EFFECT OF FORM FACTORS ON THE RELATIVE PROBABILITY FOR LEPTON DECAYS OF HYPERONS

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Irrespective of the magnitude of the weak interaction constants in the absence of form factors, the theory predicts a muon to electron hyperon decay probability ratio which should be correct to ~1 per cent. The difference between this ratio and the "theoretical" value characterizes the role of the decay-interaction form factors and is probably not greater than 30 per cent. For the ratio of the $\Sigma^- \to \Lambda + e^- + \bar{\nu}$ and $\Sigma^+ \to \Lambda + e^+ + \nu$ decays the theory predicts a value 1.67 ± 0.06.

INTRODUCTION

THE development of experimental techniques makes timely the question of determining the variants and the form factors of the interaction responsible for hyperon lepton decay. All we know at present is that the constants or, more accurately, the form factors of such an interaction are somewhat smaller than the β-decay constant $G/\sqrt{2}$, where $G = 1.41 \times 10^{-49}$ erg-cm^3. There is still no information concerning the relative values of the different form factors. From the data of the only experiment to date on the energy distributions in the $\Lambda \to p + e^- + \bar{\nu}$ decay [1] it follows only that the V-A hypothesis [2,3] does not contradict the experiment. The existence of the V-variant can be deduced only from a less direct experiment [4] in which the energy spectrum is measured in K_{e3} decay.

We shall show that the ratio W_μ/W_e of the total probabilities of hyperon muon and electron decays is sensitive to the contribution from certain form factors [principally f_3 and g_2, defined in (1)]. If such form factors are small, then the theory predicts a perfectly defined value for W_μ/W_e.

In the case of decays without a change in strangeness, the ratio $W(\Sigma^- \to \Lambda + e^- + \bar{\nu})/W(\Sigma^+ \to \Lambda + e^+ + \nu)$ can also be used to measure g_2.

The arguments presented below are valid if the decay interaction in decays with change of strangeness is the same for both electrons and muons, and if in the case of strangeness conservation the baryon current is a component of the isotopic vector. Consequently a comparison of the relations (8) and (10) below with experiment can serve with good accuracy as a check on both assumptions.

We also propose that the decay interaction includes only V- and A-variants. Such an assumption is essential only for the determination of the corrections that are brought about by the form factors.

FORM FACTORS

The matrix element of the decay $Y \to N + l^- + \bar{\nu}$ for the V, A interaction is of the form

$$\frac{G}{\sqrt{2}}\Big(\bar{u}_N\Big\{\Big[f_1\gamma_\alpha + f_2\frac{\sigma_{\alpha\beta}q_\beta}{4m_\pi} + f_3\frac{q_\alpha}{m_\mu}\Big] + \gamma_5\Big[g_1\gamma_\alpha + g_2\frac{\sigma_{\alpha\beta}q_\beta}{4m_\pi} + g_3\frac{q_\alpha}{m_\mu}\Big]\Big\}u_Y\Big)(u_l\gamma_\alpha(1+\gamma_5)u_\nu), \tag{1}$$

where

$$q = p_Y - p_N, \quad \sigma_{\alpha\beta} = (\gamma_\alpha\gamma_\beta - \gamma_\beta\gamma_\alpha)/2, \quad \gamma_5 = i\gamma_0\gamma_1\gamma_2\gamma_3.$$

The factors $1/4m_\pi$ following f_2 and g_2, or $1/m_\pi$ following f_3 and g_3, have been introduced to make these form factors dimensionless.

The ratio of the "magnetic" and "electric" form factors is usually written in the form $\mu/(m_Y + m_N)$, where μ is a certain "magnetic moment" of the $Y \to N$ transition. For nuclear β decay, μ is relatively large ($\mu = \mu_p - \mu_n = 3.7$[2]). For a strangeness-changing decay, μ is unknown. If we assume that μ is of the same order of magnitude as in nuclear β decay, then $\mu/(m_Y + m_N)$ is close to $1/4m_\pi$. We can therefore assume that in the notation employed here $|f_2| \sim |f_1|$ and $|g_2| \sim |g_1|$.

