Fermilab Proposal No. 715

Correspondent: P. S. Cooper
Yale University
Physics Dept.
New Haven, Ct. 06511
(203) 436-4890
FTS 646-4890

Precision Measurement of the Decay $\Sigma^- \to n e^- \nu$

Fermilab:
C. Ankenbrandt
J. P. Berge
D. Bogert
A. Brenner
P. Grafstrom
J. Lach
J. Marriner

Leningrad Nuclear Physics Institute (LNPI):
S. Belostotsky
A. Kulikov
V. Schegelsky
N. Terentiev
A. Vorobyov

Yale:
P. S. Cooper
L. J. Teig

Iowa State University:
W. Anderson

University of Iowa:
E. McCliment

University of Chicago:
R. Winston

February 19, 1982

DIRECTOR'S OFFICE
FEB 23 1982

Precision Measurement of the Decay $\Sigma^- \to ne^-\bar{\nu}$

We propose to make a definitive measurement of the decay parameters in the semileptonic decay of the Σ^- hyperon. Experiments investigating the electron asymmetry, α_e, of the decay $\Sigma^- \to ne^-\bar{\nu}$ have shown a systematic disagreement with Cabibbo theory over the past ten years. The most recent of these experiments, Keller 1982, confirms the previous experiments. However each of the experiments is statistically limited, most having less than 100 events. Since the ramifications of these results strike so deeply at our basic view of the weak interactions, it is imperative that a definitive high statistics, high precision experiment be performed. We propose to carry out such an experiment using the high intensity polarized Σ^- flux available from the Fermilab Proton Center charged hyperon beam.

I. INTRODUCTION

The beta decay of the Σ^- has attracted much experimental attention. However, the smallness of the branching ratio ($1.08\mathrm{x}10^{-3}$) and the difficulty in fully reconstructing the final state present formidable experimental problems. Only recently have there been experimentally consistent measurements of $|g_1/f_1|$ and historically the measurements of α_e have been in strong disagreement with Cabibbo theory. The current experimental situation is summarized in Figure 1, which shows the data from Gershwin 1968, Bogert 1970, Ellis 1972, and the recent result of Keller 1982. They all agree with each other and all disagree with the predictions of the Cabibbo model. The magnitude of the disagreement is greater than four standard deviations for the latest measurement and almost six standard deviations for the combination of the four measurements. It is interesting to note that the current measurements are consistent with the measured magnitude of the form factor ratio (g_1/f_1) if the sign is taken to be opposite to the prediction of the Cabibbo model.

Each of these measurements used the same basic experimental technique. In all of them a low energy meson beam was used to produce Σ^-. The polarization of the Σ^-'s was inferred from a phase shift analysis. Two hydrogen bubble chamber experiments and the latest electronic detector experiment were done at the $Y^*(1520)$ resonance in K^-p scattering. The fourth electronic experiment used associated production in π^-p scattering. All are low statistics experiments.

Clearly something is wrong with either these experiments or with the Cabibbo model. There is no fault that can be found with the current measurements. On the other hand, the

Cabibbo model has been so successful elsewhere, and forms the groundwork for so much new physics, that it is unthinkable to many that it might be wrong. We wish to resolve this issue by performing this measurement by a different technique.

As we will describe in some detail below, the current charged hyperon beam apparatus which we used for E-497 can, in one week of running, collect more than one hundred times the current world sample of polarized Σ^- beta decay events. With such a large sample of events we will be able to study possible systematic errors with techniques unavailable to the low statistics measurements.

The modifications to the E497 apparatus required for this experiment are a much superior electron detection system and a neutron calorimeter capable of measuring the neutron's position and energy.

II. PHYSICS

A concise description of semileptonic weak interactions has been given on the basis of the following assumptions (N. Cabibbo, 1963 and M. Gell-Mann and M. Levy, 1960). (1) The weak vector current and the electromagnetic current consist of the appropriate components of a common octet current of SU(3); (2) the axial-vector current is the same component of another octet current; and (3) there is a universal suppression factor for strangeness-changing transitions.

We write the semileptonic interaction for $B \rightarrow b + e + \bar{\nu}$ in the form

$$(G/\surd 2)\, J_\alpha l_\alpha^+ + \text{h.c.} \qquad (1)$$

where J = V + A and l is the familiar lepton current. The form factors appearing in the matrix element

$$M = \langle b|V_\alpha + A_\alpha|B\rangle\, i\bar{e}\gamma_\alpha\,(1+\gamma_5)\nu \qquad (2)$$

are defined by

$$\begin{aligned} \langle b|V_\alpha|B\rangle &= \bar{U}_b\,(\gamma_\alpha f_1 + \sigma_{\alpha\beta}q_\beta f_2/M_B)\,U_B, \\ \langle b|A_\alpha|B\rangle &= \bar{U}_b\,(\gamma_\alpha\gamma_5 g_1 + \sigma_{\alpha\beta}q_\beta\gamma_5 g_2/M_B)\,U_B \end{aligned} \qquad (3)$$

where $q = p_B - p_b = p_e + p_\nu$. We use the notation $p = (\mathbf{p}, ip_0)$, etc., with hermitian γ matrices. Terms involving q_α and $q_\alpha\gamma_5$ have been omitted because their contribution to M is proportional to the electron mass. If time-reversal invariance is assumed, the form factors $f(q^2)$ and $g(q^2)$ become real analytic functions, with g_2 being second class.

