New Experiments with Antiprotons

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Abstract

Fermilab operates the world's most intense antiproton source. Newly proposed experiments can use those antiprotons either parasitically during Tevatron Collider running or after the Tevatron Collider finishes in about 2011. For example, the annihilation of 8 GeV antiprotons might make the world's most intense source of tagged D^0 mesons, and thus the best near-term opportunity to study charm mixing and, via *CP* violation, to search for new physics. Other potential measurements include sensitive studies of hyperons and of the mysterious X, Y, and Z states. Production of antihydrogen in flight can be used for first searches for antihydrogen *CPT* violation. With antiproton deceleration to low energy, an experiment using a Penning trap and an atom interferometer could make the world's first measurement of the gravitational force on antimatter.

Key words: Antiproton, Antimatter, Charm, Charmonium, CP, CPT, Gravity, Hyperons, Mixing

1. Introduction

A number of intriguing questions — many involving symmetry, the theme of this Workshop — can be elucidated by a medium-energy antiproton-beam fixed-target experiment. Among these are the possible contributions of physics beyond the standard model to charm mixing and decay, hyperon decay, and the mechanism(s) underlying the X, Y, and Z states discovered in recent years at the B factories.

Table 1 summarizes the parameters of current and future antiproton sources. It can be seen that by far, the highest-energy and highest-intensity antiproton source is at Fermilab. Having formerly served medium-energy antiproton fixed-target experiments, including the charmonium experiments E760 and E835, it is now dedicated entirely to the Tevatron Collider, but could become available again for dedicated antiproton experiments when the Tevatron shuts down (towards the end of 2011 by present estimates). The CERN Antiproton Decelerator (AD) provides low-energy antiproton beams at a tiny fraction of the intensity now available at Fermilab. Germany's ≈billion-Euro plan for the Facility for Antiproton and Ion Research (FAIR) at Darmstadt includes construction — yet to be started — of 30 and 90 GeV rapid-cycling synchrotrons and low- and medium-energy antiproton storage rings [1]. Antiproton operation at FAIR is anticipated on or after 2017.

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

Facility	$\overline{p}$ K.E. (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:					
now	8	20	90%	5550	100
proposed	≈ 3.5–8	20	15%	5550	17
with new ring	2–20?	20	90%	5550	100
FAIR ($\gtrsim$ 2017)	2–15	3.5	90%	2780*	9

* The lower number of operating hours at FAIR compared with that at other facilities arises from medium-energy antiproton operation having to share time with other programs.

2. Physics Overview

In the absence of knowledge about the nature of the sought-for new physics, it is difficult to rank the physics topics mentioned above by impact and importance. But we can be confident that, should new physics be *discovered* in any one of them, it will immediately become the most interesting topic of the day. By current "handicapping," charm mixing is probably highest in priority. The key question is whether there is new physics in charm mixing, the signature for which is *CP* violation [2]. Despite much effort in the B and K sectors, evidence for physics beyond the standard model has proved elusive. A proper regard for the importance of these issues should prompt us to look elsewhere as well.

As pointed out by many authors [3, 4], charm is an excellent venue for such investigation. Not only is it the only up-type quark for which such effects are possible, but standard-model backgrounds to new physics are suppressed in charm: the CKM factors are small, and the most massive quark participating in loop diagrams is the

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

Expt.	Year	Mode	Events	Ref.
Belle	2003	$\pi^+\pi^- J/\psi$	35.7 ± 6.8	[5]
BaBar	2004	$\pi^+\pi^- J/\psi$	25.4 ± 8.7	[6]
CDF	2004	$\pi^+\pi^- J/\psi$	730 ± 90	[7]
DØ	2004	$\pi^+\pi^- J/\psi$	522 ± 100	[8]
Belle	2004	$\omega(\pi^+\pi^-\pi^0)J/\psi$	10.6 ± 3.6	[9]
Belle	2005	$\gamma J/\psi$	13.6 ± 4.4	[10]
Belle	2006	$D^0\overline{D}^0\pi^0$	23.4 ± 5.6	[11]
BaBar	2008	$\gamma\psi$, $\gamma\psi'$	23.0 ± 6.4,25.4 ± 7.3	[12]
BaBar	2008	$D^0\overline{D}^0\pi^0$	33 ± 7	[13]

