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**

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

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

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

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

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

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) S = 0 decays, and j = s for) S = 1.

$V_{ud} = \cos(2_C)$ V_{us} – $\sin(2_C)$

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 μ_p = 1.7928, μ_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)

$"_{e<}$ or E_B 6 $|g_1/f_1|$

$"_{e'}$ $"_{<'}$ $"_{B}$

$S_{e'}, S_{<'}, S_B$ 6 g_1/f_1

Separate “Internal” and “External” Analysis.

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

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

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

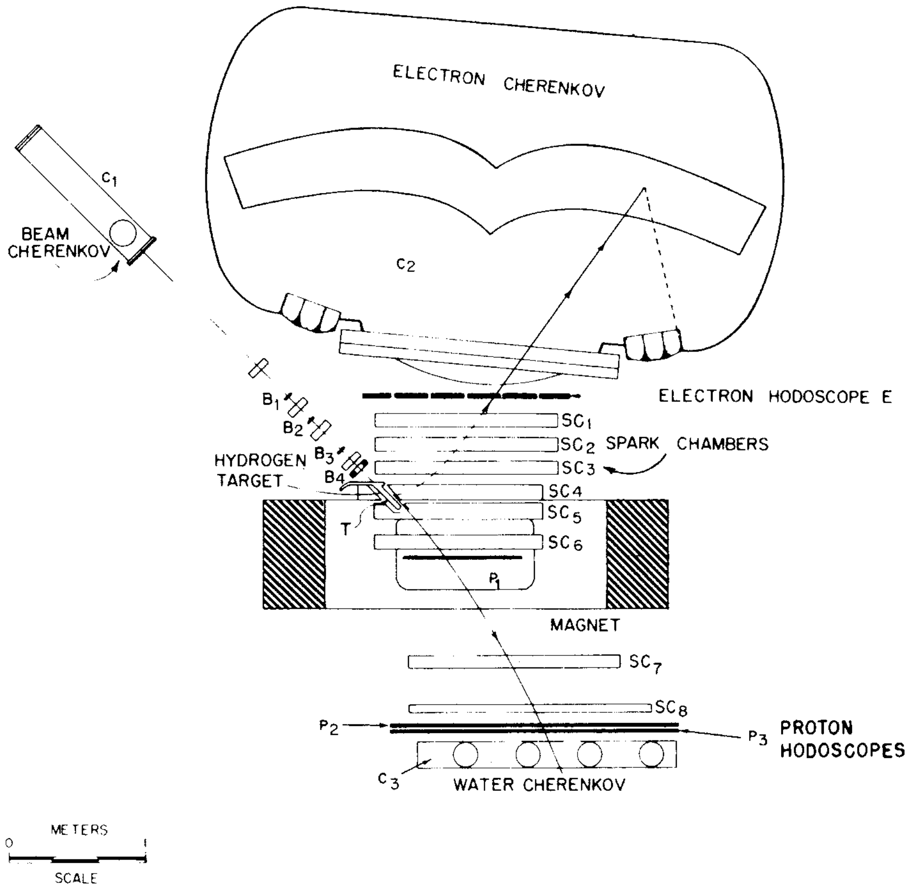
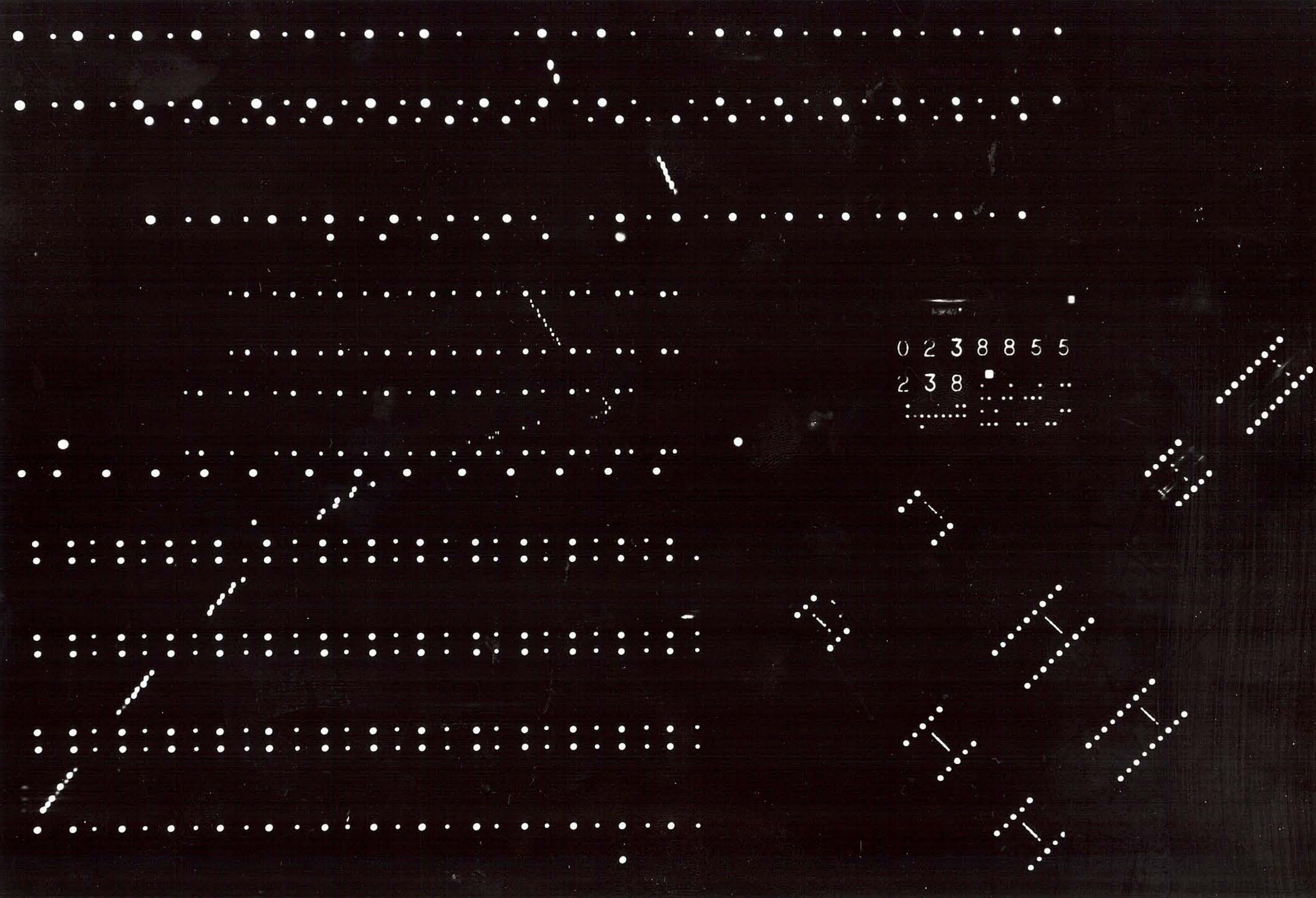


