Hyperon Beta Decay

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(Received March 4, 1959)

The complete electron spectrum is presented for polarized hyperons undergoing beta decay. Despite the rarity of such events, the availability of polarized hyperons and the favorably large energy release make an experimental analysis of these decays feasible. The basic couplings are assumed to be vector and axial vector, but the new terms which arise from couplings "induced" by the strong interactions are also included.

TWO certain examples of Λ-particle beta decay have by now been recorded[1]; but in general, hyperon beta decay turns out to be disturbingly rare.[2] The corresponding difficulty in acquiring adequate statistics for such processes is to an extent offset, however, by two favorable circumstances. Consider for example Λ-particle beta decay: $\Lambda \to p+e^-+\bar{\nu}$. In contrast to neutron beta decay, the large energy release here makes it readily possible to detect experimentally the proton recoil; in fact it is through detection of the proton, in part, that the process is identified. This means that the difficult electron-"neutrino" (recoil) experiments of neutron beta decay are automatically carried out in Λ beta decay. Moreover, the Λ particles produced in $\pi^- - p$ collisions are known to be strongly polarized.[3] One has available then the analog of the polarized beams obtained with so much effort in the case of neutron beta decay; it is an easy matter then to measure the correlation not only of the electron, but also of the proton with respect to the direction of Λ-particle polarization. In short, the availability of polarized Λ particles and the favorably large energy release make possible a fairly complete experimental analysis of Λ-particle beta decay, limited only by the rarity of such processes. Similar remarks apply to other hyperon beta-decay processes where polarized hyperons are available.[4]

For these reasons, and despite the fact that it may be some time before adequate statistics accumulate, we feel it worthwhile to record here the expected structure of the decay spectrum. Several issues are at stake. One would like to confirm the expectation that parity conservation and charge conjugation invariance are violated; in more detail, to confirm the expectations implied by the two-component theory of the neutrino and by lepton conservation, and in still more detail, by the notion that the coupling types are solely vector and axial vector. Regarding this last matter, one realizes that even if only these couplings are involved, the strong interactions in which the hyperons and nucleons participate can "induce" in the matrix element for beta decay terms of a more complicated type.[5] One would like to establish the strengths of the various "renormalized" coupling parameters.

Taking then the V and A couplings as the basic ones and accepting the two-component neutrino theory, we have for the general structure of the matrix element for say $\Lambda \to p+e^-+\bar{\nu}$ (we neglect Coulomb corrections)

$$H=[\langle p|j_\lambda^V|\Lambda\rangle+i\langle p|j_\lambda^A|\Lambda\rangle]\bar{u}_e\gamma_\lambda(1+\gamma_5)v_\nu, \qquad (1)$$

where

$$\begin{aligned}\langle p|j_\lambda^V|\Lambda\rangle&=\bar{u}_p[c\gamma_\lambda-(d/m)i(p_\Lambda-p)_\lambda\\&\qquad-(d'/m)i(p_\Lambda+p)_\lambda]u_\Lambda,\\ \langle p|j_\lambda^A|\Lambda\rangle&=\bar{u}_p[ai\gamma_\lambda\gamma_5-(b/m)\gamma_5(p_\Lambda-p)_\lambda\\&\qquad-(b'/m)\gamma_5(p_\Lambda+p)_\lambda]u_\Lambda.\end{aligned} \qquad (2)$$

