Hyperon Beta Decay and CKM Unitarity: An Appreciation

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Outline

- **Octet Baryon Beta Decay Generalities**
- **Lambda Beta Decay ($\Lambda \rightarrow pe\overline{\nu}$)**
- **Sigma Beta Decay ($\Sigma^{-} \rightarrow ne\overline{\nu}$)**
- **CKM Unitarity**
- **Concluding Remarks**

UNITARY SYMMETRY AND LEPTONIC DECAYS

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CERN, Geneva, Switzerland
(Received 29 April 1963)

We present here an analysis of leptonic decays based on the unitary symmetry for strong interactions, in the version known as "eightfold way,"[1] and the V-A theory for weak interactions.[2,3] Our basic assumptions on J_μ, the weak current of strong interacting particles, are as follows:

(1) J_μ transforms according to the eightfold representation of SU_3. This means that we neglect currents with $\Delta S = -\Delta Q$, or $\Delta I = 3/2$, which should belong to other representations. This limits the scope of the analysis, and we are not able to treat the complex of K^0 leptonic decays, or $\Sigma^+ \to n + e^+ + \nu$ in which $\Delta S = -\Delta Q$ currents play a role. For the other processes we make the hypothesis that the main contributions come from that part of J_μ which is in the eightfold representation.

(2) The vector part of J_μ is in the same octet as the electromagnetic current. The vector contribution can then be deduced from the electromagnetic properties of strong interacting particles. For $\Delta S = 0$, this assumption is equivalent to vector-

$$\theta = 0.26. \tag{5}$$

The two determinations coincide within experimental errors; in the following we use $\theta = 0.26$.

We go now to the leptonic decays of the baryons, of the type $A \to B + e + \nu$. The matrix element of any member of an octet of currents among two baryon states (also members of octets) can be expressed in terms of two reduced matrix elements[7]

$$\langle A | j_\mu^{(i)} + g_\mu^{(i)} | B \rangle = i f_{ABi} O_\mu + d_{ABi} E_\mu; \tag{6}$$

Table I. Predictions for the leptonic decays of hyperons.

Decay	Branching ratio From reference 2	Branching ratio Present work	Type of interaction
$\Lambda \to p + e^- + \bar{\nu}$	1.4 %	0.75×10^{-3}	$V - 0.72 A$
$\Sigma^- \to n + e^- + \bar{\nu}$	5.1 %	1.9×10^{-3}	$V + 0.65 A$
$\Xi^- \to \Lambda + e^- + \bar{\nu}$	1.4 %	0.35×10^{-3}	$V + 0.02 A$
$\Xi^- \to \Sigma^0 + e^- + \bar{\nu}$	0.14 %	0.07×10^{-3}	$V - 1.25 A$
$\Xi^0 \to \Sigma^+ + e^- + \bar{\nu}$	0.28 %	0.26×10^{-3}	$V - 1.25 A$

$$A \rightarrow B + e^- + \bar{\nu}$$

$$M = \frac{G_\mu}{\sqrt{2}} V_{uj} \langle B | J^\alpha | A \rangle \ell_\alpha$$

$$\langle B | J^\alpha | A \rangle =$$

$$\bar{u}(B) \left[f_1(q^2)\gamma^\alpha + \frac{f_2(q^2)}{M_A} \sigma^{\alpha\nu}\gamma_\nu + \frac{f_3(q^2)}{M_A} q^\alpha + \right.$$

$$\left. \left\{ g_1(q^2)\gamma^\alpha + \frac{g_2(q^2)}{M_A} \sigma^{\alpha\nu}\gamma_\nu + \frac{g_3(q^2)}{M_A} q^\alpha \right\} \gamma_5 \right] u(A)$$

$g_1/f_1 = +1.267$ for $n \longrightarrow p e^- \bar{\nu}$ is a "V - A" Matrix Element.

In V_{uj}, $j = d$ for $\Delta S = 0$ decays, and $j = s$ for $\Delta S = 1$.

$V_{ud} = \cos(\theta_C)$ $\qquad$ $V_{us} \cong \sin(\theta_C)$

For all decays, g_1 is a linear combination of F and D.

Flavor SU(3) Relations for
Beta Decays of Octet Baryons in the Cabibbo Model.

Here $\mu_p = 1.7928$, $\mu_n = -1.9130$, and $g_2 = 0$ for all decays. The SU(6) prediction F/D = 2/3 combined with $g_1/f_1 = 1.267 = F + D$ for neutron beta decay yields D = 0.760 and F = 0.507.

