Search for new gauge bosons in the decay $\pi\pi^0 \to \gamma +$ "nothing"

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The search for the decay $\pi^0 \to \gamma +$ "nothing" is shown to be an effective method of searching for new light gauge bosons.

The standard $SU(2) \times U(1) \times SU(3)$ model is now in good agreement with all experimental data. Because of its several flaws (the problem of hierarchy, number of generations, unification of all interactions, etc.), however, it is necessary to go beyond the scope of this model (the grand unified theory, supersymmetry, technicolor, superstrings, etc.). The low-energy gauge group in this case is often found to be wider than the $SU(2) \times U(1) \times SU(3)$. The simplest and at the same time the most common

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case is the expansion of the standard group using the additional U(1) factor. This mechanism is frequently realized in grand unified theories,[1] supersymmetric models,[2] and superstring theories.[3] An interest in the study of such models has recently increased also in view of the suggestion of the possible existence of a new long-range interaction (the "fifth force"[4]). In view of this circumstance, it is important to theoretically analyze the properties of the new U(1) bosons and to see whether an experimental search of them is feasible. In this letter our goal is to show that one of the new effective methods of searching for these bosons is the search for the decay $\pi^0 \to \gamma +$ "nothing" ("nothing" is understood to mean undetectable neutral particles).

The Lagrangian for the interaction of a hypothetical gauge boson X_μ with the quark vector current is[1)]

$$\mathcal{L} = \sum_q g_q \bar{q} \gamma_\mu q X^\mu$$

(it can be shown that the coupling of X_μ with the axial current does not contribute to the decay $\pi^0 \to \gamma X$).

Reducing the amplitude for the decay $\pi^0 \to \gamma X$ to the amplitude $\pi^0 \to 2\gamma$, we find

$$\Gamma(\pi^0 \to \gamma X) = \frac{2\alpha}{(4\pi)^4}\left(2g_u + g_d\right)^2 \frac{m_\pi^3}{f_\pi^2}\left(1 - \frac{m_X^2}{m_\pi^2}\right)^3 , \tag{1}$$

where $f_\pi = 93$ MeV, and m_X is the mass of the X boson.

Let us consider, for definiteness, Fayet's[2] $SU(3) \times SU(2) \times U(1) \times \tilde{U}(1)$ supersymmetry model with a spontaneous supersymmetry breaking due to the D term. In this model the additional gauge boson (usually called the U boson) interacts with the quark current $\bar{q}\gamma_\mu q$ with the coupling constant[2)]

$$g_q = 2 \times 10^{-3} \, m_U \, (\mathrm{GeV})\, a , \tag{2}$$

where $0 < a \lesssim 1$ is a parameter which is determined by the Higgs sector of the model and by the scale of the supersymmetry breaking (in Fayet and Weinberg's notation we have $a = r \cos \varphi$). Analysis of the possible manifestation of the U boson in various experiments, νN scattering, and the decay $K^+ \to \pi^+ U$ (and other decays[7]) show that the region 100 MeV $< m_U <$ 120 MeV is a clearly resolved region of U-boson masses.[3)] Experiments on nonconservation of P parity in atoms[8] have imposed a constraint on the parameter a: At 100–200 MeV we have $a^2 < 0.15 \cos \varphi$ for m_U. Using (1) and (2), we obtain for $m_U = 100$ MeV

$$B(\pi^0 \to \gamma U) B(U \to \nu \bar{\nu}) \lesssim 6{,}5 \times 10^{-8} \cos \varphi . \tag{3}$$

In determining (3) it was taken into account that the relative probability for the decay of a boson along an invisible channel is $B(U \to \nu\bar{\nu}) = 0.6$.

In a similar way, the probability for the production of a new gauge X boson in the decay $\pi^0 \to \gamma X$ can also be estimated on the basis of other models which contain the (1) factor.

Studies are now under way at the Institute of Nuclear Research, Academy of

Sciences of the USSR, to determine from the experimental point of view whether the process $\pi^0 \to \gamma +$ "nothing" can be detected at the sensitivity level of 10^{-7}–10^{-8}.[2)]

What sets the process $\pi^0 \to \gamma +$ "nothing" apart from others (such as the process $K^+ \to \gamma +$ "nothing") is the fact that the background from the decay $\pi^0 \to \gamma$ + scalar(s) (Goldstone or pseudo-Goldstone bosons, for example) and the decay $\pi^0 \to \gamma + f\bar{f}$, where f is a weakly coupled light fermion (a neutrino, photino, etc.), is negligible. The decay $\pi^0 \to \gamma + a$ (pseudo)scalar, for example, is forbidden. The relative probabilities for the decays $\pi^0 \to \gamma\nu\bar{\nu}$ and $\pi^0 \to \gamma\tilde{\gamma}\tilde{\gamma}$ are (for massless ν and $\tilde{\gamma}$), respectively,

$$B(\pi^0 \to \gamma\nu\bar{\nu}) \simeq 8 \times 10^{-19} \text{ (Refs. 9 and 10)}$$

$$\text{and} \quad B(\pi^0 \to \gamma\tilde{\gamma}\tilde{\gamma}) \lesssim 1{,}4 \times 10^{-16} \text{ (Ref. 9).}$$

The detection of the decay $\pi^0 \to \gamma +$ "nothing" would thus imply the discovery of a new gauge boson. A negative result of an experimental search for this decay would yield new nontrivial constraints on the possible mass a coupling constant of this boson.

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[1)]A possible existence of a vector boson which interacts with a baryon current was studied by Lee and Yang.[5] If this boson is massless, it follows from the results of experimental verification of the equivalence principle that a strong restriction is imposed on its coupling constant[6]: $g_q^2/4\pi \lesssim 10^{-47}$. If, on the other hand, this boson has a mass: its Compton wavelength has a microscopic length, then the restriction imposed on it is no longer valid.

[2)]The U boson also has an axial coupling which is unimportant in this case.

[3)]Whether the mass region $m_U < 100$ MeV (for $a \sim 1$) is forbidden by the data on the decay $K^+ \to \pi^+ U$ requires a special study because the theoretical predictions of the probability for this decay are highly ambiguous.

[4)]In the csae of a vector X boson with a rather large mass, the energy of a γ ray emitted in the decay $\pi^0 \to \gamma X$ is much lower than the energy of γ rays emitted in the decay $\pi^0 \to \gamma\gamma$. This is the key point upon which an experiment with a sensitivity of 10^{-7}–10^{-8} must be based.

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