粒子物理中的量子纠缠与量子信息
Quantum entanglement and quantum information in particle physics

施郁

复旦大学物理系

第十届全国粒子物理会议，南京，2008.4.28.

- 合作者: 吴岳良教授 (中科院理论所)

- 参考文献:

YS, Phys. Lett. B 641, 75 (06).

YS and Y. L. Wu, arXiv: 0712.2288; EPJC(in press).

Introduction

- Quantum information (information processing based on quantum resources, especially quantum entanglement) has been discussed in almost all areas reigned by quantum mechanics, probably with the exception of particle physics.

- There have been related researches, e.g. Bell inequalities in particle physics.

QI as a fundamental concept

- Quantum Information is not just useful.
- As a fundamental concept, it should be connected to particle physics and relativistic quantum field theory, which is the only consistent combination of QM and special relativity.
- In this talk, we will describe an attempt in this direction.

High energy quantum teleportation using neutral kaons.

A neutral Kaon as a two-state system

- Pseudoscalars with $J^P = 0^-$.
- $P|K^0\rangle = -|K^0\rangle$, $P|\bar{K}^0\rangle = -|\bar{K}^0\rangle$. $I_3|K^0\rangle = \frac{1}{2}|K^0\rangle$, $I_3|\bar{K}^0\rangle = -\frac{1}{2}|\bar{K}^0\rangle$.
- $S|K^0\rangle = |K^0\rangle$, $S|\bar{K}^0\rangle = -|\bar{K}^0\rangle$.
- $C|K^0\rangle = -|\bar{K}^0\rangle$, $C|\bar{K}^0\rangle = -|K^0\rangle$.

  $CP|K^0\rangle = |\bar{K}^0\rangle$, $CP|\bar{K}^0\rangle = |K^0\rangle$.
- CP eigenstates:
  $|K_1\rangle = \frac{1}{\sqrt{2}}(|K^0\rangle + |\bar{K}^0\rangle)$, with $CP = 1$;
  $|K_2\rangle = \frac{1}{\sqrt{2}}(|K^0\rangle - |\bar{K}^0\rangle)$, with $CP = -1$.

Mass (weak interaction) eigenstates

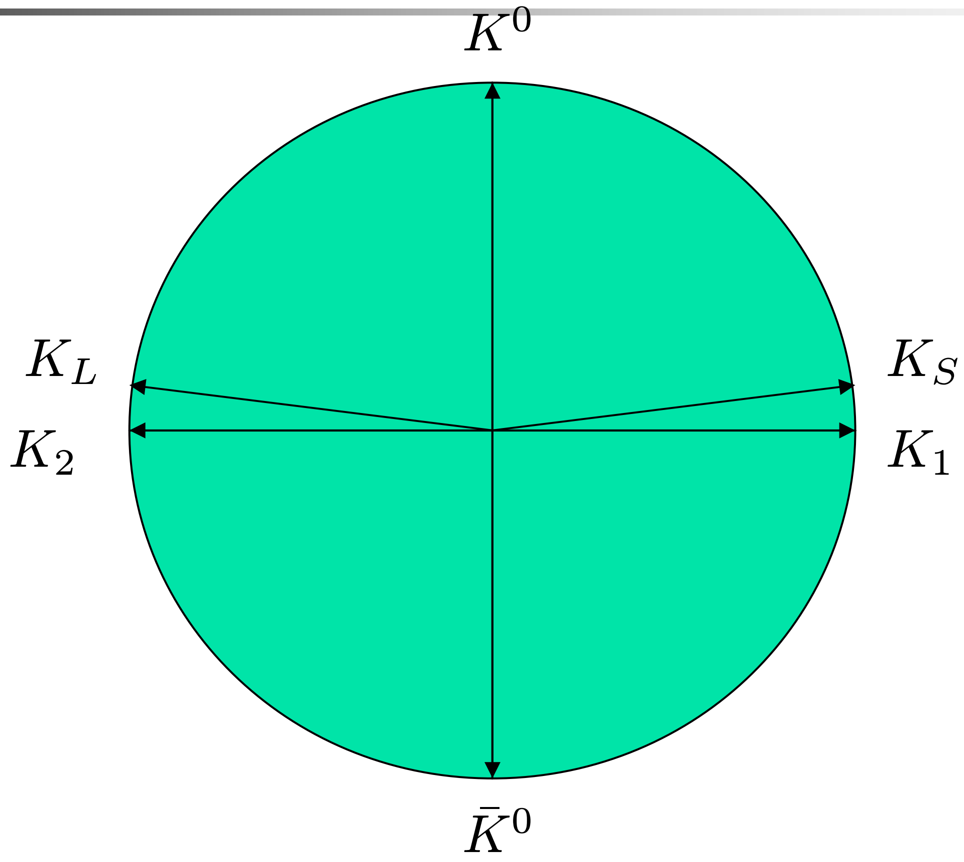
$$|K_S\rangle = \frac{1}{\sqrt{1+|\epsilon|^2}}(|K_1\rangle + \epsilon|K_2\rangle) = \frac{1}{\sqrt{|p|^2+|q|^2}}(p|K^0\rangle + q|\bar{K}^0\rangle)$$
$$|K_L\rangle = \frac{1}{\sqrt{1+|\epsilon|^2}}(|K_2\rangle + \epsilon|K_1\rangle) = \frac{1}{\sqrt{|p|^2+|q|^2}}(p|K^0\rangle - q|\bar{K}^0\rangle)$$