Decay	Scale	$f_1(0)$	$\tilde{f}_2(0)$	$g_1(0)$	f_2/f_1	f_2/f_1	g_1/f_1
$n \to p e^- \bar{\nu}$	V_{ud}	1	$\mu_p - \mu_n$	$D + F$	$\frac{M_n}{M_p}\frac{(\mu_p - \mu_n)}{2}$	1.855	**F + D**
$\Xi^- \to \Xi^0 e^- \bar{\nu}$	V_{ud}	-1	$-(\mu_p + 2\mu_n)$	D - F	$\frac{M_{\Xi^-}}{M_p}\frac{(\mu_p + 2\mu_n)}{2}$	-1.432	F - D
$\Sigma^\pm \to \Lambda e^\pm \nu$	V_{ud}	0*	$-\sqrt{\frac{3}{2}}\mu_n$	$\sqrt{\frac{2}{3}}D$	$-\frac{M_{\Sigma^\pm}}{M_p}\sqrt{\frac{3}{2}}\frac{\mu_n}{2}$	1.490	$\sqrt{\frac{2}{3}}D$
$\Sigma^- \to \Sigma^0 e^- \bar{\nu}$	V_{ud}	$\sqrt{2}$	$\frac{(2\mu_p + \mu_n)}{\sqrt{2}}$	$\sqrt{2}\,F$	$\frac{M_{\Sigma^-}}{M_p}\frac{(2\mu_p + \mu_n)}{4}$	0.534	F
$\Sigma^0 \to \Sigma^+ e^- \bar{\nu}$	V_{ud}	$\sqrt{2}$	$-\frac{(2\mu_p + \mu_n)}{\sqrt{2}}$	$-\sqrt{2}\,F$	$\frac{M_{\Sigma^0}}{M_p}\frac{(2\mu_p + \mu_n)}{4}$	0.531	-F
$\Xi^0 \to \Sigma^+ e^- \bar{\nu}$	V_{us}	1	$\mu_p - \mu_n$	$D + F$	$\frac{M_{\Xi^0}}{M_p}\frac{(\mu_p - \mu_n)}{2}$	2.597	**F + D**
$\Xi^- \to \Sigma^0 e^- \bar{\nu}$	V_{us}	$\frac{1}{\sqrt{2}}$	$\frac{(\mu_p - \mu_n)}{\sqrt{2}}$	$\frac{1}{\sqrt{2}}(D + F)$	$\frac{M_{\Xi^-}}{M_p}\frac{(\mu_p - \mu_n)}{2}$	2.609	F + D
$\Sigma^- \to n e^- \bar{\nu}$	V_{us}	-1	$-(\mu_p + 2\mu_n)$	D - F	$\frac{M_{\Sigma^-}}{M_p}\frac{(\mu_p + 2\mu_n)}{2}$	-1.297	**F - D**
$\Sigma^0 \to p e^- \bar{\nu}$	V_{us}	$-\frac{1}{\sqrt{2}}$	$-\frac{(\mu_p + 2\mu_n)}{\sqrt{2}}$	$\frac{1}{\sqrt{2}}(D - F)$	$\frac{M_{\Sigma^0}}{M_p}\frac{(\mu_p + 2\mu_n)}{2}$	-1.292	F - D
$\Lambda \to p e^- \bar{\nu}$	V_{us}	$-\sqrt{\frac{3}{2}}$	$-\sqrt{\frac{3}{2}}\mu_p$	$-\frac{1}{\sqrt{6}}(D + 3F)$	$\frac{M_\Lambda}{M_p}\frac{\mu_p}{2}$	1.0659	**F + $\frac{D}{3}$**
$\Xi^- \to \Lambda e^- \bar{\nu}$	V_{us}	$\sqrt{\frac{3}{2}}$	$-\sqrt{\frac{3}{2}}(\mu_p + \mu_n)$	$-\frac{1}{\sqrt{6}}(D - 3F)$	$-\frac{M_{\Xi^-}}{M_p}\frac{(\mu_p + \mu_n)}{2}$	0.085	F - $\frac{D}{3}$

*Since $f_1(0) = 0$ for $\Sigma^\pm \to \Lambda e^\pm \nu$, the last three columns for that process contain results for f_2 and g_1 rather than f_2/f_1 and g_1/f_1.

OBSERVABLES

(Allowed Order)

$\alpha_{e\nu}$ or $E_B \rightarrow |g_1/f_1|$

$\alpha_e, \alpha_\nu, \alpha_B$

$S_e, S_\nu, S_B \rightarrow g_1/f_1$

Separate "Internal" and "External" Analysis.

$$\text{Rate} = \frac{\text{B.F.}}{\tau} \sim$$

$$G_\mu^2 |V_{uj}|^2 |f_1|^2 [1 + 3\left(\frac{g_1}{f_1}\right)^2]\rho(1 + \varepsilon_R)$$

In V_{uj}, $j = d$ for $\Delta S = 0$ decays, and $j = s$ for $\Delta S = 1$.