The transition rate is given by

$$dW = \frac{G^2}{(2\pi)^5} \frac{M_b}{M_B} \frac{P_e^{\,2} P_\nu^{\,3}}{(P_{emax}-P_e)} \times |M|^2 \, d\Omega_e \, d\Omega_\nu \, dP_e \qquad (4)$$

where M_b and M_B are the baryon masses. We can write $|M|^2$ in the general form

$$\sim [1 + a(\hat{e}\cdot\hat{\nu}) + A\sigma_B\cdot\hat{e} + B\sigma_B\cdot\hat{\nu} + D\sigma_B\, \hat{e}\cdot\hat{\nu} + A'\sigma_B\cdot\hat{e}\,(\hat{e}\cdot\hat{\nu}) + B'\sigma_B\cdot\hat{\nu}(\hat{e}\cdot\hat{\nu}) + D'\sigma_B\cdot(\hat{e}\times\hat{\nu})\,(\hat{e}\cdot\hat{\nu})] \qquad (5)$$

where $\hat{e}$ and $\hat{\nu}$ are unit vectors in the directions p_e and p_ν and σ_B is the polarization vector of the hyperon. The coefficients are functions of p_e and $(\cos\theta)^2$ [where $\cos\theta \equiv (\hat{e}\cdot\hat{\nu})$], and they can be expressed as bilinear forms of the functions f_i and g_i [J. M. Watson and R. Winston, 1969]. The primed terms in Eq. 5 are absent if the velocity of the recoil nucleon is neglected.

In our experiment <u>all</u> the correlations expressed in Eq. 5 are measured with their energy dependence. For example, the distribution in the Dalitz plot variables E_n and E_e gives the $e\cdot\nu$ correlation as a function of electron energy. However, for the purpose of estimating the sensitivity of the data to the form factors, it is convenient to integrate over electron energy. This leaves four decay parameters, the $e\nu$ correlation $\alpha_{e\nu}$, and the three spin correlations α_e, α_ν and α_n. These are plotted in Fig. 2 as a function of $R \equiv g_1/f_1$. Note that $\alpha_{e\nu}$ is a sensitive indicator of the magnitude of R since its dependence on f_2 is at most second order in $(M_B-M_b)/M_B$ ($=\Delta M/M$) and it is measured independently of Σ^- polarization. Therefore, the magnitude of R is known from previous measurements of $\alpha_{e\nu}$ (see Figure 1) to be 0.447±0.025. The Cabibbo model, which predicts the values of the form factors at $q^2 = 0$, agrees with these measurements when minor corrections for finite q^2 are made. Furthermore, the Cabibbo model predicts the sign of R to be negative. This is in clear disagreement with present measurements. Note that if a set of measurements of these four parameters is not consistent with a single value of the form factor ratio, R, that is clear evidence for the necessity of other form factors in the interaction. Alternately, a set of four parameters all consistent with the same positive value of R would cast strong doubt on the Cabibbo prediction.

The addition of a tracking calorimeter to the E497 apparatus allows a one constraint fit and thus full reconstruction of the event. We will thus be able to determine all four decay parameters. There are two important consequences of our ability to do this. The first is a test of the Cabibbo predictions independent of the measurement of the Σ polarization. The observed distributions are given in terms of the spin correlations:

$$\frac{dN}{d\cos\theta_i} = N_0 \, [1 + \alpha_i P_\Sigma \cos\theta_i] \qquad i = e, n, \nu \tag{6}$$

where P_Σ is the magnitude of the Σ polarization and Θ_i is the angle between the particle i and the Σ polarization vector in the Σ rest frame. The α_i are extracted from the slopes of the distributions given by equation 6.

$$A_i = \alpha_i P_\Sigma \tag{7}$$

With three independent slopes, A_i, we can form two ratios independent of P_Σ. These are shown below for the two possible values of g_1/f_1

$g_1/f_1 =$	-0.447	$+0.447$
$A_e/A_n = \alpha_e/\alpha_n$	-1.015 ± 0.039	-0.465 ± 0.037
$A_\nu/A_n = \alpha_\nu/\alpha_n$	-0.352 ± 0.030	-1.123 ± 0.042

The errors above are calculated assuming $P_\Sigma = 0.15$ and 100,000 polarized Σ^- beta decay events. These errors scale as $1/(P_\Sigma\sqrt{N})$ so that the precision of the technique depends on P_Σ even though P_Σ need not be directly measured.