FIG. 2. Plan view of the experimental apparatus.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2 3 8

PHYSICAL REVIEW D VOLUME 3, NUMBER 11 1 JUNE 1971

Analysis of Spin Correlations in the β Decay of the Λ Hyperon*†

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Recent experimental data on the β decay of the Λ are analyzed. Integrated expressions for the measured quantities in terms of form factors are given up to second order in the parameter $\beta=(m_\Lambda-m_p)/m_\Lambda$. The sensitivity of these experimental quantities as functions of specific form factors is studied in detail and exhibited in a form which is useful for the analysis of present experiments and for the planning of future ones. Within the framework of $V-A$ theory, the possibility is explored that the data require the presence of an induced pseudotensor form factor. Qualitative discussions of the q^2 dependence of some form factors and of possible admixtures of scalar and tensor interactions are also given.

I. INTRODUCTION

New experimental evidence on the β decay of the Λ hyperon[1,2] is currently becoming available. In comparison with neutron β decay, Λ β decay

$$\Lambda \to p + e^- + \bar{\nu}$$

differs by the change in strangeness ($\Delta S \neq 0$) and the non-negligible magnitude of the Q value. Because our knowledge of $\Delta S\neq 0$ hyperon semileptonic decays is so limited, the analysis of this evidence is particularly interesting. We want to obtain information that might improve our picture of $\Delta S\neq 0$ decays.

In a previous paper,[3] which we shall refer to as I, a preliminary analysis was given. It was seen there that new complications might arise; in particular, some sum rules were introduced which the experimental data impose on the integrated form factors. In Sec. III, we assume that no second-class currents[4] are present and we make a detailed comparison with the predictions of Cabibbo's model.[5] In Sec. IV, we consider the influence of the q^2 dependence of some form factors. In Sec. V, we give a detailed study of the restrictions that the experimental data impose on second-class currents. In Sec. VI, we show how sensitive our results are to the actual value of the ν asymmetry, which is likely to improve in precision in the near future. Finally, in Sec. VII, we give a qualitative discussion of possible admixtures of scalar or tensor interactions to the $V-A$ theory.

II. EXPRESSIONS FOR THE PARTIAL DECAY RATE, THE e-ν CORRELATION, AND THE ASYMMETRIES

$$R = G^2 \frac{\Delta m^5}{60\pi^3} \left[(1 - \tfrac{3}{2}\beta + \tfrac{6}{7}\beta^2) |f_1|^2 + (\tfrac{4}{7}\beta^2) |f_2|^2 + (3 - \tfrac{9}{2}\beta + \tfrac{12}{7}\beta^2) |g_1|^2 + (\tfrac{12}{7}\beta^2) |g_2|^2 + (\tfrac{6}{7}\beta^2) \mathrm{Re} f_1 f_2^* + (-4\beta + 6\beta^2) \mathrm{Re} g_1 g_2^* \right], \tag{9}$$

$$R \times \alpha_{e\nu} = G^2 \frac{\Delta m^5}{60\pi^3} \left[(1 - \tfrac{5}{2}\beta + \tfrac{11}{7}\beta^2) |f_1|^2 + (-\tfrac{2}{7}\beta^2) |f_2|^2 + (-1 - \tfrac{3}{2}\beta + \tfrac{25}{7}\beta^2) |g_1|^2 + (-2\beta^2) |g_2|^2 + (-\tfrac{2}{7}\beta^2) \mathrm{Re} f_1 f_2^* + (4\beta - 2\beta^2) \mathrm{Re} g_1 g_2^* \right], \tag{10}$$

$$R \times \alpha_{e} = G^2 \frac{\Delta m^5}{60\pi^3} \left[(-\tfrac{1}{3}\beta + \tfrac{3}{14}\beta^2) |f_1|^2 + (-\tfrac{4}{21}\beta^2) |f_2{}^2| + (-2 + \tfrac{8}{3}\beta - \tfrac{9}{14}\beta^2) |g_1|^2 + (-\tfrac{4}{3}\beta^2) |g_2|^2 + (-\tfrac{2}{3}\beta + \tfrac{14}{21}\beta^2) \mathrm{Re} f_1 f_2^* + (2 - \tfrac{11}{3}\beta + \tfrac{15}{7}\beta^2) \mathrm{Re} f_1 g_1^* + (-\tfrac{2}{3}\beta + \tfrac{32}{21}\beta^2) \mathrm{Re} f_1 g_2^* + (-\tfrac{2}{3}\beta + \tfrac{32}{21}\beta^2) \mathrm{Re} f_2 g_1^* + (\tfrac{16}{21}\beta^2) \mathrm{Re} f_2 g_2^* + (\tfrac{10}{3}\beta - \tfrac{94}{21}\beta^2) \mathrm{Re} g_1 g_2^* \right], \tag{11}$$