With the introduced factor $1/m_\pi$, the form factors f_3 and g_3 have the significance of the scalar and pseudoscalar form factors, respectively (for $l = \mu$). For nuclear β decay, g_3 is large, amounting to $g_3 \approx 8g_1$ according to [5]. This estimate agrees with the experimental μ-capture data[6]. The large value of g_3 is connected here with the presence of a pion pole in the pseudoscalar form factor. For decay with nonconservation of strangeness, the pion pole is replaced by a K-meson pole, the contribution of which is many times smaller. Consequently, it is natural to expect $|g_3| \lesssim |g_1|$ for the hyperon lepton decay.

The form factor f_3 does not exist in nuclear β decay (nor does g_2). There are no grounds for assuming that it is large for hyperon decays. If the "scalar" term has the same order as the "magnetic" term, then $|f_3/4m_\pi| \approx |f_3/m_\pi|$. Therefore it can be thought that $|f_3| \sim |f_2|/5$.

It follows from the foregoing that if we assume the estimate

$$|f_1| \sim |g_1| \sim |f_2| \sim |g_2| \sim 5|f_3| \sim |g_3|, \qquad (2)$$

then the values of $|f_2|$, $|g_2|$, $|f_3|$, and $|g_3|$ can hardly turn out to be too low.

In all the preceding arguments we have ignored the fact that the form factors f_i and g_i depend on the momentum transfer q^2 (for $Y \to N + l^- + \bar{\nu}$ in the Y rest system, the equality $q^2 = (m_Y - m_N)^2 - 2m_Y T$ is valid, where T is the kinetic energy of N). In hyperon lepton decay, q^2 is not very large. Therefore in the expansion in powers of q^2 we can take into account for the form factors only the first two terms:

$$f_i(q^2) = f_i(0)\left[1 + \frac{1}{6}\frac{q^2}{4m_\pi^2}\alpha_i\right], \qquad i = 1, 2, 3. \qquad (3)$$
$$g_i(q^2) = g_i(0)\left[1 + \frac{1}{6}\frac{q^2}{4m_\pi^2}\beta_i\right].$$

For nuclear β decay, $\alpha_1 \approx \alpha_2 \approx 1$. It can be assumed that for hyperon decay, too,

$$\alpha_i \approx \beta_i \approx 1, \qquad i = 1, 2, 3. \qquad (4)$$

We shall henceforth use the estimates (2) for $f_i(0)$ and $g_i(0)$ (the index (0) will be left out throughout) and the estimates (4) for α_i and β_i.

The use of (4) for the form factor g_3 calls for some explanation. Owing to the presence of a K-meson pole, it should behave like $g_3(q^2) = g_3(0)/1(q^2/m_K^2)$. In the notation of (3) this means that $\beta_3 = 24(m_\pi/m_K)^2 \approx 1.9$, so that the estimate (4) gives a correct order of magnitude here, too.

DECAY PROBABILITY

The probability of the decay $Y \to N + l^- + \gamma$ is equal to [7]

$$W = \frac{G^2}{15\pi^3}\frac{(m_Y - m_N)^5}{(1+\xi)^3} H, \qquad (5)$$

where

$$\xi = (m_Y - m_N) / (m_Y + m_N),$$

and H can be written in the form

$$H = \frac{1}{4}\sum_{i \leqslant k = 1}^{3}\left[f_i f_k\left(n_{ik} + \nu_{ik}\frac{\alpha_i + \alpha_k}{2}\right) + g_i g_k\left(m_{ik} + \mu_{ik}\frac{\beta_i + \beta_k}{2}\right)\right]. \qquad (6)$$

The expressions for the coefficients n_{ik}, ν_{ik}, m_{ik}, and μ_{ik} in the first nonvanishing approximation in ξ^2 can be obtained from the formulas of [7]1), viz.,

