thresholds for some processes of interest.

Process	Threshold: \sqrt{s} [GeV]	momentum [GeV/c]
$\bar{p}p \rightarrow \bar{\Lambda}\Lambda$	2.231	1.437
$\bar{p}p \rightarrow \bar{\Sigma}^-\Sigma^+$	2.379	1.854
$\bar{p}p \rightarrow \bar{\Xi}^+\Xi^-$	2.642	2.620
$\bar{p}p \rightarrow \bar{\Omega}^+\Omega^-$	3.345	4.938
$\bar{p}p \rightarrow \eta_c$	2.980	3.678
$\bar{p}p \rightarrow \psi(3770)$	3.770	6.572

antiprotons at a maximum stacking rate of ≈ 20 mA/hr. Given the 474 m circumference of the Accumulator, this corresponds to a production rate of 2×10^{11} antiprotons/hr and can thus support a maximum luminosity of about $5 \times 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$ (i.e., beyond this luminosity, collisions would consume antiprotons more rapidly than they are produced). Fermilab's Main Injector project included construction (in the Main Injector tunnel) of the (permanent-magnet) Recycler ring,¹ now being put into operation. With the planned use of electron cooling in the Recycler, the stacking rate is likely to double by 2009. As discussed below, $\sim 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$ luminosity is required for competitive reach in hyperon physics.

The integrated luminosity of an experiment in the Accumulator could be limited by the beam-transfer capabilities of the complex: antiprotons can currently be transferred from the Accumulator to the Recycler, and from the Recycler to the Main Injector, but not vice versa. Since the stacking rate decreases approximately linearly with increasing store size, to maintain rapid stacking, beam is typically transferred to the Recycler when the Accumulator current reaches ≈ 100 mA. The addition of a reverse-transfer beamline would allow stacked beam from the Recycler to be injected back into the Accumulator for collisions and could thus enhance the deliverable luminosity by perhaps a factor of 2. Also desirable is the ability to stack simultaneously with experimental running, which could double the efficiency of operation. This could be provided by the addition of a small storage ring, which might be a new, custom-designed ring or an existing one, such as that from the Indiana University Cyclotron Facility or the CELSIUS ring from Uppsala University. Such a ring could also enhance the ability to decelerate antiprotons for trapping.

To understand some of the issues for a future low-energy antiproton facility (in particular, the need for 10^{33} luminosity), it is useful to consider some physics examples.

¹ So called because of its possible use to recycle antiprotons from a just-completed $\bar{p}p$ store for use in the next store; however, the Recycler ring enhances operation of the Antiproton Source in a number of ways: for example, it improves the performance of stochastic cooling as described in the text.

HYPERON CP VIOLATION

In addition to that in K - and B -meson decay [3], the Standard Model predicts CP violation in decays of hyperons [4, 5, 6]. The most accessible signals are differences between the angular distributions of polarized-hyperon decay products and those of the corresponding antihyperons [5]. Precision measurement thus requires accurate knowledge of the polarizations of the initial hyperons and antihyperons.

Angular-momentum conservation requires the final state in the decay of a spin-1/2 hyperon to a spin-1/2 baryon plus a pion to be either S- or P-wave. As is well known, interference between the S- and P-wave amplitudes causes parity violation, parametrized by Lee and Yang [7] via two independent parameters α and β (proportional respectively to the real and imaginary parts of the interference term). CP violation can arise as a difference in $|\alpha|$ or $|\beta|$ between a hyperon decay and its CP -conjugate antihyperon decay or as a particle-antiparticle difference in the partial widths for such decays [5, 8].

Table 2 summarizes the experimental situation. The first three experiments cited studied Λ decay only [9, 10, 11], setting limits on the CP asymmetry parameter [5, 8]

$$A_\Lambda \equiv \frac{\alpha_\Lambda + \alpha_\Lambda^-}{\alpha_\Lambda - \alpha_\Lambda^-}, \quad (1)$$

where α_Λ (α_Λ^-) characterizes the Λ ($\bar{\Lambda}$) decay to (anti)proton plus charged pion and, if CP is conserved, $\alpha_\Lambda = -\alpha_\Lambda^-$.

