$\overline{P}$ ACCUMULATOR PHYSICS

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Abstract

Physics interests and possible experiments using antiprotons from the Antiproton Accumulator in the 1990's are reviewed in the form of reports from several working subgroups, followed by a summary statement and recommendations.

1 Introduction*

Approximately two dozen particle physicists assembled at Breckenridge during this workshop to consider physics that could be done using antiprotons from the Antiproton Accumulator during the 1990's. After initial discussions, several working subgroups were formed to consider a variety of topics of interest. The remainder of this section provides reports from these subgroups, with summary comments and recommendations at the end. Since Fermilab is only one of two possible laboratories in the world where such work can be done in the foreseeable future, we believe that it is essential that these recommendations be given serious consideration by Fermilab and its community of users.

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2 Charmonium (E760 and Beyond)†

2.1 Introduction

The masses and widths of many of the charmonium states are still not sufficiently well known to determine the relative contributions of the various terms to the $c\bar{c}$ potential (spin-spin, tensor, etc.). Unlike the situation at e^+e^- machines, any of the charmonium mesons can be resonantly produced in $p\bar{p}$ annihilations allowing for precise spectroscopy of all states. E-760 was conceived to address this situation by taking advantage of the unique possibilities afforded by the $\bar{p}$ Accumulator ring at Fermilab. A brief description of the anticipated physics program is given.

2.2 Physics Goals

1. Discover the previously unknown narrow states $^1P_1$, $^1D_2$ and $^3D_2$. These states should all have decay modes to J/ψ which will make them easily identifiable experimentally.

2. Confirm the $\eta_c'(2^1S_0)$, observed by the Crystal Ball collaboration[1], but never unambiguously identified.

3. Accurately measure total widths for all narrow $c\bar{c}$ states.

4. Measure the ratio of all helicity amplitudes ($0,\pm1$) in $p\bar{p}$ production[2].

5. Measure the angular distributions and determine the multipole structure of radiative decays[3].

6. Scan the region from 9 GeV/c down to 3 GeV/c to search for cryptoexotics ($Q\overline{Q}c\bar{c}$ states) and glueballs.

2.3 Cross Sections and Rates

The insertion of a gas jet into a circulating, cooled $\bar{p}$ beam was first employed successfully during the abbreviated run of the R-704 experiment at the ISR. With only a handful of events (30 χ_1's and 50 χ_2's), extremely accurate masses and widths were extracted[4].

The E-760 detector has been described elsewhere[5]. Like R-704, inclusive J/ψ triggers are formed using a Čerenkov counter which tags e^+e^- pairs. The energy of electrons and photons is measured in a 1280 element lead glass array which also serves as the trigger for all-neutral events. E-760 will have 4 to 5 times the acceptance of R-704. In addition, the $\bar{p}$ Accumulator will afford the experiment a factor of 10 greater luminosity (10^{31} cm^{-2} s^{-1}) and a factor of 3 better mass resolution ($\delta m = 300 keV/c^2$). This results in 86 events/day per 100 pb of effective

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cross section. The effective cross section ranges from 3 x 10^4 pb for the J/ψ down to perhaps as low as 15 pb for the $^1P_1$. During separate 50-hour runs one would therefore expect to see 25-100 $^1P_1$'s, 160-300 η_c's, 1150 χ_1's, 1300 χ_2's and 50,000 J/ψ's.

2.4 Study of the Process $p\bar{p} \rightarrow \phi\phi \rightarrow K^+K^-K^+K^-$

A scan in the energy region around 2.8 GeV to study the process $p\bar{p} \rightarrow \eta_c \rightarrow \phi\phi \rightarrow K^+K^-K^+K^-$ is foreseen in an upgrade of the E-760 experiment.

The reaction $p\bar{p} \rightarrow \phi\phi \rightarrow K^+K^-K^+K^-$ at a center-of-mass energy in the η_c region was studied[6] in experiment R-704. The total cross section was determined to be $25.0 \pm 7.4 \pm 3.8$ nb. The limited integrated luminosity accumulated during the η_c scan did not allow a complete study of $\phi\phi$ production through η_c resonance formation.

During the $\phi\phi$ scan the threshold Čerenkov counter will be replaced by a spherical glass Čerenkov counter, based on internal reflection, that will provide multi-pion final state rejection at the trigger level[7]. The features of this Čerenkov counter will allow a $\phi\phi$ scan in a wide energy region, opening the possibility to study other $c\bar{c}$ resonances decaying into $\phi\phi$ or to search for exotic states.

3 $\bar{p}p$ Resonant Production of Heavy Hadronic Molecules ‡

The study of heavy hadronic molecules will provide an enormous stimulus to the development of nonperturbative QCD and the general theory of nuclear forces. It is now generally accepted that the basic hadronic states are color singlet $Q\overline{Q}$ mesons and QQQ baryons. These are tightly bound by single gluon exchange forces. As in atomic and nuclear physics, radial, orbital, and spin excitations occur. In the subnuclear world other forms of excitations can exist. One can imagine color singlet systems with larger aggregates of valence quarks - e.g. $QQ\overline{Q}\,\overline{Q}, QQQQ\overline{Q}, QQQ\overline{Q}\,\overline{Q}\,\overline{Q}$. Indeed, nuclei and hypernuclei are well established examples of nuclear molecules. The minimal, basic hadrons are held together by other than single gluon exchange. The attraction is due to quark exchange (a.k.a. pion exchange) and multigluon exchange (a.k.a. σ exchange). Nuclei exhibit severe short range repulsion which is fundamentally due to Pauli blocking. Other hadronic molecules should also exist and in many cases, be free of Pauli blocking. An important caveat is that the pion is too light to bind and any state ($I \neq 0$) which can decay by pion emission will be short lived.

A compelling case has been assembled that the 0^+ mesons $a_0(980)$ and $f_0(975)$ are essentially $K\overline{K}$ bound states. Other candidates for hadronic molecules

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exist as well. It is likely that many hadronic states have been incorrectly identified as orbital excitations.

If $K\overline{K}$ binds, there can be little doubt that $D\overline{D}$ binds as well. There should be $I = 1, 0$; $J^{PC} = 0^{++}$ states with masses $\approx$ 3700 MeV/c^2. It is easy to see why these states have been inaccessible to the e^+e^- annihilation experiments that have dominated heavy onium physics. Although the $\overline{p}p$ channel can resonantly produce these states, we expect strong decay channels into $\pi\eta_c$ and $\eta\eta_c$. Unfortunately η_c detection is very difficult. Some radiative decay into $\psi\gamma$ is possible, but it will have a small branching fraction.

