Quantum mechanical entanglement and tests of CPT theorem with neutral mesons at e^+e^- colliders

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The BELLE experiment at the KEK-B asymmetric B factory, which collides electrons and positrons, had announced its discovery of the phenomenon of quantum entanglement earlier this year in the neutral B-meson system. In addition to a press release which is posted on the website of the collaboration, a paper has now been submitted to *Physical Review Letters* describing the discovery[1]. The KLOE Collaboration at the ϕ factory DAFNE, which also collides electrons and positrons, has also recently demonstrated the phenomenon in the neutral *K*-meson system[2]. In addition, the KLOE Collaboration also has placed bounds on an effective parameter for possible 'CPT violation'. We review these discoveries here.

The discovery of quantum entanglement in these systems addresses some of the issues raised in a path-breaking paper several decades ago by Einstein Podolsky and Rosen[3]. The phenomenon is due to correlations between sub-systems of a larger quantum system, and is intrinsically quantum mechanical and cannot be described in terms of 'local realistic' properties. Hence, even if spatially separated, the subsystems continue to be correlated. (Of related interest is the work of Bell[4] who proposed an inequality which would be satisfied by any 'hidden variable' model respecting locality. Quantum mechanics, however, violates this inequality. In meson systems, thus far it has not been possible to test such an inequality.) Quantum entanglement was first demonstrated in experiments involving photons. Subsequently, the effects were demonstrated in neutral *K*-meson systems in proton–anti-proton collisions at the CPLEAR in the CERN Low Energy Anti-proton Ring. Here we discuss the CPLEAR experiment in order to contrast their findings with those of KLOE. For a review of the experiments and theory with photons and neutral K-mesons at CPLEAR, see Gisin and Go[5].

The CPT theorem, a consequence of the special theory of relativity when applied to elementary particle physics, implies the invariance of physical laws under the combined action of the three discrete symmetries, where C is the charge conjugation, P the parity and T the time reversal; symmetry under particle–anti-particle interchange, symmetry under mirror-reflection and under time reversal respectively. Its consequences include the equality of particle and anti-particle masses and that of the lifetime of a particle and its anti-particle, and have been extensively tested and documented widely in the literature. Thus, the new tests of the CPT theorem by the KLOE Collaboration are of a fundamental nature.

In order to discuss these experiments, we recall some elementary facts required for the discussion. Mesons are examples of strongly interacting matter consisting of a quark and anti-quark pair. Three quarks can come together to form another kind of strongly interacting matter known as baryons, of which the proton and neutron are well-known examples, and mesons and baryons together are known as hadrons. Quarks are known to come in six flavours, namely *u*, *d*, *s*, *c*, *b*, and *t*, in order of increasing mass. Note that the B^0 meson is composed of a $d\bar{b}$ pair, and the $\bar{B}^0$ meson is composed of a $b\bar{d}$ pair, while the *K*-mesons may be obtained by replacing the *b* by the *s* quark in the above. Heavier quarks decay through the weak interactions into a lighter quark and other weakly interacting particles, e.g. electron and its anti-neutrino. In other words, the weak interactions lead to transitions like $s \to u$; $b \to c$; $b \to u$; $c \to s$; $c \to d$; $t \to b$; $t \to s$ and $t \to d$. As a result, the heavy quark in the meson can decay into a lepton pair and a lighter quark, which then binds with the residual quark to produce a lighter meson. However, this is not the end of the story: the weak interactions which can cause the change of flavour, can also lead to violation of 'flavour quantum number' by two units, thereby leading to the oscillation of a neutral meson into its corresponding neutral anti-meson. The systems at hand are those in which the constituents are unstable and which oscillate back and forth.

Turning now to the BELLE experiment, the results from there are based on a large sample of about 152 million $B^0\bar{B}^0$ mesons, at a centre of mass energy that corresponds to the mass of a 'resonance', i.e. a significant bump in the production cross-section, known as the $\Upsilon(4S)$. Its mass is 10.58 GeV/c^2, and is produced in the collisions of electrons and positrons with beam energies of 3.5 and 8.0 GeV respectively, at the 'asymmetric' B-factory ('asymmetry' here refers to the unequal beam energies; such colliders have certain design advantages over symmetric colliders for the study of B-mesons). The $\Upsilon(4S)$ has the quantum numbers $J^{PC} = 1^{--}$, where *J* is the angular momentum in units of $\hbar \equiv h/(2\pi)$, where *h* is the Planck's constant, and P and C stand for parity and charge-conjugation quantum numbers (from our prior discussion it may be readily inferred that the operations C, P are such that $C^2 = P^2 = 1$, and hence the eigenvalues of these operators can only be +, –). This resonance is a bound state of a *b* and an anti-*b* quark, which subsequently decays into the desired pair, with the excess binding energy turning into a *d* and anti-*d* quark pair, resulting in the formation of the two mesons of interest. When the $\Upsilon(4S)$ decays into neutral B-mesons, the corresponding wavefunction in quantum mechanics for the pair is fixed (and is anti-symmetric under the exchange of the two mesons, the anti-symmetry dictated by the quantum numbers of the $\Upsilon(4S)$), and is said to remain 'entangled' until one of them decays. Therefore, by studying the 'non-local' correlations between the decay products, one tests the quantum mechanical entanglement of these mesons.

