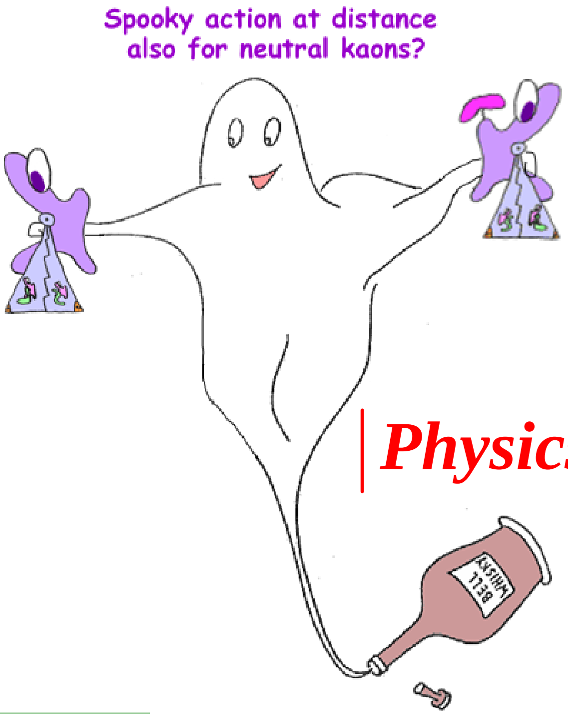
Nonlocality, Entanglement and Decoherence in High Energy Physics



by

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$$\left|Physics\right\rangle = \alpha \left|Particle\ Physics\right\rangle + \beta \left|Quantum\ Theory\right\rangle$$

experimental ↔ phenomenological ↔ conceptual ↔ mathematical aspects

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Testing QM in High Energy Physics

- **Part I: Bell inequalities 1:**

  A symmetry violation in particle physics related to nonlocality ?!

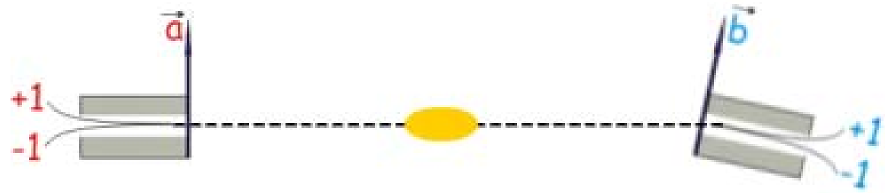
- **Part II: The quantum mechanics of neutral kaons *(Exercises)***

- **Part III: Bell inequalities 2/ How to describe the decay property?**

  "Erasing the Past and Impacting the Future" by Aharonov & Zubairy

- **Part IV: The Kaonic Quantum Eraser/ Decoherence & Measures of Entanglement or *Quantum Information* (Sets of entanglement measures of multipartite qudit systems)**

The EPR scenario



Antisymmetric Bell state:

$$\left|\psi^{-}\right\rangle = \tfrac{1}{\sqrt{2}}\left\{\left|\Uparrow\right\rangle_l \otimes \left|\Downarrow\right\rangle_r - \left|\Downarrow\right\rangle_l \otimes \left|\Uparrow\right\rangle_r\right\}$$ **... spin 1/2**

$$= \tfrac{1}{\sqrt{2}}\left\{\left|\mathbf{0}\right\rangle_l \otimes \left|\mathbf{1}\right\rangle_r - \left|\mathbf{1}\right\rangle_l \otimes \left|\mathbf{0}\right\rangle_r\right\}$$ **... qubit**

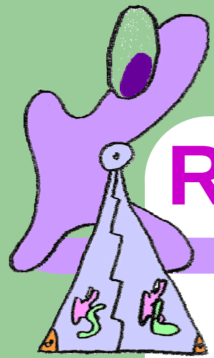
$$= \tfrac{1}{\sqrt{2}}\left\{\left|H\right\rangle_l \otimes \left|V\right\rangle_r - \left|V\right\rangle_l \otimes \left|H\right\rangle_r\right\}$$ **... photon**

$$= \tfrac{1}{\sqrt{2}}\left\{\left|K^0\right\rangle_l \otimes \left|\bar{K}^0\right\rangle_r - \left|\bar{K}^0\right\rangle_l \otimes \left|K^0\right\rangle_r\right\}$$ **... kaon**