A better bet is the axial vector states $[D\overline{D}^* \pm D^*\overline{D}]$. There should be four states ($J^{PC} = 1^{+\pm}$, I = 1,0) in the vicinity of 3850 MeV. The $D\overline{D}$ channel is forbidden. The I = 0 states will be narrower and hence more impressive. The C odd S wave channel $\eta\psi$ should be favorable for detection. The C even $\psi\gamma$ channel is also promising.

It is interesting that the quark constituency of $D\overline{D}^*$ (C even) can be rearranged into the asymmetric molecule $\psi\omega^0$ with approximately the same mass. Other asymmetric hadronic molecule configurations are worthy of extended consideration.

What about the production cross section? There are some grounds for optimism. The pioneering R704 ISR experiment has demonstrated that $\overline{p}p$ can resonantly produce ψ and χ's with useful yields. The $\overline{p}p$ transition into $c\overline{c}$ requires *all* light quarks to annihilate. The hadronic molecular system formation could be *less* OZI suppressed. Fermilab's experiment E-760 is ideally suited to this investigation. Time will tell[8].

4 CP Violation in Hyperon Decay[§]

4.1 Introduction

The purpose of this note is to discuss some recent estimates[9] of the difference between Λ and $\overline{\Lambda}$ decay parameters. This is done to help in planning experiments[10]. The salient feature of our work is to use measured CP violating (CPV) kaon observables to compute Feynman graphs at the hadronic level. By employing the hadronic basis, one avoids the difficult steps of obtaining the quark CPV parameters from the kaonic system and inserting these quark parameters into the baryon matrix elements.

4.2 Results

The details of our methods and results will be discussed in Ref. 9. Here we make a brief summary. Our method relies on using measured CPV parameters, so the value of ϵ' is important. If the CERN value[11] is used , we obtain results for the CPV decay parameters A and B that are in agreement with the standard model results

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of Ref. 12. Then A is about 10^{-4} and B is about 10^{-3}. If the recent very small result[13] from Fermilab for ϵ' is used, our results drop by roughly a factor of 6.

It is possible that the value of ϵ' is small because of a cancellation between the isospin 0 and isospin 2 CPV matrix elements for the two pion decays of the long-lived kaon. In that case, we again agree with the results of Ref. 12.

5 Prospects for a Measurement of CP Violation in $\Lambda - \overline{\Lambda}$ Decay † ‡

5.1 Introduction

The origin of CP violation (CPV) remains one of the fundamental unsolved problems in weak interactions. The only known evidence for CPV is in the neutral K system, where it is dominated by the extremely weak CPV $\Delta S=2$ interaction, giving rise to the parameter ϵ. If this were the only CPV interaction in nature, it is unlikely that its effects could be observed outside the K system. On the other hand, if there is a "milliweak" CPV $\Delta S=1$ interaction, giving rise to a non-zero value for its associated parameter ϵ', then one might expect to see CPV effects outside the neutral K system. It is still not known with certainty whether ϵ' is finite. At this workshop, we present a progress report on our ongoing efforts to explore experimental possibilities for observing such effects through a comparison of the decay parameters of hyperons and antihyperons. Thus far we have considered both the $\Lambda\overline{\Lambda}$ and the $\overline{\Xi}\Xi$ systems and have concluded[14] that the $\Lambda\overline{\Lambda}$ system will allow one to reach theoretically interesting limits more quickly than the $\overline{\Xi}\Xi$ system. Therefore, in this paper we concentrate exclusively on the $\Lambda\overline{\Lambda}$ system.

5.2 CP Violation in $\Lambda - \overline{\Lambda}$ Decay

Donoghue and collaborators[15] have suggested that a good place to look for $\Delta S=1$ CPV effects is in the decays $\Lambda \rightarrow p\pi^-$ and $\overline{\Lambda} \rightarrow \overline{p}\pi^+$. The observable of interest is the parameter α, which measures the asymmetry of the decay proton relative to the polarization direction of the Λ : $W(\theta) = 1 + \alpha P cos\theta$, where P is the polarization of the Λ. They define the quantity

$$A = \frac{(\alpha + \overline{\alpha})}{(\alpha - \overline{\alpha})}, \tag{1}$$

where $A \equiv 0$ in the limit of CP conservation. A non-zero measurement of A would be direct evidence for a CPV effect outside the neutral K system, ruling out purely

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$\Delta S = 2$ CPV theories such as the "superweak" theory. The current theoretical situation has been summarized by G. Miller in the preceeding contribution. He emphasizes that it is possible for A to be non-zero *even if* $\epsilon' = 0$, so that a CP test in hyperon decay would complement those measurements in the neutral K system. The calculations of Donoghue[15] and Miller place A_Λ in the range

$$A_\Lambda \approx (0.2 - 3.0) \times 10^{-4}. \tag{2}$$

These calculations suggest that a theoretical benchmark for a measurement of A_Λ is about 10^{-4}, which we assume in the discussion below.

5.3 Measurement of A_Λ in the $p\overline{p} \rightarrow \overline{\Lambda}\Lambda$ Reaction

We seek to measure the CPV quantity A in the reaction $\overline{p}p \rightarrow \overline{\Lambda}\Lambda$, which produces equal samples of polarized Λ and $\overline{\Lambda}$, with the polarization directions normal to the reaction plane. The measurable quantities are αP_Λ and $\overline{\alpha} P_{\overline{\Lambda}}$, which are determined from the up-down asymmetry of the decay proton and antiproton relative to that plane. C-invariance in the production reaction implies $P_\Lambda = P_{\overline{\Lambda}}$, so that the ratio

$$\frac{(\alpha P_\Lambda + \overline{\alpha} P_{\overline{\Lambda}})}{(\alpha P_\Lambda - \overline{\alpha} P_{\overline{\Lambda}})} = \frac{(\alpha + \overline{\alpha})}{(\alpha - \overline{\alpha})} = A\,, \tag{3}$$

and is independent of the magnitude of the polarization. This argument is crucial to the technique, since α is expected to differ from $-\overline{\alpha}$ by only 1 part in 10^4.

