EPJ Web of Conferences **81**, 01012 (2014)
DOI: 10.1051/epjconf/20148101012

Can strong correlations be experimentally revealed for $\mathcal{K}$-mesons?

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Abstract. In 1964 the physicists John St. Bell working at CERN took the 1935-idea of Einstein-Podolsky-Rosen seriously and found that all theories based on local realism have to satisfy a certain inequality, nowadays dubbed Bell's inequality. Experiments with ordinary matter systems or light show violations of Bell's inequality favouring the quantum theory though a loophole free experiment has not yet been performed. This contribution presents an experimentally feasible Bell inequality for systems at higher energy scales, i.e. entangled neutral $\mathcal{K}$-meson pairs that are typically produced in Φ-mesons decays or proton-antiproton annihilation processes. Strong requirements have to be overcome in order to achieve a conclusive tests, such a proposal was recently published. Surprisingly, this new Bell inequality reveals new features for weakly decaying particles, in particular, a strong sensitivity to the combined charge-conjugation-parity ($\mathcal{CP}$) symmetry. Herewith, a puzzling relation between a symmetry breaking for mesons and Bell's inequality —which is a necessary and sufficient condition for the security of quantum cryptography protocols— is established. This becomes the more important since $\mathcal{CP}$ symmetry is related to the cosmological question why the antimatter disappeared after the Big Bang.

1 Introduction

The foundations of the quantum theory have been extensively studied ever since the seminal work of Einstein, Podolsky and Rosen (EPR) in 1935, and the discovery of Bell's theorem [1] in 1964, also dubbed Bell's inequalities. Violations of these Bell inequalities reveal correlations that are stronger than any correlations that can be obtained by classical physics and guarantee the security of quantum cryptography protocols. Such violations have been found in various distinct quantum systems of ordinary matter or light systems, such as photons, ions, Josephson phase qubits or single neutrons in an interferometer device. Currently, more and more experiments in the realm of Particle Physics, i.e. for systems at a different energy scales, are exploring these fundamental issues [2–10]. These experiments presently enter precision levels where, for various reasons, new physics is expected. In Refs. [11–14] it was outlined that, in particular, the neutral $\mathcal{K}$-meson system is suitable to show quantum marking and quantum erasure procedures in a way not available for ordinary matter and light systems. This is possible because there exists two different measurement procedures, an *active* one, exerting the free will of the experimenter, and a *passive* one, with no control over the measurement basis nor on the time point. For studies of strong correlations in the Einstein-Podolsky-Rosen setup,

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one has to demand that the two experimenters, commonly called Alice and Bob, independently and *actively* choose among different alternatives. This rules out all meson systems except the neutral kaons whose sufficiently long lifetimes permit insertion of material at various places along their trajectories. Among all possible observables only strangeness measurements, i.e. being in a particle state $\mathcal{K}^0$ or an antiparticle state $\overline{\mathcal{K}}^0$, can be considered for Bell theorem tests.

There have been several proposals of Bell inequalities for the entangled kaonic system (e.g. Refs. [2–9]), but they lack a direct experimental verification since both the observable as well as state space are limited. The first Bell test overcoming this insufficiency was found in Ref. [15]. This proposal can be put to reality with current technology at current or upcoming accelerator facilities (e.g. with the the KLOE-2 detector at the DAΦNE e^+e^- collider of the Frascati Laboratory of INFN [13, 16–18]). This proposal will be presented in the following section with emphasis on the relation to $\mathcal{CP}$ violation. Last but not least we investigate entanglement and Bell's theorem in hyperon-antihyperon systems that are also decaying weakly [23]. This also completes an information theoretic approach to weakly decaying particles and Bell's theorem.

2 Bell's 1964 theorem and its relation to the tiny violation of the $\mathcal{CP}$ symmetry

The neutral K-$\mathcal{K}$-mesons or simply kaons are bound states of quarks and anti–quarks or more precis the strangeness state +1, $\mathcal{K}^0$, is composed of an anti–strange quark and a down quark and the strangeness state, $\overline{\mathcal{K}}^0$, is composed of a strange and anti–down quark. In accelerator experiments one can produce a singlet state, i.e. one has the same scenario as Einstein, Podolsky and Rosen considered in 1935 which in the following is written down for different quantum systems (spin–$\frac{1}{2}$, ground/excited state, polarisation entangled photons, single neutrons in an interferometer, molecules, $\mathcal{K}$-meson, $\mathcal{B}$-mesons):

$$
\begin{aligned}
|\psi^-\rangle &= \frac{1}{\sqrt{2}}\{|\Uparrow\rangle_l \otimes |\Downarrow\rangle_r - |\Downarrow\rangle_l \otimes |\Uparrow\rangle_r\} \\
&= \frac{1}{\sqrt{2}}\{|0\rangle_l \otimes |1\rangle_r - |1\rangle_l \otimes |0\rangle_r\} \\
&= \frac{1}{\sqrt{2}}\{|H\rangle_l \otimes |V\rangle_r - |V\rangle_l \otimes |H\rangle_r\} \\
&= \frac{1}{\sqrt{2}}\{|I\rangle_l \otimes |\Uparrow\rangle_r - |II\rangle_l \otimes |\Downarrow\rangle_r\} \\
&= \frac{1}{\sqrt{2}}\{|\text{early}\rangle_l \otimes |\text{late}\rangle_r - |\text{late}\rangle_l \otimes |\text{early}\rangle_r\} \\
&= \frac{1}{\sqrt{2}}\{|\mathcal{K}^0\rangle_l \otimes |\overline{\mathcal{K}}^0\rangle_r - |\overline{\mathcal{K}}^0\rangle_l \otimes |\mathcal{K}^0\rangle_r\} \\
&= \frac{1}{\sqrt{2}}\{|\mathcal{B}^0\rangle_l \otimes |\overline{\mathcal{B}}^0\rangle_r - |\overline{\mathcal{B}}^0\rangle_l \otimes |\mathcal{B}^0\rangle_r\} \\
&= \ldots\,.
\end{aligned} \tag{1}
$$

