Test of quantum nonlocality via vector meson decays to $K_S K_S$

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based on work DOI: 10.1142/S0217751X21501785

November 5, 2021

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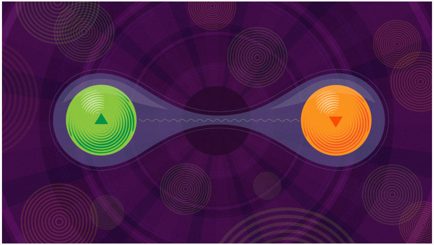
Introduction

Locality and quantum nonlocality

- In 1935, Einstein, Podolsky, and Rosen (EPR) posed the question of whether or not quantum mechanics offers a complete description of reality.
- They assumed the locality principle which states that interference effects should travel at the speed of light or slower between two objects.



The measurement of one particle in an entangled system has an instantaneous effect on the other

Why perform such tests in neutral kaons system

- the entanglement between K_S and K_L whose decay products are easy to distinguish
- the large statictics in charm (BESIII, CLEO-c), phi (KLOE), and B-meson (Belle-II, LHCb) factories with decay channel $V \to K^0\bar{K}^0$

Hidden-variable theory and Bell inequality

Bell Inequality

Original form:

$$|C_h(a,b) - C_h(a,c)| \leq 1 + C_h(b,c)$$

CHSH form:

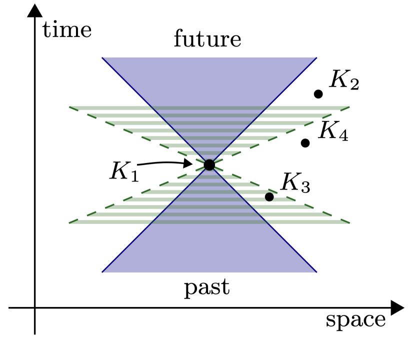
$$C_h(a,b) - C_h(a,b') + C_h(a',b) + C_h(a',b') \leq 2$$

Experimental loophole-free violation of Bell inequality precludes the explanation of hidden-variable theory.
arXiv:1508.05949, *arXiv*:1511.03190

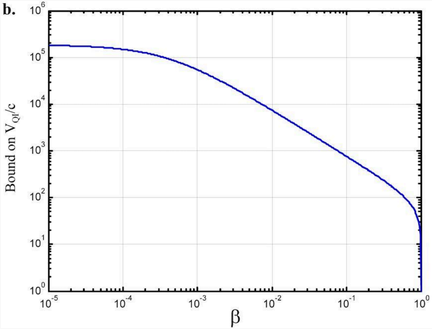
Communication between entangled particles

Alternative local explanations of QM correlations could be possible assuming some communication between entangled particles. *arXiv*:1006.2697

Space-time diagram in the privileged reference frame. *arXiv*:1110.3795

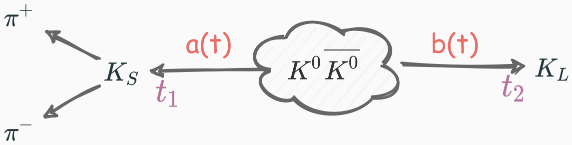


Bound obtained for $\frac{V_{QI}}{c}$ as a function of the speed β (relative to the Earth frame). *arXiv*:0808.3316



The calculation based on locality hypothesis

Entangled neutral kaons system



In the reaction $V \to K^0\bar{K}^0$, where V is a vector meson (ϕ, J/ψ, Υ...) with quantum numbers $J^{PC} = 1^{--}$.

$$\left|K^0\overline{K^0}\right\rangle = \frac{1}{\sqrt{2}}\left\{|K_S\rangle_a |K_L\rangle_b - |K_L\rangle_a |K_S\rangle_b\right\}$$

quantum mechanics

$t_2 = t_1$ The insterference effect is instantaneous.

locality principle

$t_2 = (1+\beta)/(1-\beta)t_1$ The insterference effect should travel at the speed of light in the rest frame of $K^0\bar{K}^0$.

