AN EXPERIMENTAL STUDY OF THE BETA DECAY
OF POLARIZED LAMBDA HYPERONS

MASTER

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PREFACE

The purpose of the experiment described in this thesis was to determine the form of the weak interaction in the beta decay of the lambda hyperon: $\Lambda \rightarrow p + e^- + \bar{\nu}$. This decay offers the best opportunity for studying semi-leptonic decays of strange particles. Both vector and axial-vector currents are simultaneously involved. Also, since highly polarized lambdas are easily produced in the laboratory, the spin correlations of the decay products can be included in the analysis. The beta decay of the neutron holds an analogous position in the study of non-strangeness changing decays.

We began work on this counter-optical spark chamber experiment in 1965. Extensive development of apparatus and analysis systems was required. Large thin-plate spark chambers and scintillator hodoscopes were built. The field of the wide-gap magnet spectrometer was accurately mapped. Extensive optical and electronic systems were designed and constructed. And a unique electron Cherenkov counter was developed. The experiment was installed at the Zero Gradient Synchrotron at Argonne National Laboratory in mid-1967. A total of 325 data shifts were accumulated in runs from September 1967 through October 1969. The extensive scanning and measuring required by the analysis has also encompassed several years.

An experiment of this magnitude was possible through the collaboration of experimenters from Ohio State University, Washington University in St. Louis, Argonne National Laboratory, and The University of Chicago; so a large number of people are responsible for its successful execution.

I would like to express my sincere gratitude to my faculty sponsor, Roland Winston, for suggesting this study and for providing constant help and advice. I am also very indebted to my Argonne adviser, Thomas A. Romanowski, for his continued support and his excellent leadership of this undertaking.

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TABLE OF CONTENTS

PREFACE	ii
LIST OF TABLES	vi
LIST OF FIGURES	vii
Chapter	
I. FORM OF THE BETA-DECAY INTERACTION	1
A. A Universal V-A Interaction	
B. The Cabibbo Hypothesis	
C. Hyperon Beta Decay Distribution	
II. EXPERIMENTAL APPARATUS	27
A. Introduction	
B. Beam	
C. Counters and Triggering	
D. Optical Magnet Spectrometer	
E. Time-of-Flight System	
III. DATA REDUCTION	56
A. Scanning and Measuring	
1. Phase I Scanning	
2. Scope Measuring	
3. Phase II Scanning	
4. Spark Measuring	
B. Event Selection	
1. Geometric and Momentum Reconstruction	
2. Kinematics	
3. Final Candidate Scan	
C. Summary	
IV. RESULTS	79
REFERENCES	103

LIST OF TABLES

1. Baryon decay form factors in terms of Cabibbo parameters . .	8
2. Summary of counter parameters	42
3. Spark chamber characteristics	53
4. Candidate rejection criteria	70
5. Candidate classification	75
6. Results from spin correlations in polarized lambda experiments	97
7. Results from electron-neutrino correlation measurements . .	101

LIST OF FIGURES

1. Influence of g_1 and f_2 on decay correlations with respect to the spin of the lambda ($g_2 = 0$): (a) A_p , (b) A_e , (c) A_v	16
2. Influence of g_1 and g_2 on decay correlations with respect to the spin of the lambda ($f_2/f_1 = 1.0$): (a) A_p , (b) A_e , (c) A_v , (d) A_{ev}	20
3. Effect of a phase angle between the vector and axial vector currents ($g_1/f_1 = 0.7$, $f_2/f_1 = 1.0$, $g_2 = 0$)	25
4. Experiment plan view	30
5. Data frame - plan	32
6. Data frame - elevation	34
7. Data frame - scope	37
8. Secondary beam transport system	40
9. Liquid hydrogen target assembly	45
10. Counter logic diagram	50
11. Time distribution for PH-4	61
12. CRT plot of an analyzed data frame	69
13. Data reduction summary	78
14. M_{ee} , calculated invariant pair mass distribution	82
15. $p-\pi^+$ Time-of-flight difference distribution	85
16. Scatter plot of kaon and lambda masses for $\Lambda p\pi$ hypothesis . .	87
17. Neutrino transverse momentum distribution	89

18.	$e-\pi^-$ Time-of-flight difference distribution	92
19.	Lambda lifetime distribution	94
20.	Electron energy spectrum	96
21.	1-Standard-deviation contours for least-squares fits to g_1/f_1 and f_2/f_1	99

CHAPTER I

FORM OF THE BETA-DECAY INTERACTION

A. A Universal V-A Interaction

The theory of the weak interaction in beta decay has a history which is full of surprises. It experienced several breakthroughs because of the insight of a relatively small number of individuals surveying the evolving experimental picture. Several publications¹ treat this historical development in detail; I will mention only those points which directly dictate the presently accepted phenomenological form of the decay interaction.

Fermi proposed the first plausible theory for beta decay in 1934.² His mechanism depended on the Pauli neutrino hypothesis and the then recently proposed neutron-proton composition for nuclei. Fermi was guided by the analogy with electromagnetic theory in assuming the β particle and the neutrino are formed at the moment of their emission. He proposed an interaction Hamiltonian which depends directly (without derivatives) on the wave functions of all four particles. The general form of his theory for the decay $n \rightarrow p + e^- + \bar{\nu}$ using Dirac spinors to represent the particles can be written as

$$\mathcal{H} = \sum_{i=1}^5 G_i [(\bar{\psi}_p O_i \psi_n)(\bar{\psi}_e O_i \psi_\nu) + \text{h.c.}]$$

where G_i is the weak coupling constant and the O_i are the five possible combinations of Dirac operators which form Lorentz bilinear covariants:

<u>i</u>	<u>Combination</u>	<u>Behavior under Lorentz transformations</u>
S	1	Scalar
V	γ_a	Vector
T	$\sigma_{a\beta}$	Tensor
A	$i\gamma_5\gamma_a$	Axial vector
P	γ_5	Pseudoscalar.

Because of the similarity with the electromagnetic interaction, Fermi always believed the vector bilinear form was correct.

The study of nuclear beta decay was complicated by the wide range of observed lifetimes. This range of rates can be explained by the number of units of orbital angular momentum with respect to the nucleus which are carried away by the electron-neutrino pairs. Only allowed beta decays (orbital angular momentum carried away is zero) will be considered in the subsequent discussion.

The allowed decays can be classified according to the angular momentum state of the emitted electron-neutrino system. If they are in a $J = 0$ state, they carry off no angular momentum. This is called a pure Fermi transition and can result only from S and V couplings.

The $J = 1$ state is produced by A and T interactions: pure Gamow-Teller transitions. Mixtures of these couplings can also occur; however, P coupling cannot contribute to allowed transitions.

The Fermi theory remained essentially unchanged until 1956. It predicted the lifetimes and energy distributions exceptionally well, but the experimental results concerning the choice of couplings were confusing. Since 1947 most of the developments in weak interactions have been guided by the concept of a Universal Weak Interaction³ which relates a variety of phenomena (such as pion decay, muon decay and absorption, nuclear beta decay, kaon decays). By 1956, it was apparent from the absence of Fierz interference terms in the beta energy spectra that only one of the two possible couplings could be present in a pure transition. Nucleon data favored the ST combination, the muon decay data the VA combination, and the pion decay the A interaction; so the possibility of a universal interaction seemed small. The suggestion of parity violation by Lee and Yang⁴ in solving the $\tau - \theta$ puzzle in 1956, led to a major breakthrough. Within a year several experiments had confirmed the existence of parity-violating pseudoscalars in various weak decay processes. They also demonstrated that the weak interactions are not invariant under charge conjugation. Working on the assumption of a two-component (massless) neutrino, Marshak and Sudarshan,⁵ Feynman and Gell-Mann,⁶ and Sakurai⁷ independently deduced a V-A structure for the weak interac-

tion. The contradictory experiments were soon repeated and found to be in excellent agreement with the V-A Fermi interaction. One of the best tests of the theory was the study by Burgy et al.⁸ of the angular distribution of electrons and neutrinos from the beta decays of polarized neutrons.

The success of the universal V-A formulation resulted in the acceptance of writing the interaction with a current-current structure:

$$\mathcal{H}_w = \frac{G}{\sqrt{2}} J_a J_a^\dagger + \text{h.c.}$$

where the current J_a is the sum of the leptonic and hadronic currents:

$$J_a = L_a + H_a$$

$$L_a = \bar{\psi}_\mu \gamma_a (1 + \gamma_5) \psi_{\nu_\mu} + \bar{\psi}_e \gamma_a (1 + \gamma_5) \psi_{\nu_e}$$

$$H_a = V_a + A_a.$$

The explicit form of the hadronic current cannot be written at present because no satisfactory strong interaction field theory exists. A good approximation for the term in H_a responsible for neutron beta decay can be written as

$$H_a^{\text{np}} = \bar{\psi}_p \gamma_a (1 + X\gamma_5) \psi_n$$

with the experimental value for $X = -G_A/G_V = 1.23$. The axial vector current in this decay is enhanced by the strong interaction effects, but no such renormalization is necessary for the vector current. In fact, G_V appears to be constant to within a few per cent in all weak interactions not involving strange particles. The formal understand-

ing of this was introduced by Feynman and Gell-Mann⁶ by identifying the conserved vector currents (CVC) as the charge-changing currents of the isotopic spin. The conservation of the entire current is implied by the failure of the strong interaction to modify the third component, the electromagnetic current.

B. The Cabibbo Hypothesis

When the same V-A interaction is applied to strangeness-changing ($\Delta S = 1$) hyperon decays such as $\Lambda \rightarrow p + e^- + \bar{\nu}$, the observed decay rates are more than an order of magnitude too low. Based on the validity of SU(3) symmetry in the strong interactions, an extension of the universal theory to include the $\Delta S = 1$ decays was proposed in 1963 by Cabibbo.⁹ This is the most viable extension, but the experimental data still do not provide a stringent test.

