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Abstract

The exclusive reaction $\bar{p}p \rightarrow \bar{\Lambda}\Lambda$ is an interesting laboratory in which to study both spin physics and fundamental symmetries. The PS185 collaboration at LEAR has been exploiting this fact for the last few years in an ongoing program of hyperon-antihyperon production. The motivation for this study will be outlined and the experimental technique will be described. Spin physics aspects such as the measurements of the outgoing hyperon polarization and preliminary determinations of spin correlation coefficients will be presented. Fundamental symmetry checks such as lifetime differences between Λ and $\bar{\Lambda}$ (CPT) and decay properties (CP) will be discussed. A future experiment which is quite sensitive to CP violation in a hyperon-antihyperon system will be mentioned.

Introduction and Motivation

Physics interest in the Λ particle has always been high, owing in part to its particularly simple description within the static quark model and its strange quark content. In this picture the u and d quark within the Λ are coupled in a $S=0$, $I=0$ diquark, thereby exposing the spin of the s quark directly as the spin of the Λ itself. A Rice collaboration¹ has recently completed a spin-transfer experiment using polarized protons at BNL to produce inclusive Λ 's on a Be target. The experimental fact that the Λ does not "remember" the spin orientation of the incoming proton demonstrates that the spin indeed is carried by the created strange quark and is not related to that of the non-strange quarks which remain from the beam projectile.

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This is also evident from the success of simple SU(6) wave functions in the description of baryon magnetic moments. For this measurement and for many other experiments involving Λ production, the s quark is produced with a preferred spin orientation with respect to the production plane. This is observed as a non-zero value of the Λ polarization.

In experiment PS185 we have sought to explore the s-quark spin dynamics associated with the production of $\Lambda \bar{\Lambda}$ pairs. This has been performed using the reaction $\bar{p}p \rightarrow \bar{\Lambda}\Lambda$ in a kinematic range near threshold. In principle, few partial waves contribute there and hence a theoretical study of the reaction is simplified. Data taken at an excess energy of only a few MeV above threshold show a strong anisotropy in the differential cross section, indicating that at least S and P waves are involved.² Such data have motivated numerous theoretical studies from many groups.³ These studies have considered the reaction process using simple meson exchange and by "gluon" exchange. Generally, the absolute value of the total cross section and the shape of the differential cross section is reproducible only with a substantial amount of initial- and final-state interaction strength. Thus, even at threshold, the reaction is not simple.

The focus of this report will be on the additional interesting effects which can be learned from a study of the spin properties of the system. The spin correlation coefficients lead to a determination of the singlet fraction and polarization measurements constrain theoretical descriptions of this exclusive reaction and of hyperon polarization models in general. Preliminary results will be reported below together with a direct measurement of the CP-testing difference in the weak decay asymmetry parameters for Λ and $\bar{\Lambda}$.

Experimental Signature

The experiment has been performed at the Low-Energy Antiproton Ring (LEAR) at CERN where high-intensity, cooled beams of antiprotons ($\bar{p}$) are available at extracted momenta of (0.1 to 2.0) GeV/c. The reaction $\bar{p}p \rightarrow \bar{\Lambda}\Lambda$ has a threshold at 1.435 GeV/c. The proper lifetime, $c\tau$, of a Λ is 7.9 cm and hence Λ 's produced in this reaction recoil downstream approximately 3 to 10 cm before they decay. The branching ratio for $\Lambda \rightarrow p\pi^-$ is 64%. At the highest LEAR momentum the outgoing decay proton is constrained to a lab angle of less than 40° . The pion, while Lorentz boosted downstream, can still be found at any laboratory angle. Thus the detector which is shown in Fig. 1 has a 4π center-of-mass acceptance only for the protons. In practice, the total acceptance is about 60% due to those events where the outgoing pions are at very steep lab angles or from events where the lambdas decay either before or after the tracking chamber fiducial volume.

Although the total $\bar{p}$ cross section is large (about 100 mb), data can be accumulated at high beam intensities (10^6 incident $\bar{p}/\text{sec}$)⁴ by use of a "charged-neutral-charged" trigger. The process is $\bar{p}p \rightarrow \bar{\Lambda}\Lambda \rightarrow \bar{p}\pi^+p\pi^-$. An incoming $\bar{p}$ is detected by a multielement scintillator telescope and enters a target system consisting of 4 individual cells containing 2.5 mm long cylinders of CH_2 and each surrounded by thin veto scintillators. A fifth cell containing ^{12}C is employed to determine the number of $\bar{p}p \rightarrow \bar{\Lambda}\Lambda$ "background" events from ^{12}C which survive event reconstruction kinematic cuts (typically ~6%). A decay volume follows the target and is sandwiched on the downstream side by a segmented scintillator hodoscope (Fig. 1). This completes the online trigger. The decay volume is filled

with both MWPC planes and drift chamber planes in order to record the charged-particle tracks whose pattern forms a distinctive double "Vee" signature of the events. Finally, a low-field solenoidal magnet containing an additional 3 drift chamber planes is utilized in order to distinguish the charge of the penetrating baryons and thus tag the respective lambda and antilambda. The beam and the target are unpolarized.

