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EXPERIMENTAL VERIFICATION POSSIBILITIES

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ABSTRACT

It is shown that elementary Quantum Mechanics, applied to the $K^0\overline{K}^0$ system, predicts peculiar long range EPR correlations.

Possible experimental verifications are discussed and a concrete experiment with anti-protons annihilations at rest is proposed.

A pedestrian approach to local models shows that $K^0\overline{K}^0$ experimentation could provide arguments to the local realism versus quantum theory controversy.

This internal report will be distributed to several K^0 physics specialists.
A shortened version in better English will be submitted to Physics Letters after correction or removal of wrong statements.
It can also be taken as a first draft initiating an eventual experimental proposal.

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INTRODUCTION

In the formalism of quantum mechanics, if two particles are created, by any kind of interaction, and then get spatially separated, the two-particle quantum wavefunction retains its non-separable character even if the particles are space-like separated. This feature leads to puzzling non-local correlations between the observable properties of the two concerned particles.

A measurement of some parameter on one particle, undetermined prior the measurement, may predict with certainty the outcome of the measurement of the same parameter for the second particle.

This quantum theory apparently logical failure, pointed out in 1935 by Einstein, Podolsky and Rosen [1], called the EPR paradox, gave rise to an animated debate over the past sixty years.

The compatibility of the various local models and the non-separability of the two-particle wavefunction has been largely discussed.

In 1952, it had been suggested that it may exist supplementary variables ("hidden variables") outside the scope of quantum mechanics which determine the results of individual measurements. It was then commonly admitted that hidden-variables local models can always give complete agreement with quantum mechanics [2]. Therefore, up to the sixties, the debate hold on a purely epistemological level.

In 1965 J.Bell [3] showed that the whole class of local hidden-variables models leads to an inequality (Bell's inequality) violated by quantum mechanics under some special conditions. This opened the possibility of experimental tests between quantum mechanics and local hidden variables models.

Since this prediction, numerous experiments have been performed, mostly with photon-polarisation correlation measurements using radiative atomic cascade transitions [4], or more recently [5], with down conversion generated photon pairs.

All significant results appear to violate Bell's inequality and are generally interpreted as a confirmation of quantum mechanics and as a rebuttal of local hidden-variables models.

However, the interpretation of these experimental results are still subject to some controversy[6]. It has been stated that "From a strictly logical point of view, the choice between local realism and the existing quantum theory is still undecided" [7].

Testing Bell's inequality requires several ideal experimental conditions which can hardly be achieved.

Whatever it is, and in view of the importance of the issues involved, the EPR-type non-local correlations have to be explored in other types of experiments.

The $J^{PC}=1^{--}$ spatial anti-symmetric $K^0\overline{K}^0$ state is an ideal system for testing experimentally this type of correlation. This has been pointed out first by H.J. Lipkin [8] in 1968 and later by several other authors [9,10]. Up to now, this experimental field is entirely unexplored but strong interest is manifested since copious production of $K^0\overline{K}^0$ pairs will be available with the forthcoming φ factories.

The specificity of the $K^0\overline{K}^0$ system lies in the fact that the wavefunction of a single neutral kaon involves two 2 dimensional basis:

- The production eigenstates K^0 and $\overline{K}^0$ with opposite strangeness
- The propagation eigenstates, K_S and K_L, whith different masses and lifetimes and with opposite CP parities.

The superposition of the K_S and K_L exponentially decreasing wavefunctions produces a time dependent strangeness mixing induced by the K_S K_L mass and lifetime differences.

This specific feature for single neutral kaons, applied to the $K^0\overline{K}^0$ two body wavefunction, leads to peculiar quantum EPR-type correlations.

In what follows, the theoretical formalism will be developed and some experimental tests will be suggested.

CHAP. I BASIC FORMALISM

A) SINGLE NEUTRAL K USUAL FORMULATION

$$|K_S\rangle = p|K^0\rangle + q|\overline{K}^0\rangle \qquad |K_S(t)\rangle = |K_S(0)\rangle e^{-i\alpha_s t}$$
$$|K_L\rangle = p'|K^0\rangle - q'|\overline{K}^0\rangle \qquad |K_L(t)\rangle = |K_L(0)\rangle e^{-i\alpha_L t}$$

$$\alpha_S = M_S - i\frac{\gamma_S}{2} \qquad M_{S,L} = K_S, K_L \text{ Mass}$$
$$\alpha_L = M_L - i\frac{\gamma_L}{2} \qquad \gamma_{S,L} = K_S, K_L \text{ Decay rates}$$

Neutral kaons are produced by definition in pure strangeness states, but their time evolution is controlled by the K_S and K_L exponential decay laws.

The time depending wave functions for kaons created as K or $\overline{K}$ are:

$$|\psi(t)\rangle = \frac{1}{pq'+qp'}\left[q'|K_S(0)\rangle e^{-i\alpha_s t} + q|K_L(0)\rangle e^{-i\alpha_L t}\right] \qquad I(t) = |\psi(t)|^2$$
$$|\overline{\psi}(t)\rangle = \frac{1}{pq'+qp'}\left[p'|K_S(0)\rangle e^{-i\alpha_s t} - p|K_L(0)\rangle e^{-i\alpha_L t}\right] \qquad \overline{I}(t) = |\overline{\psi}(t)|^2$$

For the decay channels where K_S *and* K_L are undistinguishable the amplitudes have to be added coherently.

For strangeness signed final states one gets the well known approximated formulas:

$$I(t)_{\to -}^{\to +} \propto e^{-\gamma_s t} + e^{-\gamma_L t} \pm 2e^{-\frac{\gamma_S+\gamma_L}{2}t}\cos(\Delta m\, t) \qquad (1)$$
$$\overline{I}(t)_{\to -}^{\to +} \propto e^{-\gamma_s t} + e^{-\gamma_L t} \mp 2e^{-\frac{\gamma_S+\gamma_L}{2}t}\cos(\Delta m\, t) \qquad (2)$$

The superposition of the K_S and K_L amplitudes leads to an interference term which mixes the strangeness and generates time dependent damped oscillations.

It can be remarked that none of these intensities vanishes for $t > 0$. After creation the kaon can never be again in a pure strangeness state but only in a statistical mixture of opposite strangeness.

These relations have been tested experimentally.

They provide an academic illustration of the quantum mechanics superposition principle applied to a single and isolated wave packet.

B) $K^0\overline{K}^0$ TWO BODY SYSTEM

A pair of indistinguishable kaon anti-kaon, arbitrarily designed by ***a*** and ***b***, have t_a and t_b for proper times. At the creation $(t_a=t_b=0)$, the pseudo-scalar particle anti-particle pair is either in a $J^{PC}=1^{--}$ vector spatial state, anti-symmetric under C and P or in a $J^{PC}=0^{++}$ scalar spatial state, symmetric under C and P.

1) $J^{PC}=1^{--}$ *anti-symmetric spatial state*

a) WAVE FUNCTION

At the creation $(t_a=t_b=0)$ in order to fulfil the symmetry requirements, the two body wave function has to be written :

$$|\psi(0,0)\rangle=\frac{1}{\sqrt{2}}\left[|K(0)\rangle_a|\overline{K}(0)\rangle_b-|\overline{K}(0)\rangle_a|K(0)\rangle_b\right] \text{ equivalent to}$$
$$|\psi(0,0)\rangle=\frac{1}{\sqrt{2}}(pq'+qp')\left[|K_S(0)\rangle_a|K_L(0)\rangle_b-|K_L(0)\rangle_a|K_S(0)\rangle_b\right] \quad (3),(4)$$

Only $K_S\,K_L$ and $K_L\,K_S$ final states are possible.

The time depending two body wavefunction can then be written as:

$$|\psi(t_a,t_b)\rangle=\frac{1}{\sqrt{2}}(pq'+qp')\left[|K_S(0)\rangle_a|K_L(0)\rangle_b e^{-i\alpha_S t_a-i\alpha_L t_b}-|K_L(0)\rangle_a|K_S(0)\rangle_b e^{-i\alpha_L t_a-i\alpha_S t_b}\right]$$

Applicated to the final states a and b by the operators f_a and f_b

$$\langle f_a;f_b|\psi(t_a,t_b)\rangle=C\left[\eta_b e^{-i\alpha_S t_a-i\alpha_L t_b}-\eta_a e^{-i\alpha_L t_a-i\alpha_S t_b}\right]$$

$$\eta_a=\frac{\langle f_a|K_L\rangle}{\langle f_a|K_S\rangle}=\frac{\text{amplitude }(K_L\rightarrow\text{final state } a)}{\text{amplitude }(K_S\rightarrow\text{final state } a)} \qquad \eta_b=\frac{\langle f_b|K_L\rangle}{\langle f_b|K_S\rangle}=\frac{\text{amplitude }(K_L\rightarrow\text{final state } b)}{\text{amplitude }(K_S\rightarrow\text{final state } b)}$$

$$C=\frac{1}{\sqrt{2}}(pq'+qp')\langle f_a|K_S\rangle\langle f_b|K_S\rangle$$

Already at this step, it can be remarked that if $\eta_a=\eta_b$ and $t_a=t_b$ the wave function vanishes.

b) TIME DEPENDENT INTENSITY

The time dependent intensity is deduced from the wave function:

$$I(t_a,t_b)=|\psi(t_a,t_b)|^2$$

And by straightforward calculations

$$I(t_a,t_b)=|C|^2\left\{|\eta_b|^2 e^{-\gamma_s t_a-\gamma_L t_b}+|\eta_a|^2 e^{-\gamma_L t_a-\gamma_s t_b}-2|\eta_a||\eta_b|e^{-\frac{\gamma_s+\gamma_L}{2}(t_a+t_b)}\cos\left[\Delta m(t_a-t_b)+\varphi_a-\varphi_b\right]\right\}$$

$\Delta m=M_L-M_S$ $\quad\varphi_{a,b}$=phase of $\eta_{a,b}$

This is the basic general equation describing the time dependent intensity for a $K_S K_L$ system for any final states. It has to be pointed out that no hypothesis has been made on the conservation laws in the decay process.

The whole wavefunction is a superposition of two amplitudes corresponding to two two-body quantum states. These amplitudes have to be added coherently if the two quantum states are indistinguishable which occurs if none of the two final states signs a K_S or a K_L.

This is an illustration of the quantum mechanics superposition principle applied to the two body wave function. The space like separated particles are controlled by a single entangled wave function which factorises at the first measurement.

The coherent addition of the two amplitudes generates a time depending interference term.

This interference is a direct consequence of the elementary quantum mechanics application, it induces long distance correlations between space like separated particles.

c) <u>IDENTICAL FINAL STATES</u>

If the final states of ***a*** and ***b*** are identical then the amplitude ratios η_a and η_b become equal.

$|\eta_a|=|\eta_b| \qquad \varphi_a=\varphi_b \qquad$ then

$$I_{like}(t_a,t_b)=|C|^2|\eta|^2\left\{e^{-\gamma_s t_a-\gamma_L t_b}+e^{-\gamma_L t_a-\gamma_s t_b}-2e^{-\frac{\gamma_s+\gamma_L}{2}(t_a+t_b)}\cos\left[\Delta m(t_a-t_b)\right]\right\} \qquad (5)$$

This intensity vanishes for $t_a=t_b$ as previously emphasised with the wave function.

For identical final states and at identical times the two body wave function vanishes; the interference becomes entirely destructive.

This allows the following fundamental statement:

For the spatial anti symmetric $K^0\overline{K}^0$ state, the K's cannot appear simultaneously in identical final states and this at any time and whatever is violated in the decay process.

This is a typical EPR-type non-local correlation.

The symmetry and conservation laws imposed by the production process are retained by the two body time depending wave function and remain valid for simultaneous measurements.

The various main identical final states will now be reviewed, regarding the anti-correlation effect at $t_a=t_b$.

Decay into two pion final states

$\pi^+\pi^-$ — $\pi^+\pi^-$

$\pi^0\pi^0$ — $\pi^0\pi^0$

A K decaying into two pions forbids the associated K to decay simultaneously into the same pion pair; a CP violating kaon is not compatible with a K_S decaying into two pions.

$\pi^+\pi^-$ — $\pi^0\pi^0$

The simultaneous existence of these two non identical final states depends on the $\eta^{+-} - \eta^{00}$ amplitude difference which would imply an I=2 2π CP violating amplitude.

Decay into identical lepton final states

$Ke3^+$ — $Ke3^+$

$Ke3^-$ — $Ke3^-$

$K\mu3^+$ — $K\mu3^+$

$K\mu3^-$ — $K\mu3^-$

The impossibility of simultaneous decays is due to the identity of the final states and thus the $\Delta S=\Delta Q$ rule is not needed .

This remark illustrates the fundamental deepness of the effect. In a first level Bose statistics forbids to the kaons to decay into identical final topological states which is entirely independent of the decay mechanism and particularly it is not affected by the weak interaction non-conservation laws.

In a second level if the final states are not identical but if they are eigenstates of the same quantum operator, the effect is extended to identical eigenvalues of this operator.

$Ke3^+$ — $K\mu3^+$

$Ke3^-$ — $K\mu3^-$

These like-sign but non-identical lepton final states needs the $\Delta S=\Delta Q$ rule. For these final states the effect is induced by strangeness conservation which has to keep valid at equal times.

From now on the $\Delta S=\Delta Q$ rule will be assumed.

Strong interaction like strangeness final states.

$Ka + N \rightarrow K^+ + (......)$ — $Kb + N \rightarrow K^+ + (......)$

$Ka + N \rightarrow K^-, \Lambda + (......)$ — $Kb + N \rightarrow K^-, \Lambda + (......)$

N is a nucleon

The two kaons cannot simultaneously interact into identical strangeness final states

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d) <u>OPPOSITE STRANGENESS STATES</u>

If ***a*** and ***b*** are opposite strangeness states
η_a and η_b are equal to $\frac{p}{p'}$ and $-\frac{q}{q'}$ (deduced from the basic K_S and K_L definitions)
If TCP is conserved $\frac{p}{p'} = \frac{q}{q'}$ and then $\eta_a = -\eta_b$

$$|\eta_a| = |\eta_b| \qquad\qquad \varphi_a = \varphi_b + \pi$$

$$\boxed{I_{unlike}(t_a,t_b)=|C|^2|\eta|^2\left\{e^{-\gamma_S t_a-\gamma_L t_b}+e^{-\gamma_L t_a-\gamma_S t_b}+2e^{-\frac{\gamma_S+\gamma_L}{2}(t_a+t_b)}\cos\left[\Delta m(t_a-t_b)\right]\right\}} \qquad (6)$$

The sign in front of the interference term is changed.

This correlation for unlike strangeness is opposite to the like strangeness correlation. Therefore the addition of like and unlike strangeness intensities cancels the interference and the kaons behave like an uncorrelated $K_S K_L$ system.

