Heavy-Quark Physics at the Antiproton Intensity Frontier

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Abstract

Fermilab operates the world's most intense antiproton source. With the end of the Tevatron Collider program, that source can support a vibrant antiproton physics program. For example, the annihilation of 8 GeV antiprotons could provide the world's most intense source of tagged D^0 mesons, an avenue to charm *CP* violation (CPV), mixing, and rare decays. A 3.5σ D^0 CPV signal is now seen by LHC*b* — the first indication of new physics at LHC — and confirming it is an urgent priority. Additional measurements include properties of the $X(3872)$, other *"XYZ"* states, and the charmonium system, and unique Drell–Yan studies, as well as world-leading studies of hyperon CPV and rare decays. Thus the Fermilab Antiproton Source offers a singular opportunity for a broad and exciting physics program in the post-Tevatron era.

1 Introduction

The Fermilab Antiproton Source has produced more than 1.5×10^{15} antiprotons per year [1] (Table 1), far exceeding the intensities available at the CERN Antiproton Decelerator (AD) and expected at Germany's Facility for Antiproton and Ion Research (FAIR). Now that the Tevatron program has ended, an internal target could once again be operated in the Fermilab Antiproton Accumulator, with beam kinetic energy in the range $\approx$3.5–8 GeV. With antiproton stacking $\approx 20\%$ of the time, $2 \times 10^{32}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ luminosity could be sustained during the remaining $\approx 80\%$. World-leading studies of charm *CP* violation (CPV), mixing, and rare decays are likely, as well as of the $X(3872)$ and other *"XYZ"* states, the charmonium system, and hyperon CPV and rare decays. A 3.5σ indication of direct CPV in D^0 decay recently announced by LHC*b* [2], if confirmed, could radically change our view of flavor physics beyond the Standard Model. It thus urgently demands independent confirmation, likely feasible using the Antiproton Source, as are new searches for non-KM CPV in other sectors such as hyperons. (Space constraints preclude discussion of Drell–Yan lepton-pair production and several other proposed measurements using the Antiproton Source [3].)

2 Charm Mixing, *CP* Violation, and Rare Decays

After a $>$20-year search, D^0–$\overline{D}^0$ mixing is now established at $>$10 standard deviations (Fig. 1, left) [4]. The level of mixing ($\sim$1%) is arguably consistent with Standard Model predictions [5]; however, this does not preclude a significant and potentially detectable contribution from new physics [6, 7]. Since differing effects are possible in the charge-2/3 ("up-type") and –1/3 quark sectors [6, 7], it is important to carry out such studies with charm mesons — the only up-type system for which meson mixing can occur.

While the total charm-production cross section for $\approx$8 GeV fixed-target antiproton collisions is challenging to compute *ab initio*, phenomenological estimates imply values in the 1–10 μb range [8]-[12] — sufficiently large that TAPAS could amass a sample some ten times larger than that of LHC*b*, years before the "super" B factories become competitive. For example, model calculations of the exclusive cross section $\sigma(\overline{p}p \to D^{*0}\overline{D}^0)$ peak at $\approx 1\,\mu$b at $\sqrt{s} \approx 4.2$ GeV [11, 12]. This is close to the 8 GeV Antiproton Source design energy and, at $2 \times 10^{32}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$, implies $\approx 4 \times 10^9$ events produced per year. Including $D^{*\pm}D^{\mp}$, $D^*\overline{D}^*$, $D\overline{D}$, $D\overline{D}\pi$,... events, the total charm sample will be

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†The AntiProton Annihilation Spectrometer

Table 1: Properties of existing and anticipated antiproton sources

Facility	$\overline{p}$ Kinetic Energy (GeV)	Stacking: Rate (10^{10}/hr)	Duty Factor	Operation: Hours /yr	$\overline{p}$/yr (10^{13})
CERN AD	0.005 0.047	–	–	3800	0.4
Fermilab Accumulator:					
current operation	8	>25	90%	5550	>150
proposed here	$\approx$3.5–8	20	20%	5550	20
FAIR ($\gtrsim$2018*)	1–14	3.5	50%*	2780*	4

*The number of operating hours at FAIR reflects time-sharing between antiproton and radioactive-beam programs. With the staged FAIR construction plan, until the stacking ring is built, antiproton stacking will occur in the experiment ring, leading to a reduced stacking duty factor, as indicated here.

