the two-component neutrino theory[10] should turn out to be incorrect (which at present seems to be rather improbable) and if the conservation law of neutrino charge would not apply, then in principle neutrino → antineutrino transitions could take place in vacuo. Even in this case, as well as in the case where one assumes that to every world there exists an antiworld, the number of neutrinos and antineutrinos in the universe would have to be the same.

The author is grateful to Ia. B. Zel'dovich, L. B. Okun', and I. G. Ivanter for critical remarks and interesting discussions.

[1] M. Gell-Mann and A. Pais, Phys. Rev. **97**, 1387 (1955); A. Pais and O. Piccioni, Phys. Rev. **100**, 1487 (1955).

[2] Balandin, Balashov, Zhukov, Pontecorvo, and Selivanov, J. Exptl. Theoret. Phys. (U.S.S.R.) 29, 265 (1955); Soviet Phys. JETP **2**, 98 (1956).

[3] L. Landau, J. Exptl. Theoret. Phys. (U.S.S.R.) 32, 405 (1957); Soviet Phys. JETP **5**, 336 (1957).

[4] Ia. Zel'dovich, Dokl. Akad. Nauk SSSR **86**, 505 (1952).

[5] Ia. Zel'dovich, Dokl. Akad. Nauk SSSR **91**, 1317 (1953); E. Konopinski and H. Mahmond, Phys. Rev. **92**, 1045 (1953).

[6] Ia. Zel'dovich, J. Exptl. Theoret. Phys. (U.S.S.R.) **30**, 1168 (1956); Soviet Phys. JETP **3**, 989 (1957).

[7] L. B. Okun' and B. Pontecorvo, J. Exptl. Theoret. Phys. (U.S.S.R.) **32**, 1587 (1957); Soviet Phys. JETP **5**, 1297 (1957).

[8] Alikhanian, Shostakovich, Dadaian, Fedorov, and Deriagin, J. Exptl. Theoret. Phys. (U.S.S.R.) 31, 955 (1956); Soviet Phys. JETP **4**, 817 (1957).

[9] R. Davis, Bull. Am. Phys. Soc. **II 1**, 219 (1956); M. Awschalom, Phys. Rev. **101**, 1041 (1956).

[10] L. Landau, J. Expt. Theoret. Phys. (U.S.S.R.) **32**, 407 (1957); Soviet Phys. JETP **5**, 337 (1957); T. D. Lee and C. N. Yang, Phys. Rev. **105**, 1671 (1957).

Translated by M. Danos
109

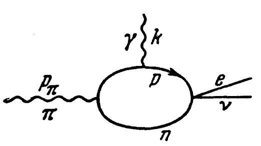
ON THE POSSIBILITY OF $\pi \to e + \nu + \gamma$ DECAY

I. IU. KOBZAREV

Submitted to JETP editor May 30, 1957

J. Exptl. Theoret. Phys. (U.S.S.R.) **33**, 551-553 (August, 1957)

In the presence of the strong interaction of π mesons with nucleons, the decay $\pi \to e + \nu$ might occur on account of the β-decay interaction, with a lifetime of the same order as that of the decay $\pi \to \mu + \nu$. In reality, however, the β-decay interaction contains scalar (S) and tensor (T) terms. The decay $\pi \to e + \nu$ obviously cannot occur on account of the T type term. It may appear that with nonconservation of parity[1] such a decay could take place on account of the S type term, but in reality experiment indicates the presence of the terms not conserving parity in the lepton part of the interaction, whereas for the absence of the $\pi \to e + \nu$ decay it is sufficient that the heavy particle interaction not contain pseudoscalar terms, since under this condition the nucleon loop reduces to zero.



It seems difficult, however, to explain the absence of the decay $\pi \to e + \nu + \gamma$. Such a decay can occur on account of the tensor interaction if the virtual nucleon emits the γ-quantum.[4] We estimate the probability of such a process in the first order of perturbation theory in terms of G, where G is the constant of the π-meson-nucleon interaction $G(\tau\Phi_\pi)(\bar{\psi}_N\gamma_5\psi_N)$.