The involved strangeness unlike final states are:

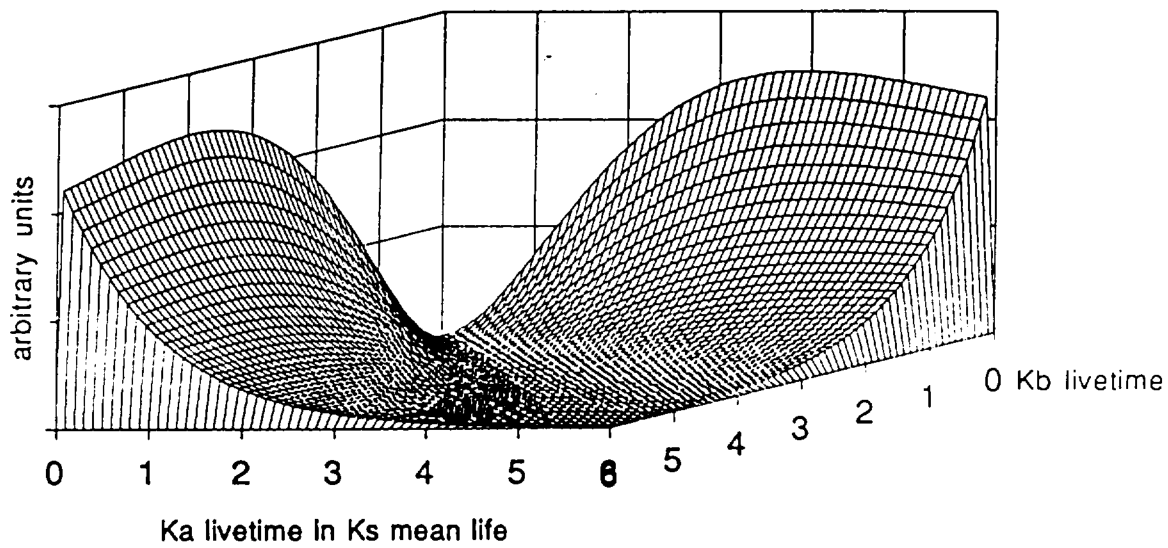
$Ke3^+$ — $Ke3^-$
$K\mu3^+$ — $K\mu3^-$
$Ke3^+$ — $K\mu3^-$
$K\mu3^+$ — $Ke3^-$

$Ka + N \rightarrow K^+ + (......)$ — $Kb + N \rightarrow K^-, \Lambda + (......)$
$Ka + N \rightarrow K^-, \Lambda + (......)$ — $Kb + N \rightarrow K^+ + (......)$

e) <u>INTENSITIES TIME DEPENDENCE REPRESENTATION</u>

Fig 1 visualises the variation of $I_{like}(t_a, t_b)$ and $I_{unlike}(t_a, t_b)$ as a function of the two kaon live-times expressed in K_S mean lifetimes (τ_S) and limited to 6 τ_S.

$I_{like}(t_a, t_b)$ LIKE STRANGENESS CORRELATION



$I_{unlike}(t_a, t_b)$ UNLIKE STRANGENESS CORRELATION

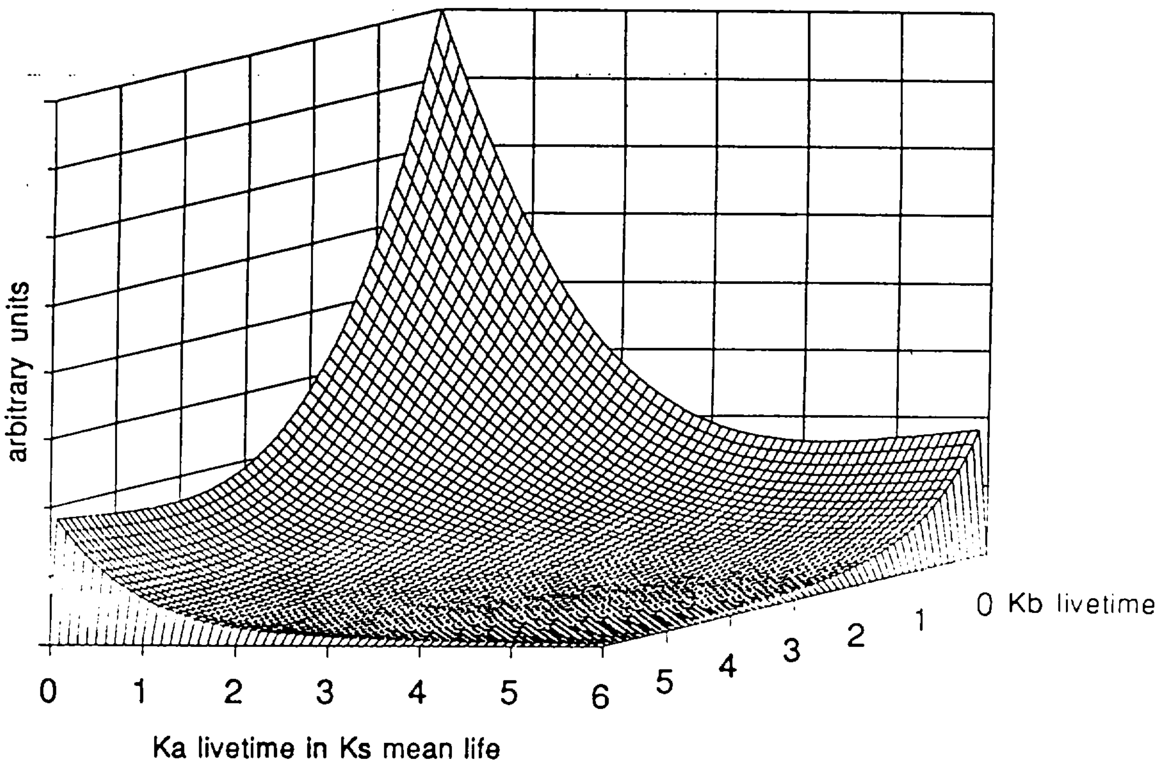


FIG 1

The two functions can be simply integrated over t_a+t_b and expressed as a function of $|t_b-t_a|$

$$I_{like}(t_b-t_a) \propto e^{-\gamma_S|t_b-t_a|}+e^{-\gamma_L|t_b-t_a|}-2e^{-\frac{\gamma_S+\gamma_L}{2}|t_b-t_a|}\cos[\Delta m(t_b-t_a)]$$

$$I_{unlike}(t_b-t_a) \propto e^{-\gamma_S|t_b-t_a|}+e^{-\gamma_L|t_b-t_a|}+2e^{-\frac{\gamma_S+\gamma_L}{2}|t_b-t_a|}\cos[\Delta m(t_b-t_a)]$$

These two functions are represented on Fig. 2

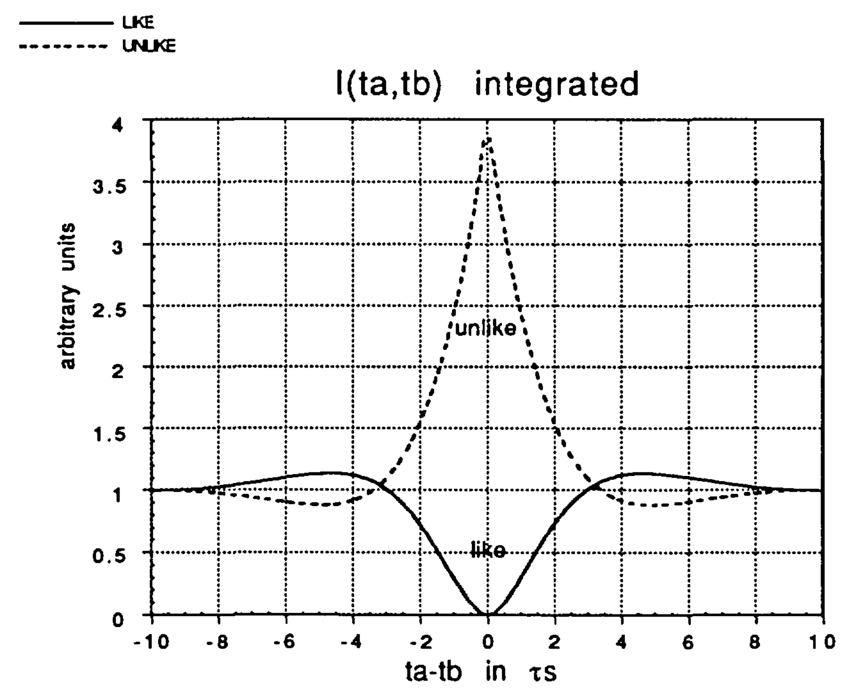


FIG 2

It can be remarked that for $|t_a-t_b| \approx 5\ \tau_S$ the like events intensity exceeds the unlike intensity and that the width of the like depletion for $|t_a-t_b| \approx 0$ is about $3\ \tau_S$. These facts will be used later for experimental considerations.

Replacing $|t_b-t_a|$ by t, one can recognise relations (1) and (2) which describe the time behaviour of a single K created in a pure strangeness state.

This illustrates the fact that when one kaon is measured to be in a given strangeness state at time t_a the surviving kaon behaves like a pure opposite strangeness created at time t_a and oscillating as a function of t_b-t_a.

The strangeness measurement of one kaon predicts with certainty the strangeness state of the unmeasured kaon at the same time and determines his further time dependence.

This is an EPR time depending correlation.

2) $J^{PC} = 0^{++}$ symmetric spatial state

The same formalism can be applied to the $J^{PC} = 0^{++}$ $K^0\overline{K}^0$ state.

The two body wave function has to be symmetric under C and P

$|\psi(0,0)\rangle = \frac{1}{\sqrt{2}}\left[|K(0)\rangle_a|\overline{K}(0)\rangle_b + |\overline{K}(0)\rangle_a|K(0)\rangle_b\right]$ which is equivalent to

$|\psi(0,0)\rangle = \frac{1}{\sqrt{2}}(pq'+qp')\left[|K_S(0)\rangle_a|K_S(0)\rangle_b - |K_L(0)\rangle_a|K_L(0)\rangle_b\right]$

Only $K_S K_S$ and $K_L K_L$ states are possible.

$$|\psi(t_a,t_b)\rangle = |C|^2\left[e^{-i\alpha_S(t_a+t_b)} - \eta_a\eta_b e^{-i\alpha_L(t_a+t_b)}\right]$$

$$I(t_a,t_b) = |C|^2\left\{e^{-\gamma_S(t_a+t_b)} + |\eta_a|^2|\eta_b|^2 e^{-\gamma_L(t_a+t_b)} - 2|\eta_a||\eta_b| e^{-\frac{\gamma_S+\gamma_L}{2}(t_a+t_b)}\cos\left[\Delta m(t_a+t_b)+\varphi_a+\varphi_b\right]\right\}$$

For like and unlike strangeness states:

$$I_{like}(t_a,t_b) \cong |C|^2\left\{e^{-\gamma_S(t_a+t_b)} + e^{-\gamma_L(t_a+t_b)} - 2\, e^{-\frac{\gamma_S+\gamma_L}{2}(t_a+t_b)}\cos\left[\Delta m(t_a+t_b)\right]\right\}$$

$$I_{unlike}(t_a,t_b) \cong |C|^2\left\{e^{-\gamma_S(t_a+t_b)} + e^{-\gamma_L(t_a+t_b)} + 2\, e^{-\frac{\gamma_S+\gamma_L}{2}(t_a+t_b)}\cos\left[\Delta m(t_a+t_b)\right]\right\}$$

There is also an interference term, but it oscillates with (t_a+t_b) instead of (t_a-t_b) and becomes rapidly negligible.

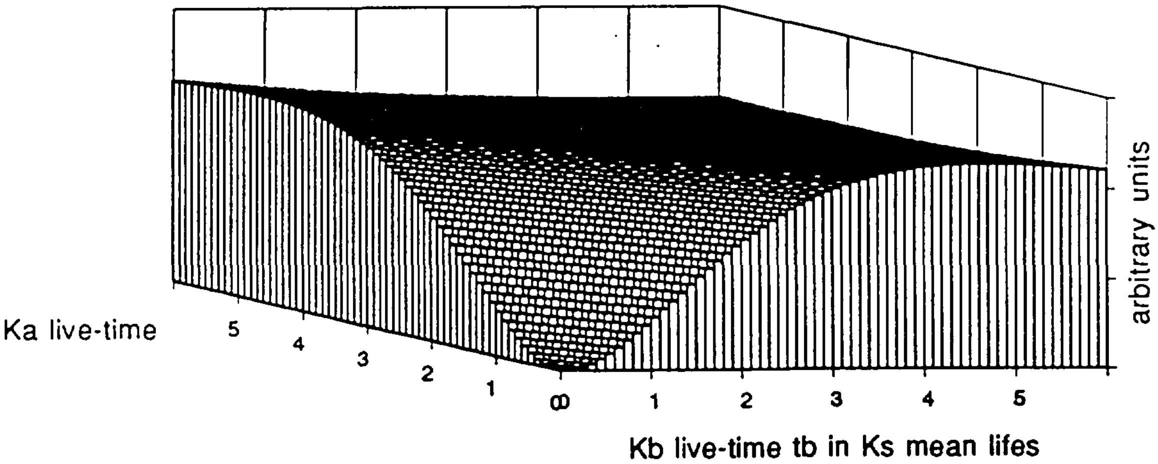
The like intensity vanishes only for $t_a = t_b = 0$ at the origin where like strangeness states are forbidden by the production mechanism.

These two functions are visualised on Fig.3.

It can be concluded that even for a symmetric $K^0\overline{K}^0$ spatial state, some strangeness correlation, close to the production point, is predicted. This feature is not an EPR type correlation. The strangeness measurement of one kaon at time $t_a > 0$ cannot predict with certainty the strangeness state of the second kaon at t_a but only a probabilistic ratio of a strangeness mixture.

It can be remarked that these two relations are similar to relations (1) and (2) for single isolated neutral kaons if t is replaced by t_a+t_b.

$I_{like}(t_a,t_b)$ *LIKE STRANGENESS CORRELATION*



$I_{unlike}(t_a,t_b)$ *UNLIKE STRANGENESS CORRELATION*

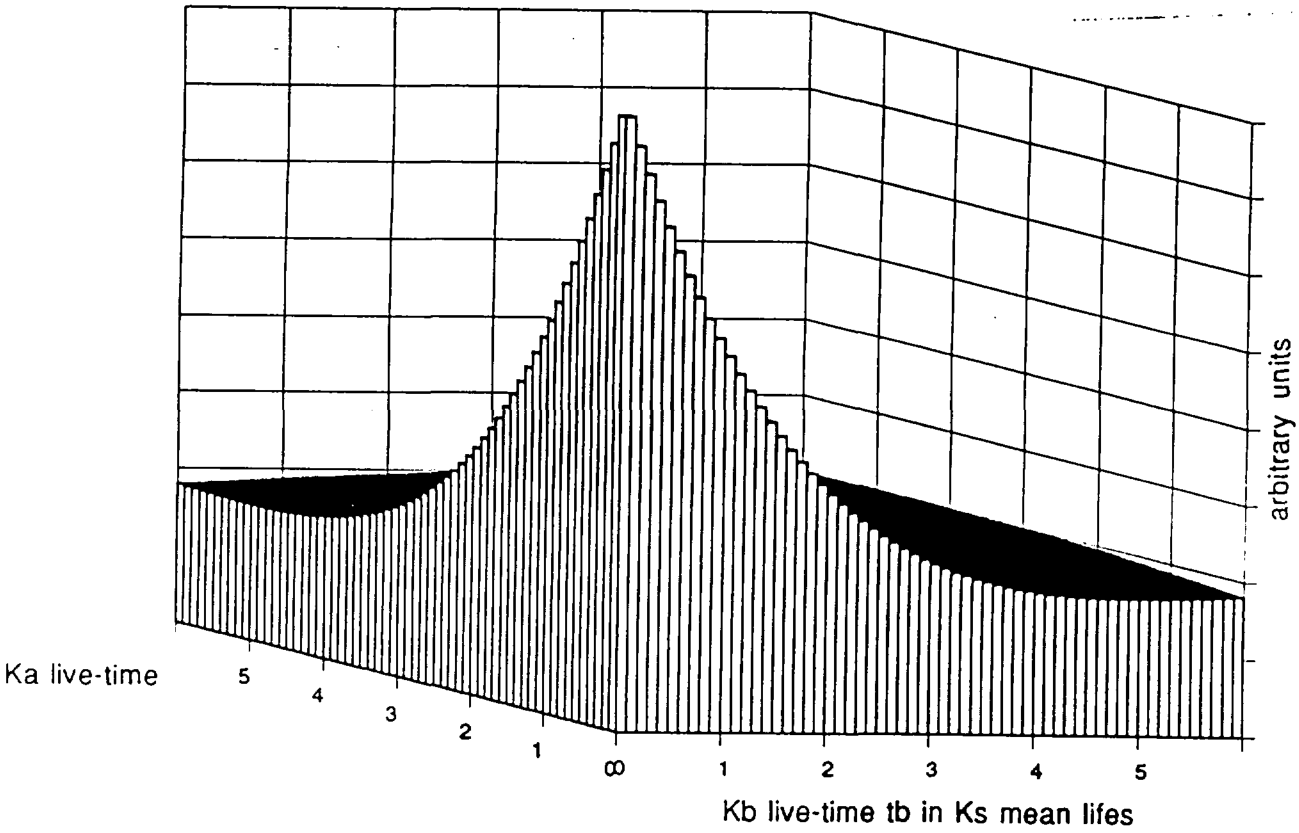


FIG 3

CHAP. II EXPERIMENTATION

A) GENERALITIES

Despite the attractive interest pointed out by several authors [8,9,10], up to now, no experiment has been performed because severe constraints are required for such an experimentation.

