POSSIBILITY OF DETERMINING THE FORM FACTORS IN LEPTONIC DECAY OF HYPERONS

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The energy correlation and asymmetry of emission of particles produced in leptonic decay of hyperons, and also the polarization of the emitted nucleons or secondary hyperons, have been calculated with account of all six form factors of the decay V-A interaction. A method of comparison of the theoretical formulas with the experimental data is suggested, which permits in principle to determine the form factor. A similar calculation is presented in the appendix, when all five types of decay interaction are retained and the form factors are neglected.

1. INTRODUCTION

THE recent observation[1,2] of the decay $\Lambda \rightarrow p + e^- + \bar{\nu}$ gives grounds for hoping that leptonic decays of hyperons will soon be experimentally investigated. Such an investigation is particularly interesting for the following reasons. On the one hand, the theoretical analysis is made much easier here by the fact that all the particles in the final states are free (accurate to inessential Coulomb forces). This permits an exact calculation of the process with account of the weak decay interaction, naturally, only in first-order perturbation theory. On the other hand, the influence of strong interactions should lead to the appearance of energy-dependent form factors of the decay interaction, which affect the experimental results. An investigation of the β decay of hyperons can therefore yield certain information on the role of strong interactions, as takes place in the scattering of fast electrons by nucleons.

The present work is devoted to a theoretical analysis of leptonic decays of hyperons. It is assumed from the outset that this decay is due to the universal four-fermion V-A interaction.[3,4] This assumption is natural, since the universal V-A theory has thus far been most brilliantly confirmed by all experiments on weak interactions (incidentally, always without participation of strange particles). The question of the possibility of determining the variants of the interaction responsible for the leptonic decay of hyperons directly from experimental data is considered in Appendix B.

The form factors of the V-A interaction are introduced in Sec. 2. Section 3 is devoted to the possibility of determining all the form factors in an investigation of the energy correlation and asymmetry of the particles emitted in the hyperon decay. Formulas for the energy distribution, asymmetry of emission, and polarization of the emitted nucleons (or secondary hyperons), and also the total probability of the decay, are written out in Sec. 4. The indicated quantities where calculated previously by one of the authors[5] only for the C_V and C_A form factors. Reference 5 contains, however, many inaccuracies which are corrected in the present paper. In section 5, some features of the decays $\Sigma \rightarrow \Lambda + e + \nu$ are considered.

2. FORM FACTORS

Leptonic decays of hyperons can be written in a unique manner

$$Y \rightarrow N + l + \bar{\nu}, \tag{1}$$

where Y is the decaying hyperon, N the nucleon or hyperon in the final state (processes of the type $\Xi^- \rightarrow \Lambda + l^- + \bar{\nu}$ are meant), l is the electron or muon, and $\bar{\nu}$ is the antineutrino. We shall henceforth omit bar over ν in the indices.

In calculating the decay probability in first-order perturbation theory, the matrix element of the S matrix is given (in the case of the VA theory) by the expression[6]

$$i\,(2\pi)^4\delta\,(p_Y - p_N - p_l - p_\nu)\left\langle N \left| \frac{G}{\sqrt{2}} J_\mu(0) \right| Y \right\rangle \times (u_l\gamma_\mu(1+\gamma_5)\,u_\nu), \tag{2}$$

where for each particle B, $|B\rangle$ is its real state, u_B is the free spinor, p_B the four-momentum, and $G = 1.4 \times 10^{-49}$ erg-cm^3 is the Feynman-Gell-

Mann constant.[3] The current $J_\mu(x) \equiv J_\mu^V(x) + J_\mu^A(x)$ is a superposition of the currents $(\bar\psi_N(x)\gamma_\mu\psi_Y(x)) + (\bar\psi_N(x)\gamma_\mu\gamma_5\psi_Y(x))$, where Y and N are different baryons ($\psi_B(x)$ is the operator of the particle B in the Heisenberg representation), and also of the currents that can be made up of the boson (i.e., K and π meson) operators.

The existence of strong interactions makes a direct calculation of $2^{-1/2}\langle N|GJ_\mu(0)|Y\rangle$ impossible. The most common form of this matrix element follows from the relativistic invariance

$$\left\langle N\left|\frac{G}{\sqrt{2}}J_\mu(0)\right|Y\right\rangle = (\bar u_N\{\gamma_\mu(C_V - C_A\gamma_5) + \sigma_{\mu\nu}(p_Y - p_N)_\nu(B_V - B_A\gamma_5) + i(p_Y - p_N)_\mu(D_V - D_A\gamma_5)\}u_Y). \quad (3)$$

In Eq. (3), C_V, C_A, B_V, B_A, D_V, and D_A are real (because of the CP invariance) functions of the invariant

$$Q^2 = -(p_Y - p_N)^2 = m_Y^2 + m_N^2 - 2m_Y E_N$$

(the last equation is true in the rest system of Y). From the conservation laws we have

$$m_l^2 \leqslant Q^2 \leqslant (m_Y - m_N)^2, \quad m_N \leqslant E_N \leqslant (m_Y^2 + m_N^2 - m_l^2)/2m_Y. \quad (4)$$

Unlike ordinary β decay,[6] in the decay of hyperons there are no grounds for assuming B_A and D_V equal to zero, so that the expression for the decay probability should include, generally speaking, the interferences of all six form factors. In the case when l is an electron, only four form factors remain, C_V, C_A, B_V, and B_A, since D_V and D_A make a contribution proportional to the square of the electron mass, which is negligibly small compared with the other quantities of the theory.

The dependence of the form factors on Q^2 is not known beforehand. If we write the power-series expansion

$$C_V(Q^2) = C_V(0)\left[1 - \frac{1}{6}Q^2a^2(C_V) + \cdots\right] \quad (5)$$

with analogous expressions for C_A, B_V, B_A, D_V, and D_A, this dependence will be determined by the quantity a, the β-decay "radius" of the hyperon, analogous to the corresponding electromagnetic radius, which characterizes the distribution of the charge or magnetic moment in the nucleon. It follows from the experimental data[7] that in electromagnetic interactions $a \sim 0.8 \times 10^{-13}$ cm $\sim 1/2m_\pi$. We have no grounds for assuming the β-decay radius to be much greater than this. But if this is so, then in (5), for example, $Q^2a^2/6 \leq 0.09$ for the decay $\Lambda \to p + l^- + \bar\nu$ and $Q^2a^2/6 \leq 0.18$ for $\Sigma^- \to n + l^- + \bar\nu$. Since these quantities are relatively small, the series (5) will apparently converge rapidly, and the high powers of Q^2 can be neglected in it. It is natural also to expect that in order of magnitude

$$B(0) \sim D(0) \sim aC(0) \quad (6)$$

with $a \sim 0.8 \times 10^{-13}$ cm; Eqs. (5) and (6) will be used later on for various estimates.

