Decays of $\pi^\pm$ mesons involving axions and massless axions: $\pi \to l + \nu_l + a(a')$

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Decays of the type $\pi^- \to l^- + \tilde{\nu}_l + a$ are analyzed. The probability for the electron version of the decay is $B(\pi^- \to e^- + \tilde{\nu}_e + a) \sim 10^{-9}$, which is comparable to the width of the primary background decay, $\pi^- \to e^- + \tilde{\nu}_e + \gamma$. Events which do not correspond to a two-particle kinematics can be identified, in the absence of an accompanying γ ray, as decays of the type $\pi^- \to e^- + \tilde{\nu}_e + a$.

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The question of the axion is quite uncertain[1]: Some experiments seem to indicate its existence,[2] while others indicate that it probably does not exist,[3,4] at least in a certain interval of the axion mass. Further arguments against its existence emerge from an analysis of some earlier experiments, which were not carried out especially to detect axions.[5]

The possible existence of a second—massless—axion (the "axion prime," a') was suggested in Ref. 6. This would be a Goldstone boson associated with a spontaneous breaking of the symmetry of the theory with respect to chiral representations of leptons. Although there are no apparent arguments why massless Goldstone particles should exist in the standard theory, which operates with elementary Higgs fields, such particles arise in a quite natural way in the technicolor representations. We wish to emphasize that it would seem extremely useful to carry out an experimental study of the existence or absence of massless particles, even if solid evidence is found that the ordinary massive axion, which decays into 2γ, does not exist. We believe that the question of the possible existence of pseudoscalar massless Goldstone bosons which have couplings with fermions of magnitude $\sim G_F^{1/2} m_f$, which conserve parity, and which do not change flavor when they are emitted, is a significantly more general question than that of the existence of the standard axion.

It may be more difficult to observe massless Goldstone particles than the standard axion, since these massless particles are stable. They should, however, participate in hadron decays along with an ordinary axion.[6] Accordingly, an experiment on the decay $\Psi \to a + \gamma$[4], which places a constraint on the value of the parameter x in the theory of the standard axion, simultaneously leads to a constraint on a combination of the two unknown parameters α and β in the model of Ref. 6 with a massless axion. As can be seen from the nature of the interaction of a and a' with the c quark,[6] the inequality $x^2 < 1$ is replaced by $\mathrm{tg}^2\,\alpha/\sin^2\beta + \mathrm{ctg}^2\,\beta < 1$. (The angles α and β are related to the ratios of the vacuum expectation values of the Higgs fields, $\varphi_1^0, \varphi_2^0, \varphi_3^0$, which give masses to the quarks with charges of $\frac{2}{3}$ and $-\frac{1}{3}$ and to leptons, respectively: $\mathrm{tg}\alpha = v_1/v_2$, $\mathrm{tg}\beta = \sqrt{v_1^2 + v_2^2}/v_3$, $v_i = \sqrt{2}\langle \varphi_i^0 \rangle$).

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In this letter we are interested in the decay of a charged π meson into a lepton, a neutrino, and an axion. Experimentally, it would be more advantageous to study the electron version of the decay, $\pi^- \to e^- + \tilde{\nu}_e + a$, rather than the other possibility—the muon version.[7] As we will see below, the width of the decay $\pi^- \to \mu^- + \tilde{\nu}_\mu + a$ turns out to be two orders of magnitude smaller simply because of the phase-space suppression. In addition, the probability for the primary background decay in the case of the electron version of the decay, $\pi^- \to e^- + \nu_e + \gamma$, is four orders of magnitude smaller than the probability for the background decay in the case of the muon version, $\pi^- \to \mu^- + \tilde{\nu}_e + \gamma$.

If events which do not correspond to a two-particle kinematics are selected, and if the emitted γ rays are detected efficiently, then the cases in which a γ ray is not observed can be identified as decays involving additional light particle (an axion, for example). The natural background (in addition to the radiative decays $\pi \to e + \tilde{\nu}_e + \gamma$) will also consist of the decays $\mu \to e + \tilde{\nu}_e + \nu_\mu$ if the incident muon is erroneously perceived as a pion or appears after the beam-particle indentification system as a result of the decay $\pi \to \mu + \tilde{\nu}_\mu$. In the c.m. frame, however, such electrons have a spectral cutoff of 53 MeV, so that there will be no background in the spectral region between 70 MeV ($\pi \to e + \tilde{\nu}_e$) and 53 MeV. In the laboratory frame, in a study of this decay in flight, there will be rather broad intervals of the emission angle and the electron energy which are free of the background reaction $\mu \to e + \tilde{\nu}_e + \nu_\mu$.

