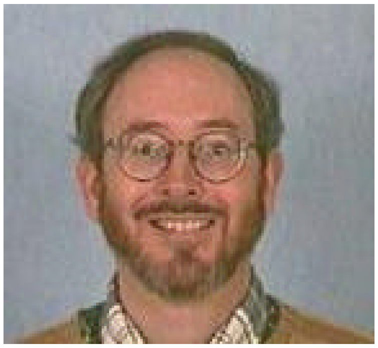
XXIV Physics in Collision - Boston, June 27-29, 2004

THE SEARCH FOR CP VIOLATION IN HYPERON DECAYS

E. Craig Dukes
University of Virginia, Charlottesville, VA 22901, USA



ABSTRACT

Searches for experimental manifestations of *CP* violation have born much fruit in recent years with the discovery of direct *CP* violation and the first evidence of *CP* violation outside of the neutral kaon system. Nevertheless we still know little about *CP* violation: its origin remains a mystery and there is little hard evidence that it is the sole province of the standard model. Searches for *CP* violation in hyperon decays offer promising possibilities as they are sensitive to certain beyond-the-standard-model sources that are not probed in other systems. We report on the status of such searches, in particular a new result from the Fermilab *HyperCP* experiment which has greatly increased the sensitivity over previous measurements and is confronting some beyond-the-standard-model theory predictions.

1 Introduction

After years of little progress in searching for new manifestations of *CP* violation, recently great advances have been made, with the unambiguous observation of direct-*CP* violation in kaon decays [1] and the first observation of *CP* violation outside of the neutral kaon system: in decays of the B_d meson [2]. Nevertheless, our fundamental understanding of *CP* violation has improved little in the forty years since its discovery. Although *CP* violation is accommodated quite nicely in the standard model — in the complex phase of the CKM matrix — its origin remains a mystery. And although *CP* violation is expected to be ubiquitous in weak interactions, albeit often vanishingly small, the experimental evidence is still meager. In addition, many beyond-the-standard-model theories can produce relatively large *CP*-violating effects, none of which have yet been seen. It behooves us then to search for other manifestations of this phenomenon. Hyperon decays offer a promising venue for such searches as hyperons can be copiously produced, are easily detected in experiments of modest cost, and are particularly sensitive to certain exotic sources of *CP* violation. We review here the status of such searches.

2 Signatures for *CP* Violation in Hyperon Decays

The most accessible signature for *CP* violation in spin-1/2 hyperons is the comparison of the angular decay distribution of the daughter baryon with that of the conjugate antibaryon in their two-body nonleptonic weak decays. These distributions are not isotropic because of parity violation, but are given by:

$$\frac{dN}{d\cos\theta} = \frac{N_0}{2}(1 + \alpha P_p \cos\theta), \tag{1}$$

where P_p is the parent hyperon polarization, $\cos\theta$ is the daughter baryon direction in the rest frame of the parent, and $\alpha = 2\mathrm{Re}(S^* P)/(|S|^2 + |P|^2)$ where S and P are the usual angular momentum amplitudes.

The behavior of the α parameter under *CP* is illustrated for the $\Lambda \to p\pi^-$ decay in Fig. 1. The daughter proton is emitted preferentially in the direction of the Λ polarization. Under *CP* the opposite is true: the daughter antiproton is preferentially emitted in the opposite direction of the $\overline{\Lambda}$ polarization. If *CP* is good $\overline{\alpha} = -\alpha$; hence a difference in the magnitudes of the hyperon and antihyperon alpha parameters, or equivalently, their angular decay distributions, is evidence of *CP* violation. To extract α, hyperons whose polarizations are *exactly known* are needed, as measuring the daughter baryon $\cos\theta$ distribution via Eq. (1) gives αP_p.