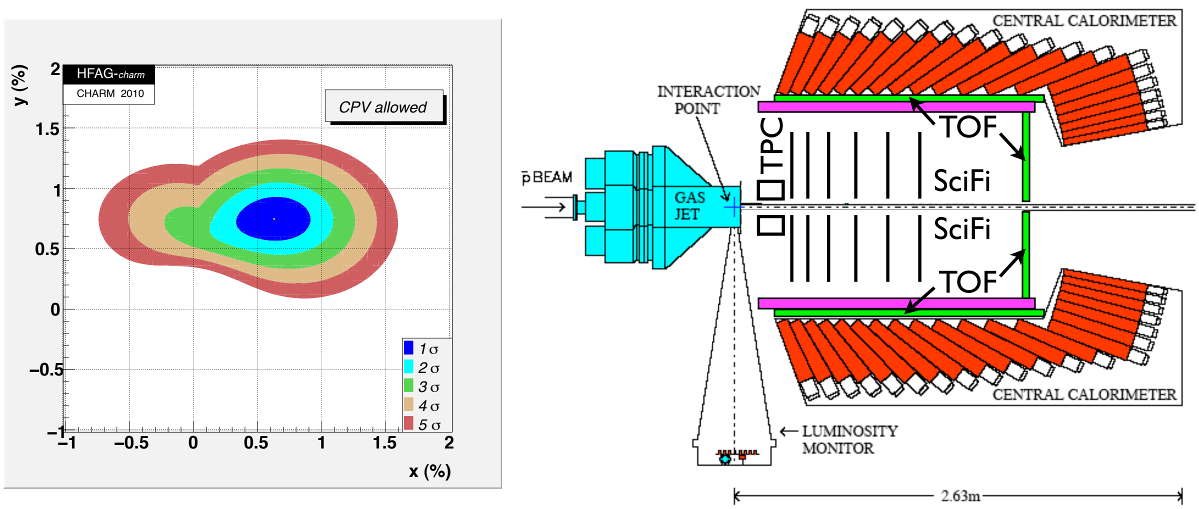

Figure 1: (Left) World average of D^0–$\overline{D}^0$ mixing parameters $x \equiv \Delta m/\Gamma$, $y \equiv \Delta\Gamma/2\Gamma$: no mixing ($x = y = 0$) is disfavored by 10.2σ (from [4]). (Right) Proposed TAPAS apparatus: 1 T solenoid surrounds small, high-rate TPC and fine-pitch SciFi detectors, and is surrounded by precision TOF counters, all within existing E760/835 Central Calorimeter. (Return yoke omitted for clarity.).

yet larger, and use of a nuclear target should enhance statistics by a further factor of a few [13]. We project in Table 2 up to 3×10^8 tagged-D^0 events reconstructed per year of running, to be compared with $\sim 10^7$ tagged $D^0 \to K\pi$ events implied in LHC*b*'s most recent presentation [2].

By localizing the primary interactions to $\sim 10\,\mu$m along the beam axis, a thin target can allow D decay vertices to be resolved. The low charged multiplicity ($n_{ch} \approx 3$) at these energies [14] implies small combinatorial background, enabling clean samples with only modest vertex cuts, thus with efficiency comparable to that at the B factories — orders of magnitude larger than that at LHC*b*. Medium-energy $\overline{p}N$ annihilation may thus be the best route to rare effects in charm.

Several signatures for D^0–$\overline{D}^0$ mixing have been observed and indicate that it is at the upper end of the range expected in the SM [14]. These involve differing time-dependences of "right-sign" Cabibbo-favored and "wrong-sign" D^0 decays (arising both from doubly Cabibbo-suppressed decay and from mixing), differing lifetimes of decays to *CP*-even and mixed-*CP* final states, and Dalitz-plot analyses of 3-body D^0 decays. These processes are sensitive to various combinations of the

Table 2: Example sensitivity estimate for D^*-tagged $D^0 \to K\pi$ decays (after Ref. [8]).

Quantity	Value	Unit
Running time	2×10^7	s/yr
Duty factor	0.8*	
$\mathcal{L}$	2×10^{32}	$\mathrm{cm}^{-2}\mathrm{s}^{-1}$
Annual integrated $\mathcal{L}$	3.2	fb^{-1}
Target A	47.9	
$A^{0.29}$	3.1	
$\sigma(\overline{p}p \to D^{*+} + \text{anything})$	1.25–4.5	μb
# $D^{*\pm}$ produced	(2.5–8.9) $\times 10^{10}$	events/yr
$\mathcal{B}(D^{*+} \to D^0\pi^+)$	0.677	
$\mathcal{B}(D^0 \to K^-\pi^+)$	0.0389	
Acceptance	0.45	
Efficiency	0.1–0.3	
Total	(0.3–3) $\times 10^8$	events/yr

*Assumes $\approx$ 15% of running time devoted to antiproton-beam stacking.

reduced mixing parameters $x \equiv \Delta m/\Gamma$, $y \equiv \Delta\Gamma/2\Gamma$.