A very high flux of known momentum K^0's and $\bar{K}^0$'s is needed to measure the time dependent strangeness states produced either by decays or by strong interactions.

In the first case the probability for a K_S and a K_L to decay into two identical final states within the first K_S lifetimes is very small.

For two leptonic decays the branching ratio $\frac{K_S \to leptonics}{K_S \to total}$ is only 0.0017, while for two 2π decay related to the CP violation the ratio $\frac{K_L \to 2\pi}{K_L \to total}$ is nearly 0.002 .

On the other hand only about 1% of the K_L decay within the first K_S mean lifetimes where the interference is measurable.

In the case of the neutral kaons reinteracting within a fraction of interaction length absorber, the detection probability is much higher if the K_S mean decay length is long enough for keeping a reasonably large K_S component at the absorber position.

In all cases the $K^0\bar{K}^0$ must be produced in a dominant $J^{PC}=1^{--}$ spatial quantum state which can be pure or a well defined mixture.

With all these conditions the K_SK_L experimentation is only conceivable with an e^+e^- phi factory or with an intense stopping anti-proton beam; both providing a reasonable production rate of K^0 and $\bar{K}^0$ with a constant momentum.

A $10^{33}cm^{-2}sec^{-1}$ luminosity phi factory (DAΦNE at FRASCATI) and a 10^6 intensity anti-proton beam annihilating at rest in hydrogen (LEAR CERN) give nearly the same $K^0\bar{K}^0$ production rate ($\approx 10^3 sec^{-1}$)

At a phi factory, one third of the total number of interactions are $K^0\bar{K}^0$ and this in a nearly pure anti-symmetric K_SK_L state. The K momentum is 110 MeV/c which corresponds to a mean decay length of 6mm for the K_S.

With stopping anti-protons in hydrogen only 0.1% of the annihilations are $K^0\bar{K}^0$, but the K momentum is 800 MeV/c corresponding to a 40mm K_S mean decay length. The $K^0\bar{K}^0$ system is a mixture of symmetric and anti-symmetric spatial states but the proportion of the symmetric state is small and can be measured accurately.

Thanks to the substantial K_S mean decay length (40mm), the $\bar{P}$ method is the only realistic possibility for measuring correlations between the strongly interacting neutral kaons.

In what follows only the experimentation with the LEAR anti-proton facility will be considered.

The LEAR possibilities for $K^0\bar{K}^0$ experimentation have already been pointed out by J.Six [9] in 1985.

B) ANTI PROTON PROTON ANNIHILATION EXPERIMENTATION

As already mentioned, $\bar{P}P$ annihilations at rest produce $K^0\overline{K}^0$ with a probability of 0.1%. The K momentum is 800MeV/c corresponding to a mean decay length of 40 mm for the short living K.

The quantum state of the $K^0\overline{K}^0$ system depends on the orbital angular momentum of the $\bar{P}P$ annihilation process. The L=0 $^3S_1$ $\bar{P}P$ state with odd C parity assigns to the $K^0\overline{K}^0$ an anti-symmetric spatial state which can only decay in the K_SK_L channel. For L=1 the even C parity states $^3P_0$ and $^3P_2$ assign a symmetrical spatial state only decaying in the K_SK_S and K_LK_L channels.

The ratio Pwave/Swave annihilation states, has been measured by several experiments in liquid and gaseous hydrogen.

For an hydrogen target at 15 atmospheres the following ratio has been measured[11]:

$$\frac{K_SK_S+K_LK_L}{K_SK_L} = (8\pm2)\%$$

This ratio decreases if the pressure increases. For liquid hydrogen it becomes 1%.

In what follows, a 30 atmospheres hydrogen target is taken and a conservative 10% contamination of $K_SK_S+K_LK_L$ in the K_SK_L sample is taken, but this ratio has to be remeasured more accurately with the final experimental conditions.

Due to the large $K_S \rightarrow 2\pi$ branching ratio and to the apparatus full acceptance for this channel, the K_SK_S contamination is always dominant in the 2π final states. This 10% contamination in the $\bar{P}P$ annihilations excludes K_SK_L experimentation with $K\rightarrow 2\pi$ decay channels.

In what follows two subjects will be discussed in detail:

-Correlations between two semi-leptonic decay final states.

-Correlations between two strongly interacting kaons into signed strangeness final states.

CHAP. III LEPTON-LEPTON CORRELATION EXPERIMENT

The aim of the experiment is to collect the annihilation channel $\bar{P}P \rightarrow \bar{K}^0 + K^0$ with both kaons decaying into semi-leptonic final states and to measure their decay lengths.

A) APPARATUS

The beam and the experimental apparatus of PS 195 (CP LEAR experiment), already taking data for single K^0 experimentation, is adequate without modifications. The small cylindrical proportional chamber PCo, surrounding a 30 atmospheres pressured hydrogen target, has to be put in anti-coincidence in order to veto $\bar{P}$ annihilations into charged particles. This trigger requirement removes *K's* with decay lengths smaller than 2cm (0.5 *Ks* lifetime).

The apparatus will be described later (Fig. 12).

The basic trigger requirements are: no charged particle coming out of the target and at least four charged particles detected in the decay region. The main expected unwanted triggering events are two neutral kaons, one of them being a *Ks* 2π decay. The probability for this channel is 600 times higher than the *Ks* leptonic decays but the corresponding trigger rate keeps small and the on line lepton identification seems not to be necessary. The main trigger difficulties are the veto inefficiency and the random coincidences rate between the scintillator hodoscopes.

This trigger rate will be measured soon by the PS195 experiment.

B) LEPTON DECAY LENGTHS CORRELATION

The correlations between the decay lengths for like and unlike lepton decay channels are given by relations (5) and (6).

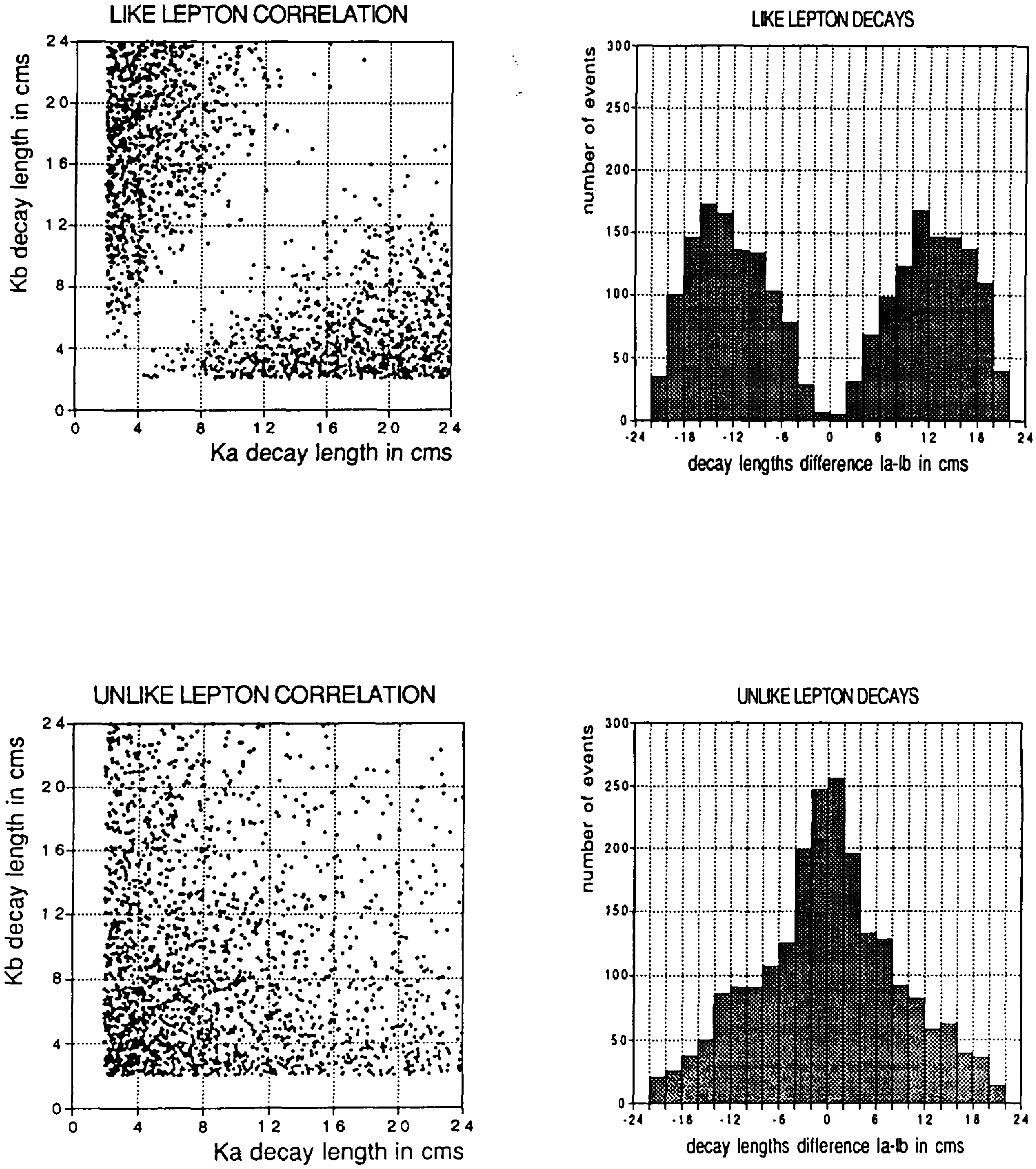
If γ_L is neglected compared to γ_S ($\gamma_S \approx 600\,\gamma_L$), these correlation functions can be rewritten as :

$$I_{likee}(t_a,t_b) \propto e^{-\gamma_s t_a} + e^{-\gamma_s t_b} - 2e^{-\frac{\gamma_S}{2}(t_a+t_b)} \cos[\Delta m(t_a - t_b)] \qquad (7)$$

$$I_{UNlikee}(t_a,t_b) \propto e^{-\gamma_s t_a} + e^{-\gamma_s t_b} + 2e^{-\frac{\gamma_S}{2}(t_a+t_b)} \cos[\Delta m(t_a - t_b)] \qquad (8)$$

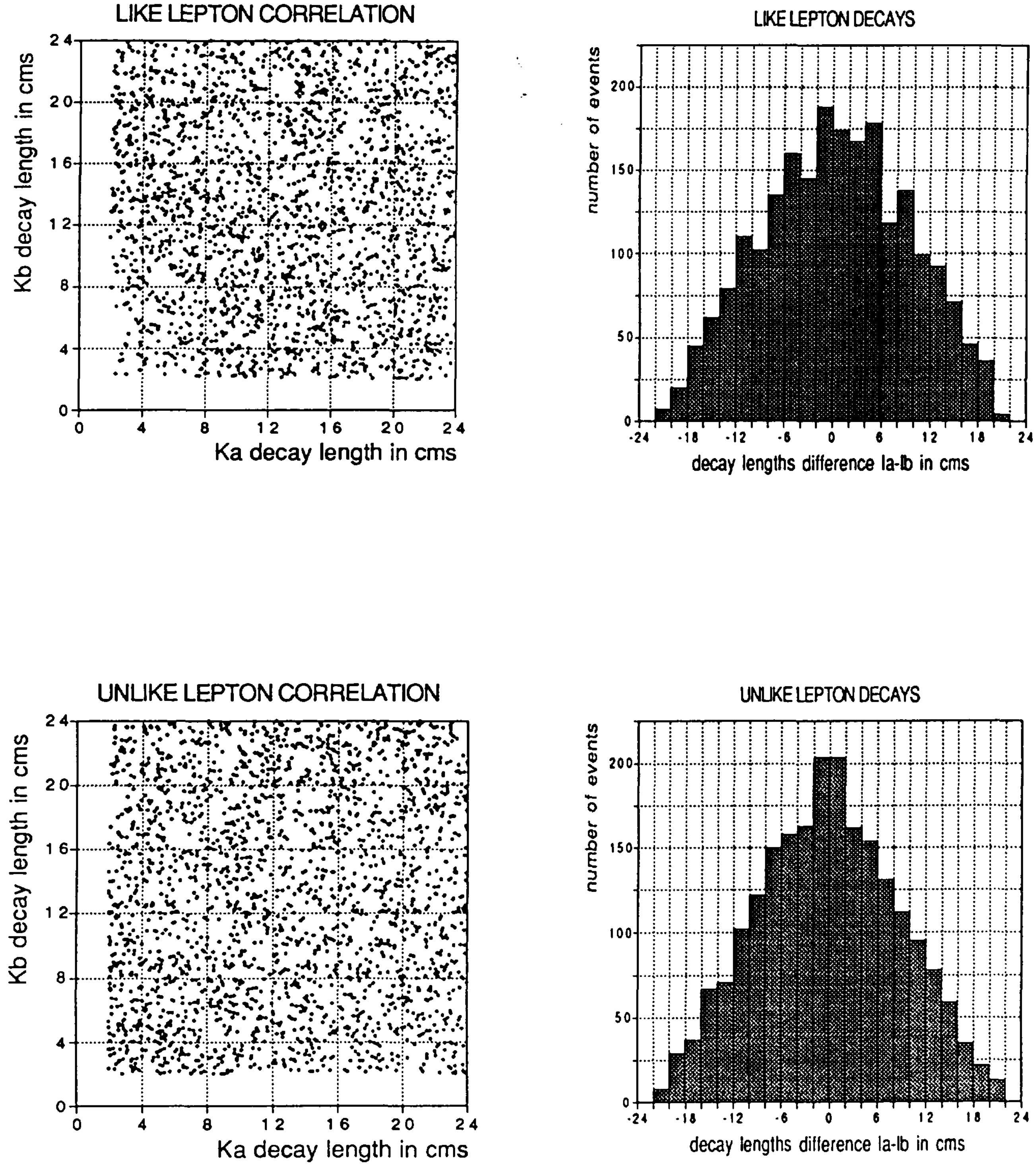
Fig. 4 shows the kaons decay lengths scatter plots for like and unlike leptons generated by Monte Carlo for decay lengths intervals between 2 and 24cm (0.5 $\tau s < t < 6\ \tau s$). The generation takes into account the measurement errors on the decay vertices and the annihilation point position uncertainty.