The Cabibbo formulation is composed of three hypotheses:

1. The weak currents V_a and A_a are members of SU(3) octets.

The vector current is a member of the octet j_{ia} to which the I spin and the electromagnetic currents belong (a natural extension of the CVC hypothesis). The axial current is a member of an octet of axial currents g_{ia} whose divergence is proportional to the fields of the pseudo-scalar octet. These assumptions are written explicitly in the SU(3) notation of Gell-Mann¹⁰ as

$$V_a = a j_a (\Delta S = 0) + b j_a (\Delta S = \pm 1)$$

$$A_a = a' g_a (\Delta S = 0) + b' g_a (\Delta S = \pm 1)$$

where

$$j_a (\Delta S = 0) = j_{1a} \pm i j_{2a}$$

$$j_a (\Delta S = \pm 1) = j_{4a} \pm i j_{5a}$$

$$g_a (\Delta S = 0) = g_{1a} \pm i g_{2a}$$

$$g_a (\Delta S = \pm 1) = g_{4a} \pm i g_{5a}$$

The selection rules associated with these currents predict the absence of $\Delta S = -\Delta Q$ currents; that the $\Delta S = \Delta Q = 1$ currents have $\Delta I = 1/2$; and that the $\Delta S = 0, \Delta Q = 1$ currents have $\Delta I = 1$: all in accord with present experimental data.

2. The vector and axial vector currents are "parallel" (in SU(3) space) members of their octets. This means that

$$a = a'$$

$$b = b'.$$

This assumption depends on the parallelism of the bare weak interaction currents and that this is preserved by SU(3) conserving strong interactions.

3. The SU(3) form of universality is obtained by letting

$$a^2 + b^2 = 1$$

or

$$a = \cos \theta, \quad b = \sin \theta,$$

The old form of universality wanted $a = b = 1$. The angle θ is referred to as the Cabibbo angle.

The Cabibbo formulation predicts the matrix elements which determine the semileptonic decays of the baryons. These can be expressed with the aid of the baryon octet Clebsh-Gordon coefficients in terms of three parameters (assuming negligible momentum transfer dependence): θ , and the reduced matrix elements of the octet, F(anti-symmetric) and D(symmetric). The predictions for the vector and axial vector form factors are listed in Table 1. The latest fit to these parameters yields¹¹

$$\theta = 0.242 \pm 0.004$$

$$F = 0.460 \pm 0.015$$

$$D = 0.771 \pm 0.016.$$

Using these values the Cabibbo predictions for the hyperon decay rates and for G_A/G_V in neutron beta decay are in good agreement.

C. Hyperon Beta Decay Distribution

The validity of the Cabibbo theory can best be observed in the decay distributions of polarized hyperons because the coefficients of the pseudoscalar correlations are very sensitive to the current form factors. In order to easily compare our results with theory, we found it necessary to calculate the decay distribution. The distribution of Jackson, Trieman, and Wyld¹² for neutron beta decay is an elegant formulation from the experimentalist's point of view; however, it does not take into account the relativistic corrections needed for the hyperon

TABLE 1

BARYON DECAY FORM FACTORS IN TERMS OF
CABIBBO PARAMETERS

Decay ($B \rightarrow b l \bar{\nu}$)	Vector (f_1)	Axial Vector (g_1)
$n \rightarrow p$	$\cos \theta$	$\cos \theta (F + D)$
$\Sigma \rightarrow \Lambda$	0	$\frac{2}{\sqrt{6}} D \cos \theta$
$\bar{\Sigma}^- \rightarrow \bar{\Sigma}^0$	$-\cos \theta$	$\cos \theta (-F + D)$
$\Lambda \rightarrow p$	$\frac{3}{\sqrt{6}} \sin \theta$	$-\frac{1}{\sqrt{6}} \sin \theta (3F + D)$
$\Sigma^- \rightarrow n$	$-\sin \theta$	$\sin \theta (-F + D)$
$\Sigma^0 \rightarrow p$	$\frac{1}{\sqrt{2}} \sin \theta$	$\frac{1}{\sqrt{2}} \sin \theta (-F + D)$
$\bar{\Sigma}^- \rightarrow \Lambda$	$\frac{3}{\sqrt{6}} \sin \theta$	$\frac{1}{\sqrt{6}} \sin \theta (3F - D)$
$\bar{\Sigma}^- \rightarrow \Sigma^0$	$\frac{1}{\sqrt{2}} \sin \theta$	$\frac{1}{\sqrt{2}} \sin \theta (F + D)$
$\bar{\Sigma}^0 \rightarrow \Sigma^+$	$\sin \theta$	$\sin \theta (F + D)$

decays. On the other hand, there are several exact treatments of the distributions,¹³ but their complex expressions obscure the physical content of the theory and do not lend themselves easily to experimental comparison. In addition, their precision is hardly necessary for the analysis of presently anticipated hyperon beta decay experiments.

R. Winston and I have calculated the decay distribution by restricting the Hamiltonian to the first order in the velocity of the recoil nucleon.¹⁴ The resulting expressions agree to within a few per cent of the exact theory for all hyperon beta decays and have a fairly simple form which is analogous to that for neutron decay. We assume a current-current form for the weak interaction and a V-A lepton current. Using the most general matrix element for the hadron current, the interaction Hamiltonian for the decay $B \rightarrow b e \bar{\nu}$ can be written in the form

$$\mathcal{H}_{\text{int}} = \frac{G}{\sqrt{2}} \bar{\psi}_b (O_a^V + O_a^A) \psi_B \bar{\psi}_e \gamma_a (1 + \gamma_5) \psi_\nu + \text{h.c.},$$

where

$$O_a^V = f_1 \gamma_a + \frac{f_2}{M_B} \sigma_{a\beta} Q_\beta + i \frac{f_3}{M_B} Q_a$$

$$O_a^A = g_1 \gamma_a \gamma_5 + \frac{g_2}{M_B} \sigma_{a\beta} \gamma_5 Q_\beta + i \frac{g_3}{M_B} \gamma_5 Q_a$$

and $Q_a = (P_e + P_\nu)_a = (P_B - P_b)_a$.

Since the induced scalar and pseudoscalar form factors, f_3 and g_3 , are proportional to the electron mass, they may be neglected for this process. Also, the use of moment-independent form factors is con-

sistent with the order of approximation we adopt. Analogous to Primakoff's treatment of muon capture, we substituted the first order approximation for the wave function ψ_b and derived the form of the Hamiltonian to operate between the resulting two-component spinors. The matrix element for the interaction can be written in the form

$$\mathcal{M} = \langle be | \mathcal{H}_{\text{eff}} | B\nu \rangle$$

where the effective Hamiltonian has the structure

$$\begin{aligned} \frac{1}{\sqrt{2}} \mathcal{H}_{\text{eff}} = & \frac{(1 - \vec{\sigma}_\ell \cdot \hat{e})}{2} \left[G_V + G_A \vec{\sigma}_B \cdot \vec{\sigma}_\ell + G_P^e \vec{\sigma}_B \cdot \hat{e} \right. \\ & \left. + G_P^\nu \vec{\sigma}_B \cdot \hat{\nu} \right] \frac{(1 - \vec{\sigma}_\ell \cdot \hat{\nu})}{2} . \end{aligned}$$

In the expression above $\hat{e}$ and $\hat{\nu}$ are unit vectors along the electron and antineutrino directions, and $\vec{\sigma}_\ell$ and $\vec{\sigma}_B$ operate solely on lepton and baryon states, respectively. The effective coupling constants are simple functions of the form factors

$$\begin{aligned} G_V &= f_1 - \frac{M_B - M_b}{M_B} f_2 + \frac{e + \nu}{2M_b} \left(f_1 + \frac{M_B + M_b}{M_B} f_2 \right) \\ G_A &= -g_1 + \frac{M_B - M_b}{M_B} g_2 - \frac{e - \nu}{2M_b} \left(f_1 + \frac{M_B + M_b}{M_B} f_2 \right) \\ G_P^e &= \frac{e}{2M_b} \left(-f_1 + g_1 - \frac{M_B + M_b}{M_B} (f_2 - g_2) \right) \\ G_P^\nu &= \frac{\nu}{2M_b} \left(f_1 + g_1 + \frac{M_B + M_b}{M_B} (f_2 + g_2) \right) . \end{aligned}$$

If the first-order momentum terms are neglected, the Hamiltonian reduces to that for neutron beta decay. The left-handed projection

operators which bracket the Hamiltonian are a result of the V-A lepton current.

To calculate the distribution with spin correlations, we sum over the unobserved decay spins:

$$\sum_{\substack{e \text{ spins} \\ b \text{ spins}}} |\langle b e | \mathcal{H}_{\text{eff}} | B \nu \rangle|^2 = \langle B \nu | \mathcal{H}_{\text{eff}}^\dagger \mathcal{H}_{\text{eff}} | B \nu \rangle$$

$$\text{and } \sum_{\nu \text{ spins}} \langle B \nu | \mathcal{H}_{\text{eff}}^\dagger \mathcal{H}_{\text{eff}} | B \nu \rangle = \langle B | \text{Tr}(\mathcal{H}_{\text{eff}}^\dagger \mathcal{H}_{\text{eff}}) | B \rangle.$$

