Elementary qualitative considerations suggest that some model which takes into account the conservation of angular momentum may be capable of accounting for both pion and nucleon angular distributions and the energy dependence of these distributions if it is assumed that

(1) the pions are emitted during the interaction time while the radiating system has no linear motion in the c.m. system of the interacting nucleons;

(2) the more isotropically distributed lower energy pions are associated with the lower total angular momentum states of the system and the higher multiplicities of pion production and, conversely, the more anisotropically distributed higher energy pions are associated with the higher total angular momentum states and the lower pion multiplicities.

VI. ACKNOWLEDGMENTS

The writers wish to express their appreciation to the staff of the Brookhaven Cosmotron Department for their assistance in making the exposures; to Dr. S. J. Lindenbaum, Dr. R. Sternheimer, and Dr. L. C. L. Yuan for information concerning the counter experiments and to Dr. E. C. Fowler, Dr. R. P. Shutt, and their collaborators for the results of the cloud chamber experiments prior to their publication.

PHYSICAL REVIEW VOLUME 108, NUMBER 5 DECEMBER 1, 1957

Capture of μ^- Mesons by Protons

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(Received August 9, 1957)

By use of a two-component theory of the neutrino the capture process and the radiative capture process of a μ^- by a proton is analyzed in some detail.

WITH the establishment[1] of the nonconservation of parity, many experiments have been done and will be done which will greatly increase our knowledge concerning the nature of the coupling in β decay, in π decay, and in μ decay. The purpose of the present note is to point out that it may be possible to do the same with the phenomenon of μ^- capture:

$$\mu^- + p \rightarrow n + \nu. \qquad (1)$$

One notices, first of all, that the two main questions concerning μ^- capture are

(a) whether the μ^- capture process is given by (1), or by

$$\mu^- + p \rightarrow n + \bar{\nu}, \qquad (1')$$

or by a combination of (1) and (1');

(b) what is the coupling that is responsible for μ^- capture.

To make the analysis definite we shall assume that the neutrino is described by a two-component theory with zero mass.[2,3] Furthermore, we assume first that process (1) prevails and write the interaction Hamiltonian as

$$H = \sum_i C_i (\psi_n^\dagger O_i \psi_p)(\psi_\nu^\dagger O_i \psi_\mu), \qquad (2)$$

where i runs over S, V, T, P, and A, and O_i are the corresponding 4×4 matrices.[4]

We list the following results for the capture of μ^- in hydrogen.

1. The rate for process (1) in hydrogen is

$$(1/\tau)_{\text{cap}} = p_\nu^2 \xi / (2\pi^2 a^3), \qquad (3)$$

where

$$\xi = |C_S + C_V|^2 + 3|C_A + C_T|^2, \qquad (4)$$

p_ν is the momentum of the neutrino, and a is the Bohr radius of the μ^- mesonic atom.

2. In process (1) with a *completely* polarized μ^-, the angular distribution of the neutron is of the form[5]

$$1 + \alpha \cos\theta_1, \qquad (5)$$

where

$$\theta_1 = \angle(\boldsymbol{\sigma}_\mu, \mathbf{p}_n),$$

representing the angle between the spin direction of μ^-, and the momentum of the neutron. The asymmetry parameter α is

$$\alpha\xi = -|C_S + C_V|^2 + |C_A + C_T|^2. \qquad (6)$$

[1] Wu, Ambler, Hayward, Hoppes, and Hudson, Phys. Rev. **105**, 1413 (1957); Garwin *et al.*, Phys. Rev. **105**, 1415 (1957); J. I. Friedman and V. L. Telegdi, Phys Rev. **105**, 1681 (1957). For other work on nonconservation of parity, see, e.g., *Proceedings of the Seventh Annual Rochester Conference on High-Energy Physics* (Interscience Publishers, Inc., New York, 1957).

[2] T. D. Lee and C. N. Yang, Phys. Rev. **105**, 1671 (1957). We adopt here the convention of that paper: that by ν is meant the state for which the angular momentum is parallel to the momentum.

[3] A. Salam, Nuovo cimento **5**, 299 (1957); L. Landau, Nuclear Phys. **3**, 127 (1957).

[4] The O_i are defined explicitly in Eq. (11) of reference 2.

[5] The angular distribution of the neutron [Eq. (5)] has also been independently considered by W. Panofsky (private communication).