Secondly, the $\alpha_{e\nu}$ measurement is also independent of P_Σ and should check the previous measurements of the magnitude of R with much higher statistics. The three spin correlations not only individually determine the sign of R but are also overdetermined by the form of the interaction. Measuring all of these quantities permits a consistency check of our measurement of Σ^- polarization. For example, we can form quantities like (Oehme 1971)

$$\frac{(\bar{B} + \frac{1}{3}\bar{A}') - (\bar{A} + \frac{1}{3}\bar{B}') - (1 - \bar{a})}{(1 + \bar{a})} \approx \frac{1}{3}\frac{\Delta M}{M}\left(1 + 2\,\frac{f_1 f_2 + g_1 g_2}{f_1^2 + g_1^2}\right) \tag{8}$$

where the coefficients defined in Eq. 5 are averaged over energy. This quantity is expected to be small for the correct Σ^- polarization but not for the wrong sign assignment (-0.05 vs. -0.50). We will determine this quantity with a precision of ±0.06.

We will, in fact, measure the Σ^- polarization via the $n\pi^-$ decay mode. The alpha parameter for this mode is quite small ($\alpha_{n\pi^-} = -0.068 \pm 0.008$) which makes this measurement difficult. It is remotely possible that the source of the discrepancy between the Cabibbo model and the α_e measurements is due to an incorrect value for $\alpha_{n\pi^-}$. Should this be the case, our asymmetry ratios will agree with the Cabibbo predictions while the asymmetries themselves will disagree indicating an error in the sign of P_Σ as determined from the $n\pi^-$ decay mode.

III. EXPERIMENTAL APPARATUS

A. Beam

We know from our E-497 data that at a production angle of 3 mrad and 250 GeV/c hyperon momentum, Σ^- are produced with significant polarization. Our analysis of the Σ^- polarization is not yet complete, so for purposes of this discussion we will use $P_\Sigma = 0.15$ which is the measured value of Σ^- polarization in the same kinematic region (Devlin 1982). We can reverse our polarization by reversing the targeting angle by means of existing dipoles in the incident beam. Simultaneous with the semileptonic running we will record a sufficient number of $\Sigma^- \to n\pi^-$ events to monitor the beam polarization.

At 3 mrad production angle with 3×10^{10} protons on target and 250 GeV/c hyperon momentum our Σ^- trigger rate in E-497 was 5000/pulse. These triggers are mainly Σ^- decays with a small contamination of cascade and K^- decays. We propose to collect a sample of 100,000 polarized Σ^- beta decays.

B. Neutron Calorimeter

Measuring the electron momentum and the neutron direction from the 3-body decay in flight will in general give two solutions for the neutron momentum. Measuring the neutron energy resolves the ambiguity. We will measure the neutron energy in an iron plate/scintillator calorimeter. A suitable device for our purposes has been used by the Cal. Tech. - Fermilab group in E379 (Dishaw 1979). The work of this group has demonstrated that the device is exceptionally linear and that the resolution function is well represented by $\Delta E/E = 0.73/\sqrt{E}$. We will reconfigure this calorimeter in the Proton Center hyperon beam.

A Monte Carlo calculation shows that this quality of energy resolution resolves the neutron energy ambiguity for about 75% of the events. Dependence of the resolved fraction on calorimeter resolution is shown in Figure 3. We remark that a large fraction of the remaining unresolved cases are in such close proximity on the Dalitz plot that further resolution would not be physically significant. Of course, measurement of the neutron asymmetry only requires measurement of the laboratory direction of the neutron with respect to the Σ^- production plane.

The neutron direction will be measured by sampling the developing hadron shower in the same calorimeter using PWC's interspersed with the iron plates. The sensitivity of the center of mass reconstructed neutron energy on the neutron spatial resolution is shown in Figure 4. This figure, calculated for a detector position 87.7 m from the decay region (at the far end of the hyperon enclosure) shows that a precision of ~6 mm would be adequate.

C. Electron Detection

Since the Σ^- leptonic branching ratio is 1.08×10^{-3} relative to the dominant hadronic decay mode $\Sigma^- \rightarrow n\pi^-$, the key to this experiment is electron identification. It is possible to reject any event which fits the hadronic decay hypothesis but this discards a significant fraction of the leptonic events and complicates any Dalitz plot analysis.

We propose to use two electron detectors, lead glass arrays and a transition radiation detector (TRD). Either of these detectors is capable of hadronic rejection factors of about 10^4 and in principle either one alone should be sufficient for this experiment. We believe, however, that both detectors provide significant advantages in mitigating the necessity of achieving the ultimate resolution limit of a single detector. Also we will be able to measure the rejection factor of each detector using the other and thus have a good measure of our background level.