$$= \tfrac{1}{\sqrt{2}}\left\{\left|B^0\right\rangle_l \otimes \left|\bar{B}^0\right\rangle_r - \left|\bar{B}^0\right\rangle_l \otimes \left|B^0\right\rangle_r\right\}$$ **... B-meson**

$$= \tfrac{1}{\sqrt{2}}\left\{\left|I\right\rangle_l \otimes \left|\Uparrow\right\rangle_r - \left|II\right\rangle_l \otimes \left|\Downarrow\right\rangle_r\right\}$$ **... single neutron in interferometer**

$$= \cdots$$



Requirements for tests LRT versus QM

Requirements for a *conclusive* proof of the existence of correlation stronger than those explainable by *locality* and *realism*:

(1) "*Active* " measurements (opening the possibility for Alice and Bob to choose among alternative setups-> free choice)

(2) "*Use all information*" (test the *whole* ensemble; decay product states are included→ this "additional" information should not be ignored)

→ are not "*only*" loopholes!

Generalized Bell inequality for kaons

local realistic theories ↓

$$S_{CHSH}(k_n,k_m,k_{n'},k_{m'};t_a,t_b,t_c,t_d)$$
$$=\left|E(k_n,t_a;k_m,t_b)-E(k_n,t_a;k_{m'},t_c)\right|+\left|E(k_{n'},t_d;k_m,t_b)+E(k_{n'},t_d;k_{m'},t_c)\right|\leq 2$$

$$|k_n\rangle=\alpha|K^0\rangle+\beta|\overline{K}^0\rangle......quasi-spin$$

- vary in times
- vary in quasi-spin

QM:

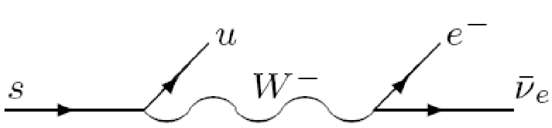
$$S^{Photon}=2\sqrt{2}=2.8$$

I. Vary in quasi-spin:

$$\delta=0$$

CP violation related to nonlocality!

Leptonic charge asymmetry:



$$\delta=\frac{\Gamma(K_L\to\pi^-l^+\nu_l)-\Gamma(K_L\to\pi^+l^-\overline{\nu_l})}{\Gamma(K_L\to\pi^-l^+\nu_l)+\Gamma(K_L\to\pi^+l^-\overline{\nu_l})}=(3.27\pm0.12)\cdot10^{-3}$$

Generalized Bell inequality for kaons

$$S_{CHSH}(\overline{K}^0,\overline{K}^0,\overline{K}^0,\overline{K}^0;t_a,t_b,t_c,t_d)$$
$$=\left|E(\overline{K}^0,t_a;\overline{K}^0,t_b)-E(\overline{K}^0,t_a;\overline{K}^0,t_c)\right|+\left|E(\overline{K}^0,t_d;\overline{K}^0,t_b)+E(\overline{K}^0,t_d;\overline{K}^0,t_c)\right|\leq 2$$

II: vary in times

$$|k_n\rangle=\alpha|K^0\rangle+\beta|\overline{K}^0\rangle\ldots\ldots quasi-spin$$

$$|\psi^-\rangle=\tfrac{1}{\sqrt{2}}\left\{|K^0\rangle_l\otimes|\overline{K}^0\rangle_r-|\overline{K}^0\rangle_l\otimes|K^0\rangle_r\right\}$$

$$S_{Photon}=2\sqrt{2}$$ Violation!

$$S_{Kaon}\left(\tfrac{3\pi}{4},\tfrac{3\pi}{4},\tfrac{\pi}{2},0\right)=1.36$$ NO violation!

Strangeness oscillation / decay:

$$x=\frac{\Delta m}{\Gamma}\approx\frac{2\Delta m}{\Gamma_S}\approx 1$$

PROPOSITION:

The CHSH-inequality is violated iff x>2 for kaons.

The dichotomic questions after evoluting to t>0?

Photons (or spin ½):

(1) Are you horizontal or vertical polarized?

(2) Are you horizontal polarized or not?

same!!

---

(1) Are you a meson K^0 or an antimeson $\bar{K}^0$ at time t?

additional information from the decay products ignored (only dichotomic if conditioned to the survival of both mesons)

(2) Are you a meson $\bar{K}^0$ or *not* at time t?