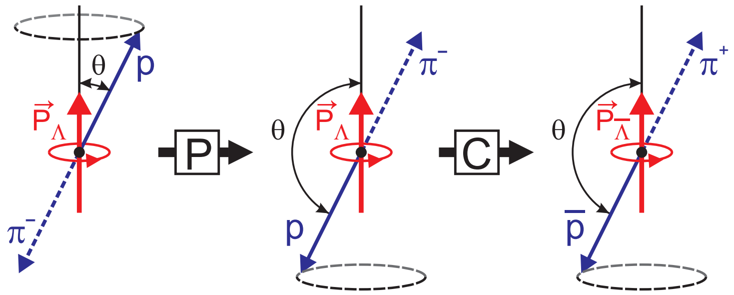


Figure 1: The $\Lambda \to p\pi^-$ decay under P and C transformations.

Several different methods of producing known polarizations are discussed below. Hyperons with large α parameters, large production cross sections, and all charged decay products are favored for obvious experimental reasons. Therefore the focus has been on $\Lambda \to p\pi^-$ and $\Xi^- \to \Lambda\pi^- \to p\pi^-\pi^-$ (and their conjugate) decays.

3 Theoretical Expectations

For CP violation to manifest itself three conditions need be met: there must be at least two different final states, these states must have nonzero strong final-state phase-shift differences, and different CP-violating weak phase shifts. Model independent expressions for the difference in alpha parameters have been explicitly calculated for various hyperon decays [3]. To leading order they are for $\Lambda \to p\pi^-$ and $\Xi^- \to \Lambda\pi^-$ decays:

$$A \equiv \frac{\alpha + \overline{\alpha}}{\alpha - \overline{\alpha}} \cong -\tan(\delta_P - \delta_S)\sin(\phi_P - \phi_S), \tag{2}$$

where the δ are the strong phase shifts and the ϕ are the weak phases. The CP asymmetry results from the interference of S- and P-wave amplitudes, not isospin amplitudes as is the case in neutral kaon decays. The strong final-state phase-shift differences are small — $7^\circ \pm 1^\circ$ for $p\pi$ [4] and $4.6^\circ \pm 1.8^\circ$ for $\Lambda\pi$ [5] — greatly reducing the size of any potential asymmetry.

A recent standard model calculation of the CP asymmetries has values that range from $-0.3\times10^{-4} \leq A_\Lambda \leq 0.4\times10^{-4}$ and $-0.2\times10^{-4} \leq A_\Xi \leq 0.1\times10^{-4}$ [6]. These magnitudes are too small to be experimentally observable at the present time. However, beyond-the-standard-model theories can produce larger asymmetries that *are not well constrained by kaon CP measurements* because hyperon CP violation probes both parity-conserving and parity-violating amplitudes whereas ϵ and ϵ' probe only parity-violating amplitudes. For example, a recent paper shows that the upper bound on the combined asymmetry $A_{\Xi\Lambda} \equiv A_\Xi + A_\Lambda$ from ϵ and ϵ' measurements is $\sim 100\times 10^{-4}$ [7]. The supersymmetric calculation of Ref. [8], which does not contribute to ϵ', can produce a value of A_Λ of $\mathcal{O}(10^{-3})$. Other beyond-the-standard-model theories, such as Left-Right mixing models [9] also have enhanced *CP* asymmetries. Therefore, any observed effect will almost certainly be due to new physics.

4 Early Experimental Results

Three ingredients are needed to mount an experiment to search for *CP* violation in hyperon decays. First, one needs to produce hyperons and antihyperons whose polarizations are known to the level of the desired sensitivity in A, or at least are known by some symmetry to be equal. Second, one needs a large number of events and large hyperon polarizations, as the error in A is $\sigma = \sqrt{3/(2N\alpha^2P^2)}$, where N is the number of hyperons and the number of antihyperons. Hence, for modest-sized alpha parameters and polarizations, on the order of 1 billion events are needed for a 10^{-4} measurement. Finally, the systematics must be controlled to the level of the measurement.

The results of the four experiments that have published searches for *CP* violation in hyperon decays are listed in Table 1 below. Each of the four experiments used a different technique, all were limited by statistical, not systematic errors, and none of the experiments was a dedicated hyperon *CP* violation experiment. Three of the four experiments quote results on A_Λ, the fourth, E756, measured the combined asymmetry $A_{\Xi\Lambda}$. All reported null results: not surprising as none of the experiments has penetrated beyond a 10^{-2} sensitivity.

