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Hardy's tests of LR with neutral kaons from phi decays

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HISTORY

1925: Quantum Mechanics

1935: Schroedinger, `entangled states´

1935: EPR argument, is QM complete?

1964: Bell's theorem and inequalities. LR vs QM.

1982: Aspect's experiment on Bell inequalities

1992: Hardy's version (PRL 68, 2981)

2006: General view: QM is confirmed, LR is refuted.

but... # LOOPHOLES

LOCALITY LOOPHOLE.

Spacelike separation of left-right measurement events.

Closed by G. Weihs et al., PRL 81, 5039 (1998) and
by W. Tittel et al., Phys Rev A59, 4150 (1999).

EFFICIENCY LOOPHOLE.

Low efficiency of photon detectors allows for LR explanations.

Closed by M. A. Rowe et al., Nature 409, 791 (2001)

Neutral kaons can contribute to close both loopholes simultaneously:

Kaons travel at relativistic velocities, around 0.22c @ Daphne, and
kaons and their decay products are detected via strong interactions.

Entanglement in meson pairs: CPLEAR, Phys. Lett. B422 (1998) 339; A. Di Domenico, hep-ex/0312032;
for B-mesons, A. Go, J. Mod. Opt. 51 (2004) 991.

On a neutral kaon you either measure strangeness or lifetime.

Strangeness measurements at T.

Place a thin and dense piece of (nucleonic) matter at T

$$K^0 p \rightarrow K^+ n, \ldots \qquad K^0\text{-projection}$$

$$\bar{K}^0 p \rightarrow \pi^+ \Lambda,\ \pi^0 \Sigma^+, \ldots \quad \bar{K}^0\text{-projection}$$

If nothing seen ... efficiency problem

Lifetime measurements.

Remove matter and detect decay vertices

Quite efficient K_S vs K_L detection and identification

QM rules + state vector + experimental setup

→ Probabilities for the various measurement outcomes are correctly PREDICTED

LR + alternative experimental setups on same system

→ Probabilities for the different outcomes in alternative setups are RELATED

Hardy's argument/ contradiction

LEFT		RIGHT
Strangeness K^0	sometimes	Strangeness $\bar{K}^0$
Strangeness K^0	always $\longrightarrow$	Lifetime K_S
Lifetime K_S	$\longleftarrow$ always	Strangeness $\bar{K}^0$
Lifetime K_S	LR: sometimes $P_{\mathrm{LR}}(K_S,\ K_S) \geq P_{\mathrm{LR}}(K^0, \bar{K}^0) > 0$	Lifetime K_S

However in QM we can have: $P_{\mathrm{QM}}(K_S,\ K_S) = 0$

State preparation

A. B. and G. Garbarino (2002), PRL 88 040403; PRL 89 160401

Phi-decay state:

$$\Phi(0) = \frac{1}{\sqrt{2}}\left[K^0\bar{K}^0 - \bar{K}^0K^0\right] \simeq \frac{1}{\sqrt{2}}\left[K_SK_L - K_LK_S\right]$$

Just after a thin regenerator close to O

$$\Phi(\Delta t << \tau_S) \simeq \frac{1}{\sqrt{2}}\left[K_SK_L - K_LK_S + rK_SK_S - rK_LK_L\right]$$

A. Di Domenico, Nucl. Phys. B450 (1995) 293

$$r \equiv i\frac{\pi\nu}{m_K}(f-\bar{f})\Delta t = i\frac{\pi\nu}{p_K}(f-\bar{f})d$$

Free propagation up to $T \quad (\tau_S << T << \tau_L \simeq 579\tau_S)$

$$\Phi(T) \simeq \frac{N(T)}{\sqrt{2}}\left[K_SK_L - K_LK_S - re^{-i\Delta mT}e^{\frac{1}{2}(\Gamma_S-\Gamma_L)T}K_LK_L + re^{i\Delta mT}e^{\frac{1}{2}(\Gamma_L-\Gamma_S)T}K_SK_S\right]$$

$$|K_{S,L}(\tau)\rangle = e^{-im_{S,L}\tau}e^{-\frac{1}{2}\Gamma_{S,L}\tau}|K_{S,L}\rangle$$

$$\Phi = \frac{1}{\sqrt{2+|R|^2}} \left[K_S K_L - K_L K_S + R\, K_L K_L \right]$$

$$\Phi = \frac{1}{\sqrt{2(2+|R|^2)}} \left[-K^0 K_S + \bar{K}^0 K_S + (1+R)\, K^0 K_L + (1-R)\, \bar{K}^0 K_L \right]$$

