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REMARKS ON THE 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

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ABSTRACT

The formulae 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 usefulness of the proposed combinations is discussed qualitatively.

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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, very preliminary data on spin correlations for $\Lambda \rightarrow p + e^- + \bar{\nu}$ decays have become available,^{3,4)} which can give a new and sensitive test of the assumptions 1-3. It is the purpose of this note to explore the possible implications of these measurements in a qualitative way. Specifically, we suggest a sum rule for the correlation coefficients which can give specific information.

We write the semileptonic interactions in the form

$$\frac{G}{\sqrt{2}} J_{\alpha} \ell_{\alpha}^{\dagger} + \text{h.c.} \quad (1)$$

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

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

are defined by*

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

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

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

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

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

* We use the notation $p = (\underline{p}, ip_0)$, etc., with hermitian γ -matrices.

where $\hat{e}$ and $\hat{v}$ are unit vectors in the directions $\underline{p}_e$ and $\underline{p}_v$, and $\underline{\sigma}$ is the polarization vector of the hyperon. The coefficients are functions of p_e and $(\cos \theta)^2$, $\cos \theta \equiv (\hat{e} \cdot \hat{v})$, 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 $\Delta m/m = (m_{\Lambda} - m_p)/m_{\Lambda} \approx 0.16$, and we reproduce in the following only terms of zeroth and first order; an exception is made for some special second order contributions to be mentioned later.

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

$$a_0 = (\bar{a} - \frac{3}{2} \frac{\Delta m}{m}) (1 - \frac{\Delta m}{2m} \bar{a})^{-1}, \quad (6)$$

the $\underline{\sigma} \cdot \hat{e}$ correlation

$$\alpha = (\bar{A} + \frac{1}{3} \bar{B}' - \frac{\Delta m}{2m} \bar{B}) (1 - \frac{\Delta m}{2m} \bar{a})^{-1}, \quad (7)$$

the $\underline{\sigma} \cdot \hat{v}$ correlation

$$\beta = (\bar{B} + \frac{1}{3} \bar{A}' - \frac{\Delta m}{2m} \bar{A}) (1 - \frac{\Delta m}{2m} \bar{a})^{-1}, \quad (8)$$

and the rate, which is proportional to

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

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

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

where we use the notation

$$\langle F \rangle = \int_0^{p_{\text{emax}}} dp_e p_e^2 (p_{\text{emax}} - p_e)^2 \frac{1}{2} \int_{-1}^{+1} d \cos \theta F(p_e, \cos^2 \theta) \cdot 30 p_{\text{emax}}^{-5} .$$

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

$$(\bar{B} + \frac{1}{3} \bar{A}') - (\bar{A} + \frac{1}{3} \bar{B}') = (1 - \frac{\Delta m}{2m} (1 + \bar{a})) (\beta - \alpha) , \quad (10)$$

$$(\bar{B} + \frac{1}{3} \bar{A}') + (\bar{A} + \frac{1}{3} \bar{B}') = (1 + \frac{\Delta m}{2m} (1 - \bar{a})) (\beta + \alpha) , \quad (11)$$

and

$$\frac{1 - \bar{a}}{1 + \bar{a}} . \quad (12)$$

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 $\Delta m/m$.

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

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

where

$$\begin{aligned} \langle \xi \rangle (1 + \bar{a}) \Sigma = & \frac{\Delta m}{m} \frac{2}{3} \{ |f_1|^2 + |g_1|^2 + 2 \operatorname{Re}(f_1 f_2^*) + 2 \operatorname{Re}(g_1 g_2^*) \} \\ & + [-(\frac{\Delta m}{m})^2 \frac{2}{21} (5 |f_2|^2 + 11 |g_2|^2)] + 0 \left((\frac{\Delta m}{m})^2 \right), \end{aligned} \quad (14)$$

and

$$\begin{aligned} \langle \xi \rangle (1 + \bar{a}) = & 2(|f_1|^2 + |g_1|^2) \left(1 + \frac{\Delta m}{m} \right) \\ & + \left[\left(\frac{\Delta m}{m} \right)^2 \frac{2}{7} (|f_2|^2 - |g_2|^2) \right] + 0 \left(\left(\frac{\Delta m}{m} \right)^2 \right). \end{aligned} \quad (15)$$

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.*

The combination Σ is constructed so as to vanish in the allowed approximation. Hence Σ is zero within errors for

