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January 2, 1992

John Peoples, Jr.,
Director
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Dear Sir,

We are writing this letter to express our interest in carrying out an experiment whose goal is the measurement of CP violation in Λ decay. We propose to study this effect in the reaction $p\overline{p} \rightarrow \Lambda\overline{\Lambda} \rightarrow p\pi^-\overline{p}\pi^+$,where we bring antiprotons circulating in a storage ring into collisions with the protons of an internal hydrogen gas jet target. A brief physics motivation and the storage ring requirements are addressed in an enclosed note.

The possibility of observing CP violation in hyperon decay has been the subject of considerable discussion ever since the observation of CP violation in the $K\overline{K}$ system. Interest in this subject was rekindled in 1986 when theoretical estimates for the asymmetry of the order of 10^{-4} were obtained. Nevertheless, not much has happened since that time, mostly due to the belief that such an experiment is not feasible. The two obstacles are the large number of events required for a statistically meaningful result ($> 10^9 \Lambda\overline{\Lambda}$ pairs), and the precise control of systematic effects to a high level of accuracy (10^{-5}). We believe that both of these problems can be overcome.

As shown in the note, we will be able to collect an adequate number of events during a 3 month run, assuming a 50% efficiency for data collection and a production rate of $6 \times 10^{10}\overline{p}$/hour. This $\overline{p}$ production rate is the one expected after the Linac upgrade; if the Main Injector is available, then the enhanced production rate puts us in an even better position. The problems of systematic control are essentially eliminated if one performs a counting experiment, rather than an experiment that measures angular distributions. This proposal, due to Donoghue *et al.*, relies on measuring the asymmetry of the final state $p\overline{p}$ relative to the $\Lambda\overline{\Lambda}$ production plane. The reduction of the systematic error to an acceptable level is achieved at the expense of a 15% loss in statistical accuracy.

The proposed experiment will require considerable resources. Besides a new storage ring, the gas jet target, and the detector, the experiment will need significant amount of running for the Antiproton source. Even though a well tuned experiment will be able to carry out the proposed measurement in three months, the development of the storage ring, its required stochastic cooling and beam handling systems, the development of efficient antiproton transfer mechanisms, and a first-time engineering run will take considerably more, both in time and money. We would like some encouragement and support from the laboratory to pursue this effort. Even though the hurdles facing such an effort are formidable, it is well worth it! The physics payoff is significant, the technical issues challenging, and the development of such a storage ring may open the field to further experiments with low energy antiprotons.

We would greatly appreciate some positive feedback to keep this effort going!

Sincerely,

Shao Yuan Hsueh

Petros Rapidis

Shao Yuan Hsueh and,
Petros A. Rapidis

encl: Search for direct CP violation in $p\overline{p} \to \Lambda\overline{\Lambda} \to p\pi^- \overline{p}\pi^+$

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Search for direct CP violation in $\bar{p} + p \rightarrow \bar{\Lambda} + \Lambda \rightarrow \bar{p}\pi^{+} + p\pi^{-}$

S.Y.Hsueh

January 2, 1992

1 Introduction

We propose to measure CP violating quantities in the decays of $\bar{\Lambda}\Lambda$ system. The experiment will use a stored $\bar{p}$ beam of 1.641 GeV/c interacting with a hydrogen gas jet to produce $\bar{\Lambda}\Lambda$ pairs exclusively. The advantage of such an arrangement comes from the fact that the initial state is CP invariant. This property of the initial state implies that final states must have identical CP symmetry if CP is conserved. Thus the observation of CP odd quantity is a signal of CP violation.

The CP odd quantities are measured by comparing the Λ decay with the $\bar{\Lambda}$ decay. In particular, we are interested in comparing the angular distributions in the center of mass frames of the Λ and the $\bar{\Lambda}$.

2 Physics Motivation

The observation of *direct* CP violation in $\bar{K}K$ system remains elusive. Recent results [1][2]suggest that $\frac{\epsilon'}{\epsilon}$ could be smaller than 10^{-3}. Within the standard model, a very heavy top quark implies a small $\frac{\epsilon'}{\epsilon}$ [3] and therefore precludes the observation of direct CP violation. This gives renewed importance to other direct CP violation not affected by the top quark mass. Hyperon decay is a natural place to search for direct CP violation. Furthermore, unlike the $\bar{K}K$ system, the CP violation effect is much less dependent on the top quark mass.