$$n_{11} = \sigma_1, \quad n_{22} = {}^2/_3\lambda^2[-2\sigma_2 + (2-\eta)\sigma_1 + \eta\sigma_0],$$
$$n_{33} = \sigma_1(m_l/m_\mu)^2, \quad n_{12} = 2\lambda\xi[-2\sigma_2 + (2-\eta)\sigma_1 + \eta\sigma_0],$$
$$n_{13} = 2\sqrt{\eta}\sigma_0(m_l/m_\mu),$$
$$\nu_{11} = {}^4/_9\lambda^2[-2\sigma_2 + (2-\eta)\sigma_1 + 4\eta\sigma_0],$$
$$\nu_{22} = {}^8/_9\lambda^4[-2\sigma_3 + (2-\eta)\sigma_2 + \eta\sigma_1],$$
$$\nu_{33} = {}^4/_3\lambda^2\sigma_2(m_l/m_\mu)^2,$$
$$\nu_{12} = {}^8/_3\xi\lambda^3[-2\sigma_3 + (2-\eta)\sigma_2 + \eta\sigma_1],$$
$$\nu_{13} = {}^8/_3\sqrt{\eta}\lambda^2\sigma_1(m_l/m_\mu);$$
$$m_{11} = 3\sigma_1, \quad m_{22} = {}^1/_3\lambda^2(2\sigma_2 + (4+\eta)\sigma_1 + 2\eta\sigma_0),$$
$$m_{33} = \xi^2(\sigma_1 - \sigma_2)(m_l/m_\mu)^2, \quad m_{12} = 2\lambda(2\sigma_1 + \eta\sigma_0),$$
$$m_{13} = 2\xi\sqrt{\eta}(\sigma_0 - \sigma_1)(m_l/m_\mu), \qquad (7)$$
$$\mu_{11} = {}^4/_9\lambda^2[4\sigma_2 + (2-\eta)\sigma_1 + 4\eta\sigma_0], \quad \mu_{22} = {}^4/_9\lambda^4[2\sigma_3 + (4+\eta)\sigma_2 + 2\eta\sigma_1],$$
$$\mu_{33} = {}^4/_3\xi^2\lambda^2(\sigma_2 - \sigma_3)(m_l/m_\mu)^2, \quad \mu_{12} = {}^8/_3\lambda^3(2\sigma_2 + \eta\sigma_1),$$
$$\mu_{13} = {}^8/_3\xi\sqrt{\eta}\lambda^2(\sigma_1 - \sigma_2)(m_l/m_\mu).$$

Here $\lambda = (m_Y - m_N)/4m_\pi, \qquad \eta = m_l^2/(m_Y - m_N)^2,$

$$\sigma_k = \frac{15}{4}\int_\eta^1 dx\sqrt{1-x}\left(1 - \frac{\eta}{x}\right)^2 x^k. \qquad (8)$$

Explicit expressions for σ_0, σ_1, and σ_2 are written out in [7]; $\sigma_3 = (4/21)(2+\eta)(1-\eta)^{7/2}$.

Equation (7) does not contain the coefficients n_{23}, m_{23}, ν_{23}, and μ_{23}, which vanish identically by virtue of the properties of the matrix element (1)[8]. For the same reason, Eq. (6) does not contain the interference of the vector and axial form factors of the type $f_i g_k$[9,8].

The numerical values of the coefficients listed above for the decays $\Lambda \to p + l^- + \bar{\nu}$, $\Sigma^- \to n + l^- + \bar{\nu}$, and $\Xi^- \to \Lambda + l^- + \bar{\nu}$ are listed in Table I. The decays $\Xi \to \Lambda + l^- + \nu$ have not been included

1)The connection with the notation of[7] is given by the equations: $q^2 = Q^2$; $f_1 = C_V\sqrt{2}/G$, $g_1 = C_A\sqrt{2}/G$, $f_2 = 4m_\pi B_V \times \sqrt{2}/G$, $g_2 = -4m_\pi B_A\sqrt{2}/G$, $f_3 = -D_V m_\mu\sqrt{2}/G$, $g_3 = D_A m_\mu \times \sqrt{2}/G$, α_1 $-4m_\pi^2 a^2(C_V)$, $\beta_1 = -4m_\pi^2 a^2(C_A)$, etc.

