number of intermediate N^* which contribute to the sum over i increases with P and is largest for small A. For reference, we show $m_{\max}^*$ for $P=100$ GeV/c for various nuclei in Fig. 1(d). We note that for sizeable reductions in the cross section, large numbers of coherent intermediate states are necessary.

It should be noted that the reductions which we have calculated depend very critically on the assumption which has been implicit in our development that the phases of the inelastic amplitudes g_i are all roughly the same, and that all g_i are nearly pure imaginary. If the phases were not roughly equal, then the effects of the intermediate N^* would tend to cancel out among themselves, and little or no reduction would occur. On the basis of the quark model, however,[6,12] one expects that the phases of all of the g_i should approach zero at high energies (more exactly, that they should be proportional to the phase of the p-p amplitude, which approaches zero), so that this assumption is probably not going to lead us into difficulties.

One can imagine many uses for this technique. One could look at the high-mass spectrum of the pion and the kaon, or one could compare p and $\bar{p}$ total cross sections to test particle-antiparticle universality. In addition, by measuring the photon-nucleus total cross section, one could look for evidence of heavy vector mesons.

In closing, one word of caution is in order. We have explicitly looked only at lowest-order terms in G^2. If the effect of these terms is appreciable, it will be necessary to consider G^3 diagrams, like the one in Fig. 1(c), which tend to lessen the decrease in σ_{pA} which we have predicted. However, since in most cases the contributions of order G^2 seem to be $\lesssim 20\%$, the inclusion of G^3 terms probably is not necessary.

Thus we see that measurement of the total particle-nucleus cross sections as a function of energy allows one to determine the general behavior of coupling strengths as a function of resonance mass, and also to make some statements about the occurrence of resonances at very high mass without actually having to produce the resonances separately.

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Beta Decay of Hyperons*

Reinhard Oehme, Roland Winston, and Augusto Garcia
The Enrico Fermi Institute, and The Department of Physics, The University of Chicago, Chicago, Illinois 60637
(Received 23 December 1970)

The formulas for spin and angular correlations in hyperon β decay are brought into forms which can give specific information about the character of possible deviations from the universal $SU(3)$ scheme. The recent experimental results for Λ-particle β decay are discussed qualitatively in terms of the proposed combinations of integrated correlation coefficients.

I. INTRODUCTION

A CONCISE description of semileptonic weak interactions has been given on the basis of the following assumptions[1,2]: (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. In particular, the measured rates and the lepton-neutrino angular correlations of $\Delta S=1$ transitions appear to fit rather well into such a framework. However, more recently, preliminary data on spin correlations for $\Lambda \to p+e^-+\bar{\nu}$ decays have become available[3,4]; these data can give a new and sensitive test of the assumptions (1)–(3). It is therefore of interest to have some means of analytically exploring the qualitative features of specific proposals for corrections to the $SU(3)$ scheme and for possible CP-violating terms.

In this paper, we suggest particular combinations of *presently observed*, integrated correlation coefficients. These combinations are constructed in order to exhibit a dominant dependence upon specific form factors. The functions Σ and Ω are sensitive to the induced tensor (f_2) and/or pseudotensor (g_2) form factors; they are independent of vector–axial-vector interference terms ($\mathrm{Re} f_1 g_1^*$), and they vanish in the allowed approxima-

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tion. By contrast, the function Π is constructed so that it is dominated by the f_1g_1 interference term in the allowed approximation.

