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POSSIBLE EPR EXPERIMENT WITH $K^0\overline{K^0}$ AND $B_d^0\overline{B_d^0}$ PAIRS

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ABSTRACT

Discrimination between local realism and quantum theory has been recently proposed in particle physics by means of EPR tests with correlated $K^0\overline{K^0}$ ($B_d^0\overline{B_d^0}$) pairs produced in $\Phi(B)$-factories: the local realistic asymmetry for observing pairs with like and unlike flavour at different proper times remarkably differs from the quantum mechanical prediction.

1 Historical view and EPR tests in particle physics

The strange nature of quantum correlation between separated system was pointed out for the first time by Einstein, Podolsky and Rosen (EPR) [1]. In 1965 the incompatibility between quantum mechanics (QM) and local realism (LR) at the empirical level became evident: Bell proved [2] that a wide class of local hidden-variable models satisfies an inequality violated by QM.

In 1969 Clauser, Holt, Shimony and Horne (CHSH) stressed that Bell's inequality could be experimentally checked with atomic cascade photon pairs emitted by single atoms [3]. In terms of detection probabilities, Bell's inequality becomes a double limitation on

$$\Gamma \equiv \omega(a,b) - \omega(a,b') + \omega(a',b) + \omega(a',b') \tag{1}$$

and reads

$$-1 + \omega_1(a') + \omega_2(b) \leq \Gamma \leq \omega_1(a') + \omega_2(b) \tag{2}$$

where: $\omega(x,y)$ is the joint probability that both photons are detected by two photomultipliers placed on their paths after crossing polarisers with axes x and y ($x = a, a'$ referred to the first photon, $y = b, b'$ referred to the second one); $\omega_1(a')$ [$\omega_2(b)$] is the probability that the first [second] photon is transmitted by the polariser with axes a' [b] and detected. Inequality (2) was not violated by the quantum mechanical predictions for experiments on atomic cascade photon pairs, but CHSH pointed out that meaningful experiments were possible, even with the available low efficiency photon counters, if the following *additional assumption* was made:

AA. Given that a pair of photons emerges from two regions of space where two polarisers can be located, the probability of their joint detection by two photomultipliers is independent of the presence and orientation of the polarisers.

This assumption allowed CHSH to deduce a different inequality

$$-1 + \omega(a',\infty) + \omega(\infty,b) \leq \Gamma \leq \omega(a',\infty) + \omega(\infty,b) \tag{3}$$

where $\omega(a',\infty)$ [$\omega(\infty,b)$] is the joint probability that both photons are detected when the polariser is not present on the trajectory of the second [first] one, and Γ is given by eq.1 again. The shift from eq.2 to eq.3 was crucial in producing a disagreement with QM.

In 1972 experiment by Freedman and Clauser [4] the inequality (3) was violated, differently from the (2). In 1974 Clauser and Horne [5] proposed a slightly different additional assumption and built an explicit model of LR reproducing the results of the Freedman-Clauser experiment within errors.

In the 1981 Orsay experiments [6] the measured value of Γ was found in agreement with the prediction of QM and was slightly above the upper limit of eq.3 but well below the upper limit of eq.2. Thus the inequality (2) was not violated and the meaning of the Orsay experiments is therefore totally dependent on the meaning of the inequality (3).

In 1983 Marshall et al. [7] showed that a consistently local and realistic picture of atomic cascades could fit the Orsay data as closely as quantum mechanical model and identified in the low efficiency of photodetectors the reason for the compatibility between QM and LR in the case of all performed EPR experiments.

During the eighties several papers [8] continued to stress the inequivalence of the inequalities (2) and (3) and in 1990 a general derivation of the two types of Bell's inequalities, those deduced from LR alone and those obtained with the essential help of an additional assumption (like AA above), was given [9]. The two types of inequalities, (2) and (3), were called "weak" and "strong" respectively, since the latter gives much stronger restrictions on Γ.