So we are left with a relatively simple trace calculation on two-by-two matrices. Keeping all terms:

$$|\mathcal{M}|^2 = \xi [1 + a \hat{e} \cdot \hat{\nu} + A \langle \vec{\sigma}_B \rangle \cdot \hat{e} + B \langle \vec{\sigma}_B \rangle \cdot \hat{\nu} + D \langle \vec{\sigma}_B \rangle \cdot \hat{e} \times \hat{\nu} \\ + A' \langle \vec{\sigma}_B \rangle \cdot \hat{e} (\hat{e} \cdot \hat{\nu}) + B' \langle \vec{\sigma}_B \rangle \cdot \hat{\nu} (\hat{e} \cdot \hat{\nu})]$$

$$\xi = |G_V|^2 + 3|G_A|^2 - 2 \text{Re}[G_A^* (G_p^e + G_p^\nu)] + |G_p^e|^2 + |G_p^\nu|^2$$

$$\xi a = |G_V|^2 - |G_A|^2 - 2 \text{Re}[G_A^* (G_p^e + G_p^\nu)] + |G_p^e + G_p^\nu|^2 \\ + 2 \text{Re}[G_p^{e*} G_p^\nu] e \cdot \nu$$

$$\xi A = -2 \text{Re}[G_V^* G_A] - 2|G_A|^2 + 2 \text{Re}[G_V^* G_p^e + G_A^* G_p^\nu]$$

$$\xi B = -2 \text{Re}[G_V^* G_A] + 2|G_A|^2 + 2 \text{Re}[G_V^* G_p^\nu - G_A^* G_p^e]$$

$$\xi D = 2 \text{Im}[G_V^* G_A] + 2 \text{Im}[G_A^* (G_p^\nu - G_p^e)] + 2 \text{Im}[G_p^e G_p^{\nu*}] (1 + e \cdot \nu)$$

$$\xi A' = 2 \text{Re}[G_p^{e*} (G_V + G_A)]$$

$$\xi B' = 2 \text{Re}[G_p^{\nu*} (G_V - G_A)].$$

Therefore, the overall distribution including the phase space becomes

$$dw = \frac{|m|^2}{(2\pi)^5} \frac{(E_b + M_b)}{2 M_B} \frac{e^2 v^3}{e^{\max} - e} de d\Omega_e d\Omega_v$$

where $e^{\max}$ is the beta endpoint energy. Subsequent to this calculation, it has been determined that the above expression is actually correct to second order in $(\frac{v}{c})_b$; ¹⁵ however, radiative corrections and form-factor momentum dependence are also of this order.

The form factors f_1 and g_1 are the vector and axial vector coefficients listed in Table 1. The induced term multiplied by f_2 is called the weak magnetism current. Its existence has been verified in nuclear beta decay and its magnitude is consistent with the CVC prediction. We call the term multiplied by g_2 the induced pseudotensor current. In the terminology of Weinberg, ¹⁶ f_1 , f_2 , and g_1 are associated with "first-class" currents (proper Lorentz vectors with G parity + 1, and axial Lorentz vectors with G parity - 1). The g_2 term is associated with a "second-class" current (G parity opposite that of the first-class currents). The existence of second-class currents depends on the form of the weak current without the strong interactions. Since the strong interactions are invariant under G, the transformation properties of currents under G will be unchanged when the strong interactions are introduced. If the bare weak current contained a small axial part with G parity + 1, with strong interactions this might contribute a relatively large term, since the effect of the strong interactions is difficult to calculate. If the lepton current is coupled to a baryon

current between members of the same isospin multiplet, then the time-reversal violating effects occur only through second-class currents (g_2 would be purely imaginary).¹⁷ It is usually assumed that SU(3) extends this result between members of an entire octet. Results from a study of the decay rates of mirror nuclei are consistent with the existence of second-class currents; however, this interpretation depends on complex nuclear-structure calculations which are still somewhat uncertain.¹⁸

In calculating the decay distribution, we maintained complex coupling constants since time-reversal invariance is still an open question in hyperon decays. The existence of the D coefficient would be explicit evidence for T violation.

The Cabibbo predictions for the form factors for lambda beta decay using the latest fit are

$$f_1 = -0.293$$

$$f_2/f_1 = 0.98$$

$$g_1/f_1 = 0.72$$

$$g_2/f_1 = 0.$$

Experiments with unpolarized lambdas can measure only the electron-neutrino correlation (or equivalently, the proton energy spectrum) and the total rate. The integrated electron-neutrino correlation is insensitive to f_2 . If a g_2 term exists, a fit to g_1/f_1 could be influenced significantly without arousing suspicion. The addition of the pseudoscalar

correlations of the decay products with respect to the lambda spin strongly enhances the analyzing sensitivity of the distribution for the individual form factors. Figure 1 illustrates the sensitivity to f_2 of the three decay correlations with respect to the lambda spin. The asymmetry parameter is defined by

$$A_i = 2 \frac{(N_i)_{\text{up}} - (N_i)_{\text{down}}}{(N_i)_{\text{up}} + (N_i)_{\text{down}}}$$

where up means $\vec{P}_i \cdot \vec{\sigma}_\Lambda > 0$

and down, $\vec{P}_i \cdot \vec{\sigma}_\Lambda < 0$.

The asymmetries were evaluated from the decay distribution by means of a Monte Carlo integration. The influence of a g_2 term is illustrated in Figure 2. The electron-neutrino correlation is included because of its sensitivity. The effects of a phase angle between the vector and axial-vector currents (T-violation) are illustrated in Figure 3.

The asymmetries are not statistically independent, which complicates a direct analysis for the form factors. A more convenient approach is to categorize each event in one of the six possible combinations of pairs of momenta along and against the spin: $p \uparrow e \uparrow$, $p \uparrow e \downarrow$, $e \uparrow \nu \uparrow$, $e \uparrow \nu \downarrow$, $p \downarrow \nu \uparrow$, $p \downarrow \nu \downarrow$. These six "bins" are mutually exclusive and statistically independent. Tables of the fraction in each bin for a range of form factors were prepared by a Monte Carlo integration of the decay distribution. The experimental fractions can then be easily fit to these tables by either maximum-likelihood or chi-squared procedures to

Fig. 1. Influence of g_1 and f_2 on decay correlations with respect to the spin of the lambda ($g_2 = 0$): (a) A_p , (b) A_e , (c) A_ν .

Fig. 1(a)

Fig. 1(b)

Fig. 1(c)

Fig. 2. Influence of g_1 and g_2 on decay correlations with respect to the spin of the lambda ($f_2/f_1 = 1.0$): (a) A_p , (b) A_e , (c) A_ν , (d) $A_{e\nu}$.

Fig. 2(a)

Fig. 2(b)

Fig. 2(c)

Fig. 2(d)

Fig. 3. Effect of a phase angle between the vector and axial vector currents ($g_1/f_1 = 0.7$, $f_2/f_1 = 1.0$, $g_2 = 0$).

Fig. 3

determine the form factors.

A fit from the combined spin asymmetries alone or from the electron-neutrino correlation alone is also easily obtained. This is most apparent from the no-recoil approximations for the bin fractions:

$$f_{1,2} = \frac{1}{8} - \frac{a}{32} \pm \frac{3}{64} A \mp \frac{5}{64} B$$

$$f_{3,4} = \frac{1}{4} + \frac{a}{16} \pm \frac{1}{8} (A + B)$$

$$f_{5,6} = \frac{1}{8} - \frac{a}{32} \mp \frac{5}{64} A \pm \frac{3}{64} B.$$

The parameters are the correlation coefficients from the decay distribution. The electron-neutrino correlation is an even function in the paired bins and the spin asymmetries are odd functions. So the internal consistency of the two may be checked by performing a "3-bin fit" to the sums and the differences of the paired bins. Of course, this is only an implicit electron-neutrino correlation; it must be compared with the direct correlation obtained from the center-of-mass solutions.

CHAPTER II

EXPERIMENTAL APPARATUS

A. Introduction

The small branching ratio for lambda beta decay makes this experiment a stringent test of presently available techniques. To obtain a statistically significant sample of beta decays from highly polarized lambdas with minimal background we designed the experiment with the following general features:

1. Production - A π^- beam incident on a liquid hydrogen target produced lambdas through the associated-production reaction $\pi^- + p \rightarrow \Lambda + K^0$. The π^- momentum was just below ΣK threshold where the cross section is maximum and the polarization is known to be high and uniform:^{19, 20} $\sigma = 0.67 \pm 0.05$ mb

$$P_{\Lambda} = 0.90 \pm 0.05$$

where the spin direction is given by

$$\hat{\sigma}_{\Lambda} = (\vec{\Lambda} \times \vec{\pi}) / |\vec{\Lambda} \times \vec{\pi}|.$$

We measure the polarization directly in our apparatus through the decay asymmetries of the dominant decay mode, $\Lambda \rightarrow p + \pi^-$. The proton distribution about $\hat{\sigma}_{\Lambda}$ for this decay is given by $dw(\theta) = 1/2(1 + aP_{\Lambda} \cos \theta) d(\cos \theta)$ where $a = 0.645 \pm .016$.²¹ We interspersed runs

to study this decay mode throughout the experiment as a continuous calibration. A comparison of our event rate with these is also a direct measurement of the branching ratio after simple solid angle corrections and small adjustments for the range and decay of the pions.

2. Detection - The rarity of this decay led to the use of numerous scintillation and Cherenkov counters in our apparatus. These provided a very selective trigger and precise time resolution. The plan view of our apparatus is shown in Figure 4. A scintillation counter surrounding the liquid hydrogen target (TAC) was used in anti-coincidence to indicate that a beam pion had interacted producing only neutral final states. Scintillation hodoscopes on opposite sides of the magnet indicated the presence of negative and positive decay products. Behind the electron hodoscope (EH) was a large gas threshold Cherenkov counter with a high efficiency for electrons. Its rejection factor for pions from $\Lambda \rightarrow p + \pi^-$ was better than 1000. A water threshold Cherenkov counter was placed behind the proton hodoscopes (PH and DH) to eliminate particles less massive than a proton. No attempt was made to detect the K^0 since this would lower the event rate by an order of magnitude. Whenever the triggering logic was satisfied, the array of optical spark chambers was pulsed and the resulting tracks photographed by two shutterless 35 mm cameras in 90° stereo. The entire experiment was located in a light-tight enclosure. The plan and elevation views of a data frame are shown in Figures 5 and 6. The dots outlining each

Fig. 4. Experiment plan view.

Fig. 4

Fig. 5. Data frame - plan.

Fig. 5

Fig. 6. Data frame - elevation.

chamber are fiducials which were used in reconstructing the events from the spark measurements.