The like sign lepton events depletion for equal lengths can be clearly seen. On Fig. 4 the lengths differences distributions corresponding to the accepted decay paths are also shown.



KsKL+KLKs correlation

FIG.4



KsKs+KLKL correlation

FIG.5

C) CONTAMINATION

1) $K_SK_S+K_LK_L$ PHYSICAL CONTAMINATION

The physical $K_SK_S+K_LK_L$ contamination is assumed to be 10%. This ratio can be measured very accurately in the experiment by the two pion decays accepted by the trigger.

The correlation functions corresponding to the leptonic channels can be written:

$$I_{like}(t_a,t_b) \propto e^{-\gamma_S(t_a+t_b)} + 1 - 2e^{-\frac{\gamma_S}{2}(t_a+t_b)} \cos\left[\Delta m(t_a+t_b)\right] \quad (9)$$

$$I_{unlike}(t_a,t_b) \propto e^{-\gamma_S(t_a+t_b)} + 1 + 2e^{-\gamma_S(t_a+t_b)} \cos\left[\Delta m(t_a+t_b)\right] \quad (10)$$

The generated distributions are shown on Fig. 5 and they can be compared with those of Fig.4.

2) EXPERIMENTAL CONTAMINATION

Beside the controlled physical contamination, there are two other experimental sources of contaminating events:

a) The annihilation channel $\overline{P}+P \to K^0\overline{K}^0$ *+(neutrals)* accepted by the trigger have a production probability of about 50% of that for the $K^0\overline{K}^0$ *+(nothing)* production probability. These events do not follow the two body kinematics for which both kaons have to be in a back to back configuration. 95% of them will be rejected by the requirement that the line joining the two decay points, has to cross the annihilation region in the target. On the other hand an overall kinematical 2C fit will improve this rejection.

b) The decay channel identification is a much more worrying problem. In spite of the low branching ratio for $K_S \to$ *leptonics* (0.16%) the lepton type and sign have to be well identified. The large number of accepted $K_S\ 2\pi$ events has already been mentioned. The present running PS 195 experiment is confronted with the same problem. It turns out that only electron final states can be reasonably identified and this with a nearly 50% of 2π contamination within the first K_S lifetimes.

This contamination amount can be precisely measured since the time dependence of a $K_S \to 2\pi$ faking a leptonic decay associated with an uncorrelated $K_L \to$ *leptonic* is well known

$$I_{like+unlike}(t_a,t_b) \propto e^{-\gamma_S t_a - \gamma_L t_b} + e^{-\gamma_L t_a - \gamma_S t_b} \quad (12)$$

$$I_{like+unlike}(t_a,t_b) \propto e^{-\gamma_S t_a} + e^{-\gamma_S t_b} \quad \text{if } \gamma_L \text{ is neglected}$$

D) EVENT RATE

Taking into account beam performances, branching ratios, overall acceptances, efficiencies and experimental losses, it has been shown [12] that with a 70 days data taking experiment the following number of events can be collected:

100 like electron events and 210 unlike electron events for the K_SK_L channel

60 like and 60 unlike electron events corresponding to the assumed 10% $K_SK_S + K_LK_L$ physical background.

150 to 300 uncorrelated 2π background events are assumed.

E) DATA ANALYSIS

The decay lengths of the collected sample of like and unlike events have to follow the five relations (8-12) weighted with the proportions of physical and experimental contaminations measured independently.

The statistics is to poor to allow an overall least square analysis in order to test experimentally the existence of correlations.

The maximum likelihood method is more adequate.

A numerical indicator α has been defined

$$I^{like}_{KsKL}(t_a,t_b) \propto e^{-\gamma_s t_a} + e^{-\gamma_s t_b} - \alpha \times 2e^{-\frac{\gamma_s}{2}(t_a+t_b)} \cos[\Delta m(t_a - t_b)]$$

$$I^{unlike}_{KsKL}(t_a,t_b) \propto e^{-\gamma_s t_a} + e^{-\gamma_s t_b} + \alpha \times 2e^{-\frac{\gamma_s}{2}(t_a+t_b)} \cos[\Delta m(t_a - t_b)]$$

$$I^{like}_{\substack{KsKs\\KLKL}}(t_a,t_b) \propto e^{-\gamma_s(t_a+t_b)} + 1 - \alpha \times 2e^{-\frac{\gamma_s}{2}(t_a+t_b)} \cos[\Delta m(t_a + t_b)]$$

$$I^{unlike}_{\substack{KsKs\\KLKL}}(t_a,t_b) \propto e^{-\gamma_s(t_a+t_b)} + 1 + \alpha \times 2e^{-\frac{\gamma_s}{2}(t_a+t_b)} \cos[\Delta m(t_a + t_b)]$$

$$I^{like+unlike}_{background}(t_a,t_b) \propto e^{-\gamma_s t_a} + e^{-\gamma_s t_b}$$

This α parameter defines the amount of interference; $\alpha = 1$ is the quantum mechanics prediction; $\alpha = 0$ should indicate that there is no interference and that the $K^0\overline{K}^0$ system is "separable" and behaves like uncorrelated K_S and K_L as it has been suggested by Furry [13]; (This theoretical assumption will be discussed later).

α can be measured by maximising the likelihood function calculated with the defined relations applied to the experimental data and properly weighted.

In order to evaluate the statistical error on α for the above mentioned number of events, several hundred of experiments have been generated randomly. The dispersion of the optimised values for α gives a realistic evaluation for the error : $\sigma_\alpha = 0.12$ with 150 background events and 0.15 with 300 background events

F) CONCLUSIONS FOR THE LEPTON LEPTON CORRELATIONS:

The experiment is feasible but it is difficult.

-The rates are small, at least 70 days data taking are necessary.

-There is a serious difficulty with the 2π decay contamination.

But the PS 195 apparatus has not to be modified, data can be taken using a parallel trigger if the rates are compatible.

(It turns out that it will be very difficult to decrease the trigger rate lower than one kilohertz)

CHAP. IV STRANGENESS SIGNED KAONS INTERACTIONS

Intuitive statement

So far it has been shown that EPR-type non-local correlations can be tested by measuring the leptonic kaons decay lengths correlations. For an external observer the decay instants are completely out of control and he is restricted to an entire passive role.

Instead of waiting for the K decays, another method is to put some material on the kaon paths at various distances ***decided*** by the experimentalist. In general the kaons strong interactions final states reveal the strangeness of the interacting kaons. With such a device the correlations between like and unlike strangeness can be measured under different free chosen conditions.

The quantum mechanics predictions for the two methods are identical but the second one is intellectually more satisfactory and one has the feeling that this "Deus ex machina " intervention, analyses more fundamentally these long distance correlations, particularly it can be tested if these correlations are naturally decided by the decay process or if they can be provoked by external occurrences.

A) EXPERIMENT

For a $K^0\overline{K}^0$pair in an antisymmetric spatial state the like and unlike strangeness time distributions follow the relations (5) and (6) defined above

If the two kaons interact strongly within an absorber and if the strangeness of the final states are identified by an hyperon or a charged kaon production the interaction distances have to follow the two calculated intensities distributions.

Two kaons cannot be, and therefore cannot interact, in the same strangeness states at equal interaction distances whatever these distances are; like strangeness are forbidden while unlike strangeness are enhanced.

For any couple of distances the number of events is obtained by multiplying the intensities (5) and (6) by the corresponding strong interaction cross sections.

Positive strangeness is identified by a K^+ in the final state and negative strangeness by a Λ or a K^-.

Six strangeness combinations can be experimentally isolated.

K^+	—	K^+	like strangeness final states
K^-	—	K^-	
K^-	—	Λ	
Λ	—	Λ	
K^+	—	K^-	unlike strangeness final states
K^+	—	Λ	

A double interacting $K^0\overline{K}^0$ event can be defined spatially by the angular co-ordinates θ (azimuth) and φ (dip) for the production line of flight Fig.6.

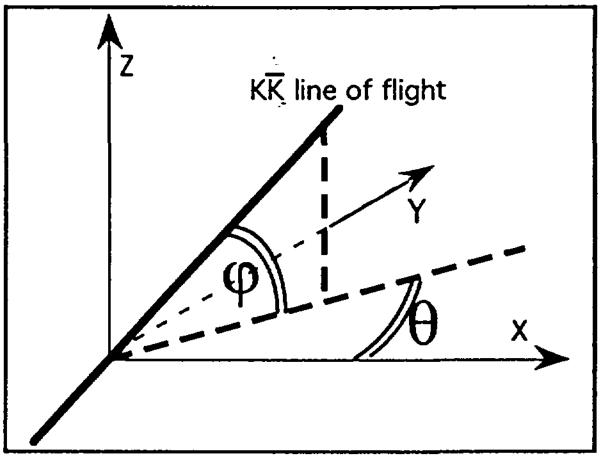


FIG 6

B)ABSORBER

The absorber shape, dimensions and position choice are of first importance and constitute the kernel of the experiment.

A cooper absorber with a 10mm thickness seems to be a reasonable compromise (7% of the interaction length).

In order to measure, with the same experimental set up, several continuous interaction positions the following asymmetric absorber is proposed on Fig.7

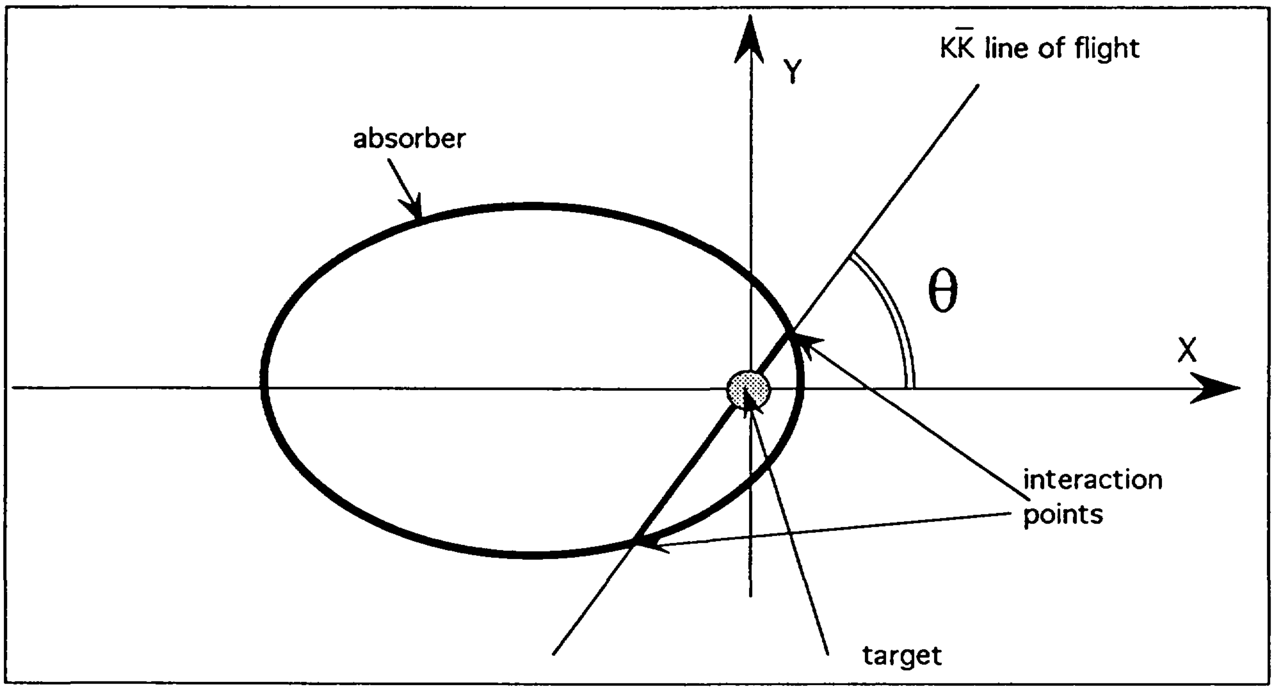


FIG 7

A cylinder with an ellipsoidal basis surrounds the target. The shape and the position of this absorber are adjusted in order to optimise the correlation effects.

The ellipse has 8 and 12 cm half axis lengths and the centre is placed 10cm horizontally from the target centre.

The $K^0\overline{K}^0$ line of flight is obtained by joining the two interaction points and the angular coordinates θ and φ as defined on Fig.6 can be calculated.

For events in a vertical plane (θ = 90° or 270°) the two interaction distances are equal for all φ angles. For horizontal events θ = 0° or 180° the lengths difference is 20cm (corresponding to 5*Ks* lifetimes) for a 0° φ angle. As a consequence events with θ = 90° or 270° are completely forbidden for like strangeness and are enhanced for unlike strangeness events. For θ = 0° or 180° the interference is such that like events have a higher predicted intensity than unlike events.

Fig.8 shows quantitatively the predicted azimuth angular distributions, integrated over the φ angle, for like and unlike strangeness events. The above mentioned effects can be clearly seen.

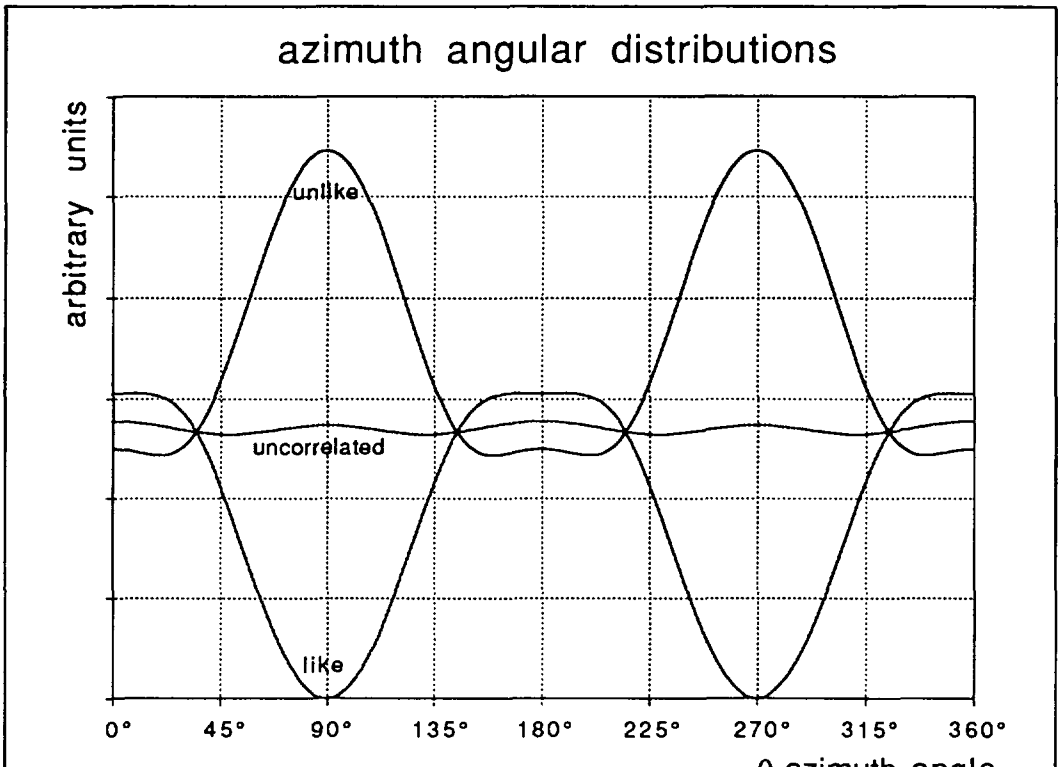


FIG 8

In a first approach only the shapes of these distributions can be checked, the normalisations depend on the $K^0\overline{K}^0$cross sections on copper for each channel, which are fairly known. For this reason the y co-ordinates of Fig.8 are expressed in arbitrary units different for each channel. It will be shown later how this problem can be overcome. On the same figure one can also see the angular distribution for uncorrelated K_SK_L interactions. The eccentricity of the ellipse has been adjusted in order to nearly flatten this distribution.

