Symmetry violation in particle physics and quantum mechanical correlations

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Abstract. We show that a symmetry violation in particle physics is related to nonlocality of quantum mechanics. This adds a new puzzle to $CP$ violation. Moreover, we discuss how the nonlocality may be tested in experiments and what more quantum features can be investigated in high energy physics.

1. Introduction
Bell inequalities are a compelling example of an essential difference between quantum mechanics and classical physics. Understanding this difference is vital in learning how a quantum world works compared to the classical one, or more practically how to use it for technical applications, such as quantum communication and the quantum computations.

Analyzing symmetries in Particle Physics and their possible violations has led to an impressive understand of our universe. E.g. the violation of $CP$ symmetry gives us the possibility to define the positive or negative charge in an absolut sense and shows the difference between particles and their antiparticles. However, it opens also new questions such as what is the origin of this violation.

This contribution cannot give an answer to the above question, however, adds a new puzzle to the topic as we will show that nonlocal correlations, correlations stronger than allowed by
classic local realistic theories, are related to the $C\!P$ symmetry violation in mixing for neutral kaons.

2. Short introduction to Bell inequalities

When one speaks in the everyday world of something like the moon or a human being, we assume that the physical properties of that object have an existence independent of its observation. The study of quantum theory and their immense verification in experiments forces us to conclude that an unobserved particle does not possess physical properties which exist independent of observation. Rather, such physical properties arise as a consequence of measurements performed upon the system. For instance a neutral kaon does not possess definite properties of being a particle with strangeness $S = +1$ and being a short–lived kaon each of which can be revealed by performing the appropriate measurement. Rather, quantum mechanics gives a set of rules which specify, given the state vector or the density matrix, the probabilities for the possible measurement outcomes if we decide to measure its strangeness content or its mass eigenstate.

Many physicists rejected this view of Nature and for non quantum physicists the above statement must sound crazy. Even the co-founders of quantum theory were not satisfied with the achievements of their own developments. The most famous paper is by Einstein, Podolsky and Rosen [1] from 1935 in which they – as they believed – demonstrated that quantum mechanics is not a complete theory of Nature. Their belief, nowadays called the EPR reality criterion, is:

“If, without in any way disturbing a system, we can predict with certainty (i.e. with the probability equal to unity) the value of a physical quantity, then there exists an element of physical reality corresponding to this physical quantity.”

They developed a gedanken experiment, nowadays known as the EPR-experiment. They considered two particles flying in opposite directions. On the left hand side the experimenter, usually called Alice, and on the right hand side the experimenter, called Bob, can perform measurements on their particle. Each of them can choose actively among alternative setups, i.e. by exerting their free will. Then later on they meet and compare their results. If the initial state is a maximally entangled one, e.g. the antisymmetric Bell state

$$|\psi^-\rangle = \frac{1}{\sqrt{2}}\left\{ |\uparrow\rangle_l \otimes |\downarrow\rangle_r - |\downarrow\rangle_l \otimes |\uparrow\rangle_r \right\}$$

$$= \frac{1}{\sqrt{2}}\left\{ |0\rangle_l \otimes |1\rangle_r - |1\rangle_l \otimes |0\rangle_r \right\}$$

$$= \frac{1}{\sqrt{2}}\left\{ |H\rangle_l \otimes |V\rangle_r - |V\rangle_l \otimes |H\rangle_r \right\}$$

$$= \frac{1}{\sqrt{2}}\left\{ |K^0\rangle_l \otimes |\bar{K}^0\rangle_r - |\bar{K}^0\rangle_l \otimes |K^0\rangle_r \right\}$$

$$= \frac{1}{\sqrt{2}}\left\{ |B^0\rangle_l \otimes |\bar{B}^0\rangle_r - |\bar{B}^0\rangle_l \otimes |B^0\rangle_r \right\}$$

