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CP VIOLATION AND INTERFERENCE PHENOMENA IN DECAY OF NEUTRAL K MESONS INTO TWO PIONS

The Princeton group has recently obtained an indication of a possible existence of the $K_2^0 \to \pi^+\pi^-$ decay[1] which is forbidden by CP -invariance. This attracted a great deal of attention.

The fundamental importance of this experimental fact requires a careful verification and an analysis of all the processes which could simulate the $K_2^0 \to \pi^+\pi^-$ decay.

In this connection it should be noted that in the experiment[1] neither decaying particle nor its decay products were identified. It is therefore not ruled out (although it seems rather unlikely) that here we are faced with the decay of another unknown particle. As was shown in[2], under certain conditions such a process could be the electromagnetic decay $\chi^0 \to e^+e^-$ where χ^0 is the hypothetical long-lived particle, the properties of which ($M \approx 412$ MeV, $S = 0$, $J^{PC} = 0^{+-}$) are in agreement with the phenomenological classification of Sternheimer[3].

Thus, in order to prove the existence of the $K_2^0 \to \pi^+\pi^-$ decay it seems necessary to identify the secondary pions what is a very complicated experimental problem. However, even if this problem is solved, there remains a possibility which will require additional experiments. We mean the $K_2^0 \to \pi^+\pi^-\gamma$ decay[1/] which could also simulate the $K_2^0 \to \pi^+\pi^-$ decay at small energies of γ quanta. $E_\gamma \lesssim 1$ MeV). The authors of paper[1] rule out this possibility because no processes which could give the corresponding form of the γ spectrum are at present known.

We think that the question about the $K_2^0 \to \pi^+\pi^-\gamma$ decay as a simulating process deserves a more serious consideration in view of a possible resonance interaction between two pions. As far as in the final state any other strongly interacting particles are absent this $\pi-\pi$ interaction can manifest itself in the considered decay process more distinctly than in the processes of strong interaction. At the same time (if we take into account the estimate of the relative probability of the $K_2^0 \to \pi^+\pi^-\gamma$ decay[5]) it suffices to assume a 10% contribution of the resonantly interacting pions to explain the effect observed in[1]. It is evident that to identify the pions in the $K_2^0 \to \pi^+\pi^-\gamma$ decay and to detect simultaneously the low-energy γ quantum as well as to measure its energy is extremely difficult. This becomes practically impossible when the γ quantum energies are very low. It is clear that any experiment in this direction is not a solution of the problem about the existence of the $K_2^0 \to \pi^+\pi^-$ decay. There is however an experimental possibility which

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1/ In particular, the decay $K^0 \to \pi^{\mp} + \kappa^{\mp}$ is possible where κ is an unknown particle with $m_\kappa \approx m_\pi$ which decays via the mode $\kappa \to \pi + \gamma$. It also may be that instead of a γ quantum any other unknown particle with a very small mass[4] is emitted.

allows a final solution of this problem not in some approximation, but as a whole.

The point is that if the decay of the long-lived component of the neutral K-meson into two pions does occur, then different interference phenomena are possible under certain conditions. If the effect observed in [1] is a result of a simulation, these interference phenomena must, in principle, be absent. (see papers [6-8]).

In particular, Sachs [7] noticed recently that the existence of the $K_2^0 \to \pi^+ \pi^-$ decay (regardless of its cause) leads to a slight deviation from the exponential form of the decay curve $K_1^0 \to \pi^+ \pi^-$ because of the additional interference term. So, at $\lambda_1 t \approx 4$ this deviation is only 5%, according to [7]. Therefore, it is very difficult to observe it experimentally.

As we will show below, however, at large t when the amplitudes of the $K_1^0 \to \pi^+ \pi^-$ and $K_2^0 \to \pi^+ \pi^-$ decays become comparable by magnitude, the interference effect is very prominent what provides very favourable conditions for its experimental observation.

These conditions could be made even more favourable if one observes the interference of the $K_2^0 \to \pi^+ \pi^-$ wave with that of $K_1^0 \to \pi^- \pi^+$ which is regenerated from the plate (see Section 4).

Thus, an observation of the the above-mentioned interference phenomena opens up at present a real possibility for a final solution of the problem concerning the existence of the $K_2^0 \to \pi^+ \pi^-$ decay. Further on, we will show that in such experiments some more essential information about the properties of neutral K mesons could be obtained.