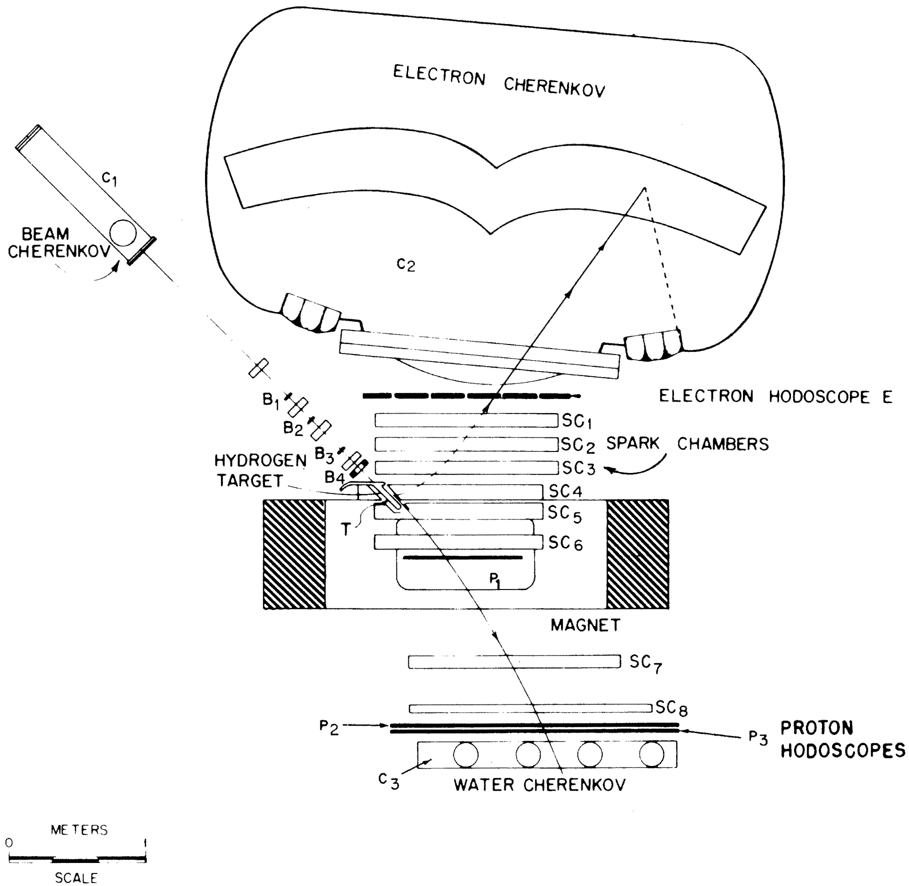
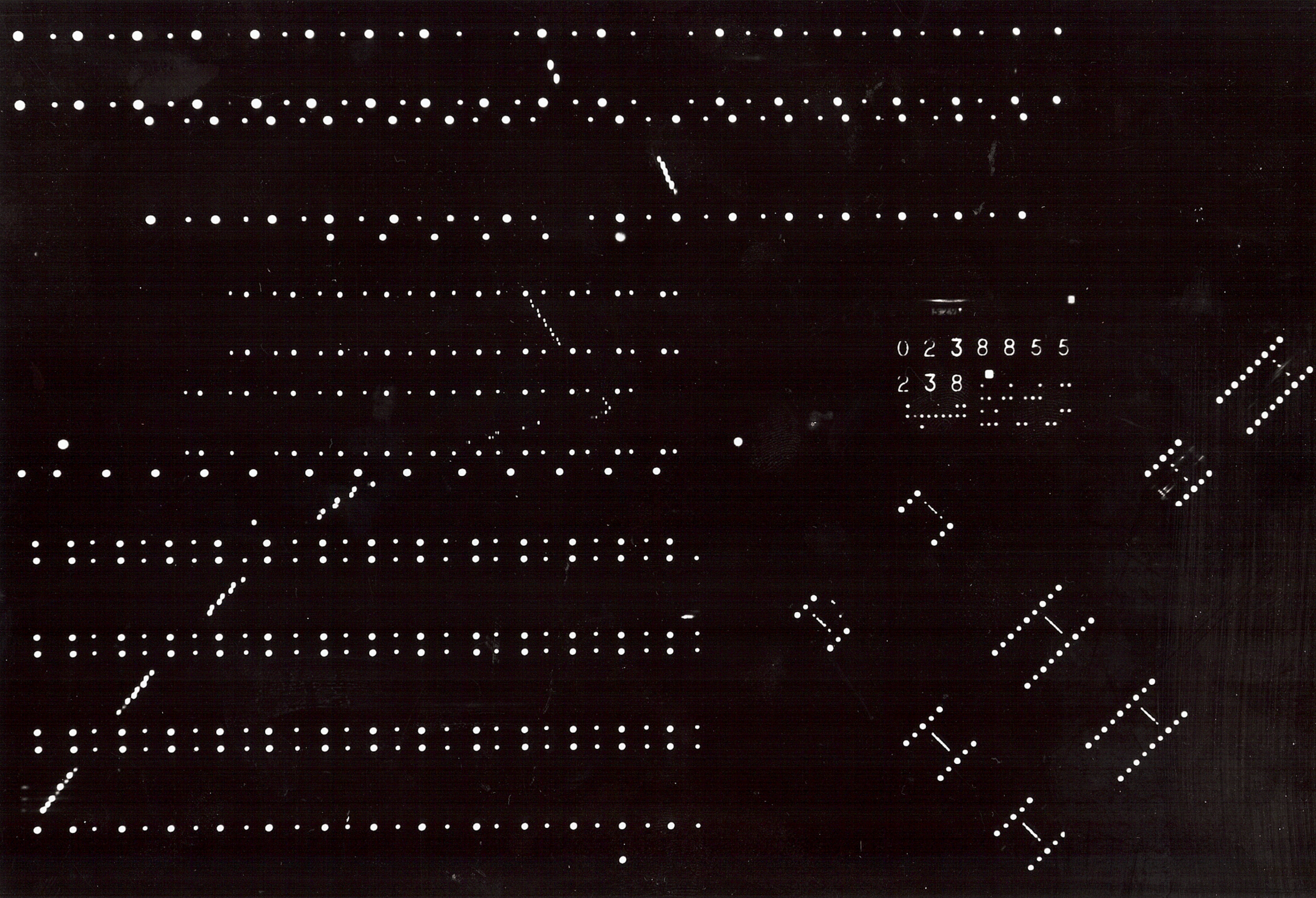


FIG. 2. Plan view of the experimental apparatus.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2 3 8

Measurement of the Up-Down Asymmetries in the β Decay of Polarized Λ Hyperons (Argonne–Chicago–Ohio State–Washington University Collaboration)*

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(Received 24 March 1971)

We report results from a counter and optical spark-chamber–spectrometer experiment on the β decay of polarized Λ hyperons. A sample of 218 decays, constituting approximately one third of the total data, has been identified. The measured up-down asymmetries from a selected subsample of 173 events are $A_\nu = 0.67 \pm 0.18$, $A_e = 0.14 \pm 0.17$, and $A_p = -0.55 \pm 0.18$. When interpreted in the framework of a $V-A$ theory with no second-class currents ($g_2 = 0$), they confirm the sign of the form-factor ratio g_1/f_1 as given by the Cabibbo model, but favor a somewhat smaller magnitude.