Matveev[8] has evaluated the probability for the decay $\pi \to e + \tilde{\nu}_e + a$. Here we will calculate this probability by the ordinary soft-pion technique.

If we ignore the emission of an axion by an electron (the corresponding probability is small, $\sim m_e^2/m_\pi^2 \sim 10^{-5}$), then the amplitude for the reaction of interest is analogous to that for the β decay of the π meson, $\pi^- \to e^- + \tilde{\nu}_e + \pi^0$, with the sole difference that the matrix element of the vector current, $\langle \pi^0 | \bar{u}\gamma_\mu d | \pi^- \rangle$, is replaced by the matrix element $\langle a | \bar{u}\gamma_\mu d | \pi^- \rangle$. The "current" π^0 meson, $\pi^0 \sim i/\sqrt{2}\,(\bar{u}\gamma_5 u - \bar{d}\gamma_5 d)$, contains in addition to the "massive" π^0 meson (i.e., a state with a definite mass), an axion with a mixing ratio[5,9]

$$\frac{f_\pi}{\mathrm{v}} y = \frac{f_\pi}{\mathrm{v}} \, , \left[\frac{1}{2} \, x \left(1 - N \frac{1-Z}{1+Z} \right) - \frac{1}{2x} \left(1 + N \frac{1-Z}{1+Z} \right) \right], \qquad (1)$$

where $\mathrm{v} = (G_F\sqrt{2})^{-1/2} \cong 250$ GeV, $f_\pi \cong 90$ MeV, N is the number of quark doublets, $Z = m_u/m_d$, and $x = \mathrm{v}_1/\mathrm{v}_2$ is the usual parameter of the standard axion theory. The ratio in (1) distinguishes the matrix element $\langle a/\bar{u}\gamma_\mu d | \pi^- \rangle$ from $\langle \pi^0 | \bar{u}\gamma_\mu d | \pi^- \rangle$; by virtue of the conservation of the vector current, the latter is simply $(p_{\pi^-} + p_{\pi^0})_\mu$.

Another way to find $\langle a | \bar{u}\gamma_\mu d | \pi^- \rangle$ is to extract the axion-field operator from the bra and to use the relation based on the partial conservation of axial vector current which relates the field $a(x)$ to the divergence of the "soft" current, which is free of the anomaly.[5,9] This "soft" current contains a third component of the isovector current A_μ^3 with a proportionality factor[5] y. (The isoscalar part of the soft current does not contribute to the G-parity matrix element.) By transforming from $\partial_\mu A_\mu^3$ to the field of the π meson, we can immediately prove this proportionality between matrix elements. Working from the arguments above, we easily find the total probability for the decay $\pi^- \to e^- + \tilde{\nu}_e + a$ to be

$$\Gamma(\pi^- \to e^- + \tilde{\nu}_e + a) = \frac{G_F^3 \cos^2\theta_c f_\pi^2 m_\pi^5}{192\sqrt{2}\,\pi^3} \cdot y^2 . \qquad (2)$$

The ratio of the width in (2) to the width of the decay $\pi\to\mu+\tilde{\nu}_\mu$ is

$$B(\pi^-\to e^-+\tilde{\nu}_e+a)=\left(\frac{G_F m_\pi^2}{48\sqrt{2}\pi^2}\right)\left(\frac{m_\pi}{m_\mu}\right)^2\frac{1}{\left(1-\frac{m_\mu^2}{m_\pi^2}\right)^2}y^2=3,2\times10^{-9}y^2. \quad (3)$$

With $N=3$ and $Z=m_u/m_d=0.56$, the quantity y is

$$y\simeq 0,077x-0,92/x\simeq -1/x. \quad (4)$$

With $x\sim 1$, the probability for the decay $\pi^-\to e^-+\tilde{\nu}_e+a$ is therefore only an order of magnitude smaller than that for the decay $\pi^-\to e^-+\tilde{\nu}_e+\gamma$ $[B(\pi^-\to e^-+\tilde{\nu}_e+\gamma)=(5,6\pm0,7)\cdot10^{-8}]$. In this situation, an experimental observation of the decay $\pi^-\to e^-+\tilde{\nu}_e+a$ by the method described schematically above seems completely feasible.