Contrary to systems of ordinary matter and light neutral kaons oscillate in time (strangeness oscillation) and are decaying and therefore entanglement manifests itself considerably differently. In the EPR setting a source produces two particles, which are separated and independently measured by Alice and Bob. Both parties can choose among two different measurements alternatives $i = n, n'$ for

Alice and $j = m, m'$ for Bob. These settings yield either the outcomes $k, l = +1$ or $k, l = -1$. Any classical or quantum correlation function can be defined in the usual way by

$$E_{AB}(i,j) = \sum_{k,l} (k \cdot l)\; P^{kl}_{AB}(i,j) \tag{2}$$

where $P^{kl}_{AB}(i,j)$ is the joint probability for Alice obtaining the outcome k and Bob obtaining the outcome l, when they chose measurements i and j, respectively. For local realistic theories Bell's locality assumption imposes a factorization of the joint probabilities. Bell inequalities are tests for correlations that can be simulated using only local resources and shared randomness (a modern terminology for local hidden variables) and have, therefore, at hitherto nothing to do with quantum theory. Inserting the probabilities derived by quantum mechanics, however, in some cases leads to a violation of the inequality, i.e. to a contradiction between predictions of local hidden variable theories and quantum theory. For bipartite entangled qubits a tight Bell inequality is the famous Clauser-Horne-Shimony-Holt (CHSH) Bell inequality [19], i.e.

$$-2 \leq S(n,m,n',m') := E_{AB}(n,m) - E_{AB}(n,m') + E_{AB}(n',m) + E_{AB}(n',m') \leq 2\;. \tag{3}$$

In Ref. [15] the bounds ±2 where derived including the decay property but without spoiling the conclusiveness. Herewith the bounds become dependent on the setup.

The only *active* measurements –a necessary requirement for a conclusive test [4]– are strangeness measurements. The experimenter places at a certain distance from the source a piece of matter that forces the incoming neutral $\mathcal{K}$-meson beam to interact with the material and to reveal the strangeness content, i.e. being at that distance in the state $|\mathcal{K}^0\rangle$ or in the state $|\overline{\mathcal{K}}^0\rangle$. Since Bell's theorem tests against all local realistic theories one is not allow to ignore the fact that the neutral kaon could have decayed before. Therefore the question that one has to raise has to include that information, i.e. one hast to ask: "*Are you at a certain distance from the source in the state* $|\overline{\mathcal{K}}^0\rangle$ *or not?*", which is obviously different to the question "*Are you at a certain distance from the source in the state* $|\overline{\mathcal{K}}^0\rangle$ *or in the state* $|\mathcal{K}^0\rangle$*?*".

Choosing appropriate settings one finds violations of Bell's theorem. Surprisingly, also for rather long distances where the short-lived component has already considerably decreased one finds violations. These are due to violation of the symmetry $\mathcal{CP}$ since the violation depends whether the data is analyzed according to the question "*Are you at a certain distance from the source in the state* $|\overline{\mathcal{K}}^0\rangle$ *or not?*" or the question "*Are you at a certain distance from the source in the state* $|\mathcal{K}^0\rangle$ *or not?*". In one case one finds a violation in the other case not! Though the effect of $\mathcal{CP}$ violation on strangeness oscillation is typically of the order of 10^{-6}, the combination of the four expectation values and the bounds give a strong sensibility. This may also be relevant for other precision measurements.

3 Bell's theorem for the $\Lambda\overline{\Lambda}$ system

Another system that is decaying via the weak interaction and has been found in an entangled state is the $\Lambda\overline{\Lambda}$ system [20–22]. The Λ particle is a hyperon having spin $\frac{1}{2}$ (in contrary to the neutral kaon system that are spinless). Hyperons are overlineyons containing in addition to up or down quarks also one or more strange quarks. Hyperon decays violate the parity ($\mathcal{P}$) symmetry. The Standard Model of elementary particles predicts also tiny contribution of $\mathcal{CP}$ violating processes, however, no violation of the $\mathcal{CP}$ symmetry has been up to now experimentally found.

In Ref. [23] Bell's theorem has been discussed –in contrary to literature– it has been concluded that no conclusive test has been found. The physical reason is given by the particular interference of the processes violation or not the $\mathcal{P}$ symmetry. These processes lead to a reduced visibility or, differently stated, to imperfect spin measurements. The imperfections turns out to be too huge to lead to a violation of Bell's theorem.

4 Outlook

Exactly 50 years after Bell's celebrated theorem his ideas to reveal the very working of Nature are applied to systems in High Energy Physics; systems that in those times he was studying for very different reasons. A promising proposal for neutral kaon is on the market, putting it to reality in current or upcoming accelerator facilities will need a dedicated experiment. In the hyperon-antihyperon system so far no conclusive test is available. Revealing these strong correlations and in particular its relation the violation to the symmetry $\mathcal{CP}$ or $\mathcal{P}$ contributes to the understanding of weak interactions and maybe to the riddle of the antimatter disappearance in our universe.

Acknowledgements

The author gratefully acknowledges the Austrian Science Fund projects: FWF-P23627 and FWF-P26783.

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