3. ENERGY CORRELATIONS AND EXPERIMENTAL DETERMINATION OF THE FORM FACTORS

The largest amount of information for the experimental determination of the form factors entering in (3) can be obtained by investigating the energy correlation of the particles produced in hyperon decays. It is convenient here to introduce the dimensionless variables (all the energies are taken in the Y rest system)

$$X = \frac{2m_Y}{m_Y^2 - m_N^2}\left[E_l - E_\nu\frac{1+\eta/J}{1-\eta/J}\right],$$

$$J = Q^2/(m_Y - m_N)^2, \quad \eta = m_l^2/(m_Y - m_N)^2, \quad (7)$$

analogous to the corresponding variables for the $K_{\pi3}$ and K_{e3} decays, considered by Dalitz[8] and Kobzarev.[9] The conservation laws limit the range of permissible variation of X and J to the line $J = \eta$ ($\eta = 0$ in the case of electronic decays) and the hyperbola

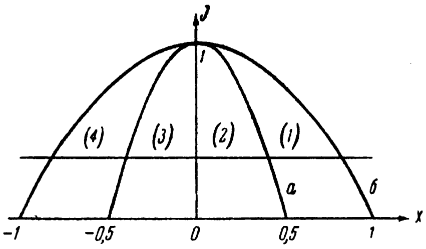
$$X^2 = X_m^2(J) \equiv (1 - J)(1 - \xi^2 J), \quad (8)$$

where the small parameter ξ is determined by the equation

$$\xi = (m_Y - m_N)/(m_Y + m_N). \quad (9)$$

The values of ξ and η (for $l = \mu$) for different decays are listed in the table. The range of variation of X and J is shown in the figure. The focus of the hyperbola is located at the point $X = 0$, $J = (\xi^{-2} + 1)/2$. When $\xi \ll 1$, the hyperbola is almost identical with the parabola

$$X^2 + J = 1. \quad (10)$$



Energy correlation on the XJ plane. Curve a: $X^2 = \frac{1}{4}(1-J) \times (1-\xi^2 J)$, curve b: $X^2 = (1-J)(1-\xi^2 J)$, line parallel to the abscissa axis: $J = \eta = m_\mu^2/(m_Y - m_N)^2$.

According to (7), E_N, $|\mathbf{p}_N|$, E_l and E_ν are expressed in terms of X and J by the equations

$$E_N = m_N + \frac{m_Y - m_N}{1+\xi}\,\xi(1-J),$$

$$|\mathbf{p}_N| = \frac{m_Y - m_N}{1+\xi} X_m(J) = \frac{m_Y - m_N}{1+\xi}\sqrt{(1-J)(1-\xi^2 J)},$$

$$E_l = \frac{m_Y - m_N}{2(1+\xi)}\left[(1+\xi J)\left(1+\frac{\eta}{J}\right) + X\left(1-\frac{\eta}{J}\right)\right],$$

$$E_\nu = \frac{m_Y - m_N}{2(1+\xi)}[1+\xi J - X]\left(1-\frac{\eta}{J}\right). \qquad (11)$$

It is seen from (11) that for electronic decays ($\eta = 0$) and for $\xi \ll 1$, E_e is expressed only in terms of X. To obtain the dependence of the decay probability on E_e it is sufficient in this case to integrate with respect to J from 0 to $1 - X^2$. The integration is always elementary, for the dependence on J is that of a power law.

The leptonic decay probability calculated according to (2) and (3) with given X and J, and also with given angle between the vector of polarization of the decaying hyperon, $\boldsymbol{\zeta}_Y$, and the unit vector $\mathbf{n}_N$ in the direction of motion of N, has the form

$$dW(X, J; \boldsymbol{\zeta}_Y, \mathbf{n}_N) = \frac{dXdJ}{16\pi^3}\frac{d\Omega_N}{4\pi}\frac{(m_Y - m_N)^5}{(1+\xi)^3}\left(1-\frac{\eta}{J}\right)^2$$
$$\times [S(X, J) + R_N(X, J)(\boldsymbol{\zeta}_Y \mathbf{n}_N)]. \qquad (12)$$

Formulas for S(X, J) and $R_N(X, J)$ are given in Appendix A.

If each decay event is now represented by the points X and J on the figure, then an analysis of the distribution of these points leads to certain conclusions regarding the magnitudes of the form factors, all of which are functions of J, but not of X. In such an analysis, in particular, one can determine independently the six coefficients of X^0, X^1, and X^2 in S(X, J) and $R_N(X, J)$. Actually, if the hyperbola $X^2 = \frac{1}{4}X_m^2(J) = \frac{1}{4}(1-J)(1-\xi^2 J)$ is drawn, the region of variation of X and J is broken up in four parts, as shown in the figure, and an integration performed with respect to X in each of the sections, one can obtain the energy distribution $S^{(i)}(J)$ and the asymmetry of emission of the nucleons $R_N^{(i)}(J)$ in the i-th section:

$$dW_i(J; \boldsymbol{\zeta}_Y, \mathbf{n}_N) = \frac{dJ}{16\pi^3} X_m(J)\frac{d\Omega_N}{4\pi}\frac{(m_Y - m_N)^5}{(1+\xi)^3}(1-\eta/J)^2$$
$$\times [S^{(i)}(J) + R_N^{(i)}(J)(\boldsymbol{\zeta}_Y \mathbf{n}_N)]. \qquad (13)$$