in this table because they have extremely low probability when $l = \mu$ (the energy released is merely ~20 MeV). The last two lines of Table I give the corrections $\sim \xi^2$ to n_{11} and m_{11}, given by the expressions

$$n_{11}' = -\xi^2(\sigma_2 - (1 - \eta/2)\sigma_1 + \eta\sigma_0),$$

$$m_{11}' = -\xi^2(2\sigma_2 + (1 + \eta/2)\sigma_1 + \eta\sigma_0). \tag{9}$$

It is seen from Table I that if we assume the estimate (2) or (4), the only coefficients of importance for electronic decays are

$$n_{11} = 1, \quad m_{11} = 3 \quad \text{and} \quad m_{12} = (m_Y - m_N) / m_\pi,$$

so that

$$H_e \approx \frac{1}{4}\left[f_1^2 + 3g_1^2 + \frac{m_Y - m_N}{m_\pi} g_1 g_2\right]. \tag{10}$$

For muon decays the role of the coefficients n_{13}, ν_{11}, m_{22} and μ_{11} becomes greater,

The ratio of the muon and electron decay probabilities is conveniently written in the form

$$W_\mu / W_e = \sigma_1(1 + \Delta / H_e), \tag{11}$$

where $\Delta = (H_\mu/\sigma_1) - H_e$. It is tacitly understood in (11) and subsequently that σ_1 is defined by (8) for $l = \mu$. The expression for Δ can also be written in the form (6). The values of the coefficients of such an expansion are listed in Table I. In the last column of Table I is indicated the contributions made to Δ/H_e by these coefficients multiplied by the corresponding form factors; the estimates (2) and (4) are used for the latter. It is assumed here in accordance with (10) that $H_c \approx 3g_1^2/4$, which is more likely to exaggerate the result of the estimate.

DISCUSSION OF RESULTS

From the formulas presented and from the numbers in the last column of Table I we can draw the following conclusions:

1) For the "pure" V-A variant, when only f_1 and g_1 differ from zero and when the dependence of these form factors on q^2 can be disregarded, we have $W_\mu/W_e = \sigma_1$ with accuracy $\sim \xi^2 \sim 1\%$. This equality is valid regardless of the value of f_1 and g_1; therefore any deviation from it characterizes the role of the other form factors.

2) The contribution from different form factors has approximately the same order of magnitude for the lepton decays of Λ, Σ, and Ξ.

3) The dependence of the form factors on q^2 is apparently less important than the interference of their static values (for $q^2 = 0$).

Table I

	$\Lambda \to p + l^- + \bar{\nu}$			$\Sigma^- \to n + l^- + \bar{\nu}$			$\Xi^- \to \Lambda + l^- + \bar{\nu}$			Order of contribution to Δ/H_e for (2) and (4), %
	H_e	H_μ	$\Delta = \frac{H_\mu}{\sigma_1} - H_e$	H_e	H_μ	$\Delta = \frac{H_\mu}{\sigma_1} - H_e$	H_e	H_μ	$\Delta = \frac{H_\mu}{\sigma_1} - H_e$	
ξ	0.0864	0.0864		0.121	0.121		0.0843	0.0843		
λ	0.317	0.317		0.463	0.463		0.368	0.368		
η	0	0.356		0	0.168		0	0.264		
σ_0	2.5	0.220		2.5	0.731		2.5	0.377		
σ_1	1	0.162		1	0.456		1	0.271		
σ_2	0.571	0.123		0.571	0.301		0.571	0.195		
σ_3	0.381	0.096		0.381	0.217		0.381	0.145		
n_{11}	1	0.162	0	1	0.456	0	1	0.271	0	0
n_{22}	0.057	0.0066	−0.016	0.123	0.051	−0.012	0.077	0.0162	−0.017	0.5
n_{33}	0	0.162	1	0	0.456	1	0	0.271	1	1
n_{12}	0.047	0.0054	−0.014	0.096	0.040	−0.009	0.053	0.011	−0.012	0.5
n_{13}	0	0.26	1.62	0	0.60	1.31	0	0.39	1.43	10
ν_{11}	0.038	0.015	0.054	0.082	0.069	0.070	0.0515	0.029	0.055	2
ν_{22}	0.0034	0.0006	0.0003	0.0155	0.0079	0.0018	0.0062	0.0019	0.0007	0.05
ν_{33}	0	0.0164	0.10	0	0.086	0.19	0	0.035	0.13	0.2
ν_{12}	0.0028	0.0005	0.0002	0.012	0.0062	0.001	0.0042	0.0013	0.0005	0.02
ν_{13}	0	0.026	0.16	0	0.11	0.235	0	0.050	0.185	1
m_{11}	3	0.486	0	3	1.367	0	3	0.813	0	0
m_{22}	0.17	0.037	0.057	0.37	0.20	0.063	0.23	0.078	0.059	2
m_{33}	0	0.0003	0.0018	0	0.0023	0.005	0	0.0005	0.002	0.1
m_{12}	1.27	0.255	0.31	1.85	0.96	0.25	1.47	0.47	0.27	10
m_{13}	0	0.006	0.037	0	0.027	0.060	0	0.0093	0.0345	1
μ_{11}	0.19	0.048	0.10	0.41	0.24	0.12	0.26	0.099	0.11	4
μ_{22}	0.0135	0.0043	0.013	0.062	0.0405	0.027	0.025	0.0115	0.0175	0.5
μ_{33}	0	0.00003	0.0002	0	0.00035	0.0008	0	0.00006	0.0002	0.02
μ_{12}	0.097	0.026	0.062	0.30	0.18	0.090	0.15	0.061	0.074	2
μ_{13}	0	0.00054	0.0033	0	0.0043	0.0094	0	0.0012	0.0044	0.2
n_{11}'	0.0032	−0.0005	−0.0063	0.0063	−0.0001	−0.0065	0.0030	−0.0004	−0.0045	−0.2
m_{11}'	−0.0160	−0.0038	−0.0075	−0.0313	−0.0178	−0.0080	−0.0152	−0.0057	−0.0060	−0.2