$$= \frac{1}{\sqrt{2}}\left\{ |I\rangle_l \otimes |\uparrow\rangle_r - |\uparrow\rangle_l \otimes |I\rangle_r \right\}$$

$$= \ldots ,$$

(1)

eye observe strong correlations. If Alice finds in a certain direction spin up, then if by chance Bob measures in the same direction he finds with 100% probability that his particle is in the spin down state. Here the first line describes two spin–$\frac{1}{2}$ particles, the second line is given in the general notation of qubits, any two level system, $|\phi\rangle = \alpha |0\rangle + \beta |1\rangle$. The third line describes entangled photons ($H/V \ldots$ horizontal/vertical polarized). The forth and fifth line gives the entangled state for neutral mesons, i.e. the K-mesons and B–mesons, respectively. $K^0$ denotes the particle (strangeness $S = +1$) and $\bar{K}^0$ denotes the antiparticle (strangeness $S = -1$). The
last line describes a single neutron propagating through a two–way interferometer (path I and path II) where the different paths correspond to different spins. Thus the single neutron is entangled in its outer degrees of freedom (path) and its inner degrees of freedom (spin).

To explain these correlations the EPR people argued that quantum mechanics (QM) is incomplete in the sense they defined above. Each particle has to carry a hidden parameter in order to ensure that the other particle always gives the opposite result, if Alice and Bob by chance have measured in the same direction.

In 1964 John S. Bell proved the important theorem that a whole class of such local realistic hidden variable theories cannot reproduce all statistical predictions of QM, refs [2, 3]. He discovered that any local realistic theory forces the obtained 2-particle correlation functions to satisfy an inequality, called Bell inequality (BI), whereas QM, in certain cases, violates explicitly this BI. The importance of Bell’s theorem lies in the experimental feasibility to discriminate between QM and local realistic theories. Abner Shimony has denoted that as a decision of a philosophical question via an experiment.

Indeed, Nature had the last laugh on the EPR paradox. Many experiments have been carried out, mainly with photons, e.g. refs [4–8], but also with atoms, e.g. ref. [9], and confirm the quantum mechanical predictions. Hasegawa et.al in ref. [10] reported an experiment with single neutrons in an interferometric device which shows a violation of a Bell–like inequality. The entanglement is achieved not between two separate particles but between two degrees of freedom of a single neutron, namely, between the path it takes in the interferometer and its spin component which is different for the two paths. The mathematical description of the entangled state is the same as for the previously mentioned systems, see Eq. (1). However, as there are no two spatially separated particles, it is contextuality rather than nonlocality that is tested.

3. Bell inequalities in high energy physics

Knowing that in high energy physics also entangled systems exist, it is obvious to ask if Bell inequalities can also be violated for such massive systems produced in accelerators? Best suited are meson–antimeson systems which we focus on and among them only the neutral kaon system is of interest [11].

It turned out that the question is not that simple to be answered because of their different nature and the experimental limitations. To describe the challenging difference of mesons compared to other quantum systems, e.g. photons, is one important requirement. A general formalism has been developed in order to describe decaying systems within quantum mechanics, see [12] and applied to kaons in [13].

The derivation of the CHSH–Bell type inequality for neutral kaons is straightforward to the original proof of Clauser, Horne, Shimony and Holt in 1969, ref. [14], which is an extension of Bell’s original proof but under the more realistic assumption that due to experimental imperfections not all particles can be detected. Different from photons for kaons two properties can be chosen by each experimenter, i.e. the “quasispin” (a certain superposition of the particle and antiparticle state)

\[ |k_n⟩ = α_n|K^0⟩ + β_n|K^0⟩ \quad \text{with} \quad |α_n|^2 + |β_n|^2 = 1 , \tag{2} \]

and the time \( t \) the kaon propagates until the measurement. The detailed derivation for kaons can be found in [16]. The most general Bell inequality of the CHSH–type is given by

\[ S_{k_n,k_m,k'_n,k'_m}(t_1,t_2,t_3,t_4) = |E_{k_n,k_m}(t_1,t_2) − E_{k_n,k'_m}(t_1,t_3)| + |E_{k'_n,k_m}(t_4,t_2) + E_{k'_n,k'_m}(t_4,t_3)| ≤ 2 . \tag{3} \]