For electronic decays ($\eta = 0$), the only ones considered in this section, it follows from (A.1) and (A.2) that

$$S^{(1)} + S^{(2)} + S^{(3)} + S^{(4)} = \frac{4}{3}\{C_A^2(1+2J)(1-\xi^2 J) + C_V^2(1-J)(1+2\xi^2 J) + (m_Y - m_N)^2 J[B_A^2(2+J)(1-\xi^2 J)$$
$$+ B_V^2(1-J)(2+\xi^2 J)] - 6(m_Y - m_N)J[C_A B_A(1-\xi^2 J) - C_V B_V \xi(1-J)]\},$$

$$[S^{(1)} + S^{(4)}] - [S^{(2)} + S^{(3)}] = \frac{1}{2}X_m^2(J)[-(C_V^2 + C_A^2) + (m_Y - m_N)^2 J(B_V^2 + B_A^2)],$$

$$[S^{(1)} + S^{(2)}] - [S^{(3)} + S^{(4)}] = 4\xi J X_m(J)[-C_V C_A + B_V B_A(m_Y^2 - m_N^2) + (m_Y - m_N)C_V B_A - (m_Y + m_N)C_A B_V],$$

$$R_N^{(1)} + R_N^{(2)} + R_N^{(3)} + R_N^{(4)} = \frac{8}{3}X_m(J)\{C_V C_A(1-2\xi J)$$
$$+ (m_Y - m_N)^2 J B_V B_A(2-\xi J) - (m_Y - m_N)J[C_V B_A(1-2\xi) + C_A B_V(2-\xi)]\}$$

$$[R_N^{(1)} + R_N^{(4)}] - [R_N^{(2)} + R_N^{(3)}] = X_m(J)\{[-C_V C_A + (m_Y - m_N)^2 J B_V B_A](1+\xi J) + (m_Y - m_N)J(1+\xi)(C_V B_A - C_A B_V)\},$$

$$[R_N^{(1)} + R_N^{(2)}] - [R_N^{(3)} + R_N^{(4)}] = 2J\{[C_A - (m_Y - m_N)B_A]^2(1-\xi^2 J) + [\xi C_V + (m_Y - m_N)B_V]^2(1-J)\}. \qquad (14)$$

Further analysis, generally speaking, requires that the expressions obtained upon substitution of (5) in (14) be compared with the experimental dependence of $S^{(i)}$ and $R_N^{(i)}$ on J. Such a comparison, however, requires the accumulation of much statistical material. If, however, we neglect in first approximation quantities of order $(m_Y - m_N)^2 a^2/3$, i.e., leave only the statistical values of the form factors, then (14) can be integrated with respect to J, after which comparison with experiment means simply the counting of the number of points entering into each of the four regions on the diagram. The total probability of decay with entry into the i-th region and the integral asymmetry in the same region are given by

$$dW_i(\boldsymbol{\zeta}_Y; \mathbf{n}_N) = \frac{(m_Y - m_N)^5}{30\pi^3(1+\xi)^3}\frac{d\Omega_N}{4\pi}[s^{(i)} + r_N^{(i)}(\boldsymbol{\zeta}_Y \mathbf{n}_N)]; \qquad (15)$$

if we neglect quantities of order $(m_Y - m_N)^2 a^2/3$ and ξ, then, taking (6) into account:

$$s^{(1)} + s^{(2)} + s^{(3)} + s^{(4)} = 3C_A^2 + C_V^2 - 4(m_Y - m_N)C_A B_A,$$

$$[s^{(1)} + s^{(4)}] - [s^{(2)} + s^{(3)}] = -\frac{3}{8}(C_V^2 + C_A^2),$$

$$[s^{(1)} + s^{(2)}] - [s^{(3)} + s^{(4)}] = -\frac{5}{4}\xi[C_V C_A + (m_Y + m_N)C_A B_V$$
$$+ (m_Y^2 - m_N^2)B_V B_A],$$

$$r_N^{(1)} + r_N^{(2)} + r_N^{(3)} + r_N^{(4)}$$
$$= \frac{5}{2}\left[C_V C_A - \frac{1}{3}(m_Y - m_N)(C_V B_A + 2C_A B_V)\right],$$

$$[r_N^{(1)} + r_N^{(4)}] - [r_N^{(2)} + r_N^{(3)}] = -\tfrac{5}{16}[3C_VC_A + (m_Y - m_N)(C_AB_V - C_VB_A)],$$
$$[r_N^{(1)} + r_N^{(2)}] - [r_N^{(3)} + r_N^{(4)}] = C_A^2 - 2(m_Y - m_N)C_AB_A. \quad (16)$$

It is interesting to note that if estimate (6) is correct then, both in (16) and in (14), the decisive rôle is played in the third expression by the product C_AB_V; the effect itself is in this case of order $(m_Y - m_N)a$, i.e., it is not too small.

Expressions (16) make it possible in principle to determine C_V, C_A, B_V, and B_A in such an approximation, that their dependence on J can be disregarded. If expansion (5) is substituted in (14) for the form factors, then additional terms appear in (16). An experimental determination of $s^{(i)}$ and $r_N^{(i)}$ would then yield six relations between the eight unknowns

$$C_V(0), C_A(0), B_V(0), B_A(0), a(C_V), a(C_A), a(B_V), a(B_A). \quad (17)$$

The additional relations between these quantities, and consequently also the possibility of their determination, can be obtained by investigating the emission asymmetry not of the nucleon alone, but of the electron and neutrino, too. If $R_e(X, J)$ is defined in analogy with (12), its expression is

$$\begin{aligned} R_e(X, J) = {} & \frac{J(1+\xi)^2}{1+X+\xi J}\{-(C_V - C_A)^2\,(1 + X - \xi J) \\ & - (m_Y - m_N)^2 \times (B_V - B_A)^2 J(1 - X - \xi J) \\ & + 2(m_Y - m_N)J(1-\xi)(C_V - C_A)(B_V - B_A)\} \\ & + (C_V^2 + C_A^2)2\xi XJ + (C_V^2 - C_A^2)(1-\xi^2)J \\ & - 2C_VC_A(1 - X^2 - \xi^2J^2) + (m_Y - m_N)^2 J\{-(B_V^2 + B_A^2) \\ & \times 2X + (B_V^2 - B_A^2)(1-\xi^2)J - 2B_VB_A(1 + X^2 - \xi^2J^2)\} \\ & + 2(m_Y - m_N)J\{(C_VB_V + C_AB_A)(1-\xi)X \\ & + (C_AB_A - C_VB_V)(1+\xi)(1-\xi J) + (C_AB_V - C_VB_A) \\ & \times (1+\xi)X + (C_VB_A + C_AB_V)(1-\xi)(1+\xi J)\} \end{aligned} \quad (18)$$

with $R_\nu(X, J)$ obtainable from (18) by substituting $-X$ for X, $-C_A$ for C_A, and $-B_A$ for B_A, and reversing the sign of the entire expression. Integrating R_e and R_ν with respect to X and [after substituting (5)] with respect to J within the limits of each of the four regions in the diagram, and comparing the resultant expressions with the experimental data on the asymmetry of emission of the electron and the neutrino, new relations are obtained between the parameters (17).