Fermilab experiments 756 [12] and 871 (“HyperCP”) [13] and CLEO [14] used Ξ^- ($\bar{\Xi}^+$) decay to produce polarized Λ ’s, in whose subsequent decay the slope of the (anti)proton angular distribution in the “helicity” frame measures the product $\alpha_\Xi \alpha_\Lambda$; for CP conservation this should be identical for Ξ and $\bar{\Xi}$ events. The CP asymmetry parameter measured is thus

$$A_{\Xi\Lambda} \equiv \frac{\alpha_\Xi \alpha_\Lambda - \alpha_{\bar{\Xi}} \alpha_\Lambda^-}{\alpha_\Xi \alpha_\Lambda + \alpha_{\bar{\Xi}} \alpha_\Lambda^-} \approx A_\Xi + A_\Lambda. \quad (2)$$

The power of this technique derives from the large α value ($\alpha = 0.64$) in the $\Xi \rightarrow \Lambda\pi$ decay. Also, in the fixed-target case, for a given ($\bar{\Xi}$) momentum bin the acceptances and efficiencies for Ξ and $\bar{\Xi}$ decays are very similar: Between Ξ and $\bar{\Xi}$ runs one reverses magnet polarities, making the spatial distributions of decay products across the detectors almost identical for Ξ and $\bar{\Xi}$. (There are still residual systematic uncertainties arising from the differing momentum dependences of the Ξ and $\bar{\Xi}$ production cross sections and of the cross sections for the p and \bar{p} and π^+ and π^- to interact in the material of the spectrometer.)

HyperCP took data during 1996–99, recording the world’s largest samples of hyperon decays (2.0×10^9 Ξ and 4.6×10^8 $\bar{\Xi}$ events), and has set the world’s best limit on hyperon CP violation [13], based on about 5% of the recorded data sample. The complete analysis should determine $A_{\Xi\Lambda}$ with a statistical uncertainty $\delta A = \sqrt{3/N_{\Xi^-} + 3/N_{\bar{\Xi}^+}}/2\alpha_\Xi \alpha_\Lambda \lesssim 2.0 \times 10^{-4}$. The Standard Model predicts $A_{\Xi\Lambda} \sim 10^{-5}$ [5]. Thus any significant effect seen in HyperCP will be evidence for CP violation in the baryon sector substantially larger than predicted by the Standard Model. Various Standard Model extensions predict effects as large as $\mathcal{O}(10^{-3})$ [15].

TABLE 2. Summary of experimental limits on CP violation in hyperon decay.

Experiment	Facility	Year	Ref.	Mode	A_Λ [*] or $A_{\Xi\Lambda}$ [†]
R608	ISR	1985	[9]	$pp \rightarrow \Lambda X, pp \rightarrow \bar{\Lambda} X$	$-0.02 \pm 0.14^*$
DM2	Orsay	1988	[10]	$e^+e^- \rightarrow J/\psi \rightarrow \Lambda \bar{\Lambda}$	$0.01 \pm 0.10^*$
PS185	LEAR	1997	[11]	$\bar{p}p \rightarrow \bar{\Lambda} \Lambda$	$0.006 \pm 0.014^*$
CLEO	CESR	2000	[14]	$e^+e^- \rightarrow \Xi^- X, \Xi^- \rightarrow \Lambda \pi^-$, $e^+e^- \rightarrow \bar{\Xi}^+ X, \bar{\Xi}^+ \rightarrow \bar{\Lambda} \pi^+$	$-0.057 \pm 0.064 \pm 0.039^\ddagger$
E756	Fermilab	2000	[12]	$pN \rightarrow \Xi^- X, \Xi^- \rightarrow \Lambda \pi^-$, $pN \rightarrow \bar{\Xi}^+ X, \bar{\Xi}^+ \rightarrow \bar{\Lambda} \pi^+$	$0.012 \pm 0.014^\ddagger$
HyperCP	Fermilab	2004	[13]	$pN \rightarrow \Xi^- X, \Xi^- \rightarrow \Lambda \pi^-$, $pN \rightarrow \bar{\Xi}^+ X, \bar{\Xi}^+ \rightarrow \bar{\Lambda} \pi^+$	$(0.0 \pm 5.1 \pm 4.4) \times 10^{-4 \ddagger, \ddagger}$

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

STUDY OF FCNC Σ^+ DECAY

In addition to its high-rate charged-particle spectrometer, HyperCP had a muon detection system aimed at studying rare decays of hyperons and charged kaons [16, 17, 18]. A recent HyperCP result is the observation of the rarest hyperon decay ever, $\Sigma^+ \rightarrow p\mu^+\mu^-$ [17]. As shown in Fig. 1, based on the 3 observed events, the decay is consistent with being two-body, i.e., $\Sigma^+ \rightarrow pX^0, X^0 \rightarrow \mu^+\mu^-$, with branching ratio $\mathcal{B} = (3.1_{-1.9}^{+2.4} \pm 1.5) \times 10^{-8}$ and X^0 mass $m_{X^0} = (214.3 \pm 0.5) \text{ MeV}$. With the available statistics this interpretation is of course not definitive: the probability that the 3 signal events are consistent with the form-factor decay spectrum of Fig. 1d is estimated as 0.8%; in this interpretation the measured branching ratio is $\mathcal{B}(\Sigma^+ \rightarrow p\mu^+\mu^-) = (8.6_{-5.4}^{+6.6} \pm 5.5) \times 10^{-8}$.

