COMITATO NAZIONALE PER L'ENERGIA NUCLEARE
Laboratori Nazionali di Frascati

LNF-62/29

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Nota interna: n° 132
18 Aprile 1962

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A. Fujii: BETA DECAY OF HYPERONS VIA K' PARTICLE.

Recent experiments(1) confirmed the fact that the observed beta decay rate of the hyperon is an order of magnitude smaller than that predicted by the unrenormalized universal V - A theory(2). This suggests either the universality breaks down or the renormalization effects are of vital importance if the conventional V - A theory still holds in this process. The vector and axial vector weak current between the hyperon and nucleon can be written in a general form, on the basis of covariance,

$$\langle N|V_\mu|Y\rangle = \bar{u}_N [f_1(s)\gamma_\mu + f_2(s)\sigma_{\mu\nu}\frac{k_\nu}{m_N} + f_3(s)\frac{k_\mu}{m_N}] u_Y$$

$$\langle N|P_\mu|Y\rangle = \bar{u}_N [g_1(s)\gamma_\mu + g_2(s)\sigma_{\mu\nu}\frac{k_\nu}{m_N} + g_3(s)\frac{k_\mu}{m_N}] \gamma_5 u_Y$$

where the six form factors f and g are functions of the foursquare of the momentum transfer k,

$$s = k^2, \qquad k = P_Y - P_N .$$

Several(3-6) authors made use of the dispersion theoretic approach to compute these form factors. The intermediate states which connect the hyperon-nucleon current and the lepton current must be characterized by charge -1, strangeness -1, angular momentum either 0 or 1. Only two simple states, i.e. the single kaon state and the single kaon plus single pion state, were included in the computation so far. Their conclusions may be summarized briefly as follows[6]. In case of the ΛNK relative parity odd and $\Lambda\Sigma$ parity even, the single kaon state contributes only to g_3. The kaon plus pion state makes a contribution to all f's, but those to f_1 and f_2 are negligibly small. However, the form factors f_3 and g_3 have very little effect on the decay rate, because when the accompanying operator K_μ/m_N is transfered to the lepton current it yields a small factor m_e/m_N:

$$K_\mu \bar{u}_e \gamma_\mu (1+\gamma_5) u_\nu = \bar{u}_e (\not{p}_e + \not{p}_\nu)(1+\gamma_5) u_\nu = i m_e \bar{u}_e (1+\gamma_5) u_\nu \ .$$

Thus the decay rate is mainly controlled by the "subtraction constants" $f_1(0)$ and $g_1(0)$, which the theory leaves undetermined. When f_1 and g_1 are normalized such that the case

$$f_1(0) = g_1(0) = 1$$

corresponds to the unrenormalized V - A theory, the decay rate reads, e.g. for the Λ hyperon[7],

$$w(\Lambda_\beta) = 1.43 \times 10^7 \ sec^{-1} \left[|f_1(0)|^2 + 2.96 \, |g_1(0)|^2 \right] \ .$$

A further dynamical model is required to find the "renormalized coupling costants" $f_1(0)$ and $g_1(0)$. For the nucleon beta decay the hypotesis of partially conserved axial vector current[8] was remarkably successful. This hy pothesis assumes that the divergence of the axial vector nucleon current P'_μ is proportional to renormalized pion field

$$\partial_\mu P'_\mu = i a_\pi \phi_\pi ,$$

where the real constant a is determined by the pion decay rate

$$w(\pi^+ \to \mu^+ + \nu) = \frac{G^2}{8\pi m_\pi}\left(\frac{m_\mu}{m_\pi}\right)^2\left(1-\frac{m_\mu^2}{m_\pi^2}\right)^2 a_\pi^2 ,$$

G being the Fermi constant

$$G m_N^2 \sim 1.0 \times 10^{-5} ,$$

The renormalized axial vector coupling constant G_A for nucleon beta decay is then shown to be related to the renormalized pion-nucleon coupling constant g_π by

$$\lambda \equiv \frac{G_A}{G} = \frac{a_\pi g_\pi}{2 m_N m_\pi^2} \sim 1.2 .$$

This was actually first derived by Goldberger and Treiman by the dispersion theoretic method(9). We may analogously assume that the divergence of P_μ is proportional to the renormalized kaon field

$$\partial_\mu P_\mu = i a_K \phi_K ,$$

where a_k is given in terms of the $K_{\mu 2}$ decay rate

$$w(K^+ \to \mu^+ + \nu) = \frac{G^2}{8\pi m_K}\left(\frac{m_\mu}{m_K}\right)^2\left(1-\frac{m_\mu^2}{m_K^2}\right)^2 a_K^2 .$$