$$\Phi = \frac{1}{\sqrt{2(2+|R|^2)}} \left[K_S K^0 - K_S \bar{K}^0 - (1-R)\, K_L K^0 - (1+R)\, K_L \bar{K}^0 \right]$$

$$\Phi = \frac{1}{2\sqrt{2+|R|^2}} \left[R\, K^0 K^0 + R\, \bar{K}^0 \bar{K}^0 + (2-R)\, \bar{K}^0 K^0 - (2+R)\, K^0 \bar{K}^0 \right]$$

$$R \equiv -r e^{-i\Delta m T} e^{\frac{1}{2}(\Gamma_S - \Gamma_L)T}$$

Hardy's test: choose $(R + 1) = 0$

$$P_{\mathrm{QM,LR}}(K^0, \bar{K}^0) = \frac{1}{12}$$

$$P_{\mathrm{QM,LR}}(K^0, K_L) = 0$$

$$P_{\mathrm{QM,LR}}(K_L, \bar{K}^0) = 0$$

$$P_{\mathrm{QM}}(K_S, K_S) = 0 \quad \Leftrightarrow \quad P_{\mathrm{LR}}(K_S, K_S) \geq P_{\mathrm{LR}}(K^0, \bar{K}^0) = \frac{1}{12}$$

Ideal case: ``all-versus-nothing´´ Hardy's test

$$P_{\mathrm{QM,LR}}(K_S, K_S) = 0$$

$$P_{\mathrm{QM,LR}}(K^0, K_L) = 0$$

$$P_{\mathrm{QM,LR}}(K_L, \bar{K}^0) = 0$$

$$P_{\mathrm{QM}}(K^0, \bar{K}^0) = \frac{1}{12} \Leftrightarrow 0 = P_{\mathrm{LR}}(K^0, \bar{K}^0) \leq P_{\mathrm{LR}}(K_S, K_S)$$

Ideal case: ``all-versus-nothing´´ Hardy's test

HIC SUNT LEONES

See M. Genovese, Phys. Rev. A69 (2004) 022103;
A. B., R. Escribano and G. Garbarino, Found. Phys. (2006).

$$P_{\mathrm{QM}}(K^0, \bar{K}^0) = \frac{\eta\bar{\eta}}{12}$$

$$P_{\mathrm{QM}}(K^0, K_L) = 6.77 \times 10^{-4} \eta\, \eta_\tau$$

$$P_{\mathrm{QM}}(K_L, \bar{K}^0) = 6.77 \times 10^{-4} \bar{\eta}\, \eta_\tau$$

$$P_{\mathrm{QM}}(K_S, K_S) = 1.19 \times 10^{-5} \eta_\tau^2$$

Eberhard's inequality

P. H. Eberhard, Phys. Rev. A47 (1993) R747

$$H_{\rm LR} \equiv \frac{P_{\rm LR}(K^0, \bar{K}^0)}{P_{\rm LR}(K^0, K_L) + P_{\rm LR}(K_S, K_S) + P_{\rm LR}(K_L, \bar{K}^0) + P(K^0, U_{\rm Lif}) + P(U_{\rm Lif}, \bar{K}^0)} \leq 1$$

$$P_{\rm QM}(K^0, U_{\rm Lif}) = \frac{1}{6}\eta\,(1-\eta_\tau)\,,\ P_{\rm QM}(U_{\rm Lif}, \bar{K}^0) = \frac{1}{6}\bar{\eta}\,(1-\eta_\tau)$$