It is important to emphasize that a new experiment to measure A_Λ in the $\overline{p}p \rightarrow \overline{\Lambda}\Lambda$ reaction would be a second generation experiment, since the reaction is already being thoroughly studied in the PS185 collaboration at LEAR[14,16]. The PS185 technique is to produce $\overline{\Lambda}\Lambda$ pairs using an extracted beam of cooled $\overline{p}$'s and then to observe their characteristic two - "Vee" charged decays with a set of tracking wire chambers. A weak magnetic field downstream of the decay volume is used to distinguish particles from antiparticles. The data show that for energies not far above the production threshold, $\alpha P_\Lambda \approx 0.3$ over a broad range of production angles. With a sample of 16,000 $\overline{\Lambda}\Lambda$ events, they find[14,16] $A = -0.023 \pm 0.057$. Many more events have been accumulated and are yet to be analyzed. However, in order to extend the result to the theoretically interesting limit of 10^{-4}, requiring about $5\text{x}10^9$ analyzed $\overline{p}p \rightarrow \overline{\Lambda}\Lambda$ events[14], a new technique specifically designed for a dedicated, high luminosity experiment would be needed.

The essential parameters of an improved experiment can be understood from the following considerations. We assume a $\overline{p}p \rightarrow \overline{\Lambda}\Lambda$ production cross section[14,16] of 80μb, a luminosity of $5\text{x}10^{31}$ cm^{-2}sec^{-1}, a total acceptance (including branching ratio) of 0.15, and a macroscopic duty factor of 0.5. One reaches the desired level in about 200 days of running. Such an experiment would create very demanding requirements on the $\overline{p}$ beam, the detector and data acquisition system, and the understanding of systematic errors.

The ideal $\bar{p}$ momentum for such an experiment is 1.65 GeV/c, which is enough above threshold that the polarization is large[14], but below the background-producing $\Lambda\bar{\Sigma}$ threshold. The $\bar{p}p$ luminosity would require an intense internal cooled $\bar{p}$ beam and a gas-jet target. The short flight path of the Λ, and the requirement that the decay vertex occur within a tracking chamber, together imply that the diameter of the beam pipe should be small, probably $\leq$1cm. The combination of low beam momentum, high luminosity, and small beam pipe rule out the use of the present antiproton Accumulator at Fermilab. A new low-energy antiproton ring which would meet the requirements of this and other experiments is discussed in the contribution of D. Möhl *et al.* in Section 7.

A major problem to be solved with the detector/data acquisition system is how to cope with a $\bar{p}p \rightarrow \bar{\Lambda}\Lambda$ event rate of about 300/sec in a background about 10^4 times larger. This means the first-level trigger must be both very fast ($\leq$ 100 nsec) and very selective. A conceptual design that addresses these issues has been discussed in Ref. 14. Briefly, it consists of concentric layers of inner veto scintillators surrounding the beam pipe, followed by wire tracking chambers and by two or more concentric outer shells of projective scintillator strips. These strips would be arranged in a geometry to veto events with trajectories projecting back to the jet-beam crossing, since the events of interest should instead project downstream of the crossing. A backward detector would veto γ's and charged particles outside the forward cone of good events. The fast trigger would require 4 charged hits in the outer scintillator strips and no veto. A second-level trigger ($\leq$ 10μsec) would require 4 good tracks and possibly good azimuthal balance for these tracks. A weak magnetic field downstream of the decay would be needed to distinguish particles from antiparticles, as in the PS185 experiment.

At the 10^{-4} level there are many potential sources of false asymmetry. For example, the detector is made of matter, yet is expected to detect both matter and antimatter without bias. However, there are also some built-in checks on the apparatus. For example, one can analyze the decay asymmetry with respect to a fixed but arbitrary plane in order to check for false asymmetries. We are currently studying sources of systematic error both through Monte Carlo calculations and through close examination of the PS185 experiment.

5.4 Summary and Conclusions

We have discussed an experiment to search for CP violating effects at theoretically interesting levels. One would do this by comparing the decay asymmetries of Λ and $\bar{\Lambda}$. A new $\bar{p}$ ring at Fermilab would probably be required. We are continuing to study detector designs, fast data acquisition and analysis, and sources of systematic errors, with the intention of preparing a detailed proposal for the experiment if it proves feasible.

6 Physics with Ultra-Low Energy Antiprotons §

The experimental observation that all forms of matter experience the same gravitational acceleration is embodied in the weak equivalence principle of gravitational physics. However, no experiment has tested this principle for particles of antimatter such as the antiproton or the antihydrogen atom[17]. Clearly the question of whether antimatter is in compliance with weak equivalence is a fundamental experimental issue, which can best be addressed at an ultra-low energy antiproton facility.

Some thirty years ago the notion of "antigravity", according to which antimatter would fall up, enjoyed a brief popularity. However, theoretical arguments were raised against this idea[18] and it was not until the development of supergravity theories that weak equivalence for antimatter was again questioned.

In 1979 Joel Scherk pointed out[19] that certain supergravity theories could allow the antiproton to fall down faster than ordinary matter. This idea, which is in a sense the exact opposite of "antigravity", avoids the old objections, and connects the anomalous gravity for antimatter with both "fifth-force"[20] and gravitational redshift experiments[21]. In Scherk's model, as developed in Ref. 20, the graviton, which provides the conventional infinite range attractive force, has two partners, known as the "graviphoton" and "graviscalar", which are capable of providing additional gravitational strength forces of macroscopic range. The graviphoton is a vector field and so must be coupled to some conserved charge, which could be taken phenomenologically to be the baryon number. This field would then give a repulsive force between "like" charges, so that it would tend to repel normal matter from the earth. However, the graviscalar, which is a spin zero field, would always be attractive, and therefore tend to mask the effects of the graviphoton on normal matter.

For antiprotons, on the other hand, both graviphoton and graviscalar would give attraction in the Earth's field, and so the antiproton would experience a larger gravitational acceleration than normal matter. The strongest constraints on Scherk's model come from gravitational redshift experiments, and allow a few percent larger gravitational acceleration for antiprotons and antihydrogen than for normal matter. A first-generation experiment capable of testing this idea by comparing the gravitational acceleration of antiprotons and of negative hydrogen ions is scheduled for CERN's LEAR facility. It is based upon the "Time-of-Flight" method pioneered by Fairbank and Witteborn for electrons.

Anomalous gravitational effects could also show up in a comparison of atomic transition frequencies in hydrogen and antihydrogen. An experiment to produce antihydrogen and measure its hyperfine transition and the Lamb shift to high precision would therefore provide a fundamental test of both gravity and CPT symmetry.

Before any of these questions can be addressed experimentally it is nec-

§by D.B. Holtkamp, M.H. Holzscheiter, R.J. Hughes (Los Alamos National Laboratory) essary to reduce the kinetic energy of the antiprotons from the production and accumulation energy of typically several GeV/c to energies comparable to room temperature or below. The first step of this deceleration process has been achieved at the Low Energy Antiproton Ring (LEAR) at CERN, where antiprotons are decelerated and stored at kinetic energies as low as 2 MeV.