b. As detailed below, a charm experiment at the Fermilab Antiproton Source might be the world's most sensitive. This is because $\overline{p}p$ or $\overline{p}N$ collisions have an enormous charm-production advantage relative to e^+e^- colliders: charm hadroproduction cross sections are typically $\sim \mu$b, vs. 1 nb for e^+e^-. Of course, luminosity favors e^+e^- (by $\sim 10^2$), and typically backgrounds do as well. Moreover, hadroproduction at high energy has the advantage of longer decay distances. But the countervailing disadvantage is higher multiplicity ($\langle n_{ch}\rangle \sim 10$) in the underlying event, which is responsible for the dominant, combinatoric background, suppressed via vertex cuts. The much lower charged-particle multiplicity ($\langle n_{ch}\rangle \approx 2$) in $\overline{p}p$ collisions near open-charm threshold should enable charm samples with cleanliness comparable to that at the B factories, with the application of only modest cuts, and hence, high efficiency. (More details of this argument are presented in Sec. 3.1.) The competition for this program is LHC*b* and a possible "super-*B* factory," which may have significant systematic biases, due e.g. to large rates of $b \to c$ decays.

Probably next in priority, the $X(3872)$ has been observed by several groups (see Table 2), and is incontrovertibly a real state [14]. Despite its proximity in mass to various charmonium levels, it does not appear to be one itself. As we will see, $\overline{p}p$ annihilation has the potential to make uniquely incisive measurements of its properties and thereby reveal its true nature. By scanning the Antiproton Accumulator beam energy across the resonance, Fermilab experiments E760 and E835 made the world's most precise measurements of charmonium masses and widths [15, 16]. Besides this precision, the other key advantage of the antiproton-annihilation technique is its ability to produce charmonium states of all quantum numbers, in contrast to e^+e^- machines which produce primarily 1^{--} states and the few states that couple directly to them, or (with relatively low statistics) states accessible in B decay or 2γ production.

The final physics example we consider is rare effects in hyperon physics. Two potentially interesting hyperon signals may have been glimpsed in the Fermilab HyperCP experiment, albeit with low statistical significance: evidence for *CP* violation (CPV) in $\Xi^\mp$ decay [17] and for flavor-changing neutral currents [18] in Σ^+ decay. While a dedicated experiment to follow up these $< 3\sigma$ effects would be hard to justify, the opportunity for substantial increases in hyperon statistics using the same apparatus that can make the other measurements described here is appealing. As discussed below, other potentially interesting hyperon effects are also within reach of such an experiment and offer a window into new physics different from those of K, B, and D studies.

The E835 apparatus did not include a magnet, hence various cross sections needed to assess the performance and reach of a new experiment remain unmeasured. However, they can be estimated with some degree of confidence. We are proposing to assemble, quickly and at modest cost, an "upgraded E835" apparatus including a magnetic spectrometer. If these cross sections are of the expected magnitude, it should be possible with this apparatus to make the world's best measurements of charm mixing and CPV, as well as of the other effects mentioned above. (To take full advantage of the capabilities of the Fermilab Antiproton Source, a follow-on experiment in a new, dedicated ring à la Table 1 might then be designed for even greater sensitivity.)

3. Proposed Antiproton Experiments at Fermilab

3.1. Medium-energy $\overline{p}p$-annihilation experiment

By adding a small magnetic spectrometer and precision time-of-flight (TOF) counters to the E835 calorimeter as in Fig. 1, plus modern, high-bandwidth triggering and data-acquisition systems, several important topics can be studied. This can be accomplished at modest cost: the solenoid we consider is small compared to other HEP solenoids, and the very capable scintillating-fiber readout system from the Fermilab DØ experiment [19] should become available once the Tevatron finishes. Cost-effective precision ($\delta t \lesssim 10$ ps) TOF counters are under development [20]. We assume $\overline{p}p$ or $\overline{p}N$ luminosity of $2 \times 10^{32}\,\text{cm}^{-2}\text{s}^{-1}$, one order of magnitude beyond that of E835, which can be accomplished by use of a denser internal target than the E835 hydrogen cluster jet [21].