While mixing at the observed level could be due to SM physics, there could also be an appreciable, or even dominant, contribution from new physics, possibly indicated by *CP* violation. LHC*b* observes a 3.5σ direct-CPV signal in D^0 decay, in the *CP*-asymmetry difference between K^+K^- and $\pi^+\pi^-$ final states: $\delta A = [-0.82 \pm 0.21 \pm 0.11]\%$, based on $1.4\,(0.4) \times 10^6$ tagged, reconstructed $K^+K^-(\pi^+\pi^-)$ events [2]. Per year of running, we expect up to a factor ≈ 5 better statistical sensitivity than LHC*b* (already at its design luminosity) has currently. While both experiments will have biases to correct, ours will differ from theirs in important ways (*CP*-symmetric initial state, no B background, much lower charged multiplicities). For such subtle measurements, it is crucial to have independent corroborating evidence, such as TAPAS can provide.

3 Measurements in the Charmonium Region

Fermilab experiments 760 and 835 made the world's most precise measurements of charmonium masses and widths [17]. This (<100 keV) precision reflects the small energy spread of the stochastically cooled antiproton beam and negligible energy loss and Fermi motion of the H_2-jet target. Urgent questions remain in this region, most notably the nature of the mysterious $X(3872)$ and its "cousins" [18], as well as improved measurement of h_c and η_c' parameters [19]. The width of the X may well be small compared to 1 MeV [20]. The $\overline{p}p$ energy-scan technique is the only way to make the precise mass, lineshape, and width measurements needed to test the intriguing hypothesis that the $X(3872)$ is a $D^{*0}\overline{D}^0$ molecule [21], which implies distinctive and mode-dependent lineshapes.

While unmeasured, the formation cross section of $X(3872)$ in $\overline{p}p$ annihilation is estimated to be comparable to that of the χ_c states [22, 8]. This implies ≈ 500 events/day observed in the $\pi^+\pi^-J/\psi$ mode at the $X(3872)$ peak. Even if this estimate is off by an order of magnitude, TAPAS should obtain the world's largest clean $X(3872)$ samples.[1] A few months of data should yield thousands of events in known decay modes, and reveal many unknown modes. Along with angular distributions, this could provide a definitive test of the nature of the $X(3872)$. Although the other X, Y, and Z states are broader than the $X(3872)$, their $\overline{p}p$ formation and observation in a variety of decay modes could nevertheless shed light on whether a new spectroscopy of meson-antimeson molecules, multiquark states, gluonic hybrids — or something else entirely — is being glimpsed.

[1] CDF and DØ sensitivities are limited by large backgrounds.

Table 3: Summary of predicted hyperon CP asymmetries

Asymm.	Mode	SM	Ref.	NP	Ref.
A_Λ	$\Lambda \to p\pi$	$\lesssim 4\times10^{-5}$	[27]	$\lesssim 6\times10^{-4}$	[30]
$A_{\Xi\Lambda}$	$\Xi^\mp \to \Lambda\pi,\ \Lambda \to p\pi$	$\lesssim 5\times10^{-5}$	[27]	$\leq 1.9\times10^{-3}$	[31]
$A_{\Omega\Lambda}$	$\Omega \to \Lambda K,\ \Lambda \to p\pi$	$\leq 4\times10^{-5}$	[28]	$\leq 8\times10^{-3}$	[28]
$\Delta_{\Xi\pi}$	$\Omega \to \Xi^0\pi$	2×10^{-5}	[29]	$\leq 2\times10^{-4}$ *	[29]
$\Delta_{\Lambda K}$	$\Omega \to \Lambda K$	$\leq 1\times10^{-5}$	[28]	$\leq 1\times10^{-3}$	[28]

*Final-state interactions neglected in [29] should make this comparable to that for $\Omega \to \Lambda K$ [32].

4 Hyperon *CP* Violation and Rare Decays

Searches for hyperon CPV are complementary to studies in the K^0 and beauty systems; for example, hyperon and K^0 CPV probe new-physics phases in parity-conserving (violating) currents, respectively. Depending on its nature, the new physics we seek could thus be entirely missed (or misinterpreted) if we look for it only with mesons. The expected levels of CPV in hyperon decay are $\lesssim 10^{-5}$ in the Standard Model, but can be up to $\sim 10^{-3}$ if dominated by new physics (Table 3). With the HyperCP (Fermilab E871) [23] result, $A_{\Xi\Lambda} \approx (\alpha_\Xi\alpha_\Lambda - \alpha_{\overline{\Xi}}\alpha_{\overline{\Lambda}})/(\alpha_\Xi\alpha_\Lambda + \alpha_{\overline{\Xi}}\alpha_{\overline{\Lambda}}) = (-6.0 \pm 2.1 \pm 2.1)\times10^{-4}$ [24], the most sensitive to date, experimental sensitivities in $\Xi^\mp \to \overset{(-)}{\Lambda}\pi^\mp \to \overset{(-)}{p}\pi^\mp\pi^\mp$ have reached the few $\times10^{-4}$ level. The indication of possible new physics in D^0 CPV at LHC*b* underscores the need for renewed searches in hyperons as well.