Fig.9 shows the geometrical correlation between t_a and t_b produced by the absorber. for φ=0°. This curve is smeared if all φ angles are taken into account.

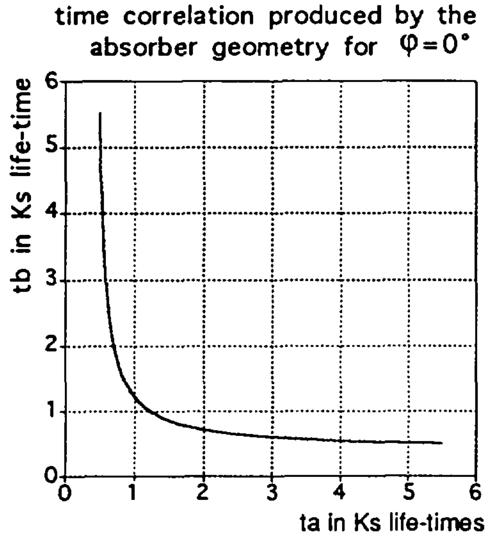


FIG 9

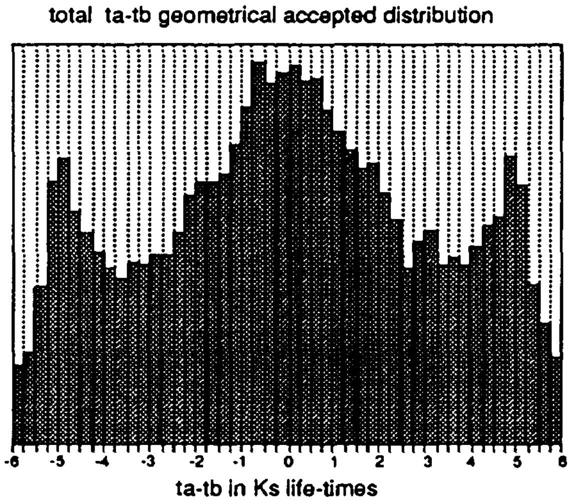


FIG 10

Fig.10 shows the geometrical accepted distribution for *ta-tb* integrated over all the solid angle intercepted by the absorber. The interesting regions $|t_a-t_b|\approx 0$ and $|t_a-t_b|\approx 5\,\tau_s$ are enhanced.

The aim of the experiment is to identify and measure produced lamdas and charged kaons, and to check if the azimuth angular distributions for each of the four like and the two unlike channels, follow the predicted distributions.

C) EXPERIMENTAL SET UP

For this experiment the PS 195 apparatus needs to be modified. The absorber size is not compatible with the PC1 and PC2 proportional chambers which have to be removed. No other modification is needed.

The modified set up is shown on Fig.11 and 12.

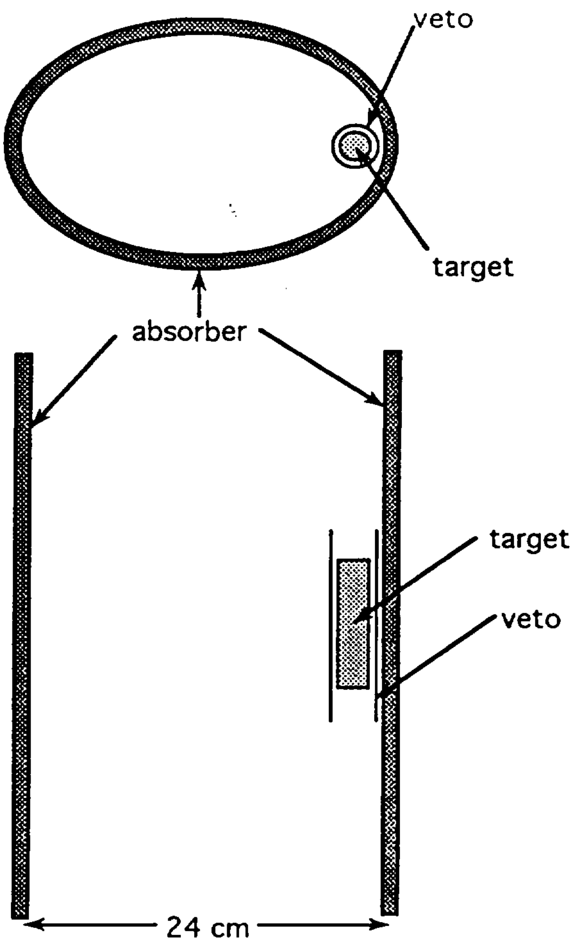

veto
target
absorber
target
veto
24 cm

FIG 11

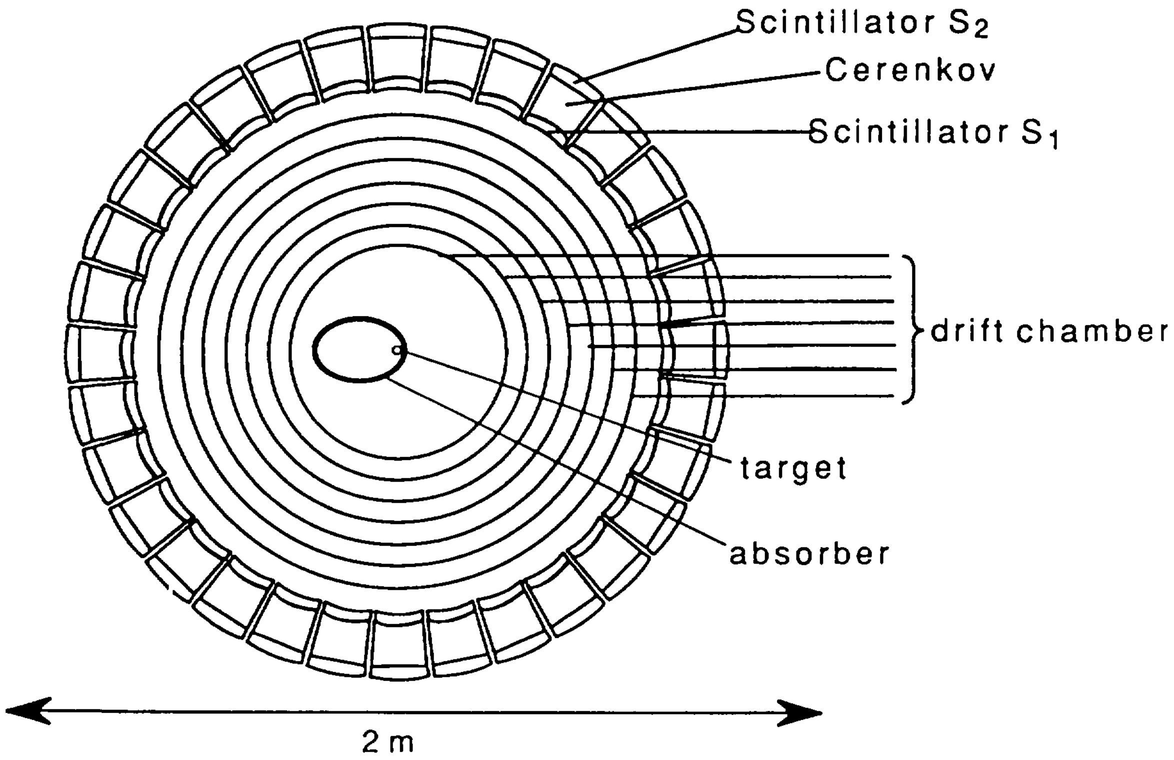

Scintillator S2
Cerenkov
Scintillator S1
drift chamber
target
absorber
2 m

FIG 12

The cylindrical target filled with 30 atmospheres pressured hydrogen has a length of 120mm and a diameter of 30mm. The anti-protons annihilation volume within the hydrogen is 6mm wide and 18mm long.

An anti coincidence device around the target is needed to veto the annihilations with charged particles production. This can be achieved by the actual PC0 proportional chamber or with a new scintillating optical fibres veto counter.

The six drift chambers and the 0.46 tesla magnetic field give enough resolution for reconstructing the lambda and charged kaons trajectories and for extrapolating to the interaction points at the absorber.

D) TRIGGER

The trigger is performed by 32 Cerenkov cells sandwiched between two scintillator hodoscopes S1 and S2. The Cerenkov counters filled with liquid FC72TM (refractive index=1.26) have a 200MeV/c threshold for the pions and 700MeV/c for the kaons.

The trigger requirements are:

- A charged particle anti-coincidence performed by the veto device around the target

- At least two low beta charged particles each giving a S1 S2 coincidence and vetoed by the corresponding Cerenkov cells.

The trigger accepts low momenta pions ($p < 250$MeV/c), nearly all kaons and high momenta protons ($p > 500$MeV/c). Low momenta protons stopped within the 3cm thick S1 counters and the 8cm Cerenkov liquid do not fire the S2 counter.

The flux of the different type of charged hadrons created by $K^0\overline{K}^0$ interactions are of the same order of magnitude.The main on line utility of the Cerenkov is to veto electrons and positrons produced by the gamma's showering in the absorber or in the apparatus material. These gamma's are produced by multi pi zeros annihilation final states not vetoed by the anti counter. Charged annihilation final states escaping to the initial veto and the *Ks* decaying into two pions are also rejected if they have not two low momenta pions.

The π-K separation for momenta < 250MeV/c, and the *K-P* identification for momenta > 500MeV/c can be easily achieved in the off-line analysis by the ionisation loss in the S1 and S2 counters (dE/dX).

The time of flight measurement can be used as a cross check for the identifications. But the incoming annihilating anti proton cannot provide a precise start signal, only the time of flight differences between two particles can be used.

The kaon trigger is straightforward all kaons are accepted. For the lamda's, 80% have a decay proton with a momenta lower than 500MeV/c and do not trigger the apparatus but the accompanying decay π^- has always a momenta lower than 250MeV/c. On the other hand more than 70% of the lamda's are produced in the absorber together with a π^+ or with a $\pi^+\pi^-$ pair of low momenta. This increases the trigger efficiency and the accuracy of the lamda production point measurement.

E) BACKGROUND

The physical background due to the symmetric $K^0\overline{K}^0$ spatial state contamination has to be taken into account.

On Fig.13 and 14 one can see the azimuth distributions for like and unlike events generated by 10% $K_S K_S + K_L K_L$ physical background compared to the $K_S K_L$ distributions. (The relative normalisation is correct for a given final state.)

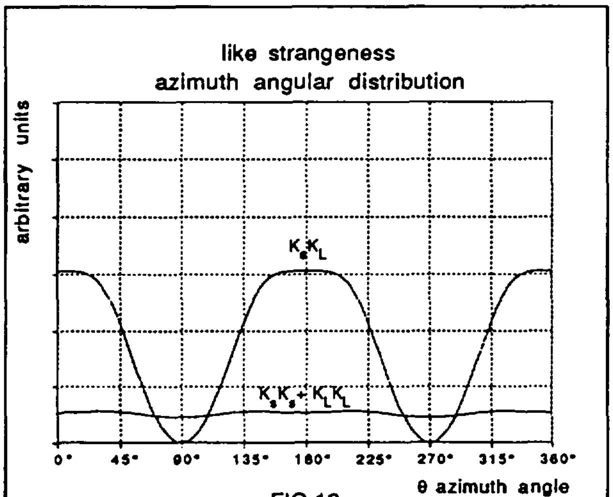


FIG 13

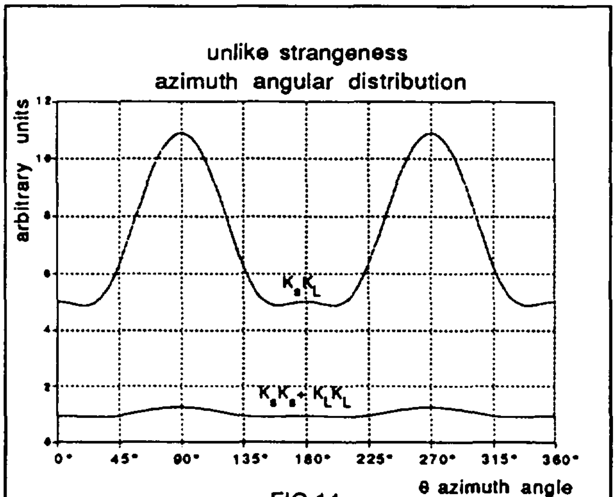


FIG 14

Fig.15 shows the angular distributions of Fig.6 after background addition. These are the distributions which have to checked by the experimental results.

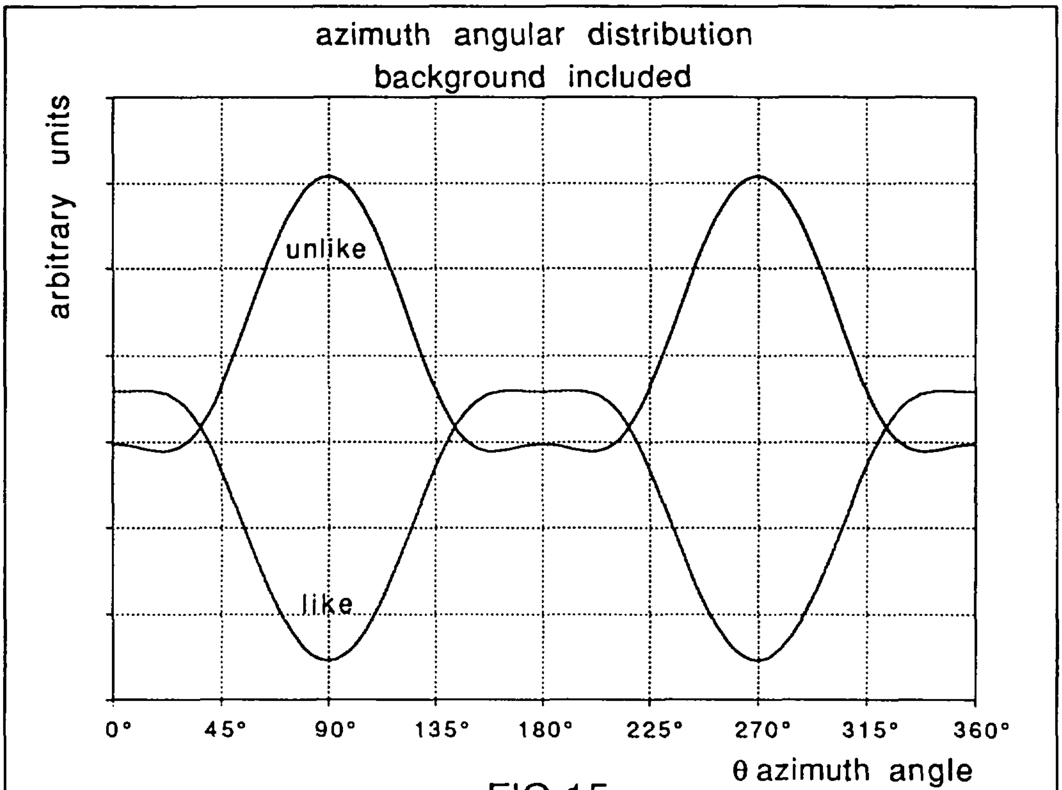


FIG 15

EXPERIMENTAL BACKGROUND:

The unwanted triggering physical events will consist on:

- Primary or scattered Ks decaying into low momenta pions.
- High momenta recoil protons.
- Low momenta charged pions due to the veto inefficiency.
- $K^0\overline{K}^0$ *+(neutrals)* annihilation final states.