Charm mixing and CP violation. After a more than 20-year search, D^0–$\overline{D}^0$ mixing is now established at > 10 standard deviations [22], thanks mainly to the B factories. The level of mixing ($\approx 1\%$) is consistent with the wide range of standard-model predictions [2]; however, this does not preclude a significant and potentially detectable contribution from new physics [3, 23]. Since some new-physics models predict different effects in the charge-2/3 ("up-type") quark sector than in the down-type [3, 23], 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 occur.

While challenging to compute from first principles, recent phenomenological estimates of $\overline{p}p$ annihilation cross sections to open charm near threshold show $\sigma(\overline{p}p \to$

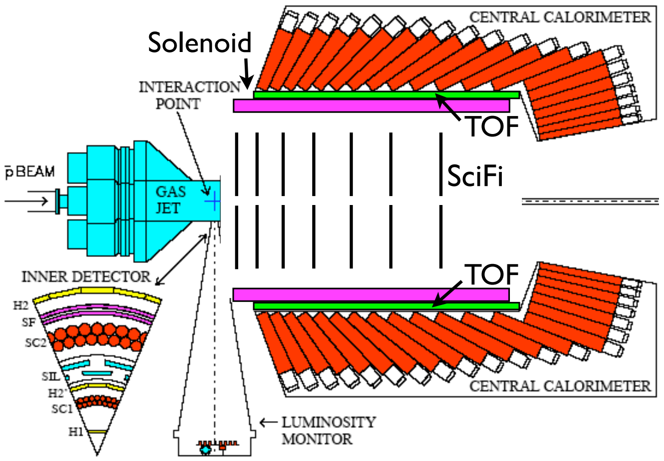

Figure 1: Sketch of upgraded E835 apparatus as discussed in text: a 1 T solenoid surrounds fine-pitch scintillating-fiber detectors, and is surrounded by precision TOF counters, all within the existing E835 Central Calorimeter. A possible return yoke is not shown; if the solenoid is not self-shielding, one would be needed for proper functioning of calorimeter phototubes.

$D^{*0}\overline{D}^0$) peaking at $\sqrt{s} = 4.2\,\text{GeV}$, at about $1\,\mu$b [24]. (It is interesting to note that the peak of this exclusive cross section fortuitously occurs at the Antiproton Source design energy.) At $\mathcal{L} = 2 \times 10^{32}\,\text{cm}^{-2}\text{s}^{-1}$, this 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 even larger, and with the use of a target nucleus heavier than hydrogen, the charm-production A-dependence [25] 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. By localizing the primary interactions to $\sim 10\,\mu$m along the beam (z) direction, a wire target can also allow the D-meson decay distance to be cleanly resolved. Medium-energy $\overline{p}N$ annihilation may thus be the optimal way to study charm mixing, and to search for possible new-physics contributions via the clean signature [26, 3] of charm CPV.

We have carried out preliminary simulations of such events with the apparatus of Fig. 1; key parameters of the simulation are given in Table 3. In particular we looked at $\overline{p}n \to D^{*-}D^0$, with subsequent decays $D^{*-} \to \pi_s^-\overline{D}^0$, $\overline{D}^0 \to K^+\pi^-$, for which the D^{*-} geometric acceptance is about 45%. To estimate the combinatoric background, we rely on a preliminary analysis of events from the MIPP experiment [27], using a 20 GeV $\overline{p}$ beam (the lowest energy for which a useful amount of data was available) and scaling the laboratory-frame longitudinal momenta of all secondaries by a factor 0.65 to approximate the effect of running at 8 GeV.[1] We searched the MIPP data sample for events containing three charged hadrons, two of one sign