There are three basic methods to decelerate antiprotons from MeV energies to energies appropriate for trapping experiments: a) a radio frequency quadrupole (RFQ) decelerator, b) and "anti-cyclotron", and c) a simple degrader foil.

An RFQ is potentially the most efficient of the three options discussed. With proper phase space matching from (say) 2 MeV kinetic energy ($\sim$ 60 MeV/c), one can decelerate 40-50% of the incident particles to 20keV where they can be trapped in a Penning trap. A design study for these specific requirements has been performed by P. Zhou and Fred Mills from Fermilab[22]. Additional phase space cooling of the beam in the low energy storage ring was required to attain small enough transverse and longitudinal emittances to obtain a good match to the RFQ. External bunching of the beam was required before injection into the RFQ to match the RF time structure of the deceleration bucket.

An alternative approach has been explored by a European team[23]. By using a magnetic "bottle" with specially shaped fields, a dilute gas can be used to decelerate particles as they spiral towards the center of the "Cyclotron Trap". The velocity dependence of the cyclotron equations of motion and of dE/dx conspire to cool the beam as it degrades. This device has been successfully used to study the annihilation of antiprotons at rest and to detect the characteristic K- and L- X-rays emitted when the antiproton captured into an excited Bohr orbit cascades down. As an extension to this method it has been proposed to use appropriately shaped electrical fields to extract the antiprotons from the center of the trap into an ultra-high vacuum vessel before capture and annihilation occur. Preliminary computer studies show that an ultimate extracted efficiency of 20% seems to be feasible. This would provide an antiproton bunch at approximately 10$\pm$5 keV kinetic energy which can either be used directly or be recaptured in a small Penning trap for further reduction of total energy and temperature of the bunch.

The least expensive option for obtaining very low energy antiprotons might use a smooth, low-Z degrader foil to degrade from 5 or 2 MeV to tens of keV. We have performed detailed experimental studies of this process using 5 MeV protons and antiprotons from LEAR[24]. Individual particles derived from a slow spill from LEAR were passed through a degrading foil stack which incorporated a scintillator set-up providing a start signal. At the end of a drift length of approximately .5 meters these particles were detected by a variety of different detectors, allowing a detailed analysis of the time-of-flight distribution, pulse height distribution, and angular distribution of the particles emerging from the foil. Experimental results were in very good agreement with predictions from the TRIM code[25] and therefore indicate that degrading from 2 MeV will yield about 20% of the incident beam in an energy bite of 50 keV: *i.e.* a trap with a well depth of 50 keV could trap almost 20% of a fast extracted spill. At a nominal bunch length of 250 ns (8^{th} harmonic bunching inside the LEAR ring) this trap will have to be approximately 50 cm in length and would allow the capture of around 1×10^8 antiprotons from a single spill from LEAR. In a recent experiment[26] approximately 6×10^4 antiprotons have been captured into a smaller trap employing a 3 keV energy bite.

Lastly, it should be mentioned that combinations of the above techniques are also attractive. For example, an RFQ that decelerates to only 200 keV would be easier to build and the beam could easily be transported to several experimental areas, a circumstance not so easy to obtain at 20 keV. At the experiment itself, a very thin degrader (3-4 micron scintillator) will degrade from 200 to 15±5 keV with $> 95\%$ efficiency. This would require a much simpler trap than one with a 50 keV bite and one single RFQ could serve several experiments.

In this initial trap stage (commonly referred to as the catching trap) the antiprotons can easily be cooled to room temperature by mixing the antiproton cloud with an electron cloud of sufficient density[27,28]. At this point the antiprotons can be extracted (and reaccelerated if necessary) at very low energy spread for collision type experiments, or they can be transported to a next stage trapping experiment, better suited for the specific physics case at issue. Both experiments currently under preparation at LEAR with ultra-low energy antiprotons, the comparison of the inertial mass of the antiproton and the proton[29] and the study of the gravitational acceleration of antiprotons in the Earth's gravitational field[30], require cooling to cryogenic temperatures and extreme vacua, more easily obtainable in a specifically designed, small Penning trap.

The inertial mass measurement will be carried out by comparing the cyclotron frequencies of antiprotons and protons in the same magnetic field using a single particle of each species stored in a cylindrical Penning trap. The proposed accuracy of 1 part in 10^9 will constitute the most accurate CPT test for the baryon sector to date.

To study the gravitational acceleration of antiprotons in the Earth's gravitational field it is proposed to perform a "Time-of-Flight" measurement of ultra-cold antiprotons launched from a Penning trap. Such a measurement will yield a time-of flight distribution exhibiting a "cut-off time" independent of the details of the initial energy distribution of the particles in the trap. The main difficulty of this conceptually very simple experiment[31] comes from the fact that the gravitational force is so weak in comparison to electromagnetic forces acting on the charged antiproton. Shielding of stray electric fields to the level below 10^{-7} Volts/m presents the major technological challenge in view of the electric fields produced by work function fluctuations on metal surfaces, the so called "patch-effect". Other problems are the avoidance of relative magnetic gradients to the order of $10^{-5} m^{-1}$ and the control of the coulomb repulsion between neighboring particles.

A test experiment to study these effects with "normal matter" ions is currently under preparation at the Los Alamos National Laboratory. The actual experiment with antiprotons has been approved for beam time at LEAR and is expected to yield a statistical accuracy of a few tenths of a percent based on the total number of particles which can be launched on a reasonable time scale. An improvement of this accuracy would require a larger number of antiprotons to be available to the experiment and therefore could be conducted at a new dedicated facility.

Considering the technical difficulties of shielding stray electric fields to the required level, it has been frequently discussed if a simpler approach to the study of the gravitational acceleration of antimatter would be possible with neutral antihydrogen atoms.

Two main ideas for the production of antihydrogen have been discussed. Simple radiative capture of a positron by an antiproton in a merged beam geometry[32], and a three-body reaction using either positronium atoms and antiprotons[33] or a dense positron plasma and antiprotons at very low temperature[34].