To determine the remaining form factors, i.e., $D_V(0)$, $D_A(0)$, and $a(D_V)$, it is necessary to investigate analogously the μ-mesic decays of hyperons, starting with the equations of Appendix A.

4. ENERGY DISTRIBUTION, EMISSION ASYMMETRY, AND POLARIZATION OF THE EMITTED NUCLEONS OR HYPERONS

The energy distribution and the emission asymmetry of N in the case of electronic decays are given by the first and fourth equations of (14). Analogous expressions for μ-mesic decays are obtained by integrating Eqs. (A.1) and (A.2) with respect to X. The result is

$$dW(J; \zeta_Y, \mathbf{n}_N) = \frac{dJ}{24\pi^3}\frac{(m_Y - m_N)^5}{(1+\xi)^3}X_m(J)\left(1 - \frac{\eta}{J}\right)^2\frac{d\Omega_N}{4\pi} \times S_N(J)[1 + \alpha_N(J)(\zeta_Y\mathbf{n}_N)], \quad (19)$$

$$\begin{aligned} S_N(J) = {} & (C_V^2 + C_A^2)\{2 + J + \xi^2J(1-4J) \\ & + \eta[4 - J - \xi^2J(1 + 2J)]/J\} \\ & + 3(C_A^2 - C_V^2)(1-\xi^2)J + 2(m_Y - m_N)^2J(1 + \eta/2J) \\ & \times [B_V^2(1-J)(2+\xi^2J) + B_A^2(2+J)(1-\xi^2J)] \\ & + 3\eta(m_Y - m_N)^2J[D_V^2(1-\xi^2J) + D_A^2\xi^2(1-J)] \\ & - 12(m_Y - m_N)J(1 + \eta/2J)[C_AB_A(1-\xi^2J) \\ & - C_VB_V\xi(1-J)] - 6\eta(m_Y - m_N)[C_VD_V(1-\xi^2J) \\ & - C_AD_A\xi(1-J)]; \end{aligned} \quad (20)$$

$$\begin{aligned} \alpha_N(J) = {} & 4S_N^{-1}(J)X_m(J)\{C_VC_A[1 - 2\xi J + \eta(2-\xi J)/J] \\ & + (m_Y - m_N)^2J(1 + \eta/2J)(2-\xi J)B_VB_A \\ & - \tfrac{3}{2}\eta(m_Y - m_N)^2J\xi D_VD_A - \tfrac{3}{2}\eta(m_Y - m_N) \\ & \times (C_AD_V - C_VD_A\xi) \\ & - (m_Y - m_N)J(1 + \eta/2J)[C_VB_A(1-2\xi) \\ & + C_AB_V(2-\xi)]\}. \end{aligned} \quad (21)$$

The polarization vector of the emitted nucleon (or hyperon) is determined by

$$\mathbf{P}_N = P_1(J)\mathbf{n}_N + P_2(J)\mathbf{n}_N(\zeta_Y\mathbf{n}_N) + P_3(J)[\mathbf{n}_N[\zeta_Y\mathbf{n}_N]], \quad (22)$$

with (the method of calculating P_i was described earlier[5])

$$\begin{aligned} P_1(J)S_N(J)[1 + \alpha_N(J)(\zeta_Y\mathbf{n}_N)] = {} & 4X_m(J)\{C_VC_A[1 + 2\xi J \\ & + (\eta/J)(2+\xi J)] - (m_Y - m_N)^2J(1 + \eta/2J) \\ & \times (2+\xi J)B_VB_A - \tfrac{3}{2}\eta(m_Y - m_N)^2J\xi D_VD_A \\ & - \tfrac{3}{2}\eta(m_Y - m_N)(C_AD_V - C_VD_A\xi) + (m_Y - m_N) \\ & \times J(1 + \eta/2J)[C_AB_V(2+\xi) - C_VB_A(1+2\xi)]\}; \end{aligned}$$

$$\begin{aligned} P_2(J)S_N(J)[1 + \alpha_N(J)(\zeta_Y\mathbf{n}_N)] = {} & (C_V^2 + C_A^2)\{2 - 3J - \xi^2J \\ & \times (3-4J) + \eta[4 - 3J - \xi^2J(3-2J)]/J\} + (C_V^2 - C_A^2) \\ & \times (1-\xi^2)J(1 + 2\eta/J) - 2(m_Y - m_N)^2J(1 + \eta/2J) \\ & \times [B_V^2(1-J)(2-\xi^2J) + B_A^2(2-J)(1-\xi^2J)] \\ & + 3\eta(m_Y - m_N)^2J[D_V^2(1-\xi^2J) + D_A^2\xi^2(1-J)] \\ & + 4(m_Y - m_N)J(1 + \eta/2J)[C_AB_A(1-\xi^2J) \\ & - C_VB_V\xi(1-J)] - 6\eta(m_Y - m_N)[C_VD_V(1-\xi^2J) \\ & - C_AD_A\xi(1-J)]; \end{aligned}$$

$$P_3(J)\,S_N(J)\,[1+\alpha_N(J)(\zeta_Y \mathbf{n}_N)] = -(C_V^2+C_A^2)(1-\xi^2)J(1-\eta/J) + (C_V^2-C_A^2)(1+2\eta/J)(2-J-\xi^2 J) - 2(m_Y-m_N)^2 J^2(1+\eta/2J)[B_A^2(1-\xi^2 J)-B_V^2\xi^2(1-J)] + 3\eta(m_Y-m_N)^2 J[D_V^2(1-\xi^2 J)-D_A^2\xi^2(1-J)] + 4(m_Y-m_N)J(1+\eta/2J)[C_A B_A(1-\xi^2 J) + C_V B_V \xi(1-J)] - 6\eta(m_Y-m_N)[C_V D_V(1-\xi^2 J) + C_A D_A \xi(1-J)]. \quad (23)$$

We see that (20) — (23) do not contain interferences between the form factors B and D. In addition, S_N, P_2, and P_3 have no "cross products" C_VC_A, C_VB_A, C_VD_A, C_AB_V, C_AD_V, B_VB_A, or D_VD_A, which enter only in α_N and P_1. This is the consequence of certain formal properties of the invariance of the matrix element (2) — (3), discussed in reference 10.