$$R \times \alpha_{\nu} = G^2 \frac{\Delta m^5}{60\pi^3} \left[(\tfrac{1}{3}\beta - \tfrac{3}{14}\beta^2) |f_1|^2 + (\tfrac{4}{21}\beta^2) |f_2{}^2| + (2 - \tfrac{8}{3}\beta + \tfrac{9}{14}\beta^2) |g_1|^2 + (\tfrac{4}{3}\beta^2) |g_2|^2 + (\tfrac{2}{3}\beta - \tfrac{14}{21}\beta^2) \mathrm{Re} f_1 f_2^* + (2 - \tfrac{11}{3}\beta + \tfrac{15}{7}\beta^2) \mathrm{Re} f_1 g_1^* + (-\tfrac{2}{3}\beta + \tfrac{32}{21}\beta^2) \mathrm{Re} f_1 g_2^* + (-\tfrac{2}{3}\beta + \tfrac{32}{21}\beta^2) \mathrm{Re} f_2 g_1^* + (\tfrac{16}{21}\beta^2) \mathrm{Re} f_2 g_2^* + (-\tfrac{10}{3}\beta + \tfrac{94}{21}\beta^2) \mathrm{Re} g_1 g_2^* \right] \tag{12}$$

$$R \times \alpha_{p} = G^2 \frac{\Delta m^5}{60\pi^3} \, \tfrac{5}{2} \left[(-1 + \tfrac{11}{6}\beta - \beta^2) \mathrm{Re} f_1 g_1^* + (\tfrac{1}{3}\beta - \tfrac{5}{6}\beta^2) \mathrm{Re} f_1 g_2^* + (\tfrac{2}{3}\beta - \tfrac{7}{6}\beta^2) \mathrm{Re} f_2 g_1^* + (-\tfrac{2}{3}\beta^2) \mathrm{Re} f_2 g_2^* \right], \tag{13}$$

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Tom Romanowski

Alan Stevens

$$\Sigma^- \rightarrow \mathbf{ne}^- \overline{\nu}$$

Nicola Cabibbo Model (1964)