The lead glass system will consist of two arrays as shown in Figure 5. The first is upstream of Magnet B and has one block missing to leave a hole for the decay neutron to pass through the array. The second array 5 m behind Magnet B is there to detect most of the electrons which go through the hole in the first array. The geometrical efficiency of the two arrays for electrons is greater than 90%.

The lead glass is the same type as we used in E-497 and was originally from E-288. A detailed study of this glass (Appel, 1975) shows that hadronic rejection factors of 10^4 on an event by event basis can be achieved. Statistically, rejections of 10^5 are possible and an online electron trigger will reject hadrons at the 10^3 level.

The TRD has been designed and is being built by the Leningrad Group. The design is along the lines of Fabjan 1981 and Ludlam 1981 and will consist of 12 planes. Hadronic rejection factors will be 10^3 offline and 20-50 at the trigger level. The electron detection efficiency is ~80%.

The CERN charged hyperon beam experiment has built and used a similar lead glass and TRD electron detection system (Bourquin 1981). They achieved overall hadronic rejection factors of 3-5 x 10^4, with overall electron detection efficiency of 70%. With such a system the remaining hadronic background in the leptonic decay sample will be 2-3% without any kinematic cuts.

D. Decay Spectrometer

The balance of the apparatus is exactly as used in E-497. Most of it is still in the Proton Center pit. The fast electronics is still largely intact and both online and offline software will require only minimal changes.

IV. Rates

In Table 1 we show a rate calculation based upon observed rates from E-497 together with conservative estimates for the performance of the electron and neutron detectors. The Σ^- trigger rate in E-497 for the kinematic conditions shown was 5000/pulse for a total hyperon beam flux of 25K/pulse. This trigger only required one particle exiting the hyperon magnet and a count in the neutron counter. This trigger is dominated (95%) by real Σ^- decays though some of them (~25%) occur upstream of the fiducial decay region. The semileptonic decay of K^- particles in the beam (see Table 1) has been investigated and is not a source of concern.

We expect that online the lead glass system (PbG) and transition radiation detector (TRD) will provide hadron rejection factors of 50 and 70 respectively. Offline we expect a combined hadronic rejection factor of 20,000. The efficiency for finding the neutron interaction point in the neutron calorimeter is taken as 75% (Tannenbaum 1975). The efficiency for a Σ^- trigger successfully reconstructing as a Σ^- decay in the decay volume is known from E-497 to be 70%.

The net result is 1.4 reconstructed leptonic decays per pulse with a background from the hadronic decay mode of less than 10%. Thus assuming 300 pulses per hour and 100 hours per week we will reconstruct 40,000 leptonic decays per week. We propose to run for one month and collect a total of over 100,000 reconstructed events.

V. Summary

We intend to do a definitive Σ^- leptonic decay experiment using polarized Σ^- and collecting two orders of magnitude more events than all previous experiments. These events will be fully reconstructed. We require the Proton Center charged hyperon beam and the existing E497 apparatus augmented by a neutron detector capable of measuring both the neutron energy and angle and a double level of electron identification (lead glass and transition radiation). We will be ready by early 1983 and will require approximately one month of checkout and one month of data taking.

The combination of high statistics, excellent electron identification, full event reconstruction, and extensive internal consistency checks should finally allow a resolution of this long-standing puzzle.