Decay rates

$$A\left(f_a, t_a; f_b, t_b\right) = \frac{1}{\sqrt{2}}\left[\left\langle f_a|T|K_S\left(t_a\right)\right\rangle\left\langle f_b|T|K_L\left(t_b\right)\right\rangle - \left\langle f_a|T|K_L\left(t_a\right)\right\rangle\left\langle f_b|T|K_S\left(t_b\right)\right\rangle\right]$$

For $K^0\overline{K^0} \to anything$, we have

$$\Gamma_{ent}(t_a, t_b) = N\Sigma_{f_a,f_b}\left|A\left(f_a, t_a; f_b, t_b\right)\right|^2 =$$
$$\frac{N}{2}\Gamma_L\Gamma_S\left\{e^{-\Gamma_S t_a - \Gamma_L t_b} + e^{-\Gamma_S t_b - \Gamma_L t_a} - 2\cos\left[\left(m_L - m_S\right)\left(t_b - t_a\right)\right]e^{-\frac{1}{2}\left(t_b + t_a\right)\left(\Gamma_S + \Gamma_L\right)}\right\}$$

$$\Gamma_{non\_ent}\left(t_a, t_b\right) = \frac{1}{2}\Gamma_L\Gamma_S\left\{e^{-\Gamma_S t_a - \Gamma_L t_b} + e^{-\Gamma_S t_b - \Gamma_L t_a}\right\}$$

$$\Gamma_a\left(t_a\right) = \int_0^{t_a} dt_b \Gamma_{non\_ent}\left(t_a, t_b\right) + \int_{t_a}^{+\infty} dt_b \Gamma_{ent}\left(t_a, t_b\right)$$

Decay rate of the first decay at time t_1:

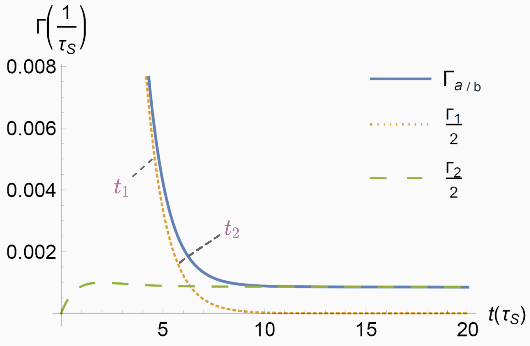
$$\Gamma_1(t_1) = 2\int_{t_1}^{+\infty} dt_2 \Gamma_{ent}\left(t_1, t_2\right)$$

Decay rate of the second decay at time t_2:

$$\Gamma_2(t_2) = 2\int_0^{t_2} dt_1 \Gamma_{non\_ent}\left(t_1, t_2\right)$$

$$\Gamma_a(t) = \Gamma_b(t) = \Gamma_1(t)/2 + \Gamma_2(t)/2$$

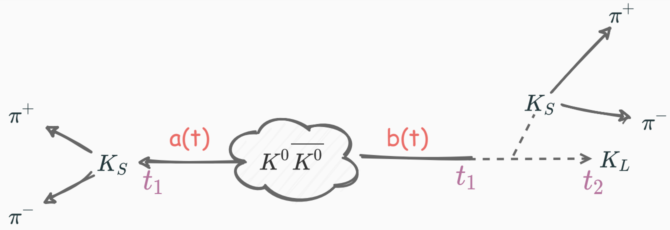
Decay process



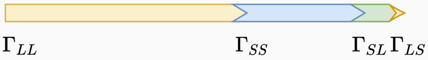
When kaon **a** decays first at time t_1,

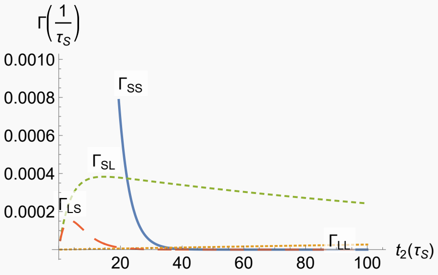
- the decay rate of kaon **b** changes instantaneously from $\Gamma_1(t_1)/2$ to $\Gamma_2(t_1)/2$ (**quantum mechanics**).
- the decay rate of kaon **b** remains $\Gamma_1(t)/2$ until $t_2 = \gamma' t_1 = (1+\beta)/(1-\beta)t_1$ (**locality principle**).

The yield of $K_S K_S$

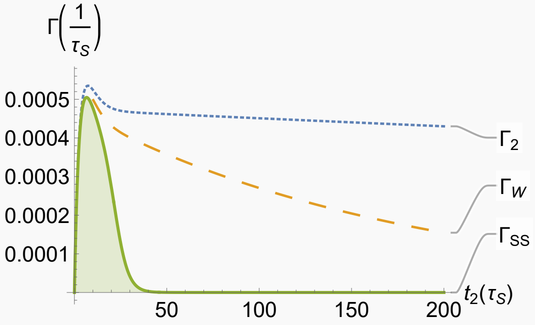


The $K^0\bar{K}^0$ state consists of the incoherent states $|K_S\rangle_1 |K_S\rangle_2$, $|K_S\rangle_1 |K_L\rangle_2$, $|K_L\rangle_1 |K_S\rangle_2$, and $|K_L\rangle_1 |K_L\rangle_2$ with equal weights in the time window (t_1, t_2).