The corresponding Goldberger-Treiman relation is

$$g_1(0) = \frac{a_K g_K}{m_K^2 (m_Y + m_N)} ,$$

g_k being the renormalized YNK coupling constant, hence

$$\frac{g_1(0)}{\lambda} = \frac{a_K}{a_\pi}\left(\frac{m_\pi}{m_K}\right)^2 \frac{2 m_N}{m_Y + m_N}\cdot\frac{g_K}{g_\pi} \sim 0.1 \qquad 10)$$

which alone seems to be too small to fit the experimental decay rate.

To obtain an estimate of the renormalized vector coupling constant $f_1(0)$ we assume no subtraction and introduce a stable vector meson K', the experimentally observed $K\pi$ resonance state at 885 MeV[11] and compute $f_1(0)$ in the pole approximation. In the same model the leptonic decay rate of the kaon is called for to find the unknown coupling constants. The K' particle is assumed to couple strongly to the baryon and meson current by the phenonemonological hamiltonians

$$H_1 = ig_Y \bar{N}\gamma_\mu Y K'_\mu + h.c.$$
$$H_2 = g\left(K\frac{\partial\pi^*}{\partial x_\mu} - \pi^*\frac{\partial K}{\partial x_\mu}\right)K'_\mu + h.c. \,,$$

which are further assumed to be isoscalar.
The K' particle is coupled weakly to the lepton current by

$$H_3 = f\left(\bar{e}\gamma_\mu(1+\gamma_5)\nu + \bar{\mu}\gamma_\mu(1+\gamma_5)\nu\right)K'_\mu + h.c.$$

The possible couplings of the K' particle through the "moment" type interaction are ignored. The decay diagram of the hyperon and kaon are shown in fig. 1. We can immediately see that the decays

$$\Sigma^+ \to n + e^+ + \nu, \quad K^0 \to \pi^+ + e^- + \bar{\nu}, \quad K^0 \to \pi^+ + \mu^- + \bar{\nu}$$

are forbidden in this picture, because $K^{\pm\prime}$ has strangeness ± 1 and strangeness has to be conserved in a strong vertex. This is in accordance with $\Delta S = \Delta Q$ rule, however this rule seems to have been experimentally disproved recently[12]. The vector meson K' actually reproduces the contact interaction of the baryon and lepton currents, because the essential part of the matrix element becomes

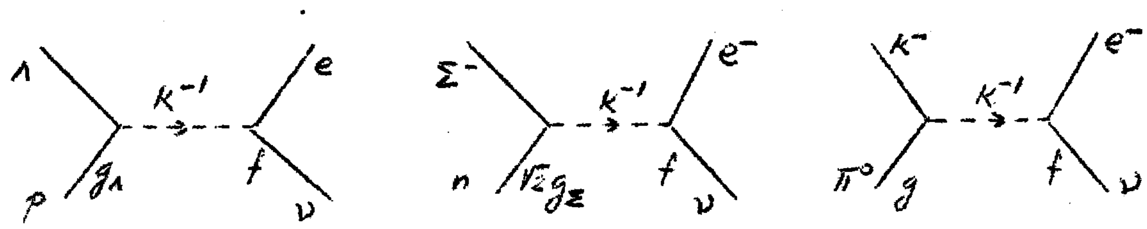

FIG. 1 - Leptonic decay diagrams of the hyperon and kaon via K' particle.