Both three body reactions exhibit a much larger cross section than simple radiative capture. The dense positron plasma approach makes it necessary to cool the antiprotons and positrons to temperatures of approximately 1°K or below, but in turn offers the advantage of the production of ultra-cold antihydrogen atoms which consequently could be trapped in a magnetic bottle for further investigation. Possible experiments include the measurement of the gravitational acceleration of antihydrogen by measuring a displacement of the antihydrogen cloud in a very shallow magnetic bottle by the additional force of gravity. Such and experiment would require ultra-cold antihydrogen atoms ($< .1$°K) and, therefore, the development of suitable laser cooling for the antihydrogen atoms once they are trapped. Other possibilities are spectroscopic measurements of the energy levels in antihydrogen compared to hydrogen atoms, *i.e.* Lamb shift and hyperfine structure (Hfs). The Hfs frequency for hydrogen is known at the 10^{-13} level[35] and a measurement of the Hfs for antihydrogen at an even 10^{-10} level would rival known CPT tests in the baryon sector.

The collision between positronium and antiprotons does not require these low temperatures and leads to the production of low energy (few keV) antihydrogen beams. These are ideally suited for experiments using Doppler free laser spectroscopy or the classical Lamb shift measurements as performed by Lamb and Retherford[36].

Again, CPT tests at a level below 10^{-10} would become possible if the number of trapped antiprotons could be increased to the level of 10^{10} which would produce an antihydrogen beam intensity of 500 - 2000 atoms per second. This will be possible at a dedicated low energy ring fed by the Fermilab Accumulator, which provides a higher antiproton accumulation rate than the CERN accumulator. Ideally the ring would operate from 1 GeV/c (for injection from the Booster) down to 60 MeV/c or below (for optimum injection into a Penning trap system). In such a facility all of the above mentioned, very challenging and fundamental experiments, could be performed in addition to a number of other measurements, which are currently not being seriously discussed because of the lack of an appropriate facility.

7 Low Energy Antiproton Rings at Fermilab †

7.1 Introduction

Two special purpose rings have been investigated, each specialized for its particular experiment. One experiment studies CP violation in $\Lambda - \overline{\Lambda}$ decays from $p\overline{p}$ collisions, and the other is the measurement of CPT violation and the force of gravity on antimatter. The first ring operates at fixed momentum, while the second ring is used to decelerate antiprotons to such an energy (2 MeV) that they may be extracted and decelerated in an RFQ to 5-10 keV, and then captured in a Penning or Paul trap.

7.2 $\Lambda - \overline{\Lambda}$ Ring

The preferred momentum for this ring is 1.65 GeV/c, just below the threshold for competing hyperon-antihyperon production channels. To get sufficient data (5×10^9 events) in, say one year, a luminosity of about 5×10^{31} cm^{-2} sec^{-1} is needed. Gas jet technology can produce a target whose density is 10^{14} cm^{-3} with an effective target length of 1 cm. Since the revolution frequency will turn out to be about 4 MHz, 10^{11} antiprotons are needed in the ring. In order to utilize a large fraction of the events, the beam pipe must have a diameter of one cm or less for 40 cm from the target.

Choosing the bend radius r to be 3.8 m (B=1.5 T), we consider a FODO arc lattice with QF O B O QD O B. Choosing 16 bends of 1.5 m length and 60° phase advance per cell gives a tune ν_x in the arcs and a γ_t of $\frac{4}{3}$. We will assume an arc mean radius R_{arc} of 7 m, so the typical β-function R_{arc}/ν_x is 5 m and the typical dispersion is 4 m. We will assume a beam emittance of 10π mm mrad and that the momentum aperture is 1% or greater for injection and stacking purposes. To fit the beam in the 5 mm radius pipe at the experiment requires that the β-function be about 2 m and that the dispersion be less than 1 m. Thus we will assume two 13 m straight sections with dispersion suppressors and low β sections, one for the experiment and the other for injection, RF, and diagnostics. The shuttered kicker for injection can be located at the missing dipole for the dispersion suppressor.

The lifetime due to target interactions is about 30,000 sec, while the time to double the emittance due to multiple scattering in the target is about 5000 sec. A stochastic cooling system is needed to obtain adequate luminosity lifetime. The system will be similar to the core cooling system in the Accumulator, *i.e.* low power

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with large signal to noise ratio. For these parameters, and $\Delta p/p = 10^{-3}$, a 1 GHz bandwidth system can provide 1200 sec cooling time. The mean hydrogen pressure due to the jet, scaled by β-function, is about 2×10^{-7} Torr. This means an in situ baking system is probably not necessary and that prebaking and careful choice of materials will be sufficient.

Since the antiproton beam needs to be cooled prior to injection at 1.65 GeV/c, a likely way is to decelerate the beam in the Accumulator and cool prior to extraction. The circumference of the ring is about seven times less than that of the Accumulator, so the beam in the Accumulator must be kept bunched while six or seven pieces of it are extracted from it, injected and RF stacked in the $\Lambda - \overline{\Lambda}$ ring. Alternatively, if the DDR exists (see below), the ring can be charged from it at 1 GeV/c. This avoids the RF stacking, but requires acceleration in the $\Lambda - \overline{\Lambda}$ ring.

7.3 Dedicated Decelerator Ring

Good practice will require an initial to final magnetic field ratio of about 15. The final momentum needs to be about 0.06 GeV/c (2 MeV kinetic energy) to decelerate in an RFQ or stop the beam with a foil. The upgraded Booster injection momentum will be about 1 GeV/c. Then we can supply the DDR by extracting in the standard way (eleven 52.8 MHz bunches) from the Accumulator, sending the 8 GeV beam backward through the Main Ring or Main Injector into the Booster, decelerating to 1 GeV/c (400 MeV kinetic), extracting the bunches at the bottom of the magnetic field cycle, and transporting them to the DDR. Here they must be cooled and decelerated to 2 MeV. The lattice design is patterned after several previous studies at CERN. The ring would have four bends, 16 quads, and four long straight sections. Other properties of the ring are given in Table 1, and a sketch is shown in Fig. 1.

Injection is single turn via a magnetic septum in a medium straight and a fast kicker in a long straight. Ejection can be either single turn or slow. Cooling is needed at several stages: after injection, during deceleration, and at .06 GeV/c. At injection, stochastic cooling of 1-2 GHz bandwidth will provide a cooling time of 1-2 minutes. At low energy, electron cooling will be more favorable because of the η value. For cooling times of 100 sec, beams of $10^{10}\,\overline{p}$ with emittance 30π mm mrad and $\Delta p/p = \pm2 \times 10^{-3}$ can be maintained at .06 GeV/c against intrabeam scattering. For $10^{9}\,\overline{p}$'s, the corresponding numbers are 10π mm mrad, and $\pm1\times10^{-3}$.