Predicts "$_e$ = ! 0.60 ± 0.04

“Like the others” "$_e$ = +0.28 ± 0.03

Experiment

1968 "$_e$ = ! 0.26 ± 0.37

1970 "$_e$ = +0.36 ± 0.39

1972 "$_e$ = +0.39 ± 0.53

Ave. 1975 "$_e$ = +0.04 ± 0.27

COMMENTS

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

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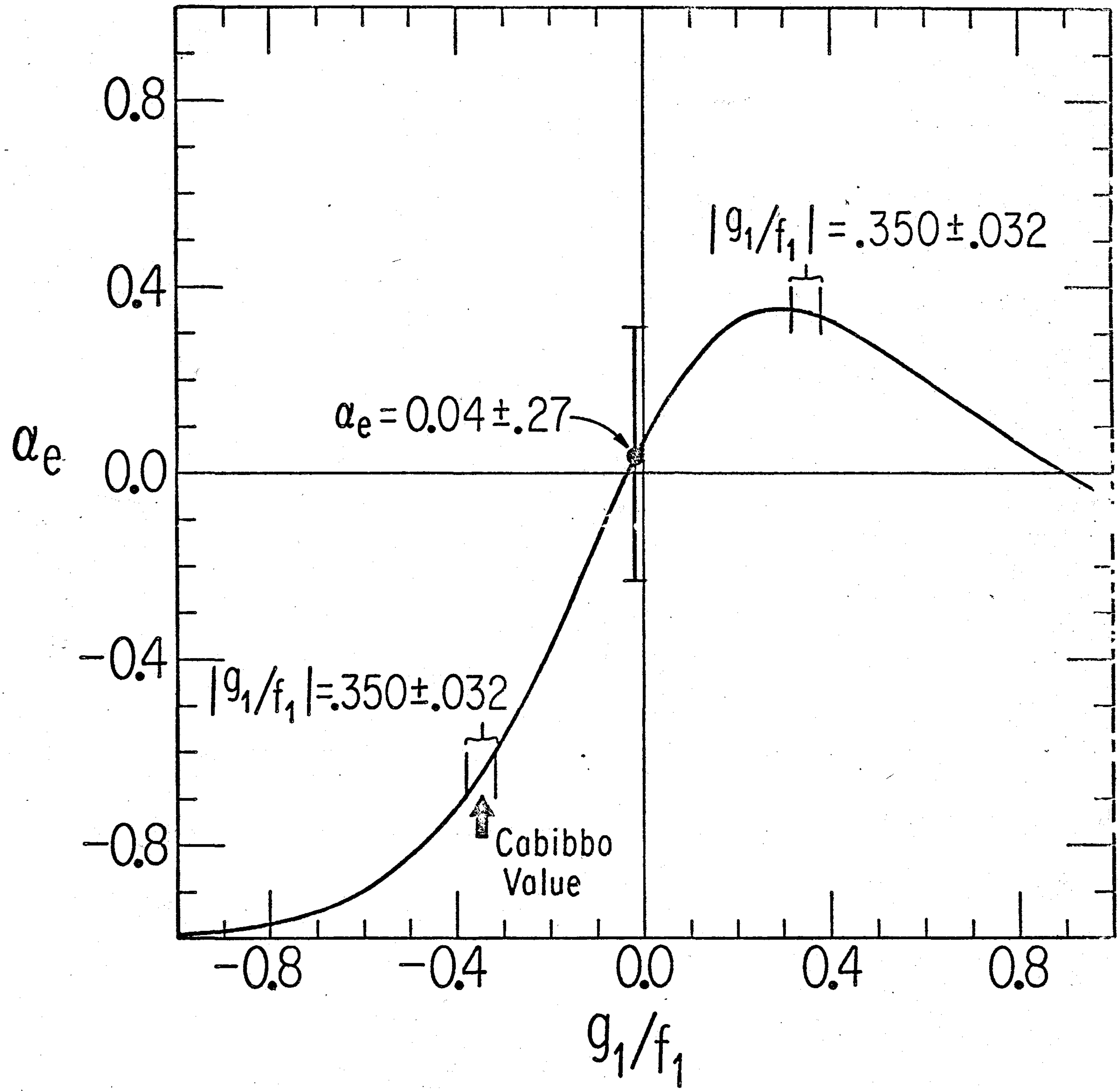
A recent measurement of the electron-neutrino angular correlation in $\Sigma^- \rightarrow ne\nu$, taken by itself, is shown to be in remarkable agreement with the Cabibbo model. In contrast, the electron-spin asymmetry combines with it to distinctly favor the *wrong sign* for the axial-vector–to–vector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