... is dichotomic

Unitary time evolution:

surviving component

decaying component

$$U(t,0)\left|K_{S/L}\right\rangle = \left|K_{S/L}(t)\right\rangle = e^{-im_{S/L}t-\frac{\Gamma_{S/L}}{2}t}\left|K_{S/L}\right\rangle + \left|\Omega_{S/L}(t)\right\rangle$$

$$H_{survive} \oplus H_{decay}$$

The BI sensitive to strangeness

(1) Are you a meson K^0 or an antimeson $\overline{K^0}$ at time t?

additional information from the decay products ignored (only dichotomic if conditioned to the survival of both mesons)

$$E^{non-unitary}(t_l;t_r) = P(K^0 t_l; K^0 t_r) + P(\overline{K}^0 t_l; \overline{K}^0 t_r) - P(K^0 t_l; \overline{K}^0 t_r) - P(\overline{K}^0 t_l; K^0 t_r) \cong$$

$$-\cos(\Delta m(t_l - t_r)) \cdot e^{-\frac{\Gamma_S + \Gamma_L}{2}(t_l + t_r)} \overset{\Gamma_L \ll \Gamma_S}{\cong} -\cos(\Delta m(t_l - t_r)) \cdot e^{-\frac{\Gamma_S}{2}(t_l + t_r)}$$

(2) Are you a meson $\overline{K^0}$ or *not* at time t?

$$E^{unitary}(\overline{K}^0, t_l; \overline{K}^0, t_r) = P(Y, t_l; Y, t_r) + P(N, t_l; N, t_r) - P(Y, t_l; N, t_r) - P(N, t_l; Y, t_r)$$

$$= -\cos(\Delta m(t_l - t_r)) \cdot e^{-\frac{\Gamma_S + \Gamma_L}{2}(t_l + t_r)}$$

$$+ \tfrac{1}{2}(1 - e^{-\Gamma_S t_l})(1 - e^{-\Gamma_L t_r}) + \tfrac{1}{2}(1 - e^{-\Gamma_L t_l})(1 - e^{-\Gamma_S t_r})$$

$$\overset{\Gamma_L \ll \Gamma_S}{\cong} -\cos(\Delta m(t_l - t_r)) \cdot e^{-\frac{\Gamma_S}{2}(t_l + t_r)}$$

The BI sensitive to strangeness

(1) Are you a meson K^0 or an antimeson $\bar{K}^0$ at time t?

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$$E^{non-unitary}(t_l;t_r) = -\cos(\Delta m(t_l - t_r)) \cdot e^{-\frac{\Gamma_S + \Gamma_L}{2}(t_l + t_r)} \overset{\Gamma_L \ll \Gamma_S}{\cong} -\cos(\Delta m(t_l - t_r)) \cdot e^{-\frac{\Gamma_S}{2}(t_l + t_r)}$$

$$\sum P = \cosh(\frac{\Gamma_L - \Gamma_S}{2}(t_l - t_r)) \neq 1$$

normalize

$$E^{non-unitary}_{normalized}(t_l;t_r) = \frac{-\cos(\Delta m(t_l - t_r))}{\cosh(\frac{\Gamma_L - \Gamma_S}{2}(t_l - t_r))}$$

violates *formaly* the BI!

Gisin, Go
Am.J.Phys. (2001)

• *strangeness oscillation* = birefringence of photons in asymmetric optical fibers

• *decay* = polarization dependent loss for photons

mayr

Th

(1) Are you

E^{nc}

$\sum P = \cosh(\frac{\Gamma_L - \Gamma_S}{2}(t_l -$ … $m(t_l - t_r))$

maly

PhysicsWeb - Mesons violate Bell's inequality - Microsoft Internet Explorer von Lycos Bertelsmann

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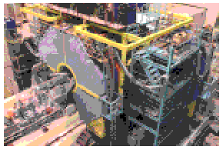
Mesons violate Bell's inequality

6 November 2003

The famous Bell's inequality of quantum mechanics has been tested in a high-energy particle physics experiment for the first time. The inequality was violated by three standard deviations in experiments with B mesons at the KEK laboratory in Japan - yet again confirming the predictions of quantum theory (arxiv.org/abs/quant-ph/0310192; *J. Mod. Optics* to be published). Previously most Bell's inequality experiments have been performed with photons or ions.