References

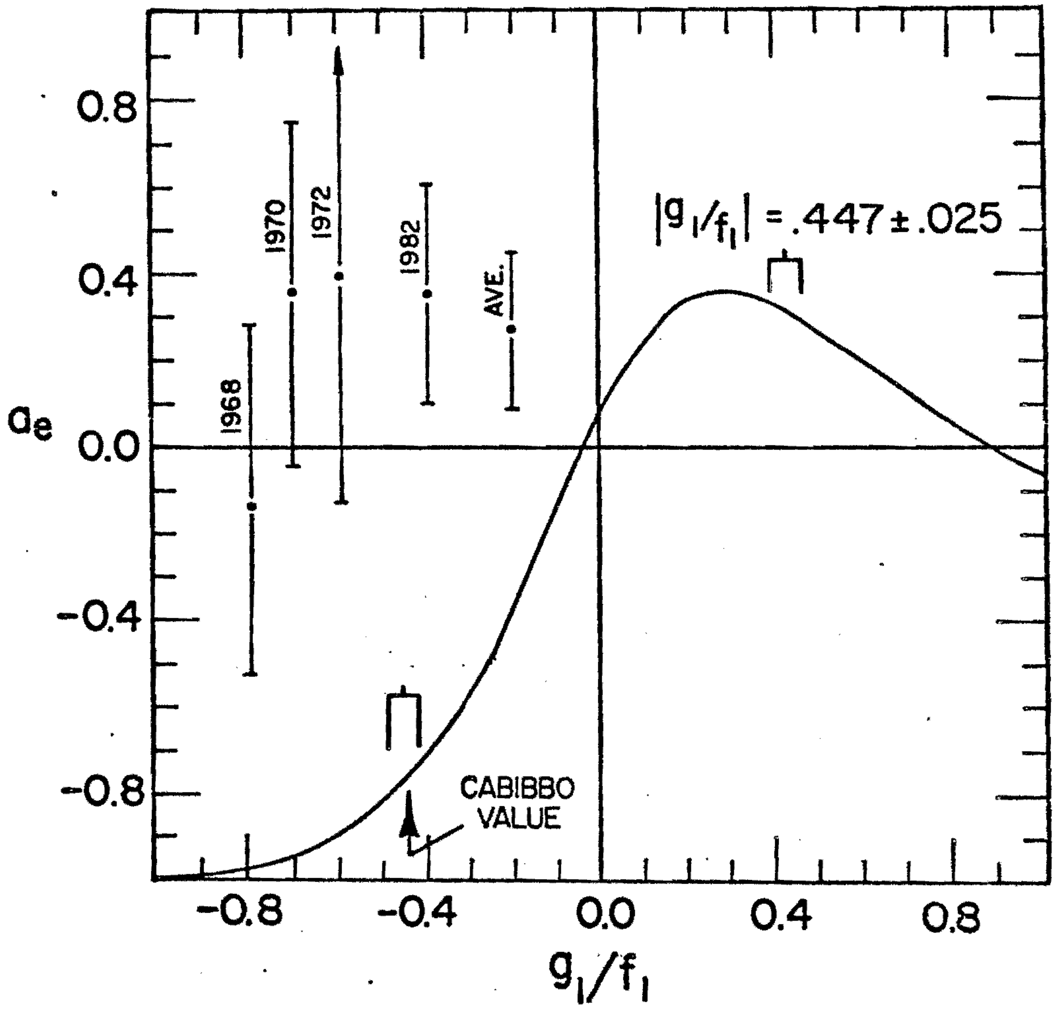
Appel, J. A. et al. 1975. Nucl. Instr. and Methods. 127:495.
Bogert, D. et al. 1970. Phys. Rev. D2:6.
Bourquin, M. et al. 1981. Preprint LAL 81/18.
Cabibbo, N. 1963. Phys. Rev. Lett. 10:531.
Devlin, T. 1982. Fermilab seminar.
Dishaw, John Patrick, 1979. Thesis, SLAC-216, UC-34d (T/E).
Ellis, R. J. et al. 1972. Nucl. Phys. B39:77.
Fabjan, C. W. et al. 1981. Nucl. Instr. and Methods. 185:119.
Gell-Mann, M. and Levy, M. 1960. Nuovo Cimento 16:706.
Gershwin, L. K. et al. 1968. Phys. Rev. Lett. 20:1270.
Keller, P. et al. 1982. Measurement of the Electron Asymmetry In the Beta Decay of Polarized Sigma Minus Hyperons, submitted to Phys. Rev. Lett.
Ludlam, T. et al. 1981. Nucl. Instr. and Methods. 180:413.
Oehme, R. et al. 1971. Phys. Rev. D3:1618.
Tanrenbaum, W. et al. 1975. Phys. Rev. D12:1871.
Watson, J. M. and Winston, R. 1969. Phys. Rev. 181:1907.

Rate Calculation

Primary beam:	400 GeV/c	momentum
	$3\text{x}10^{10}$	protons per pulse
	1 sec	spill length
Hyperon beam:	250 GeV/c	momentum
	300,000	background muons per pulse
	25,000	beam particles $\pi^-/K^-/\Sigma^-/\Xi^-$ 19,000/750/5000/250
	5,000	Σ^- triggers $\pi^-/K^-/\Sigma^-/\Xi^-$ 150/50/4700/100

RATES/Pulse	$\Sigma^-\to n\pi^-$	$\Sigma^-\to ne^-\nu$	$\Xi^-\to\Lambda\pi^-$ $\hookrightarrow n\pi^0$
Σ^- TRIGGER	4700	5.00	100
PbG Trigger	2%	90%	2%
TRD Trigger	5%	80%	5%
Geometrical acceptance	95%	90%	95%
TRIGGER	4.47	3.24	0.09
Offline electron	5%	80%	5%
Offline neutron	75%	75%	75%
Tracking efficiency	70%	70%	70%
ANALYZED	0.11	1.38	0.00