To obtain the energy distribution and the emission asymmetry for l (or $\bar{\nu}$), it is necessary to integrate over variable N and $\bar{\nu}$ (or l). It is possible to obtain in this manner also the polarization of the emitted muons (the electrons should be almost totally polarized). The foregoing integration can be performed, however, only by specifying a concrete dependence of the form factors on Q^2, such as the expansion (5). The results are too cumbersome and will not be written out here.

Similarly, to obtain the total decay probability and emission asymmetry of N, it is necessary to integrate over J in (19) — (21) and substitute (5) therein. If quantities of order ξ^2, $\xi(m_Y-m_N)^2a^2$, and $(m_Y-m_N)^4a^4$ are neglected and the estimate (6) is used, the integration is easy. In this approximation, the total decay probability is

$$W = \frac{1}{30\pi^3}\frac{(m_Y-m_N)^5}{(1+\xi)^3}\{[C_V^2(0)+3C_A^2(0)]\sigma_1 + \tfrac{1}{3}(m_Y-m_N)^2[B_V^2(0)(-4\sigma_2-(4-2\eta)\sigma_1+2\eta\sigma_0) + B_A^2(0)(2\sigma_2+(4+\eta)\sigma_1+2\eta\sigma_0)] + \eta(m_Y-m_N)^2 D_V^2(0)\sigma_1 - 2\eta(m_Y-m_N)[C_V(0)D_V(0)\sigma_0 + C_A(0)D_A(0)\xi(\sigma_1-\sigma_0)] - 2(m_Y-m_N)[C_A(0)B_A(0) \times(2\sigma_1+\eta\sigma_0) + C_V(0)B_V(0)\xi(2\sigma_2-(2-\eta)\sigma_1-\eta\sigma_0)] - \tfrac{1}{9}(m_Y-m_N)^2[C_V^2(0)\,a^2(C_V)+C_A^2(0)\,a^2(C_A)] \times[\sigma_2+(2-\eta)\sigma_1+4\eta\sigma_0] - \tfrac{1}{3}(m_Y-m_N)^2[C_A^2(0)\,a^2(C_A) - C_V^2(0)\,a^2(C_V)]\sigma_2 + a^2(B_A)](2\sigma_2+\eta\sigma_1) + \tfrac{1}{3}(m_Y-m_N)^3 C_A(0)B_A(0)[a^2(C_A) + \tfrac{1}{3}\eta(m_Y-m_N)^3 C_V(0)D_V(0) \times[a^2(C_V)+a^2(D_V)]\sigma_1\}. \quad (24)$$

The quantities

$$\sigma_k \equiv \frac{15}{4}\int_\eta^1 dJ\sqrt{1-J}\,(1-\eta/J)^2 J^k$$

have values

$$\sigma_0 = \frac{5}{4}(2+13\eta)\sqrt{1-\eta} - \frac{15}{8}\eta(4+\eta)\ln\left|\frac{1+\sqrt{1-\eta}}{1-\sqrt{1-\eta}}\right|,$$

$$\sigma_1 = \left(1-\frac{9}{2}\eta-.4\eta^2\right)\sqrt{1-\eta} + \frac{15}{4}\eta^2\ln\left|\frac{1+\sqrt{1-\eta}}{1-\sqrt{1-\eta}}\right|,$$

$$\sigma_2 = \frac{4}{7}(1-\eta)^3\sqrt{1-\eta}. \quad (25)$$

To estimate the probabilities of leptonic hyperon decays, one can put in (24) $B_V = B_A = D_V = D_A = 0$, $a(C_V) = a(C_A) = 0$, and $C_V = -C_A = G/\sqrt{2}$. We give below a table of the probabilities thus calculated. Also given are the values of ξ, η (for $l = \mu$), τ (the experimental lifetime of the hyperon), and $W_l\tau$ (ratio of the number of events of corresponding lepton decay to the total number of hyperon decay). The last two columns list the experimental values[2] of $W_l\tau$. In the case of Ξ^- decays, $W_l\tau$ is assumed to be less than 0.7, since up to now 14 $\Xi^- \to \Lambda + \pi^-$ events have been observed,[17,11] but not a single leptonic decay. For the sake of completeness, the table includes the decays $\Sigma^+ \to n + l^+ + \nu$ for a reduction of 1 in the baryon charge and $\Xi^- \to n + l^- + \bar{\nu}$ for a change of 2 in strangeness.

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

The table includes also the decays $\Sigma^+ \to n + e^\pm + \nu(\bar{\nu})$, in which both baryons have the same strangeness, as in ordinary β decay. According to reference 3, the divergence of the current responsible for these processes is equal to zero. This means[12,13] that in (3) we have for the same spatial parity of Σ and Λ

$$C_V = D_V Q^2/(m_\Sigma - m_\Lambda), \quad (26)$$

and for different parity

$$C_A = -D_A Q^2/(m_\Sigma + m_\Lambda). \quad (27)$$

It is seen from (26) and (27) that as $Q^2 \to 0$, $C_V(C_A)$ also vanishes. This is the consequence of the absence of a direct interaction, responsible for the decay $\Sigma \to \Lambda + e + \nu$, if the divergence of the vector portion of the baryon current is zero.[14] It is therefore natural to turn again to the analogy with electrodynamics and, assuming as in Sec. 2 that $C_V(C_A) \sim GQ^2a^2/6\sqrt{2}$, put $a \sim 0.8 \times 10^{-13}$ cm. In this case $C_V(C_A) \lesssim 0.014\,G/\sqrt{2}$, i.e., it is sufficiently small. Inasmuch as the form factor $C_A(C_V)$ should not vanish as $Q^2 \to 0$, there are

