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 5 to 8 GeV antiprotons is expected to yield world-leading sensitivities to hyperon rare decays and *CP* violation. It could provide the world's most intense source of tagged D^0 mesons, hence the best near-term avenue to charm mixing and *CP* violation. Other possible measurements include properties of the $X(3872)$ and the charmonium system, and unique Drell–Yan studies. Thus the Antiproton Source offers a great opportunity for a broad and exciting physics program at Fermilab in the post-Tevatron era.

1 Introduction

The Fermilab Antiproton Source has routinely produced more than 1.5×10^{15} antiprotons per year [1] (Table 1), substantially exceeding the intensity available at the CERN Antiproton Decelerator (AD) and that anticipated at Germany's Facility for Antiproton and Ion Research (FAIR). With the end of Tevatron running, an internal target could again be operated in the Fermilab Antiproton Accumulator, with beam kinetic energy in the range ≈ 3.5–8 GeV. With antiproton stacking 10–20% of the time, a luminosity of $2 \times 10^{32}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ could be sustained during the remaining $\approx 80\%$. Such a program could allow world-leading studies of hyperon rare decays and *CP* violation (CPV), the $X(3872)$ and other "mystery states" in the charmonium region, and the charmonium system. While the open-charm production cross section at these energies has not been measured, world-leading studies of charm mixing, rare decays, and CPV may also be possible [2].

2 Hyperon *CP* Violation and Rare Decays

Searches for hyperon CPV are complementary to studies of the K^0 and beauty systems; for example, hyperon and K^0 CPV probe new-physics phases in parity-conserving (violating) currents,

Table 1: Properties of existing and anticipated antiproton sources

Facility	$\overline{p}$ Kinetic Energy (GeV)	Stacking: Rate (10^{10}/hr)	Stacking: Duty Factor	Operation: Hours /yr	Operation: $\overline{p}$/yr (10^{13})
CERN AD	0.005 0.047	–	–	3800	0.4
Fermilab Accumulator:					
current operation	8	>25	90%	5550	>150
proposed here	≈ 3.5–8	20	15%	5550	17
FAIR ($\gtrsim 2018$*)	1–14	3.5	15%*	2780*	1.5

*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 small stacking duty factor, as indicated here.

Table 2: Summary of predicted hyperon *CP* asymmetries

Asymm.	Mode	SM	Ref.	NP	Ref.
A_Λ	$\Lambda \to p\pi$	$\lesssim 4 \times 10^{-5}$	[7]	$\lesssim 6 \times 10^{-4}$	[10]
$A_{\Xi\Lambda}$	$\Xi^\mp \to \Lambda\pi$, $\Lambda \to p\pi$	$\lesssim 5 \times 10^{-5}$	[7]	$\leq 1.9 \times 10^{-3}$	[11]
$A_{\Omega\Lambda}$	$\Omega \to \Lambda K$, $\Lambda \to p\pi$	$\leq 4 \times 10^{-5}$	[8]	$\leq 8 \times 10^{-3}$	[8]
$\Delta_{\Xi\pi}$	$\Omega \to \Xi^0\pi$	2×10^{-5}	[9]	$\leq 2 \times 10^{-4}$ *	[9]
$\Delta_{\Lambda K}$	$\Omega \to \Lambda K$	$\leq 1 \times 10^{-5}$	[8]	$\leq 1 \times 10^{-3}$	[8]

*Final-state interactions neglected in [9] should make this comparable to that for $\Omega \to \Lambda K$ [12].

respectively. The expected level of CPV in hyperon decay is $\lesssim 10^{-5}$ in the Standard Model, but up to $\sim 10^{-3}$ in models with new physics (see Table 2). With the HyperCP (Fermilab E871) [3] result, $A_{\Xi\Lambda} \approx (\alpha_\Xi\alpha_\Lambda - \alpha_{\overline{\Xi}}\alpha_{\overline{\Lambda}})/(\alpha_\Xi\alpha_\Lambda + \alpha_{\overline{\Xi}}\alpha_{\overline{\Lambda}}) = (-6.0 \pm 2.1 \pm 2.1) \times 10^{-4}$ [4], 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 $\times 10^{-4}$ level.

HyperCP also observed for the first time the flavor-changing neutral-current decay $\Sigma^+ \to p\mu^+\mu^-$ [5]. The narrow dimuon-mass distribution 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 $(214.3 \pm 0.5)\,\mathrm{MeV}/c^2$ [5]. Such a state could not be an ordinary meson, but could arise in models with new physics [6]. Given the small number of observed 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, which could be done 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 $5.1\,\mathrm{GeV}/c$. A 1-year run at $2 \times 10^{32}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ luminosity should produce some 10^8 $\Omega^-\overline{\Omega}^+$ pairs, giving statistical sensitivities of $\approx 7.8 \times 10^{-5}$ and 1.3×10^{-4}, respectively, for the *CP*-violating observables,

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

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. [13]).