Eigenvalues: $\lambda_S = m_S - i\Gamma_S/2$ and $\lambda_L = m_L - i\Gamma_L/2$.

- "S", "L": short and long life times of weak decays $1/\Gamma_S$ and $1/\Gamma_L$.
- $\epsilon \approx 10^{-3}$ characterizes CP violation, $p = 1+\epsilon$, $q = 1-\epsilon$. For our purpose, $\epsilon \approx 0$.
- $m_L - m_S \approx 3.483 \times 10^{-12} MeV$ is negligible, as $m_L \approx m_S \approx 497.648 MeV$.
- Lifetimes differ significantly: $1/\Gamma_S \approx 0.8953 \times 10^{-10} s$, $1/\Gamma_L \approx 5.114 \times 10^{-8} s$
- $|K_S(\tau)\rangle = e^{-i\lambda_S \tau}|K_S\rangle$

  $|K_L(\tau)\rangle = e^{-i\lambda_L \tau}|K_L\rangle$ τ: proper time. $\hbar = c = 1$.

Two dimensional Hilbert space



EPR entangled state of neutral kaons

$$|\Psi_-\rangle = \frac{1}{\sqrt{2}}(|K^0\rangle|\bar{K}^0\rangle - |\bar{K}^0\rangle|K^0\rangle).$$

- $J^{PC} = 1^{--}$
- Generated from the strong decay of vector meson ϕ , which can be created in ee+ annihilation at 1GeV; or from pp- annihilation at rest.
- Similar for neutral B mesons, from Upsilon (4S) resonance, generated in ee+ annihilation at 10GeV.

Why entangled

- They must satisfy bose statistics under exchange.
- Exchange: C combines with coordinate permutation $(-1)^l$.
- Thus C=-1 implies antisymmetry under coordinate permutation.

First noted by Lee and Yang in 1960.

REVIEWS OF

MODERN PHYSICS

VOLUME 33, NUMBER 1 JANUARY, 1961

Completeness of Quantum Mechanics and Charge-Conjugation Correlations of Theta Particles*

D. R. INGLIS

Argonne National Laboratory, Argonne, Illinois

ment of spin. Lee and Yang[5] have suggested an experiment involving thetas that is related to the EPR question. The possibility of investigating in more detail

[5] T. D. Lee and C. N. Yang (unpublished);