Type of decay	ξ	η	$10^{10}\tau$, sec	W_e, sec^{-1}	W_μ, sec^{-1}	$W_e\tau$, %	$W_\mu\tau$, %	Experimental values	
								$W_e\tau$, %	$W_\mu\tau$, %
$\Lambda \to p + l^- + \bar{\nu}$	0.086	0.355	2.8	$5.8 \cdot 10^7$	$9.4 \cdot 10^6$	1.7	0.26	~0.13	<0.12
$\Sigma^- \to n + l^- + \bar{\nu}$	0.12	0.17	1.7	$3.4 \cdot 10^8$	$1.5 \cdot 10^8$	5.7	2.5	≲0.5	≲0.5
$\Xi^- \to \Lambda + l^- + \bar{\nu}$	0.084	0.265	~2	$1.2 \cdot 10^8$	$3.2 \cdot 10^7$	2.4	0.64	<7	<7
$\Xi^- \to \Sigma^0 + l^- + \bar{\nu}$	0.052	0.66	~2	$1.4 \cdot 10^7$	$2.1 \cdot 10^5$	0.3	0.004	<7	<7
$\Sigma^+ \to n + l^+ + \nu$	0.12	0.18	0.8	$3.0 \cdot 10^8$	$1.3 \cdot 10^8$	2.4	1.0	<1.1	<1.3
$\Xi^- \to n + l^- + \bar{\nu}$	0.17	0.077	~2	$2.1 \cdot 10^9$	$1.5 \cdot 10^9$	40	30	<7	<7
$\Sigma^- \to \Lambda + e^- + \bar{\nu}$	0.035		1.7	$1.4 \cdot 10^6$		0.024			
$\Sigma^+ \to \Lambda + e^+ + \nu$	0.032		0.8	$8.6 \cdot 10^5$		0.007			

no grounds for assuming it to be as small. Therefore one can expect in the decays $\Sigma \to \Lambda + e + \nu$ that $C_A \gg C_V$ $(C_V \gg C_A)$. There are less grounds for assuming that $C_A \gg B_V$ $(m_\Sigma - m_\Lambda)$ $[C_V \gg B_A$ $(m_\Sigma - m_\Lambda)]$, but if it assumed in analogy with (6) that $B \sim Ga/\sqrt{2}$, then when $a \sim 0.8 \times 10^{-13}$ cm we have $(m_\Sigma - m_\Lambda) a \sim 1/3$, i.e., an additional small factor arises. If the foregoing inequalities are correct, then according to (19) — (23) the asymmetry of emission of $\Lambda(\alpha)$ and the polarization of $\Lambda(P_1)$ will be small in the decay of unpolarized Σ. It would be interesting to verify this fact experimentally.

Unfortunately, the $\Sigma \to \Lambda + e + \nu$ decays can hardly be observed in the near future; the lack of a direct decay current $[\bar{\psi}_\Lambda \gamma_\mu (1 + \gamma_5) \psi_\Sigma]$ can reduce the decay probability by an additional several times.

APPENDIX

A. Energy Correlation and Asymmetry of Hyperon Decay

The formulas for $S(X, J)$ and $R_N(X, J)$, determined in accordance with (12), are

$$\begin{aligned} S(X, J) = {} & (C_V^2 + C_A^2)\{1 - X^2 - \xi^2 J^2) + \eta[(1 - X)^2 - \xi^2 J^2]/J\} \\ & + (C_A^2 - C_V^2)(1 - \xi^2) J - 4 C_V C_A \xi X J \\ & + (m_Y - m_N)^2 J \{(B_V^2 + B_A^2)[(1 + X^2 - \xi^2 J^2) \\ & + \eta[1 - X^2 - J(1 + \xi^2)/2]/J] + (B_A^2 - B_V^2)(1 + \eta/2J) \\ & \times (1 - \xi^2) J + 4 B_V B_A X\} + \eta (m_Y - m_N)^2 J \{D_V^2 (1 - \xi^2 J) \\ & + D_A^2 \xi^2 (1 - J)\} + 4(m_Y - m_N) J \{-C_A B_A [(1 - \xi^2 J) \\ & + \eta(1 - X - \xi^2 J)/2J] + C_V B_V \xi [1 - J \\ & + \eta(1 - J - X)/2J] - C_A B_V X \\ & + C_V B_A \xi X\} \\ & - 2\eta (m_Y - m_N)\{C_V D_V (1 - \xi^2 J - X) \\ & - C_A D_A \xi (1 - J - X)\} \\ & + 2\eta (m_Y - m_N)^2 (B_V D_V + B_A D_A) \xi X J. \end{aligned} \tag{A.1}$$

$$\begin{aligned} R_N(X, J) = {} & 2X_m(J)\{[C_A^2(1 - \xi^2 J) + C_V^2 \xi^2 (1 - J)] X J / X_m^2 \\ & + C_V C_A [(1 - \xi J) - X^2 (1 + \xi J)/X_m^2 + \eta\{(1 - \xi J) \\ & + X^2 (1 + \xi J)/X_m^2 - X[2 - J(1 + \xi^2)]/X_m^2\}/J] \\ & + (m_Y - m_N)^2 X J [B_V^2 (1 - J) + B_A^2 (1 - \xi^2 J)]/X_m^2 \\ & + (m_Y - m_N)^2 J B_V B_A [(1 - \xi J) + X^2 (1 + \xi J)/X_m^2 \\ & + \eta\{1 - X^2 X_m^{-2}(1 + \xi J)\}/J] - \eta (m_Y - m_N)^2 J \xi D_V D_A \\ & - 2(m_Y - m_N) J X X_m^{-2} [C_A B_A (1 - \xi^2 J) \\ & - C_V B_V \xi (1 - J)] - (m_Y - m_N) J C_A B_V [(1 - \xi) \\ & + X^2 (1 + \xi)/X_m^2 + (\eta/J)\{1 - X^2 (1 + \xi)/X_m^2 + \xi X \\ & \times (1 - J)/X_m^2\}] \\ & - (m_Y - m_N) J C_V B_A [(1 - \xi) - X^2 (1 + \xi)/X_m^2 \\ & - \eta J^{-1} \times \{\xi - X^2 (1 + \xi)/X_m^2 + X(1 - \xi^2 J)/X_m^2\}] \\ & - \eta (m_Y - m_N)[C_A D_V \{1 - X(1 - \xi^2 J)/X_m^2\} \\ & - C_V D_A \xi \{1 - X(1 - J)/X_m^2\}] \\ & - \eta (m_Y - m_N)^2 X J X_m^{-2} \\ & \times [B_A D_V (1 - \xi^2 J) + B_V D_A \xi^2 (1 - J)]\}. \end{aligned} \tag{A.2}$$

