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## EPR in B physics and elsewhere

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**Abstract.** The application of Einstein-Podolsky-Rosen correlations in  $\Upsilon(4s) \rightarrow B\bar{B}$  decays to research in CP violation is the first and probably only use of EPR as a technique for research in new physics. Elsewhere highly sophisticated EPR projects *question* EPR and test its predictions to look for violations of quantum mechanics, hidden variables, Bell's inequalities, etc.

In 1995 an international conference was held celebrating 60 years of EPR [1]. Nathan Rosen (the R of EPR) was still active and told us about Einstein's view of EPR. My paper on applications to kaon and B physics ( $\phi$  and B factories) [2] was the only talk on the program suggesting that EPR might be *useful*. All the others were on tests of quantum mechanics and included very beautiful photon interferometry experiments using the latest solid state technology to split a photon in a crystal into two photons with different energies and show that the split photons with only a piece of the original energy still exhibited the EPR correlations.

- Elsewhere: EPR was questioned and used to check Quantum Mechanics
  - Hidden Variables, Bell's Inequality and Bohmian QM
  - Sophisticated photon interferometry experiments confirm QM.
- B physics: EPR not only accepted but also crucial for BaBar.
  - Lepton asymmetry observed in decay of one B of pair from  $\Upsilon(4S)$  "entangled" with  $\psi K_S$  decay observed from other B.

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### The problem of Entangled Wave functions

$$\Psi_{(S=0)} = |-\vec{k}(\uparrow); \vec{k}(\downarrow)\rangle - |-\vec{k}(\downarrow); \vec{k}(\uparrow)\rangle = |-\vec{k}(\leftarrow); \vec{k}(\rightarrow)\rangle - |-\vec{k}(\rightarrow); \vec{k}(\leftarrow)\rangle$$

Triggering on events with (Spin  $\uparrow$ ) and momentum  $-\vec{k}$  creates a polarized (Spin  $\downarrow$ ) beam with momentum  $\vec{k}$

But triggering on events with (Spin  $\leftarrow$ ) and momentum  $-\vec{k}$  creates a polarized (Spin  $\rightarrow$ ) beam with momentum  $\vec{k}$

- **Elsewhere:** How is this possible? How can the particle with momentum  $\vec{k}$  know what is measured at momentum  $-\vec{k}$ ? Something must be wrong with Quantum Mechanics!
- **B physics:** Great! We can make polarized beams with momentum  $\vec{k}$  and arbitrary polarizations by choosing the right triggers with momentum  $-\vec{k}$ !

### EPR and Entangled Wave functions in B physics at $\Upsilon(4S)$ [3]

Define  $B^L$  and  $B^H$  as the linear combinations of  $B^0$  and  $\bar{B}^0$  that are mass eigenstates.

Both  $B^0$  and  $\bar{B}^0$  decay into  $\psi K_S$ .

Define  $B^1$  and  $B^2$  as just those particular linear combinations of  $B^0$  and  $\bar{B}^0$  such that  $B^1 \rightarrow \psi K_S$ , but  $B^2$  does not decay to  $\psi K_S$ ; i.e. the  $B^0$  and  $\bar{B}^0$  contributions to  $B^2 \rightarrow \psi K_S$  exactly cancel one another.

$$\Upsilon(4S) \rightarrow |B_{-\vec{k}}^0; \bar{B}_{\vec{k}}^0\rangle - |\bar{B}_{-\vec{k}}^0; B_{\vec{k}}^0\rangle = |B_{-\vec{k}}^H; B_{\vec{k}}^L\rangle - |B_{-\vec{k}}^L; B_{\vec{k}}^H\rangle = |B_{-\vec{k}}^1; B_{\vec{k}}^2\rangle - |B_{-\vec{k}}^2; B_{\vec{k}}^1\rangle$$

Triggering on events with  $B^0$  decay observed with momentum  $-\vec{k}$  creates a  $\bar{B}^0$  beam with momentum  $\vec{k}$

Triggering on events with  $B^H$  observed with momentum  $-\vec{k}$  creates a  $B^L$  beam with momentum  $\vec{k}$

Triggering on events with  $B \rightarrow \psi K_S$  decay observed with momentum  $-\vec{k}$  creates a  $B^2$  beam with momentum  $\vec{k}$

If CP is conserved,  $B^1$  and  $B^2$  are both mass eigenstates. Then  $B^2$  decays have no time dependence; no lepton asymmetry.

If CP is violated,  $B^1$  and  $B^2$  are not mass eigenstates. Time dependent lepton asymmetry oscillations can then be observed in  $B^2$  decays.

### "B Spin" and CP violation for Pedestrians [4]

Define "B spin" eigenstates in which  $B^0$  and  $\bar{B}^0$  are states of spin-up and spin down in the z-direction of a fictitious B-spin space, the mass eigenstates  $B^H$  and  $B^L$  are up and down in the x-direction, and the state  $B^1 \rightarrow \psi K_S$  has its B spin at some angle in the xy plane with respect to the x axis. The angle is zero if CP is conserved and is simply related to one of the angles of the unitarity triangle in the standard model when CP is violated. The states  $B^1$  and  $B^2$  precess around the x-axis with a frequency given by the  $B^H - B^L$  mass difference. All experiments are simply described as measurements of polarizations and polarization correlations in this B spin space.

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