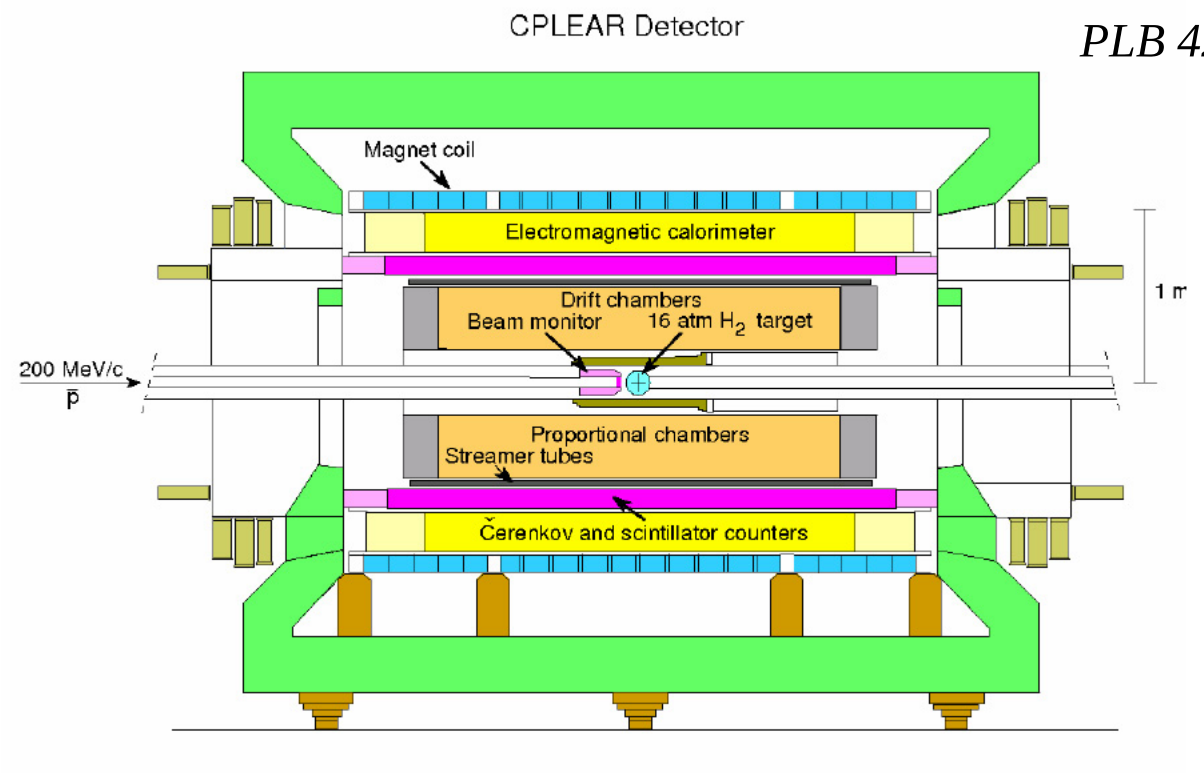
Previous works on entangled kaons

- A lot of discussions have been made on using entangle kaons to test QM against local hidden variable models (Bell theorem).
- It was claimed that this system may close the locality loophole and detection loophole in testing Bell theorem.

Experimental confirmations of EPR correlation (1)

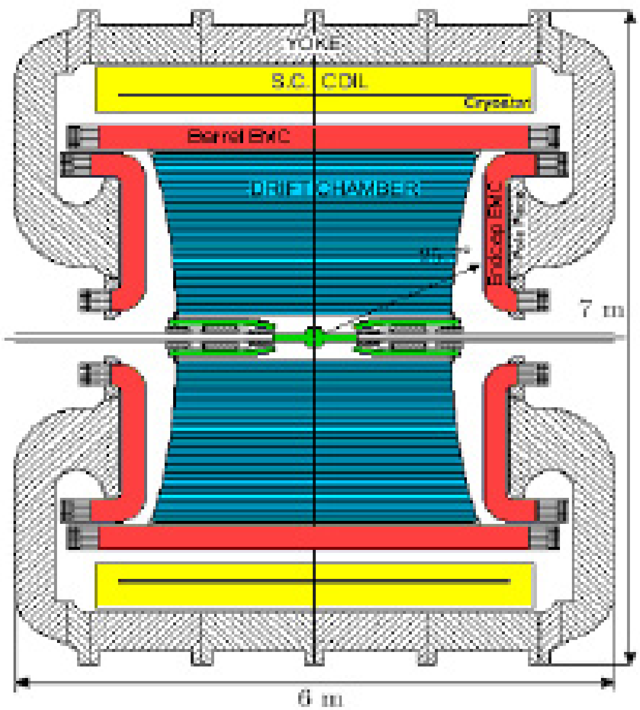
- $K^0\bar{K}^0$ produced in pp- annihilation in the CPLEAR detector in CERN (1998).

