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LEPTONIC DECAYS OF HYPERONS WITH EMISSIONS OF PIONS

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The total probabilities for leptonic decays of hyperons with emission of a pion, $Y \to N(Y') + l + \nu + \pi$, ($l$ denotes an electron or μ meson) are estimated in the case of the simplest matrix element of the universal V-A interaction for one of the possible perturbation theory diagrams.

In view of the successes of the universal theory of weak interactions[1] it is of interest to study theoretically leptonic decays of hyperons. The probability of such decays was first obtained by Behrends and Fronsdal[2] and Feynman and Gell-Mann,[1] and the energy spectra and angular distributions by Shekhter;[3,4] experimentally a few events of leptonic hyperon decays were observed.[5]

In this work we consider hyperon decay processes of the type

$$Y \to N(Y') + l + \nu + \pi, \tag{1}$$

where in addition to leptons a pion is emitted:

$$\Lambda^0 \to n + l^- + \tilde{\nu} + \pi^+, \quad \Lambda^0 \to p + l^- + \tilde{\nu} + \pi^0;$$
$$\Sigma^- \to n + l^- + \tilde{\nu} + \pi^0, \quad \Sigma^- \to p + l^- + \tilde{\nu} + \pi^-,$$
$$\Sigma^+ \to p + l^- + \tilde{\nu} + \pi^+; \quad \Xi^- \to \Lambda^0 + l^- + \tilde{\nu} + \pi^0,$$
$$\Xi^0 \to \Lambda^0 + l^- + \tilde{\nu} + \pi^+$$

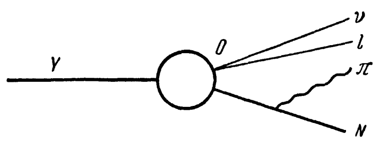
[the letters and subscripts Y, N, π, l (μ, e), ν refer here and in the following to hyperons, nucleons, pions, charged leptons (μ meson, electron), and neutrinos]. All these decays are described (see Okun'[6]) by the universal weak interaction Hamiltonian

$$H_{\text{inc}} = (G/\sqrt{2})(\bar{\psi}_N \gamma_\alpha (1 + \gamma_5)\psi_Y)(\bar{\psi}_l \gamma_\alpha (1 + \gamma_5)\psi_\nu) \tag{2}$$

(we consider the case $C_V = -C_A = G/\sqrt{2}$). In the absence of a consistent theory of strong interactions we use for the description of process (1) a phenomenological matrix element. The invariant matrix element for the strongly interacting particles in this process contains eight unknown scalar functions of the invariants constructed out of the four-momenta of the various interacting particles and can be written as

$$M'_\alpha = f_1\gamma_\alpha + f_2(\gamma_\alpha\hat{k} - \hat{k}\gamma_\alpha) + f_3k_\alpha + f_4p_{\pi\alpha}$$
$$+ g_1\gamma_\alpha\gamma_5 + g_2(\gamma_\alpha\hat{k} - \hat{k}\gamma_\alpha)\gamma_5 + g_3k_\alpha\gamma_5 + g_4p_{\pi\alpha}\gamma_5, \tag{3}$$

where $k = p_l + p_\nu$, p being the four-momentum of the particle in question. We make use of one of the possible perturbation theory diagrams (see figure) to estimate the probability of the decay (1); the weak interaction acts at the point O and the loop represents the virtual strong interactions.



Since it is not possible at this time to determine the unknown functions f and g we consider the simplest case obtained by taking $f_1 = g_1 = 1$ and f_i, $g_i = 0$ ($i = 2, 3, 4$), the matrix element for the decay (1) becomes

$$M = \frac{G}{(2\pi)^8\sqrt{2}}\left(\bar{\psi}_N\gamma_5\frac{g}{\sqrt{4\pi E_\pi}}\frac{1}{\hat{p}_N + \hat{p}_\pi - m_N}(1 + \gamma_5)\gamma_\alpha\psi_Y\right)$$
$$\times (\bar{\psi}_l(1 + \gamma_5)\gamma_\alpha\psi_\nu), \tag{4}$$

where g is the strong interaction coupling constant ($g^2/4\pi = 14$). E and m are the total energy and mass of the particle and we use the system of units in which $\hbar = c = 1$.

The decay probability is calculated from the usual formula

$$W = (2\pi)^{-8}\int \langle |M|^2\rangle d^3p_N d^3p_\pi d^3p_l d^3p_\nu \delta(p_Y - p_N - p_\pi - p_l - p_\nu);$$

where we make use of the method of Dalitz[7] (see also Okun' and Shebalin[8]) to reduce the integration over d^3p_N, d^3p_π, d^3p_l, d^3p_ν to the invariant integration over d^4Q^*, d^4R^* ($Q^* = p_l + p_\nu$, $R^* = p_l - p_\nu$) followed by the integration over d^4Q, d^4R ($Q = p_N + p_\pi$, $R = p_N - p_\pi$).