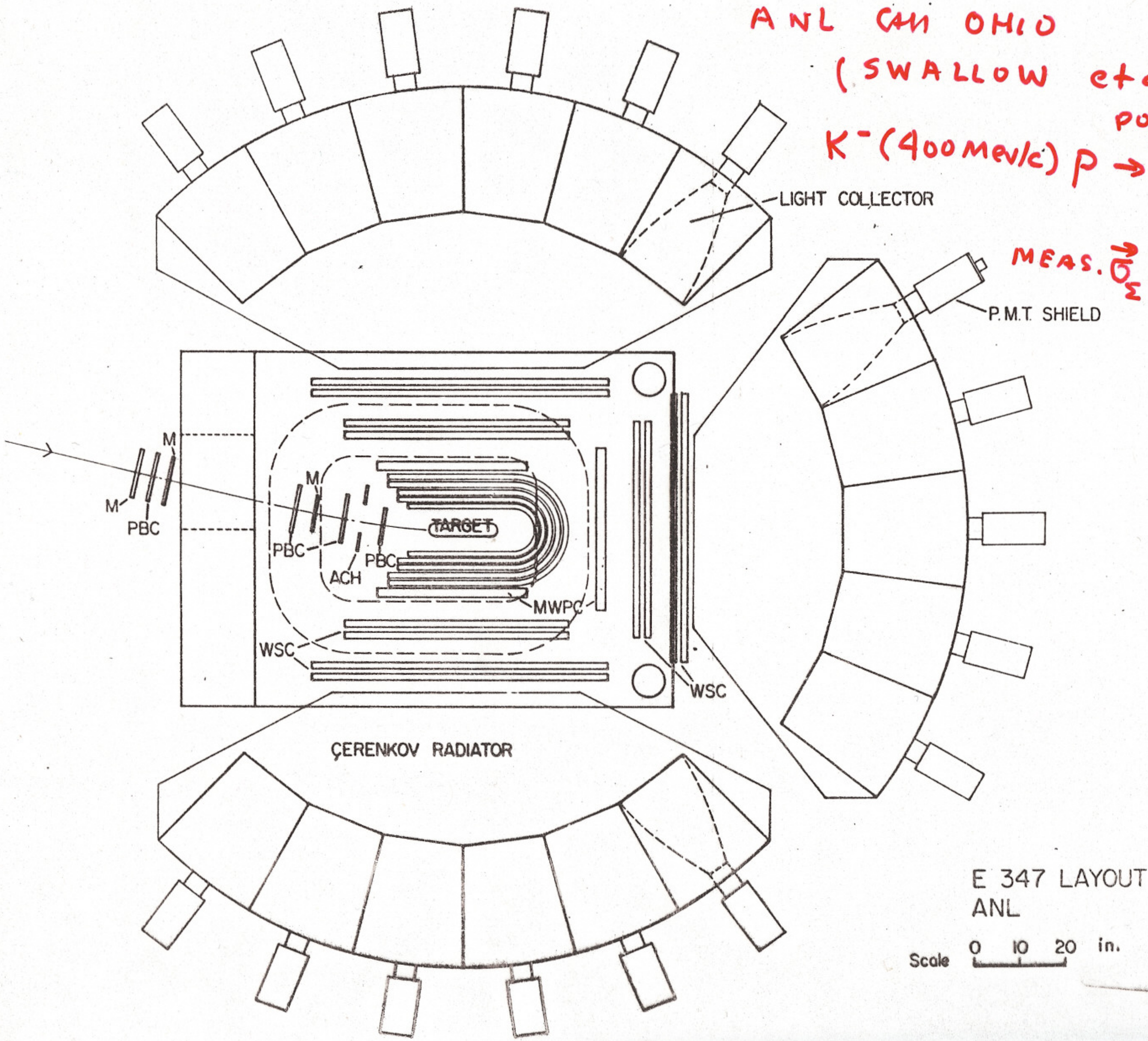
A precise measurement of the electron-neutrino angular distribution in the decay $\Sigma^- \rightarrow ne\nu$ has recently been reported.[1] The magnitude of the axial-vector–to–vector form-factor ratio was

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-



0.8
0.4
0.0
-0.4
-0.8
αe
|g1/f1| = .350 ± .032
αe = 0.04 ± .27
|g1/f1| = .350 ± .032
Cabibbo
Value
-0.8
-0.4
0.0
0.4
0.8
g1/f1



ANL CAN OHIO

(SWALLOW et al)

$K^-(400\ \mathrm{MeV/c})\ p \rightarrow \overset{\text{POL.}}{\Sigma^-}\ \pi^+$

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

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

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

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1972 "$_e$ = +0.39 ± 0.53

Ave. 1975 "$_e$ = +0.04 ± 0.27

1982 "$_e$ = +0.35 ± 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!

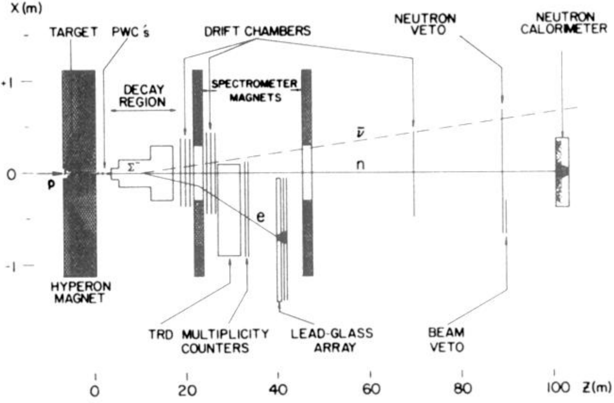

FIG. 1. Plan view of the experimental apparatus.