Table 1: Hyperon *CP* violation searches.

Experiment	Mode	Technique	Result	Events	Date
R608	A_Λ	$pp \to \Lambda X$, $\overline{p}p \to \overline{\Lambda}X$	-0.02 ± 0.14	26 581	1985
DM2	A_Λ	$e^+e^- \to J/\psi \to \Lambda\overline{\Lambda}$	$+0.01 \pm 0.10$	770	1988
PS185	A_Λ	$p\overline{p} \to \Lambda\overline{\Lambda}$	$+0.013 \pm 0.022$	95 832	1996
E756	$A_{\Xi\Lambda}$	$pN \to \Xi X$	$+0.012 \pm 0.014$	280 000	2000

The first result in Table 1 is from an ISR experiment (R608) which produced Λ and $\overline{\Lambda}$'s in $pp \to \Lambda X$ and $\overline{p}p \to \overline{\Lambda}X$ reactions [10]. They find $\alpha P(\overline{\Lambda})/\alpha P(\Lambda) = -1.04 \pm 0.29$ from 17 028 Λ and 9 553 $\overline{\Lambda}$ decays. Assuming that the Λ and $\overline{\Lambda}$ polarizations are identical — which is rigorously true only if the Λ and $\overline{\Lambda}$ polarizations are independent of the target identity — their result can be converted to a measurement of $A_\Lambda = 0.02 \pm 0.14$.

The next two results of Table 1 come from experiments that produced $\Lambda\overline{\Lambda}$ pairs exclusively and hence reduced potential systematic errors due to any temporal changes in their detectors. The second result is from $J/\psi \to \Lambda\overline{\Lambda}$ decays measured by the DM2 detector at the Orsay DCI e^+e^- colliding ring [11]. Measuring the correlation between the proton and antiproton momenta allows the product $\alpha_\Lambda\overline{\alpha}_\Lambda$ to be extracted. Fixing α_Λ to its known value (0.642 ± 0.013 [12]) they obtained from 770 events $\overline{\alpha}_\Lambda = -0.63 \pm 0.13$ corresponding to $A_\Lambda = 0.01 \pm 0.10$. The problem with pushing this method further is obvious: since only the product $\alpha_\Lambda\overline{\alpha}_\Lambda$ is measured, an independent measurement is needed to decouple the two to extract the *CP* asymmetry.

The third result is from a fixed-target experiment at the CERN Low-Energy Antiproton Ring (LEAR), PS185 [13]. The experiment was designed to have high-acceptance for $\Lambda\overline{\Lambda}$ pairs produced near threshold. Antiprotons from the LEAR ring impacted a CH_2 target with the decay products from the exclusive reaction $\overline{p}p \to \Lambda\overline{\Lambda}$ momentum analyzed in a magnetic spectrometer. The Λ and $\overline{\Lambda}$ were found to have large predominately negative polarizations which varied from approximately $+0.2$ to -0.6. The two polarizations are rigorously equal by *C*-parity conservation in strong interactions: hence knowledge of the magnitudes of the polarizations were not needed for the determination of A_Λ. The collaboration took data at several different beam momenta, below and above the $\overline{p}p \to \Sigma^\circ\Lambda$ threshold of 1.653 GeV/c. Their last result, from an analysis of part of their entire dataset, is $A_\Lambda = -0.013 \pm 0.022$.