The strategy of the BELLE experiment is to demonstrate the phenomenon of quantum entanglement in this system by observing the 'asymmetry' in the signs from the decay of the two B-mesons that are born out of the $\Upsilon(4S)$, keeping in mind that in addition to the decay, the oscillation phenomenon also takes place. As a result, from the decay products, one reconstructs the events as having arisen from $B^0\bar{B}^0$, B^0B^0 and $\bar{B}^0\bar{B}^0$. The first of these is called opposite-flavour (OF), and the other two together are known as same-flavour (SF) events. The flavour of, for example the B^0 is detected from the charge of the lepton in a decay chain whose first step is $B^0 \rightarrow D^{*-} \bar{l}^{+} \nu_l$, while the corresponding decay of the anti-meson would have a lepton of the opposite charge. Quantum mechanics would say that if the two mesons decayed simultaneously, then they would necessarily have to have been of opposite flavours, and one would have detected only $B^0 \bar{B}^0$. Using these as inputs, the BELLE Collaboration measures the asymmetry defined by $(R_{\mathrm{OF}} - R_{\mathrm{SF}})/(R_{\mathrm{OF}} + R_{\mathrm{SF}})$, where R_i, i = OF, SF stands for the rate of the decay of the meson pair into the desired channels.

In order to have a meaningful comparison with models that provide predictions different from that of quantum mechanics, the BELLE Collaboration considers those of two popular scenarios. The first is known as the spontaneous disentanglement (SD) model, and the second is a version of a 'locally realistic theory' tailored for the B-meson system due to Pompili and Selleri (PS). In Figure 1 the expected asymmetries for each of these are shown. Data of the BELLE experiment are analysed in terms of bins in the variable Δt, with bins of width 0.5 ps between 0 and 2 ps, 1 ps between 2 and 7 ps and bins of widths 2, 4 and 7 ps, between 7 and 9, 9 and 13 and 13 and 20 ps respectively. The asymmetries are measured in these bins and tabulated by the BELLE Collaboration. They are compared with the predictions for the asymmetries from each of the models of interest. The results are displayed in Figure 2. The top part of Figure 2 shows the contrast between data the predictions of the theory, while the lower part shows data with the shaded boxes giving the predictions of each of the models for the asymmetries. In order to obtain the predictions of each model, the parameter Δm_d, the mass difference between those of the two neutral B-meson mass eigenstates is fitted to the data and is determined for each of the models. The height of the shaded boxes is determined by the standard deviation to the resulting fits. The reader is referred to the paper of BELLE[1] for details of the analysis. It may be readily seen from the upper part of each of the three panels that the results of QM are most consistent with zero. The final results of the analysis is that their data prefer QM over SD model at 13σ and over PS at 5.1σ.

Quantum entanglement has also been seen in a meson system involving K-mesons. This was first seen in proton–antiproton collisions by the CPLEAR Collaboration[6]. The physics of the phenomenon observed by CPLEAR with K-mesons is analogous to that observed by BELLE with B-mesons. While BELLE tagged the flavour of the decaying mesons through the decay products, CPLEAR did so through the products of their interactions with the nuclei in the absorbers that are intrinsic components of their detectors. CPLEAR also measured the time asymmetry between SF and OF events. Some limitations in this experiment are due to the kaon pair not necessarily being produced in the 1^{--} configuration, since there is also the contribution to the desired final state from what are known as 0^{++} and 2^{++}. These latter contributions do not necessarily imply that in simultaneous decays of the mesons, the probability for producing like strangeness is 0. Despite the limitations imposed by this, the quantum mechanical entanglement was clearly demonstrated.

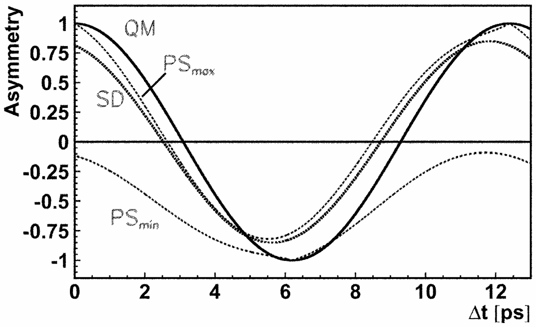

Figure 1. Time-dependent asymmetry as a function of Δt, the time interval between the two observed decays predicted by quantum mechanics (QM), and spontaneous and immediate disentanglement of the meson pair (SD) and the range of asymmetries allowed by the Pompili-Selleri (PS) model ($\mathrm{PS_{min}}$ to $\mathrm{PS_{max}}$). For SD an integration over $t_1 + t_2$, the individual decay times is carried out (for details see Go *et al.*[1]).