We have performed an experiment on the decay $\Lambda^0 \to pe^-\bar{\nu}$ at the Argonne National Laboratory zero-gradient synchrotron using optical spark-chamber and counter techniques. Our objective was to study the form of the weak interaction in this decay by measuring the up-down asymmetries of neutrinos, electrons, and protons with respect to the Λ spin.

Polarized Λ hyperons were produced in the reaction $\pi^- p \to \Lambda^0 K^0$ using (1025 ± 3)-MeV/c π^- (just below ΣK threshold) incident on a liquid-hydrogen target.[1] The e^- and p momenta for each $\Lambda \to pe\nu$ event were measured with a magnetic spectrometer. We determined the plane of production

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Hyperon Production by Neutrinos in an SU_3 Model*

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AND

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(Received 5 November 1964)

An SU_3 model of weak interactions is used to discuss amplitudes and cross sections for hyperon production by neutrinos. Numerical results for the cross sections are given. The notion of first- and second-class currents is extended to currents transforming like multiplets under SU_3.

I. INTRODUCTION

THIS paper presents a study of the production of hyperons by neutrinos through the "elastic" mechanism[1]

$$\bar{\nu}+N \rightarrow B+\bar{l}.$$

Using an SU_3 model of weak interactions due to one of us,[2] we make detailed predictions of cross sections and polarizations for all the possible processes of

Formulas for the differential cross section,[8–10] polarization,[10,11] and total cross section[9] have been given by one of us, among others.

Let us review briefly the relevant facts. The matrix element has the form

$$\langle Bl|T|N\bar{\nu}\rangle=(G/\sqrt{2})\langle B|J_\lambda^\dagger|N\rangle\bar{u}_l\gamma^\lambda(1+i\gamma_5)u_{\bar{\nu}}. \quad (4)$$

The matrix element of J_λ, the weak current of strongly interacting particles, can be expressed in a general form

$$\Sigma^- \rightarrow n e^- \bar{\nu}$$

Nicola Cabibbo Model (1964)

Predicts $\alpha_e = -0.60 \pm 0.04$

"Like the others" $\alpha_e = +0.28 \pm 0.03$

Experiment

1968 $\alpha_e = -0.26 \pm 0.37$

1970 $\alpha_e = +0.36 \pm 0.39$

1972 $\alpha_e = +0.39 \pm 0.53$

COMMENTS

Implications of Recent Data on $\Sigma^- \to ne^- \nu$ for the Cabibbo Model

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(Received 9 June 1975)

A recent measurement of the electron-neutrino angular correlation in $\Sigma^- \to ne\nu$, taken by itself, is shown to be in remarkable agreement with the Cabibbo model. In contrast, the electron-spin asymmetry combines with it to distinctly favor the *wrong sign* for the axial-vector–to–vector form-factor ratio.

A precise measurement of the electron-neutrino angular distribution in the decay $\Sigma^- \to ne\nu$ has recently been reported.[1] The magnitude of the axial-vector–to–vector form-factor ratio was determined to be

ever, when they are combined with the available phase-sensitive measurements, the wrong sign is favored.

First, it is important to recognize that the lev-

$$\Sigma^- \rightarrow n e^- \bar{\nu}$$

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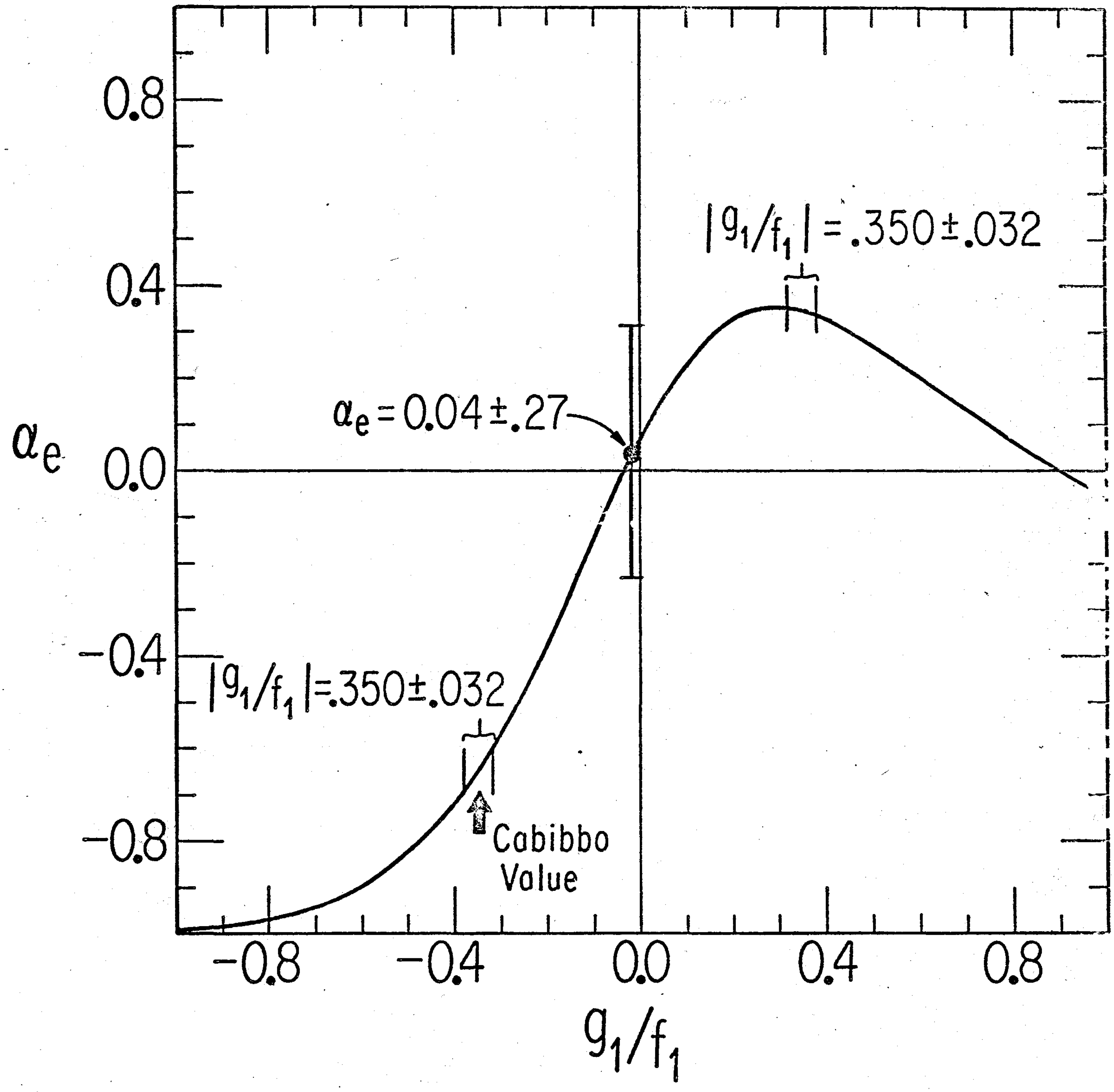