3. Identification - Even though the selective triggering reduces the ratio of candidates per lambda beta decay by several orders of magnitude, accurate kinematic reconstruction coupled with precise timing is required to reduce the background contamination to a few per cent of the events. The two charged decay tracks are momentum analyzed by the large gap magnet spectrometer system. The positive and negative momentum distributions are so different that only the protons pass through the magnet; the electrons are deflected to the EH by the large fringe field. A non-constrained kinematic solution is possible since the beam momentum is known and the target proton is at rest. The precision timing was achieved by displaying the discriminator pulses from the hodoscopes and the $C\beta$ counter on a CRT oscilloscope with two 4-gun tubes. This was photographed every time the spark chambers were triggered. Figure 7 is a typical data frame. The time marker is generated when the beam pion passed through beam counter #2. The sweep speed was calibrated every 100 triggers by displaying a 50 MHz sine wave on all traces. Background rejection is detailed in Chapter III.

B. Beam

The π^- beam entering our apparatus was produced at the second focus of the 12.3 GeV/c Extracted Proton Beam (EPB-I) of the ZGS.

Fig. 7. Data frame - scope.

Trace 4
 Trace 3
 Trace 2
 Trace 1

Trace 8
 Trace 7
 Trace 6
 Trace 5

Fig. 7

The typical intensity was 5×10^{10} protons per 500 ms pulse with a repetition period of 3.6 seconds. This was focussed onto a beryllium production target 0.50" wide by 0.25" high by 4.0" long. The monitors for this beam in addition to the secondary beam included a three-scintillator telescope viewing the target at 90° , a thin-window gas ionization chamber at the target, and a TV-viewed scintillator sheet which could be remotely inserted into the beam to verify its position at the target.

The transport system for the secondary beam is shown in Figure 8. The foci of the system are at the production target, the momentum slits (just upstream of S1), and at the LH_2 target. The bending magnet XBK1 provided the momentum dispersion at the slit and XBK11 gave a deflection from the forward direction for the selected beam. The fields in these two magnets were monitored throughout the experiment by nuclear magnetic resonance probes and by the voltage drops across precision resistance in series with the magnet coils. The secondary beam was tuned to a transport momentum of $1038 \pm 2 \text{ MeV}/c$ before the experiment was installed. A positive beam was used in the momentum measurements, but the use of NMR probes ensured the same fields in the bending magnets for either polarity. The momentum was measured using three methods (all with an accuracy of approximately 0.5%):

1. Floating wire measurements through the system.

Fig. 8. Secondary beam transport system.

Fig. 8

2. Simultaneous integral and differential deuteron range measurements using scintillation counters and precision aluminum range plates.
3. Precise time-of-flight difference measurements between S1 and the final focus for π^+ , p, and d.

The momentum loss in the beam detection apparatus and the liquid hydrogen was 13 ± 1 MeV/c, so the π^- momentum at the nominal focus was 1025 ± 3 MeV/c. The spot size at the focus was measured to be 1.1" wide by 0.7" high with a horizontal divergence of 4.5 mrad and a vertical divergence of 31.5 mrad. These were determined by scanning the beam with a small solid state counter on a calibrated manipulator. The momentum bite of the beam was approximately ± 7 MeV/c and the solid angle was 5 msr. Under the above typical EPB-I conditions the secondary intensity was about 4.5×10^5 particles per pulse. Approximately 74% of these were π^- , 23% e^- , and 3% μ^- .

C. Counters and Triggering

The triggering logic consisted of three major systems:

1. Neutral-final-state π^- interaction
2. Electron detection
3. Proton detection.

The components of these systems can be located in Figure 4 and their characteristics are summarized for reference in Table 2.

TABLE 2
SUMMARY OF COUNTER PARAMETERS

Counter	Type	Size (inches)	Phototubes	Mode of Operation	Measured Efficiency
GAC	Cerenkov (CO ₂)	10(dia.)	56AVP	Anticoinc.	>.99
BC1	Scint.	5x3 $\frac{1}{2}$ x $\frac{1}{8}$	56AVP	Coinc.	>.98
BC2	Scint.	4x2 $\frac{1}{2}$ x $\frac{1}{8}$	56AVP	Coinc.	>.99
BC3	Scint.	2 $\frac{1}{2}$ x2 $\frac{1}{2}$ x $\frac{1}{16}$	56AVP	Coinc.	>.94
HAC	Scint.	1(dia.)	56AVP	Anticoinc.	>.99
TAC	Scint.	i. d. = 1.18 o. d. = 1.62	56AVP	Anticoinc.	>.99999
S14	Scint.	5x7x $\frac{1}{4}$	56AVP	Anticoinc.	>.998
Single EH Paddle	Scint.	60x10x $\frac{1}{4}$	2 56AVP	Both Tubes in Coinc.	>.95
C β	Cerenkov (Freon 13)	~40(dia.)	4 Groups of 7 58AVP	Coinc. (Any Tube)	>.99
S12	Scint.	22x26x $\frac{1}{16}$	3 56AVP	Coinc. (Any Tube)	>.996
Single PH Paddle	Scint.	10x70x $\frac{3}{8}$	2 56AVP	Both Tubes in Coinc.	>.99
Single DH Paddle	Scint.	10x70x $\frac{3}{8}$	56AVP	Coinc.	>.99
WAC	Cerenkov (Water)	72x72x8	16 58AVP	Anticoinc. (2 or more)	~.92

1. Neutral-final-state π^- interaction - Electrons in the beam were rejected by the gas anticoincidence counter (GAC) which was placed at the exit of the final beam quadrupole magnet. It was a CO_2 threshold Cherenkov counter operated at atmospheric pressure. The beam was geometrically forced into the LH_2 target by requiring a coincidence between the three beam counters ($\text{BC1} \cdot \text{BC2} \cdot \text{BC3}$) and no signal from the hole anticoincidence counter (HAC). HAC was a 0.25" thick plastic scintillator counter with a 1.0" diameter aperture located on the beam line just upstream from the LH_2 target.

The lack of a signal from the target anticoincidence counter (TAC) shown in Figure 9 signified a neutral-final-state π^- interaction in the liquid hydrogen. The gravity-fed LH_2 container was constructed of 0.001" Dupont H-Film in the shape of a cylinder 1.00" in diameter by 14.4" long. The plastic scintillator outer vessel served as the vacuum jacket for the LH_2 flask as well as an anticoincidence counter. Five layers of about 0.0002" aluminized Mylar ("super insulation") were wrapped around the LH_2 flask for radiation shielding. This target geometry provided a large interaction volume with powerful discrimination against interactions with charged final states. The escape requirement resulted in the loss of approximately 78% of the lambdas. The charged decay mode of the K_s^0 component caused an additional 34% rejection. Approximately 16% of the remaining lambdas rejected themselves when a charged decay particle passed through TAC. The neutral

Fig. 9. Liquid Hydrogen Target Assembly.

Fig. 9

trigger rejected the less useful lambdas for two reasons: first, those with a small perpendicular distance from the beam orbit to the decay vertex will have a poorly determined production plane; secondly, the lambdas produced very forward or very backward (production center-of-mass system) are unpolarized. The main drawback encountered in this design was the difficulty of maximizing the effective pion beam. Only 40% of the beam could be made to traverse the entire length of the hydrogen and half of this was lost because of random anticoincidences and absorption or delta ray production in the hydrogen.

A guard counter (S14) was placed alongside the target vacuum can to help reject triggers from beam interactions in the target hardware.

2. Electron detection - Negatively charged particles were deflected by the large fringe field of the magnet toward the electron hodoscope (EH). This contained six vertically mounted scintillator "paddles" with photomultiplier tubes on both ends. Coincident signals from both tubes were required for a paddle logic signal.

Immediately behind the EH was a large gas threshold Cherenkov counter (C β). The details of this counter's design and performance at the University of Chicago have been published.²² It was operated with Freon 13 at 65 psia. Through the use of a unique light collecting system, the counter was highly efficient to an apparent source of about 0.6 m^2 in area while subtending a half-angle of 30° . This was achieved using

four quasi-ellipsoidal mirrors each of which was viewed by a cluster of seven funnel-photomultiplier tube combinations. The seven signals from each quadrant were linearly added; then the four quadrant signals were mixed and amplified. The linear quadrant pulses were displayed on a CRT trace (Figure 7) since the independence of the quadrants was useful in rejecting random triggers or scintillation light detection.

$C\beta$ was essentially 100 per cent efficient for all electrons within the geometric acceptance, and eliminated non-electrons by a factor greater than 1000. Some non-electron triggers resulted because of random background from the radiation levels in the experimental area and because of a small amount of scintillation light which is produced in the gas. This rejection factor was of great importance because of the ratio $\Lambda\pi/\Lambda\beta = 800$.

Approximately 10% of the electrons were detected by the EH; of these, 58% were detected by $C\beta$. The overall electron detection efficiency as determined by our Monte Carlo simulation was 5.8%.

3. Proton detection - The thin scintillation counter S12 provided an early "yes" on the proton side. Beyond the magnet were located two proton hodoscopes (PH and DH). Both consisted of seven horizontally mounted scintillator paddles. DH had phototubes only on the +X ends of the paddles. Immediately behind this double hodoscope was a water Cherenkov counter (WAC). WAC was used in anticoincidence to suppress background events with fast particles on the proton

side. Protons from lambda decays in our apparatus were below the threshold for Cherenkov light in water. On the other hand, all pions and electrons with momenta sufficient to pass through the magnet were well above this threshold. By requiring at least two of the sixteen tubes in coincidence, the proton efficiency (due to scintillation) was held to less than 2% and the random anti loss was greatly reduced.

The overall detection efficiency for lambda decay protons by our apparatus was estimated as 76% by our Monte Carlo simulation.

4. Triggering - A simplified logic diagram for the lambda beta trigger is shown in Figure 10. The major logic blocks described in the preceding sections had their signals inserted directly into the final $\Lambda\beta$ trigger except for the neutral interaction signal (NEUTRALS) which was fanned out many times so that it could be put in coincidence with the other counters early in the logic. This reduced and localized the dead-time losses and simplified the timing in the later parts of the logic. The neutral rate was 0.5% of the beam rate (primarily due to charge exchange scattering) so it played a predominant role in suppressing random background triggers.