$$\bar{u}_N \gamma_\mu u_Y \frac{1}{K^2+m_{K'}^2}\left(\delta_{\mu\nu}+\frac{k_\mu k_\nu}{m_{K'}^2}\right)\bar{u}_e \gamma_\nu (1+\gamma_5) u_\nu =$$

$$= \frac{1}{K^2+m_{K'}^2}\left[\bar{u}_N \gamma_\mu u_Y \cdot \bar{u}_e \gamma_\mu (1+\gamma_5) u_\nu - \frac{m_e(m_Y-m_N)}{m_{K'}^2}\bar{u}_N u_Y \cdot \bar{u}_e (1+\gamma_5) u_\nu\right],$$

where the second term is completely negligible due to a small factor $m_e/m_{K'}$. The decay rates are found in a straightforward manner as

$$w(\Lambda_\beta) = \frac{2}{\pi}\frac{g_\Lambda^2}{4\pi}\frac{f^2}{4\pi} m_\Lambda \times 5.42 \times 10^{-5}$$

$$w(\Sigma_\beta) = \frac{2}{\pi}\frac{(\sqrt{2} g_\Sigma)^2}{4\pi}\frac{f^2}{4\pi} m_\Sigma \times 3.05 \times 10^{-4}$$

$$w(K_{e3}) = \frac{2}{3\pi}\frac{g^2}{4\pi}\frac{f^2}{4\pi} m_K \times 3.85 \times 10^{-3}$$

$$w(K_{\mu 3}) = \frac{1}{\pi}\frac{g^2}{4\pi}\frac{f^2}{4\pi} m_K \times 2.12 \times 10^{-3},$$

in fact a completely analytic integration in phase space is possible for the electron decay modes putting the electron mass zero.

We see immediately that the branching ratio

$$\frac{w(K_{e3})}{w(K_{\mu 3})} \sim 1.2$$

is consistent with the experimental value ~ 1. For the purpose of reference in future experiments we draw the lepton spectrum of the kaon decay in figs. 2 and 3. The muon spectrum in the $K_{\mu 3}$ mode has a peak at muon total energy of 167 MeV, which offers the possibility of distinguishing our model experimentally from the other models[13]. The $K'K\pi$ coupling constant g is related to the full width of the K' particle Γ by[14]

$$\Gamma = w(\bar{K}' \to \bar{K}^0 + \pi^-) = \frac{(\sqrt{2} g)^2}{4\pi}\frac{2\kappa^3}{3} m_{K'},$$