The simplest diagram for the $\pi \to e + \nu + \gamma$ decay is shown in the figure. With e in rationalized units and h = c = 1, we get for the matrix element

$$M = g_T e (2k \cdot 2m_\pi)^{-1/2} \sqrt{2}\, G I_{\varepsilon\mu} (\psi_e \gamma_5 \gamma_\varepsilon \gamma_\mu \psi_\nu)\, \delta(p_\pi - p_\nu - p_e - k),$$

where $I_{\epsilon\mu}$ is a logarithmically divergent integral over the variables of the virtual nucleons,

$$I_{\varepsilon\mu} = \mathrm{Sp}\int d^4p\,\frac{i\hat{p} - M}{p^2 + M^2}\,\hat{e}\,\frac{i(\hat{p} - \hat{k}) - M}{(p-k)^2 + M^2}\,\gamma_5\gamma_\varepsilon\mu_\mu\,\frac{i(p - p_\pi) - M}{(p - p_\pi)^2 + M^2}\,\gamma_5.$$

Here M is the mass of the nucleon, e and k are the polarization and four-dimensional momentum of the γ-quantum, and the other symbols are standard. Taking account of only the logarithmically divergent term, we have

$$I_{\varepsilon\mu} \approx 2\pi^2 F_{\varepsilon\mu} G \ln(\Lambda^2/M^2); \qquad F_{\varepsilon\mu} = e_\varepsilon k_\mu - e_\mu k_\varepsilon.$$

For the probability of the $\pi \to e + \nu + \gamma$ decay we get

$$dW = g_T^2\left(\frac{e^2}{4\pi}\right)\left(\frac{G\sqrt{2}}{4\pi^2}\ln\frac{\Lambda^2}{M^2}\right)^2 \frac{1}{(2\pi)^2}\,4m_\pi\left(\frac{m_\pi}{2} - q\right)\left(q + k - \frac{m_\pi}{2}\right)dp\,dq.$$

Here q and k are the momenta of the electron and the γ-quantum; we neglect the mass of the electron.

For the total probability we find

$$W = \frac{1}{96}\,\frac{1}{4\pi^2}\left(\frac{e^2}{4\pi}\right)\left(\frac{G\sqrt{2}}{4\pi^2}\ln\frac{\Lambda^2}{M^2}\right)^2 g_T^{02}\left(\frac{m_\pi}{m_e}\right)^4 m_\pi.$$

Substituting

$$g_T = 1.8\cdot 10^{-49}\ \text{erg/cm}^3 = g_T^0/m_e^2,\ g_T^0 = 3.8\cdot 10^{-12},\ \ \ln\Lambda^2/M^2 \sim 1,\ \ G^2/4\pi \sim 10$$

and going over to ordinary units, we get $W \sim 0.5\times 10^4\,\text{sec}^{-1}$. The ratio of the decay probabilities is

$$(\pi \to e + \nu + \gamma)/(\pi \to \mu + \nu) = \rho_\gamma \sim 0.5\cdot 10^4/0.4\cdot 10^8 \sim 10^{-4} \qquad (\tau(\pi + \mu + \nu) = 2.5\cdot 10^{-8}\,\text{sec}).$$

The ratio ρ_γ has been estimated by Treiman and Wyld.[4] In doing so they assumed that the decay $\pi \to \mu + \nu$ goes through a nucleon loop and a pseudovector interaction of the β-decay type. The logarithmically diverging integral for the nucleon loop then has the form $I_\nu = p_\nu M f_p$, where p is the momentum of the meson, M is the mass of the nucleon, and f_p is a dimensionless factor. Similarly the corresponding part of the matrix element of the $\pi \to e + \nu + \gamma$ decay was taken in the form $I_{\mu\nu} = e_\mu k_\nu f_T$, based on considerations of dimensional and gauge invariance. Then $\rho_\gamma \sim (g_T f_T/g_p f_p)^2$, and it was assumed that $f_p \sim f_T$ and $g_T/g_p > 50$. This last estimate is based on the assumption that the values of g_p for the meson and the electron are the same, and then β-decay gives $g_p < g_T/50$. With this approach, $\rho_\gamma \sim 1/500$. In Ref. 4 it is shown that the correct lifetime of the π meson is obtained for $g_p \sim 10^{-49}\,\text{erg/cm}^3$, $f_p \sim 0.1$. But $g_p \approx g_T/50$ gives $g_p \approx (1/25)\,10^{-49}\,\text{erg/cm}^3$ and it is necessary to take $f_p \sim 2.5$ in order to get the same lifetime. In our work the lifetime of the $\pi \to \mu + \nu$ decay is taken from experiment; the value of f_T corresponds to $(G\times 2^{1/2}/4\pi^2)\ln(\Lambda^2/M^2) \sim 0.4$.

At the Seventh Rochester Conference Cassels reported that experiment gives $\rho_\gamma < 2\times 10^{-6}$.

I express my gratitude to Prof. I. Ia. Pomeranchuk for suggesting the problem and for discussions, and to Iu. A. Simonov for valuable remarks.

[1] T. D. Lee and C. N. Yang, Phys. Rev. **104**, 254 (1956).

[2] C. S. Wu et al., Phys. Rev. **105**, 1413 (1957).

[3] Garwin, Lederman, and Weinrich, Phys. Rev. **105**, 1415 (1957).

[4] S. B. Treiman and H. W. Wyld, Jr., Phys. Rev. **101**, 1552 (1956).

Translated by W. H. Furry
110