As an application of the combinations Σ, Π, and Ω, we give a brief, qualitative analysis of the presently available data for Λ β decay. We restrict ourselves to $V-A$ current-current interactions. The effects of additional scalar and tensor interactions will be discussed elsewhere by one of us (A.G.).[4a]

II. INTEGRATED CORRELATION COEFFICIENTS

We write the semileptonic interactions in the form

$$(G/\sqrt{2})J_\alpha l_\alpha^\dagger+\text{H.c.}, \tag{1}$$

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

$$M=\langle p|V_\alpha+A_\alpha|\Lambda\rangle i\bar{e}\gamma_\alpha(1+\gamma_5)\nu_e \tag{2}$$

are defined by

$$\begin{aligned}\langle p|V_\alpha|\Lambda\rangle&=\bar{u}_p(\gamma_\alpha f_1+\sigma_{\alpha\beta}q_\beta f_2/m_\Lambda)u_\Lambda,\\ \langle p|A_\alpha|\Lambda\rangle&=\bar{u}_p(\gamma_\alpha\gamma_5 g_1+\sigma_{\alpha\beta}q_\beta\gamma_5 g_2/m_\Lambda)u_\Lambda,\end{aligned} \tag{3}$$

where $q=p_\Lambda-p=p_e+p_\nu$. 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

$$d\omega=\frac{G^2}{(2\pi)^5}\frac{p_e^2(p_{e\max}-p_e)^2}{[1+(p_e/m_\Lambda)(\hat{e}\cdot\hat{\nu}-1)]^3}\frac{m_p}{m_\Lambda}\times|M|^2d\Omega_e d\Omega_\nu dp_e, \tag{4}$$

and we can write $|M|^2$ in the general form

$$\begin{aligned}\xi\{1+a(\hat{e}\cdot\hat{\nu})+A\boldsymbol{\sigma}_\Lambda\cdot\hat{e}+B\boldsymbol{\sigma}_\Lambda\cdot\hat{\nu}+L\boldsymbol{\sigma}_\Lambda\cdot\hat{e}\times\hat{\nu}\\ +A'\boldsymbol{\sigma}_\Lambda\cdot\hat{e}(\hat{e}\cdot\hat{\nu})+B'\boldsymbol{\sigma}_\Lambda\cdot\hat{\nu}(\hat{e}\cdot\hat{\nu})\\ +D'\boldsymbol{\sigma}_\Lambda\cdot(\hat{e}\times\hat{\nu})(\hat{e}\cdot\hat{\nu})\},\end{aligned} \tag{5}$$

where $\hat{e}$ and $\hat{\nu}$ are unit vectors in the directions $\mathbf{p}_e$ and $\mathbf{p}_\nu$, and $\boldsymbol{\sigma}_\Lambda$ 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.[5] The primed terms in Eq. (5) are absent in the allowed approximation.

In view of limited experimental information which is now becoming available, we are mainly interested in correlations integrated over p_e and averaged over the appropriate angle. We evaluate these quantities as expansions in $\Delta m/m=(m_\Lambda-m_p)/m_\Lambda\simeq0.16$, and we reproduce in the following only terms of zeroeth and first order; an exception is made for some special second-order contributions to be mentioned later.

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In terms of the coefficients appearing in Eq. (5), the actually measured quantities presently available are the following: the $\hat{e}\cdot\hat{\nu}$ correlation

$$A_{e\nu}=\left(\bar{a}-\frac{3}{2}\frac{\Delta m}{m}\right)\left(1-\frac{\Delta m}{2m}\bar{a}\right)^{-1}, \tag{6}$$

the $\boldsymbol{\sigma}_\Lambda\cdot\hat{e}$ correlation

$$A_e=\left(\bar{A}+\frac{1}{3}\bar{B}'-\frac{\Delta m}{2m}\bar{B}\right)\left(1-\frac{\Delta m}{2m}\bar{a}\right)^{-1}, \tag{7}$$

the $\boldsymbol{\sigma}_\Lambda\cdot\hat{\nu}$ correlation

$$A_\nu=\left(\bar{B}+\frac{1}{3}\bar{A}'-\frac{\Delta m}{2m}\bar{A}\right)\left(1-\frac{\Delta m}{2m}\bar{a}\right)^{-1}, \tag{8}$$

and the rate, which is proportional to

$$\langle\xi\rangle\left(1-\frac{\Delta m}{2m}\bar{a}\right). \tag{9}$$

In addition there is the proton asymmetry or $\boldsymbol{\sigma}_\Lambda\cdot\hat{p}$ correlation A_p, which will be considered later.

