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ABOUT POSSIBLE TYPES OF NEUTRINO OSCILLATIONS

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Various aspects of the problem of oscillations of massive neutrinos [1], based on the analogy with $K^o\tilde{K}^o$ [2] oscillations, are discussed quite extensively. A characteristic feature of this approach is that the neutrino is considered to be a wave packet and neutrinos resulting from oscillation to be real particles by precise analogy with the oscillations of K^o and $\tilde{K}^o$ mesons.

However, from available physical examples one may arrive at the conclusion that there may, also, exist alternative types of oscillations. Owing to specific features we shall term these oscillations virtual. The consideration will be performed in the framework of the ordinary quantofield approach.

Before passing to this type of oscillation we shall analyze in greater detail some features of $K^o\tilde{K}^o$ oscillations. In doing so we only claim to provide a general qualitative description of the process of $K^o\tilde{K}^o$ oscillation. One of the fundamental requirements of physics is the requirement of relativistic invariance. If a particle travels in vacuum without suffering interactions, then:

$$P^2 = inv = m^2 \qquad (1)$$

What will happen with K^o and $\tilde{K}^o$ mesons travelling in vacuum? It is clear that if K^o and $\tilde{K}^o$ mesons were stable particles with masses m_{K^o} and $m_{\tilde{K}^o}$, respectively, then these particles would travel in vacuum satisfying the conditions:

$$P^2 = inv = m^2_{K^o, \tilde{K}^o}.$$

Switching on the weak interaction results in these particles becoming non-stable, and they, then, acquire widths Γ_{K^o} and $\Gamma_{\tilde{K}^o}$, together with masses. It must be noted that in the first order in the weak interaction (without taking into account CP violation) all the characteristics of K^o and $\tilde{K}^o$

mesons should be identical and they can transform into each other via $K^0 \Leftrightarrow Z^0 \Leftrightarrow \tilde{K}^0$, and the miuxing angle must be 45° ($s\bar{d} \Leftrightarrow d\bar{s}$ and all characteristics of these systems must coincide, if CP-parity is conserved). The appearing decay widths, Γ_{K^0} in the case of K^0 and $\Gamma_{\tilde{K}^0}$ in the case of $\tilde{K}^0$, signify that, owing to these particles decaying, their flux in vacuum will decrease following the known exponential law.

Now let us return to formula (1) and see, what will happen to this formula and to $K^0\tilde{K}^0$ oscillations, if K^0 and $\tilde{K}^0$ are non-stable particles that have widths. In this case expression (1) for K^0 and $\tilde{K}^0$ will assume the form:

$$p^2 = m^2_{K^0} \quad ; \quad p^2 = m^2_{\tilde{K}^0} \qquad (2)$$

now, since K^0 and $\tilde{K}^0$ have definite widths, no longer will K^0 and $\tilde{K}^0$ have fixed masses (taking into account the uncertainty relations). On the basis of general arguments we may assume (at a qualitative level) the masses of K^0 and $\tilde{K}^0$ to be distributed according to the Breit-Wigner formula [3]:

$$m'^2_{K^0} \longrightarrow m^2_{K^0} \frac{(\Gamma_{K^0}/2)^2}{(m'_{K^0} - m_{K^0})^2 + (\Gamma_{K^0}/2)^2} \qquad (3)$$

In the case of $\tilde{K}^0$ precisely the same formula holds if the substitution $K^0 \rightarrow \tilde{K}^0$ is performed.

When (3) is substituted into (2), it can be seen that, owing to the widths of the K^0 and $\tilde{K}^0$ mesons, the masses of the K^0 and $\tilde{K}^0$ mesons (taking into account the uncertainty relations) follow certain distributions and formula (1) acquires a new meaning.

We still consider the CP violating terms not to be switched on. Then all the characteristics of the K^0 and $\tilde{K}^0$ mesons will coincide, and the mixing angle will, accordingly, be 45°.

Now let us switch on the CP violating terms. In this

case the masses m_{K^0} and $m_{\tilde{K}^0}$ will change. If the difference between the K^0 and $\tilde{K}^0$ masses is of the order of, or smaller than, the width $\Gamma = \Gamma_{K^0} + \Gamma_{\tilde{K}^0}$ (experimentally $4m \approx 3.5\cdot10^{-12}$ MeV, $\Gamma \approx 7.0\cdot10^{-12}$ MeV), then from formula (2), taking into account (3), we obtain overlapping mass distributions for the K^0 and $\tilde{K}^0$ mesons, and therefore $K^0 \Leftrightarrow \tilde{K}^0$ transitions remain possible (moreover, the overlapping of the mass distributions the K^0 and $\tilde{K}^0$ mesons is nearly complete). This means that within the framework of the uncertainty relation the $\tilde{K}^0$ has time to develop into a real particle during the $K^0 \Leftrightarrow \tilde{K}^0$ transition. If the mass difference between the K^0 and $\tilde{K}^0$ were significantly larger than the widths, then $\tilde{K}^0$ would not have time to develop into a real particle and the real transition of K^0 into $\tilde{K}^0$ could not occur (we recall that in a real transition of one particle into another momentum transfer is required for passing to the mass surface (if $m_1 \neq m_2$), while in the example given above such a transition is possible, since, owing to the existence of widths of the K^0 and $\tilde{K}^0$ an uncertainty depending on these widths is permissible, which allows the $\tilde{K}^0$ meson to develop as a real particle). If the mass difference between the K^0 and $\tilde{K}^0$ were to exceed significantly the widths of these mesons, it is clear that the $\tilde{K}^0$ could not develop as a real particle. But, in this case, oscillations between K^0 and $\tilde{K}^0$ should remain, since this is permitted by weak interaction.

