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THE $\mu \to e + \gamma$ *AND* $\mu \to e + \nu + \bar{\nu} + \gamma$ *DECAYS*

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THE main characteristics of universal A-V interaction can be explained by the hypothesis of the existence of an intermediate boson of large mass.[1] One of the consequences of this hypothesis is the possibility of μ-meson decay according to the scheme $\mu \to e + \gamma$. For a point A-V interaction such a decay is forbidden. Feinberg[2] calculated the probability of the decay $\mu \to e + \gamma$ and showed that the ratio $\rho_1 = R(\mu \to e + \gamma)/R(\mu \to e + \nu + \bar{\nu})$ depends on the cutoff parameter Λ. If $\Lambda = M$, where M is the boson mass, then $\rho_1 \cong 10^{-4}$. For $\Lambda < M$, ρ_1 can be arbitrarily small.

In the present work, a search for the decay $\mu \to e + \gamma$ was made, using a 17-liter freon bubble chamber, sensitive to γ rays.[3] The chamber was placed in the external π^+ beam of the synchrocyclotron of the Joint Institute for Nuclear Research. π^+ mesons of energy approximately 200 Mev were slowed by a graphite filter, and stopped inside the chamber. About 20,000 stereophotographs were obtained and scanned twice.

In the scanning, a search was made for cases in which the π-μ-e decay was accompanied by an electron-positron pair directed along and following the end of a π- or μ-meson track. The direction of the pair corresponded to the direction of flight of the γ ray to within an accuracy of $\sim 5 - 7°$, and the length of the track of the μ meson from the π-meson decay was 0.16 cm. Therefore, the case in which the π-μ-e decay was accompanied by a directed pair could relate to one of three processes:

$$\mu \to e + \nu + \bar{\nu} + \gamma, \quad (1)$$

$$\pi \to \mu + \nu + \gamma, \quad (2)$$

$$\mu \to e + \gamma. \quad (3)$$

In the decay (3) the angle between electron and γ ray is 180°. In 91,000 π-μ-e decays, not a single such case was found. From this, knowing the efficiency of the chamber for detecting γ rays, it is possible to determine an upper limit for the quantity ρ_1. The efficiency was calculated on an electronic computer for various γ-ray energies by the Monte-Carlo method, taking into account the distribution of the number of π mesons stopping inside the chamber. The efficiency turned out to be equal to 0.253 for the decay (3). From this, $\rho_1 \leq 4.3 \times 10^{-5}$. This quantity is in agreement with results of experiments in which the decay (3) was studied using counter methods.[4-6]

In scanning the photographs, cases of directed pairs with various angles $(e, \gamma) < 180°$ were found. One of these cases is shown in Fig. 1. We interpret

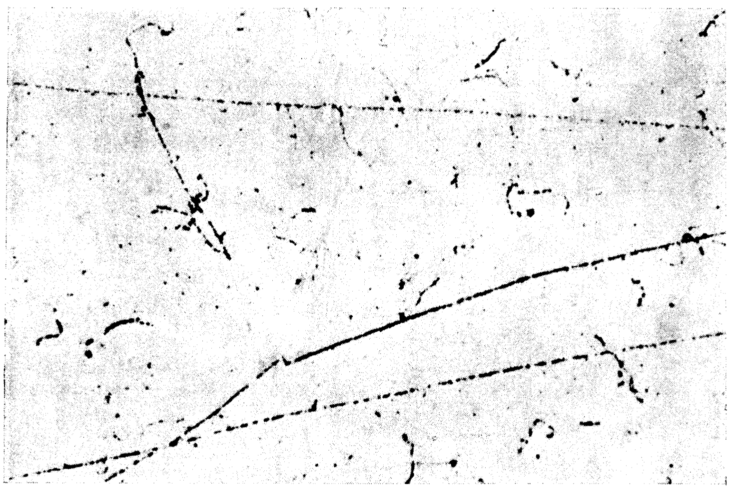

FIG. 1. Radiative decay of a μ meson by scheme (1).