where κ is the momentum of the final kaon or pion in u-

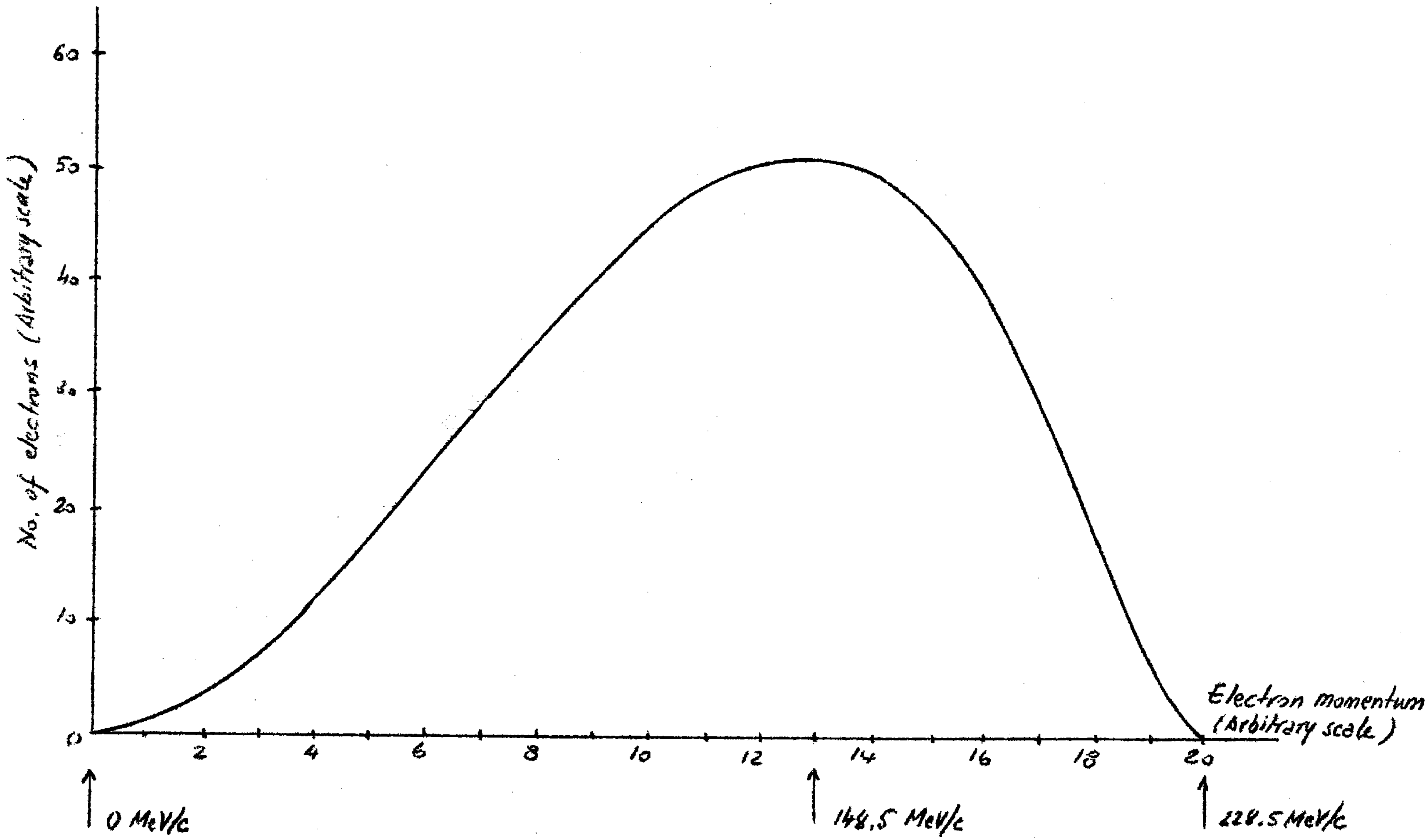

FIG. 2 - Electron spectrum in K_{e3} decay mode. The abscissa is linear in the electron momentum.