The data discussed in this paper at 1.546 and 1.695 GeV/c incident $\bar{p}$ momentum represent the highest-statistics samples which have been analyzed to date. Here the total cross section is 44 and 85 μb respectively. The above targets and beam intensity yield a luminosity of $8.6 \times 10^{28} \text{ cm}^{-2}\text{s}^{-1}$. Using the higher cross section figure, a 60% acceptance, the double branching ratio of 41% to charged final states, a baryon number figure of merit of 80%, and a livetime of 80%, one achieves an event rate of approximately 1 per second. Unfortunately, this rate is nearly halved when one includes the real operational environment of LEAR, which includes filling and cooling times for the storage ring, and normal down times on either the machine or experimental side. This number is presented in order to better understand the limitations of our technique for serious CP tests requiring very large data samples.

Figure 1
Plan view of detector.

Polarization Measurements

The reaction $\bar{p}p \rightarrow \bar{\Lambda}\Lambda$ as viewed in the center of mass (COM) is illustrated in Fig 2. Parity conservation in the strong interaction forbids final hyperon polarization in any plane other than that which is normal to the production plane. The normal direction is defined here as $\hat{y} = (\vec{p}_p \times \vec{p}_\Lambda)$. Charge invariance in the strong production guarantees that $P_\Lambda = P_{\bar{\Lambda}}$. For Λ production from a variety of other reactions such as $\gamma p \rightarrow \Lambda K^+$, $\pi^- p \rightarrow \Lambda K^0$, $K^- p \rightarrow \Lambda X$, and $pA \rightarrow \Lambda X$, large polarizations have been observed. This is usually at a high reduced four momentum transfer squared, $-t'$, where $-t' = t - t_{\min} = 2|p_p^*||p_\Lambda^*|(1 - \cos \theta_\Lambda^*)$. We have been particularly interested in whether this experimental fact remains true at small $|t'|$ where presumably different dynamics are required to describe polarization.

Hyperon decays are well suited for the study of production polarization owing to the fact that they "self-analyze" their spin orientation through their parity-violating weak decays. For the case of the lambda, the outgoing spin- $\frac{1}{2}$ proton can have its spin either aligned or anti-aligned with that of the lambda leading to both S

wave and P wave possible decay amplitudes. The decay can thus be described by these amplitudes and their relative phase.

Figure 2
The $\bar{p}p \rightarrow \bar{\Lambda}\Lambda$ reaction as viewed in the center-of-mass frame.

Lee and Yang⁵ proposed an alternate description which is more accessible to experiment using the parameters α , β , and γ with the definitions for the decay asymmetry parameters given as

$$\alpha = \frac{2\text{Re}(S^*P)}{|S|^2 + |P|^2} \quad \text{and} \quad \beta = \frac{2\text{Im}(S^*P)}{|S|^2 + |P|^2}.$$

For a sample of polarized Λ 's, the decay angular distribution in the COM frame is

$$I(\theta) = I_0 [1 + \alpha P_\Lambda \cos(\theta)],$$

and the measureable quantity is the up-down asymmetry of the decay protons with respect to the production plane. The method of weighted sums⁶ is used as a statistical instrument for polarization determinations. This method only requires a symmetry condition in the detector efficiency $\epsilon(\theta) = \epsilon(\pi - \theta)$, which is well fulfilled in this experiment in the $\hat{y}$ direction. The parameter $\alpha_\Lambda = 0.642 \pm 0.013$ is measured in separate experiments in which the polarization of the decay protons from unpolarized lambdas is determined in a second scattering experiment⁷. In the limit of CP conservation, $\alpha = -\bar{\alpha}$. The polarization data presented below are thus averaged from both Λ and $\bar{\Lambda}$ decays.