Experiments to test Bell's inequality involve measuring the properties of pairs of particles that are space-like separated in the sense of special relativity: in other words, there is no time for a light signal to travel between them within the duration of the experiment. In a typical Bell's inequality experiment the polarizations of a pair of photons are measured as the relative angle between the axes of polarizers making the measurements is varied.



Belle experiment

Quantum mechanics predicts that "non-local" correlations can exist between the particles. This means that if one photon is polarized in, say, the vertical direction, the other will always be polarized in the horizontal direction, no matter how far away it is. However, some physicists argue that this cannot be true and that quantum particles must have local values - known as "hidden variables" - that we cannot measure.

Bell and others showed that it was possible to distinguish between quantum mechanics and these hidden-variable theories in a certain type of experiment that measure a parameter known as S. Put simply, the local theories predict that S will always be less than two, whereas the quantum prediction is $S = 2\sqrt{2}$. When S is greater than two, Bell's inequality is said to be violated.

Apollo Go of the National Central University in Taiwan and co-workers in the Belle collaboration performed the experiment at the KEK B-factory. At this accelerator beams of electrons and positrons are collided to produce pairs of B mesons and their antiparticles, which then decay into lighter particles. The meson pairs behave like photon pairs, but instead of analyzing correlations between directions of polarization, the Belle team study particle-antiparticle correlations using a technique known as "flavour tagging". Go and colleagues calculated that S = 2.725, with error bars that mean that the inequality is violated by three standard deviations.

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B mesons decay in a new way

Author
Peter Rodgers

Internet

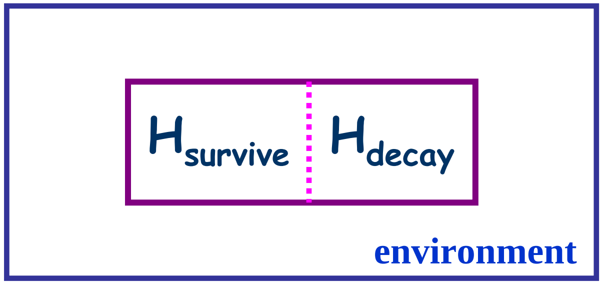
Decay is "kind of decoherence" ?

Kaon in time:

short-lived state — long-lived state

$$\left|K^0(t)\right\rangle \cong \frac{1}{\sqrt{2}}\left\{e^{-\frac{\Gamma_S}{2}t-im_S t}\left|K_S\right\rangle + e^{-\frac{\Gamma_L}{2}t-im_L t}\left|K_L\right\rangle\right\}$$

→ **state not normalized !!**



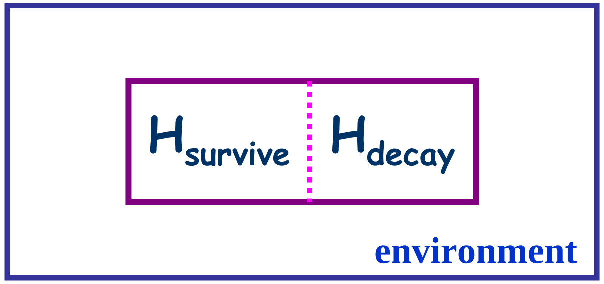
An open-quantum-system formulation of particle decay

(**Bertlmann, Grimus, Hiesmayr;** Phys. Rev. A 73, 054101 (2006))

Wigner-Weisskopf approximation is completely positive!

!! particle decay is ``kind of decoherence" !!

Decay is “kind of decoherence” ?