Table II

	$\Lambda \to p + l^- + \bar{\nu}$		$\Sigma^- \to n + l^- + \bar{\nu}$		$\Xi^- \to \Lambda + l^- + \bar{\nu}$	
	theor.	exp	theor	exp	theor	exp
W_e (10^8 sec^{-1}) for $H = 1$	0.586		3.58		1.24	
$W_e \tau \cdot 10^3$	14	0.82±0.13	57	$1.0 \begin{smallmatrix} +0.5 \\ -0.3 \end{smallmatrix}$	22	3±2
$W_\mu \tau \cdot 10^3$	2.2	0.1±?	26	0.8±0.3	6	≤1
W_μ / W_e	0.16	0.12±?	0.46	0.8±0.45	0.27	≤1
$\frac{W_e \text{ (theor)}}{W_e \text{ (exp)}} = \frac{1}{H_e}$	17±3		$57 \begin{smallmatrix} +17 \\ -28 \end{smallmatrix}$		7±5	
$\frac{W_\mu}{W_e}$ (exp) $\frac{1}{\sigma_1}$	0.75±?		1.7±1		≤3	

4) The greatest contribution (~10%) to W_μ/W_e is made by the interference of the form factors g_1g_2 and f_1f_3. In order for the contribution from the form factor g_3 to have the same order of magnitude, it is necessary to have $g_3 \sim 10g_1$, and this, as already noted, is of little likelihood. Therefore, with good approximation,

$$\Delta \approx {}^1/_4 (n^\Delta{}_{13} f_1 f_3 + m^\Delta{}_{12} g_1 g_2) \approx 0.4 f_1 f_3 + 0.07 g_1 g_2. \quad (12)$$

5) The deviation of $W_\mu/W_e\sigma_1$ from unity, determined by the total contribution of all the form factors [it can be characterized approximately by the ratio of (12) and (10)], hardly exceeds ~30%. In the opposite case at least one of the form factors f_3, g_2, f_2, g_3 (more likely one of the first ones) should be anomalously large.

EXPERIMENTAL DATA

Table II lists the data on lepton decays of hyperons taken from [10,11]. The theoretical numbers in Table II correspond to $W_\mu/W_e = \sigma_1$, i.e., "pure" V, A interaction, while the numbers in the W_e entry correspond to the stronger assumption that $H_e = 1$. We see that although $|f_1|$ and $|g_1|$ are certainly several times smaller than unity, the equality $W_\mu/W_e = \sigma_1$ is satisfied within a rather large experimental error. The deviations of W_μ/W_e from σ_1 can be estimated only after larger experimental statistics are accumulated.