Figure 1

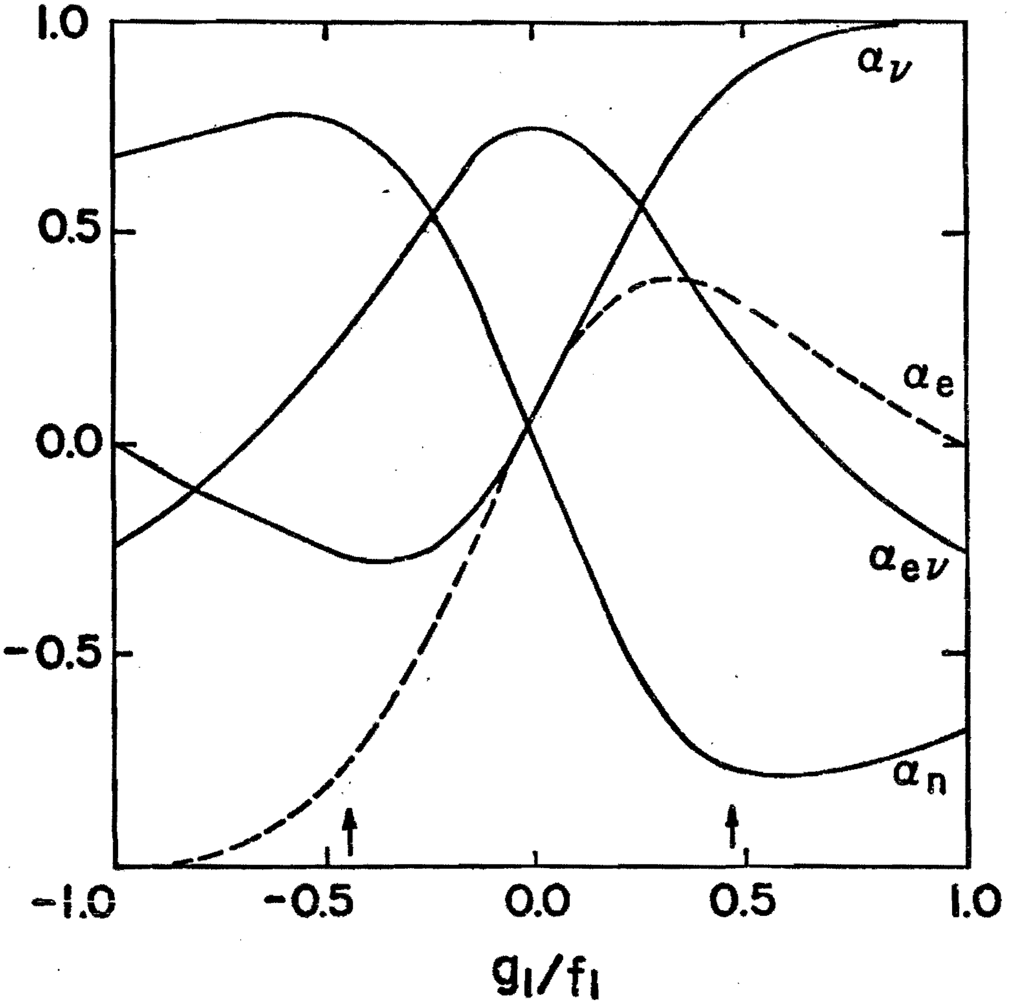


Summary of $\Sigma^- \rightarrow ne\tilde{\nu}$ Form Factor Experiments

Experiment	Year	No. of Events	$\lvert g_1/f_1 \rvert$
Maryland	1969	49	0.23 ± 0.16
Heidelberg	1969	33	$0.37\ {}^{+0.26}_{-0.19}$
Columbia-Stony Brook	1972	35	$0.29\ {}^{+0.28}_{-0.29}$
Yale-Fermilab-BNL	1973	3507	0.435 ± 0.035
CERN SPS	1981	4740	$0.458 \pm 0.035 (\pm 0.020)$

Polarized Σ^- Experiments

			α_e
Gershwin	1968	53	-0.13 ± 0.41
Bogert	1970	63	0.36 ± 0.39
Ellis	1972	43	$0.39\ {}^{+1.9}_{-0.53}$
Keller	1982	193	0.35 ± 0.25
Average			0.27 ± 0.18



g_1/f_1 =	-0.447	+0.447
α_e	-0.768	+0.352
α_ν	-0.266	+0.850
α_n	+0.758	-0.758
$\alpha_{e\nu}$	+0.259	+0.259