Fig. 3 shows a representation of polarization data from our experiment to date displayed as a function of four momentum transfer squared and invariant mass. The solid curve defines the kinematic boundaries from $t_{\min}$ to $t_{\max}$ for a given value of $\sqrt{s}$; thus the separate abscissae contained are really axes in t' (which are also linearly related to axes in $\cos \theta_\Lambda^*$). Like other experimenters, we observe strong polarization for $|t'| \geq 0.18 \text{ (GeV/c)}^2$. Note, though, that a common zero crossing point exists for all the data (dashed curve) and a subsequent positive polarization for $|t'| \leq 0.18 \text{ (GeV/c)}^2$ is observed. The positive polarization tends to decrease in strength at the higher values of $\sqrt{s}$. The physical origin of this trend has yet to be determined and remains one of the intriguing results of these measurements.

Figure 3
Differential polarization results from all analyzed data to date. The enclosed axes are in $-t'$ which is linearly related to $\cos \theta_{\lambda}^*$.

Spin Correlation Coefficients

The double intensity distribution in the respective rest frames of the lambda and antilambda for an unpolarized beam and target takes on the more complicated form

$$I = I_0 \left[1 + \alpha P_{\Lambda} \cos \theta_{p,y} + \bar{\alpha} P_{\bar{\Lambda}} \cos \theta_{\bar{p},y} + \alpha \bar{\alpha} \sum_{ij} C_{ij} \cos \theta_{p,i} \cos \theta_{\bar{p},j} \right]$$

where the C_{ij} are the normalized averages of products of Λ and $\bar{\Lambda}$ spin components, the spin correlation coefficients. From these one can determine the fraction of the time that the Λ and $\bar{\Lambda}$ are produced with their spins anti-aligned. Individually, the C_{ij} are determined from the angles of the decays as follows

$$C_{ij} = \frac{9}{\alpha \bar{\alpha}} \langle \cos \theta_i \cdot \cos \theta_j \rangle.$$

Parity conservation requires $C_{xy} = C_{yz} = 0$ and from charge invariance, $C_{ij} = C_{ji}$. The singlet fraction (SF) is defined in the coordinate system of Fig. 2 to be

$$SF = \frac{1}{4}[1 - \langle \vec{\sigma}_\Lambda \cdot \vec{\sigma}_{\bar{\Lambda}} \rangle] = \frac{1}{4}[1 + C_{xx} - C_{yy} + C_{zz}].$$

The determination of these coefficients requires a very large data sample and complicated efficiency corrections. A preliminary result (i.e. without final efficiency corrections⁸) from the 1.695 GeV/c data is shown in Fig. 4. The singlet fraction, averaged over COM antilambda angles is $SF = -0.034 \pm 0.06$ which indicates pure triplet production. Similar conclusions can be drawn from other reactions and from the data⁹ at 1.546 GeV/c. The origin of pure triplet production is not well understood.

Figure 4
Preliminary singlet fraction results from 1.695 GeV/c incident $\bar{p}$ data.

Tests of Fundamental Symmetries

Although very sensitive tests of CPT non-conservation have been made in many particle-antiparticle systems, no violation at any level has yet been observed. With equally large and well-prepared samples of Λ 's and $\bar{\Lambda}$'s, tests of fundamental symmetries can be made. A comparison of the lifetimes, τ_Λ vs $\tau_{\bar{\Lambda}}$, is one such test of CPT. The analysis of the 1.546 GeV/c data is complete and the result obtained is

$$\frac{(\tau_\Lambda - \tau_{\bar{\Lambda}})}{\tau_{\text{average}}} = 0.022 \pm 0.051.$$

This result is somewhat more precise than the existing Particle Data Group value of 0.044 ± 0.085 and it is consistent with expectations of CPT conservation.

CP conservation, however, is violated in the decays of neutral kaons (and only there so far) as evidenced for example in the decay $K_L \rightarrow \pi\pi$. For the Standard Model with 3 quark generations, this and other CP-odd observables are expected to be seen, including differences in the decay properties of hyperon and antihyperon systems. Modern CP-related efforts include the Fermilab and the (non-zero!) CERN measurements¹⁰ of the ratio ϵ'/ϵ , the investigations of $B^0\bar{B}^0$ mixing¹¹, and the CP-LEAR experiment¹² which is under construction. Donoghue et al.¹³ have discussed the magnitudes of possible CP violations specifically for hyperon-antihyperon systems in the context of various models. They construct a number of CP testing ratios including those which are of particular interest here,

$$A = \frac{(\alpha + \bar{\alpha})}{(\alpha - \bar{\alpha})} \quad \text{and} \quad B' = \frac{(\beta + \bar{\beta})}{(\alpha - \bar{\alpha})}.$$

The value of A for a $\Lambda\bar{\Lambda}$ system is expected to be non-zero and small in the range $(0.1 - 3.0) \times 10^{-4}$ depending on whether the standard Kobayashi-Maskawa, the Weinberg-Higgs, or the Left-Right Symmetric Model is employed. Of course within the context of the superweak model in which only $\Delta S=2$ transitions occur, there is no predicted violation. The largest violation is realized in the KM model using the non-zero value of ϵ'/ϵ . However, in order to measure even the largest predicted effect, a sample of about 10^9 or more events is needed (to be compared with the PS185 upper limit of $\sim 3 \times 10^5$ events/week).