Given the 2σ indication of possible CPV in $\Xi^\mp \to \Lambda\pi \to p\pi\pi$ decay [4], it is also desirable to decelerate antiprotons to just above $\Xi^-\overline{\Xi}^+$ threshold. This should be possible in the Accumulator; the key question is with what efficiency. The E835 collaboration developed the "snowplow" technique to retune the lattice while decelerating, in order to avoid transition-induced beam losses [14]. R&D is required to see whether the method can be extended so low in momentum (3.0 GeV/c).

3 Measurements in the charmonium region

Experiments E760 and E835 made the world's most precise measurements of charmonium masses and widths [15]. This ($<100\,\mathrm{keV}$) precision reflected the small energy spread of the antiproton beam and the absence of Fermi motion and negligible energy loss in the H_2-jet target. Despite years of charmonium studies, a number of questions remain in this region, most notably the nature of the mysterious $X(3872)$ and its "cousins" [16] and improved measurement of h_c and η_c' parameters [17]. The width of the X may well be small compared to $1\,\mathrm{MeV}$ [18]. The unique precision of the $\overline{p}p$ energy-scan technique is ideally suited to making 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 [19]. This hypothesis implies distinctive and mode-dependent lineshapes. These measurements will require a hydrogen target: either a gas jet or a windowless, frozen-hydrogen target [20].

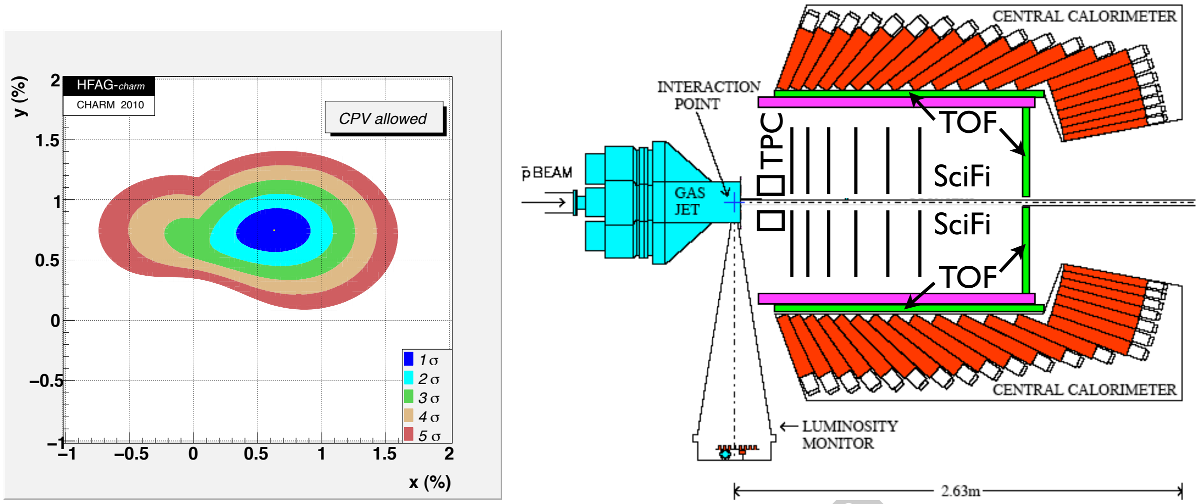

Figure 1: (Left) World average of D^0–$\overline{D}^0$ mixing parameters $x \equiv \Delta m/\Gamma$, $y \equiv \Delta\Gamma/2\Gamma$: no mixing ($x = y = 0$) is disfavored by 10.2σ (from [?]). (Right) Proposed TAPAS apparatus: 1 T solenoid surrounds small, high-rate TPC and fine-pitch SciFi detectors,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

The formation cross section of $X(3872)$ in $\overline{p}p$ annihilation is unmeasured, but has been estimated as similar in size to that of the χ_c states [21, 22]. By extrapolation from E760, ≈ 500 events/day will be observed in the $\pi^+\pi^- J/\psi$ mode at the $X(3872)$ peak. While this may be an under- or overestimate of the rate by as much as an order of magnitude, a new experiment at the Accumulator should obtain the world's largest clean $X(3872)$ samples,[1] in $\sim$1 month of running. A few months of data should yield thousands of events in known decay modes and discover many unknown modes. Along with angular distributions, this could provide a definitive test of the nature of the $X(3872)$.