2. At the present time in numerous theoretical papers different hypotheses are discussed according to which the existence of the $K_2^0 \to 2\pi$ decay could be accunted for.

In spite of the seeming variaty of approaches, all these hypotheses may be divided into three basic groups in accordance with three possible assumptions about the character of CP -violation.

Group A

CP -invariance is violated directly in the $K^0(\overline{K^0}) \to 2\pi$ decay. The quasi-stationary states having definite values of mass and lifetime are the states with a definite CP - parity

$$K_1^0 = \frac{K^0 + \overline{K^0}}{\sqrt{2}} \quad \text{and} \quad K_2^0 = \frac{K^0 - \overline{K^0}}{\sqrt{2}} \tag{1}$$

Group B

CP -parity is conserved in the $K^0(\overline{K^0}) \to 2\pi$ decay. There are, however, factors (internal or external) which lead to a mixing of the K_1^0 and K_2^0 states. As a result, the quasi-stationary states are no longer K_1^0 and K_2^0 determined by (1), but new states K'_1 and K'_2 which have no definite parity. Let

$$K'_1 = \frac{K_1^0 - \epsilon K_2^0}{\sqrt{1+|\epsilon|^2}} \qquad (2)$$

$$K'_2 = \frac{K_2^0 + \epsilon K_1^0}{\sqrt{1+|\epsilon|^2}} \qquad (3)$$

It should be emphasized that the complex parameter ϵ in (2) and (3) is chosen so that $|\epsilon|^2$ is the ratio of the probabilities of the decays into two charged pions for long-lived and short-lived components3/. ($|\epsilon| \approx 2.3 \cdot 10^{-3}$/1/)^3 .

Group C (intermediate). The quasistationary states do not possess a definite CP -parity. Besides, CP -invariance is violated directly in the decay. As far as all the effects for this goup may be reduced to the effects characteristic of the groups A and B , in what follows we restrict ourselves to an analysis of the interference phenomena in the framework of the assumptions A and B.

3. Consider now the "beating" in the $K^0 \to 2\pi$ and $\overline{K^0} \to 2\pi$ decays. Let us analyse the structure of the amplitude of this "beating" from the standpoint of the hypotheses A and B

We assume that the amplitudes of the $K_2^0 \to \pi^+\pi^-$ and $K_1^0 \to \pi^+\pi^-$ decays are related by

$$A(K_2^0 \to \pi^+\pi^-) = \epsilon A(K_1^0 \to \pi^+\pi^-) . \qquad (4)$$

Then assuming everywhere that $\hbar = c = 1$, we obtain

$$A(K^0 \to \pi^+\pi^-) = A(K_1^0 \to \pi^+\pi^-)(e^{-(im_1 t + \frac{\lambda_1}{2} t)} + \epsilon e^{-(im_2 t + \frac{\lambda_2}{2} t)})$$

$$A(\overline{K}^0 \to \pi^+\pi^+) = A(K_1^0 \to \pi^+\pi^-)(e^{-(im_1 t + \frac{\lambda_1}{2}} - \epsilon e^{-(im_2 t + \frac{\lambda_2}{2} t})) \qquad (6)$$

2/ The K'_1 and K'_2 states thus determined are in accord with the model [8,9]. In the general case, another independent complex parameter ξ should be introduced into the formula (2). As a detailed analysis shows, however, at small $|\epsilon|$ and $|\xi|$, if we restrict ourselves to the terms of the second order in ϵ and ξ , all further conclusions will remain unaltered. Note, that the K'_1 and K'_2 states are orthogonal only if $\xi = \epsilon^*$.

3/It is easy to see that for the variant B the ratio of the probabilities of the $K'_2 \to \pi^+\pi^-$ and $K'_2 \to 2\pi^0$ decay is the same as for the K_1 meson. On the other hand, for the variant A it may, in principle, take any value.

where m_1, m_2 are mass of the K_1^0 and K_2^0 mesons, respectively, λ_1 and λ_2 are their decay rates, t is the proper time of the K -meson which is equal to $\frac{L}{v}\sqrt{1-v^2}$ where v is the K meson velocity, L is the distance from the source.