In spite of these unequivocal developements there still are papers (like that in reference [10]) which conclude that LR is experimentally violated without examining carefully the underlying assumptions. As argumented by Garuccio [11] and by Cabello and Santos [12] in different ways, the experiment carried out by the Rochester group [10] is not able to distinguish quantum mechanics and LR without supplementary assumptions.

Because of low detection efficiency the same considerations apply both to the Orsay experiments and to the recent Zeilinger's experiment [13]. Thus the comparison between LR and QM is as open as it always was.

The behaviour of a pair of neutral pseudo-scalar mesons (e.g. $K^0-\overline{K^0}$ or $B_d^0-\overline{B_d^0}$), anti-correlated in flavour if produced by the decay of a $J^{PC}=1^{--}$ state (e.g. the Φ or the $\Upsilon(4S)$ resonances, produced respectively at Φ-*factories* and *B-factories*) seems even more puzzling than the behaviour of spin correlated pairs of stable particles (photons or electrons). Indeed hopes of a final resolution of the EPR paradox lie in the study of these meson pairs because particle physics detectors are much more efficient than those for optical photons and the distinction between "strong" and "weak" formulations of LR becomes much less important, both conceptually and numerically. Possible EPR tests in particle physics are discussed in the present contribution.

A critical discussion of the EPR paradox for $K^0\overline{K^0}$ pairs and of the earlier attempts to check Bell's inequality in Φ decays was made by Ghirardi, Grassi and Weber [14]. The main argument was that Bell's inequality, written in terms of four different times of flight of the Kaons, is not violated by the quantum-mechanical two-time joint probability for correlated strangeness, due to the specific values of kaon masses and decay widths. It can be easily shown in the same way that an analogous argument holds for B_d mesons.

Recently further Bell-type tests involving new Bell-like inequalities for correlated neutral meson-anti meson pairs have been proposed and discussed [15] (most of them consider the $K^0-\overline{K^0}$ system). However, some of them would probe only a restricted class of local realistic theories whereas others avoid this difficulty but require experimental set-ups not available in the near future [16].

One of the few works on EPR tests with the B_d^0–$\overline{B_d^0}$ system [17] deduces a clear indication in favour of QM combining already published data (from *CLEO* and *Argus* and from LEP experiments). However this is an expected conclusion: a *decoherence parameter* ζ (such that the QM interference term is multiplied by a factor $(1-\zeta)$) is used to measure deviations from QM but the falsification of $\zeta=1$ means simply a falsification of the spontaneous factorization hypothesis (SFH). On one hand SFH was already falsified with gamma ray pairs from $e^- - e^+$ annihilations [18], with atomic photon pairs [4] [6] and recently with Kaons pairs produced in p–$\overline{p}$ annihilations [19]; on the other hand it is possible to reproduce within the local realistic approach all non paradoxical predictions of QM, including anti-correlations in *strangeness* and *CP* (or *beauty* and *mass*), which are absent in SFH; thus SFH violation is also predicted by any reasonable approach based on LR.

Bell's inequality is only one of the many consequences of LR: EPR correlations can provide tests sensitive to possible deviations from QM. Meaningful tests of LR, not of the Bell-type, have been proposed for the K^0–$\overline{K^0}$ system [20] [21] and for the $B_d^0-\overline{B_d^0}$ system [22].

2 Pseudo-scalar meson pair correlations and probabilities within QM and LR

Let us consider EPR-correlated $K^0\overline{K^0}$ and $B_d^0\overline{B_d^0}$ pairs produced in the strong decays of Φ and $\Upsilon(4S)$ resonances respectively. The created $M^0\overline{M^0}$ pairs ($M = K, B_d$) inherits the resonances quantum numbers $J^{PC} = 1^{--}$. Since the mesons are spinless, $J^P = 1^-$ implies that the $M^0\overline{M^0}$ pair is in a *p-wave* total angular momentum state. $C=-1$ implies that the flavour part of the pair wavefunction is antisymmetric. Therefore immediately after the decay (namely at $t=0$) the $M^0\overline{M^0}$ state vector is given, in the resonance-frame, by