PLB 42, 339(98)



Experimental confirmations of EPR correlation (2)

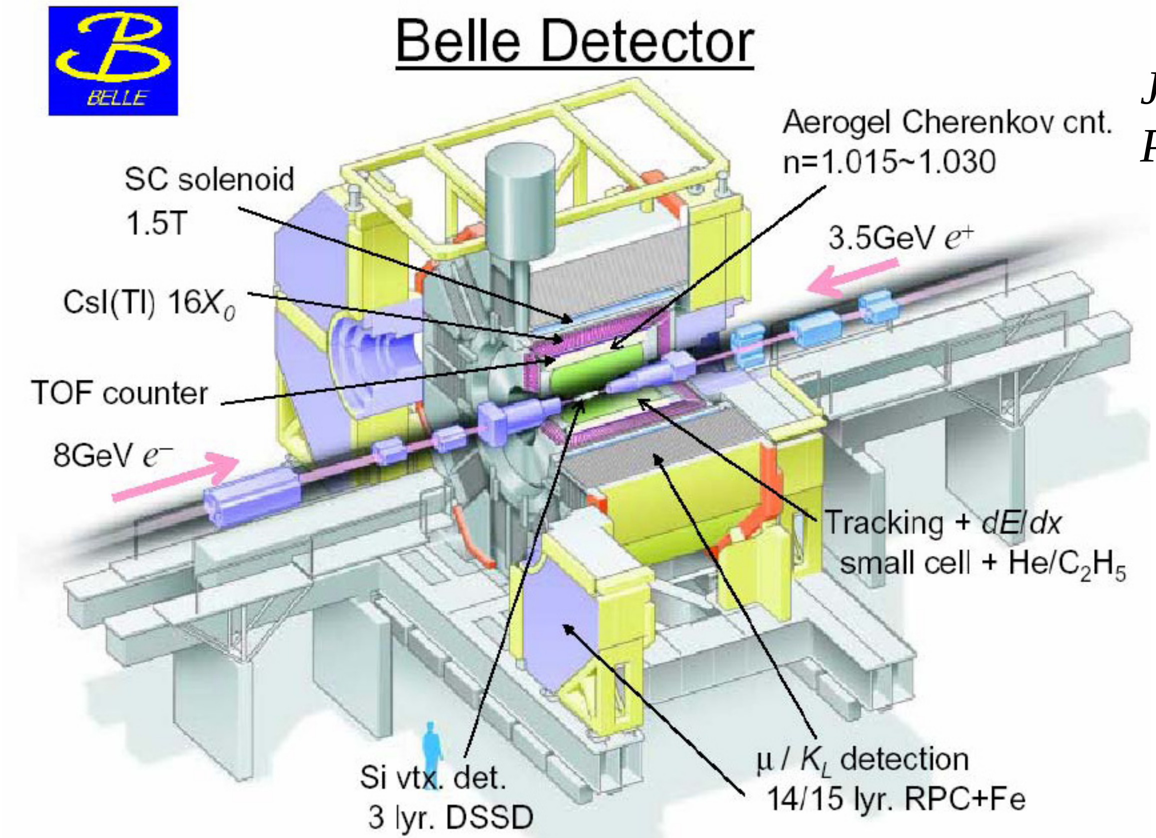
- $K^0\bar{K}^0$ produced in ϕ decay in the KLOE detector in $\mathrm{DA\Phi NE}$ (2003, 2006)



hep-ex/0312032;
PLB 642,315(06)

Experimental confirmations of EPR correlation (3)

- $B^0\bar{B}^0$ produced in ee+ annihilation in the BELLE detector in KEKB (2004.2007).



J.Mod.Opt. 51,991(04); PRL 99, 131802 (07)

Introduction to teleportation

- Alice and Bob share an EPR pair a and b.
- Alice also holds another qubit c in a certain state.
- Alice makes Bell measurement on qubits a and c. (projection on Bell basis).
- Depending on Alice’s result, Bob perform one of four unitary transformation on his qubit b, thus obtain the original state of c.