Represent now ϵ in the form

$$\epsilon = |\epsilon| e^{i\delta} . \tag{7}$$

Then, for the probabilities of the decays into $\pi^+\pi^-$ we get the following expressions

$$P(K^0 \to \pi^+\pi^-) = P_0 \left(e^{-\lambda_1 t} + 2|\epsilon| \cos(\Delta m t + \delta)\, e^{-\frac{\lambda_1+\lambda_2}{2} t} + |\epsilon|^2 e^{-\lambda_2 t}\right) \tag{8}$$

$$P(\overline{K^0} \to \pi^+\pi^-) = P_0 \left(e^{-\lambda_1 t} - 2|\epsilon| \cos(\Delta m t + \delta)\, e^{-\frac{\lambda_1+\lambda_2}{2} t} + |\epsilon|^2 e^{-\lambda_2 t}\right) \tag{9}$$

It should be stressed that the interference term for the K^0 and $\overline{K^0}$ decays are equal in magnitude, but have opposite signs. Therefore, in order to obtain the effect in a pure form it is reasonable to make use of the reactions in which single K^0 and $\overline{K^0}$ mesons are produced[4].

At small t, the relative contribution of the interference terms will be insignificant (Fig. 1). At large t, the role of these terms is becoming more important, and at $\lambda_1 t = 10 \div 14$ they turn out to be comparable with the main exponential terms what leads to a very pronounced interference effect (Fig. 2).

Evidently, this effect will depend essentially on the difference in the phases (see Fig. 3). Thus, by observing the interference at different distances from the point at which the neutral K -mesons are produced we are able not only to establish the very existence of the $K_2^0 \to \pi^+\pi^-$ decay but also to determine the phase difference δ between the amplitudes of $K_1^0 \to \pi^+\pi^-$ and $K_2^0 \to \pi^+\pi^-$. Thereby, we can obtain some important information about the mechanism of the $K_2^0 \to \pi^+\pi^-$ decay.

B. Since the quasi-stationary states are the K_1' and K_2' then, as it is easy to show, the wave function of the produced meson changes in time according to the law

$$K^0 \to \frac{\sqrt{1+|\epsilon|^2}}{\sqrt{2}\cdot(1+\epsilon^2)} \left\{(1-\epsilon) K_1' \cdot e^{-(im_1 + \frac{\lambda_1}{2})t} + (1+\epsilon) K_2' e^{-(im_2 + \frac{\lambda_2}{2})t}\right\} \tag{10}$$

As far as the $\overline{K^0}$ meson is concerned, it is

4/ If $\overline{K^0}$ and K^0 mesons are produced in pairs, a special analysis is required which is not, by the way, difficult to make.

$$\overline{K^0} = \frac{\sqrt{1+|\epsilon|^2}}{\sqrt{2}\cdot(1+\epsilon^2)}\{(1+\epsilon)K_1' e^{-(im_1+\frac{\lambda_1}{2})t} - (1-\epsilon)K_2' e^{-(im_2+\frac{\lambda_2}{2})t}\} \tag{11}$$

Using (2) and (3) for the amplutude of the $K^0 \to 2\pi$ and $\overline{K^0} \to 2\pi$ decay it is not difficult to write down the following expressions

$$A(K^0 \to 2\pi) = A(K_1^0 \to 2\pi) \times$$
$$\times \left\{\frac{1-\epsilon}{\sqrt{2}(1+\epsilon^2)} e^{-(im_1+\frac{\lambda_1}{2})t} + \frac{\epsilon(1+\epsilon)}{\sqrt{2}(1+\epsilon^2)} e^{-(im_2+\frac{\lambda_2}{2})t}\right\} \tag{12}$$

$$A(\overline{K}^0 \to 2\pi) = A(K_1^0 \to 2\pi) \times$$
$$\times \left\{\frac{1+\epsilon}{\sqrt{2}(1+\epsilon^2)} e^{-(im_1+\frac{\lambda_1}{2})t} - \frac{\epsilon(1-\epsilon)}{\sqrt{2}\cdot(1+\epsilon^2)} e^{-(im_2+\frac{\lambda_2}{2})t}\right\} \tag{13}$$