No. p/p	Angle between electron and γ ray, degrees	Electron energy, Mev	γ-ray energy, Mev	Energy of the decay products, Q, Mev
1	52±3	> 1	>16	⩾ 35
2	61±2	>40	>15	⩾105
3	76±2	>11	>19	⩾ 55
4	98±3	>14	>18	⩾ 53
5	101±2	>15	>24	⩾ 65
6	120±2	>13	>13	⩾ 40
7	128±3	>15	>31	⩾ 72
8	143±4	>13	>13	⩾ 35
9	144±2	> 7	> 8	⩾ 21
10	151±4	>15	>20	⩾ 44

such an event as the result of a radiative decay of a μ meson according to the scheme (1). This decay has not been observed before experimentally.

All of the cases in which the γ-ray energy was $\gtrsim 15-20$ Mev and the angle $(e,\gamma) \gtrsim 50-60°$ are given in the table. In addition, two doubtful cases, not given in the table, were found, so that the total number was $12^{+3.5}_{-5.5}$. In the table we indicate results of measurements of the angle (e,γ), the energy of the γ-ray and electron energy, and also the lower limit Q to the energy of the decay products, calculated from conservation laws.

For process (1), the kinetic energy of the decay products $Q_1 = 105.2$ Mev; for process (2), $Q_2 = 33.9$ Mev. As follows from the table, there is no case with $Q > Q_1$. In addition, in only one case (No. 9) is it possible that $Q < Q_2$, so that the interpretation of this event is ambiguous [(1) or (2)]. The remaining cases give $Q > Q_2$, and can therefore be related to the decay (1). The small contribution of decay (2) can be confirmed from measurements of the probability of this decay.[7] Calculations show that the background from the decay (2) constitutes about 3%.

In scanning the photographs, 109 randomly oriented pairs were found. In order to evaluate the background of random superpositions, a search was made for cases in which these pairs coincided with six markings made on the inside of the glass of the chamber. No such cases were observed. Another way of measuring the background consisted in measuring, for all observed pairs, the angle of revolution necessary to turn the pair towards the point at which the μ-meson stopped. Results of the measurements are given in Fig. 2. The distribution has a peak at 0°, coming from the effect studied. The level of events outside of the region near to 0° corresponds to random superpositions. From the graph it can be seen that the ratio of this level to that of the effect is approximately 0.2, but since there measurements were carried out for only one of the stereophotographs, the actual background is substantially lower (roughly 10 times) and, consequently, does not exceed a few per cent.

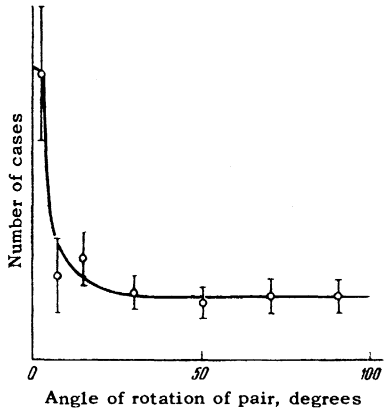

FIG. 2. Distribution of pairs with angle necessary to turn them into the point at which the μ meson stopped.

The ratio, calculated from 12 cases and taking into account the efficiency for detecting γ rays, was

$$\rho_2 = R(\mu \rightarrow e + \nu + \bar{\nu} + \gamma) / R(\mu \rightarrow e + \nu + \bar{\nu})$$
$$= \left(0.80^{+0.24}_{-0.36}\right) \cdot 10^{-3}.$$

In order to compare this result with theory, we calculated the total probability and angular distribution of the decay (1) for various values of the minimum detection energy of γ-rays for the A-V variant of interaction. We started with work of Lenard[8] in which an expression for the differential probability for the decay (1) was obtained. The calculations showed that the theoretical value of the quantity ρ_2 should lie within the limits $1.02 \times 10^{-3} < \rho_2 < 1.80 \times 10^{-3}$. These limits correspond to the indeterminacy in the minimum values of the angle (e,γ) and γ-ray energy, referred to above. We see that the experimental value of ρ_2 is near to the theoretical one.