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

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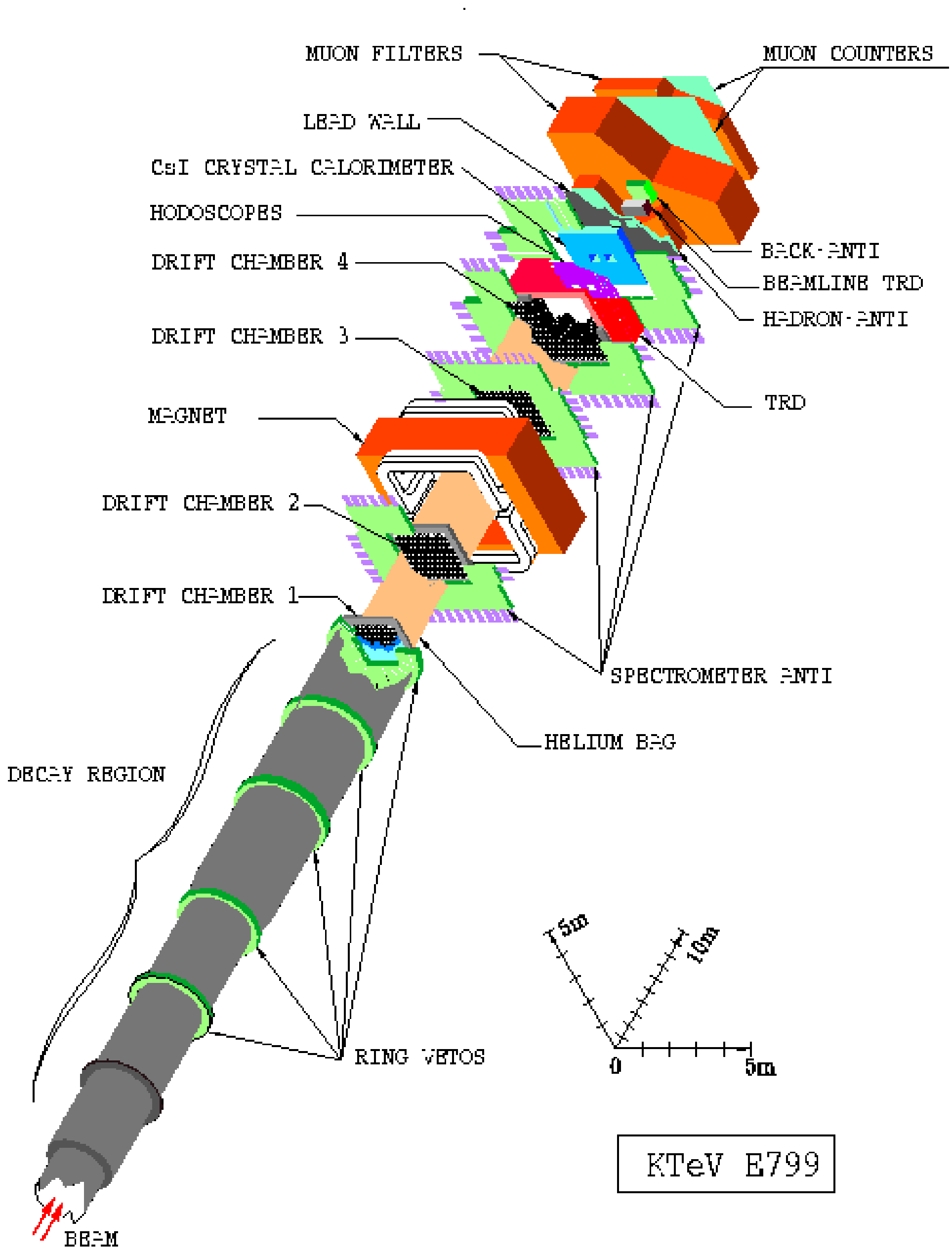
We report the results of a polarized-Σ^- beta-decay experiment carried out in the Fermilab Proton Center charged-hyperon beam. These results are based on 49 671 observed $\Sigma^- \to ne^-\bar{\nu}$ decays. The Σ^- beam had a nominal momentum of 250 GeV/c and was produced by 400-GeV/c protons impinging 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 $|g_1/f_1-0.237g_2/f_1|=0.327\pm0.007\pm0.019$ 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