Comparing (12) and (13) with (5) and (6), we see that they depend on the parameter ϵ in a different fashion. This parameter is equal, in both variants A and B, to the ratio of the 2π decay amplitudes for the long-lived and short-lived components. If the parameter $|\epsilon|$ were large, this difference would be essential. But, in fact $|\epsilon| \ll 1$, and we can write with an accuracy up to the terms of the second order in

$$P(K^0 \to 2\pi) = \{e^{-\lambda_1 t} + 2|\epsilon|(1+2\cos\delta|\epsilon|)\cos(\Delta m t+\delta)e^{-\frac{\lambda_1+\lambda_2}{2}t} + |\epsilon|^2 e^{-\lambda_2 t}\} \tag{14}$$

$$P(\overline{K}^0 \to 2\pi) = \{e^{-\lambda_1 t} - 2|\epsilon|(1-2|\epsilon|\cos\delta)\cos(\Delta m t+\delta)e^{-\frac{\lambda_1+\lambda_2}{2}t} + |\epsilon|^2 e^{-\lambda_2 t}\} \qquad (15)^{5/}$$

When comparing the expressions (15) and (16) we obtained with the formulae (8) and (9) for the variant A , we see that there appear the additional terms proportional to $2|\epsilon|^2\cos\delta$. It is interesting to note that the interference terms for the $K^0 \to 2\pi$ and $\overline{K}^0 \to 2\pi$ decays (in the variant B) have the amplitudes which are slightly different, while in the framework of hypotheses of the group A these amplitudes must be equal. As far as the sign of the interference terms are concerned, there is no difference between the variants A and B Thus, the variants A and B may in principle, be distinguished experimentally, though it is not an easy matter because the effect is too small. Under certain conditions, however, (in the region of the interference minimum) the difference in the decay curves may amount to 20-30%.

5/ Strictly speaking, instead of δ under the Cos in (14) there must be $\delta' = \delta + \arg\frac{1+\epsilon}{1-\epsilon}$ and in (5) $\delta'' = \delta - \arg\frac{1+\epsilon}{1-\epsilon}$. It is clear that if ϵ is small δ' and δ'' cannot be distinguished from δ .

4. From the experimental point of view the observation of the effects we have considered is somewhat inconvenient. The point is that these interference phenomena occur practically in a narrow interval of the distances from the K^0 - meson source. Besides, the character of these phenomena is wholly determined by the parameters which cannot be changed.

This difficulty may be, however, avoided if use is made of the coherent regeneration of K_1^0 mesons when K_2^0 mesons are passing through medium.

Consider the interference phenomena in the decay into two pions which take place behind the plate through which a beam of long-lived neutral mesons is passing. It should be placed at such a distance from the source of K^0 mesons that the short-lived compontnt vanishes completely. Hence, the "beating" in the $K^0(\overline{K^0}) \to 2\pi$ decays considered in the previous section does not occur.

A. Since in fact the regeneration coefficient is small, we can neglect the change in the intensity of the K - meson beam due to the regeneration. In this approximation the wave function of the neutral K_2+RK_1-meson, (when it emerges from the plate, may be represented as $K_2 + RK_1$, where

$$R = \frac{i\pi\{A(0) - \overline{A(0)}\}N}{m(i\Delta m + (\frac{\lambda_1}{2} - \frac{\lambda_2}{2})\}}\{e^{-(im_2 + \frac{\lambda_2}{2})\frac{\ell}{v\gamma}} - e^{-(im_1 + \frac{\lambda_1}{2})\frac{\ell}{v\gamma}}\} \times e^{(im_2 + \frac{\lambda_1}{2})\frac{\ell}{v\gamma}} . \tag{16}$$

Here $\Delta m = m_1 - m_2$, N is the number of nuclei per unit of the volume, $A(0)$ and $\overline{A(0)}$ are the amplitudes of the elastic scattering of K_0 and K^0 at zero angle, ℓ is the thickness of the plate, $\gamma = (1-v^2)^{-1/2}$ |10,11|.

It can be easily understood, that behind the plate, at a distanct of $x = v\gamma t$, the amplitude of the neutral K meson decay into π^+ and π^- will have the form

$$A = A(K_1^0 \to \pi^+\pi^-)\{Re^{-(im_1+\frac{\lambda_1}{2})t} + \epsilon e^{-(im_2+\frac{\lambda_2}{2})t}\} \tag{17}$$

Represent R as

$$R = i|R|e^{i\Delta} \tag{18}$$

Then, for the decay probability we obtain

$$P = \{|R|^2 e^{-\lambda_1 t} + 2|R||\epsilon| \operatorname{Sin}(\Delta m t - \Delta + \delta) e^{\frac{-\lambda_1+\lambda_2}{2}t} + |\epsilon|^2 e^{-\lambda_2 t}\} . \tag{19}$$