*We also omit radiative corrections, which may be permissible for our qualitative considerations.

neutron β -decay.* For the Λ - β -decay, we may use the assumptions 1.-3. of Cabibbo, which yield⁷⁾

$$g_1 \approx 0.74 f_1, \quad f_2 = \frac{1}{2} \mu_p f_1, \quad g_2 = 0, \quad (16)$$

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 the expressions (12-13) and

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

where

$$\begin{aligned} \langle \xi \rangle (1 - \bar{a}) &= 4 |g_1|^2 - \frac{\Delta m}{m} 8 \operatorname{Re}(g_1 g_2^*) \\ &+ [(\frac{\Delta m}{m})^2 \frac{2}{7} (3 |f_2|^2 + 13 |g_2|^2)] + 0 ((\frac{\Delta m}{m})^2), \end{aligned} \quad (18)$$

and

$$\begin{aligned} \langle \xi \rangle (1 + \bar{a}) \Pi &= 4 \operatorname{Re}(f_1 g_1^*) \\ &+ \frac{\Delta m}{m} \frac{4}{3} \operatorname{Re}(2 f_1 g_1^* - g_1 f_2^* - f_1 g_2^*) \\ &+ [(\frac{\Delta m}{m})^2 \frac{32}{21} \operatorname{Re}(f_2 g_2^*)] + 0 ((\frac{\Delta m}{m})^2). \end{aligned} \quad (19)$$

We note that, in contrast to Σ , the combination Π is dependent only upon interference terms, in particular the main term is proportional to $f_1 g_1$. With the Cabibbo values (16), we obtain

$$\Pi \approx 0.86$$

* For the relevant data see Ref. 6.

In order to illustrate the possible applications of our combinations let us take a specific example. We suppose that the correlation experiments give a result for Σ which is negative.* 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 phase¹³⁾ 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 sign relative to f_1, g_1 because the f_2^2 and g_2^2 terms in Σ have very small coefficients.

*We give here some very preliminary data obtained from recent correlation experiments. It is important to note that these are meant only as an example for the purpose of illustrating the possible usefulness of our combinations Σ , Π , etc.. For the actual experimental results, the forthcoming publications of the experimental groups should be consulted.

$$a_0 = -0.08 \pm 0.11 \quad (\text{Ref. 8, 9, 10, 11})$$

$$\alpha = 0.18 \pm 0.13 \quad (\text{Ref. 3, 10, 12})$$

$$\alpha = 0.10 \pm 0.10 \quad (\text{Ref. 4})$$

$$\beta = 0.73 \pm 0.19 \quad (\text{Ref. 3, 10}).$$

From these numbers we obtain:

$$\Sigma = -0.26 \pm 0.19$$

$$\Pi = 0.79 \pm 0.19$$

$$\frac{1-\bar{a}}{1+\bar{a}} = 0.72 \pm 0.14$$

From the universal SU(3) scheme, we find approximately

$$\Sigma = 0.10$$

$$\Pi = 0.86$$

$$\frac{1-\bar{a}}{1+\bar{a}} = 0.61$$

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 $f_1 f_2$ term in Σ in order to obtain a negative value for this expression.* 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.

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 $g_1 g_2$ 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.

Of interest is also the possibility of a large, time reversal invariance violating second class contribution.¹⁴⁾ For Λ - β -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 $\hat{\sigma}_\Lambda \cdot \hat{e} \times \hat{\nu}$ 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.

* For $\Sigma = -0.3$, about $f_2 \sim -4 f_1$ is required; for $\Sigma = 0$, we find $f_2 \sim -0.8 f_1$.

(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) and (19). Such solutions should be looked for with relations complete up to second order in $\Delta m/m$, or with the exact formulae*.

The example discussed above is meant to give an indication for the possible usefulness of the combinations Σ and Π 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. They show that these hyperon β -decay experiments provide a most interesting independent test of the SU(3) scheme and perhaps even of the current-current form of the semileptonic interaction, at least as far as strangeness-changing transitions are concerned.

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.¹⁵⁾ Using the SU(3) properties of the weak current, and the SU(3) x SU(3) algebra, we have shown some time ago that this suppression cannot be understood as a strong interaction effect.¹⁶⁾ However,

* Another source of information is of course the shape of the electron spectrum.

if there is other evidence for large symmetry breaking effects, these assumptions may have to be reassessed.

The Λ - β -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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