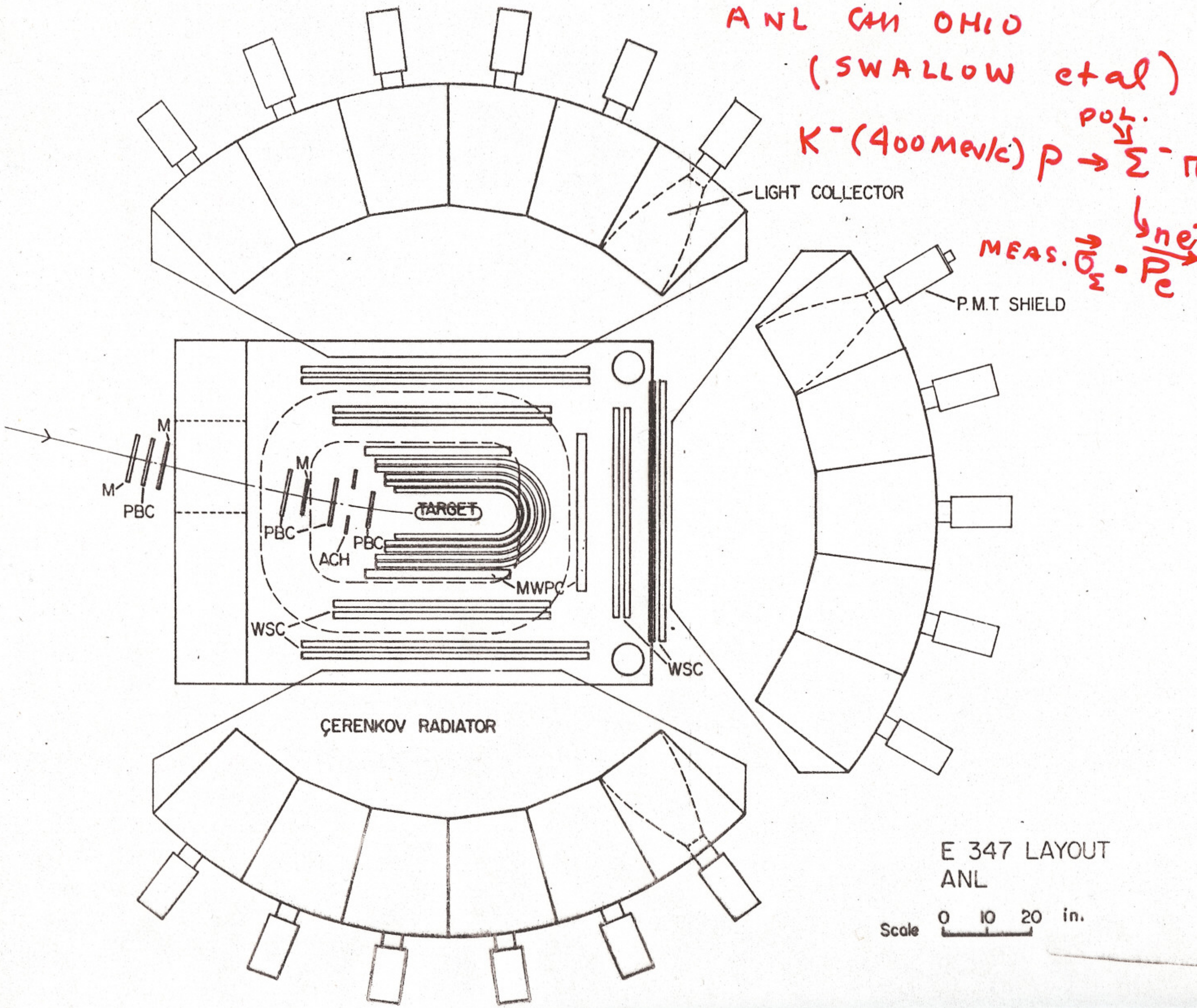
0.8
0.4
0.0
-0.4
-0.8
α_e
$|g_1/f_1| = .350 \pm .032$
$\alpha_e = 0.04 \pm .27$
$|g_1/f_1| = .350 \pm .032$
Cabibbo Value
-0.8
-0.4
0.0
0.4
0.8
g_1/f_1