For thin plates $(\ell \ll v\gamma/\lambda_1)$

$$|R| = \frac{\pi N |A(0) - \overline{A(0)}|}{k} \ell$$

$$\Lambda = \text{arct} \frac{\text{Im} \{A(0) - \overline{A}(0)}{\text{Re} \{A(0) - \overline{A}(0)\}} \tag{20}$$

In the case of thicker plates when $v\gamma/\lambda_1 \ll \ell \ll v\gamma/\lambda_2$

$$|R| = \frac{\pi N |A(0) - \overline{A}(0)|}{m \sqrt{4 (\frac{\Delta m}{\lambda_1})^2 + 1}}$$

$$\Lambda = \text{arctg} \frac{\text{Im} \{A(0) - \overline{A}(0)\}}{\text{Re} \{A(0) - \overline{A}(0)\}} - \text{arctg} \frac{2 \Delta m}{\lambda_1} \tag{21}$$

B. If the regeneration coefficient K'_1, when the K'_2 passes through the plate, is equal to R', then with account of (2) and (3), the amplitude of the decay into two pions takes the form

$$A = A(K_1^0 \to \pi^+ \pi^-) \{ R' e^{-(im_1 + \frac{\lambda_1}{2})t} \frac{1}{\sqrt{1 + |\epsilon|^2}} + \\ + \frac{\epsilon}{\sqrt{1 + |\epsilon|^2}} e^{-(im + \frac{\lambda_2}{2})t} \} \tag{22}$$

Now we have to determine R'. Let

$$K'_1 = \alpha K^0 + \beta \overline{K^0}$$
$$K'_2 = \beta K^0 - \alpha \overline{K^0} \tag{23}$$

where

$$\alpha = \frac{1 - \epsilon}{\sqrt{2} \sqrt{1 + |\epsilon|^2}} , \quad \beta = \frac{1 + \epsilon}{\sqrt{2} \cdot \sqrt{1 + |\epsilon|^2}}$$

Then

$$K^0 = (\alpha K'_1 + \beta K'_2) \frac{1}{\alpha^2 + \beta^2}$$
$$\overline{K^0} = (\beta K'_1 - \alpha K'_2) \frac{1}{\alpha^2 + \beta^2} \tag{24}$$

The main equations for the K' meson regeneration are reduced to the following form

$$\frac{dc_1}{dx} = -(im_1 + \frac{\lambda_1}{2}) \frac{1}{v\gamma} c_1 + \frac{ik(n_1 + n_2)}{2} c_1 + \\ + ik \frac{(n_1 - n_2)}{2} \frac{\alpha^2 - \beta^2}{\alpha^2 + \beta^2} c_1 + \frac{2\alpha\beta}{\alpha^2 + \beta^2} \frac{ik(n_1 - n_2)}{2} c_2$$

$$\frac{dc_2}{dx} = -(im_2 + \frac{\lambda_2}{2}) \frac{1}{v\gamma} c_2 + \frac{ik(n_1 + n_2)}{2} c_2 - \\ - ik \frac{n_1 - n_2}{2} \frac{\alpha^2 - \beta^2}{\alpha^2 + \beta^2} c_2 + \frac{2\alpha\beta}{\alpha^2 + \beta^2} \frac{ik(n_1 - n_2)}{2} c_1 , \tag{25}$$

where the notations of Good's paper were used [10]. Solving a system of equations (25) and neglecting the decreese in the intensity of K'_2 mesons due to the K'_1 regeneration we can obtain the following expression for

$$R' = \frac{2\alpha\beta}{\alpha^2 + \beta^2} R \quad , \tag{26}$$

where R is the regeneration coefficient for the variant A (see (16), (20), (21)[6/].

Substituting (26) into (22) and taking into account that

$$\frac{2\alpha\beta}{\alpha^2 + \beta^2} = \frac{1-\epsilon^2}{1+\epsilon^2}$$

we get

$$A = \frac{A(K_1^0 \to \pi^+ \pi^-)}{\sqrt{1+|\epsilon|^2}} \{ Re^{-(im + \frac{\lambda_1}{2})t} + \frac{\epsilon(1+\epsilon^2)}{1-\epsilon^2} e^{-(im + \frac{\lambda_2}{2})t} \} . \tag{27}$$

Comparing (27) with (17) and passing then to the expression for the decay probability P we find that the interference terms in the case of the variants A and B differ by a magnitude of the order $|\epsilon|^3$. To analyse, therefore, the interference effects behing the plate, we have to use the formula (19), regardless of the mechanism of CP breakdown,

As is seen from the formulae derived above, the character of the interference phenomena depends on the material of which plate is made, as well as on its thickness.