More recently, kaon systems at the e^+e^- collider DAFNE have also been used to demonstrate quantum entanglement. Here the beams are symmetric in energy and have a centre of mass energy of $\sqrt{s}$ = 1.02 GeV. In this experiment the principle that is used is somewhat different, in that strangeness tagging is not what is used, but other properties of this neutral meson complex are. Due to the phenomenon of oscillation, the two kaons that are produced propagate as certain well-defined linear combinations known as K_S and K_L, while moving away from the point of production. If the first decay is associated with the production of a $\pi^+\pi^-$ pair, then at that instant, the other meson cannot decay into the same pair (up to corrections due to CP violation which is neglected for the purposes of this effect). However, if the second decay takes place after a time Δt, quantum mechanical interference leads to the possibility of such a decay. This is what has been measured by the KLOE Collaboration to demonstrate the interference effect[2], with a data sample of about 50,000 neutral kaon pairs.

In addition, the KLOE experiment has also been able to test the CPT theorem in novel ways. In particular, it places bounds on a parameter known as ω, which effectively parametrizes CPT violation in a model-independent manner, and may have its origins in exotic theories or in theories of quantum gravitation[7,8]. This parameter arises in such theories as a result of pure states getting mixed due to space–time fluctuations at the Planck scale. This then shows up in the intensity distribution function for the decays of the two mesons. The KLOE Collaboration gives for this parameter Re $\omega = (1.1^{+8.7}_{-5.3} \pm 0.9) \times 10^{-4}$ and Im $\omega = (3.4^{+4.8}_{-5.0} \pm 0.6) \times 10^{-4}$, which is consistent with 0. This is the first experimental constraint on this parameter.

In the past, another CPT violating parameter δ was also studied by the CPLEAR Collaboration[9]. δ parametrizes the violation of CPT invariance in terms of the difference between the diagonal elements of the matrix that governs the time evolution of the $K^0 \bar{K}^0$ complex. The values for Reδ and Imδ from CPLEAR which is consistent with 0 read $(2.4 \pm 2.8) \times 10^{-4}$ and $(2.4 \pm 5) \times 10^{-5}$ respectively. The imaginary part of the parameter has also been

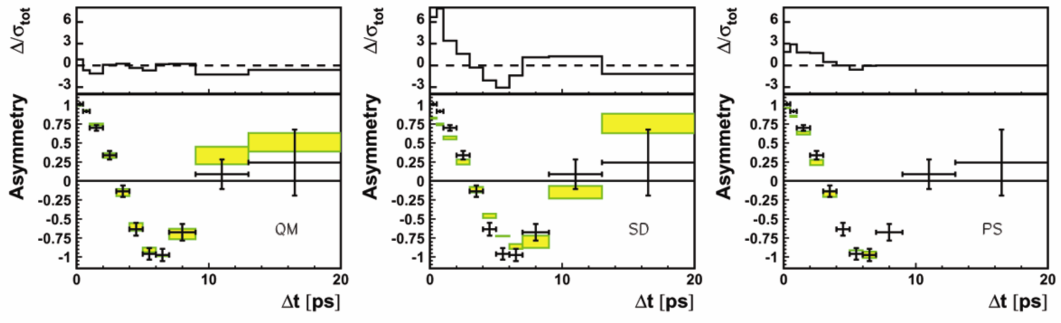

Figure 2. (Bottom) Time-dependent flavour asymmetry (crosses) and the results of weighted least-squares fits to the (left to right) QM, SD, and PS models (rectangles, showing $\pm 1\sigma$ errors on Δm_d). (Top) Differences $\Delta \equiv A_{\rm data} - A_{\rm model}$ in each bin, divided by the total experimental error $\sigma_{\rm tot}$. Bins where $A_{\rm PS}^{\rm min} < A_{\rm data} < A_{\rm PS}^{\rm max}$ have been assigned a null deviation (for details see Go *et al.*[1]).

recently constrained better by the KLOE Collaboration[10] and reads $(0.4 \pm 2.1) \times 10^{-5}$.

In summary, we have reviewed the recent discoveries of quantum entanglement and interference phenomena at electron–positron colliders in the *B*- and *K*-meson systems. No evidence has been found for CPT violation at these experiments.

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