The off line particles identification and the topology measurement reject nearly all of these unwanted triggering events except the last category.

The main foreseen contamination will be the $K^0\overline{K}^0$*+(neutrals)* annihilation channel with both kaons interacting in the absorber. The production ratio is nearly 50% of the single $K^0\overline{K}^0$ production ratio. This contamination can be decreased by requiring that the two interacting kaons are produced in a back to back configuration which implies that the line connecting the interaction points crosses the $\overline{P}$ annihilation volume. Low momenta missing neutrals will not be rejected by this cut. This contamination depends on the geometrical resolution, it has been estimated to be of the order of 5%. An extra rejection based on the detection of at least one of the gamma's showering in the absorber (1 radiation length) has so far not been evaluated. The target can also be surrounded by one or two mm of lead, but this would probably saturate the veto counter. Finally if there is not to much random background, the use of the existing electromagnetic calorimeter could also be considered.

Anyhow a 5% background can be tolerated, although this contamination is slightly θ dependent.

All these foreseeable effects give a moderate trigger rate.

The overall trigger frequency, with such an absorber, depends on the veto device inefficiency and mostly on S1S2 random coincidences. This trigger rate can only be measured experimentally.

One has also to check if the number of random particles, multiplied by the absorber, can be tolerated by the drift chambers.

F) *K* AND *Λ* PRODUCTION REACTIONS AND RATES

K^+ production	$K^0 + P \rightarrow K^+ + N$	additional pion production is
K^- production	$\bar{K}^0 + N \rightarrow K^- + P$	negligible at 800 MeV/c

Λ production

$$\bar{K}^0 + N \rightarrow \Lambda(\Sigma^0) + (n\, \pi^\circ)$$

$$\bar{K}^0 + N \rightarrow \Lambda(\Sigma^0) + \pi^+ + \pi^- + (\pi^\circ)$$

$$\bar{K}^0 + P \rightarrow \Lambda(\Sigma^0) + \pi^+ + (n\, \pi^\circ)$$

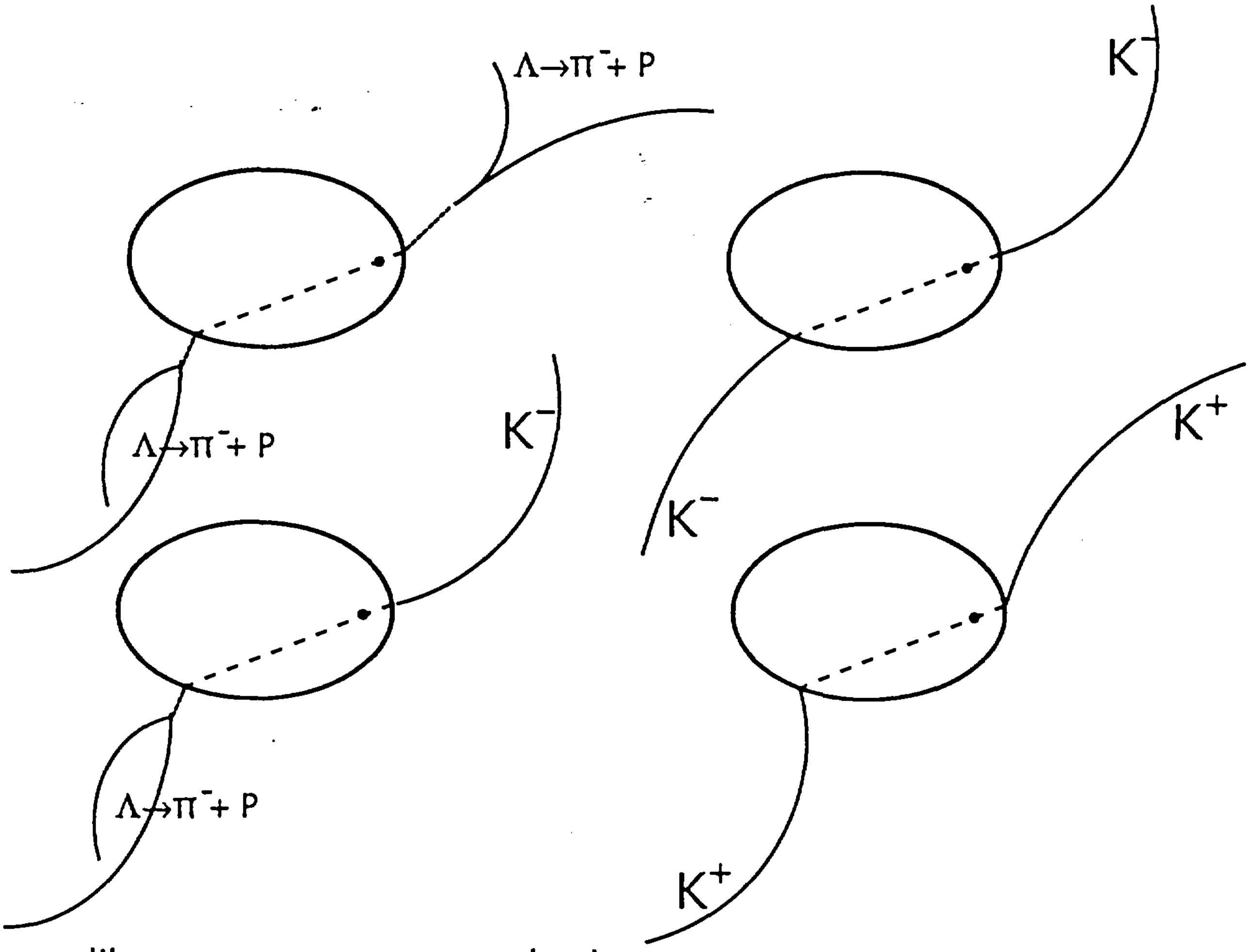
N is a neutron and *P* is a proton.

The event rates with a 7% interaction length absorber are substantially superior than for the lepton lepton decay experiment. The interacting probabilities are much higher than the leptonic branching ratios multiplied by the K_L apparatus acceptance.

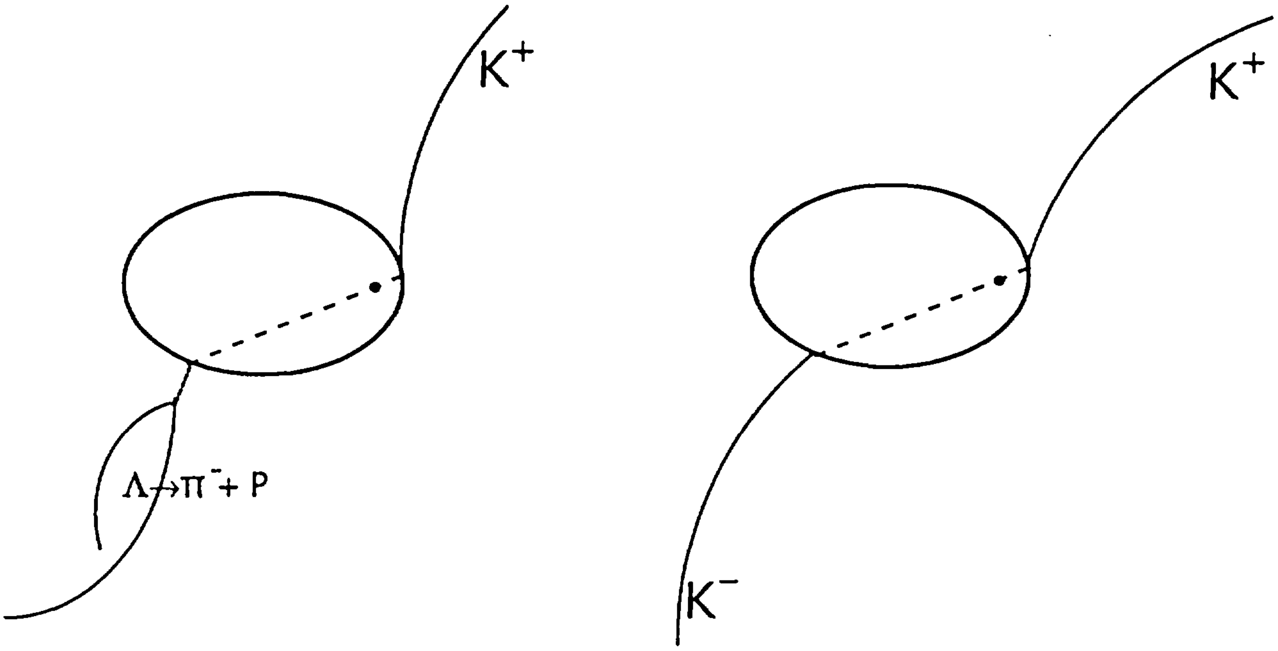
Using a 10 mm thick cooper absorber, $K^0\bar{K}^0$ cross sections evaluated with K^+K^- interactions on hydrogen and deuterium, apparatus acceptance and efficiencies and usual experimental losses, the following rates for the six channels have been evaluated. For twenty days data taking the number of events for the six final states is expected to amount to:

$K^+ — K^+$	350 events	like strangeness
$K^- — K^-$	200	
$\Lambda — K^-$	600	
$\Lambda — \Lambda$	450	
$K^+ — K^-$	1100 events	unlike strangeness
$K^+ — \Lambda$	1600	

The six corresponding geometrical topologies are shown on Fig.16



like strangeness topologies



unlike strangeness topologies

FIG 16

G) DATA ANALYSIS

The θ azimuth angular distributions for each of the four like strangeness and the two unlike strangeness channels must be compatible with the correlations functions including the contamination contribution plotted on Fig.15.

This provides six experimental angular distributions, with different systematic errors, each of them has to be compared to the theoretical predictions..

1) NORMALISATION

The absolute normalisations and the channels comparison would need a precise knowledge of the cross sections and of the experimental efficiencies for each channel at each angle, this is not the case. Relative normalisations can be achieved, without knowing these quantities, by the following apparently complicated but logically simple method.

For each $K^o\overline{K}^o$configuration (θ is the angle of the first kaon and $\theta+\pi$ the angle for the second kaon), the number of events within an interval $\Delta\theta$ and integrated over φ, are given by the expressions:

$$N^{++}(\theta) = C\, \sigma^{+}\sigma^{+}\varepsilon^{+}(\theta)\varepsilon'^{+}(\theta)\, I_{like}(\theta)\Delta\theta$$

$$N^{--}(\theta) = C\, \sigma^{-}\sigma^{-}\varepsilon^{-}(\theta)\varepsilon'^{-}(\theta)\, I_{like}(\theta)\Delta\theta$$

$$N^{-o}(\theta) = C\, \sigma^{-}\sigma^{o}\varepsilon^{-}(\theta)\varepsilon'^{o}(\theta)\, I_{like}(\theta)\Delta\theta$$

$$N^{o-}(\theta) = C\, \sigma^{o}\sigma^{-}\varepsilon^{0}\theta)\varepsilon'^{-}(\theta)\, I_{like}(\theta)\Delta\theta$$

$$N^{oo}(\theta) = C\, \sigma^{o}\sigma^{o}\varepsilon^{o}(\theta)\varepsilon'^{o}(\theta)\, I_{like}(\theta)\Delta\theta$$

$$N^{+-}(\theta) = C\, \sigma^{+}\sigma^{-}\varepsilon^{+}(\theta)\varepsilon'^{-}(\theta)\, I_{unlike}(\theta)\Delta\theta$$

$$N^{-+}(\theta) = C\, \sigma^{-}\sigma^{+}\varepsilon^{-}(\theta)\varepsilon'^{+}(\theta)\, I_{unlike}(\theta)\Delta\theta$$

$$N^{+o}(\theta) = C\, \sigma^{+}\sigma^{o}\varepsilon^{+}(\theta)\varepsilon'^{o}(\theta)\, I_{unlike}(\theta)\Delta\theta$$

$$N^{o+}(\theta) = C\, \sigma^{o}\sigma^{+}\varepsilon^{o}(\theta)\varepsilon'^{+}(\theta)\, I_{unlike}(\theta)\Delta\theta$$

Definitions:

$+$	K^+ final state
$-$	K^- final state
o	Λ final state
$N(\theta)$	number of events expected at the θ angle for a $\Delta\theta$ interval
$I(\theta)$	QM intensity
σ	cross section
$\varepsilon(\theta)$	detection efficiency for θ
$\varepsilon'(\theta)$	detection efficiency for $\theta+\pi$
C	constant parameter related to the $K^o\overline{K}^o$ integrated flux. and to the absorber material and thickness.

For the three channels (ΛK^+, ΛK^-, K^+K^-) where both final states are different there are two possible combinations corresponding to the two positions obtained by interchanging the neutral kaons.The experimental detection efficiencies for the two combinations are different. (In general for a given particle $\varepsilon(\theta) \neq \varepsilon(\theta+\pi)$; this is due to the asymmetric position of the absorber).

$I_{like}(\theta)$ and $I_{unlike}(\theta)$ can be simply deduced from the above equations and expressed as functions of the measured event numbers for the nine final states at each angle without any assumption.

$$k(\theta)\ I_{like}(\theta) = 2\ sqrt\left\{N^{++}(\theta)\left[N^{oo}(\theta) + N^{--}(\theta) + 2\sqrt{N^{o-}(\theta)N^{-o}(\theta)}\right]\right\}$$

$$k(\theta)\ I_{unlike}(\theta) = 2\sqrt{N^{+-}(\theta)N^{-+}(\theta)} + 2\sqrt{N^{+o}(\theta)N^{o+}(\theta)}$$

$$k(\theta) = C\,\sigma^{+}\sqrt{\varepsilon^{+}(\theta)\varepsilon'^{+}(\theta)}\left[\sigma^{o}\sqrt{\varepsilon^{o}(\theta)\varepsilon'^{o}(\theta)} + \sigma^{-}\sqrt{\varepsilon^{-}(\theta)\varepsilon'^{-}(\theta)}\right]$$

The like/unlike ratio $R(\theta)$ and the asymmetry $A(\theta)$ can be expressed independently of $k(\theta)$

$$R(\theta) = \frac{I_{like}(\theta)}{I_{unlike}(\theta)} = \frac{sqrt\left\{N^{++}(\theta)\left[N^{oo}(\theta) + N^{--}(\theta) + 2\sqrt{N^{o-}(\theta)N^{-o}(\theta)}\right]\right\}}{\sqrt{N^{+-}(\theta)N^{-+}(\theta)} + \sqrt{N^{+o}(\theta)N^{o+}(\theta)}}$$

$$A(\theta) = \frac{I_{unlike}(\theta) - I_{like}(\theta)}{I_{unlike}(\theta) + I_{like}(\theta)} = \frac{1 - R(\theta)}{1 + R(\theta)}$$

These two ratios do not depend on the cross sections and on the detection efficiencies for the different channels.

The cross sections and the angular depending efficiencies are contained in $k(\theta)$ which for a given θ angle is the same for like and unlike intensities.

All experimentally detected channels can be mixed together in the above defined formulas for an overall test of the quantum mechanics predictions and this without any corrections for the cross sections and the various acceptances and efficiencies.

This is the second cornerstone of the proposed experiment.