Thus, the interference phenomena can be observed at any distance from the target by choosing the material and the thickness of the plate so that these effects would be the most prominent. (see Fig. 4).

5. There remains only to consider the interference effects inside the material. (see also [8]). The method of the analysis here is, evidently, not different from that developed in the previous section. At a distance of from the front edge of the plate the amplitude of the neutral K meson decay is of the form

$$A = A_0 (K_1^0 \to 2\pi) \{ R(x) + \epsilon \} e^{-(im_2 + \frac{\lambda_2}{2})\frac{x}{v\gamma}} \tag{28}$$

where $R(x)$ is determined by (16) where ℓ should be replaced by x.

Note, that at $x \gg \frac{v\gamma}{\lambda_1}$, the interference term in the expression for the decay probability depens nc longer on x, i.e., the "beating" disappears. In this case the expression for the decay probability is of the form

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[6/] By m_1 and m_2, λ_1 and λ_2 we mean now the masses and the decay rates of the K'_1 and K'_2 meson respectively.

$$P \sim (|R|^2 + |\epsilon|^2 - 2|R||\epsilon| \sin(\Delta - \delta)) \qquad (29)$$

where $|R|$ and Λ are determined from (21).

6. It should be noted in conclusion that the interference phenomena treated in the paper turn out to be very sensitive to the magnitude of the $K_1^0 - K_2^0$ mass difference (Δm). To illustrate this, Fig. 5 shows the interference curves in the K^0 meson beam which were calculated for different values of Δm . The estimates indicate that in order to determine with an accuracy of some percent it sufficies to detect some 100 decays in the region of the minimum. The formula for the interference effects in the case of the regeneration (see (19)) contains the term $\sin(\Delta m t + \delta - \Delta)$ dependent upon the sign of Δm . This allows a determination of the sign for the $K_1^0 K_2^0$ mass difference.[7] (see Fig. 6).

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7/ Here one can draw an analogy with the phenomena occurring by the K_2^0 meson traversal of the two plates made of different materials. (see, e.g.,/13/). The CP violation can be treated as a second plate.

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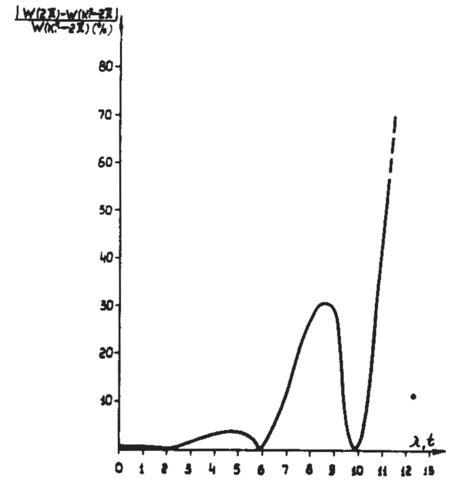
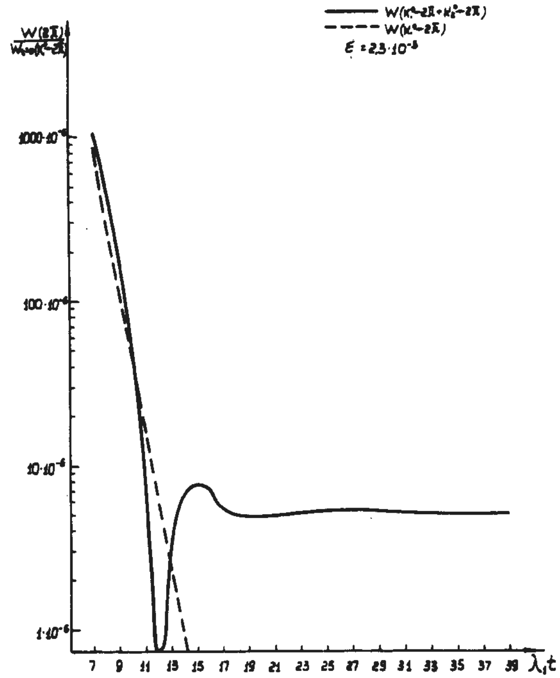
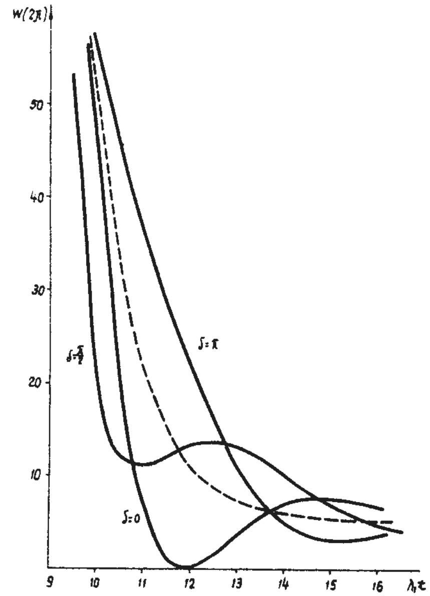