Table 3: Key detector parameters used in simulations

Parameter	value	unit
Target (D study):		
material	Al	
configuration	wire	
diameter	30	μm
Target (X study):		
material	H	
configuration	cluster jet	
Beam pipe:		
material	Be	
diameter	5	cm
thickness	350	μm
Solenoid:		
length	1.6	m
inner diameter	90	cm
field	1	T
SciFi detectors:		
total thickness per doublet	360	μm
fiber pitch	272	μm
fiber diameter	250	μm
number of stations	8	
number of views	3	
number of channels	≈90,000	

and one of the other, consistent with being decay products of a $D^{*+} \to \pi_s^+D^0$, $D^0 \to K^-\pi^+$ or $D^{*-} \to \pi_s^-\overline{D}^0$, $\overline{D}^0 \to K^+\pi^-$ decay sequence. We found one such event, corresponding to a continuum cross section of about $1\,\mu$b before hadron-ID and vertex cuts.

Given the product branching ratio for the $\pi^\mp K^\pm\pi^\mp$ final state in question and the rarity of charged kaons in 8 GeV $\overline{p}N$ interactions, we estimate a signal-to-background ratio of about 10-to-1 before vertex cuts. With $150\,\mu$m resolution in decay-vertex z, >100-to-1 signal-to-background should be possible with efficiency $\gtrsim 10\%$. For example, we could expect to reconstruct $\approx 3 \times 10^7$ tagged $D^0 \to K^-\pi^+$ events per year, to be compared with some 1.2×10^6 events in the largest published sample to date [28], based on $540\,\text{pb}^{-1}$ of data taken at Belle. We also note that the Belle result — a $D^0 \to K\pi$ vs. $D^0 \to KK/\pi\pi$ lifetime difference of $(1.31 \pm 0.32 \pm 0.25)\%$ — has comparable statistical and systematic uncertainties. Thus the precision in a super-B factory may well not improve with increased statistics by as large a factor as naively expected.

Hyperon CP violation and rare decays. The Fermilab HyperCP Experiment [29] amassed the world's largest samples of hyperon decays, including 2.5×10^9 reconstructed $\overset{(-)}{\Xi}{}^\mp$ decays and 10^{10} produced Σ^+. HyperCP observed

[1] The lab-momentum scale factor was determined by comparing the longitudinal-momentum distributions from Monte Carlo simulations of D^* production and decay at 20 GeV and 8 GeV beam energy; we note that it is close to the ratio of $\sqrt{s}$ at the two energies. This procedure is conservative in that it neglects the reduction in charged-particle multiplicities and transverse momenta at 8 GeV compared to 20 GeV.

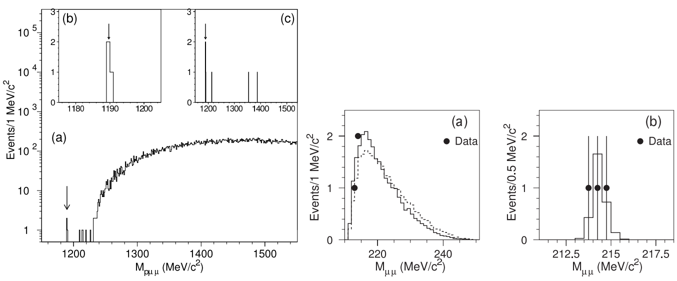

Figure 2: (Left) Mass spectrum for 3-track final states consistent with being single-vertex $p\mu^+\mu^-$ events in HyperCP positive-beam data sample: (a) wide mass range (semilog scale); (b) narrow range around Σ^+ mass; (c) after application of additional cuts as described in Ref. [18]. (Arrows indicate mass of Σ^+.) (Right) Dimuon mass spectrum of the three HyperCP $\Sigma^+ \to p\mu^+\mu^-$ candidate events compared with Monte Carlo spectrum assuming (a) SM virtual-photon form factor (solid) or isotropic decay (dashed), or (b) decay via a narrow resonance X^0.