A third relation is of some interest:

$$k(\theta)\left[I_{unlike}(\theta) - I_{like}(\theta)\right] = 2\sqrt{N^{+-}(\theta)N^{-+}(\theta)} + 2\sqrt{N^{+o}(\theta)N^{o+}(\theta)} - 2\ sqrt\left\{N^{++}(\theta)\left[N^{oo}(\theta) + N^{--}(\theta) + 2\sqrt{N^{o-}(\theta)N^{-o}(\theta)}\right]\right\}$$

This last distribution cannot be properly normalised. The shape depends on the $k(\theta)$ variations and one has to assume that these variations are known or keep small . But this distribution isolates the interference term and is nearly independent on all uncorrelated backgrounds.

The time depending quantum mechanics predictions for the three relations are:

$$\frac{I_{like}}{I_{unlike}} = \frac{e^{-\gamma_s t_a} + e^{-\gamma_s t_b} - 2e^{-\frac{\gamma_s}{2}(t_a+t_b)}\cos[\Delta m(t_a - t_b)]}{e^{-\gamma_s t_a} + e^{-\gamma_s t_b} + 2e^{-\frac{\gamma_s}{2}(t_a+t_b)}\cos[\Delta m(t_a - t_b)]}$$

$$\frac{I_{unlike} - I_{like}}{I_{unlike} + I_{like}} = \frac{2e^{-\frac{\gamma_s}{2}(t_a+t_b)}\cos[\Delta m(t_a - t_b)]}{e^{-\gamma_s t_a} + e^{-\gamma_s t_b}}$$

$$I_{unlike} - I_{like} \propto e^{-\frac{\gamma_s}{2}(t_a+t_b)}\cos[\Delta m(t_a - t_b)]$$

One can see that the second and third relations describe mostly the interference term.
The three relations are physically and statistically equivalent, but the background contributions are different.

2)LIKE UNLIKE CORRELATED DISTRIBUTIONS

It has been shown that no calibration nor experimental detection corrections are necessary. But the background contribution has to be taken into account properly.
The three calculated θ dependent distributions corresponding to the three above relations are plotted on Fig.(17,18,19,) after integration over the dip angle. The same distributions, corrected for 10% *KsKs+KLKL* background, are also shown on the same figures.

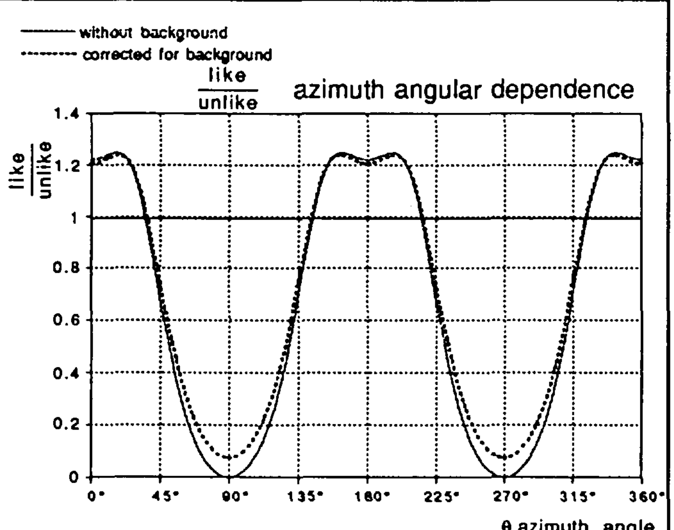


FIG 17

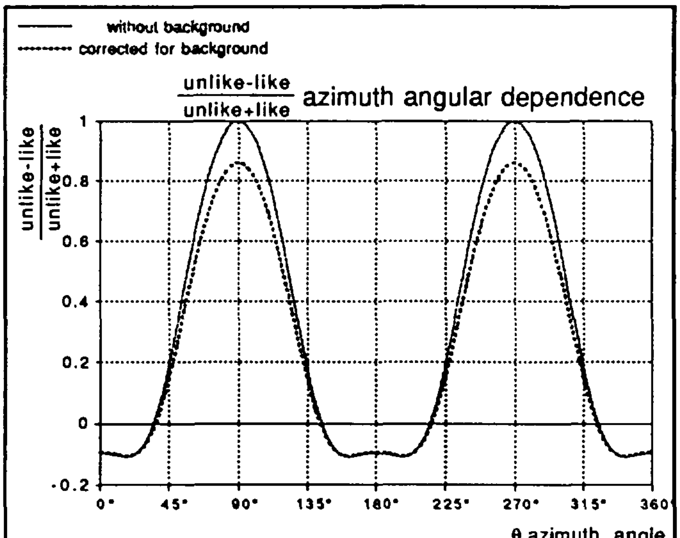


FIG 18

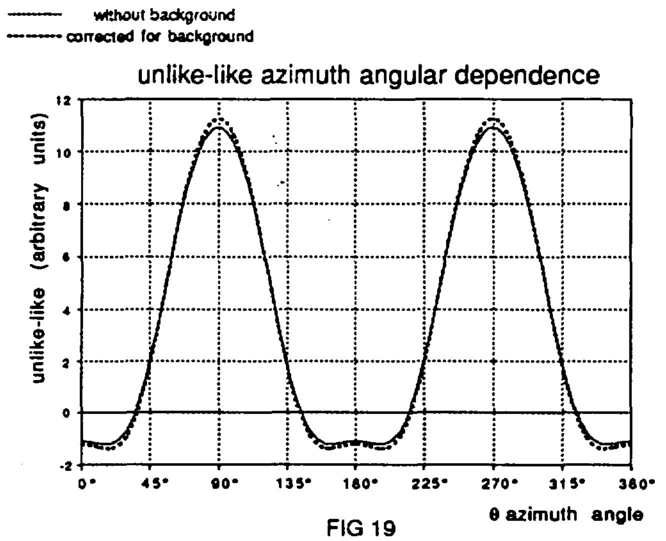


FIG 19

The correlations already mentioned can be clearly seen on Fig.17,18,19. There are two main effects further referred as effect 1) and effect 2)

1) For 90° and 270°(equal *K* lengths) like strangeness are forbidden and unlike strangeness are enhanced

2) At 0° and 180° the like intensity becomes higher than the unlike intensity

GEOMETRICAL RESOLUTION.

The accuracy of the θ angle measurement is not crucial, the physical effect ranging over a large angular interval.

The errors on the *K* decay lengths due to the uncertainties on the interactions positions within the absorber and also to the size of the annihilation volume, have only a small effect. This is due to the fact that the interference depends on the sum and on the difference of the two lengths and it has been shown earlier that the half width of the like destructive interference depletion is nearly ±1.5 τ_s (Fig 2) which corresponds to ±6cm for the lengths difference, this is an order of magnitude higher that the uncertainties on the lengths determinations.

In order to illustrate the above statements, events have been generated taking into account all the mentioned uncertainties. Fig. 20 show the distributions obtained for a 4000 events experiment corresponding roughly to 20 days data taking.

In order to isolate the resolution effect, no background has been generated and added to the distributions.

MONTE CARLO GENERATED DISTRIBUTIONS
WITHOUT BACKGROUND

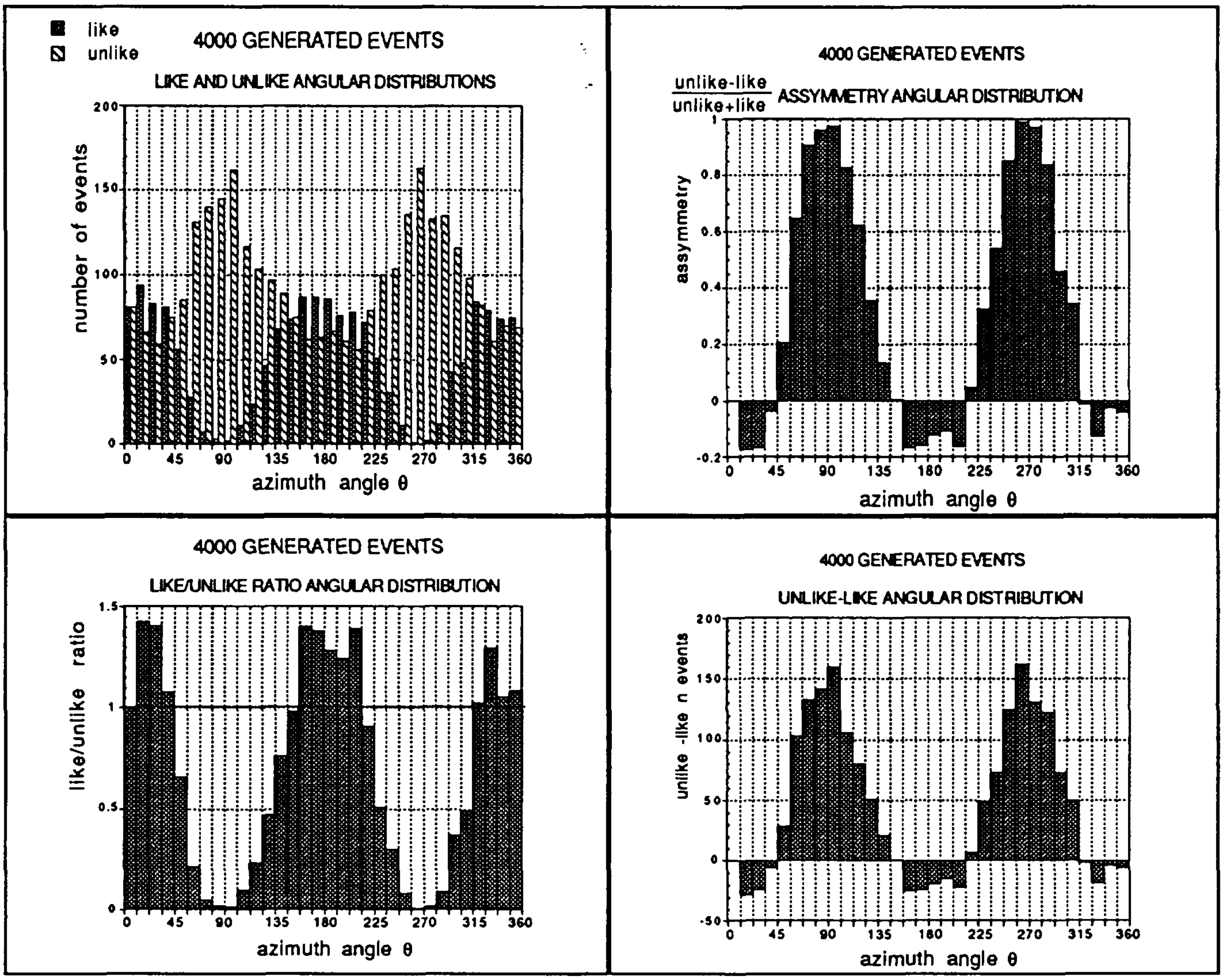


FIG. 20

For this experiment the geometrical resolutions are not crucial for testing the striking correlation effects but a good accuracy is needed for rejecting the experimental backgrounds $K^0\overline{K}^0$+*(neutrals)* and for which no primary photon could be detected.

STATISTICS.

For an experimental test of quantum mechanics effect 1), a sample of a few hundred events is sufficient. More statistics is needed for testing the effect 2).

In order to get a realistic evaluation of the statistical error for the existence of a negative asymmetry for $\theta \approx 0°$ and $\theta \approx 180°$ (corresponding to the effect 2)), 250 experiments with 4000 events have been generated. The asymmetry distribution within the angular intervals $-25° < \theta < 25°$ and $155° < \theta < 205°$ is shown on Fig 21. The mean value is –0.105 as expected, and the statistical error ± 0.025.

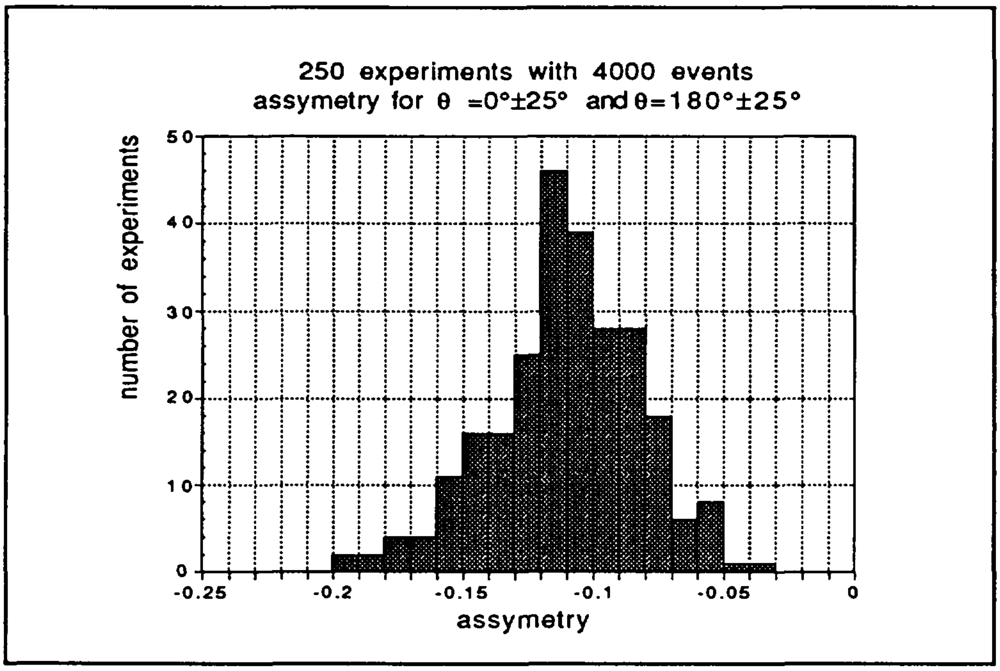


FIG. 21

CHAP. V QUANTUM MECHANICS VERSUS LOCAL REALISM PEDESTRIAN APPROACH.

A) QUANTUM MECHANICS GENERALITIES

In this report, up to now, it has been suggested to verify experimentally EPR-type non-local correlations predicted by simple basic quantum mechanics applied to the antisymmetric $K^0\overline{K}^0$ system.

These correlations mainly due to what can be called "strangeness-CP duality" are logically puzzling at least in the frame for a macroscopic physical conception. They imply a long distance influence among the probabilistic behaviour of spatially separated particles.

The symmetry and conservation laws defined at the origin are retained by the two body wave function and remain valid if both particles are measured simultaneously despite their space-like separation.

If the particles are not measured together, the first measurement at t_a reduces (or factorises or disentangles or collapses) the two body wavefunction and the surviving particle evoluates with his own wave function like if it would have been created by the first measurement at $t_b=t_a$. Its strangeness state will be opposite to that identified with the measured *K*. The time evolution of the continuing *K* is described by a t_b-t_a time depending strangeness mixture and therefore is correlated to the strangeness state and to the live-time t_a of the first measured *K*.

This time dependence is the basic difference with the photon-photon system where polarisation correlations are ***time independent***. Being constant no simple experiment can measure if these correlations have been fixed at the origin or if they have been created by the measurements. Therefore the quantum mechanics and the most elementary local model cannot be distinguished. This explains why, for photon-photon and fermion-fermion systems, no conclusive experiment could be possible prior the Bell's inequality formulation.

Another obvious argument would be to state that spin and polarisation correlations for a two body photon or fermion system is nothing else than the conservation of the total angular momentum which has to be true wherever it is measured.

This is not the case for the antisymmetric two body $K^0\overline{K}^0$ system. The equivalent argument would be to state that, if one *K* is measured as a K_S the other one has to be a K_L and vice-versa and this at any time. This can be simply explained by the CP conservation in the production process. The quantum versus local alternative consists in the differentiation between the K_S and K_L assignment at the production against a K_S randomly defined at the measurement, accompanied by an EPR order to the unmeasured *K* to be definitively a K_L.