The bound 2 is valid for any local realistic theory. As in the usual photon setup, Alice and Bob can choose among two settings, i.e. Alice: \{\(k_n, t_1\); \(k'_n, t_3\)\} and Bob: \{\(k_m, t_2\); \(k'_m, t_3\)\}.
Let us first set all times equal to zero and choose the quasispin states to the time evolution and the decay property the kaon system is more complex and involved. We notice already that in the neutral kaon case we have more options than in the photon. The expectation value between a short-lived state of the kaon propagating to her side and Bob chooses to measure the quasispin is measured to be $\delta$ which is the maximal violation of the Bell inequality, thus when we optimize over that nonphysical phases in the definition of the CP violation parameter in mixing. Then the inequality (3) turns into the Wigner-type inequality

$$P(K_S, \bar{K}^0) \leq P(K_S, K^0_1) + P(K^0_1, \bar{K}^0)$$

(5)

where $P(K_S, \bar{K}^0)$, respectively, denotes the probability to measure on the left-hand side a short-lived kaon $K_S$ and on the right-hand side an anti-kaon $\bar{K}^0$.

For the initial antisymmetric Bell state (1) it is straightforward to calculate the quantum mechanical probabilities. However, there is a nonphysical phases in the definition of the CP states for the neutral kaon system which is in conventional physics set to zero. We are interested in the maximal violation of the Bell inequality, thus when we optimize over that nonphysical phase inequality (5) can be turned into (see [17])

$$\delta \leq 0,$$

(6)

where $\delta$ is the CP violating parameter in mixing. The Bell inequality (6) is experimentally testable!

Experimentally, $\delta$ corresponds to the leptonic asymmetry of kaon decays

$$\delta = \frac{\Gamma(K_L \to \pi^- l^+ \nu_l) - \Gamma(K_L \to \pi^+ l^- \bar{\nu}_l)}{\Gamma(K_L \to \pi^- l^+ \nu_l) + \Gamma(K_L \to \pi^+ l^- \bar{\nu}_l)},$$

(7)

which is measured to be $\delta = (3.27 \pm 0.12) \cdot 10^{-3}$. This value is in clear contradiction to $\delta \leq 0$, the value required by the Bell inequalities! In this sense the violation of a symmetry in particle physics is surprisingly related to nonlocality.

Note also that if we interchange $\bar{K}^0$ with $K^0$ in inequality (5), we obtain $\delta \geq 0$. Thus both BIs induce that the premises of local realistic theories require $\delta = 0$ and hence that the CP symmetry is conserved.

Although the Bell inequality (5) is as loophole free as possible, however, the probabilities involved are not directly measurable, because it is experimentally impossible to distinguish between a short-lived state $|K_S\rangle$ and the CP plus state $|K^0_1\rangle$.

3.2. Variation in the detection times

Now let us assume that the detection times are varied and the quasispin is chosen in each case to be the antikaon state $\bar{K}^0$, thus the CHSH–Bell type inequality turns into

$$S_{\bar{K}^0, \bar{K}^0}(t_1, t_2, t_3, t_4) = \left| E_{\bar{K}^0, \bar{K}^0}(t_1, t_2) - E_{\bar{K}^0, \bar{K}^0}(t_1, t_3) \right| + \left| E_{\bar{K}^0, \bar{K}^0}(t_4, t_2) + E_{\bar{K}^0, \bar{K}^0}(t_4, t_3) \right| \leq 2$$

(8)
Starting from the initial antisymmetric maximally entangled Bell state (1) there can be found no violation for any choice of the four times!