THE DECAYS $\Sigma \to \Lambda + e + \nu$

So long as the baryon current is a component of an isotopic vector in the interaction responsible for strangeness-conserving decays, all the form factors for the decays $\Sigma^- \to \Lambda + e^- + \bar{\nu}$ and $\Sigma^+ \to \Lambda + e^+ + \nu$ should be the same. If we write the probabilities of such decays in the form (5), then their ratio is equal to

$$\frac{W_-}{W_+} = \left(\frac{m_- - m_\Lambda}{m_+ - m_\Lambda}\right)^5 \left(\frac{1 + \xi_+}{1 + \xi_-}\right)^3 \frac{H_-}{H_+}$$
$$= (1.67 \pm 0.06) \left[1 + \frac{\Delta}{H_+}\right], \quad (13)$$

where $\Delta = H_- - H_+$. The coefficients of the expansion (6) for H_-, H_+, and Δ can be obtained from formula (7)–(9). Almost all are extremely small. The largest ones in $\Delta = H_- - H_+$ are $m^\Delta_{12} = 0.59 - 0.53 = 0.06$, $m^\Delta_{22} = 0.037 - 0.030 = 0.007$, and $\mu^\Delta_{11} = 0.041 - 0.034 = 0.007$. Thus only one term with m_{12} is of practical importance for Δ. Consequently

$$\Delta \approx \frac{m_- - m_+}{4m_\pi} g_1 g_2 = 0.015 g_1 g_2. \quad (14)$$

If we assume the vector-current conservation hypothesis [12], then the statistical value of the form factor f_1 turns out to be equal to zero [7]. Therefore, with good accuracy

$$H_+ = {}^1/_4 [3g_1^2 + (m_+ - m_\Lambda) g_1 g_2 / m_\pi]$$
$$= 0.75 g_1^2 + 0.13 g_1 g_2. \quad (15)$$

Substituting (14) and (15) in (13) and multiplying the entire expression by τ_-/τ_+, where $\tau_\pm$—lifetimes of the $\Sigma^\pm$ hyperon, we get

$$(W\tau)_- / (W\tau)_+ = (3.4 \pm 0.2) [1 + 0.02 (g_2/g_1)]. \quad (16)$$

Experiment yields for the ratio (16) a value ~2.4, and this experiment is still not accurate enough to yield any information on the ratio g_2/g_1. It is all the more true that for all reasonable values of g_2/g_1 the correction term in (16) is very small. On the other hand, a check on the ratio (13) would be all the more interesting, since it will make it possible to confirm the hypothesis of the isovector character of the β-decay current with the same accuracy (~2%) with which $H_-/H_+ = 1$.

In conclusion we can note that from the data of Table III it follows that

$$(W\tau)_- \text{ (exp)} / (W\tau)_- \text{(theor)} = H_- = 0.26 \pm 0.14. \quad (17)$$

Table III

	$\Sigma^- \to \Lambda + e^- + \bar{\nu}$	$\Sigma^+ \to \Lambda + e^+ + \nu$
$W \cdot 10^{-6}$ (sec^{-1}) (theor. for H = 1)	1.45±0.05	0.87±0.01
$W\tau \cdot 10^4$ (theor)	2.3±0.1	0.68±0.03
$W\tau \cdot 10^4$ (exp)	0.6±0.3	0.25

Putting $H_- \approx 3g_1^2/4$ we get

$$g_1 = 0.6 \pm 0.2. \qquad (18)$$

Inasmuch as g_1 is known, measurement of the ratio (16) with sufficiently high accuracy makes it possible to determine g_2 directly.

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Note added in proof (JETP 47, no. 5, 1964). It is stated on pp. 175 and 178 that comparison of the theoretical and experimental values of the probabilities of the decays $\Sigma^+ \to \Lambda + e^+ + \nu$ and $\Sigma^- \to \Lambda + e^- + \bar{\nu}$ can be used to check the hypothesis that the β-decay current is isovector. This statement is incorrect. The comparison referred to can only establish that these decays are due to different components of the same isovector current. So long as this is true, such components are Hermitian conjugates and the β-decay current has a definite G-parity (which is of opposite sign for the V and A components in the case of the V, A interaction).

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40