unexpected possible signals at the $\gtrsim 2\sigma$ level for new physics in the rare hyperon decay $\Sigma^+ \to p\mu^+\mu^-$ [18] and the $\Xi^- \to \Lambda\pi^-$ *CP* asymmetry [17]: $A_{\Xi\Lambda} = [-6.0 \pm 2.1(\text{stat}) \pm 2.0(\text{syst})] \times 10^{-4}$. Since the $\overline{p}p \to \Omega^-\overline{\Omega}^+$ threshold lies in the same region as the open-charm threshold, the proposed experiment can further test these observations using $\Omega^- \to \Xi^-\mu^+\mu^-$ decays and potential $\overset{(-)}{\Omega}{}^{\mp}$ CPV (signaled by small Ω–$\overline{\Omega}$ decay-width differences in $\overset{(-)}{\Lambda}K^{\mp}$ or $\overset{(-)}{\Xi}{}^0\pi^{\mp}$ final states) [30]. The HyperCP evidence is suggestive of the range of possible new physics effects. More generally, high-sensitivity hyperon studies are well motivated irrespective of those "signals."

While the $\overline{p}p \to \Omega^-\overline{\Omega}^+$ cross section has not been measured, by extrapolation from $\overline{p}p \to \Lambda\overline{\Lambda}$ and $\overline{p}p \to \Xi^-\overline{\Xi}^+$ one obtains an estimate just above $\Omega^-\overline{\Omega}^+$ threshold of ≈ 60 nb, implying $\sim 10^8$ events produced per year. In addition the measured ≈ 1 mb cross section for associated production of inclusive hyperons [31] would mean $\sim 10^{12}$ events produced per year, which could directly confront the HyperCP evidence (at $\approx 2.4\sigma$ significance) for a possible new particle of mass $214.3\,\text{MeV}/c^2$ in the three observed $\Sigma^+ \to p\mu^+\mu^-$ events (Fig. 2).[2] Further in the future, the dedicated $\overline{p}$ storage ring of Table 1 could decelerate antiprotons to the $\Lambda\overline{\Lambda}$, $\Sigma^+\overline{\Sigma}^-$, and $\Xi^-\overline{\Xi}^+$ thresholds, where an experiment at 10^{33} luminosity could amass the clean, $> 10^{10}$-event samples needed to confirm or refute the HyperCP evidence [17] for *CP* asymmetry in the $\Xi\Lambda$ decay sequence.

Precision measurements in the charmonium region. Using the Fermilab Antiproton Source, experiments E760 and E835 made the world's most precise measurements of charmonium masses and widths [15, 16]. This precision ($\lesssim 100$ keV) was enabled by the small energy spread of the stochastically cooled antiproton beam and the absence of Fermi motion and negligible energy loss in the H_2 cluster-jet target. Although charmonium has by now been extensively studied, a number of questions remain, most notably the nature of the mysterious $X(3872)$ state [14] and improved measurement of h_c and η_c' parameters [33]. The width of the X may well be small compared to 1 MeV [34]. 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 [35].

The production cross section of $X(3872)$ in $\overline{p}p$ annihilation has not been measured, but it has been estimated to be similar in magnitude to that of the χ_c states [36, 37]. In E760, the χ_{c1} and χ_{c2} were detected in $\overline{p}p \to \chi_c \to \gamma J/\psi$ (branching ratios of 36% and 20%, respectively [38]) with acceptance times efficiency of $44\pm2\%$, giving about 500 observed events each for an integrated luminosity of $1\,\text{pb}^{-1}$ taken at each resonance; at the mass peak 1 event per nb^{-1} was observed [39]. The lower limit $\mathcal{B}[X(3872) \to \pi^+\pi^- J/\psi] > 0.042$ at 90% C.L. [40] implies that in a day at the peak of the $X(3872)$ ($8\ \text{pb}^{-1}\times$ $[1000\ \text{events/pb}^{-1}] \times 0.04/0.36 \times$ acceptance-efficiency ratio of final states of $\approx 50\%$), about 500 events would be observed. Even if the production cross section is an order of magnitude less than those of the χ_c states, the tens of events per day at the peak will be greater than the background observed by E835. By way of comparison, Table 2 shows current sample sizes, which are likely to increase by not much more than an order of magnitude as these experiments complete during the current decade.[3] (Although CDF and DØ could amass samples of order 10^4 $X(3872)$ decays, the large backgrounds in the CDF and DØ observations, reflected in the uncertainties on the numbers of events listed in Table 2, limit their incisiveness.)