8 Nuclear Tests of QCD Using Anti-Protons [‡]

8.1 Shadowing and Anti-Shadowing

Measurements of deep inelastic lepton-nucleus scattering at SLAC and CERN show that nuclear structure functions are depressed below simple additivity at $x \leq 0.1$ and

[‡] by Stanley J. Brodsky (SLAC) and Mark Strikman (Leningrad)

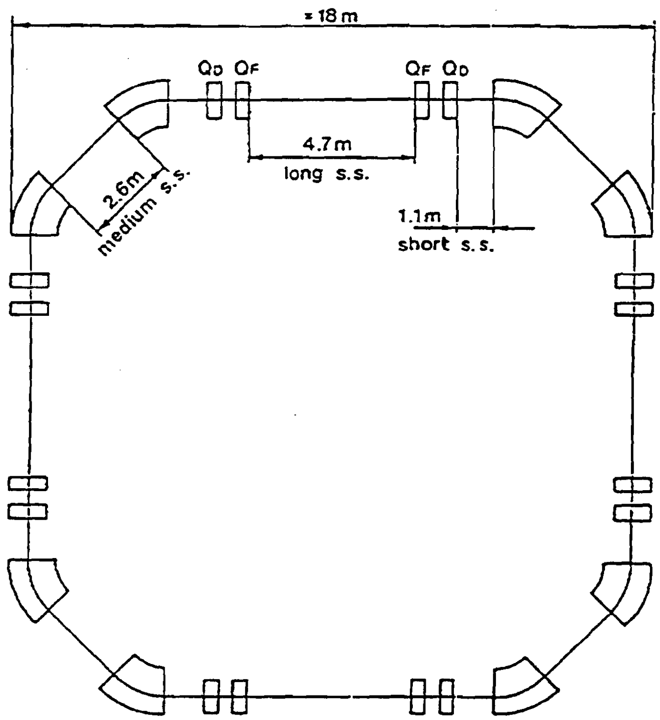

Figure 1: DDR Geometry

Table 1 : DDR Parameters

Momentum Range	60 MeV/c to 1 GeV/c
Circumference	60 m
Long Straight Section Free Length	4.7 m
β_x, maximum	6 m
β_y, maximum	12 m
Dispersion, maximum	3.1 m
Tunes (ν_x, ν_y, γ_t)	(2.3, 2.7, 3.0)
Dipole Bend Radius (0.087 to 1.6 Tesla)	2.3 m
Dipole Bend Angle	45°
Dipole Gap	10 cm
Quadrupole Gradients (F, D)	(7.4 , -9.1) Tesla/m
Quadrupole Length, Poletip Radius	30 , 7 cm
Revolution Frequency (at 0.06 , 1 GeV/c)	0.32, 3.60 MHz
RF Voltage (h=1, $\Delta p/p = \pm 3 \times 10^{-3}$, 1 GeV/c)	3.7 kV
Laslett tune shift; $10^{10}\bar{p}$, 60 MeV/c, unbunched	0.02

enhanced above additivity at $x \simeq 0.15$. The shadowing and anti-shadowing appear to be Q^2-independent; *i.e.*, leading twist. It then follows from the QCD factorization theorem for inclusive reactions that the same nonadditive nuclear features must appear at small values of $x_{q/A}$ in processes such as $\overline{p}A \to \ell^+\ell^- X$, $\overline{p}A \to \gamma\gamma X$, etc. Since the structure functions of anti-protons are well-understood, high energy fixed-target $\overline{p}$-nucleus measurements at Fermilab can provide a definitive test of this fundamental QCD prediction[37].

8.2 Charmonium Production in Nuclei

The production of the J/ψ in high energy anti-proton nuclear reactions at Fermilab is of interest for several reasons:

1. Measurements of J/ψ production by protons and pions in nuclei show an anomalous nuclear A-dependence and an x_F distribution at large longitudinal momentum beyond that predicted from the leading-order fusion subprocesses[38] $gg \to c\overline{c}$ and $q\overline{q} \to c\overline{c}$.

2. Formation zone arguments[39] predict that the time for forming the J/ψ in a high energy collision grows linear with lab energy. The nuclear A-dependence of inclusive $\overline{p}A \to J/\psi X$ can be used to determine the cross section for the interactions of the $c\overline{c}$ as it traverses the nucleus. Low energy $\overline{p}$-nuclear reactions can determine J/ψ-nucleon cross section; at high energies, the physical J/ψ is formed outside the nucleus.

3. Measurements of the quasi-exclusive reactions $\overline{p}p \to J/\psi$ in a nucleus can be used to probe the proton's momentum distribution and the short-distance structure of the nucleus. The dependence of the cross section $\overline{p}A \to J/\psi$ (A-1) on the nuclear proton number Z also tests QCD "color transparency". Similar considerations are involved in the production of other $c\overline{c}$ and $b\overline{b}$ states by anti-protons in nuclei.

8.3 Anti-Proton Tests of QCD Color Transparency

An essential feature of perturbative QCD analyses[40] of large momentum transfer exclusive reactions such as $\overline{p}p \to \overline{p}p$, $\pi\pi$, $K\overline{K}$, $\Lambda\overline{\Lambda}$, J/ψ, $\gamma\pi$, etc., is that the amplitude is dominated by wave configurations in which the valence quarks of each hadron are at small relative impact parameter: $b_\perp \sim 1/Q$. Up to small power corrections[41], this is even the case when multiple scattering (the "pinch" contribution) is the dominant subprocess. In QCD small color-singlet wave have diminished strong interactions; thus corrections due to initial and final state interactions can be neglected in large momentum transfer exclusive reactions. In particular, perturbative QCD predicts that the cross sections for quasi-exclusive processes such as $\overline{p}A \to \ell^+\ell^-(A-1)$ or $\overline{p}A \to \overline{p}p(A-1)$ are not effected by nuclear attenuation at high pair mass and is linear in the number of protons in the target. This is the prediction of QCD "color transparency"[42]. Some evidence for this novel effect has been reported at BNL in quasi-elastic large angle pp scattering in nuclei[43]. Two effects are important in the theoretical analysis: the dominance of small color-singlet wave function configurations, and the persistence of the small configurations over time as this state progresses through the nucleus[44]. Studies of both the energy and angular dependence of quasi-exclusive anti-proton reactions are needed to separate and test these ideas. The large angle tests can be done at $\bar{p}$ Fermilab Accumulator energies. It is also important to test color transparency at large t in the $s >> -t$ diffractive regime where multi-gluon exchange contributions dominate.