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ON THE CONNECTION OF ISOTOPIC SPIN AND STRANGENESS WITH THE BEHAVIOR OF SPINORS UNDER INVERSION

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THE usual treatments of isotopic and strangeness properties involve an isotopic space of two, three, or four dimentions, sometimes with the possibility of transitions to a pseudo-Euclidean space. One can, however, try to describe these properties within the framework of ordinary space, by bringing in hitherto unused possibilities of different behaviors of spinors under inversions and taking into account nonconservation of the parity P. The interpretation of isotopic properties in the framework of ordinary space that we propose here is a development of earlier more special considerations.[1-8]

As has been pointed out,[8,9] under both space and time reflections spinors can behave in different ways, with transformation matrixes that differ by factors -1, i, γ_5, or products of these. In addition to $\psi' = \gamma_4\psi$ (under $x'_{1,2,3} = -x_{1,2,3}$), etc., there are also the possibilities $\psi' = \gamma_5\gamma_4\psi$ or $\psi' = i\gamma_4\psi$, etc. Thus there arise different spinor representations of the Lorentz group, some of which are equivalent by unitary transformations (but differ from each other under charge conjugation).

A more important difference between spinors, not having the property of unitary equivalence, appears when the additional factors that have been mentioned occur under space reflections only or under time reflection only. We shall characterize spinors by two pairs of indices a, b and α, β. The index a takes one of the two values 1 or 2, depending on whether or not the additional factor γ_5 is used for space reflection. Similarly, the index b = 1, 2 characterizes the geometrical time reflection T^0, which can be replaced by the Schwinger reflection $T^S = T^0 \times (\tilde{\ }) = TC$, where $(\tilde{\ })$ denotes transposition in Hilbert space and T the Wigner time reversal. The indices α, β run through the four values (0, 1, 2, 3) corresponding to the appearance of the additional factors i^α for space inversion and i^β for time inversion. The essential difference between two spinors is characterized by the differences $(a-b)$ and $(\alpha-\beta)$, or, more precisely, by their absolute values. In particular, the "mixed" spinors with $(a-b) \neq 0$ that we introduced earlier[8] provide a realization, without doubling of the number of components, of the "anomalous" representation, for which $T^0P = +PT^0$, in contrast to the usual anticommutation. For the "mixed" spinors the construction of the Dirac equation with a mass is possible only with violation of invariance with respect to P, together with preservation of the invariance with respect to the strong (combined) inversion $P^S = PC$.[8]

When there is invariance only with respect to P^S and T^S we have the question of the characteristics of spinors of distinct types. To solve it we introduce the self-adjoint ("large") spinors

$$\Psi(1) = {}^1/_2\,[(1 + i\gamma_5)\,\psi + (1 - i\gamma_5)\,\psi^c],$$
$$\Psi(2) = {}^1/_2\,[(1 - i\gamma_5)\,\psi + (1 + i\gamma_5)\,\psi^c],$$
$$\Psi^c(1, 2) = C\Psi^*(1, 2) = \Psi(1, 2), \qquad \gamma_5^2 = -1. \tag{1}$$

Under the strong inversions of the small ψ the quantities $\Psi(1,2)$ transform linearly, each one by itself, in complete analogy with the transformation of the ordinary ψ under geometrical inversions. Corresponding to the phase transformation $\psi' = e^{i\alpha}\psi$ we have $\Psi'(1,2) = \exp(\pm\gamma_5\alpha)\cdot\Psi(1,2)$. For self-adjoint small ψ (neutrino), $\Psi(1)$ and $\Psi(2)$ coincide. An additional difference between $\Psi(1)$ and $\Psi(2)$ is due to the possibility of different or equal relative signs under inversions. Self-adjoint ψ's are possible only for those $\Psi(1,2)$ for which these signs are the same.

For characterizing the behavior of spinors under the strong inversions P^S, T^S we need only the pairs of indices $J = a + \alpha$, $K = b + \beta$, and accordingly the one difference

$$N = J - K = (a - b) + (\alpha - \beta)\,(\mathrm{mod}\,2). \tag{2}$$

Here a, b, α, β relate to the original small spinors ψ from which the $\Psi(1,2)$ are constructed. $\Psi(1)$ and $\Psi(2)$ form a doublet, whose components go over into each other under geometrical inversions or charge conjugation of the original ψ. These transformations, together with the Salam-Touschek transformation, can be put in basic correspondence with three-dimensional isotopic rotations.[10] The