These early results showed much promise and led to proposals in the early 1990s for much higher-statistics experiments, both at e^+e^- and $p\overline{p}$ colliders. The limitations of the DM2 technique in measuring A_Λ were to be overcome by analyzing $J/\psi \to \Lambda\overline{\Lambda}$ decays produced from *polarized* e^+e^- collisions at a tau-charm factory [14]. There was also much interest in a gas-jet target experiment at an upgraded SuperLEAR at CERN [15]. Unfortunately funding was not forthcoming for either of these projects. At the same time it became apparent that a fresh approach taking advantage of the much larger fluxes of hyperons available in a fixed-target experiment was feasible. The conventional wisdom had been that any fixed-target *CP* violation experiment would be impossible due to the problem of producing hyperons and antihyperons of precisely known polarizations. However, a group from Berkeley and the University of Virginia realized a simple solution to the problem (described below) which would allow $A_{\Xi\Lambda}$ to be measured with great precision. This work led to the *HyperCP* experiment at Fermilab [16]. The feasibility of this new experimental technique was successfully tested on data from Fermilab experiment E756 (designed to measure the Ω^- magnetic moment), which had run in the late 1980s, resulting in the most sensitive limit on *CP* violation in hyperon decays [17].

5 The First Dedicated Hyperon *CP* Violation Experiment: *HyperCP*

The *HyperCP* experiment produced Λ's and $\overline{\Lambda}$'s with *almost* precisely known polarizations by requiring that they come from $\Xi^- \to \Lambda\pi^-$ and $\overline{\Xi}^+ \to \overline{\Lambda}\pi^+$ decays. The Ξ^- and $\overline{\Xi}^+$ hyperons were required by parity conservation in the strong interaction to have *zero* polarization by producing them with an average angle of 0° with respect to the incident proton beam. A Λ from the weak decay of an unpolarized Ξ is found in a pure helicity state with a polarization magnitude given by the parent Ξ alpha parameter: $P_\Lambda = \alpha_\Xi = -0.458$ [12]. Hence, if *CP* is a good symmetry in Ξ decays, then the Λ and $\overline{\Lambda}$ have equal and opposite polarizations. The decay distributions of the proton and antiproton in the frame in which the Λ direction in the Ξ rest frame defines the polar axis — the Lambda Helicity Frame in Fig. 2 — are given by:

$$\frac{dN}{d\cos\theta} = \frac{N_0}{2}(1 + \alpha_\Lambda P_\Lambda \cos\theta) = \frac{N_0}{2}(1 + \alpha_\Lambda \alpha_\Xi \cos\theta). \tag{3}$$

If *CP* symmetry is good in *both* Ξ and Λ decays then $\overline{\alpha}_\Xi = -\alpha_\Xi$ and $\overline{\alpha}_\Lambda = -\alpha_\Lambda$ and the decay distributions of the proton and antiproton are identical. Any difference is evidence of *CP* violation. It is evident from Eq. (3) that differences between the slopes of the two $\cos\theta$ distributions can be due to *CP* violation in either the Ξ or Λ decay; the experiment is sensitive to *CP* violation in both:

$$A_{\Xi\Lambda} \equiv A_\Lambda + A_\Xi \cong \frac{\alpha_\Lambda\alpha_\Xi - \overline{\alpha}_\Lambda\overline{\alpha}_\Xi}{\alpha_\Lambda\alpha_\Xi + \overline{\alpha}_\Lambda\overline{\alpha}_\Xi}. \tag{4}$$

The *HyperCP* spectrometer (Fig. 3) was designed to be simple, fast, and to have considerable redundancy [18]. A charged secondary beam with a mean momentum of about 160 GeV/c was produced by steering the Tevatron 800 GeV/c primary proton beam onto a $2\times2\,\mathrm{mm}^2$ Cu target which was immediately followed by a collimator — with a 5.38 μsr solid angle acceptance — embedded in a 6.1 m long dipole magnet (Hyperon Magnet). The central orbit of the secondary beam exited the collimator upward at 19.51 mrad. Following an evacuated decay region was a magnetic spectrometer employing nine high-rate, narrow-pitch wire chambers. The spectrometer magnets (Analyzing Magnets) had sufficient field integrals to insure that the protons from $\Xi \to \Lambda\pi \to p\pi\pi$ decays were always deflected to one side of the spectrometer, with the two pions deflected to the opposite side, and that both

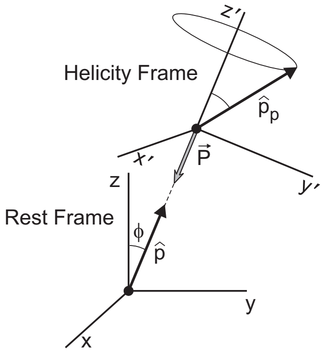


Figure 2: The Lambda Helicity Frame.