$$
\begin{aligned}
|\psi(0,0)> &= \tfrac{1}{\sqrt{2}}\{|M^0>_l\,|\overline{M^0}>_r - |\overline{M^0}>_l\,|M^0>_r\} \\
&= \tfrac{1}{\sqrt{2}}\{|M_1>_l\,|M_2>_r - |M_2>_l\,|M_1>_r\}
\end{aligned}
\tag{4}
$$

where $l(r)$ denote the mesons motion directions "left"("right"); $|M^0>$, $|\overline{M^0}>$ are *quark (strangeness* or *beauty) eigenstates*, whereas $|M_1>$, $|M_2>$ are *CP eigenstates*. Small effects due to CP-violation can be neglected here since it can not appreciably modify the large difference between LR and QM predictions that will be found. Thus $|M_1>$ and $|M_2>$ represent *short-lived* and *long-lived* Kaons or *heavy* and *light* B-mesons.

The time evolution operator for state in eq.4 is the product of the time evolution operators for single mesons states, so that, at proper times t_l and t_r, the time evolved state for the $M^0\overline{M^0}$ pair can be written as

$$
|\psi(t_l,t_r)>= \frac{1}{\sqrt{2}}\{|M_1>_l\,|M_2>_r\,e^{-\alpha_1 t_l-\alpha_2 t_r} - |M_2>_l\,|M_1>_r\,e^{-\alpha_2 t_l-\alpha_1 t_r}\} \tag{5}
$$

with

$$
\alpha_1 = \frac{1}{2}\Gamma_1 + im_1 \qquad , \qquad \alpha_2 = \frac{1}{2}\Gamma_2 + im_2 \tag{6}
$$

where, for *long* and *short-lived* Kaons, $\Gamma_1 \equiv \Gamma_S$ and $\Gamma_2 \equiv \Gamma_L$ respectively, whereas $\Gamma_1 \equiv \Gamma_H = \Gamma_2 \equiv \Gamma_L$ since the two neutral B-mesons are expected to have a negligible difference in lifetime.

The different exponentials in eq.5 generate M^0M^0 and $\overline{M^0M^0}$ components. Indeed the time evolution of M^0 and $\overline{M^0}$ is governed by a weak interaction that does not conserve flavour and thus allows $M^0-\overline{M^0}$ oscillations to take place between the *flavour eigenstates*.

From the eq.5 the probabilities of $M^0\overline{M^0}$, M^0M^0 and $\overline{M^0M^0}$ observations can be obtained. For $t_l=t_r$ the probability of having like flavours is zero. This flavour anti-correlation means that the two neutral mesons evolve in phase so that at equal proper times, until one of them decays, there are always a M^0 and a $\overline{M^0}$ present.

Let us consider the following flavour asymmetry

$$
A(t_l,t_r) = \frac{P[M^0(t_l);\overline{M^0}(t_r)] - P[\overline{M^0}(t_l);\overline{M^0}(t_r)]}{P[M^0(t_l);\overline{M^0}(t_r)] + P[\overline{M^0}(t_l);\overline{M^0}(t_r)]} \tag{7}
$$

that is the fundamental parameter for the comparison between quantum theory and the local realistic predictions in references [21) 22)]. From the experimental point of view the advantage of considering ratios of probabilities or number of events is that systematic errors tend to cancel out.

In QM the asymmetry in eq.7 is predicted to be a very simple function of $t_r - t_l$ only; for Kaons:

$$A^{QM}(t_l, t_r) = \frac{2\sqrt{E_L(t_r - t_l)E_S(t_r - t_l)}}{E_L(t_r - t_l) + E_S(t_r - t_l)} cos(\Delta m \ (t_r - t_l)) \tag{8}$$

with $E_{1,2}(t_{l,r}) \equiv e^{-\Gamma_{1,2} t_{l,r}}$, whereas for B-mesons ($E_1 = E_2$) it reduces to:

$$A^{QM}(t_l, t_r) = cos(\Delta m \ (t_r - t_l)) \tag{9}$$

The asymmetry predicted by LR results to be quite different from eq.8 and eq.9 as explained in detail in references [21) 22)] for Kaons and B-mesons respectively.