Liouville-von Neumann Eq.:

$$\frac{\partial \rho}{\partial t} = -i[H, \rho] - D[\rho]$$

Dissipation / Decoherence

$$D[\rho] = \tfrac{1}{2}\sum_i \lambda_i (A_i^t A_i \rho + \rho A_i^t A_i - 2 A_i \rho A_i^t)$$

1976: Lindblad; Gorini-Kossakowski-Sudarshan

single kaon described by 4x4 matrix:

$$\rho = \begin{pmatrix} \rho_{ss} & \rho_{sf} \\ \rho_{fs} & \rho_{ff} \end{pmatrix}$$

$\rho_{sf}, \rho_{fs} \rightarrow 0$

s … survive; f … final / decay

Open quantum formalism for single kaons

single kaon described by 4x4 matrix:

$$\rho = \begin{pmatrix} \rho_{ss} & \rho_{sf} \\ \rho_{fs} & \rho_{ff} \end{pmatrix} \qquad \rho_{sf},\ \rho_{fs} \rightarrow \mathbf{0}$$

$s \ldots survive;\ f \ldots final/decay$

$$\rho(t) = \begin{pmatrix} e^{-\Gamma_s t}\rho_{SS} & e^{-i\Delta m t - \Gamma t}\rho_{SL} & 0 & 0 \\ e^{i\Delta m t - \Gamma t}\rho_{LS} & e^{-\Gamma_L t}\rho_{LL} & 0 & 0 \\ 0 & 0 & (1-e^{-\Gamma_L t})\rho_{LL} & X \\ 0 & 0 & X^* & (1-e^{-\Gamma_s t})\rho_{SS} \end{pmatrix}$$

X...can be set to zero, because only on surviving component can be *actively* projected

Generalized Bell inequality for kaons

$$S_{CHSH}(\overline{K}^0,\overline{K}^0,\overline{K}^0,\overline{K}^0;t_a,t_b,t_c,t_d)$$
$$=\left|E(\overline{K}^0,t_a;\overline{K}^0,t_b)-E(\overline{K}^0,t_a;\overline{K}^0,t_c)\right|+\left|E(\overline{K}^0,t_d;\overline{K}^0,t_b)+E(\overline{K}^0,t_d;\overline{K}^0,t_c)\right|\leq 2$$

$$|k_n\rangle=\alpha|K^0\rangle+\beta|\overline{K}^0\rangle\ldots\ldots quasi-spin$$

II: vary in times

"Are you an antikaon or not at a certain time?"

$$S_{Photon}=2\sqrt{2}$$ Violation!

$$S_{Kaon}(\tfrac{3\pi}{4},\tfrac{3\pi}{4},\tfrac{\pi}{2},0)=1.36$$ NO violation!

Strangeness oscillation / decay:

$$x=\frac{\Delta m}{\Gamma}\approx\frac{2\,\Delta m}{\Gamma_S}\approx 1$$

PROPOSITION:

The CHSH-inequality is violated iff x>2 for kaons.

Bell inequality sensitive to strangeness violated?

$$S_{CHSH}(\overline{K}^0,\overline{K}^0,\overline{K}^0,\overline{K}^0;t_a,t_b,t_c,t_d)$$
$$=\left|E(\overline{K}^0,t_a;\overline{K}^0,t_b)-E(\overline{K}^0,t_a;\overline{K}^0,t_c)\right|+\left|E(\overline{K}^0,t_d;\overline{K}^0,t_b)+E(\overline{K}^0,t_d;\overline{K}^0,t_c)\right|\leq 2$$

Can we violate the BI for a certain initial state and what is the maximum value?

Arbitrary initial state:

$$|\psi\rangle = r_1 e^{i\varphi_1}|K_S K_S\rangle + r_2 e^{i\varphi_2}|K_S K_L\rangle + r_3 e^{i\varphi_3}|K_L K_S\rangle + r_4 e^{i\varphi_4}|K_L K_L\rangle$$

Expectation value:

$$\begin{aligned}
E_{\bar{K}^0,\bar{K}^0}(t_l,t_r) \;=\; & 1 + r_1^2\, e^{-\Gamma_S(t_l+t_r)} + r_2^2\, e^{-\Gamma_S t_l - \Gamma_L t_r} + r_3^2\, e^{-\Gamma_L t_l - \Gamma_S t_r} + r_4^2\, e^{-\Gamma_L(t_l+t_r)} \\
& - r_1^2\,(e^{-\Gamma_S t_l} + e^{-\Gamma_S t_r}) - r_2^2\,(e^{-\Gamma_S t_l} + e^{-\Gamma_L t_r}) - r_3^2\,(e^{-\Gamma_L t_l} + e^{-\Gamma_S t_r}) - r_4^2\,(e^{-\Gamma_L t_l} + e^{-\Gamma_L t_r}) \\
& + 2\, r_1 r_2\,(1 - e^{-\Gamma_S t_l}) \cos(\Delta m t_r + \phi_1 - \phi_2)\, e^{-\Gamma t_r} + 2\, r_1 r_3 \cos(\Delta m t_l + \phi_1 - \phi_3)\, e^{-\Gamma t_l}\,(1 - e^{-\Gamma_S t_r}) \\
& + 2\, r_2 r_4 \cos(\Delta m t_l + \phi_2 - \phi_4)\, e^{-\Gamma t_l}\,(1 - e^{-\Gamma_L t_r}) + 2\, r_3 r_4\,(1 - e^{-\Gamma_L t_l}) \cos(\Delta m t_r + \phi_3 - \phi_4)\, e^{-\Gamma t_r} \\
& + 2\, r_1 r_4 \cos(\Delta m (t_l + t_r) + \phi_1 - \phi_4)\, e^{-\Gamma(t_l+t_r)} + 2\, r_2 r_3 \cos(\Delta m (t_l - t_r) + \phi_2 - \phi_3)\, e^{-\Gamma(t_l+t_r)}\,.
\end{aligned}$$

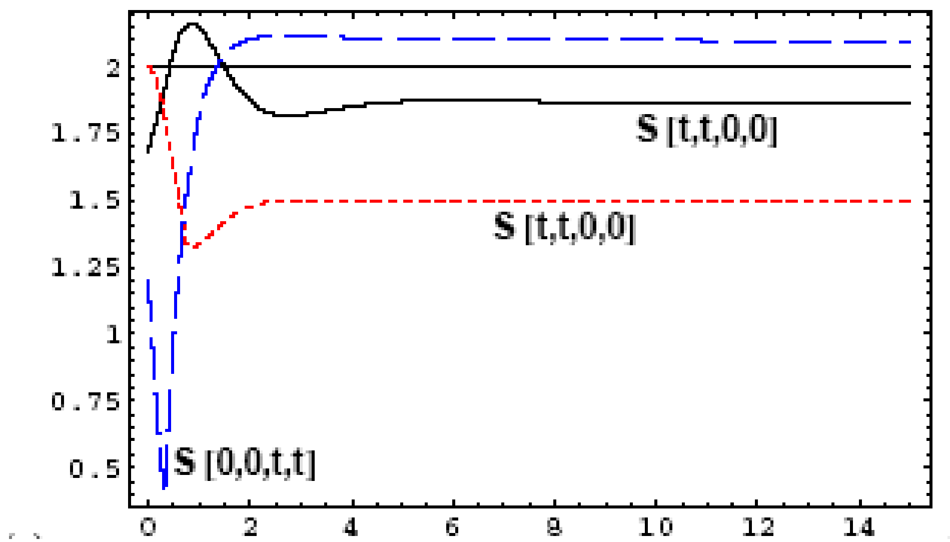
$$E^{photons}(\vec{a},\vec{b}) = 2 r_1 r_4 \sin 2(\varphi_a - \varphi_b) + 2 r_2 r_3 \cos 2(\varphi_a - \varphi_b)$$

Bell inequality sensitive to strangeness violated?

Can we violate the BI for a certain initial state and what is the maximum value?

Hiesmayr, European Journal C (2007) or quant-ph/0607210

!! YES !!