Teleportation (continued)

$$|\Psi\rangle_{ab} = \frac{1}{\sqrt{2}}(\uparrow_a\downarrow_b - \downarrow_a\uparrow_b)$$

$$|\Psi\rangle_c = \alpha \uparrow_c + \rho \downarrow_c .$$

$$|\Psi\rangle_{cab} = \frac{1}{2}|\Phi_+\rangle_{ca}(\alpha \downarrow_b - \rho \uparrow_b) + \frac{1}{2}|\Phi_-\rangle_{ca}(\alpha \downarrow_b + \rho \uparrow_b)$$
$$- \frac{1}{2}|\Psi_+\rangle_{ca}(\alpha \uparrow_b - \rho \downarrow_b) - \frac{1}{2}|\Psi_-\rangle_{ca}(\alpha \uparrow_b + \rho|w_2 \downarrow_b),$$

$$|\Psi_+\rangle = \frac{1}{\sqrt{2}}(\uparrow_a\downarrow_b + \downarrow_a\uparrow_b)$$

$$|\Psi_-\rangle = \frac{1}{\sqrt{2}}(\uparrow_a\downarrow_b - \downarrow_a\uparrow_b)$$

$$|\Phi_+\rangle = \frac{1}{\sqrt{2}}(\uparrow_a\uparrow_b + \downarrow_a\downarrow_b)$$

$$|\Phi_-\rangle = \frac{1}{\sqrt{2}}(\uparrow_a\uparrow_b - \downarrow_a\downarrow_b)$$

Teleportation using neutral kaons

Generation of an EPR pair

- At t=0, a and b is created as

$$\begin{aligned} |\Psi_{ab}(0)\rangle &= \frac{1}{\sqrt{2}}(|K^0\rangle_a|\bar{K}^0\rangle_b - |\bar{K}^0\rangle_a|K^0\rangle_b) \\ &= \frac{1}{\sqrt{2}}(|K_2\rangle|K_1\rangle - |K_1\rangle|K_2\rangle) \\ &= \frac{r}{\sqrt{2}}(|K_L\rangle_a|K_S\rangle_b - |K_S\rangle_a|K_L\rangle_b), \end{aligned}$$

$$r = (|p|^2 + |q|^2)/2pq = (1 + |\epsilon|^2)/(1 - \epsilon^2)$$

- Decay under weak interaction:

$$|\Psi_{ab}(t)\rangle = M(t)|\Psi_-\rangle_{ab},$$

$$M(t) = \exp[-i(\lambda_S + \lambda_L)\Lambda_b t],\ \Lambda_b = 1/\sqrt{1 - v_b^2}$$

The third koan

- A third koan c is generated at t_z in an unknown state

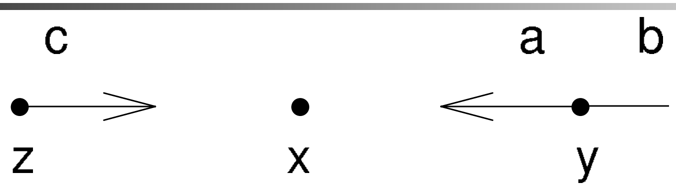
$$|\Psi_c(t_z)\rangle = \alpha|K^0\rangle_c + \beta|\bar{K}^0\rangle_c.$$

- Naturally decays

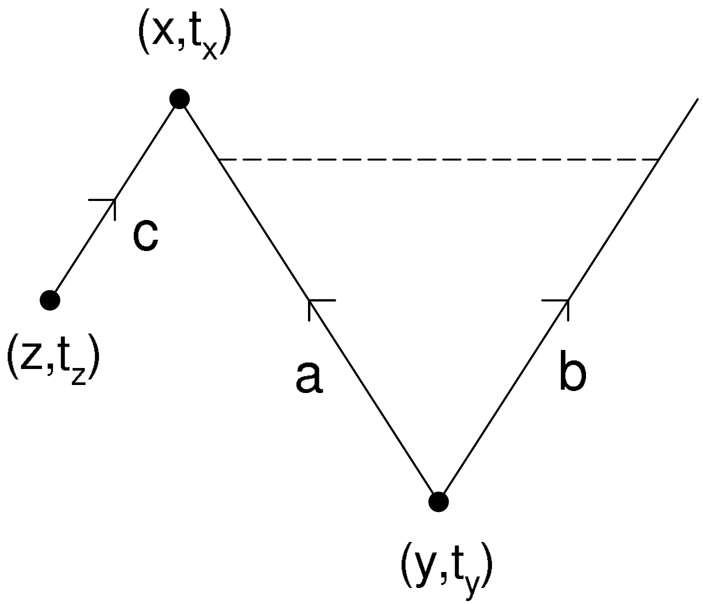
$$|\Psi_c(t)\rangle = F(t)|K^0\rangle_c + G(t)|\bar{K}^0\rangle_c,$$