HyperCP also made the first observation of the flavor-changing neutral-current decay $\Sigma^+ \to p\mu^+\mu^-$ [25]. The proximity in dimuon mass of the three observed events suggests a new pseudoscalar or axial-vector resonance as an intermediate state: $\Sigma^+ \to pP^0$, $P^0 \to \mu^+\mu^-$, with P^0 mass of $(214.3 \pm 0.5)\,\mathrm{MeV}/c^2$ [25]. If real, this P^0 could not be an ordinary meson, but could arise in new-physics models [26]. With the small number of events, the effect could alternatively be a $\approx 2.4\sigma$ fluctuation of the Standard Model virtual-photon coupling.

These topics motivate an experiment with substantially higher hyperon statistics than HyperCP, feasible with fixed-target running of the Antiproton Accumulator, whose beam can be decelerated to just above the $\overline{p}p \to \Omega^-\overline{\Omega}^+$ threshold of 5.1 GeV/c. A 1-year run at $2\times10^{32}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ luminosity should produce some 2×10^8 $\Omega^-\overline{\Omega}^+$ pairs, giving statistical sensitivities of $\approx 8.0\times10^{-5}$ and 1.4×10^{-4}, respectively, for the CP-violating observables

$$\Delta_{\Lambda K} \equiv \frac{\Gamma(\Omega^- \to \Lambda K^-) - \Gamma(\overline{\Omega}^+ \to \overline{\Lambda}K^+)}{\Gamma(\Omega^- \to \Lambda K^-) + \Gamma(\overline{\Omega}^+ \to \overline{\Lambda}K^+)}\ ,\ \Delta_{\Xi\pi} \equiv \frac{\Gamma(\Omega^- \to \Xi^0\pi^-) - \Gamma(\overline{\Omega}^+ \to \overline{\Xi}^0\pi^+)}{\Gamma(\Omega^- \to \Xi^0\pi^-) + \Gamma(\overline{\Omega}^+ \to \overline{\Xi}^0\pi^+)}\ . \quad (1)$$

Systematic uncertainties are under study, but it appears that the uniquely clean environment of $\overline{p}p$ annihilation just above threshold will permit measurements at the 10^{-4} level (cf. [33]).

The 2σ indication of CPV in $\Xi^\mp \to \Lambda\pi \to p\pi\pi$ decay [24] motivates decelerating antiprotons to just above $\Xi^-\overline{\Xi}^+$ threshold. This is feasible in the Accumulator; the question is with what efficiency. The E835 "snowplow" technique entailed retuning the lattice while decelerating, in order to avoid transition-induced beam losses [34]. R&D is required to see whether the method can be extended so low in momentum (3.0 GeV/c). If it can, there is potential to measure A_Ξ and B_Ξ as well [33].

5 Proposed apparatus

The medium-energy antiproton-annihilation studies described above can all be carried out with a common apparatus, which can be assembled quickly and cost-effectively thanks to the availability of key existing components: the E760/835 barrel electromagnetic lead-glass calorimeter [35], a thin superconducting solenoid from BESS [36], the DØ scintillating-fiber readout system [37], and plentiful trigger and data-acquisition electronics from DØ and CDF. Augmented with a small, high-rate TPC, new, thin, fine-pitch scintillating-fiber planes, and picosecond time-of-flight detectors currently under development [38], these can form a very powerful general-purpose spectrometer (Fig. 1, right) for the low-multiplicity hadronic events that are produced by $\overline{p}p$ or $\overline{p}N$ annihilation in this energy range. Thin wire and frozen-hydrogen [39] targets can be deployed in the halo of the circulating antiproton beam [40]. Further details may be found in the proposal [41].

6 Outlook

Reconfiguration of the Antiproton Source has been proposed in order to form the muon and proton beams respectively needed for the $g-2$ and Mu2e experiments at Fermilab. At least one proposed $g-2$ configuration is potentially compatible with antiproton running, which requires the Antiproton Accumulator all the time but the Debuncher only 20% of the time (i.e., during antiproton stacking), while $g-2$ requires the Debuncher all the time (as a π-to-μ decay channel) but not the Accumulator. The two experiments could thus run concurrently with time-sharing of the Debuncher; other solutions are also possible. One configuration proposed for Mu2e is incompatible with antiproton running; however, Mu2e's likely >2018 start leaves a several-year antiproton window of opportunity. Moreover, non-Antiproton Source alternatives for Mu2e are also under consideration. While the TAPAS proposal is not yet approved, the collaboration and proposal are being strengthened in order to enhance the prospects for approval. It is hoped that apparatus assembly and development of the needed software and firmware can commence soon enough for data-taking to begin in 2014.

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