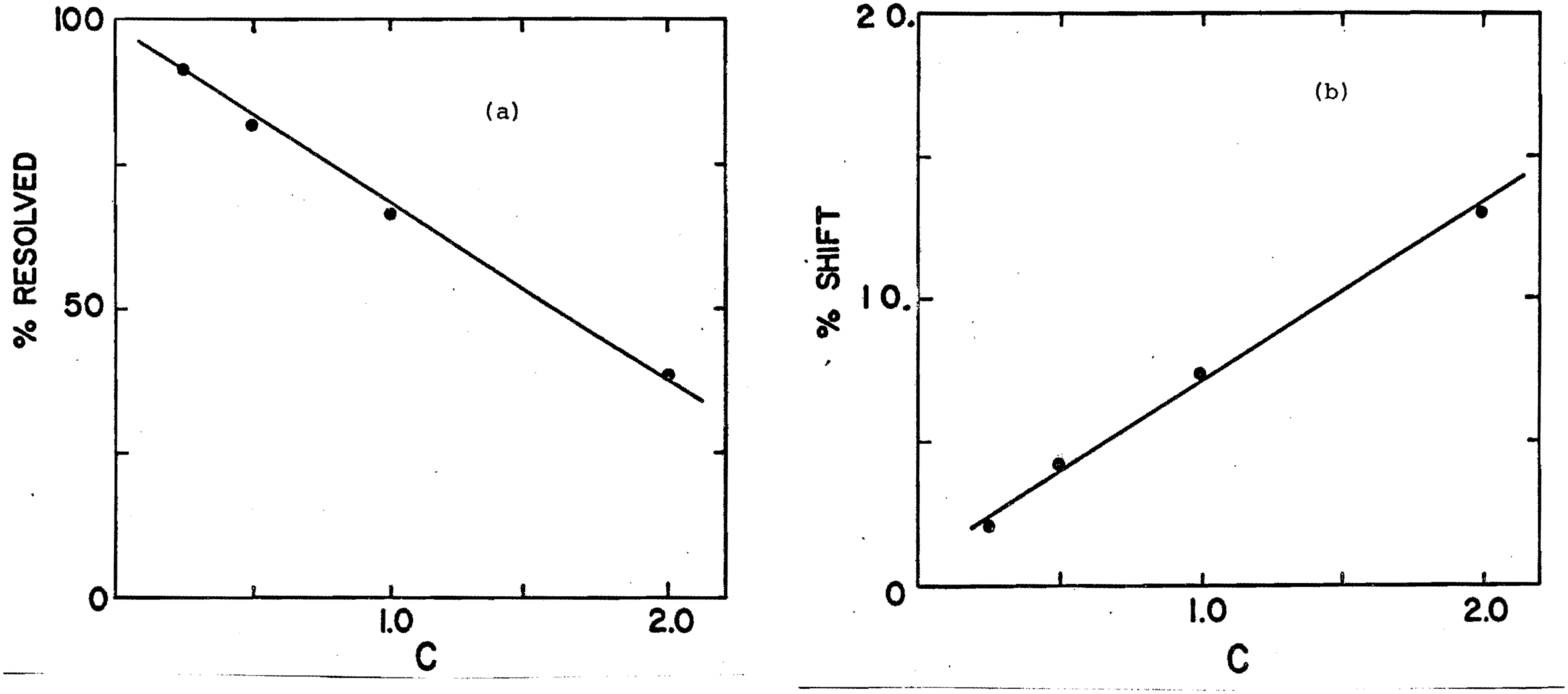


Figure 3 a. Fraction of events for which the two neutron solutions are resolved verses calorimeter performance.

b. Fractional shift on Dalitz plot of those events not resolved. We assume the calorimeter performance can be parameterized as