The local realism can be expressed by the following three assumptions:

(I) If, without in any way disturbing a system, we can predict with certainty the value of a physical quantity, then there exists an element of physical reality corresponding to this physical quantity (*EPR reality criterion*).

(II) If two physical systems (e.g. the two neutral mesons) are separated by a large distance, an element of reality belonging to one of them cannot have been created by a measurement performed on the other one (*separability*).

(III) If at a given time t a physical system has an element of reality, the latter cannot be created by measurements performed on the same system at time $t' > t$ (*no retroactive causality*).

Local realism can be applied to the meson pairs described quantum mechanically by the state vector in eq.5, by considering only those predictions of eq.5 to which EPR reality criterion can be applied. These are *flavour* and *mass* or *CP* anti-correlations.

According to the exposition in references [21) 22)] the $M^0\overline{M^0}$ pair is local-realistically described by means of two hidden variables:

a) each meson of every pair has an associated element of reality λ_1 which determines a well defined value of mass or CP eigenvalue ($\lambda_1 = +1, -1$ corresponds to m_H, m_L, respectively);

b) each meson of every pair has an associated element of reality λ_2 which determines a well defined value of flavour ($\lambda_2 = +1, -1$ corresponds to $q =$

+1,−1, respectively). Furthermore q is not a stable property: it has sudden jumps, from +1 to −1 and vice-versa, that are simultaneous for the two mesons of every pair but happen at random times in a statistical ensemble of many pairs.

The application of LR to the physical situation described by eq.5 leads outside the quantum theory: no quantum mechanical state vector exists which can describe a meson as having simultaneously well defined CP (or mass) and flavour values. Thus four meson basic states can be introduced:

$$\begin{array}{l} \mathcal{M}_1 = K_S\,[B_H] \;:\; state\;\; with\;\; s\,[b] = +1\;\; and\;\; CP = +1\,[m = m_H] \\ \mathcal{M}_2 = \overline{K}_S\,[\overline{B_H}] \;:\; state\;\; with\;\; s\,[b] = -1\;\; and\, CP = +1\,[m = m_H] \\ \mathcal{M}_3 = K_L\,[B_L] \;:\; state\;\; with\;\; s\,[b] = +1\;\; and\;\; CP = -1\,[m = m_L] \\ \mathcal{M}_4 = \overline{K}_L\,[\overline{B_L}] \;:\; state\;\; with\;\; s\,[b] = -1\;\; and\, CP = -1\,[m = m_L] \end{array} \tag{10}$$

The first two concern *short-living* Kaons (*heavy* B-mesons), the other two the *long-living* (*light*) ones.

The treatment given in references [21) 22)] provides the asymmetry parameter in eq.7 for LR. It turns out to have maximum and minimum values given by

$$\left\{ \begin{array}{l} A^{LR}_{max}(t_l;t_r) = 1 - 2 \mid Q^l_+ - Q^r_+ \mid \\ A^{LR}_{min}(t_l;t_r) = 1 - 2Min[(Q^l_+ + Q^r_+);(Q^l_- + Q^r_-)] \end{array} \right. \tag{11}$$

where, for Kaons,

$$Q^{l,r}_{\pm} \equiv \frac{1}{2}[1 \pm \frac{2\sqrt{E_L(t_{l,r})E_S(t_{l,r})}}{E_L(t_{l,r}) + E_S(t_{l,r})} cos(\Delta m\ t_{l,r})] \tag{12}$$

whereas for B-mesons

$$Q^{l,r}_{\pm}(t) \equiv \frac{1}{2}[1 \pm cos(\Delta m\ t_{l,r})] \tag{13}$$

so that $Q_+(t) + Q_-(t) = 1$. The behaviour of eq.9 and eq.11 for B-mesons is shown in fig. 1.