B. Variants of Decay Interaction

The universal V-A interaction scheme[3,4] is at present in splendid agreement with all experimental data on β decay, K capture, induced antineutrino absorption, and pion and muon decay. An extension of this scheme to include the decays of strange particles is at the same time a hypothesis, the likelihood of which is based essentially on the agreement between the orders of magnitude of the decay constants of strange and ordinary particle. Contemporary experimental data[2] indicate, in particular, that the $\Lambda \to p + e^- + \bar{\nu}$ decay is approximately one-tenth as frequent as in the universal V-A scheme without renormalization. This agrees both with the relatively low probability of $K_{\mu 2}$, $K_{\mu 3}$, and K_{e3} decays,[13,15] and with the fact that in the V-A scheme one must have a renormalization of the decay constants[16,14] which can fully lead to their reduction by a factor of several times. At the same time, the rule $\Delta T = \pm 1/2$, which holds with good accuracy for leptonless decays of strange particles,[17,18] is accidental in the Feynman-Gell-Mann theory, if one excludes from it the neutral baryon and meson currents. In the latter case, the universality of the scheme would necessitate also the introduction of neutral lepton currents, which would lead to the presence of the decays $K^0 \to \mu^+ + \mu^-$, $K^+ \to \pi^+ + e^+ + e^-$, $K^+ \to \pi^+ + \nu + \bar{\nu}$, and $K^+ \to \pi^+ + \mu^+ + \mu^-$, which have not been observed experimentally. Therefore, the extent to which the V-A scheme describes the decay of strange particles remains, strictly speaking, moot.

The fullest answer to this question could be obtained by an experimental study of leptonic hyperon decays. The determination of the variations of decay interaction, to be sure, is made difficult here by the presence of many (12) energy-dependent form factors, the determination of which calls for an accuracy and completeness of experimental data hardly attainable now. The problem becomes much simpler if the contribution from the form factors is assumed small. Under this assumption one can start the calculations with the form of the Lee-Yang matrix element of the S matrix

$$i(2\pi)^4\delta(p_Y - p_N - p_l - p_\nu)\sum_{j=1}^{5}(\bar{u}_N O_j u_Y)(\bar{u}_l O_j (C_j + C_j'\gamma_5) u_\nu), \tag{A.3}$$

where

$$O_j = 1,\ \gamma_5,\ 2^{-1/2}\sigma_{\alpha\beta},\ \gamma_\mu,\ i\gamma_\mu\gamma_5,$$

and C_j and C_j' are assumed constant.

If the energy correlation and the decay asymmetry are investigated on the basis of the matrix element (A.3), the following expressions will hold for $S(X, J)$, and $R_N(X, J)$, determined according to (12),

$$S(X,J) = (a_{VV} + a_{AA})\{(1 - \xi^2J^2 - X^2) + \eta J^{-1}[(1 - X)^2 - \xi^2J^2]\} + (a_{AA} - a_{VV})(1 - \xi^2)J - 4a_{AV}\xi XJ$$
$$+ J[a_{SS}(1 - \xi^2J) + a_{PP}\xi^2(1 - J) - 2(a_{ST} + a_{PT})\xi X] + a_{TT}\{[2 - 2X^2 - J - \xi^2J] + 2\eta J^{-1}[(1 - X)^2 - \xi^2J^2]\}$$
$$+ 2\eta^{1/2}[(a_{SV} + 3a_{AT})(1 - X - \xi^2J) + \xi(a_{PA} + 3a_{VT})(1 - X - J)]; \tag{A.4}$$

$$R_N(X,J) = 2X_m(J)\{[b_{AA}(1 - \xi^2J) + b_{VV}\xi^2(1 - J)]XJ/X_m^2 + b_{VA}[(1 - \xi J) - X^2(1 + \xi J)/X_m^2 + \eta J^{-1}\{(1 - \xi J)$$
$$+ X^2(1 + \xi J)/X_m^2 - X[2 - J(1 + \xi^2)]/X_m^2\}] + J[b_{SP}\xi - XX_m^{-2}\{b_{ST}(1 - \xi^2J) + b_{PT}\xi^2(1 - J)\}]$$
$$- b_{TT}[1 - X^2(1 + \xi J)/X_m^2 + \eta J^{-1}\{(1 - \xi J) + X^2(1 + \xi J)/X_m^2 - X[2 - J(1 + \xi^2)]/X_m^2\}] + \eta^{1/2}b_{AS}[1 - X(1 - \xi^2J)/X_m^2]$$
$$+ \eta^{1/2}\xi b_{VP}[1 - X(1 - J)/X_m^2] - \eta^{1/2}b_{AT}[2 - \xi - XX_m^{-2}\{2 - \xi(1 - J) - 2\xi^2J\}]$$
$$+ \eta^{1/2}b_{VT}[1 - 2\xi - XX_m^{-2}\{1 - 2\xi(1 - J) - \xi^2J\}]\}, \tag{A.5}$$

where

$$a_{jk} \equiv (C_jC_k + C_j'C_k')/2, \qquad b_{jk} \equiv (C_jC_k' + C_j'C_k)/2. \tag{A.6}$$