The hyperon decay proceeds into both s-wave and p-wave final states with amplitudes S and P, respectively. We parametrize the decay amplitudes as[4]:

$$S = \sum_i S_i e^{i(\delta_i^S - \phi_i^S)},$$

$$P = \sum_i P_i e^{i(\delta_i^P - \phi_i^P)}. \tag{1}$$

Where i runs over all possible isospin final states, δ is the final state interaction phase and ϕ is the weak interaction (CP violating) phase. S_i and P_i are real. In the case of Λ decay, the allowed isospin final states are $\Delta I = \frac{1}{2}$ and $\frac{3}{2}$. Experimentally we know the $\Delta I = \frac{1}{2}$ amplitude dominates the $\Delta I = \frac{3}{2}$ amplitude. The CP violation is due to the interference of s-wave and p-wave of the $\Delta I = \frac{1}{2}$ amplitude. This is unlike the $\bar{K}K$ system in which the direct CP violation effect is due to the interference of $\Delta I = \frac{1}{2}$ and $\frac{3}{2}$ amplitudes.

The experimental observables of the hyperon decay are the total decay rate Γ and the angular distribution parameters α and β. The angular distribution of the final baryon in the center of mass frame of the initial baryon is $1 + \alpha\mathcal{P}\cos(\theta_{cm})$ where $\mathcal{P}$ is the polarization of the initial baryon. β is the polarization of the final baryon. The CP violation is observed by comparing the experimental observables(Γ, α, β) of the hyperon with those of the anti-hyperon $(\bar{\Gamma}, \bar{\alpha}, \bar{\beta})$. The three CP odd observables are usually defined as[4]:

$$\Delta = \frac{\Gamma - \bar{\Gamma}}{\Gamma + \bar{\Gamma}},$$

$$A = \frac{\alpha + \bar{\alpha}}{\alpha - \bar{\alpha}},$$

$$B = \frac{\beta + \bar{\beta}}{\beta - \bar{\beta}}. \tag{2}$$

Δ is too small to be experimentally observable. To measure B, we need to analyze the polarization of the final baryon. This can be done with the decay $\Xi \rightarrow \pi + \Lambda$ since the subsequent decay of $\Lambda \rightarrow \pi + p$ can be used to measure the polarization of Λ. The standard model prediction of B is $\approx 10^{-3}$. The experimentally measurable quantity $\beta + \bar{\beta}$ is $\approx 10^{-3}(\beta - \bar{\beta}) = 5 \times 10^{-5}$ for the $\bar{\Xi}\Xi$ decays. This is about the same magnitude as A of the $\bar{\Lambda}\Lambda$ decays. Since the production cross section of $\bar{\Xi}\Xi$ is expected to be a factor of 40 less than the $\bar{\Lambda}\Lambda$ production, we will focus on measuring A of the $\bar{\Lambda}\Lambda$ decays.

The most recent standard model calculation[5] of $\bar{\Lambda}\Lambda$ by the CERN study group predicts the range of A to be $(0.5\text{–}0.05)\times 10^{-4}$. The range is even larger if different models are included. They also conclude that since the decay is dominated by the $\Delta I = \frac{1}{2}$ amplitude, the decay asymmetry is *insensitive* to the top quark mass. At present, the best experimental number comes from the LEAR experiment PS 185[6]. They get $A = 0.013 \pm 0.029$ with 60000 $\Lambda \rightarrow \pi + p$ decays. *We propose to improve this measurement to* 10^{-4}.

There are several other experiments in which direct CP violation is expected. We have discussed the $\frac{\epsilon'}{\epsilon}$ experiment and stressed that $\bar{\Lambda}\Lambda$ is less sensitive to the top quark mass than $\frac{\epsilon'}{\epsilon}$. Another way is to measure the branching ratio of $K_L \rightarrow \pi^0 e^+ e^-$[7]. The decay can proceed through (1) the direct CP violation; and (2) the small CP even part of the K_L wavefunction proportional to ϵ. The decay rate due to direct CP violation is predicted to be $2\times 10^{-12} < Br(K_L \rightarrow \pi^0 e^+ e^-) < 3\times 10^{-11}$. The indirect CP violation due to K_L–K_S mixing is expected to be $\epsilon^2 \times Br(K^+ \rightarrow \pi^+ e^+ e^-)$, giving about 6×10^{-12}. Thus the indirect CP violation is expected to be comparable to direct CP violation, and the observation of the decay is not a conclusive evidence of direct CP violation. The third possibility is the $\bar{B}B$ system. Here the decay asymmetry can be as large as 50% in some rare decay modes for which the number of B mesons required to make a statistically significant measurement is large. We want to emphasize that it is important to pursue all avenues. While the standard model allows for the CP violation, we want to observe it in several different systems to be sure that a *single* set of KM matrix elements is able to fit all of them.