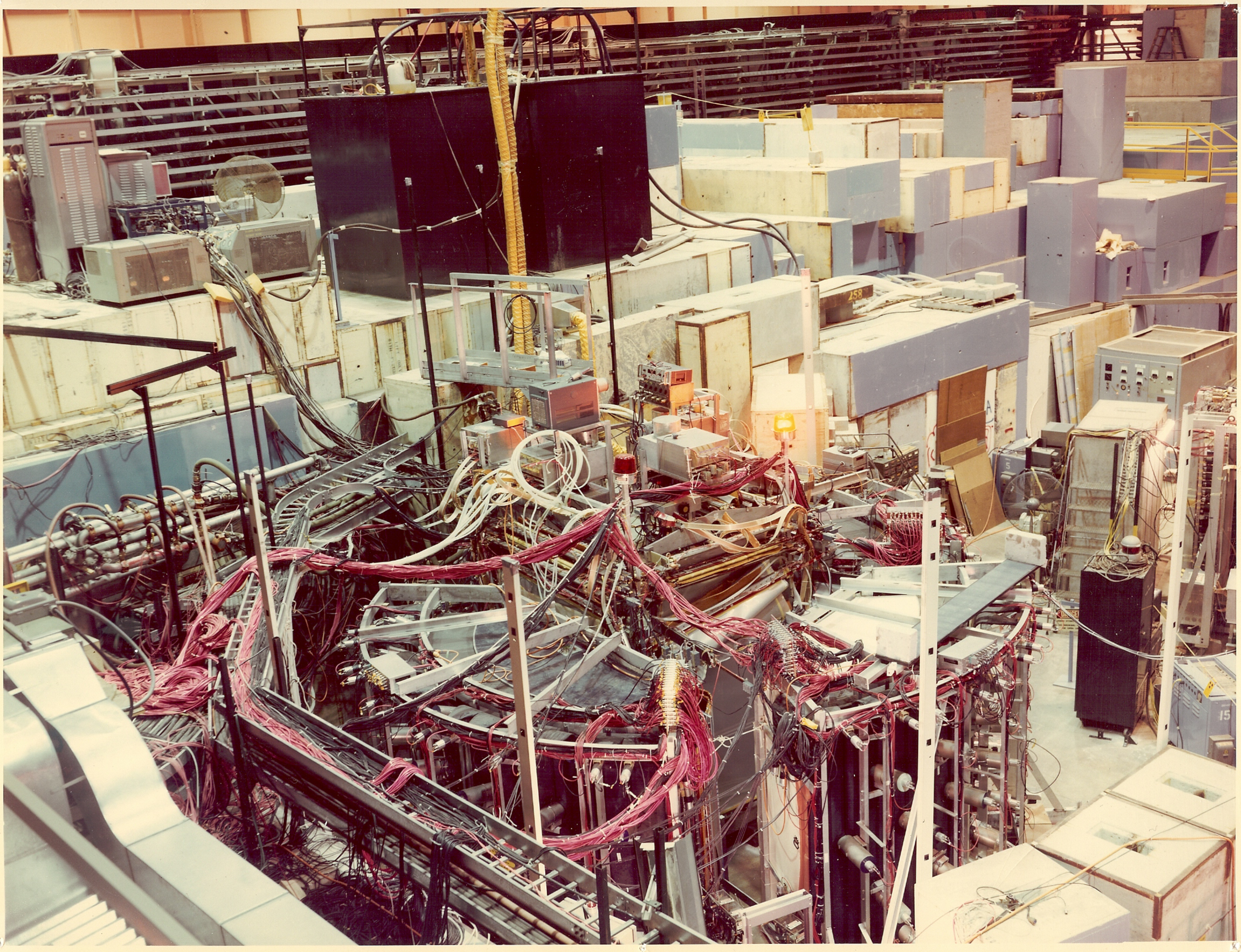
ANL CAN OHIO
(SWALLOW et al)

$K^-(400\,\text{MeV/c})\, p \to \vec{\Sigma}^- \pi^+$ (POL.)

$\hookrightarrow n e^- \bar{\nu}$

MEAS. $\vec{\sigma}_\Sigma \cdot \vec{P}_e$

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15

$\Sigma^- \to n e^- \bar{\nu}$

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1982 $\alpha_e = +0.35 \pm 0.29$

E 715 IS HONORED AND PROUD TO BE

THE FIRST ENERGY SAVER USER

OCTOBER 1, 1983

Peter S Cooper

Joseph Lach

Roland Winston

Ed McCliment

Edward Jastrzembski

John Marriner

Geordie Zapalac

THANK YOU FERMILAB!

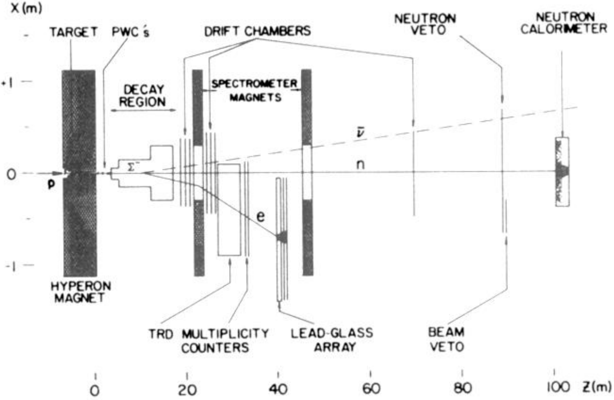

FIG. 1. Plan view of the experimental apparatus.

$$\Sigma^- \rightarrow n e^- \bar{\nu}$$

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Ave. 1975 $\alpha_e = +0.04 \pm 0.27$