An analysis fully analogous to the one of Sec. 3, allows separation of the coefficients of the different powers of X in (A.4) and (A.5). In the case of electronic decays ($\eta = 0$) and neglecting terms of order ξ, one can obtain, as in (16),

$$s^{(1)} + s^{(2)} + s^{(3)} + s^{(4)} = a_{SS} + a_{VV} + 3(a_{AA} + a_{TT}),$$
$$[s^{(1)} + s^{(4)}] - [s^{(2)} + s^{(3)}] = -\tfrac{3}{8}(a_{VV} + a_{AA} + 2a_{TT}),$$
$$[s^{(1)} + s^{(2)}] - [s^{(3)} + s^{(4)}] = -\tfrac{5}{8}\xi(a_{ST} + a_{PT} + 2a_{VA}),$$
$$r_N^{(1)} + r_N^{(2)} + r_N^{(3)} + r_N^{(4)} = \tfrac{5}{2}(b_{VA} - b_{TT}),$$
$$[r_N^{(1)} + r_N^{(4)}] - [r_N^{(2)} + r_N^{(3)}] = -\tfrac{15}{16}(b_{VA} - b_{TT}),$$
$$[r_N^{(1)} + r_N^{(2)}] - [r_N^{(3)} + r_N^{(4)}] = b_{AA} - b_{ST}. \tag{A.7}$$

For the asymmetry of emission of l, in the case of electronic decays, the following expression holds

$$R_e(X,J) = -J(1 + \xi)^2(1 + X - \xi J)(1 + X + \xi J)^{-1}$$
$$\times [(b_{VV} + b_{AA} - b_{TS} - b_{TP}) - 2(b_{VA} - b_{TT})]$$
$$+ (b_{VV} + b_{AA} - b_{TS} - b_{TP})$$
$$\times 2\xi XJ - (b_{AA} - b_{VV} + b_{TP} - b_{TS})(1 - \xi^2)J$$
$$- 2(b_{VA} - b_{TT})(1 - X^2 - \xi^2J^2)$$
$$- 2(b_{SP} - b_{TT})\xi J[1 + \xi J - J(1 + \xi)^2/(1 + X + \xi J)]. \tag{A.8}$$

As in (A.7), we neglect terms of order ξ and obtain

$$r_e^{(1)} + r_e^{(2)} + r_e^{(3)} + r_e^{(4)} = -2[(b_{AA} - b_{TS}) + (b_{VA} - b_{TT})],$$
$$[r_e^{(1)} + r_e^{(4)}] - [r_e^{(2)} + r_e^{(3)}] = \tfrac{3}{4}(b_{VA} - b_{TT}),$$
$$[r_e^{(1)} + r_e^{(2)}] - [r_e^{(3)} + r_e^{(4)}] = \tfrac{5}{24}\xi\{(b_{VV} + b_{AA} - b_{TS}$$
$$- b_{TP}) + 2(2b_{VA} - b_{TT} - b_{SP})\}. \tag{A.9}$$

$R(X, J)$ is obtained from (A.8) by reversing the sign of X and of the constants C_T, C'_T, C_V, and C'_A, followed by reversal of the sign of the entire expression. It is easily seen that knowledge of (A.7) and (A.9) alone is not enough for the determination of the variants of the decay interactions, since these formulas yield only the combinations of constants

$$a_{VV}+a_{AA}+2a_{TT},\ b_{VA}-b_{TT},$$
$$a_{AA}-a_{VV}-a_{TT}+a_{SS},\ b_{AA}-b_{ST} \qquad (A.10)$$

(the combinations of constants which are further multiplied by ξ cannot be determined with any degree of accuracy, since the unaccounted form factors should make a large contribution to the corresponding terms).

Such a result was obvious from the very outset, since the transition from the V-A to the S+P-T variant for C′ = C leads in the case of hyperon decay, as shown in the Appendix of reference 5, only to a reversal of the polarization of N and l, and this cannot affect in any manner the energy distribution and asymmetry of emission of N, l, and $\bar{\nu}$. To determine the decay interaction it is therefore necessary to study the polarization of N or l. In particular, in the case of electronic decays the polarization of N can be determined from the formulas of reference 19, where the muon decay is calculated, by making the substitutions $\mu \to Y$, $e \to N$. In our notation, these formulas are [S_N, α_N, and P_i are determined from (19) and (22)]:

$$S_N(J)=2a_{AA}(1+2J)(1-\xi^2J)+2a_{VV}(1-J)(1+2\xi^2J)$$
$$+3a_{SS}J(1-\xi^2J)+3a_{PP}\xi^2J(1-J)$$
$$+a_{TT}[4-J-\xi^2J(1+2J)],$$

$$\alpha_N(J)=2S_N^{-1}(J)X_m(J)\{2b_{VA}(1-2\xi J)$$
$$+3b_{SP}\xi J-b_{TT}(2-\xi J)\},$$

$$P_1(J)=2S_N^{-1}(J)[1+\alpha_N(J)(\zeta_Y\mathbf{n}_N)]^{-1}X_m(J)\{2b_{VA}(1+2\xi J)$$
$$+3b_{SP}\xi J+b_{TT}(2+\xi J)\},$$

$$P_2(J)=S_N^{-1}(J)[1+\alpha_N(J)(\zeta_Y\mathbf{n}_N)]^{-1}\{2a_{VV}(1-J)(1-2\xi^2J)$$
$$+2a_{AA}(1-2J)(1-\xi^2J)+3a_{SS}J(1-\xi^2J)$$
$$+3a_{PP}\xi^2J(1-J)-a_{TT}[4-3J-\xi^2J(3-2J)]\},$$

$$P_3(J)=S_N^{-1}(J)[1+\alpha_N(J)(\zeta_Y\mathbf{n}_N)]^{-1}\{2a_{VV}(1-J)$$
$$-2a_{AA}(1-\xi^2J)+3a_{SS}J(1-\xi^2J)$$
$$-3a_{PP}\xi^2J(1-J)-a_{TT}(1-\xi^2)J\}. \qquad (A.11)$$

When $\xi \ll 1$, we obtain in (A.11) $\alpha_N S_N = 4(b_{VA}-b_{TT})$, $P_1 \sim (b_{VA}+b_{TT})$, i.e., a study of the asymmetry of emission as well as the polarization of N make it possible to determine the variant of the decay interaction. The situation here is fully analogous with the case of muon decay.[19]

The formulas for the polarization of l when $\xi \ll 1$ coincide with the known expression for electron polarization in the decay of the free neutron.

To find the polarization of Λ in the decay $\Xi^- \to \Lambda + l^- + \bar{\nu}$ one can use the known asymmetry of the decay $\Lambda \to p + \pi^-$. Analogously, in the decays $Y \to N + \mu + \nu$ the polarization of μ leads to asymmetry of the decay $\mu \to e + \nu + \bar{\nu}$.

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