A^{QM} depends only on the difference of the two proper times and remains unchanged under the $t_l \leftrightarrow t_r$ exchange. Therefore with $t_l > t_r$, the study of A^{QM} is reduced to the case $t_r > t_l$. On the other hand A^{LR} depends not only on this difference but also on one given absolute proper time. However, under the $t_l \leftrightarrow t_r$ exchange A^{LR} is symmetric as can be easily shown and as should

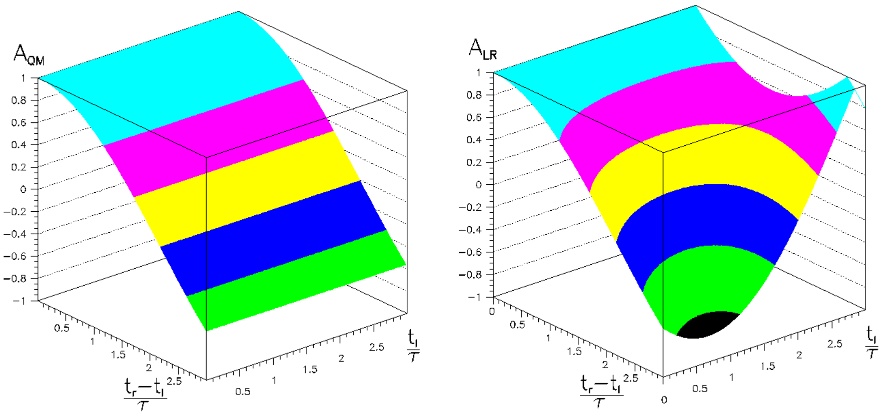

Figure 1: $B_d^0\overline{B_d^0}$ *flavour asymmetry predicted by QM (left) and LR (right; maximum values).*

be expected from the conventionality of l and r tags. Thus the study of A^{LR} can be limited to the case $t_r \geq t_l$ establishing, by convention, the dependence of A^{LR} on the shorter absolute time.

To appreciate the difference between the prediction of QM and the maximum prediction of LR it is useful to represent the asymmetry parameter as a function of $(t_r - t_l)/\tau$ for some given values of t_l/τ as in fig. 2 (where $\tau \equiv \tau_S$ for Kaons).

The comparison of the whole LR prediction with the MQ one, for two representative values of t_l, is given in fig. 3 for B-mesons.

It is interesting to notice that the difference between the predictions of QM and LR is higher in the B^0–$\overline{B^0}$ system than in the K^0–$\overline{K^0}$ system. However from an experimental point of view B-mesons require measuring smaller decay times that is more challenging.

3 Conclusions

Developing a very general local realistic theory of correlated $M^0\overline{M^0}$ ($M = K, B_d$) a not-of-Bell-type EPR test was proposed in references [21) 22)] to discriminate between quantum mechanics and local realism. Indeed the asymmetry for observing neutral pseudo-scalar meson pairs with like and unlike

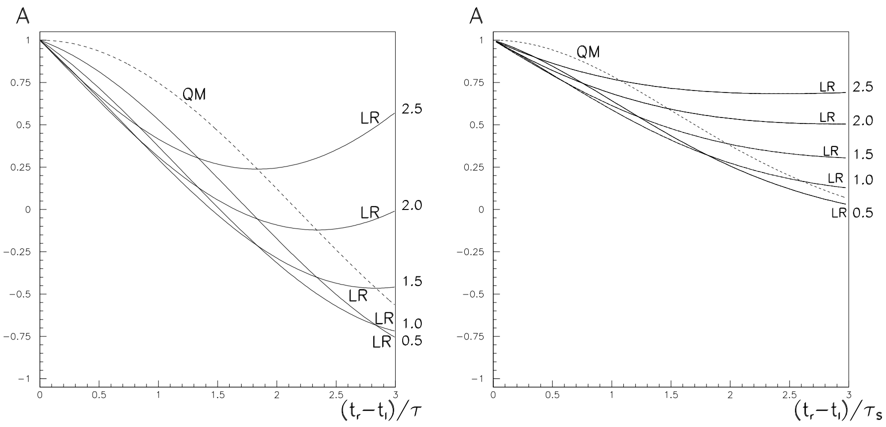

Figure 2: $B^0_d\overline{B^0_d}$ *(left) and* $K^0\overline{K^0}$ *(right) flavour asymmetry predicted by QM and LR (maximum values) for some fixed* t_l/τ *values.*

flavour predicted by local realism is significantly different from the quantum mechanical prediction.