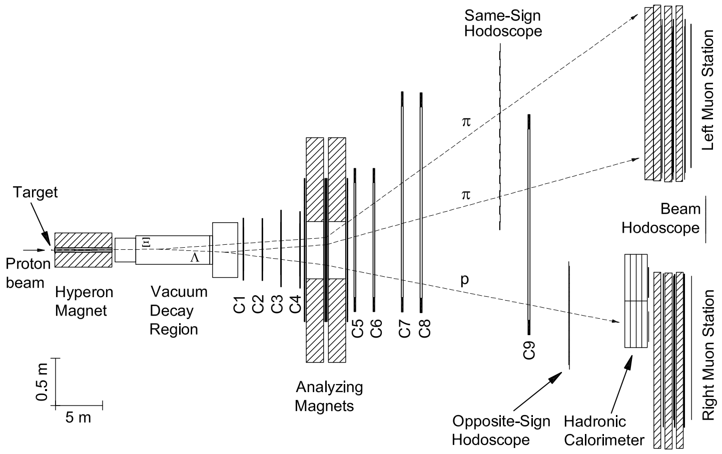


Figure 3: Plan view of the *HyperCP* apparatus.

were well separated from the intense ($\sim 13\times 10^6\,\mathrm{s}^{-1}$) secondary beam exiting the collimator. A simple trigger was formed by requiring the coincidence at the rear of the spectrometer of charged particles in two hodoscopes (Same Sign and Opposite Sign Hodoscopes) situated on either side of the spectrometer, as well as a minimum amount of energy in a hadronic calorimeter on the proton side of the spectrometer. The calorimeter made the trigger "blind" to muons and reduced the trigger rate due to interactions of the secondary beam with material in the spectrometer. The Ξ^- and $\overline{\Xi}^+$ hyperons were not produced simultaneously, as is the case with the DM2 and PS185 experiments. Rather the experiment periodically switched from one running mode to the other by reversing the polarities of the Hyperon and Analyzing Magnets.

A high-rate data acquisition system enabled up to 100 000 events per spill second to be recorded onto magnetic tape. In two running periods (1997 and 1999) of about 12 months duration one of the largest data samples ever was recorded, at 231 billion events, and by far the largest number of hyperons. The final dataset was approximately 2.5 billion $\Xi^- \to \Lambda\pi^- \to p\pi^-\pi^-$ and $\overline{\Xi}^+ \to \overline{\Lambda}\pi^+ \to \overline{p}\pi^+\pi^+$ decays, *four orders of magnitude more than that of all other hyperon CP violation searches combined.*

Since the experiment was probing sensitivities far beyond any previously attained, two *CP* analyses were attempted in parallel. One analysis separately extracted $\alpha_\Xi\alpha_\Lambda$ and $\overline{\alpha}_\Xi\overline{\alpha}_\Lambda$ by correcting for the apparatus acceptance using a hybrid Monte Carlo (HMC) technique. The HMC took real $\Xi \to \Lambda\pi \to p\pi\pi$ events, discarded the proton and pion, substituting MC-generated proton and pions in order to measure the acceptance. Ten accepted HMC events were generated for every real event. Although this method had the advantage of providing an absolute measurement of the product of the alpha parameters, it required an extremely faithful MC simulation of the apparatus. The MC also had to be extremely fast as on the order of tens of billions of events needed to be generated for the analysis of the full dataset. Although considerable progress was made in refining this method, it was ultimately abandoned because of systematic difficulties.