To conclude this discussion of the decay $\pi^-\to e^-+\tilde{\nu}_e+a$, we write out the energy distribution of the decay electrons:

$$dw(\pi^-\to e^-+\tilde{\nu}_e+a)=12\Gamma(\pi^-\to e^-+\tilde{\nu}_e+a)\,\epsilon^2(1-\epsilon)d\epsilon,\quad \epsilon=\frac{E}{E_{max}}=\frac{2E}{m_\pi}. \quad (5)$$

Although the muon decay is less interesting than the electron decay from the experimental standpoint, as mentioned earlier, we will derive an expression for the width of the decay $\pi^-\to\mu^-+\tilde{\nu}_\mu+a$. Since we cannot ignore the quantity $(m_\mu/m_\pi)^2$ in this case, the amplitude for the decay consists of two parts: (a) the transition $\langle a|\bar{u}\gamma_\mu d|\pi^-\rangle$, which is discussed above, and which is accompanied by the emission of a lepton pair, and (b) the emission of an axion by a muon from the decay $\pi^-\to\mu^-+\tilde{\nu}_\mu$. A direct calculation yields

$$\Gamma(\pi^-\to\mu^-+\tilde{\nu}_\mu+a)=\frac{G_F^3 f_\pi^2 m_\pi^5}{192\sqrt{2}\pi^3}\left[\sigma_1(\rho)y^2+\sigma_2(\rho)\left(\left(\frac{1}{x}\right)^2+2\frac{y}{x}\right)\right],\quad \rho=m_\mu^2/m_\pi^2,$$

$$\sigma_1(\rho)=1-7\rho-6\rho^2-12\rho^2\ln\rho+11\rho^3-6\rho^3\ln\rho+\rho^4=1,91\times10^{-2}, \quad (6)$$

$$\sigma_2(\rho)=\rho(1+3/2\rho+3\rho\ln\rho-3\rho^2+1/2\rho^3)=0,65\times10^{-2}.$$

We see that the probability for the decay $\pi^-\to\mu^-+\tilde{\nu}_\mu+a$ is two orders of magnitude smaller than that for the electron version of the decay. With $y=-1/x$ [see (4)], for example,

$$\Gamma(\pi^-\to\mu^-+\tilde{\nu}_\mu+a)=1,26\times20^{-2}\Gamma(\pi^-\to e^-+\tilde{\nu}_e+a). \quad (7)$$

Finally, let us examine how these results change for (1) the model of Ref. 6 with a second, massless axion, a', and (2) the model with an additional U(1) symmetry in which, in addition to one Higgs doublet ϕ_1, which gives masses to *all* the fermions (as in the bare bones Weinberg-Salam model), there is also one doublet ϕ_2, which does not interact with fermions.

In case (1) the quantity y^2 in Eq. (3) and in the first term in Eq. (6) must be replaced by $y^2/\sin^2\beta + \mathrm{ctg}^2\beta$, where y is again defined by Eq. (1) with $x = v_1/v_2 = \tan\alpha$, and where $\mathrm{tg}\beta = \sqrt{v_1^2 + v_2^2}/v_3$ (Ref. 6). The first term here corresponds to a decay into an ordinary axion, while the second corresponds to a decay into an a'.

For model (2), $y^2 \to 1/x^2$, $x = v_1/v_2$. Corresponding substitutions can be made in the second term in expression (6). For model (1) here we have $(1/x)^2 + 2(y/x) \to \mathrm{tg}^2\beta + 2$, while for model (2) we have $(1/x)^2 + 2(y/x) \to -(1/x)^2$.

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1. S. Weinberg, Phys. Rev. Lett. **40**, 223 (1978); F. Wilczek, *ibid.* **40**, 279 (1978).
2. H. Fassner, Talk given at 1981 International Symposium on Lepton and Photon Interactions at High Energies, Bonn, October 1981.
3. A. Zehnder, Phys. Lett. **104B**, 494 (1981).
4. F. C. Porter, Preprint SLAC-pub-2785, August 1981.
5. T. W. Donnelly and S. J. Freedman *et al.*, Phys. Rev. **D 18**, 1607 (1978).
6. A. A. Anselm and N. G. Uraltsev, Phys. Lett. (in press); Preprint LNPI-720, 1981.
7. V. M. Lobashev, "Fundamental research at the meson factory," in Trudy II Vsesoyuznogo seminara po programme éksperimental'nykh issledovaniĭ na mezonnoĭ fabrike IYaI AN SSSR (Proceedings of the Second All-Union Seminar on the Program of Experimental Research at the Meson Factory of the Institute of Nuclear Research, Academy of Sciences of the USSR), Zvenigorod, 1981.
8. V. A. Matveev, "The axion and possibilities for observing it," in Trudy II Vsesoyuznogo seminara po programme éksperimental'nykh issledovaniĭ na mezonnoĭ fabrike IYaI AN SSSR (Proceedings of the Second All-Union Seminar on the Program of Experimental Research at the Meson Factory of the Institute of Nuclear Research, Academy of Sciences of the USSR), Zvenigorod, 1981.
9. W. A. Bardeen and S. H. Tye, Phys. Lett. **74B**, 229 (1978).

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