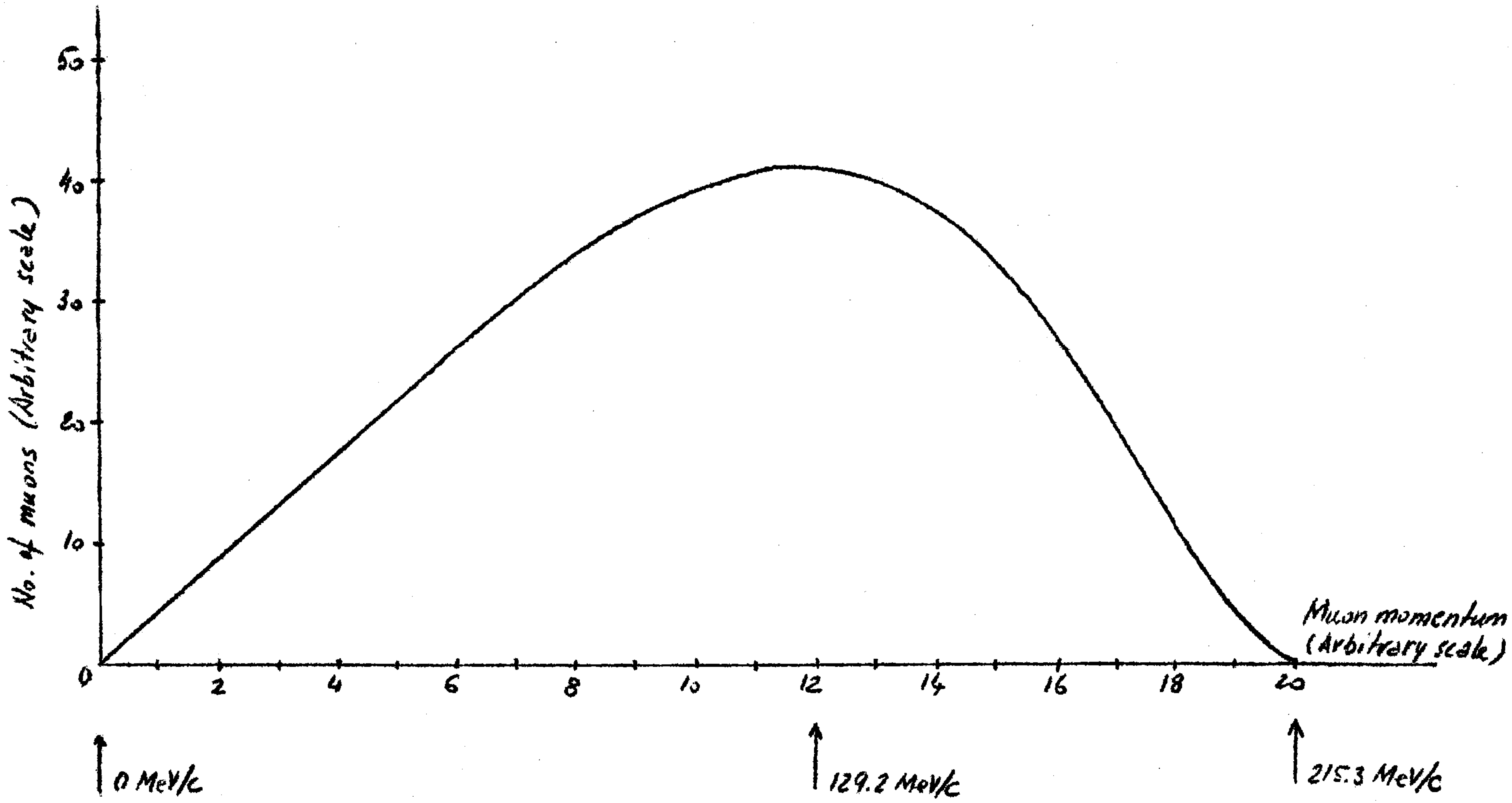

FIG. 3 - Muon spectrum in $K_{\mu 3}$ decay mode. The abscissa is linear in the muon momentum. In the energy scale the endpoint corresponds to muon total energy of 239.8 MeV and the peak to 166.9 MeV.

nits of $m_{k'}$. The experimental width 16 MeV gives the estimate

$$\frac{g^2}{4\pi} \sim 0.83 \ .$$

The weak $K'_{e\nu}$ coupling constant f then will be found from the experimental decay rate of K_{e3} , $w(K_{e3})=3.36 \times 10^6 \ \mathrm{sec}^{-1}$, as

$$\frac{f^2}{4\pi} \sim 6.7 \times 10^{-15} .$$

Inserting this value we obtain

$$w(\Lambda_\beta) = \frac{g_\Lambda^2}{4\pi} \times 4.1 \times 10^5 \ \mathrm{sec}^{-1}$$

$$w(\Sigma_\beta) = \frac{(\sqrt{2}\, g_\Sigma)^2}{4\pi} \times 2.4 \times 10^6 \ \mathrm{sec}^{-1}$$

or alternatively the form factor $f_1(0)$ of the Λ hyperon becomes

$$|f_1(0)|^2 \sim \frac{g_\Lambda^2}{4\pi} \times 0.029 \ .$$

To obtain the experimental decay rate, $w(\Lambda_\beta) \sim 5 \times 10^6 \ \mathrm{sec}^{-1}$, the coupling constant $g_\Lambda^2/4\pi$ must be of the order of 10. Gourdin and Rimpault(15) analized the production process $\pi + N \longrightarrow Y + K$ in the pole approximation and arrived at the estimate

$$\frac{g_\Lambda^2}{4\pi} \sim 1.8$$

as well as the assignment that the $\Lambda\Sigma$ relative parity be odd. If we accept this estimate, the "reduced" decay rate of the Λ hyperon becomes

$$|f_1(0)|^2 + 2.96\, |g_1(0)|^2 \sim 0.052 + 0.043 \sim 0.09 ,$$

while experimentally it should be 0.35.
If the Σ hyperon has opposite parity to Λ our model gives

$$w(\Sigma_\beta) = \frac{(\sqrt{2}\, g_\Sigma)^2}{4\pi} \times 7.4 \times 10^6 \ \mathrm{sec}^{-1} \qquad ,$$

hence assuming $g_\Sigma \sim g_\Lambda$ we obtain

$$w(\Sigma_\beta) \sim 2.8 \times 10^7 \text{ sec}^{-1},$$

which is fortuitously close to the experimental finding $w(\Sigma_\beta) \sim 2 \times 10^7 \text{ sec}^{-1}$.

It is hard to draw any definite conclusion out of this model because it depends on the numerical estimates of very preliminary nature. The meson cloud effects alone could explain about 1/4 of the observed beta decay rate of the hyperon. However, it would be more sensible at the present stage to accept the breakdown of the universality in the unrenormalized V - A scheme phenomenologically, allowing the possibility that the beta decay of the hyperon may be mediated by mosons partially.

The author would like to thank Prof. R. Gatto for his discussions and comments.

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