4 Charm mixing, *CP* violation, and rare decays

After a $>$20-year search, D^0–$\overline{D}^0$ mixing is now established at $>$10 standard deviations (Fig. 1, left) [23], thanks to the B factories and CDF. The level of mixing ($\sim$1%) is consistent with the wide range of Standard Model predictions [24]; however, this does not preclude a significant and potentially detectable contribution from new physics [25, 26]. Since some new-physics models predict differing effects in the charge-2/3 ("up-type") and −1/3 quark sectors [25, 26], it is important to carry out such studies not only with s and b hadrons, but with charm mesons as well — the only up-type system for which meson mixing can be measured.

While the total charm-production cross section for ≈ 8 GeV antiprotons incident on proton or nucleon targets is challenging to compute from first principles, recent phenomenological estimates imply values in the 1–10 μb range [22],[27]-[30]. This is sufficiently large that the experiment we propose could amass a sample ten or more times larger than those of the B factories, years before the super-B factories reach comparable sensitivities. For example, model calculations of the exclusive cross section $\sigma(\overline{p}p \to D^{*0}\overline{D}^0)$ peak at about 1 μb at $\sqrt{s} \approx 4.2$ GeV [29, 30]. This corresponds to antiprotons of 8 GeV kinetic energy (the Antiproton Source design energy) impinging on a fixed target and, at $\mathcal{L} = 2 \times 10^{32}$ cm^{-2}s^{-1}, represents some 4×10^9 events produced per year. Since there will also be $D^{*\pm}D^{\mp}$, $D^*\overline{D}^*$, $D\overline{D}$, $D\overline{D}\pi$,... events, the total charm sample will be yet larger, and with the use of a target nucleus heavier than hydrogen, the charm-production A-dependence [?]

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

Table 3: Example sensitivity estimate for D^*-tagged $D^0 \to K\pi$ decays (after Ref. [22]).

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	(0.3–1) $\times 10^{11}$	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 ≈15% of running time is devoted to antiproton-beam stacking.

should enhance statistics by a further factor of a few. The total sample could thus substantially exceed the 10^9 events now available at the B factories. Indeed, we project in Table 3 in excess of 10^{10} tagged-D^0 events produced per year of running.

By localizing the primary interactions to $\sim 10\,\mu$m along the beam direction, a thin wire or frozen-hydrogen target can allow the D decay to be resolved. The low charged multiplicity at these energies [32] implies small combinatorial background, so that clean samples can be amassed using only modest vertex cuts, and thus, with high efficiency. Medium-energy $\overline{p}p$ or $\overline{p}N$ annihilation may thus be the optimal way to study charm mixing, and to search for possible new-physics contributions via the clean signature [25, 33, 34] of charm CPV.

4.1 D^0 mixing

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 [32]. 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 reduced mixing parameters $x \equiv \Delta m/\Gamma$, $y \equiv \Delta\Gamma/2\Gamma$. As already mentioned, mixing at the observed level could be due to SM physics, but there could also be an appreciable or even dominant contribution from new physics, which could be indicated by *CP* violation.

Given the kinematic similarities between the B-factory D samples and that in our proposed experiment, we anticipate performing all of these mixing analyses with significantly greater sensitivity than previously achieved. Table 3 gives an example sensitivity calculation in D^*-tagged $D^0 \to K\pi$ decays. Our sensitivity in semileptonic decays will depend on the efficiency and purity of lepton identification, which we have not yet simulated. In hadronic modes, we could be the world’s most sensitive experiment, exceeding current B-factory statistics by a factor of 10 or more, and perhaps in semileptonic modes as well. Depending on their trigger and reconstruction efficiencies for charm, LHC*b* may achieve statistical sensitivities comparable to or exceeding ours, but we expect them to have appreciable systematic uncertainties for small ($\lesssim 10^{-3}$) charm CPV asymmetries. We will also have biases to correct, but ours will differ from theirs in important ways (*CP*-symmetric initial state, no B background, much lower charged multiplicities). It will be crucial to have independent corroborating evidence for these subtle measurements, such as we and LHC*b* can provide.

5 Proposed apparatus

The medium-energy antiproton-annihilation studies described above can all be carried out with a common apparatus, which can be assembled relatively 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. Further details may be found in the proposal [39].

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. The g–2 configuration is potentially compatible with antiproton running, which requires the Antiproton Accumulator all the time but the Debuncher only 10 to 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 proposed Mu2e configuration is incompatible with antiproton running; however, Mu2e's likely 2018 start leaves a several-year antiproton window of opportunity. Moreover, alternatives to using the Antiproton Source for Mu2e are also under consideration. While the TAPAS proposal has yet to obtain approval at Fermilab, the collaboration and proposal are being strengthened in order to enhance the prospects for such 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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