The calculation

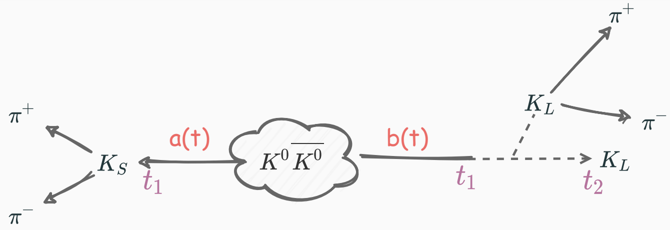


The ratio of double K_S events to single K_S events will be given by

$$R = P_W(K_S K_S) / [P_{QM}(K_S K_L) + P_W(K_S K_L)]$$

$P_W(K_S K_S)$ is the probability of the state $|K_S\rangle_1 |K_S\rangle_2$ during the time window $(t_2/\gamma', t_2)$. $P_W(K_S K_L)$ and $P_{QM}(K_S K_L)$ is the probability of single K_S events during the time window and outside the time window, respectively.

Experimental effects and correction



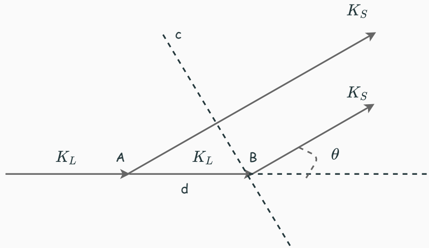
Only considering the K_S decay mode $K_S \to \pi^+\pi^-$, the final state of reaction $V \to K_S K_S$ is $\pi^+\pi^-\pi^+\pi^-$.

Since the decay $K_L \to \pi^+\pi^-$ may happen, the states $|K_S\rangle_1 |K_L\rangle_2$, $|K_L\rangle_1 |K_S\rangle_2$, and $|K_L\rangle_1 |K_L\rangle_2$ can be misreconstructed as $|K_S\rangle_1 |K_S\rangle_2$.

The branching ratio of $V \to K_S K_S$ should be corrected with (1+σ), where

$$\sigma = \frac{\int_0^{+\infty} dt_2 [\zeta \Gamma_{SL}(t_2) + \zeta \Gamma_{LS}(t_2) + \zeta^2 \Gamma_{LL}(t_2)]}{\int_0^{+\infty} dt_2 \Gamma_{SS}(t_2)}$$

Experimental effects - kaon regeneration

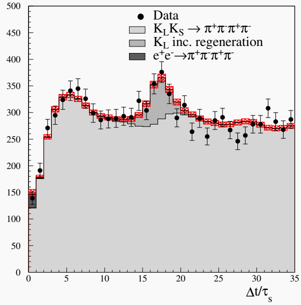


Regeneration originates from the fact that the K^0 meson interacts differently with matter (generally with protons and neutrons) than $\bar{K}^0$.

There are two kinds of regeneration processes:

- coherent regeneration $p_{regen} = |\rho|^2 p_{thru}$
- incoherent regeneration

The distribution of kaon regeneration in $\phi \to K_S K_L \to \pi^+\pi^-\pi^+\pi^-$ from the KLOE Collaboration. *arXiv*:0607027



In BESIII, kaon regeneration can happen in the beam pipe and the inner wall of the main draft chamber.

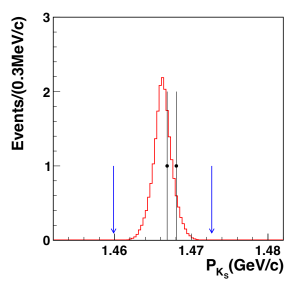
The results of calculation

- The corrected value of R can be expressed as $R' = (1+\sigma)R + p_{regen}$.
- Knowing the branching ratio of $V \to K_S K_L$, multiplied by R' and divided by $Br(K_S \to \pi^+\pi^-)$, the branching ratio of decay $V \to K_S K_S$ can be obtained.
- Input parameters:
  mean lifetime of K_S and K_L, mass of the vector and K^0 meson, branching ratio of $K_S \to \pi^+\pi^-$.
- The uncertainty of R' value mainly comes from the uncertainty of K_L's lifetime.