8.4 Charmonium Bound to Nuclei

A $c\bar{c}$ bound-state will interact with nucleons through multiple-gluon exchange. This provides an attractive potential analogous to the van der Waals interaction between neutral atoms in QED. It has recently been predicted that this potential is sufficiently strong to bind the η_c to nuclei such as He^3 or heavier[45]. One can search for this state at the Fermilab anti-proton Accumulator by studying the reaction $\bar{p}He^4 \to He^3(c\bar{c})$ just below the η_c threshold. The signal for a charmonium-nucleus bound state is an enhancement in the recoil spectrum at $M_X \sim M_{\eta_c}$, isotropic in the CM frame, with a sharp peak at incident energy $E_{CM} = M_{He^3} + M_{\eta_c} - \epsilon$ with the width of the η_c. A precision measurement of the incident energy is needed to determine the binding energy ϵ. The momentum distribution of the recoil nucleus is given by $|\psi_{\eta_c He^3}(p_{CM})|^2$. The spontaneous hadronic decay of the η_c in the nucleus could provide a novel opportunity to study the interactions and evolution of hadrons formed from a point-like source $l \sim 1/M_{\eta_c}$ within the nucleus with a position distribution determined by $|\psi_{\eta_c He^3}(r)|^2$. It is also interesting to study the reaction $\bar{p}d \to n(c\bar{c})$ and look for isotropic enhancements of the production cross section at the heavy quark threshold - a sign of an almost-bound nucleon-η_c system.

9 Applications of Color Transparency with Antiprotons [§] [¶]

Large angle, large transverse momentum (p_t) exclusive hadronic scattering is an area of strong interaction physics where the relevant distance scale involved in the interaction process has been controversial. Perturbative QCD demands that for the scattering to be exclusive, each of the valence quarks must scatter within a short distance of the interaction point to maintain the coherence and suppress gluon radiation. In other words, this scattering only occurs if the initial and final state protons fluctuate to a physical size which is on the order of the q^2 scale.

[§] by S. Heppelmann (Pennsylvania State U.)

[¶] Work supported by the National Science Foundation Grant PHY 88-15259

When such hard nucleon nucleon interactions take place within nuclear matter, it has been pointed out that the normal strong interactions between initial or final state nucleons tends to vanish during a short time before and after the hard interactions, while the interacting nucleons are small. It is expected that as the energy scale increases, the initial and final state interactions in (p,2p) hard quasi-elastic scattering will tend to vanish. This phenomena is referred to as color transparency[46,47].

Experiments at Brookhaven suggest that these kinds of effects have been seen[48,49]. These data can be interpreted as indicating that filtering the scattering constituents through nuclear matter passes only the components of the cross section for which PQCD is most applicable[50].

Measurements will continue at Brookhaven with hadronic beams scattering at 90° CM and q^2 in the 5-20 GeV^2 range. Complementary experiments can be done at Fermilab at similar q^2 but forward angles. Comparisons between these experiments can illuminate the role of the Landshoff processes[51], and in particular, the precise nature of the Sudakov suppression of these processes[52,53].

Another class of hadron color transparency experiment involves the quasi-exclusive production of J/ψ's with $\bar{p}p$ collisions inside nuclei. In addition to the expected reduction in absorption from a nominal value, the unique kinematics and narrow width of the J/ψ make it possible to measure the energy loss of the initial and final state particles as they pass through nuclear matter. This can be separated from the nuclear binding energy so that information on both quantities is obtained.

Extraction of nuclear spectral momentum distributions with the use of this interaction offers a powerful new tool for the study of the motion of nucleons in a nucleus. Such data are important for their own sake and provide the information necessary to untangle other high energy nuclear data such as the EMC effect.

With a high momentum resolution beam like that used in E-760, the use of nuclear targets will reduce the cross section for J/ψ production per target proton by a factor of 2000. This is due to the Fermi motion of the nuclear proton. The rates expected for the experiment with existing facilities could be around 100 events/week of running[54].

A fixed target facility at 3-5 GeV/c momentum and providing 10^7 per second could offer a competitive alternative.

10 Production of Charmed Baryons with Antiprotons †

The symmetric production of hyperon-antihyperon pairs can be exploited to learn more about the basic properties of charmed baryons[55]. There are fifteen predicted low-lying charmed baryons shown in Fig. 2. Of these fifteen, only five rate at least one star in the Review of Particle Properties[56]. Hence, this is a wide-open field which, incidentally, will be the subject of a future major experiment at Fermilab[57].

† by Gerald A. Smith (Pennsylvania State U.)

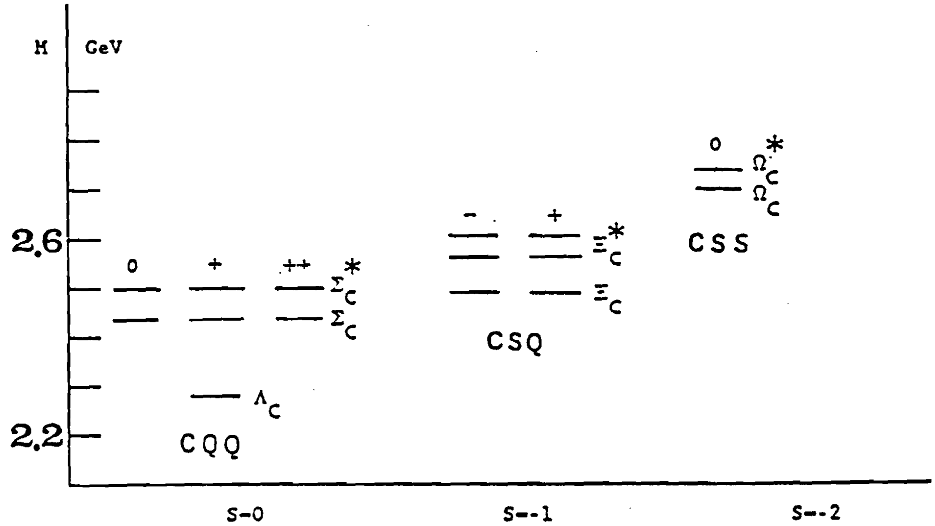

Figure 2: Low-lying Charmed Baryons

The goals of such investigations are precise measurements of masses, lifetimes, decay branching ratios and production dynamics, including polarization.