We have concentrated here on one decay mode of the $X(3872)$: $X(3872) \to \pi^+\pi^- J/\psi$. Large samples will of course also be obtained in other modes as well, increasing the statistics and allowing knowledge of $X(3872)$ branching ratios to be improved. Given the uncertainties in the cross section and branching ratios, the above may well be an under- or overestimate of the $\overline{p}p$ formation and observation rates, 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 $\overline{p}p$ formation technique could enable the world's smallest systematics. Such an experiment could thus provide a definitive test of the nature of the $X(3872)$.

[2] Such a particle, if confirmed, could be evidence for nonminimal SUSY [32].

[3] The $\overline{p}p \to X(3872)$ sensitivity will be competitive even with that of the proposed SuperKEKB [43] upgrade, should that project go forward.

3.2. Antihydrogen Experiments

In-flight CPT tests. Antihydrogen atoms in flight may offer a way around some of the difficulties encountered in the CERN trapping experiments. First steps in this direction were taken by Fermilab E862, which observed formation of antihydrogen in flight during 1996–7 [41]. Methods to measure the antihydrogen Lamb shift and fine structure (the $2s_{1/2}$–$2p_{1/2}$ and $2p_{1/2}$–$2p_{3/2}$ energy differences) were subsequently worked out [42]. Progress towards this goal may be compatible with normal Tevatron Collider operations — a possibility currently under investigation. If the feasibility of the approach is borne out by further work, the program could continue into the post-Tevatron era.

Antimatter Gravity Experiment. While General Relativity predicts that the gravitational forces on matter and antimatter should be identical, no direct experimental test of this prediction has yet been made [44]. Attempts at a quantized theory of gravity generally introduce non-tensor forces, which could cancel for matter-matter and antimatter-antimatter interactions but add for matter-antimatter ones. In addition, possible fifth forces or non-$1/r^2$ dependence have been discussed. Such effects can be sensitively sought by measuring the gravitational acceleration of antimatter ($\overline{g}$) in the field of the earth. While various such experiments have been discussed for many years, one — measurement of the gravitational acceleration of antihydrogen — has only recently become feasible and is now proposed both at CERN and at Fermilab [45, 46].

The principle of the Antimatter Gravity Experiment (AGE), proposed at Fermilab [46], is to form a beam of slow (≈ 1 km/s) antihydrogen atoms in a Penning trap and pass the beam through an interferometer. The interferometer can employ material gratings, giving sensitivity to $(\overline{g} - g)/g$ at the 10^{-4} level, or use laser techniques as pioneered by Chu and Kasevich [47], with estimated 10^{-9} sensitivity. In either approach, a decelerated antiproton beam suitable for trapping is required. With the high antiproton flux available at Fermilab, this can be rather inefficient (say $\sim 10^{-4}$) and still provide enough antiprotons for competitive measurements. Ideas for such deceleration start with the Main Injector, which appears capable of decelerating from 8 GeV down to ≈ 400 MeV. Below this energy, one possible approach is the "antiproton refrigerator" [48], employing "frictional" cooling. More elaborate, higher-efficiency solutions, for example a small synchrotron with stochastic cooling, have also been discussed [46].

4. Outlook

With the end of the Tevatron Collider program in sight, new and unique measurements are possible at the Fermilab Antiproton Source [49, 50]. If approved, such a program will substantially broaden the clientele and appeal of US particle physics. A "protocollaboration" has been formed and approval is being sought.

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