The electron hodoscope was allowed to have only one paddle in coincidence with NEUTRALS. This was imposed to reduce the trigger rate. No analogous constraint was necessary for the PH and DH since the proton side already contained a triple coincidence. The $\Lambda\beta$ trigger can be summarized as

Fig. 10. Counter Logic Diagram.

Fig. 10

$$T = \text{NEUT} \cdot \text{ELECTRON} \cdot \text{PROTON}$$

where $\text{NEUT} = \overline{\text{GAC}} \cdot \text{BC1} \cdot \text{BC2} \cdot \text{BC3} \cdot \overline{\text{HAC}} \cdot \overline{\text{S14}} \cdot \overline{\text{TAC}}$

$$\text{ELECTRON} = \text{NEUT} \cdot \text{EH(only 1)} \cdot \text{C}\beta$$

$$\text{PROTON} = \text{NEUT} \cdot \text{S12} \cdot \text{PH} \cdot \text{DH} \cdot \overline{\text{WAC}}$$

The trigger for the $\Lambda p \pi$ calibration runs was exactly the same except $\text{C}\beta$ was switched out of the ELECTRON requirement.

The circles in the logic diagram are scalar outputs which were monitored continuously. The individual hodoscope paddles were also scaled. $\text{C}\beta$ had a pickoff which allowed any one tube (or quadrant) to be scaled.

A "data box" was flashed to identify each trigger and contained information to aid scanning. It can be seen in both views of a data frame (see Figures 5 and 6). Besides the frame number and run number, it contained triggering information. Just below the run number are located two rows of nine lights separated by a fiducial row. The first six lights in the upper row are for EH 1-6. The first seven lights in the lower row are for DH 1-7. These greatly assist scanners in locating logical events.

D. Optical Magnet Spectrometer

The optical magnet spectrometer (see Figure 4) consisted of a wide-gap magnet (SCM-104), twelve optical spark chambers (SC1 - SC12), and the associated hardware and optics.

The spectrometer magnet had poles 40" by 20" with a 40" gap. It was operated with a central field of 5.720 kilogauss. The operating current through a precision shunt was continuously monitored. The vertical field component was extensively mapped prior to the experiment. A small search coil on a precision manipulator was used to obtain a grid of vertical field differences (1" by 4" on planes spaced 4" apart). This was combined with several absolute measurements for a field map which is accurate to about 0.3% of the central field at each grid point. The non-vertical field components were obtained by fitting to a model using uniformly charged rectangles to represent field sources. The final fit used 70 such rectangles to provide a reliable analytic representation of the field over the entire useful volume.

The basic characteristics of the spark chambers are summarized in Table 3. The details of their construction and performance have been published.²³ SC9-12 were small chambers used to detect the beam pion. Both views of these chambers are shown in the plan view of a data frame. The protons from lambda decays passed through SC5-8 while the negative particles were deflected by the magnetic field through SC1-4. The tracks through SC4-6 depended upon the exact event topology (the target passed through SC4 and into SC5). Multiple scattering was held to a minimum by using stretched-foil plates of 0.0008" thick aluminum (except SC8 had 0.032" thick aluminum sheet). The efficiency and spark brightness for each chamber was optimized by varying

TABLE 3

SPARK CHAMBER CHARACTERISTICS

Spark Chamber	No. Gaps	Gap Width (inches)	Nominal Size Width x Height (inches)	Charging Capacitance (pF)	High Voltage (kV)
1	8	0.400	50 x 50	4000	10.0
2	8	0.400	50 x 50	4000	10.0
3	8	0.400	50 x 50	4000	10.0
4	8	0.400	50 x 36	4000	10.0
5	10	0.400	46 x 21	8000	6.5
6	10	0.400	46 x 21	8000	6.5
7	8	0.400	60 x 53	4000	10.0
8	4	0.400	70 x 70	4000	12.5
9	10	0.188	4 x 10	1000	9.0
10	10	0.188	4 x 10	1000	9.0
11	10	0.188	4 x 10	1000	9.0
12	10	0.188	3 x 3	1000	9.0

the charging capacitance and pulse high voltage. A 90% Ne - 10% He gas mixture flowed continuously through each chamber at a rate of 5 cc/min.

The optical system²⁴ consisted of two 35 mm Flight Research Cameras in 90° stereo. A demagnification of 75 was used through a high-precision mirror system. Kodak 2475 Shellburst film was used. Optical distortions were suppressed by outlining every chamber with electroluminiscent fiducials with separations of a few inches.

Reconstruction of known fiducial positions and fitting to straight cosmic rays and beam tracks (magnet off) indicate an rms spatial resolution of 0.015" - 0.020". From an analysis of 750 MeV/c positive beam tracks, our rms momentum resolution for the protons from Λ decays was less than 3.4%. The mean Λ mass from 1700 $\Lambda\pi$ decays set an upper limit of 0.2% on any systematic momentum reconstruction error.

E. Time-of-Flight System

Discriminator pulses and $C\beta$ information were displayed on an oscilloscope having two four-gun CRT's. A typical data frame is shown in Figure 7. This was photographed by a third 35 mm Flight Research camera using Kodak 2484 RAR film. The scope and its amplification system were operated in an air-conditioned rf-insulated enclosure.

The frame and run numbers were displayed at the bottom of the frame and were coded in the BCD lights immediately above the nixies.

Six fiducials used in measurement reconstruction are visible. Traces 1-7 had EH and PH discriminator pulses. The trace and paddle numbers coincide except PH-4 and PH-7 were interchanged so that the high rate PH-4 could have an entire trace. The EH pulses were displayed on the first half of the traces followed by the PH pulses. A time marker generated by the passage of a beam pion through beam counter #2 was shown on every trace. A triggered hodoscope had two discriminator pulses: one for each tube. The cable lengths and amplifications were adjusted so that the first pulse for each pair was 20% larger in amplitude than the second. This aided measurers in rejecting random pulses. Trace 8 displayed the single $C\beta$ discriminator pulse followed by the linearly summed anode pulses from each quadrant (the quadrants were delayed with different length cables to provide dispersion across the trace). The time scales were calibrated every 100 frames by imposing a 50 MHz sine wave on all the traces. This removed nonlinearities in the nominal 50 ns/cm sweep speed of the scope. This system achieved rms time resolutions of approximately 1 ns. Analysis of timing information is discussed further in Chapter III.

CHAPTER III

DATA REDUCTION

A. Scanning and Measuring

1. Phase I Scanning— In the first scan of the film the scanners were instructed to locate the frames with logical vees of the required topology; that is, a positive track into the triggered DH and a negative track into the triggered EH. Scanning masks with the hodoscope and fiducial positions were used to check the data box lights. The vertex was required to be between SC3 and SC6. Only 20% of the data frames contained a candidate at this point.

A positive momentum cut was made during the scan on all vees which had the WAC indicator light on (a coincident signal from only one tube). It was made using a template to check the bending angle between SC6 and SC7. The rejection angle inscribed on the template corresponded to 250 MeV/c. A calibration of this using electron-positron pairs which were measured and momentum analyzed indicated an rms resolution of approximately 40 MeV/c over the entire range of trajectories. The apparatus imposed a lower limit on the proton momentum at 350 MeV/c. Also, only 11% of the protons would have a WAC light

on. This cut rejected about 25% of the vees with an estimated event loss of less than 0.2%.

A rough measurement of the flight path for the positive particle was made during this scan for every accepted vee. At first, this was done by drawing a simple scale sketch. It was then determined that a linear function of the position on the PH intersected by the particle was adequate. Both methods were accurate to better than 0.3 ns for a $\beta = 1$ particle. This information was coded on a scan card along with the frame and run numbers and data box lights.

All of the data film was rescanned to prevent losses due to inefficient scanners. Care was taken to prevent a scanner from doing both scans on the same roll. The accepted vees from the first scan (not including the low momentum rejects) were skipped in the rescan. The two were then combined before further processing. The scan in which a vee was accepted was also coded on the scan card. Several rolls were scanned twice as if both were first scans to check these procedures. Using the number of accepted vees from both scans indicates a combined efficiency better than $96 \pm 2\%$. This is probably a lower limit for real events since most Phase I scanners accept some vees which would be rejected if carefully scrutinized. The fraction of analyzed $\Lambda p \pi$ events found during rescans indicates a combined efficiency for these events greater than 98%.

2. Scope Measuring — The time-of-flight information displayed on the double 4-gun CRT oscilloscope (Figure 7) was measured for all of the vees accepted in the Phase I scans. This was combined with the path length measurements to reject most of the vees with a fast ($\beta = 1$) positive particle. About 90% of the Phase I vees were electron-positron pairs which WAC failed to reject.

The separate pulse positions of the EH and PH pulse-pairs and the $C\beta$ information were measured using image-plane digitizing measuring machines. The times are referenced to the small triangular time marker near the beginning of each trace. The distance-time conversion was accomplished by measuring calibration frames which displayed a 50 MHz sine wave on all the traces. All of the positive and negative peaks of the sine waves were measured. Measured data points were converted to times by linearly interpolating from the four nearest calibration points.

The pulse time from one end of a hodoscope paddle is given by

$$t_1 = z_1 + t_s + c_1$$

where z_1 is a constant determined by cable lengths, photomultiplier times, etc; t_s is the particle time-of-flight; and c_1 is the light travel time in the paddle. The pulse from the other end of the paddle is given by

$$t_2 = z_2 + t_s + c_2.$$

It is seen that $t_s = 1/2(t_1 + t_2) - 1/2(z_1 + z_2) - 1/2(c_1 + c_2)$, but this

can be written as $t_s = 1/2 (t_1 + t_2) - z$ since the sum of the z 's and c 's is constant. z is the "zero" for the paddle. The separation between the two pulses is determined by the position the particle struck the paddle. The accuracy of the separation measurements was approximately ± 1.5 ns which corresponds to a position constraint of ± 4 inches in our hodoscopes. From the measured times-of-flight of the Phase I vees, the zeroes for the PH were determined by subtracting the hand measured track lengths. A typical distribution is shown in Figure 11. The narrow peak contains all particles with $\beta = 1$. The slower particles are seen at later times. The width of the peak corresponds to a time-of-flight measurement accuracy of 1 ns.