The proton mass m is introduced so that all coupling constants have the same dimensions. The form factors are functions of momentum transfer, $\xi=(p_\Lambda-p)^2$, and for the sake of completeness, we permit them to be complex. The usual direct vector and axial vector coupling constants are just $c(0)$ and $a(0)$, while the remaining terms represent the "induced" couplings. By use of energy-momentum conservation and the Dirac equation, the matrix element can be rewritten in the form

$$\begin{aligned}H=&\bar{u}_p[c\gamma_\lambda-(d'/m)i(p_\Lambda+p)_\lambda]u_\Lambda\bar{u}_e\gamma_\lambda(1+\gamma_5)v_\nu\\&+(m_e/m)d\bar{u}_pu_\Lambda\bar{u}_e(1+\gamma_5)v_\nu\\&+\bar{u}_p[ai\gamma_\lambda\gamma_5-(b'/m)\gamma_5(p_\Lambda+p)_\lambda]u_\Lambda\bar{u}_ei\gamma_\lambda\gamma_5(1+\gamma_5)v_\nu\\&+(m_e/m)b\bar{u}_p\gamma_5u_\Lambda\bar{u}_e\gamma_5(1+\gamma_5)v_\nu,\end{aligned} \qquad (3)$$

from which we see that the induced scalar and pseudoscalar coupling constants are

$$g_S=(m_e/m)d,\quad g_P=(m_e/m)b. \qquad (4)$$

With the assumption that the form factors are essentially constant over the range of momentum transfers involved, the calculation for the spectrum can be readily carried out. The distribution in electron energy and

[1] Crawford, Cresti, Good, Kalbfleisch, Stevenson, and Ticho, Phys. Rev. Letters **1**, 377 (1958); Nordin, Orear, Reed, Rosenfeld, Solmitz, Taft, and Tripp, Phys. Rev. Letters **1**, 380 (1958).
[2] R. P. Feynman and M. Gell-Mann, Phys. Rev. **109**, 193 (1958).
[3] F. S. Crawford *et al.*, Phys. Rev. **108**, 1102 (1957); F. Eisler *et al.*, Phys. Rev. **108**, 1353 (1957); *Proceedings of the 1958 Annual International Conference on High-Energy Physics at CERN*, edited by B. Ferretti (CERN, Scientific Information Service, Geneva, 1958).
[4] Cool, Cork, Cronin, and Wenzel, Phys. Rev. **114**, 912 (1959).
[5] M. L. Goldberger and S. B. Treiman, Phys. Rev. **111**, 354 (1958).

direction and neutrino direction for a polarized hyperon is given by Eq. (5) below, where we have used natural units such that $c=\hbar=1$. M is the mass of the hyperon, while $\langle\boldsymbol{\sigma}\rangle$ is the expectation value of the hyperon spin. The electron mass is everywhere neglected except where it appears in Eq. (4). This very good approximation greatly simplifies the final form and yet leaves open the possibility that d and/or b are abnormally very large. As a first approximation, the recoil energy can be neglected as in neutron decay; in this case, R can be replaced by 1 and E_ν set equal to $M-m-E_e$ in the formulas given below.

$$\omega(\langle\boldsymbol{\sigma}\rangle|E_e,\Omega_e,\Omega_\nu)dE_e d\Omega_e d\Omega_\nu$$

$$=\frac{1}{(2\pi)^5}2\frac{R}{E}E_e^2E_\nu^2dE_e d\Omega_e d\Omega_\nu \times\Bigg\{A+B(\mathbf{k}\cdot\mathbf{l})+D\frac{\mathbf{p}_e\cdot\mathbf{p}_\nu}{m^2}(\mathbf{k}\cdot\mathbf{l}) +\langle\boldsymbol{\sigma}\rangle\cdot\bigg[F\mathbf{k}+G\mathbf{l}+K\frac{\mathbf{p}_e}{m}(\mathbf{k}\cdot\mathbf{l}) +L\frac{\mathbf{p}_\nu}{m}(\mathbf{k}\cdot\mathbf{l})+N\frac{\mathbf{p}_e+\mathbf{p}_\nu}{m}\left(\frac{\mathbf{p}_e\cdot\mathbf{p}_\nu}{m^2}\right)\mathbf{k}\cdot\mathbf{l}\bigg] +T\langle\boldsymbol{\sigma}\rangle\cdot(\mathbf{k}\times\mathbf{l})\Bigg\}, \quad (5)$$