Production of exclusive pairs (e.g. $\Lambda_c\overline{\Lambda}_c$) of hyperons provides very strong kinematic constraints and a handle on systematic errors. Using QCD as a guide ($\sigma \propto m_q^{-8}$) and scaling from $\Lambda_s\overline{\Lambda}_s$, the cross section for $\Lambda_c\overline{\Lambda}_c$ is estimated to be ~ 200 nb[55]. As with $\Lambda_s\overline{\Lambda}_s$, one would sit somewhat above threshold (10 GeV/c), perhaps at 15 GeV/c. To access the heaviest charmed baryons, a beam momentum of $\sim$ 20-25 GeV/c would be appropriate. Suppose, for example, one were interested in studying the rare semi-leptonic decays $\Lambda_c^+ \rightarrow \Lambda_s^\circ e^+\nu$ ($\sim$ 2% BR), $\Lambda_s^\circ \rightarrow p\pi^-$ (64%). Then, with a luminosity of $10^{31}\text{cm}^{-2}\text{sec}^{-1}$, one would collect pairs of semileptonic decays at a rate of $\sim$ 30 per day. Assuming one could be sensitive to $\sim$ 30% BR for each decay, the rate increases to $\sim$ 3000 per day. Therefore, in one running cycle (6 months) one could accumulate $\sim$ one-half million decays. For comparison, a recent paper from Fermilab (E-691) reports $\sim$ 200 hadronic decays utilizing a tagged photon beam[58].

A Monte Carlo analysis of $\overline{p}p \rightarrow \overline{\Lambda}_c^F \Lambda_c^B$, $\overline{\Lambda}_c^F \rightarrow \overline{\Lambda}_s e^-\nu$, $\Lambda_c^B \rightarrow pK^-\pi^+$ (F = *forward*, B = *backward*) at 15 GeV/c shows that the reaction could be adequately analyzed using a forward ($0 < \theta_{LAB} < 90^\circ$) magnetic spectrometer with $\delta p/p \simeq 5\%p$. To uniquely identify close-in charmed hyperon decays, a silicon-strip micro-vertex detector is required. It is found, for example, that the transverse impact parameter between the e^- and p peaks at zero, with a long tail reaching out to $\sim 400\mu m$. It is estimated that a device with $30\mu m$ pitch would have an efficiency of $\sim$50% for separating decay vertices. The logical place to do this is in the Main

Injector itself, using it as a storage ring with a gas jet target, or to extract from the Main Injector.

11 Polarized Antiprotons at Fermilab [‡]

The spin-splitter method described here, has been proposed by the SPLIT collaboration at LEAR. It is based on the spatial separation of circulating particles with opposite spin directions, without appreciable loss of intensity, by means of the Stern-Gerlach effect in the field gradients of quadrupoles in the machine. Although the effect of the field gradient on the magnetic moment is extremely small compared to the effect on it from the charge of the circulating particles, the choice of specific coherence conditions between the orbit and spin motions allows a constructive buildup of spatial separation and provides for a mechanism of self-polarization.

The field of a quadrupole magnet is described to first order by

$$B_x = b \cdot y, \quad B_y = b \cdot x, \tag{4}$$

where x and y are the horizontal and the vertical axes, and z lies along the design orbit. The force acting on a magnetic dipole is

$$\mathbf{F} = \nabla(\mu \cdot \mathbf{B}) = b(\mu_x \hat{\mathbf{y}} + \mu_y \hat{\mathbf{x}}) \tag{5}$$

and the deflections of the particles in the $x - z$ and $y - z$ planes are, respectively,

$$\delta x' = b\mu_y L/p\beta, \quad \delta y' = b\mu_x L/p\beta \tag{6}$$

where μ_x and μ_y are the projections of the magnetic moment, L is the length of the quadrupole, and p is the beam momentum. Since the difference in the deflection angle is extremely weak for particles with opposite spin, the next quadrupole in the ring, with opposite polarity, would almost exactly cancel the effects of the first. Elements between the quadrupoles have to rotate the spin in such a way that the kicks obtained in the quadrupoles add up. In order to achieve a build-up over many revolutions, the spin tune and betatron frequency must be, modulo 2π, identical. This can be expressed by

$$\nu_s = a \cdot \gamma = Q \pm n, \tag{7}$$

where $a = (g-2)/2$ (=1.793 for protons); $\gamma = (1-\beta^2)^{-1/2}$ is the Lorentz factor, n is an integer, ν_s is the spin tune, and Q is the betatron tune of the appropriate (vertical or horizontal) plane.

This spin splitter consists of two quadrupoles with a solenoid between them, placed in one straight section of the ring. The quadrupoles have opposite polarity. The characteristics of this configuration are as follows: 1) The existing machine lattice is not changed and the spin-splitter configuration will not have any

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effect on the rest of the ring for the orbit motion. 2) The spin tune is affected in a characteristic way by the spin splitter because the solenoid behaves like a 'Siberian snake'. Each second revolution, the spin of each particle points in the same direction. The non-integer part of the spin tune is therefore 1/2 and is independent of the energy of the particle: $\nu_s = 1/2 + m$ (m integer). This has two consequences. First of all, it significantly reduces the depolarization due to the finite energy spread. On the other hand, according to Eq. (7) the machine would run on a half-integer betatron tune. One possible way of avoiding this half-integer resonance is to make the rotation angle of the solenoid slightly smaller than π and allow vertical periodic spin motion. This increases the polarization time by a modest amount with respect to an ideal situation.

We have started to investigate the possibility of installing a spin-splitter in the Fermilab Accumulator. The preliminary study shows that at 3.3 GeV/c, with a 9.3 Tesla solenoid 4 m long, the spin-splitter can run with some modification of the present optics, while keeping the maximum β-function at its normal value of 33 m.

12 Summary and Recommendations [§]

Apart from charmonium physics which is already under way in the form of E-760, this study has identified three important areas of physics which can be engaged with the addition of major facilities to the Antiproton Accumulator. These areas are:

1. Search for CP Violation in Hyperon Decay,
2. Test of the Weak Equivalence Principle in Gravity and
3. Test of CPT in Atomic Antihydrogen.

Topics (1) and (2,3) require two, small storage, decelerator rings to be effectively exploited. Each ring is estimated to cost 10-20M$, or approximately the same as a large fixed target experiment at Fermilab. The observation of CP violation in other than the K^0 system after 25 years would unquestionably lead to a better understanding of the phenomenon and its origins. Although tests of gravitational invariance and CPT in atomic systems do not fall exactly within the traditional particle physics program profile, they address very fundamental physics issues and do require facilities (rings) and particles (antiprotons) which can be found and utilized only at Fermilab and CERN. These projects would also clearly lead to a healthy synergism between the atomic and particle physics communities.

We have identified compelling experiments to be done with nuclear targets, where antiprotons act as a probe of QCD inside the nucleus. It would also appear that charmed baryons could be produced copiously with antiprotons, leading to the study of their properties. Techniques to be used to carry out such experiments

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remain to be resolved. Finally, with the rings proposed above, one can foresee important experiments leading to polarized antiprotons.

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