Vector meson	Mass(MeV)	σ	p_{regen}	R'	$Br(V \to K_S K_S)$	experimental UL
$\phi(1020)$	1019.46 ± 0.016	5.0×10^{-5}	1.4×10^{-6}	0.0005 ± 0.0033	$(0.4 \pm 2.5) \times 10^{-2}$	-
J/ψ	3096.90 ± 0.006	3.7×10^{-4}	1.8×10^{-6}	0.0196 ± 0.0032	$(5.5 \pm 1.0) \times 10^{-6}$	1.4×10^{-8} (BESIII Collab. 2017)
$\psi(2S)$	3686.10 ± 0.06	5.1×10^{-4}	1.8×10^{-6}	0.0275 ± 0.0032	$(2.1 \pm 0.3) \times 10^{-6}$	4.6×10^{-6} (BES Collab. 2004)
$\Upsilon(1S)$	9460.3 ± 0.26	2.2×10^{-3}	1.9×10^{-6}	0.1282 ± 0.0033	-	-
$\Upsilon(2S)$	10023.26 ± 0.31	2.3×10^{-3}	1.9×10^{-6}	0.1378 ± 0.0033	-	-
$\Upsilon(3S)$	10355.2 ± 0.5	2.4×10^{-3}	1.9×10^{-6}	0.1425 ± 0.0035	-	-

Experimental upper limits

Results from the BESIII collaboration.
arXiv:1710.05738



N_{obs}	2
N_{bkg}	2.4
N^{UL}	4.7
$\epsilon_{\text{MC}}(\%)$	25.7
$\mathcal{B}(J/\psi \to K_S K_S)$ (95% C.L.)	$< 1.4 \times 10^{-8}$

The upper limit of $Br(J/\psi \to K_S K_S)$ from the BESIII Collaboration in 2017 is two orders of magnitude smaller than the expected value under the locality assumption, from which we can obtain that the speed of quantum information $V_{QI} > 45.1c$ in the $K^0\bar{K}^0$ rest frame.

The BES Collaboration has given an upper limit at 95% C.L.
$Br(\psi(2S) \to K_S K_S) < 4.6 \times 10^{-6}$ in 2004.
It is compatible with the calculated value.

For $\Upsilon(nS)$, the distinction between quantum mechanics and the locality hypothesis may be more pronounced.

Conclusion

Conclusion

- In this work, we have estimated the branching ratios of $V \to K_S K_S$ under the locality assumption.
- The experimental result of J/ψ is significantly less than the prediction and the present upper limit of $\psi(2S)$ is compatible with the prediction.
- $\Upsilon(nS)$ could also be used to test the locality hypothesis and we propose Belle-II and LHCb experiments to perform such studies.
- It is a fairly small step, but more progress is expected in this field!

Thanks!

Backup

$\Gamma_{SS}(t_2) = \left(\frac{\Gamma_S^0}{\gamma}\right)^2 \int_{F_1} dt_1 \exp\left[\frac{-\Gamma_S(t_1+t_2)}{\gamma}\right]$, where γ is the Lorentzian factor $\gamma = 1/\sqrt{1-\beta^2}$ and F_1 represents time interval $[t_2/\gamma' < t_1 < t_2; 0 < t_1 < +\infty; 0 < t_2 < +\infty]$. Expressions of the others are analogously defined as that of $\Gamma_{SS}(t_2)$.

$P_{QM}(K_S K_L)$ is obtained by integrating $\frac{2}{\gamma^2}\frac{\Gamma_S^0}{\Gamma_S}\Gamma_{non\_ent}\left(\frac{t_1}{\gamma}, \frac{t_2}{\gamma}\right)$ over the time-like fiducial region $F_2\,[0 < t_1 < t_2/\gamma'; 0 < t_1 < +\infty; 0 < t_2 < +\infty]$.

At fixed time t_2 the probability of the first decay occurring in the space-like region P_W can be obtained by integrating $\frac{2}{\gamma^2}\frac{\Gamma_S^0}{\Gamma_S}\Gamma_{non\_ent}\left(\frac{t_1}{\gamma}, \frac{t_2}{\gamma}\right)$ in the time window $F_1\,[t_2/\gamma' < t_1 < t_2; 0 < t_1 < +\infty; 0 < t_2 < +\infty]$.

Next we can get the fraction of events decaying in the fiducial region as $K_S K_S$ is

$$p_{ss} = \frac{\int_0^{+\infty} dt_2 \Gamma_{SS}(t_2)}{\int_0^{+\infty} dt_2 [\Gamma_{SS}(t_2) + \Gamma_{SL}(t_2) + \Gamma_{LS}(t_2) + \Gamma_{LL}(t_2)]}. \quad (1)$$

Multiply it by P_W to get $P_W(K_S K_S)$ and same with $P_W(K_S K_L)$.