The second analysis method was simple: compare the proton and antiproton $\cos\theta$ distributions directly, without acceptance corrections. Before this could be done the momentum and spatial distributions of the Ξ^- and $\overline{\Xi}^+$ events at the collimator exit (their effective production point) had to be made identical, since different production dynamics give different momentum spectra for the two. This was done by weighting the Ξ^- and $\overline{\Xi}^+$ events in each of the three momentum-dependent parameters at the collimator exit: the magnitude of the Ξ momentum, the y slope of the Ξ, and the y position of the Ξ. Each parameter was binned in 100 bins for a total of one million weights. The ratio of the weighted proton and antiproton $\cos\theta$ distributions was then made. Any nonzero slope in that ratio is evidence of *CP* violation. The ratio was fit to the following form,

$$R = C\frac{1+\alpha_\Xi\alpha_\Lambda\cos\theta}{1+(\alpha_\Xi\alpha_\Lambda-\delta)\cos\theta}, \tag{5}$$

to extract the asymmetry $\delta \equiv \alpha_\Xi\alpha_\Lambda - \overline{\alpha}_\Xi\overline{\alpha}_\Lambda \cong 2\alpha_\Xi\alpha_\Lambda \cdot A_{\Xi\Lambda}$, where the known value of $\alpha_\Xi\alpha_\Lambda = 0.294$ [12] was used.

About 117 (41) million Ξ^- ($\overline{\Xi}^+$) decays selected from the end of the 1999 run were used — roughly 10% of the total dataset. Figure 4 shows the Ξ^- and $\overline{\Xi}^+$ masses after all cuts. The background under the peak is 0.42% for both. The data were divided into 18 parts (Analysis Sets) each of roughly equal size. Each set was analyzed separately. Figure 5 shows the $\cos\theta$ ratios for one of the Analysis Sets, before and after weighting. Fits to Eq. (5) were good: the average chi-squared per degree of freedom for all 18 Analysis Sets was 0.97.

The average asymmetry from all 18 Analysis Sets, after background subtraction and with no acceptance or efficiency corrections, was found to be zero: $A_{\Xi\Lambda} = [0.0\pm5.1(\mathrm{stat})\pm4.4(\mathrm{syst})]\times10^{-4}$, with $\chi^2 = 24$. This is a factor of twenty improvement in sensitivity over the best previous result [17]. A HMC analysis of about 5% of the total data sample, from all of the good 1997 and 1999 runs, also found no evidence of a *CP* asymmetry: $A_{\Xi\Lambda} = [-7\pm12(\mathrm{stat})\pm6(\mathrm{syst})]\times10^{-4}$.

Systematic errors were small for several reasons. First, taking the ratio of $\cos\theta$ distributions reduced those common to the proton and antiproton. Second,

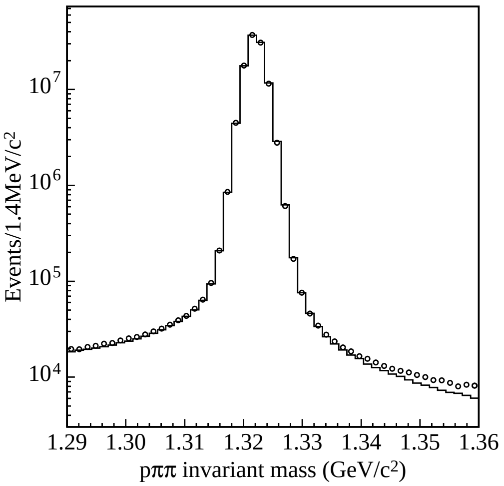


Figure 4: The unweighted $p\pi^-\pi^-$ (histogram) and $\overline{p}\pi^+\pi^+$ (circles) invariant masses.