This result is particularly intriguing given predictions by D. S. Gorbunov *et al.* [19] of a pair of SUSY “sgoldstino” states (supersymmetric partners of Goldstone fermions). These can be scalar or pseudoscalar and they could be low in mass. It is thus conceivable that the lightest supersymmetric particle has now been glimpsed—and in a most unexpected place! This result demands further experimental study. But note that the HyperCP Σ^+ sensitivity was $\approx 2 \times 10^{10}$ decays. No planned experiment is capable of producing and detecting the $\mathcal{O}(10^{11})$ Σ^+ hyperons that would be required to confirm or refute HyperCP’s putative X^0 signal.

A FUTURE EXPERIMENT

The Fermilab Antiproton Source is a suitable venue for a high-sensitivity experiment studying (*inter alia*) $\bar{p}p \rightarrow$ hyperons.² An appropriate goal would be an order-

² Given the high rate of secondary beam in the HyperCP MWPCs — about 13 MHz spread over an area of several cm^2 — the HyperCP approach could not be pushed much further even were Tevatron fixed-target

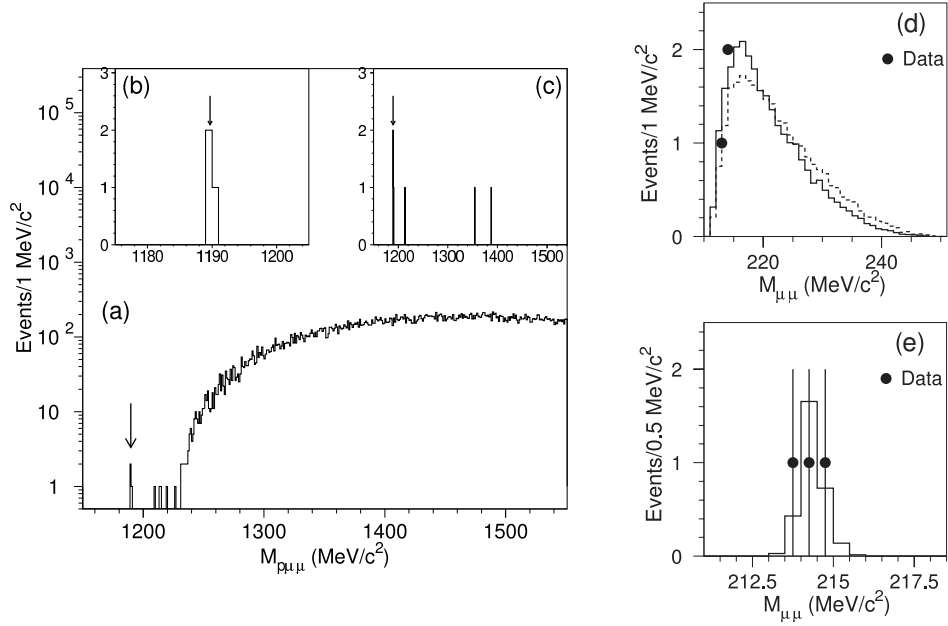


FIGURE 1. Mass spectrum for single-vertex $p\mu^+\mu^-$ candidates in HyperCP positive-beam data sample: a) wide mass range (semilog scale); b) narrow range around Σ^+ mass; c) wide mass range after application of additional cuts as described in Ref. [17]; dimuon mass spectrum of the three $\Sigma^+ \rightarrow p\mu^+\mu^-$ 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 .

of-magnitude increase in sensitivity — two orders of magnitude increase in sample size for the CP study and one order of magnitude for the rare-decay search — i.e., $\sim 10^{11}$ $\bar{\Lambda}\Lambda$ and $\bar{\Sigma}\Sigma$ events. Cleanliness of the produced samples suggests operating just above threshold as in PS185 [11]. Given the $\approx 60\mu\text{b}$ cross sections [11], $10^{33}\text{cm}^{-2}\text{s}^{-1}$ luminosity means 6×10^{11} events produced per 10^7 -s year (which, with the inevitable acceptance and efficiency losses, probably reaches the goal). A proto-collaboration is now forming to design and simulate the apparatus and produce a Letter of Intent.

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operation once again to be made available.

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