3 Experimental Technique

We propose to measure the process $\bar{p} + p \rightarrow \bar{\Lambda} + \Lambda \rightarrow \bar{p}\pi^+ + p\pi^-$. The angular distribution of the final proton is $1 + \alpha\mathcal{P}\cos(\theta_{cm})$ where $\mathcal{P}$ is the polarization of Λ. In the strong production process, $\bar{\Lambda}\Lambda$ will be produced with equal polarization normal to the production plane. To fit the angular distributions of $\bar{\Lambda}$ and Λ independently to obtain $\bar{\alpha}\mathcal{P}$ and $\alpha\mathcal{P}$ requires the detector acceptance and efficiency to be CP symmetric to the same level. This is impossible considering the accuracy required. We will follow the suggestion[8] to measure

$$\bar{A} = \frac{N_p(up) - N_p(down) + N_{\bar{p}}(up) - N_{\bar{p}}(down)}{N} = \frac{1}{2}\mathcal{P}(\alpha + \bar{\alpha}) \qquad (3)$$

for $\bar{\Lambda}\Lambda$ decays where up(down) refers to particles above or below the production plane defined by $\vec{p_i} \times \vec{\Lambda}$. Thus up(down) corresponds to $\vec{p_i} \times \vec{\Lambda} \cdot \vec{p_f} > 0 (< 0)$. Such counting asymmetry is relatively easy to measure. The statistical accuracy suffers some. We get

$$\delta A = \frac{1}{|\alpha\mathcal{P}|}\sqrt{\frac{2}{N}}. \qquad (4)$$

The $\bar{\Lambda}\Lambda$ production cross section and polarization have been measured by PS 185[6]. The $\bar{\Lambda}$ production is peaked forward. The forward events are hard to detect because of the beam pipe. However, the forward events have small polarization and therefore do not contribute to the measurement ($\delta A \propto \frac{1}{\mathcal{P}}$). We will select only the $\bar{\Lambda}$ events in the range of $-0.75 < \cos(\theta_{cm}) < 0.3$ where production is isotropic. The production cross section integrated over this region is 16.955 μb with an average polarization of 0.46.

Given the large $\bar{p}p$ total cross section ($\approx$ 100 mb), we need a very selective trigger to pick out the $\bar{\Lambda}\Lambda$ pairs. We will trigger on the events that have no charged particles at the exit of the beam pipe and 4 charged particles in the detector. This trigger is relatively easy to implement with the disadvantage that all events that decay in the beam pipe are lost.

Substitute in Eq. (4) $\alpha = 0.642$ and $\mathcal{P} = 0.46$, we get $N = 2.29 \times 10^9$ if $\delta A = 10^{-4}$. The efficiency of the detection is estimated from:

$$\epsilon = (Br)^2 \; l \; D. \qquad (5)$$

Where Br is the branching ratio of $\Lambda \rightarrow \pi p$, $(Br)^2 = 0.41$. l is the fraction of $\bar{\Lambda}\Lambda$ that do not decay in the beam pipe. Assuming the beam pipe diameter is 1 cm, we get $l = 60\%$. D is the detector geometric acceptance. We assume the detector covers from 10° to 90° in the lab. The acceptance is 90% for $\bar{\Lambda}\Lambda$ produced in the isotropic region defined earlier and decay outside the beam pipe. Multiplying the three, we get $\epsilon = 0.22$. The total luminosity required is $6.14 \times 10^{38} cm^{-2}$ to produce $2.29 \times 10^9/0.22 = 1.04 \times 10^{10}$ $\bar{\Lambda}\Lambda$ paris.

4 Storage Ring Requirements

In the following discussion of the storage ring for the experiment, we will assume an $\bar{p}$ stacking rate of 6×10^{10} per hour after the Linac upgrade. The Main Injector project will increase the stacking rate even more, thus providing a comfortable cushion.

The maximum luminosity is limited by the $\bar{p}$ production rate. The rate of $\bar{p}$ consumed by the experiment has to be equal to the $\bar{p}$ production rate. The $\bar{p}p$ annihilation cross section (σ) is 52 mb at the energy of $\bar{\Lambda}\Lambda$ production. We will use 100 mb as a conservative value of the cross section in order to estimate the maximum luminosity. Since

$$L\sigma = \bar{p}\ consumed = \bar{p}\ produced = 6 \times 10^{10}/hour, \tag{6}$$

we find that the average luminosity is $1.6 \times 10^{32} cm^{-2} sec^{-1}$. To accumulate $6.14 \times 10^{38} cm^{-2}$ total luminosity, we need 44 days. Assuming 50% running efficiency, the time required for this experiment is 3 months.