3. The transition probability $\tau_{\rm rad}^{-1}$ for the radiative capture process of μ^- in hydrogen,

$$\mu^- + p \rightarrow n + \nu + \gamma, \tag{7}$$

is

$$\tau_{\rm rad}^{-1} = [e^2\eta/(6\pi\xi)]\tau_{\rm cap}^{-1}, \tag{8}$$

where

$$\eta = |C_S|^2 + |C_V|^2 + 3|C_A|^2 + 3|C_T|^2. \tag{9}$$

4. In process (7) the γ ray is circularly polarized.[6] A polarization parameter β may be defined:

$$(N_R - N_L)/(N_R + N_L) = \beta, \tag{10}$$

where

$$\beta\eta = |C_S|^2 - |C_V|^2 - 3|C_A|^2 + 3|C_T|^2. \tag{11}$$

In Eq. (10), N_R and N_L are, respectively, the number of right-handed γ rays and left-handed γ rays.[7] Equation (11) is independent of either the state of polarization of the captured μ^- meson or the energy of the γ ray.

5. For the radiative capture of a 100% polarized μ^-, the angular distribution of γ ray is of the form

$$1 + \beta \cos\theta_2, \tag{12}$$

where β is given by Eq. (11) and

$$\theta_2 = \angle(\boldsymbol{\sigma}_\mu, \mathbf{p}_\gamma), \tag{13}$$

with $\mathbf{p}_\gamma$ the momentum of the γ ray.

6. In the radiative capture process (7), the angular distribution of the γ ray with respect to the momentum of the neutrino $\mathbf{p}_\nu$ is of the form

$$1 + \gamma \cos\theta_3, \tag{14}$$

where

$$\theta_3 = \angle(\mathbf{p}_\gamma, \mathbf{p}_\nu),$$

and

$$\gamma\eta = -|C_S|^2 + |C_V|^2 - |C_A|^2 + |C_T|^2. \tag{15}$$

In all the above expressions, we have neglected (v/c) terms for the nucleon wave function. We replace the wave function of the μ^- meson everywhere by its value at the origin.

7. If the law of conservation of leptons is valid,[8,9] then in the capture of μ^- a neutrino must be emitted. Otherwise, instead of Eqs. (1) and (7), we may have

$$\mu^- + p \rightarrow n + \bar{\nu}, \tag{1'}$$

and

$$\mu^- + p \rightarrow n + \bar{\nu} + \gamma. \tag{7'}$$

In the measurements of $(\tau^{-1})_{\rm cap}$, $(\tau^{-1})_{\rm rad}$, θ_1, θ_2, and θ_3 for reactions (1′) and (7′), the corresponding parameters α, β, γ, ξ, η are replaced by α', β', γ', ξ', η'. These new parameters are

$$\xi' = \xi = |C_S + C_V|^2 + 3|C_A + C_T|^2, \tag{4'}$$

$$\eta' = \eta = |C_S|^2 + |C_V|^2 + 3|C_A|^2 + 3|C_T|^2, \tag{9'}$$

$$\alpha'\xi' = -\alpha\xi = |C_S + C_V|^2 - |C_A + C_T|^2, \tag{6'}$$

$$\beta'\eta' = -\beta\eta = -|C_S|^2 + |C_V|^2 + 3|C_A|^2 - 3|C_T|^2, \tag{11'}$$

and

$$\gamma'\eta' = -\gamma\eta = |C_S|^2 - |C_V|^2 + |C_A|^2 - |C_T|^2. \tag{15'}$$

Thus a complete measurement of these five parameters may also give a check on the validity of the law of conservation of leptons.

All the above formulas are calculated for μ^- capture in hydrogen. For μ capture in heavier nuclei, the parameter β and β' are unchanged, provided $Ze^2/\hbar c \ll 1$. All other parameters depend sensitively on the nuclear matrix elements which can be calculated by assuming a certain definite nuclear model.

One of us (K. Huang) would like to thank Dr. Robert Oppenheimer for the hospitality extended him during his stay at The Institute for Advanced Study.

[6] The radiative capture process of μ^- mesons and the polarization of γ rays have also been independently considered by R. Cutkosky (private communication) and R. Glauber (private communication).

[7] A right-handed (or left-handed) γ ray is defined to be a photon with its spin $J_x = +1$ (or -1) along its momentum.

[8] T. D. Lee and C. N. Yang, Phys. Rev. **105**, 1671 (1957). See T. D. Lee, *Proceedings of the Seventh Annual Rochester Conference on High-Energy Physics* (Interscience Publishers, Inc., New York, 1957).

[9] The concept of a possible law of conservation of leptons has been discussed by many authors in the past. See, e.g., E. J. Konopinski and H. M. Mahmoud, Phys. Rev. **92**, 1045 (1953).