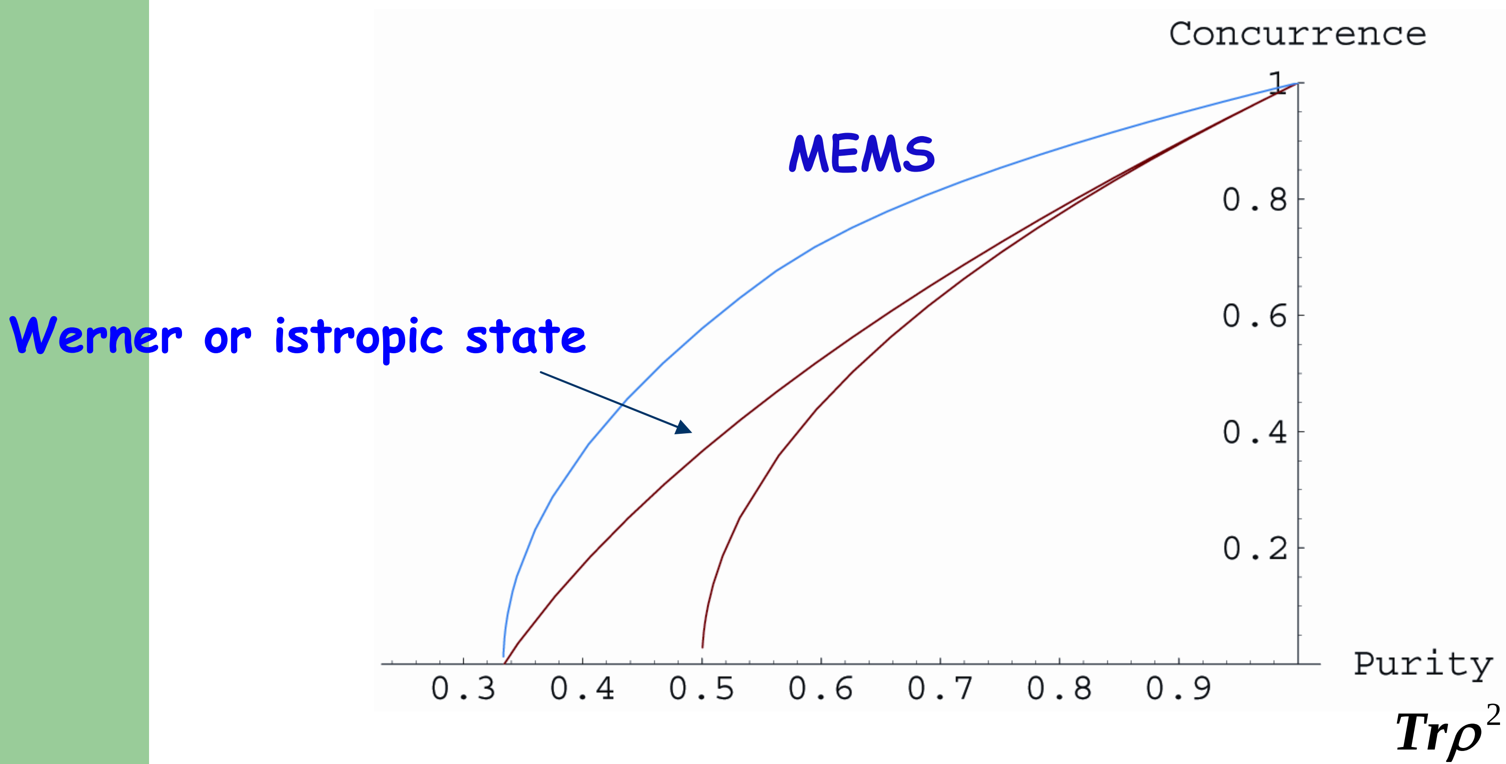
S=2.1596

χ: (r1=-0.7823; r2=r3=0.1460;r4=0.5877; Φ1=;...; t1=t2=1.79τ_S; t3=t4=0)

S=2.1175

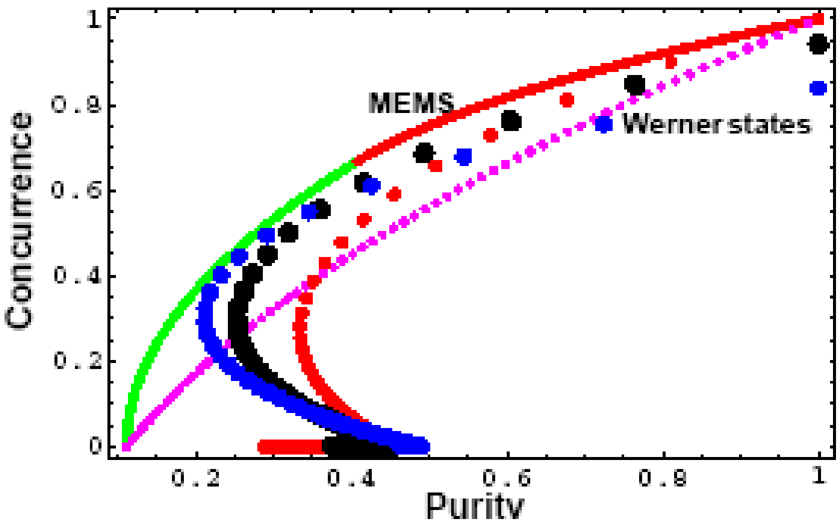
ξ: (r1=-0.8335; r2=r3=-0.2446; r4=0.4415; t1=t2=0; t3=t4=5.77τ_S)