1982 $\alpha_e = +0.35 \pm 0.29$

1987 $\alpha_e = -0.52 \pm 0.10$

PHYSICAL REVIEW D VOLUME 38, NUMBER 7 1 OCTOBER 1988

High-precision measurement of polarized-Σ^- beta decay

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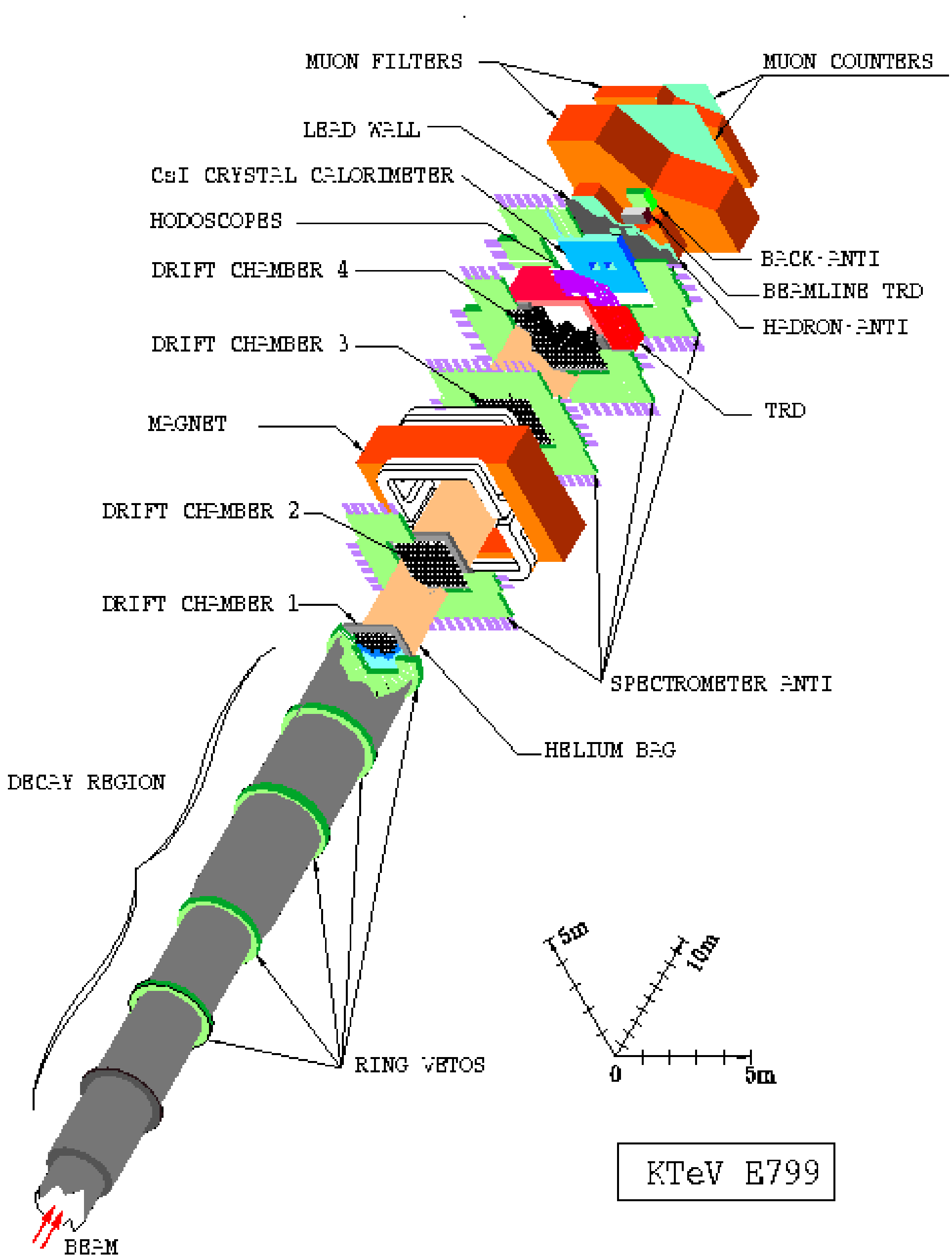
(Received 22 January 1988)

We report the results of a polarized-Σ^- beta-decay experiment carried out in the Fermilab Proton Center charged-hyperon beam. These results are based on 49 671 observed $\Sigma^- \to n e^- \bar{\nu}$ decays. The Σ^- beam had a nominal momentum of 250 GeV/c and was produced by 400-GeV/c protons impinging on a Cu target. At a production angle of 2.5 mrad, the polarization was $(23.6\pm4.3)\%$. The decay asymmetries of the electron ($\alpha_e = -0.519\pm0.104$), neutron ($\alpha_n = +0.509\pm0.102$), and antineutrino ($\alpha_\nu = -0.230\pm0.061$) were measured and used to establish sign and approximate magnitude of the axial-vector-to-vector form-factor ratio g_1/f_1. The form-factor ratios $|g_1/f_1|$ and f_2/f_1 were determined most sensitively from the neutron and electron center-of-mass spectra, respectively. We obtain $|g_1/f_1 - 0.237 g_2/f_1| = 0.327\pm0.007\pm0.019$ and $f_2(0)/f_1(0) = -0.96 \pm0.07\pm0.13$, where the stated errors are statistical and systematic, respectively. A general fit that includes the asymmetries and makes the conventional assumption $g_2 = 0$ gives the final value $g_1(0)/f_1(0) = -0.328\pm0.019$. The data are also compatible with positive values for g_2/f_1 combined with corresponding reduced values for $|g_1/f_1|$.