$$F(t) = [(\alpha + \beta p/q)e^{-i\lambda_S \Lambda_c (t-t_z)} + (\alpha - \beta p/q)e^{-i\lambda_L \Lambda_c (t-t_z)}]/2,$$
$$G(t) = [(\alpha q/p + \beta)e^{-i\lambda_S \Lambda_c (t-t_z)} - (\alpha q/p - \beta)e^{-i\lambda_L \Lambda_c (t-t_z)}]/2.$$

Let c and a collide!



Spacetime diagram:



Eigenstates of P, S and I of c+a

- P, S, I are conserved by strong interaction, which governs c-a collision.

$$|\phi_1\rangle_{ca} = |K^0 K^0\rangle \text{ with } P=1,\ S=2,\ I=1;$$
$$|\phi_2\rangle_{ca} = |\bar{K}^0 \bar{K}^0\rangle \text{ with } P=1,\ S=-2,\ I=1;$$
$$|\phi_3\rangle_{ca} = |\Psi_+\rangle = \frac{1}{\sqrt{2}}(|K^0\rangle|\bar{K}^0\rangle + |\bar{K}^0\rangle_c|K^0\rangle), \text{ with } P=1,\ S=0,\ I=1;$$
$$|\phi_4\rangle_{ca} = |\Psi_-\rangle = \frac{1}{\sqrt{2}}(|K^0\rangle|\bar{K}^0\rangle - |\bar{K}^0\rangle_c|K^0\rangle \text{ with } P=-1,\ S=0,\ I=0.$$

Three-kaon state before collision,decomposed in the strong interaction basis

$$
\begin{aligned}
|\Psi_{cab}(t)\rangle &= |\Psi_c(t)\rangle \otimes |\Psi_{ab}(t)\rangle \\
&= \frac{M(t)}{2}\{\sqrt{2}F(t)|\phi_1\rangle_{ca}|\bar{K}^0\rangle_b \\
&\quad -\sqrt{2}G(t)|\phi_2\rangle_{ca}|K^0\rangle_b \\
&\quad -|\phi_3\rangle_{ca}[F(t)|K^0\rangle_b - G(t)|\bar{K}^0\rangle_b] \\
&\quad -|\phi_4\rangle_{ca}[F(t)|K^0\rangle_b + G(t)|\bar{K}^0\rangle_b]\}.
\end{aligned}
$$

It is not a Bell basis. This basis is physical, while Bell basis is not.

Collision

- The collision effects a unitary transformation $\mathcal{S}$ in a negligible time interval

$$\begin{aligned} |\Psi_{cab}(t_x)\rangle &= \tfrac{M(t_x)}{2}\{\sqrt{2}F(t_x)\mathcal{S}|\phi_1\rangle_{ca}|\bar{K}^0\rangle_b \\ &-\sqrt{2}G(t_x)\mathcal{S}|\phi_2\rangle_{ca}|K^0\rangle_b \\ &-\mathcal{S}|\phi_3\rangle_{ca}[F(t_x)|K^0\rangle_b - G(t_x)|\bar{K}^0\rangle_b] \\ &-\mathcal{S}|\phi_4\rangle_{ca}[F(t_x)|K^0\rangle_b + G(t_x)|\bar{K}^0\rangle_b]\}. \end{aligned}$$

- As $\mathcal{S}$ is governed by strong interaction, $\mathcal{S}|\phi_i\rangle_{ca}$ $(i = 1, 2, 3, 4)$ is still an eigenstate of S, P and I, with the same eigenvalues as for $|\phi_i\rangle_{ca}$.