F i g. 1.

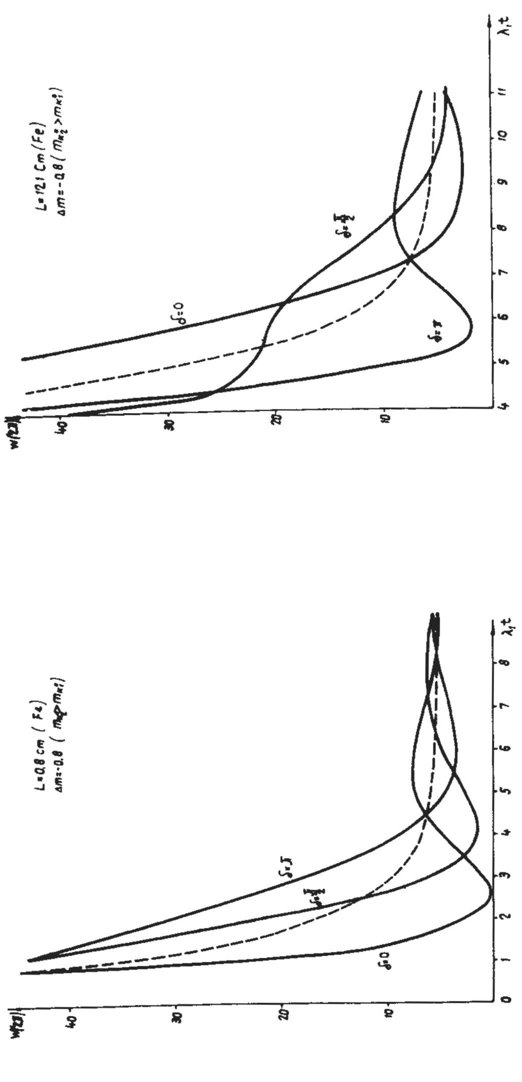
Deviation from the exponential form of the $K^0 \to \pi^+\pi^-$ decay cur
due to the interference effect.