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}
$\Lambda \rightarrow p e^- \overline{\nu}$	3.161(58)	0.718 (15)	0.2224 ± 0.0034
$\Sigma^- \rightarrow n e^- \overline{\nu}$	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

$P^2 = 2.26/3$d.f.

$V_{us}(K_{R3}) = V_{us}(B_{R3})$?

$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1$?

Note: $|V_{ub}|^2$ - 10^{-5}

Source	Measured V_{us}	Unitarity $V^U_{ud} = (1 - \|V_{us}\|^2)^{1/2}$
K_{e3}	0.2196(23)	0.9756(5)
Hyperon $	0.2250(27)	0.9744(7)
		Measured V_{ud}
Nuclear ft Values	—	0.9740(5)
Neutron Decay Ave.	—	0.9728(12)
PERKEO II Neutron Decay	—	0.9713(13)

Semileptonic Hyperon Decays and Cabibbo-Kobayashi-Maskawa Unitarity

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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)

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Value of the Kobayashi-Maskawa-Cabibbo matrix element V_{us} and flavor-symmetry breaking in hyperon semileptonic decays

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(Received 25 April 1991)

We perform a detailed model-independent analysis of the determination of V_{us} in the $\Delta S=1$ decays $\Lambda \to pe\nu$, $\Sigma^- \to ne\nu$, and $\Xi^- \to \Lambda e\nu$. Values systematically higher than the K_{e3} one are obtained. A reconciliation may be only obtained through second-order changes of a few percent in the leading vector form factors f_1, provided that these changes always increase their magnitudes over their conserved vector current (CVC) predictions. Using the CVC or the recoil part of recent flavor-symmetry-breaking calculations, the value $V_{us}=0.2258\pm0.0027$ is obtained, which is higher than the K_{e3} one by 2.6 standard deviations.

PACS number(s): 13.30.Ce, 12.15.Ff

I. INTRODUCTION

The precise determination of the Kobayashi-Maskawa-Cabibbo matrix [1] element V_{us} is very useful not only in testing the unitarity of this matrix but also in helping to establish the importance of flavor SU(3) symmetry breaking (SB) effects in other decays where it appears. At present V_{us} can be meaningfully obtained from only four semileptonic decays, namely, $K \to \pi l \nu$, $\Lambda \to pe\nu$, $\Sigma^- \to ne\nu$, and $\Xi^- \to \Lambda e\nu$.

Its value from K_{e3} has been already discussed in great detail. The original value of [2]

$$V_{us}=0.2196\pm0.0023 \quad (1)$$

and g_1/f_1 ratios, but we shall in addition and alternatively use the available data on angular correlation and angular spin-asymmetry coefficients along with the decay rates. This latter set of data is richer than the former. Also in contrast with both these references, we shall not perform global fits to all $\Delta S=0$ and $\Delta S=1$ baryon decays, but we shall study individually each of the three relevant $\Delta S=1$ decays. The reason for this is that the appreciably higher χ^2 of a global fit may easily mask deviations of the value of V_{us} from Eqs. (1) and (2), which may be more clearly seen in the lower χ^2 of each individual decay.

Because of its model independence our analysis may provide useful guidance for model calculations of flavor

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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LOVE IS A LABYRINTH FULL OF GLITTERING MIRRORS