In Eqs. (6–9), the bar indicates the average over the spectrum and also over the angle. We have, for example,

$$\bar{A}=\langle\xi A\rangle/\langle\xi\rangle,$$

where we use the notation

$$\langle F\rangle=\int_0^{p_{e\max}}dp_e p_e^2(p_{e\max}-p_e)^2\times\frac{1}{2}\int_{-1}^{+1}d\cos\theta\, F(p_e,\cos^2\theta)\times30p_{e\max}^{-5}.$$

The measured correlations determine three independent combinations of the coefficients appearing in Eq. (5). For the purpose of our discussion, we find it convenient to introduce the expressions

$$(\bar{B}+\tfrac{1}{3}\bar{A}')-(\bar{A}+\tfrac{1}{3}\bar{B}')=\left[1-\frac{\Delta m}{2m}(1+\bar{a})\right](A_\nu-A_e), \tag{10}$$

$$(\bar{B}+\tfrac{1}{3}\bar{A}')+(\bar{A}+\tfrac{1}{3}\bar{B}')=\left[1+\frac{\Delta m}{2m}(1-\bar{a})\right](A_\nu+A_e), \tag{11}$$

and

$$(1-\bar{a})/(1+\bar{a}). \tag{12}$$

In writing Eqs. (10) and (11), we have made use of the fact that the coefficients $\bar{A}'$ and $\bar{B}'$ are of first order in $\Delta m/m$.

III. FUNCTIONS Σ, Π, AND Ω

We now construct a very specific combination of correlation coefficients which is of particular interest for the interpretation of experiments. We consider the ratio

$$\Sigma=\frac{(\bar{B}+\frac{1}{3}\bar{A}')-(\bar{A}+\frac{1}{3}\bar{B}')-(1-\bar{a})}{1+\bar{a}}, \tag{13}$$

where

$$\langle\xi\rangle(1+\bar{a})\Sigma = (\Delta m/m)\times\tfrac{2}{3}[|f_1|^2+|g_1|^2+2\,\mathrm{Re}(f_1f_2^*) +2\,\mathrm{Re}(g_1g_2^*)]+[-(\Delta m/m)^2(2/21) \times(5|f_2|^2+11|g_2|^2)]+O((\Delta m/m)^2), \quad (14)$$

and

$$\langle\xi\rangle(1+\bar{a})=2(|f_1|^2+|g_1|^2)(1+\Delta m/m) +[(\Delta m/m)^2\times(2/7)(|f_2|^2-|g_2|^2)] +O((\Delta m/m)^2). \quad (15)$$

As mentioned before, we have included only those second-order terms which depend solely upon f_2 and g_2. We ignore the q^2 dependence of form factors as a small, second-order correction. We also omit radiative corrections, which may be permissible for our qualitative considerations.

The combination Σ is constructed so as to vanish in the allowed approximation. Hence Σ is zero within errors for neutron β decay.[6] For the Λ-particle β decay, we may use the assumptions (1)–(3) of Cabibbo,[1] which yield[7]

$$g_1\approx 0.72f_1,\quad f_2=\tfrac{1}{2}\mu_p f_1,\quad g_2=0, \quad (16)$$

and hence

$$\Sigma\approx 0.10.$$

Besides being first forbidden, the combination Σ has the important property that it does not contain any interference term between f_1 and g_1.