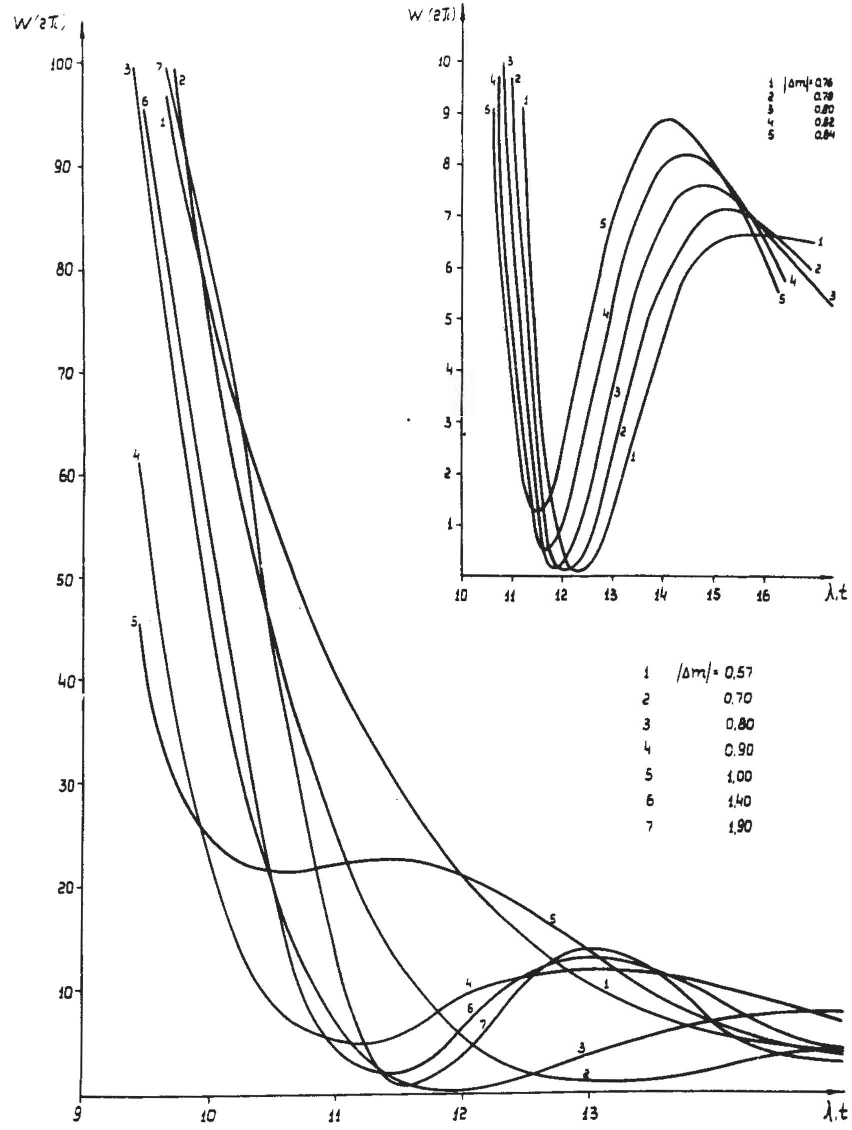
F i g . 2. The time dependence of the number of $K^0 \to \pi^+ \pi^-$ decays for large $\lambda_1 t$.



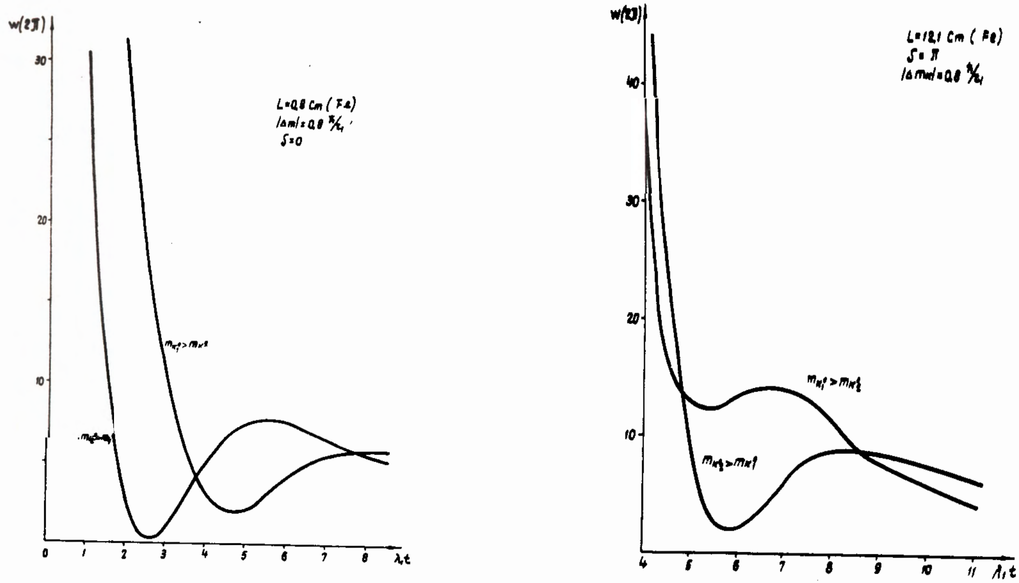
F i g. 3. The dependence of the interference effects on the phase difference between the transition amplitudes of $K_1^0 \to \pi^+ \pi^-$ and $K_2^0 \to \pi^+ \pi^-$.



F i g. 4. The interference effects for different thicknesses of the plate (L) and for different values of δ (parameters determining the regeneration are taken from /12/).



F i g. 5. The dependence of the interference effects in the $K^0 \to \pi^+$ decay (in arbitrary units) on the magnitude of the $K_1^0 K_2^0$ mas difference (Δm) at $\delta = 0$.



F i g. 6. The interference effects for different values of the sign of the $K_1^0 K_2^0$ mass difference ($\delta = 0$ and $\delta = \pi$).