Our Monte Carlo simulation indicates the fastest event protons had flight times 3 ns longer than a $\beta = 1$ particle. We therefore made a "pair cut" 1.5 ns later than the paddles' zeroes as determined by such distributions. This should reject a negligible number of events, but it eliminated about 70% of the Phase I vees. Approximately 7% of the vees were lost because of repeated measuring mistakes or extraneous pulses obscured the correct ones. A time card was punched for every vee surviving this cut which contained the information from the Phase I scan card in addition to the timing information.

The oscilloscope information for $C\beta$ consisted of a time measurement of the discriminator pulse and position and amplitude measurements for the linear pulses. The position of the linear pulse indicated

Fig. 11. Time distribution for PH-4.

Fig. 11

the quadrant from which it came. Large amplitude pulses were good indicators of Cherenkov light from electrons.

3. Phase II Scanning—The vees which survived the $\beta = 1$ time cut were listed on sheets produced during the computer analysis of the timing information. This showed the triggering information from the data box and the hodoscope times processed in scope measuring. The Phase II scanners were asked to verify that there were indeed acceptable vees on the film and that no mistakes had been made in their processing. When the positive particle had a time of flight within 3 ns of the cut, a message was printed on this scan sheet. The scanners performed the 250 MeV/c momentum cut on these using the template as described under Phase I scanning. There was essentially no chance that a proton could have been rejected in this cut.

The accepted Phase II vees were then prepared for spark measurement. A sketch of each frame was made on printed forms showing which sparks should be measured in each chamber. These were approximately to one-fourth real space scale (scanning table image plane). The sparks for the three tracks were color-coded for easy recognition among the extra tracks in the chambers. They also had to reject sparks which were far from a desired particle's trajectory. The sparks following a large kink in the negative track were omitted if the kink was in SC1 or 2; otherwise, the vee was rejected. Approximately one out of every five $\Lambda p\pi$'s in our apparatus had its pion decay before detection

in the EH. The decay angle was greater than 5° for 98% of these, so they were easily detected on the scanning table. If the beam pion could be easily chosen, it was also included for measurement. Since the beam pion was not very important in event selection, it was more efficient to repeat Phase II and spark measurement for the fully analyzed candidates with several beam pions. The beam selection for these candidates was made by determining which pion in the beam chambers went through HAC and "disappeared" in the target. A printed mask was used on the scanning table to project beam tracks from the elevation view of the beam chambers through HAC and into the elevation view of SC5 and 6. By eliminating the tracks hitting HAC and those which did not interact, the correct beam track could be picked on the scanning table for 80% of the candidates. For the rest, all possible beam tracks were measured so that a more accurate selection could be made after a complete event reconstruction.

The Phase II scanners had to be familiar with the Phase I and scope measuring procedures as well as their own special instructions. At first, this was done only by physicists. After procedures had been determined which covered almost all possibilities, the most capable scanners and measurers assumed this role under close supervision.

The Phase II scan was time consuming, but it saved much more time in the spark measuring operation. It typically rejected 40% of the candidates - most were unrelated tracks and other Phase I errors.

The remainder were electron-positron pairs. It also substantially decreased the chances for error in the measuring due to confusing tracks and sparks (only one view at a time was available during measurement).

4. Spark Measuring — The spark chamber data for the vees surviving Phase II were measured at Ohio State University with image-plane digitizing machines with an effective least-count of less than 0.003" in real space. The first frame of each data run was measured as a calibration frame. This consisted of measuring front and rear fiducials at all four corners of every chamber in both views. An ordinary data frame measurement consisted of measuring every spark on each track as indicated by the Phase II sketch. In addition, a front fiducial near a track's entry and a rear fiducial near its exit were measured for each chamber. These eliminated local distortions in the mirrors or in the measuring projection system.

The spark chamber measurements were output onto punched cards. These were then computer checked for character validity and procedural accuracy, then merged onto a BCD magnetic tape. A typical data tape contained approximately 500 measurements from 3 film rolls. This included about 150 measurements from the $\Lambda p\pi$ calibration runs on the same rolls. The magnetic tapes were transferred to ANL where they were edited onto an Argonne computation center library tape. During this edit, residual errors in frame numbers were corrected, missing frames were added, and the timing information from

the time cards was inserted. A low-density copy of each edited tape was made and stored at a different ANL location.

B. Event Selection and Analysis

1. Geometric and Momentum Reconstruction—The spark chamber measurements were reconstructed using two programs which were combined into an overlay system on the CDC 3600 computer. These were primarily developed by P. R. Phillips and D. M. Schwartz.

The geometry routines first unpacked and ordered the spark and fiducial measurements in both views. The measurements were then roughly checked in the film plan coordinates: fiducial measurements were required to be within their surveyed areas and spark measurements had to be within chambers. These failures were rejected and scheduled for remeasurement. The remainder (usually greater than 85%) had their sparks transformed into real-space coordinates. These were done chamber by chamber using the transformation parameters determined from the calibration frame measurements.

The real-space spark coordinates were the input of the momentum analysis routines. Because of our highly non-uniform magnetic field, a sophisticated fitting procedure was required.²⁵ This entailed iteratively tracing orbits from a common vertex by solving the differential equations of motion by numerical integration. Nearby sub-orbits were traced to obtain the derivatives of the fitted parameters. The magnetic field along each orbit was obtained by a second-order

interpolation of nearby points in the fitted field grid. The best estimates were determined by minimizing the χ^2 of the weighted least-squares fit. After three iterations the fit was usually sufficiently accurate to allow a correction for the spark staggering. This correction was made on the paired sparks (in successive gaps with symmetrical shifts) for the final two iterations so that the line joining the two sparks was parallel to the local slope of the orbit. The equations of motion also allowed for energy loss by the decay products. At this stage the particles were assumed to be a proton and pion unless the momentum of a particle was too low to penetrate the chambers. For those cases a positron or electron mass was assumed. The standard errors in calculating the χ^2 were considered to be 0.015" for each coordinate of a spark or fiducial measurement.

The output of this analysis consisted of printed results, CRT plots of the sparks and fitted vees, and a record on a magnetic tape of the results. The results included such quantities as decay vertex position, initial momenta and directions, path lengths, flight times, invariant masses for various hypotheses, χ^2 , and complete error matrices of the fitted parameters. The beam tracks were fit using a fixed momentum. Their results were primarily a projected orbit position and direction near the nominal beam focus in the LH_2 target.

A physicist scanned these results with the aid of the CRT plots to reject most of the processed measurements. A typical CRT plot of

an analyzed data frame is shown in Figure 12. An abbreviated version of the kinematics program was used to reject measurements with good fits which failed a set of simple criteria. This typically reduced the number of measurements for review by the physicist by 40%. Of the remaining measurements, 75% were rejected by the physicist as failing the set of criteria mentioned above. These criteria are listed in Table 4 with their typical rejection efficiencies. Most of the rejected measurements reviewed thoroughly by the physicist either had a poor fit yet clearly failed the criteria or the tracks were unrelated.

2. Kinematics — The remaining 15% of the measurements were carefully scrutinized with the aid of a kinematics program which was also run on the CDC 3600 computer. The magnetic tape produced by the momentum program was its input. Each event was reconstructed kinematically using the decay hypotheses $\Lambda \rightarrow p + \pi^-$, $K^0 \rightarrow \pi^+ + \pi^-$, $\gamma \rightarrow e^+ + e^-$, and $\Lambda \rightarrow p + e^- + \bar{\nu}$. In addition, numerous triggering and timing checks were made. If the measurement did not include a beam track, an orbit along the nominal beam line was inserted. This was done only to get realistic estimates of times-of-flight, decay vertex-beam line distance, etc. Non-beam candidates in the final sample of events had to be remeasured with a beam track to be useful. The high rejection efficiency of the analysis kept these to less than 10% of our overall measuring load.

Fig. 12. CRT plot of an analyzed data frame.

Fig. 12

TABLE 4
CANDIDATE REJECTION CRITERIA

- I. Electron-positron pair (40%)
 - A. $M_{ee} < 50$ MeV, and
 1. Positron time-of-flight (± 3 ns) and 4 ns from proton, or
 2. Positive momentum greater than 600 MeV/c and positron time-of-flight (± 4 ns), or
 3. Hardware vertex.
 - B. $M_{ee} < 100$ MeV, and
 1. Positron time-of-flight (± 3 ns) and 5 ns from proton, or
 2. Positive momentum greater than 700 MeV/c and positron time-of-flight (± 4 ns), or
 3. Positive momentum less than 300 MeV/c, or
 4. Both times-of-flight more than 5 ns late, but have electron-positron relative times-of-flight (± 4 ns).
- II. $\Lambda \rightarrow p + \pi^-$ (25%)

Proton with momentum in 300-900 MeV/c range, and
Negative momentum in 30-200 MeV/c range, and
 $M_{p\pi} = 1115 \pm 15$ MeV, and

 - A. Negative track misses $C\beta$ window, or
 - B. Wrong $C\beta$ quadrant triggered, or
 - C. Non-electron $C\beta$ time-of-flight (± 4 ns), or
 - D. Large kink in negative track near vertex.
- III. K^0 (2%)
 - A. $M_{\pi\pi} = 498 \pm 8$ MeV, and
 1. Positive momentum less than 300 MeV/c, or
 2. Fails $C\beta$ requirements, or
 3. Positive pion time-of-flight (± 2 ns) and more than 5 ns from proton.
 - B. Flight length greater than 7 inches, and
 1. Positive momentum less than 300 MeV/c, or
 2. Positive pion time-of-flight (± 2 ns) and more than 5 ns from proton.
- IV. Other (25%)
 - A. Outside fiducial volume, or
 - B. Unrelated tracks, or
 - C. Pion-proton scatter.