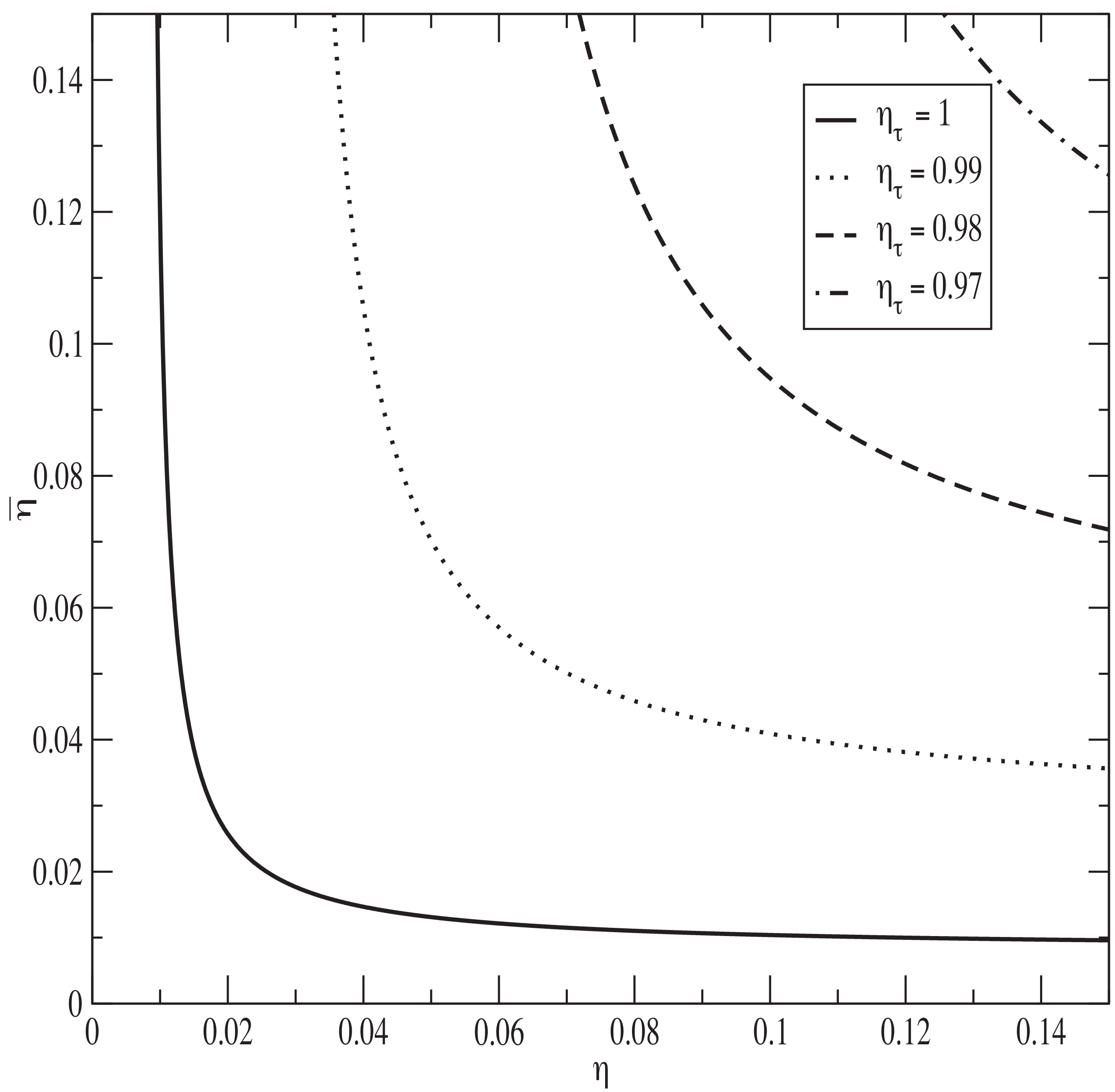
Clauser-Horne inhomogeneous ineq.

J. F. Clauser and M. A. Horne, Phys. Rev. D10 (1974) 526

$$Q_{\rm LR} \equiv \frac{P_{\rm LR}(K_S, \bar{K}^0) - P_{\rm LR}(K_S, K_S) + P_{\rm LR}(K^0, \bar{K}^0) + P_{\rm LR}(K^0, K_S)}{P_{\rm LR}(K^0, *) + P_{\rm LR}(*, \bar{K}^0)} \leq 1$$

$$P_{\rm LR}(K^0, *) = P_{\rm LR}(K^0, K_S) + P_{\rm LR}(K^0, K_L) + P_{\rm LR}(K^0, U_{\rm Lif})$$

$$P_{\rm LR}(*, \bar{K}^0) = P_{\rm LR}(K_L, \bar{K}^0) + P_{\rm LR}(K_S, \bar{K}^0) + P_{\rm LR}(U_{\rm Lif}, \bar{K}^0)$$



QM violates Bell inequalities for strangeness detection efficiencies above the curves.
Each curve refers to lifetime detection efficiency.

Correct identification of $K_S \; vs \; K_L$ $\Delta\tau = 4.8\,\tau_S$

$$p_S \equiv 1 - \exp\left(-4.8\right) = p_L \equiv \exp\left(-4.8/579\right) = 0.9918$$

Improve

$$p_S = 1 - BR(K_S \to \pi e \nu_e \text{ or } \pi\mu\nu_\mu) - BR(K_S \to \pi\pi)\exp(-5.82)$$

$$= BR(K_S \to \pi\pi)[1 - \exp(-5.82)] = 0.99594$$

$$p_L = 1 - BR(K_L \to \pi\pi)[1 - \exp(-5.82/579)] = 0.99997$$