For our later discussions, we also need the other independent combinations of correlation coefficients: Let us take expressions (12) and (13) and

$$\Pi=\frac{(\bar{B}+\frac{1}{3}\bar{A}')+(\bar{A}+\frac{1}{3}\bar{B}')}{1+\bar{a}}, \quad (17)$$

where

$$\langle\xi\rangle(1-\bar{a})=4|g_1|^2-(\Delta m/m)\times 8\,\mathrm{Re}(g_1g_2^*) +[(\Delta m/m)^2\times(2/7)(3|f_2|^2+13|g_2|^2)] +O((\Delta m/m)^2) \quad (18)$$

and

$$\langle\xi\rangle(1+\bar{a})\Pi=4\,\mathrm{Re}(f_1g_1^*) +\Delta m/m\times\tfrac{4}{3}\,\mathrm{Re}(2f_1g_1^*-g_1f_2^*-f_1g_2^*) +[(\Delta m/m)^2\times(32/21)\,\mathrm{Re}(f_2g_2^*)] +O((\Delta m/m)^2). \quad (19)$$

We note that, in contrast to Σ, the combination Π is dependent only upon interference terms; in particular, the main term is proportional to f_1g_1. With the Cabibbo values (16), we obtain $\Pi\approx 0.86$.

It is of interest to construct a third function Ω with the help of the integrated proton asymmetry A_p, which has also been measured. We consider the expression

$$T=\frac{A_p}{1+\bar{a}}\left[1+\frac{\Delta m}{2m}(1-\bar{a})\right] \quad (20)$$

and combine it with the function Π which has been defined in Eq. (17). In particular, we introduce the function

$$\Omega=\Pi+(8/5)T, \quad (21)$$

which is given in terms of the form factors by

$$\langle\xi\rangle(1+\bar{a})\Omega=-\frac{4}{3}\frac{\Delta m}{m}\,\mathrm{Re}(g_1f_2^*) +\left[-\frac{8}{7}\left(\frac{\Delta m}{m}\right)^2\mathrm{Re}(g_2f_2^*)\right]+O((\Delta m/m)^2), \quad (22)$$

where again only second-forbidden terms depending solely upon f_2 and/or g_2 have been included. Similar to Σ, the function Ω also vanishes in the allowed approximation. It is dominantly dependent upon the induced tensor form factor f_2, and in the Cabibbo scheme it has the value $\Omega\approx 0.04$.

IV. APPLICATIONS TO Λ β DECAY

We now use the functions Σ, Π, and Ω in order to discuss the presently available data for Λ β decay in a qualitative fashion. The measured correlations may be summarized as follows:

$$A_{e\nu}=-0.01\pm0.07 \quad \text{(Refs. 8–12)},$$
$$A_e=0.13\pm0.07 \quad \text{(Refs. 3, 4, 10, 13)},$$
$$A_\nu=0.70\pm0.15 \quad \text{(Refs. 3, 10)},$$
$$A_p=-0.53\pm0.08 \quad \text{(Refs. 3, 4)}.$$

From these numbers we obtain

$$\Sigma=-0.21\pm0.14,\qquad \Pi=0.72\pm0.15,$$
$$\Omega=0.00\pm0.18,\qquad (1-\bar{a})/(1+\bar{a})=0.63\pm0.09;$$

the universal $SU(3)$ scheme gives approximately

$$\Sigma=0.10,\qquad \Pi=0.86,$$
$$\Omega=0.04,\quad (1-\bar{a})/(1+\bar{a})=0.59.$$

Let us first consider only the combination Σ, for which

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the experiments indicate a negative value. If we accept this result, then we see from Eq. (14) that

(1) a simple adjustment of the g_1/f_1 ratio, or the introduction of a time-reversal-invariance-violating phase[14] between g_1 and f_1, would generally not lead to a negative value for Σ;

(2) what would apparently be required are rather large values of $|f_2|$ and/or $|g_2|$. In particular, these form factors should have negative signs relative to f_1, g_1 because the f_2^2 and g_2^2 terms in Σ have very small coefficients.