Even though the $\Lambda \rightarrow p + \pi^-$ solution has 3 constraints, we extracted unconstrained solutions. This was performed on the calibration $\Lambda p \pi$ events to determine our experimental accuracy. These results are discussed in Chapter IV. The three constraints used as $\Lambda p \pi$ cuts in our final sample were the mass of the $p + \pi^-$ system ($M_{p\pi} = M_{\Lambda}$ if hypothesis correct), the missing mass ($M_X = M_{K^0}$ if hypothesis correct), and the net transverse momentum ($P_t = \hat{\sigma}_{\Lambda} \cdot \vec{p} + \hat{\sigma}_{\Lambda} \cdot \vec{\pi} = 0$ for a 2-body decay). The production point was determined using two methods for comparison. The first projected the sum of the two decay momenta to the closest approach to the beam pion; the second slashed the geometric plane formed by the two orbits through the beam pion. The first method was more reliable and is used in all $\Lambda p \pi$ distributions shown in Chapter IV. The $K^0_{\pi\pi}$ hypothesis was solved identically by assuming the analyzed tracks were π^+ and π^- . In this case the missing mass should correspond to that of the lambda.

The primary kinematic result of the $e^+ + e^-$ hypothesis was the invariant mass. This is used in conjunction with the times-of-flight to reject both external and Dalitz pairs with very high efficiency (see Final Candidate Scan below).

Since the $\Lambda\beta$ hypothesis has an additional unanalyzed decay particle, it is reduced to a zero-constraint analysis. Actually, the azimuthal angle of the lambda about the beam line was observed, but this provided a weak constraint. This constraint exhibited itself in the ability

to reject about one-third of the solutions because the production point was either downstream of the decay vertex or far behind the LH_2 target. About one-third of our events gave no good solution because of measurement errors. These were "stretched" to a nearby good solution. The extent of the stretch was compared with a Monte Carlo simulation with our expected accuracies. To determine quantities which were solution dependent, each solution of a two-solution event was weighted according to the product of the lambda's probability for survival and its production probability as determined by its production angle in the $\pi^- + p$ center-of-mass system. Most of the results from polarized lambda's do not depend on a unique center-of-mass analysis. The asymmetries of the decay particles which provide most of our analyzing power are of course Lorentz invariant. The neutrino momentum can be calculated uniquely and the electron momentum can differ only slightly between solutions. The solution-dependent quantities of most interest to us were the angle between the electron and neutrino and the time-reversal violating correlation, $\hat{\sigma}_\Lambda \cdot \hat{e} \times \hat{\nu}$. Kinematics was used in the event identification to the extent that all accepted events were required to be consistent within the expected errors. Numerous production and decay distributions were calculated for comparison with the Monte Carlo simulation. Some of these are shown in Chapter IV.

In addition to the kinematic calculations, the kinematics routines computed triggering and timing parameters. The times-of-flight were

calculated for various particle hypotheses taking into account the contributions from momentum loss and lambda flight time. The hodoscopes entered by the tracks were obtained for comparison with the scanning data. The pulse separations of the hodoscope pulses were calculated. The negative track was extrapolated into $C\beta$ to determine the proper quadrant and the time-of-flight to $C\beta$ for an electron hypothesis was calculated. The results of the timing measurements were listed for easy comparison with these. Any discrepancies were noted on candidate sheets for investigation in the final scan.

3. Final Candidate Scan—A physicist checked the original spark chamber frames for every candidate at this stage. The objective of this was to verify that an acceptable vee was indeed present, note dubious tracks from the decay vertex region, and to check any discrepancies observed in the kinematics procedure. He typically rejected about 10% of the candidates as being unrelated tracks.

The scope film was remeasured under close supervision for all candidates with an invariant pair mass less than 100 MeV or with a timing or triggering discrepancy. The remeasurement results typically allowed the rejection of 40% of the candidates using the criteria of Table 4. Most of these were electron-positron pairs for which the time measurement error was large or extra pulses confused the measurer. Some were $\Lambda p\pi$'s for which no $C\beta$ information was initially processed.

The remaining candidates were then momentum and kinematically analyzed again under both $\Lambda p\pi$ and $\Lambda\beta$ hypotheses. This time the errors on the sparks in the momentum fitting were adjusted to allow for Coulomb scattering in the spark chambers. The fitting was also allowed to use eight iterations to be sure of convergence. The results of the scope remeasurements were inserted during this pass through kinematics. The information from the various procedures was then correlated and a final classification of each candidate was made. Those without beam tracks were returned to the Phase II scan for beam selection and remeasurement.

The classification criteria are listed in Table 5 along with the fractional distribution of our sample of candidates. Estimations of the possible background events using these classification criteria indicate only three of any significance:

1. $\Lambda p\pi$ - Approximately a 6% contamination with a loss of less than 5% of the $\Lambda\beta$'s.
2. Pairs - Less than a 5% contamination with a loss of less than 2% of the $\Lambda\beta$'s.
3. Unrelated p and e^- - Enough data taken with the beam pion below the threshold for lambda production has been analyzed to date indicating this is less than 20% (with 95% confidence).

TABLE 5
CANDIDATE CLASSIFICATION

Code for classification contains two parts, A/B:

A = Event type

- 1 Proton and Electron - Good $\Lambda\beta$ kinematic solution.
- 0 Proton and Electron - No $\Lambda\beta$ solution, but stretch within expected range.
- Proton and electron - Far from a $\Lambda\beta$ kinematic solution.
- 2 $\Lambda p\pi$ - $M_{p\pi}$ (1105 - 1125 MeV), and
 M_K (482 - 514 MeV), and
 $| \text{Net transverse momentum} | < 50 \text{ MeV/c}$, and negative pion time-of-flight ($\pm 3 \text{ ns}$).
- 3 Electron-positron pair - M_{ee} less than 100 MeV, and
 Positron time-of-flight ($\pm 3 \text{ ns}$).
- 4 K_S^0 - $M_{\pi\pi}$ (490 - 506 MeV), and
 M_Λ (1095 - 1135), and
 Negative momentum greater than 150 MeV/c, and
 Positive pion time-of-flight ($\pm 3 \text{ ns}$).
- 5 K_L^0 - M_{ee} greater than 100 MeV, and
 Flight length greater than 7 inches, and
 Positive pion time-of-flight ($\pm 3 \text{ ns}$).
- 6 Non-hydrogen $\Lambda p\pi$ - $M_{p\pi}$ (1105 - 1125 MeV), and
 $| \text{Net transverse momentum} | < 50 \text{ MeV/c}$, and
 Non-hydrogen production vertex, and
 Negative pion time-of-flight ($\pm 3 \text{ ns}$).

B = Sum of applicable comment codes

- 0 Measurement and final scan acceptable.
- 1 Negative track has a noticeable kink.
- 2 An extra track appears to emanate from decay vertex.
- 4 Fitted decay vertex in TAC.

CANDIDATE DISTRIBUTION

A/B	1/	0/	-/	2/	3/	4/	5/	6/
/0	0.23	0.09	0.05	0.17	0.10	0	0.01	0.01
/1	0.01	0.01	0.01	0.04	0.0	0	0	0.0
/2	0.04	0.0	0.04	0.0	0.0	0	0.0	0
/3	0.0	0	0.0	0	0	0	0	0
/4	0.04	0.0	0.08	0.0	0.0	0	0	0
/5	0	0	0.0	0	0	0	0	0
/6	0.01	0	0.04	0.0	0	0	0	0

C. Summary

The data reduction procedures are summarized in Figure 13. The number of candidates from a typical data roll is shown at each stage. The efficiency of each procedure for real $\Lambda\beta$ events is also shown within each box.

Fig. 13. Data reduction summary.

Fig. 13

CHAPTER IV

RESULTS

The results reported in this thesis represent the complete analysis of approximately 290,000 data frames which should yield nearly one-fourth of the final sample of events. A total of 151 $\Lambda\beta$ events have been accumulated in the "best" four categories outlined in Table 5. These do not include any events for which a beam track could not be chosen or which had an extra track coming from the vicinity of the decay vertex. The analyzed $\Lambda p\pi$ calibration runs have yielded 1,627 useful events. Making straightforward corrections for the differences in the triggering rates, solid angles, and pion decay loss; these indicate a branching ratio $R_\beta = (8.8 \pm 1.0) \times 10^{-4}$. This is in excellent agreement with the latest experimental average,¹¹ $R_\beta = (8.60 \pm 0.45) \times 10^{-4}$.

Since our results obtain primarily from the asymmetries, it is very important that we understand any detection bias in our apparatus or ensuing analysis. Our Monte Carlo simulation indicates the geometric triggering bias of our apparatus on the asymmetries was negligible for both $\Lambda\beta$ and $\Lambda p\pi$ decays. The up-down asymmetries of the actual apparatus were checked by selectively triggering on $\pi^- p$

scatters and electron-positron pairs. The π^-p scatters check all of the hodoscopes while the pairs include a test of the $C\beta$ asymmetry. Both of these indicate an asymmetry less than 0.03.

The proton asymmetry of our $\Lambda p\pi$ events provides a test of detection bias in addition to a measurement of our lambda sample polarization. The proton asymmetry for the $\Lambda p\pi$ decays with the spin projection up relative to the magnet midplane is $(\alpha P_\Lambda)_{\text{up}} = 0.56 \pm 0.10$; and for spin projection down, $(\alpha P_\Lambda)_{\text{down}} = 0.55 \pm 0.06$. The lambda beta asymmetries also show no bias with respect to spin orientation. Since $\alpha = 0.645 \pm 0.16$,²¹ our $\Lambda p\pi$ sample indicates a lambda spin polarization of $P_\Lambda = 0.87 \pm 0.08$. This agrees with the expected value of 0.90 ± 0.05 ²⁰ from hydrogen. The target shape should have increased the polarization a few per cent by suppressing directly forward and backward lambdas, but the fraction of lambdas produced in the hydrogen vessel, radiation insulation, and inner surface of the TAC scintillator would have reduced the polarization by a few per cent. The production rate in target-empty $\Lambda p\pi$ runs and the reconstructed $\Lambda p\pi$ production vertices for the calibration runs are both consistent with a non-LH₂ fraction of 0.14. Measuring and scanning errors are expected to have a negligible effect on the polarization measurement.