Neglecting the electron mass in comparison with the masses of all other particles and assuming that the condition $\Delta/m_Y \ll 1$ is satisfied, where $\Delta = m_Y - (m_N + m_\pi)$, we find for the decays (1) with the emission of an electron or μ meson respectively the following expressions for the total

Decay	τ_e, sec	τ_μ, sec	$10^6\,\tau_e^{Sh}$, sec	$10^6\,\tau_\mu^{Sh}$, sec	$10^{10}\,\tau$, sec
$\Lambda^0 \to p + l^- + \tilde{\nu} + \pi^0$	29	—	1.7	10.6	2.4
$\Lambda^0 \to n + l^- + \tilde{\nu} + \pi^+$	76	—			2.4
$\Sigma^- \to n + l^- + \tilde{\nu} + \pi^0$	0.48	3.15	0.3	0.7	1.7
$\Sigma^- \to p + l^- + \tilde{\nu} + \pi^-$	0.57	0.79			1.7
$\Sigma^+ \to p + l^- + \tilde{\nu} + \pi^+$	0.77	0.93			0.8
$\Xi^- \to \Lambda^0 + l^- + \tilde{\nu} + \pi^0$	0.0033	—	0.8	3.1	~10
$\Xi^0 \to \Lambda^0 + l^- + \tilde{\nu} + \pi^+$	0.0051	—			~10

probabilities:*

$$W \approx \frac{2^7 G^2 (g^2/4\pi)}{1\cdot3\cdot5\cdot7\cdot9\cdot11\cdot13\pi^5}\left(\frac{m_N}{2m_Y}\right)^{3/2}\frac{\sqrt{m_\pi}\,\Delta^{13/2}}{(m_Y+m_N-\Delta/2)(1-\Delta/2m_Y)^{3/2}(1+\Delta/2m_\pi)^2}, \tag{5}$$

$$W \approx \frac{G^2 (g^2/4\pi)}{2^7\cdot 3\pi^4}\left(\frac{m_N}{2m_Y}\right)^{3/2}\frac{\sqrt{m_\pi}\sqrt{\Delta/2+3m_\pi/2}\,K^6}{(m_Y+m_N-\delta/2)(1-\delta/2m_Y)^{3/2}(1+\delta/2m_\pi)^2}, \tag{6}$$

where

$$K^6 = \Big[\left(\Delta^4 - \tfrac{1}{6} m_\pi^2\Delta^2 + \tfrac{41}{24} m_\pi^4\right)\Delta^{*2} + \left(\tfrac{1}{3} m_\pi^2\Delta - 4\Delta^3\right)\tfrac{1}{2}\Delta^{*3} + \left(6\Delta^2 - \tfrac{1}{6} m_\pi^2\right)\tfrac{5}{16}\Delta^{*4} - \tfrac{7}{8}\Delta\Delta^{*5} + \tfrac{21}{128}\Delta^{*6} - \tfrac{61}{3} m_\pi^6\left(1 - \frac{\Delta^*}{2\sqrt{\Delta m_\pi}}\right)\Big],$$

$$\Delta^* = m_Y - (m_N + m_\pi + m_\mu) = \Delta - m_\mu,$$

$$\delta = m_Y - m_N - m_\pi + m_\mu = \Delta + m_\mu.$$

It follows from a comparison of theory and experiment for hyperon leptonic decays (see Shekhter[4]) that the effective weak interactions coupling constant is approximately an order of magnitude smaller than its usual value $G = 10^{-5}/m_p^2$ (m_p — mass of the proton). This fact may be due to a renormalization of the C_V and C_A coupling constants due to the strong interactions. Following Shekhter[4] we take $G = 10^{-6}/m_p^2$. The table shows the hyperon lifetimes τ_e and τ_μ, corresponding to electron and μ-meson decays with the emission of a pion, as calculated from Eqs. (5) and (6) using the above value for the coupling constant. For purposes of comparison we also list in the table the hyperon lifetimes τ_e^{Sh} and τ_μ^{Sh} referring to the normal leptonic decays and taken from Shekhter.[4] The lifetimes τ_e, τ_μ for the cascade hyperon were calculated from Eqs. (5) and (6) with the nucleon mass replaced by the mass of the lambda particle; the crossed out entries refer to reactions energetically forbidden.

*It should be noted that the transition to the limit $m_\pi = 0$ is not allowed in Eqs. (5) and (6), since they were derived on the assumption $2m_\pi \gg \Delta$ or Δ^*.

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