Thanks to the time dependent strangeness oscillations, a simple $K^0\overline{K}^0$ experiment allows a much deeper investigation.

B) SOME LOCALITY CONSIDERATIONS

Pedestrian local definition.

A pair of indistinguishable particles *a* and *b* are created in two states $|u\rangle$ and $|\overline{u}\rangle$ with time dependent probabilities $|u(t)|^2$ and $|\overline{u}(t)|^2$. These individual probability distributions ***must be defined at the creation***, they contain all the informations, and may be some functions of non measurable hidden variables, which control the future evolution. They can be summations of non existing physical states probabilities. For any local model the two body time distribution will be the product of the two single probability distributions.

As they are indistinguishable the two body time dependent probability distribution has to be written:

$$I(t_a,t_b)=|\ u(t_a)\ |^2*|\ \bar{u}(t_b)\ |^2+|\ u(t_b)\ |^2*|\ \bar{u}(t_a)\ |^2$$

In all cases there is no time dependent interference.

This, allows the important remark that, for any local model, if $I(t_a,t_b)$ vanishes for $t_a=t_b=t$ will imply that $u(t)$ or $\bar{u}(t)$ must vanish for any time before the first measurement.

This remark applied to the antisymmetric $K^0\bar{K}^0$ system means that, for any local theory if the above described experimental effect 1) exists, the kaons have to be, at any time, in pure opposite strangeness states prior the first measurement. The strangeness states have to bepure but as they are time dependent the kaons must flip synchronously from one strangeness to the other.

This peculiar requirement is not necessary for photon or fermion local theories where the correlation is time independent; the spin and polarisation states have to be pure but they can keep constant.

SOME ELEMENTARY LOCAL MODELS.

Going back to the to the initial $K^0\bar{K}^0$wave function (4) :

$$|\psi(0,0)\rangle=\frac{1}{\sqrt{2}}(pq'+qp')\left[|K_S(0)\rangle_a|K_L(0)\rangle_b-|K_L(0)\rangle_a|K_S(0)\rangle_b\right].$$

Instead of adding coherently the two amplitudes one can assume that the wave function factorises immediately after the two particles have been created. It remains two incoherent K_SK_L states with the following time dependent intensity of the local type.

$$I(t_a,t_b)\ \propto\ |\eta_b|^2e^{-\gamma_st_a-\gamma_Lt_b}+|\eta_a|^2e^{-\gamma_Lt_a-\gamma_st_b}$$

which is the uncorrelated distribution for a K_S and a K_L decaying into final states a and b

This spontaneous factorisation of the wave function has been proposed by Furry [13] in 1936 and has been called the particle separability which has never been tested experimentally.

Applied to the strangeness distributions of the $K^0\bar{K}^0$ system, this hypothesis leads to the loss of the strangeness correlation contained in the interference and like and unlike strangeness would have the same distributions. This is not satisfactory since strangeness have to be partially correlated at least close to the production point.

This hypothesis can be easily tested by the suggested experiment.

Another elementary local model can be obtained by taking the second expression of the wavefunction (3)

$$|\psi(0,0)\rangle=\frac{1}{\sqrt{2}}\left[|K(0)\rangle_a|\bar{K}(0)\rangle_b-|\bar{K}(0)\rangle_a|K(0)\rangle_b\right]$$

Adding incoherently the two amplitudes one gets the following time depending intensity.

$$I(t_a,t_b)=I(t_a)\bar{I}(t_b)+\bar{I}(t_a)I(t_b)$$

$$I(t_a,t_b) = I(t_a)\overline{I}(t_b)+\overline{I}(t_a)I(t_b)$$

This is the distribution which would be obtained for a $K^0\overline{K}^0$ pair which disentangle after their creation, each of the kaons following his own one body strangeness distribution.

The intensity functions are the relations (1) and (2) defined in CHAP I with the single K formulation.

The like and unlike strangeness intensities functions can be obtained by choosing the appropriate single kaon intensities which never vanish for t >0.

$$I_{like}(t_a,t_b) = I^+(t_a)\overline{I}^+(t_b) + \overline{I}^+(t_a)I^+(t_b) = I^-(t_a)\overline{I}^-(t_b) + \overline{I}^-(t_a)I^-(t_b)$$
$$I_{unlike}(t_a,t_b) = I^+(t_a)\overline{I}^-(t_b) + \overline{I}^+(t_a)I^-(t_b) = I^-(t_a)\overline{I}^+(t_b) + \overline{I}^-(t_a)I^+(t_b)$$

This is the most uncorrelated indistinguishable $K^0\overline{K}^0$ pair which can be imagined. It can be shown that strangeness are nevertheless statistically correlated. However the spatial anti-symmetry of the wave function and therefore the K_SK_L correlation contained in the interference will be lost. The kaons behaves like an equal mixture of symmetric and anti-symmetric spatial states and this is experimentally excluded.

The predicted intensities can be obtained by taking 100% spatially symmetric background instead of 10% in the already calculated distributions (Fig. 13,14,15). The above named effect 2) is attenuated but is still present, and the effect 1) is washed out. Each of the kaons follows the quantum mechanics strangeness distributions for single kaons entirely predicted at the creation.

This example of a simple local model is mentioned in order to illustrate that probabilistic correlations can be measured even if the kaon and anti-kaon are completely independent, but the intensity never vanishes, therefore these correlations are not of EPR type. A K strangeness measurement cannot predict with 100% probability the outcome of the second measurement but only a statistical distribution which is nevertheless correlated to the first measurement.

Much more sophisticated local models are necessary if one admits intuitively that strangeness correlations must exist together with the obvious K_SK_L correlation.

The formal definitions and properties of the various types of published realistic local theories will not be reviewed in this report. They can be probabilistic or deterministic, with or without hidden variables.

Since the fundamental bases have been defined by Einstein, Podolsky and Rosen [1], a huge number of theoretical papers have been published.

Only the subtle and pioneering work of J.Bell [3] completed by [14,15] initiated experiments to test the upper limit given by the whole sample of local realistic theories with hidden variables (Bell's inequality).

The polarisations of two photons, produced in a pure quantum state, measured four times by two polarisers with a variable relative angle, are correlated. Quantum Mechanics predictions, for four special angle values exceeds the local theories upper limit. The experimental results [4,5] seem to confirm quantum mechanics and exclude locality, at least in quantum optics. Nevertheless none of these experiments fulfils the required ideal experimental conditions and they have been criticised by numerous authors[6].

For an ideal experiment the apparatus should have a total geometrical acceptance, the detectors efficiencies have to be close to 100%, the random background must be negligible, the detectors arms significantly space like separated and the four set-up randomly chosen.

Most of these difficulties have been theoretically or experimentally overcome, but this has to be paid by the lost of the absolute significance of the violation of the pure Bell's inequality.

For the $K^0\overline{K}^0$ experimentation, it has been shown [16] that, due to the decay amplitudes attenuations, it is not possible to find conditions where QM disagrees with inequalities given by the Bell's formalism applied to $K^0\overline{K}^0$ system and therefore it is generally admitted that with $K^0\overline{K}^0$ experimentation it is not possible to reach a final conclusion about local realistic theories non-validity.

In what follows, it is assumed that Bell's inequality cannot be applied and an alternative pragmatic approach to the local theories exclusion is proposed.

Bell's formalism provides limits excluding ***all*** possible local theories with hidden variables.

This , for the $K^0\overline{K}^0$ system, is an ***unnecessary generalisation***..

As a matter of fact the time dependent strangeness correlations if measured by a simple two *K* experiment, can test very specific QM correlation predictions and therefore provide strong constraining conditions on possible local models which all have to agree with the experimental results. This requirement reduces the local theories sample to a restricted subsample with singular properties and therefore the general boundaries imposed by the Bell's inequality for all possible local theories are not longer necessary. The demonstration will be completed if one can prove theoretically or experimentally that this subsample is empty and that no local formalism fulfils these conditions.

With the proposed experiment two main correlation features can be tested. They have been called effect 1) and effect 2)

Effect 1) The two *K's* cannot be in the same strangeness states at equal time and this whatever this time is.

Effect 2) At a time difference around 5 *Ks* lifetimes, the probability of like strangeness states exceeds the probability of unlike strangeness states.

If this two features predicted by QM are experimentally verified, all local theories have to be compatible with these two effects.

As already stated above the effect 1) imposes drastic conditions to any local formalism:

The two spatially isolated kaons, if not submitted to long range mutual influence, must be, prior the measurement and at any time, in opposite ***pure strangeness*** states in order to verify the 100% simultaneous strangeness anti-correlation. The time dependence requires that both strangeness have to flip simultaneously to the opposite pure states. The flipping sequence for each *K* pair has to be defined at the creation. The flipping time depending law has to be the same for both kaons but it must be different for each pair.

A local approach for the $K^0\overline{K}^0$ system has been made by Privitera and Selleri[7]. A local formalism including all models verifying the above effect 1) has been developed and the following inequality has been obtained for the like strangeness time depending distribution.

$$I^{like}_{K_SK_L}(t_a,t_b) \le \frac{1}{8}\left[\frac{3}{2}-\frac{1}{2}H(t_a)\right]\left[1+H(t_b)\right]e^{-\gamma_s t_a}e^{-\gamma_L t_b}+\frac{1}{8}\left[1+H(t_a)\right]\left[1-H(t_b)\right]e^{-\gamma_s t_b}e^{-\gamma_L t_a}$$

$$H(t)=\frac{2e^{\frac{1}{2}(\gamma_s+\gamma_L)t}}{e^{\gamma_s t}+e^{\gamma_L t}}\cos\Delta m t \qquad t_a < t_b$$

In order to compare to the experimental QM predictions, without caring about all normalisation and efficiencies problems, the unlike strangeness limit has been calculated assuming that the "like + unlike" intensity follows the simple uncorrelated K_SK_L decay exponential laws. $I^{like+unlike}_{K_SK_L}(t_a,t_b) = e^{-\gamma_s t_a}e^{-\gamma_L t_b} + e^{-\gamma_L t_a}e^{-\gamma_s t_b}$

The like and unlike functions have been applied to the experimental absorber and, as for QM, have been integrated over the dip angle φ.

The θ depending limits for the like/unlike ratio and the asymmetry have been calculated and plotted on Fig.22 and 23 together with the corresponding QM prediction.

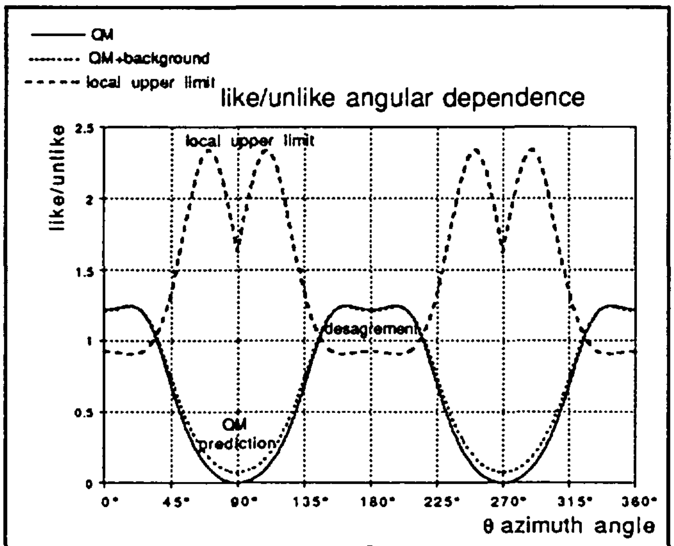


FIG 22

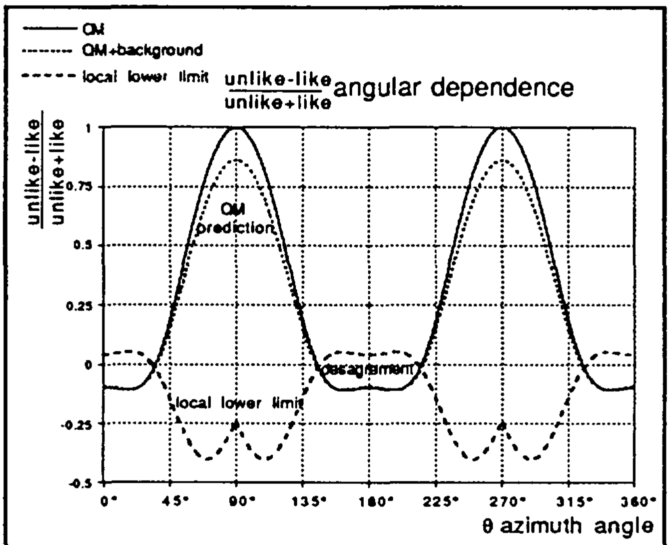


FIG 23

It can be clearly seen that this inequality is incompatible with Q.M. for θ around 0% and 180% corresponding to the existence of the effect 2). Therefore this local theory is not compatible with the like strangeness events excess predicted by QM around $|t_a-t_b| \approx 5\tau_s$ and the experimental evidence of effect 2) would exclude this approach.

It is difficult for an experimentalist to judge the validity of this local formalism and if it includes the whole possible sample of local models compatible with effect 1).

Unfortunately no other approach could be found in the literature.

A local model or a class of local models, ***compatible with effects 1) and 2)*** have so far never been proposed [17]. If such models can be defined, the new deduced predictions or boundaries have to be tested by more accurate or elaborated experiments; otherwise if no local model or sample of local models can be found, the described experiment would exclude locality " by default ".

CONCLUSION

It has been shown that, for an anti-symmetric $K^0\overline{K}^0$ system, elementary quantum mechanics predicts a peculiar EPR-type non-local correlation.

Experimental verification seems to be possible in a near future, with the LEAR low energy anti-protons facility and a modified PS 195 apparatus. But this has to be cross checked by PS 195 specialists.

The small $K^0\overline{K}^0$ symmetric spatial state contamination in anti-protons annihilations can be determined and the antisymmetric $K_S K_L$ state properly isolated

Lepton-lepton decay correlations can be measured but it is difficult; on the other hand phi factories can do it with less background.

The possibility to measure the strangeness states of both kaons by signing their strangeness through strong interactions within a free chosen absorber is particularly attractive and this can only be performed with a stopping anti-proton experiment.

Quantum Mechanics provides an intriguing challenge to classical intuition. Up to now all possible experimental results, in all scientific microscopic fields, confirm the validity of this fundamental theory. If the proposed experiment disagrees with the predictions, it would reveal a basic failure of Quantum Mechanics in the $K^0\overline{K}^0$formalism. Such a conclusion is highly improbable, but it would not be the first time that K experimentation leads to surprising results.

If an agreement is found, Quantum Mechanics, once more, will be confirmed.

Concerning the validity of local theories, Bell's formalism can probably not be applied properly to the $K^0\overline{K}^0$ experimentation.

A particular emphasis has been made in order to prove that the $K^0\overline{K}^0$ system is more complicated than photon-photon or fermion-fermion systems and that a simple two body $K^0\overline{K}^0$ experiment verifying the predicted time dependent EPR-type non-local correlation imposes severe constraining conditions on all local theories.

The experiment can also check the separability of the wave function as suggested by Furry[13] and test the local formalism proposed by Selleri[7].

FINAL CONCLUDING SUMMARY:

- A $K^0\overline{K}^0$ interaction experiment could be performed, and this, exclusively with the already existing CERN installations.
- The outcome does not only test quantum theory, but it reduces considerably the boundaries of local theories for the $K^0\overline{K}^0$physics.

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