Figures 14 to 20 are a few of the distributions which illustrate the effectiveness of our background rejection and which support our identification of lambda beta decays. Figure 14 is the distribution of

Fig. 14. M_{ee} , Calculated Invariant Pair Mass Distribution.

Fig. 14

the invariant mass for our events assuming an electron mass for both particles. The distribution for analyzed electron-positron pairs which triggered our apparatus is also shown. The absence of a significant excess near zero mass supports our contamination estimate for these ($< 5\%$). Figure 15 illustrates why the time-of-flight of the positive particle provides a unique identification for the protons from lambda decays. The frequency of the WAC indicator light for a one-tube coincidence is also a good test of background with light positive particles. This indicator was coded onto the scan cards and propagated through the data analysis, but it was not used in any rejection procedures. The calibration tests of the counter indicated a proton efficiency of 10-15% for a single-tube requirement. The $\Lambda p \pi$ events from the calibration runs measured this to be $13 \pm 1\%$. The $\Lambda \beta$ events are in good agreement with $15 \pm 3\%$. On the other hand, over 65% of identified analyzed pairs have the WAC indicator light on.

Figures 16 and 17 compare the $\Lambda p \pi$ constraints with the distributions for the $\Lambda \beta$ events. The dashed lines in Figure 16 are the 1 and 2-standard deviation contours enclosing the lambda and kaon mass point for analyzed $\Lambda p \pi$ events: rms errors of $5 \text{ MeV}/c^2$ in lambda mass and $9 \text{ MeV}/c^2$ in missing kaon mass. The distribution of the net transverse momentum of the two charged particles is shown in Figure 17 for both $\Lambda \beta$ and $\Lambda p \pi$ events. This is a direct measurement of the neutrino transverse momentum for $\Lambda \beta$ decays. The rms error for the $\Lambda p \pi$

Fig. 15. $p-\pi^+$ Time-of-flight difference distribution.

Fig. 15

Fig. 16. Scatter plot of kaon and lambda masses for
 $\Lambda p \pi$ hypothesis.

Fig. 16

Fig. 17. Neutrino transverse momentum distribution.

Fig. 17

events is 13 MeV/c. A unique identification for most of the electrons from the $\Lambda\beta$ events is indicated in Figure 18. These distributions are in agreement with an upper limit for $\Lambda p\pi$ contamination of approximately 6%.

Figure 19 compares the lambda (proper) lifetime distribution for the lambda beta sample with the Monte Carlo simulation. The mean experimental lifetime, 0.67 ± 0.04 ns, is in good agreement with that for the Monte Carlo events, 0.617 ± 0.004 ns. The beta spectrum shown in Figure 20 also shows no indication of significant background.

The asymmetries with respect to the lambda spin are presented in Table 6 along with those measured by other experiments. The values for g_1/f_1 and f_2/f_1 were determined by a least-squares fit to the differences of the bin fractions as described in Chapter I. A plot of this contour is shown in Figure 21. A six per cent $\Lambda p\pi$ contamination would decrease g_1/f_1 by 0.06 in this region -- this possibility is reflected in the values and errors listed in Table 6. The proton asymmetry measurements are in good agreement with each other and are consistent with the Cabibbo prediction. The electron and neutrino measurements are not inconsistent with the Cabibbo prediction when analyzed separately, but in a combined analysis they depress g_1/f_1 well over a standard deviation from the expected value. The weak magnetism term, f_2/f_1 , has the correct sign and a magnitude consistent with the generalized CVC hypothesis.

Fig. 18. $e-\pi^-$ Time-of-flight difference distribution.

Fig. 18.

Fig. 19. Lambda lifetime distribution.

Fig. 19

Fig. 20. Electron Energy Spectrum.

Fig. 20

TABLE 6
RESULTS FROM SPIN CORRELATIONS IN POLARIZED LAMBDA EXPERIMENTS*
(ASSUME $g_2/f_1 = 0$)

Experiment	No. Events	A_p	A_e	A_ν	g_1/f_1	f_2/f_1
This Experiment	151	$-0.48 \pm .23$	$0.14 \pm .22$	$0.77 \pm .21$	$0.35^{+0.23}_{-0.16}$	$1.4^{+1.6}_{-1.3}$
Heidelberg- CERN ²⁶	1136	-0.53 ± 0.09	0.12 ± 0.09	-	$0.35^{+0.28}_{-0.09}$	1.1 ± 0.6
Barlow, et.al. ²⁷	84	-	0.06 ± 0.19	-	$(0.66^{+0.44}_{-0.63})$	-
Lind, et.al. ²⁸	22	-	0.60 ± 0.35	0.74 ± 0.39	(0.35)	-
Weighted Mean		-0.52 ± 0.08	0.13 ± 0.07	0.76 ± 0.18	$0.35^{+0.18}_{-0.08}$	$1.2^{+0.6}_{-0.5}$
Cabibbo Prediction		-0.56	0.03	0.97	0.72	0.98

* Values in parentheses are derived -- were not supplied by reference.

Fig. 21. 1-Standard-deviation contours for least-squares
fits to g_1/f_1 and f_2/f_1 .

Fig. 21

A least-squares fit to the sums of the paired bins (essentially a fit to the electron-neutrino correlation, $A_{e\nu}$) yields $g_1/f_1 = 0.90^{+1.5}_{-0.40}$. Our measured value for $A_{e\nu}$ and the corresponding g_1/f_1 are listed in Table 7 and compared with other experiments. The weighted mean is dominated by the recent bubble chamber experiments using stopping K^- beams to produce unpolarized lambdas and the Heidelberg-CERN experiment using a π^+ beam into beryllium. The electron-neutrino correlation is in remarkable agreement with the Cabibbo prediction.

The basic problem to be resolved in lambda beta decay is whether or not the discrepancy between the spin asymmetries and the electron-neutrino correlation is real. In the 3-bin fit to the bin differences, the change in χ^2 between the minimum and the Cabibbo value is $\Delta\chi^2 = 2.0$. This corresponds to a discrepancy of 1.4 standard deviations with an occurrence probability of $P = 0.16$. The addition of the other asymmetry experiments increases the discrepancy to about 1.8 standard deviations with $P = 0.07$. This is very suggestive, but additional data is required to resolve this uncertainty. The asymmetries may be indicating a 10 - 15% SU(3) breaking of the theory. Possibilities within a VA framework are a T-violating phase angle between the vector and axial-vector currents or a non-zero pseudotensor (g_2) term. I have analyzed our data for these possibilities. A non-zero phase angle does not improve the fit (primarily because it reduces A_e substantially while adjusting A_p and A_ν - see Figure 3). Our data also

TABLE 7

RESULTS FROM ELECTRON-NEUTRINO CORRELATION
MEASUREMENTS* (ASSUME $f_2/f_1 = 1.0$, $g_2/f_1 = 0$)

Experiment	No. Events	A_{ev}	g_1/f_1
This Experiment	151	-0.27 ± 0.22	$1.36^{+3.0}_{-0.53}$
Heidelberg-CERN ²⁶	1136	(0.09 ± 0.08)	0.65 ± 0.09
Baggett, et.al. ²⁹	239	(0.05 ± 0.10)	$0.71^{+0.14}_{-0.11}$
Maryland ³⁰	137	0.08 ± 0.17	$0.68^{+0.19}_{-0.14}$
Columbia-SUNY ³¹	127	-0.19 ± 0.22	$1.03^{+0.51}_{-0.25}$
Baglin, et.al. ³²	102	-0.21 ± 0.24	$0.80^{+0.9}_{-0.8}$
Ely, et.al. ³³	59	(< 0.05)	> 0.70
Lind, et.al. ²⁸	22	-0.06 ± 0.34	$(0.85^{+1.6}_{-0.37})$
Weighted Mean		0.02 ± 0.05	$0.73^{+0.07}_{-0.05}$
Cabibbo Prediction		0.03	0.72

* Values in parentheses are derived -- were not supplied by reference.

yields a direct measurement of D , the coefficient of the T -violating spin-lepton plane correlation, $D = -0.03 \pm 0.27$. This corresponds to a limit on the VA phase angle of $|\delta| < 45^\circ$ in the usual notation, $g_1/f_1 = |g_1/f_1| e^{i\delta}$, with $g_1/f_1 = 0.7$. A non-zero g_2 does improve the overall fit to our data and tends to remove the discrepancy between the spin asymmetries and the electron-neutrino correlation. The χ^2 for the 6-bin fit is smaller by $\Delta\chi^2 = -0.5$ with the results $g_1/f_1 = 0.38^{+.28}_{-.22}$, $g_2/f_1 = -1.2 \pm 1.8$. However, g_2 is consistent with zero. Oehme, Winston, and Garcia³⁴ have also considered possible $SU(3)$ deviations and procedures for estimating the magnitude of induced terms.

If I assume that the discrepancy between the spin asymmetries and the electron-neutrino correlation is only a statistical fluctuation, the most appropriate analysis of this data is a 6-bin fit to g_1 and f_2 with $g_2 = 0$. The experimental bin fractions are $p\uparrow e\uparrow = 0.073$, $p\uparrow e\downarrow = 0.146$, $e\uparrow\nu\uparrow = 0.331$, $e\downarrow\nu\uparrow = 0.146$, $p\uparrow\nu\uparrow = 0.185$, and $p\downarrow\nu\uparrow = 0.119$. These give a minimum χ^2 of 2.6 for 3 degrees of freedom when corrected for $P_\Lambda = 0.87$ and a $3 \pm 3\%$ $\Lambda p\pi$ contamination. The results (shown in Figure 21)

$$g_1/f_1 = 0.52^{+.38}_{-.20} \quad f_2/f_1 = 0.9^{+1.7}_{-1.5}$$

easily embrace the Cabibbo prediction.

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