The asymmetric B-factories (high luminosity asymmetric e^+e^- colliders operating at the $\Upsilon(4S)$ resonance), i.e. the PEP-II storage ring instrumented with *BaBar* detector at SLAC [23], and the KEK-B storage ring with *Belle* detector at KEK [24], can provide a powerful tool to perform the EPR test just proposed. In reference [22] the experimental feasibility of this EPR test is discussed for B-mesons; the technique for time-dependent di-lepton mixing measurement, properly adapted, seems to be suitable to provide a separation of several standard deviations between QM and LR predictions, with an integrated luminosity of 30 fb^{-1} that has already been collected by *BaBar* and *Belle*. The same EPR test can be performed with Kaons at the DaΦne Φ-factory when higher luminosities will be reached.

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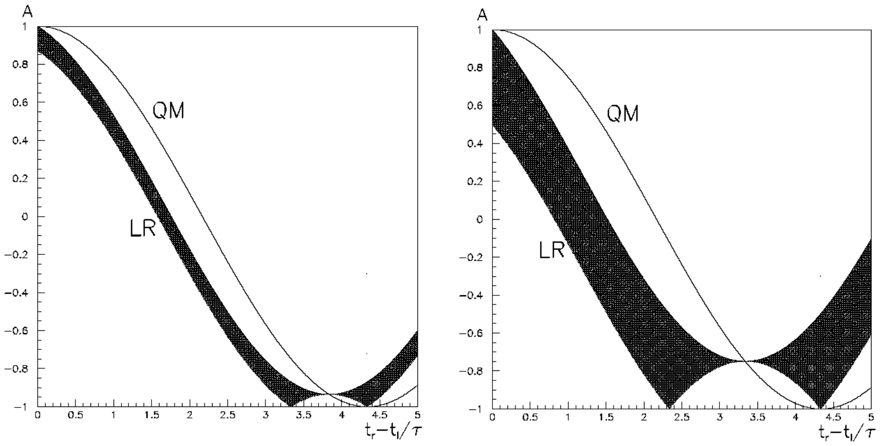

Figure 3: $B_d^0\overline{B_d^0}$ *flavour asymmetry predicted by QM and LR for* $t_l/\tau = 0.5$ *(left) and* $t_l/\tau = 1.0$ *(right).*

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Discussion

Isidori - I have a comment: at KLOE it will be very difficult to measure independently the two times. What you measure well is the time difference, but the interaction point is not well determined. So, you see the distance of the two interaction points but you don't know exactly where the zero point is. So, probably it's better to reformulate everything in terms of time difference.

Mannelli - Why do you say so for semileptonic decays? You should have two vertices. The beam is long but the size, at least in the transverse direction, is small. What I'm worried, but surely Selleri must have calculated it, is the fraction of the total phi produced which would decay in the vicinity of these time intervals which are quoted, both in the semileptonic fashion. That is perhaps the weak point where you would require all the luminosity that you could possibly collect.

Selleri - It is an important region. We take not a marginal part but the central part of the two proper times so that integrating over a big thing we still have a 30-40% difference. Then of course you have to reduce for the branching ratio to two leptonic and so on, but it remains a large effect.

Ecker - I'm confused by statements at the beginning of your talk. I thought the violation of Bell's inequality has now been demonstrated at the level of hundreds of standard deviations. Are you saying this is still not true, with photons of course?

Selleri - Right. They have violated - everybody - the strong inequality but never the weak inequality. So the problem is to know what is the strong inequality. The strong inequality has been deduced from local realism and additional assumptions. But practically all the way down to the narrow interval which is allowed by the inequality is done with additional assumptions. So, in my opinion, they have violated the additional assumptions and they could say nothing about local realism.