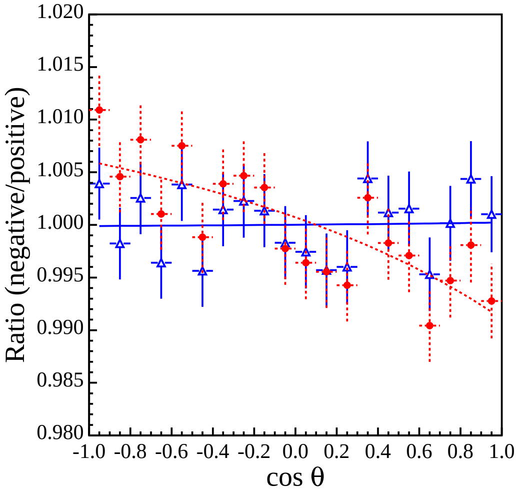


Figure 5: Fits to the weighted (triangles) and unweighted (circles) p to $\overline{p}$ $\cos\theta$ ratios from Analysis Set 1.

the analysis locked in to the signal, in a manner analogous to a lock-in amplifier, by measuring the proton $\cos\theta$ distribution in the Lambda Helicity Frame, the polar axis of which changed from event to event. The largest systematic error (2.4×10^{-4}) is due to the uncertainty in the calibration of the Hall probes situated in the Analyzing Magnets. The next largest (2.1×10^{-4}) is the statistics-limited uncertainty due to differences in the calorimeter efficiencies between positive- and negative-polarity running. The only other significant systematic error is the uncertainty in the validation of the analysis code (1.9×10^{-4}), again a statistics-limited result. Wire chamber and hodoscope efficiency differences were so small that they were not corrected for, but rather added in as negligibly small systematic errors. No dependence of the asymmetry on Ξ momentum, secondary-beam intensity, or time was found.

The analysis of the entire 1999 *HyperCP* dataset is well underway and it is hoped that within a year a result with an improvement in precision of at least two will be obtained, both in statistical and systematic errors.

6 Acknowledgments

I wish to thank the organizers of the XXIV PHYSICS IN COLLISION for a most enlightening and entertaining conference, and, as always, my *HyperCP* colleagues. This work was supported in part by the U.S. Department of Energy and the Institute for Nuclear and Particle Physics at the University of Virginia.

References

1. A. Alavi-Harati, *et al.*, Phys. Rev. Lett. **83**, 22 (1999); V. Fanti *et al.*, Phys. Lett. B **465**, 335 (1999).
2. For a review, see T.E. Browder and R. Faccini, Ann. Rev. Nucl. Part. Sci. **53**, 353 (2003).
3. J.F. Donoghue and S. Pakvasa, Phys. Rev. Lett. **55**, 162 (1985);
   J.F. Donoghue, X.-G. He, and S. Pakvasa, Phys. Rev. D **34**, 833 (1986).
4. L.D. Roper, R.M. Wright, and B.T. Feld, Phys. Rev. **138**, B190 (1965).
5. M. Huang *et al.*, Phys. Rev. Lett. **93**, 011802 (2004).
6. J. Tandean and G. Valencia, Phys. Rev. D **67**, 056001 (2003).
7. J. Tandean, Phys. Rev. D **69**, 076008 (2004).
8. X.-G. He *et al.*, Phys. Rev. D **61**, 071701 (2000).
9. D. Chang, X.-G. He, and S. Pakvasa, Phys. Rev. Lett. **74**, 3927 (1995).
10. P. Chauvat *et al.*, Phys. Lett. B **163**, 273 (1985).
11. M.H. Tixier *et al.*, Phys. Lett. B **212**, 523 (1988).
12. S. Eidelman *et al.* (Particle Data Group), Phys. Lett. B **592**, 1 (2004).
13. P.D. Barnes *et al.*, Phys. Rev. C **54**, 1877 (1996).
14. E. González-Romero, Nucl. Phys. A **558**, 579 (1993).
15. D. Hertzog, Nucl. Phys. A **558**, 499 (1993).
16. E.C. Dukes, G. Gidal, P.M. Ho, and K.B. Luk, Fermilab Proposal P-871, 21 March 1993.
17. K.B. Luk *et al.*, Phys. Rev. Lett. **85**, 4860 (2000).
18. R. Burnstein *et al.*, hep-ex/0405034, to be published in Nucl. Instrum. and Methods.