KTeV Detector, E799 Configuration



Prospect of

$$\Xi^0 \to \Sigma^+ e^- \overline{\nu}$$

in KTeV
and then NA48/1

Request for
Annual Reviews article
from Chris Quig

Hyperon Beta Decay: A Contemporary Review

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BEACH2002 June 29, 2002

Octet Baryon Beta Decay
V_{us} Analysis

Decay	Rate	g_1/f_1	V_{us}
$\Lambda \rightarrow pe^- \overline{\nu}$	3.161(58)	0.718 (15)	0.2224 ± 0.0034
$\Sigma^- \rightarrow ne^- \overline{\nu}$	6.88(24)	-0.340 (17)	0.2282 ± 0.0049
$\Xi^- \rightarrow \Lambda e^- \overline{\nu}$	3.44(19)	0.25(5)	0.2367 ± 0.0099
$\Xi^0 \rightarrow \Sigma^+ e^- \overline{\nu}$	0.876(71)	1.32(+.22/-.18)	0.209 ± 0.027
Combined			0.2250 ± 0.0027

$$\chi^2 = 2.26/3\text{d.f.}$$

CKM Unitarity
Towner & Hardy

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1 - \Delta$$

$$|V_{ud}| = 0.9740(5)$$

$$|V_{us}| = 0.2196(23)$$

$$|V_{ub}| \approx 10^{-5}$$

$$\Delta = 0.0032(14)$$

2.3 s.d.

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SEMILEPTONIC HYPERON DECAYS

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Key Words beta decay, Cabibbo angle, CKM matrix, weak interaction, baryon

PACS Codes 12.15.Hh, 13.30.Ce, 14.20.Jn

■ **Abstract** We review the status of hyperon semileptonic decays. The central issue is the V_{us} element of the CKM matrix, for which we obtain $V_{us} = 0.2250(27)$. This value is similar in precision to the one derived from K_{l3}, but higher, and in better agreement with the unitarity requirement, $|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1$. We find that the Cabibbo model gives an excellent fit to baryon–beta-decay form-factor data ($\chi^2 = 2.96$ for 3 degrees of freedom) with $F + D = 1.2670 \pm 0.0030$, $F - D = -0.341 \pm 0.016$, and no indication of flavor-SU(3)–breaking effects. We indicate the need for more experimental and theoretical work, both on hyperon beta decays and on K_{l3} decays.

Semileptonic Hyperon Decays and Cabibbo-Kobayashi-Maskawa Unitarity

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(Received 11 June 2003; published 23 June 2004)

Using a technique that is not subject to first-order SU(3) symmetry breaking effects, we determine the V_{us} element of the Cabibbo-Kobayashi-Maskawa matrix from data on semileptonic hyperon decays. We obtain $V_{us} = 0.2250(27)$, where the quoted uncertainty is purely experimental. This value is of similar experimental precision to the one derived from K_{l3}, but it is higher and thus in better agreement with the unitarity requirement, $|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1$. An overall fit, including the axial contributions and neglecting SU(3) breaking corrections, yields $F + D = 1.2670 \pm 0.0035$ and $F - D = -0.341 \pm 0.016$ with $\chi^2 = 2.96/3$ degrees of freedom.

DOI: 10.1103/PhysRevLett.92.251803 PACS numbers: 12.15.Hh, 13.30.Ce, 14.20.Jn

The determination of the elements of the Cabibbo-Kobayashi-Maskawa (CKM) matrix [1,2] is one of the main ingredients for evaluating the solidity of the standard model of elementary particles. This is a vast subject which has seen important progress with the determination [3,4] of ϵ'/ϵ and the observation [5,6] of CP violation in B decays.

While a lot of attention has recently been justly devoted to the higher mass sector of the CKM matrix, it is the low mass sector, in particular, V_{ud} and V_{us}, where the highest precision can be attained. The most sensitive test of the unitarity of the CKM matrix is provided by the relation $|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1 - \Delta$. Clearly, the unitarity condition is $\Delta = 0$. The $|V_{ub}|^2$ contribution [7]

decay, and this in turn allows for a redundant determination of V_{us}. The consistency of the values of V_{us} determined from the different decays is a first confirmation of the overall consistency of the model. A more detailed discussion may be found in the Annual Reviews of Nuclear and Particle Sciences [12].

In 1964, Ademollo and Gatto proved [13] that there is no first-order correction to the vector form factor, $\Delta^1 f_1(0) = 0$. This is an important result: since experiments can measure $V_{us} f_1(0)$, knowing the value of $f_1(0)$ in $\Delta S = 1$ decays is essential for determining V_{us}.

The Ademollo-Gatto theorem suggests an analytic approach to the available data that first examines the vector form factor f_1 because it is not subject to first-order SU(3)

A Determination of the Cabibbo-Kobayashi-Maskawa Parameter $|V_{us}|$ Using K_L Decays

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We present a determination of the Cabibbo-Kobayashi-Maskawa parameter $|V_{us}|$ based on new measurements of the six largest K_L branching fractions and semileptonic form factors by the KTeV (E832) experiment at Fermilab. We find $|\mathrm{V_{us}}| = 0.2252 \pm 0.0008_{\mathrm{KTeV}} \pm 0.0021_{\mathrm{ext}}$, where the errors are from KTeV measurements and from external sources. We also use the measured branching fractions to determine the CP violation parameter $|\eta_{+-}| = (2.228 \pm 0.005_{\mathrm{KTeV}} \pm 0.009_{\mathrm{ext}}) \times 10^{-3}$.

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$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1 - \Delta$$

$$|V_{ud}| = 0.97425(22)$$

$$|V_{us}| = 0.2252(9)$$

$$|V_{ub}| \approx 10^{-5}$$

$$\Delta = 0.0001(6)$$


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