Maximally entangled maximally mixed states MEMS

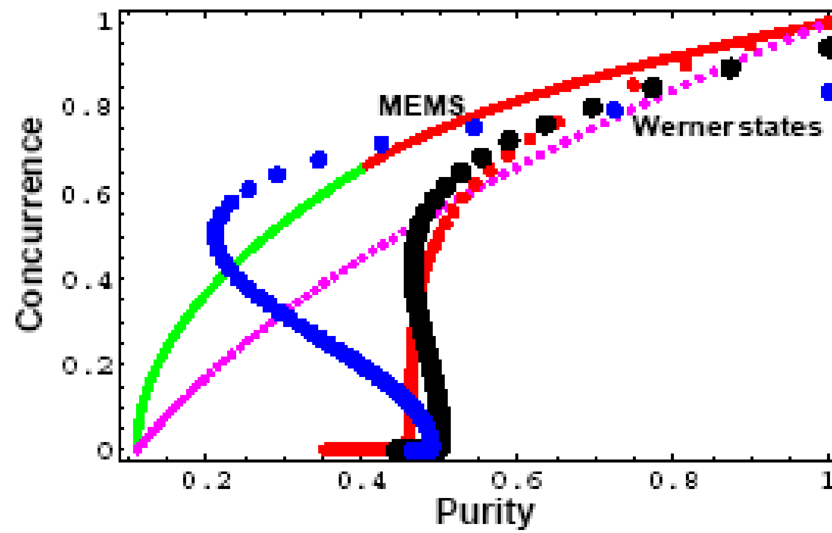


Entanglement—purity relation

$t_l = t_r = t$



$t_l = 0;\ t_r = t$



Normalized purity: $$\frac{d Tr \rho^2 - 1}{d - 1}$$

Entanglement of formation=Concurrence for kaons

The generalized BI for kaons

$$|k_n\rangle = \alpha |K^0\rangle + \beta |\overline{K}^0\rangle \ldots\ldots quasi-spin$$

valid for any LRT and QM

Expectation value:

$$E(k_n,t_a;k_m,t_b) = P_{n.m}(Y,t_a;Y,t_b) + P_{n.m}(N,t_a;N,t_b) - P_{n.m}(Y,t_a;N,t_b) - P_{n.m}(N,t_a;Y,t_b)$$
$$= -1 + 2\{P_{n.m}(Y,t_a;Y,t_b) + P_{n.m}(N,t_a;N,t_b)\}$$

Generalized CHSH-Bell inequality

$$S(k_n,k_m,k_{n'},k_{m'};t_a,t_b,t_c,t_d) =$$
$$|E(k_n,t_a;k_m,t_b) - E(k_n,t_a;k_{m'},t_c)| + |E(k_{n'},t_d;k_m,t_b) + E(k_{n'},t_d;k_{m'},t_c)| \leq 2$$

local realistic theories

- inequality sensitive to strangeness — S
- inequality sensitive to CP violation in mixing — δ
- inequality sensitive to CP violation in the decay amplitudes — ε'
- inequality sensitive to regeneration — $E[\tau,\delta\tau]$

Summary

- decay is a `kind of decoherence´
- Bell inequality sensitive to strangeness can be maximally violated for a non-maximally entangled state!

Nonlocality and entanglement are different quantum features!

Literature:

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- **B.C. Hiesmayr. *A generalized Bell inequality and decoherence for the K0 anti-K0 system*. Found. of Phys. Lett. 14, 231 (2001).**
- **Bertlmann, Hiesmayr, *Bell inequalities for entangled kaons and their unitary time evolution*, Phys. Rev. A 63, 062112 (2001)**
- **B.C. Hiesmayr, *Nonlocality and Entanglement in a strange system*, European Journal C 50, 73-79 (2007)**
- **Bertlmann, Bramon, Garbarino, Hiesmayr, *Violation of a BI in particle physics experimentally verified?*, Phys. Lett. A 332, 355 (2004)**