From Eqs. (15) and (18), we see that the rate and the $e\nu$ angular correlation are relatively insensitive to f_2, and since these quantities agree reasonably well with the Cabibbo scheme, it may be suggestive to leave g_2 small or zero and allow a negative f_1f_2 term in Σ in order to obtain a negative value for this expression. For example, for $\Sigma=-0.2$, we need about $f_2\sim-3.5f_1$; $\Sigma=0$ is obtained for $f_2\sim-0.8f_1$, and $\Sigma=-0.3$ for $f_2\sim-4.5f_1$. However, as seen from Eq. (19), such a choice of f_2 would give a positive contribution to the combination Π in Eq. (17). This may lead to a value for Π which is too large in comparison with experiment. Also for Ω we would obtain a negative number which moves away from the experimental result, although the errors of this function are rather large.

As far as Σ and Π are concerned, a negative value of g_2 relative to g_1 and f_1 has effects rather similar to the corresponding choice of f_2 discussed above, but the g_1g_2 term appears in the expression $(1-\bar{a})(1+\bar{a})^{-1}$ with a relatively large coefficient, and hence a complete reevaluation of the fit for the rates and the $e\nu$ correlation would be required. Calculations of this type have been performed by one of us (A.G.), and they will be reported elsewhere.[4a]

Of interest is also the possibility of a large, time-reversal-invariance-violating second-class contribution.[15] For $\Lambda\,\beta$ decay, this can be realized with a form factor g_2 which has a phase of 90° relative to the first-class terms. Except for the T-violating terms proportional to $\boldsymbol{\sigma}_\Lambda\cdot\hat{e}\times\hat{p}$ in Eq. (5), an imaginary g_2 contribution can have an effect only in the order $(\Delta m/m)^2$. Although a very large $|g_2|^2$ term in Σ could give a negative value, the corresponding contributions to Π and to Eq. (12) may create additional discrepancies unless sizable changes are made in the real form factors.

At present, in view of the uncertainty of the experimental results, we do not want to consider complete solutions of the system of equations (14), (15), (18), (19), and (22). Such solutions should be looked for with relations complete up to second order in $\Delta m/m$, or with the exact formulas. Another source of information is of course the shape of the electron spectrum.

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V. CONCLUSIONS

The qualitative analysis discussed in Sec. IV is meant to give an indication for the possible usefulness of the combinations Σ, Π, and Ω in the analysis of hyperon β-decay experiments. In particular, these expressions are very helpful for the analysis of possible deviations from the $SU(3)$ scheme described in the Introduction.

At present, possible discrepancies between experimental data and the Cabibbo scheme are not yet established experimentally. But our analysis shows that, if the present data are taken seriously, they may require some unexpected symmetry breaking. An example is the introduction of a real negative pseudotensor form factor g_2 and a corresponding rearrangement of the values for the other form factors. Under these circumstances, one may also want to analyze the influence of scalar and tensor interactions, and hence of possible deviations from the $V-A$ theory. Certainly, more accurate data are required in order to draw definite conclusions. We hope that such data are forthcoming with the completion of the present experiments or from future ones.

Independent of the outcome of experiments, the functions Σ, Π, and Ω are of interest as a means for analytically assessing the sensitivity of these experiments as a test for the universal $SU(3)$ scheme, as a guide for models of CP violation, and for other purposes.

If the final analysis of the data should indicate that there are larger deviations from the universal $SU(3)$ scheme, then such a result may also have implications for the understanding of the common suppression factor for $\Delta S=1$ transitions.[16] Using the $SU(3)$ properties of the weak current, and the $SU(3)\times SU(3)$ algebra, it has been shown some time ago that this suppression cannot be understood as a strong-interaction effect.[17] However, if there is other evidence for large symmetry-breaking effects, these assumptions may have to be reassessed.

The $\Lambda\ \beta$ decay is distinguished from the neutron β decay by a much larger Q value and by the change of strangeness. It would be most interesting to have spin-correlation experiments for $\Delta S=0$ transitions with larger Q values.

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