The ratio $(\alpha P_{\Lambda} + \bar{\alpha} P_{\bar{\Lambda}})/(\alpha P_{\Lambda} - \bar{\alpha} P_{\bar{\Lambda}})$ reduces to A when charge invariance is invoked ($P_{\Lambda} = P_{\bar{\Lambda}}$). The quantity A is proportional to the difference in the fraction of proton decays above the production plane to the fraction of antiproton decays below the plane. Thus the result is achieved directly and without analysis modifications from our polarization determinations. A portion of this data based on 4063 events has been reported¹⁴. Here we report a new and preliminary result based on additional data from a total sample of 16,000 events and find that

$$\langle A \rangle = -0.023 \pm 0.057.$$

The extension of this technique to a sensitivity level on A of $\sim 5 \times 10^{-3}$ is possible. A sample of more than 10^6 events would be required along with a sizeable amount of computer time for the analysis. Beyond this, we feel that alternate techniques must be considered.

As first pointed out by Donoghue¹³, and further discussed from the experimental side by Hamann¹⁵, a "three-in-one" experiment examining the reaction

$$\bar{p}p \rightarrow \Xi^- \bar{\Xi}^+ \rightarrow \Lambda \pi^- \bar{\Lambda} \pi^+ \rightarrow p \pi^- \pi^- \bar{p} \pi^+ \pi^+$$

should be performed. The reaction has the possibility of testing the ratio B' which isolates only the weak phases in the amplitudes and is expected to be about 10 times more sensitive to CP violation than A. The quantity B' requires a determination of the decay baryon polarization. This would mean an impractical polarization analysis of the decay protons in the reaction $\bar{p}p \rightarrow \Lambda\bar{\Lambda}$. In the more exotic $\Xi^- \bar{\Xi}^+$ experiment, the Λ is the "decay baryon" and its polarization is revealed in the usual manner through the parity violation of the weak decay. Thus, by observing the complete decay chain, as shown for a typical event in Fig. 5, one

can assemble the quantities A_{Ξ} , A_{Λ} , and B'_{Ξ} . The experiment needs a high-intensity antiproton beam of about 3.5 GeV/c which is presently only available at the FNAL accumulator (site of $c\bar{c}$ experiment E760) or at the proposed CERN facility SuperLEAR. Rough event rates, based on a full-acceptance detector surrounding a gas-jet target installation in an antiproton storage ring, indicate that an experiment sensitive to B' to a level of 10^{-3} could be achieved in only a few weeks of operation. Triggering would be based on the characteristic charged-particle multiplicity jumps (6 charged particles in the final state after all decays). Systematic errors can largely be held in check since only complete events are considered. Asymmetries in the apparatus can be tested by rotating the true production planes in the analysis to arbitrary directions in order to uncover any unphysical polarizations. Some members of our collaboration are exploring the feasibility of such an experiment.

Figure 5

A characteristic $\Xi^- \bar{\Xi}^+$ event with well-separated, delayed decays. An antiproton enters from the left at 3.5 GeV/c.

Summary

The spin physics of the $\Lambda \bar{\Lambda}$ system is being vigorously explored in experiment PS185 at LEAR. The $\Lambda \bar{\Lambda}$ pairs appear to be produced with the s and $\bar{s}$ quark spins aligned (pure triplet). Results from polarization analysis have been presented. An unexplained common zero crossing of the sign of the polarization at a momentum transfer of approximately $|t| = 0.18(\text{GeV}/c)^2$ for different values of the invariant mass is noted. The data have been further used to determine the CP-testing ratio A relating to the difference in particle and antiparticle decay properties. No effect is seen. However, this experiment is not yet, nor ever will be capable of a test at the predicted level of violation. A future experiment which could achieve the statistics required for a *real* test of CP violation in hyperon-antihyperon systems is

$\bar{p}p \rightarrow \Xi^- \bar{\Xi}^+ \rightarrow \Lambda \pi^- \bar{\Lambda} \pi^+ \rightarrow p \pi^- \pi^- \bar{p} \pi^+ \pi^+$. This would require an antiproton beam of higher momentum than that of LEAR.

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