To get an intuition why this is the case we can consider the ratio of the oscillation to decay given by \( x = \frac{\Delta m}{\Gamma} \approx 2 \frac{\Delta m}{\Gamma} \approx 1 \). If Nature provided the neutral kaon system with a ratio that would have been greater than 2, the above Bell inequality would have been violated (see also H.19). Differently stated the system oscillates too slow compared to the decay or vice versa.

Of course any Bell test in an experiment requires a detailed study of loopholes. For meson–antimeson systems there are two main drawbacks for any study of Bell inequalities which are not loopholes (see [11]). The main message is that the above expectation values are appropriate for a Bell test in a real experiment, e.g. at DAΦNE machine in Frascati. Therefore let us investigate the situation again: Is there really no way to violated the above Bell inequality?

Developing the general formalism one learns that decay is a “kind of decoherence” [12]. One knows from decoherence studies that some states are more robust against the interaction with the environment, i.e. decoherence, than others. This obviously rises the question if we can find an initial state which is more robust against the “decoherence” caused by the decay property and thus would enable us to violate the Bell inequality.

The surprising result was indeed YES [13]! Indeed, a non–maximally entangled state violates the Bell inequality maximal. Summing up we conclude that there exist states which do violate the Bell inequality, however, until now there have not yet been found a way to produce that states in experiments. Therefore it is still open if Einsteins’ spooky action at distant can be experimentally shown for neutral kaons.

4. More quantum features of the neutral kaon system

The massive meson-antimeson systems turn out to be also suitable to test other quantum features (for an overview see for instance [19]). Let us just pick up two topics: the quantum eraser concepts and decoherence.

Kaons are also suitable systems to exhibit the amazing features of a quantum marking and eraser concepts: “Erasing the Past and Impacting the Future” as Y. Aharanov and M.S. Zubairy phrased it in their review article where they also discussed the proposed neutral kaon eraser or shortly named the kaonic eraser [20–22]. Moreover, it turned out that there are setups which are conceptually different for other two–level system where the eraser concepts are usually tested. This means that these system in high energy physics offers the possibility to prove novel eraser concepts and therewith the very nature of a quantum eraser experiment can be nicely illustrated: it essentially sorts different events according to available information. Kaon experiments verifying the proposed quantum marking and eraser procedures have not been performed till this day. Only the CPLEAR collaboration [23] did part of the job required for the first setup of the active eraser with active measurements. However, at the upgraded detector KLOE 2 kaonic eraser experiments could be performed.

One key idea —besides entanglement— is that single kaons evolving in time are “kind of double slits” [24]. Bohr’s complementarity principle was phrased in an attempt to express the most fundamental difference between classical and quantum physics. In ref. [25] it was shown that the \( CP \) violation shifts “particle like” information to “wave like” information. Neutral kaons encapsulate indeed this peculiar feature in the very same way as a particle traveling through a double slit. But kaons are double slits provided by Nature for free!

Another approach to study quantum features in high energy physics is via decoherence models. This approach enables us to confront very basic mathematical and theoretical concepts directly with experiments. For a certain model an upper bound on the strength of a decoherence parameter \( \lambda \) —describing the interaction of the system with the environment— can be found via comparison with experimental data [26]. One can also relate \( \lambda \) to an effective decoherence parameter \( \zeta \) [27], better suited for experimental investigations. Remarkably, for the model under
investigation it turns out that the amount of decoherence is very simply connected to measures of entanglement, i.e. the von Neumann entropy, the loss of entanglement of formation \(1 - E\) and the loss of concurrence \(1 - C\). For the entangled K–meson pairs produced at the accelerator DAΦNE (Frascati, Rome) the KLOE collaboration published newly improved bounds on the parameter \(\zeta, \lambda\) [28]. There exists also certain quantum gravity models [29, 30] which lead to decoherence which can be tested at DAΦNE.

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