Following conventional definitions we shall call oscillations of this sort (if such oscillation is allowed by the interaction), in the case of which the other particle cannot develop into a real particle, owing to the requirement of relativistic invariance (1) and the absence of overlapping between the mass distributions (2, 3), virtual oscillations.

Now let us proceed to consider mixing (oscillations), which occurs in the vector dominance model [4]. In this model (oscillations) mixings occur of the vector fields of strong interaction, $V_\mu(\rho^0, \omega, \ldots)$, and of electromagnetic interaction, A_μ. The initial fields $\begin{pmatrix} V_\mu \\ A_\mu \end{pmatrix}$ mix when the strong and elctromagnetic interactions are switched on [5]:

$$V'_\mu = \cos\phi \; V_\mu - \sin\phi \; A_\mu , \quad \cos\phi = \frac{G}{\sqrt{G^2 + e^2}}$$

$$A'_\mu = \sin\phi \; V_\mu + \cos\phi \; A_\mu \qquad (4)$$

G-and e-are the constants of the strong and electromagnetic interactions, respectively.

From formula (1) it is clear that in the case of a high energy γ quantum propagating in vacuum it cannot undergo real transformation into $\rho°$, ω, ... $\left(p^2_{\rho°,\omega} = m^2_{\rho°,\omega}\right)$

$$P^2_\gamma = P^2_{\rho°,\omega} = 0 \qquad (5)$$

i.e. in this example we are dealing with a virtual (oscillation) transition. For this virtual transition to become real the γ quantum must interact with the target for momentum transfer and transitions to corresponding mass surfaces to occur.

Making use of the two examples presented above we shall proceed to consider various versions of neutrino oscillations.

a. 1) If all neutrinos ν_e, ν_μ (for simplification we shall consider the case of two sorts of neutrinos, the case of three sorts of neutrinos can be analyzed in a similar way) have identical masses,

$$P^2_{\nu_e} = P^2_{\nu_\mu} = m^2_{\nu_e,\nu_\mu} \qquad (6)$$

then oscillations between ν_e and ν_μ may occur. For this such a mechanism (or interaction) must exist which violates l_e and l_μ. Unlike the case of $K°$ and $\tilde{K}°$ mesons, where the mixing angle is about 45°, the mixing angle Θ

$$\begin{pmatrix} \nu'_e \\ \nu'_\mu \end{pmatrix} = \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} \qquad (7)$$

for the neutrinos will depend on the interaction violating l_e and l_μ (a model of such violation is proposed in ref. [6]).

a. 2) If ν_e and ν_μ are not stable and have widths Γ_{ν_e} and Γ_{ν_μ}, which make the masses m_{ν_e} and m_{ν_μ} overlap, then oscillations in this system will be absolutely identical to the oscillations of $K°$ and $\tilde{K}°$, considered above, with the exception of the mixing angle Θ, that will be determined by the violation mechanism of l_e and l_μ. In cases a. 1) and a. 2) the neutrino oscillations will be real.

b. Now assume the difference between the masses of ν_e and ν_μ to be large and let this difference not to be overlapped by the widths Γ_{ν_e} and Γ_{ν_μ} (if these neutrinos are stable, then $\Gamma_{\nu_e} = 0$, $\Gamma_{\nu_\mu} = 0$), then no real transition between these sorts of neutrinos will occur. Like in the considered example with oscillation arising in the framework of the model of vector dominance, in this case virtual neutrino oscillations will take place. The mixing angle will be determined by the mechanism violating l_e and l_μ. For a real transition of ν_e into ν_μ to occur interaction is necessary with the target for momentum transfer and transition to the mass surface of the muon neutrino.

Evidently, the most realistic case is the one, when one of the neutrinos is stable, while the other neutrino is non-stable and has a definite width Γ; if this width overlaps the difference between the neutrino masses, real neutrino oscillations will take place, otherwise virtual neutrino oscillations will occur.

The formulas for the neutrino oscillation will have the form:

$$\begin{pmatrix} \nu'_e \\ \nu'_\mu \end{pmatrix} = U^+ \begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix}, \quad U^+ = \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix}$$

$$\nu'_1 = \sum_{k=1}^{2} \exp\left[-i(E_k - i \Gamma_k) t \right] U^*_{ik} \nu_k$$

$U^+$is the matrix describing neutrino mixing; in this case the probability $P_{\nu_1 \nu_{1'}}$ is the following:

$$P_{\nu_e \nu_\mu} = \left| \sum_{k=1}^{2} U^+ \exp\left[-i(E_k - i \Gamma_k) t \right] U \right|^2$$

$$P_{\nu_e \nu_e} = 1 - P_{\nu_e \nu_\mu}$$

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О возможных типах осцилляций нейтрино

Рассматриваются возможные типы осцилляций нейтрино. Наряду с осцилляциями нейтрино, которые основаны на аналогии с осцилляциями K^0 и $\tilde{K}^0$ мезонов, рассматриваются виртуальные осцилляции нейтрино (когда появившиеся в результате осцилляции нейтрино не переходят на массовую поверхность). Изучаются условия, при которых такие осцилляции появляются.

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About Possible Types of Neutrino Oscillations

Possible types of neutrino oscillations are considered. Together with neutrino oscillations based on analogies with oscillations of K^0 and $\tilde{K}^0$ mesons, virtual neutrino oscillations (here neutrinos produced in the oscillations do not undergo transition to the mass surface) are considered. Conditions in which such oscillations occur are studied.

The investigation has been performed at the Laboratory of Computing Techniques and Automation, JINR.

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