We will assume that the gas jet density = $10^{14} atoms/cm^2$ and the diameter is 0.1 cm. Given that $\sigma = 100$ mb, we find the lifetime of the beam is $(10^{-11} f)^{-1}$. A ring of 1/3 of the size (f=1.8 MHz) of the Accumulator will have a lifetime of 15 hours. The peak beam intensity is 1.35×10^{12} $\bar{p}$ to get the average intensity of 0.85×10^{12} $\bar{p}$. Each refill will take 0.85×10^{12} $\bar{p}$ from the Accumulator. The lifetime of a smaller ring of 1/4 the size of the Accumulator is 8 hours thus requires too frequent refill of $\bar{p}$.

We desire a small beam at the interaction region (IR) to reduce the loss due to $\bar{\Lambda}\Lambda$ decay inside the beam pipe. A small beam also helps define the vertex and improve the kinematic reconstruction. We will assume that the dispersion at the IR is zero. One would expect that the β functions at the IR are determined by the beam size desired, but it turns out that in reality they are dictated by the cooling rate achievable. Specifically, the intrabeam scattering (ib) sets the limit for the transverse emittance of the beam; the beam-gas(b-g) scattering determines the β functions at the IR. We will assume the cooling bandwidth(W) is 8 GHz(8–16 GHz). $\Delta f/f$ is 10^{-4} to avoid Schottky band overlap at 16 GHz. The cooling rate at peak current of 400 mA is

$$\frac{1}{\epsilon}\frac{d\epsilon}{dt}_{cooling} \approx -\frac{\delta f}{f}\frac{W^2}{(I/e)}, \tag{7}$$

where I is the current and e is the charge of the proton. Substituting in the numbers, we get $\frac{1}{\epsilon}\frac{d\epsilon}{dt}_{cooling} \approx -2.5 \times 10^{-3}$ sec^{-1}. The heating rates have to be smaller than the cooling rate. The heating due to intrabeam scattering has been calculated. We found that the emittance of the beam has to be larger than 2π mm-mrad (95%) for the cooling to compensate the heating. (At 2π mm-mrad, $\frac{1}{\epsilon}\frac{d\epsilon}{dt}_{ib} = 1.3 \times 10^{-3}$ sec^{-1} assuming the average value of the lattice functions are the same as the Accumulator.) The beam-gas scattering heating due to the gas jet is

$$\frac{1}{\epsilon}\frac{d\epsilon}{dt}_{b-g} = \frac{1}{\epsilon} f\beta(\frac{14.1}{p^2/E})^2 \frac{L}{L_{rad}}. \tag{8}$$

We find that β has to be smaller than 0.5 m. Combining the emittance and the β function, we find the beam radius at the IR is 1 mm. It is small enough to fit in a 1 cm diameter beam pipe.

The $\bar{\Lambda}\Lambda$ production threshold corresponds to beam momentum of 1.435 GeV/c. The experiment will be run just below the $\Lambda\Sigma$ threshold which is 1.653 GeV/c. We will use 1.641 GeV/c as PS 185 did. This will be the bottom energy of the new machine. A fixed energy machine at 1.641 GeV/c is not desirable mainly because of the difficulties associated with $\bar{p}$ transfer. The emittance of the beam in the Accumulator before transfer is about 2π mm-mrad. The emittance will grow as $1/\beta\gamma$ as the momentum of the beam decreases. The momentum of the Accumulator is about 8.85 GeV/c. At 1.641 GeV/c, the emittance will have grown from 2 π to 11 π mm-mrad. We consider this to be too large. The top energy of a ring of 1/3 the size of Accumulator is probably 3 GeV/c. Transfer of beam from Accumulator to the new ring at 3 GeV/c is possible since the emittance will only grow to 6 π mm-mrad, and this can still fit in the small beam pipe at the IR. A plausible scenario may be to use the Booster to decelerate the $\bar{p}$ beam from 8.85 GeV/c to 3 GeV/c and inject it to the new ring. The Booster aperture is about 25 π mm-mrad horizontally and 16 π mm-mrad vertically, and the 6 π beam can be decelerated efficiently. It is clear to us that the efficiency of $\bar{p}$ transfer is very important. The top energy of the machine will be determined by the energy which efficient $\bar{p}$ transfer can be done.

5 Conclusion

We have discussed the physics motivation of the $\bar{p}+p \rightarrow \bar{\Lambda}+\Lambda \rightarrow \bar{p}\pi^+ + p\pi^-$ experiment. We will have enough $\bar{p}$ to improve the measurement by 2 order of magnitude after the Linac upgrade. The storage ring for such an experiment is within the reach of current technology. A more rigorous design study of the machine is obviously needed.

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