$$\frac{\Delta E}{E} = \frac{C}{\sqrt{E}}$$

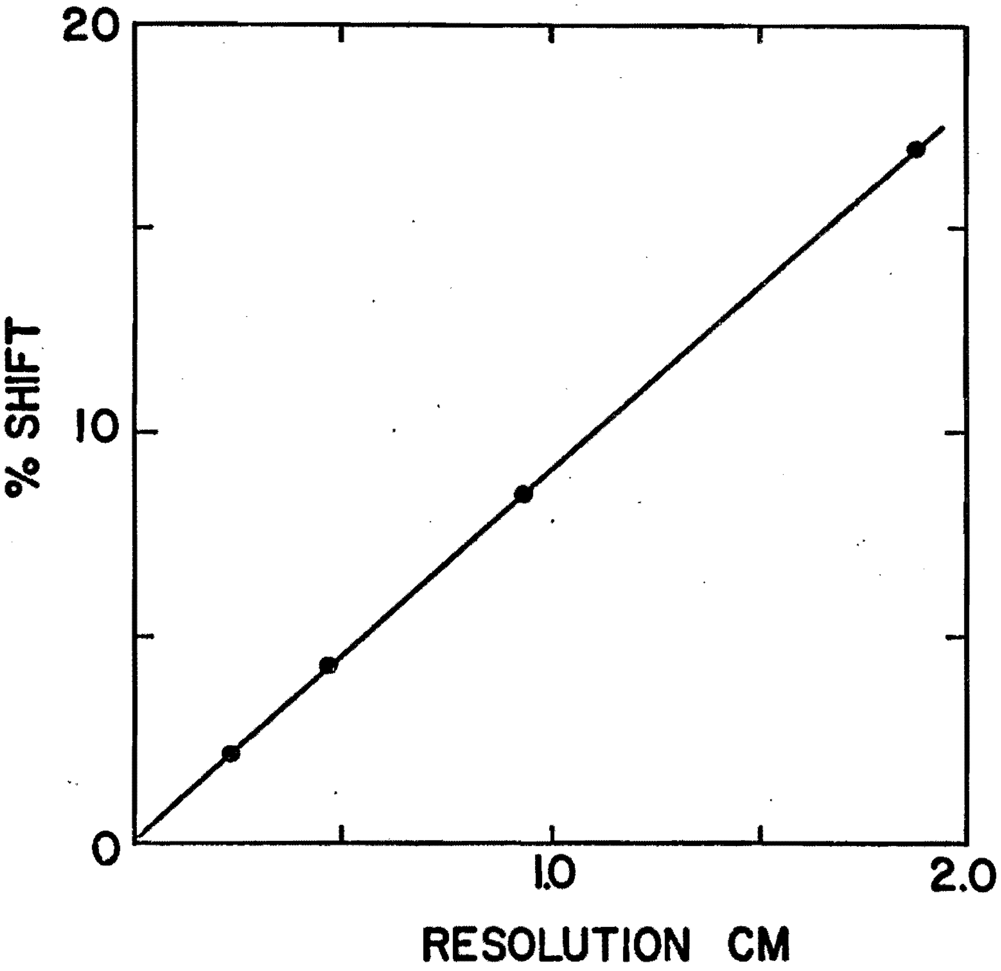


Figure 4 Fractional shift on Dalitz plot as a function of neutron detector spatial resolution.

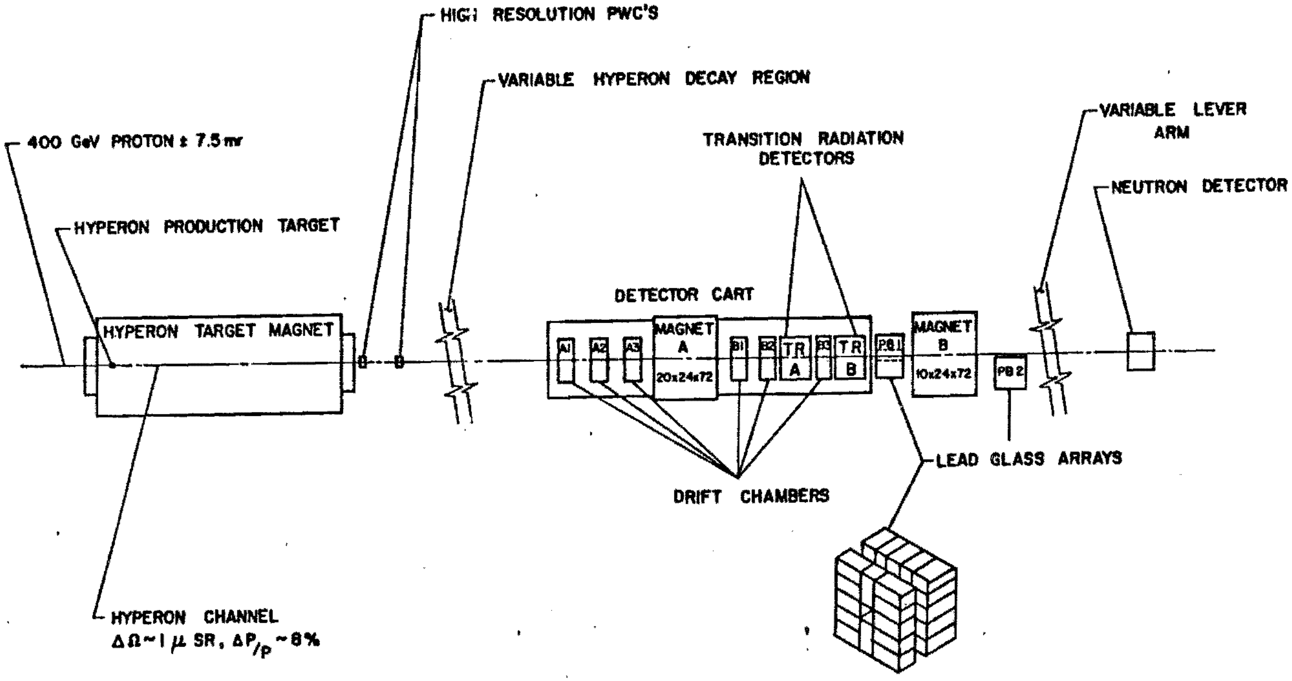

HIGH RESOLUTION PWC'S
VARIABLE HYPERON DECAY REGION
400 GeV PROTON ± 7.5 mr
HYPERON PRODUCTION TARGET
TRANSITION RADIATION DETECTORS
VARIABLE LEVER ARM
NEUTRON DETECTOR
DETECTOR CART
HYPERON TARGET MAGNET
A1
A2
A3
MAGNET A
20x24x72
B1
B2
TR A
B3
TR B
PB1
MAGNET B
10x24x72
PB 2
LEAD GLASS ARRAYS
DRIFT CHAMBERS
HYPERON CHANNEL
ΔΩ~1 μ SR, ΔP/p ~8%

Figure 5