where

$$E=[(\mathbf{p}_e+\mathbf{p}_\nu)^2+m^2]^{\frac{1}{2}}, \quad (6)$$

$$E_\nu=\frac{1}{2}\frac{M^2-m^2-2ME_e}{M-E_e(1-\mathbf{k}\cdot\mathbf{l})}, \quad (7)$$

$$R=\frac{E}{M-E_e(1-\mathbf{k}\cdot\mathbf{l})}, \quad (8)$$

$$\mathbf{k}=\mathbf{p}_e/E_e, \quad \mathbf{l}=\mathbf{p}_\nu/E_\nu, \quad (9)$$

$$A=\alpha+\alpha'+\tfrac{1}{2}xD, \quad (10)$$

$$B=\alpha-\alpha'+\tfrac{1}{2}yD, \quad (11)$$

$$D=(E+m)|d'|^2+(E-m)|b'|^2+2m\,\mathrm{Re}(cd'^*+ab'^*), \quad (12)$$

$$F=-\alpha''-\beta-\gamma E_\nu+\delta E_e, \quad (13)$$

$$G=\alpha''-\beta+\delta E_\nu+\gamma E_e, \quad (14)$$

$$K=-m(\gamma+\epsilon), \quad (15)$$

$$L=m(\gamma-\epsilon), \quad (16)$$

$$N=-2m\,\mathrm{Re}(d'b'^*), \quad (17)$$

$$T=-2\,\mathrm{Im}\{m(ca^*)+(M/m)[(E_e-E_\nu)(cd'^*+ab'^*)-(E-m)cb'^*-(E+m)ad'^*]\}, \quad (18)$$

$$\alpha=M(|c|^2+|a|^2)-2(M/m)\,\mathrm{Re}[(M-m)cd'^*+(M+m)ab'^*], \quad (19)$$

$$\alpha'=\alpha''+\tfrac{1}{2}[(E+m)|g_S|^2+(E-m)|g_P|^2]-2(E_e-E_\nu)\,\mathrm{Re}(ca^*), \quad (20)$$

$$\alpha''=(E-m)|c|^2+(E+m)|a|^2, \quad (21)$$

$$\beta=2\,\mathrm{Re}\{M(ca^*)+(M/m)\times[(E-m)cb'^*+(E+m)ad'^*]\}, \quad (22)$$

$$\gamma=|c|^2+|a|^2+2(M/m)\,\mathrm{Re}(cd'^*+ab'^*), \quad (23)$$

$$\delta=\mathrm{Re}\{2ca^*-2(M/m)(cb'^*+ad'^*)-xd'b'^*-g_Sg_P^*\}, \quad (24)$$

$$\epsilon=\mathrm{Re}\{2ca^*+2(M/m)(cb'^*+ad'^*)+yd'b'^*-g_Sg_P^*\}, \quad (25)$$

$$x=(1/m^2)[3M^2+2ME-m^2+2E_eE_\nu], \quad (26)$$

$$y=(1/m^2)[5M^2-2ME+m^2-4E_eE_\nu]. \quad (27)$$

The first three terms in Eq. (5) are the customary ones appearing in electron-neutrino correlation experiments with unpolarized particles. Terms F through N give the electron and neutrino asymmetries relative to the hyperon polarization direction. The term whose coefficient is T is just the asymmetry which appears if time reversal invariance is invalid in the decay.

ACKNOWLEDGMENT

It is a pleasure to thank Professor S. B. Treiman for his helpful suggestions in connection with this problem.

Note added in proof.—After this manuscript was submitted for publication, it was brought to the author's attention that V. M. Shekhter has investigated other kinematical aspects of hyperon beta decay.[6] In his discussion, the induced couplings have been neglected and only the direct vector and axial vector interactions are considered.

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[6] V. M. Shekhter, J. Exptl. Theoret. Phys. (U.S.S.R.) **35**, 458 (1958) [translation: Soviet Phys. JETP **35**, (8), 316 (1959)].