Detection of outgoing particles of c-a collision

- Using strong interaction with nuclear matter, the detection completes Alice's two-particle projection in the basis $\{\mathcal{S}|\phi_i\rangle_{ca}\}$.
- Probabilities:
$$|M(t_x)|^2|F(t_x)|^2/2,$$
$$|M(t_x)|^2|G(t_x)|^2/2,$$
$$|M(t_x)|^2[|F(t_x)|^2+|G(t_x)|^2]/4,$$
$$|M(t_x)|^2[|F(t_x)|^2+|G(t_x)|^2]/4.$$
- Corresponding projected state of b:
$$|\bar{K}^0\rangle_b,\ |K^0\rangle_b,\ [F(t_x)|K^0\rangle_b - G(t_x)|\bar{K}^0\rangle_b]/\sqrt{|F(t_x)|^2+|G(t_x)|^2},$$
$$[F(t_x)|K^0\rangle_b + G(t_x)|\bar{K}^0\rangle_b]/\sqrt{|F(t_x)|^2+|G(t_x)|^2}.$$
- Decay affects the probabilities.

Adopt a stochastic strategy

- This is because it is hard to implement subsequent unitary transformation on b.
- Bob chooses to retain or abandon b particle, based on the projection result of c-a.
- Teleportation of $F(t_x)|K^0\rangle_b + G(t_x)|\bar{K}^0\rangle_b$

  is made if projection result of c-a is

  $\mathcal{S}|\Psi_-\rangle_{ca}$.

Verification scheme (1)

- Different projection results lead to different values of strangeness ratio ξ.
- For $|\Psi(t)\rangle_b = f(t)|K^0\rangle_b + g(t)|\bar{K}^0\rangle_b$, $\xi(t) = |f(t)|^2/g(t)|^2$.
- No projection/teleportation: $\xi(t) = 1.$
- Successful teleportation:

$$\xi(t) = \frac{|F(t_x)(e^{-\Gamma_S\tau/2}+e^{-\Gamma_L\tau/2})+G(t_x)(e^{-\Gamma_S\tau/2}-e^{-\Gamma_L\tau/2})|^2}{|F(t_x)(e^{-\Gamma_S\tau/2}-e^{-\Gamma_L\tau/2})+G(t_x)(e^{-\Gamma_S\tau/2}+e^{-\Gamma_L\tau/2})|^2},$$
$$\tau = \Lambda_b(t - t_x - 0).$$

very different from 1

Actual way of obtaining strangeness ratio

- Repeat many runs of the procedure.
- No projection ($\xi(t) = 1$): all runs are considered.
- Teleported state: only consider those runs in which c-a are projected to $\mathcal{S}|\Psi_-\rangle_{ca}$.
- "Many runs of the procedure" can be done simultaneously in a beam of particles, so realized by different events.

Verification scheme (2)

- Different projection results lead to different values of CP ratio .
- For $|\Psi(t)\rangle_b = u_1(t)|K_1\rangle_b + u_2(t)|K_2\rangle_b$, $\zeta(t) = |u_1(t)|^2/u_2(t)|^2$.
- No projection/teleportation: $\zeta(t) = 1$.
- Successful teleportation: significantly different from 1.
- Advantage 1: valid no matter whether CP is violated.
- Advantage 2: easy experimental implementation, using non-leptonic decays (CP=1: decay to 2 pions; CP=-1: decay to 3 pions).

Another process: Entanglement swapping

- A and B are entangled, C and D are entangled.
- A and C are subject to a measurement (projection).
- Then B and D become entangled, though they never meet.
- Entangling partners are swapped.

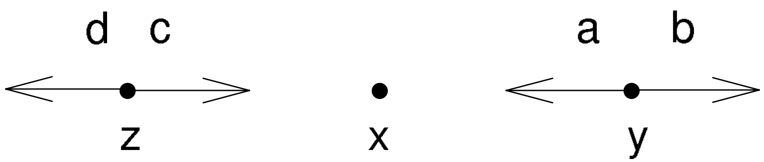
Preparation

In addition to $|\Psi_-\rangle_{ab}$ generated at $t=0$,
another kaon pair d and c is generated as $|\Psi_-\rangle_{dc}$ at time t_z.
$|\Psi_{dc}(t)\rangle = M'(t-t_z)|\Psi_-\rangle_{dc}$,
$M'(t-t_z) = \exp[-i(\lambda_S+\lambda_L)\Lambda_d(t-t_z)]$.

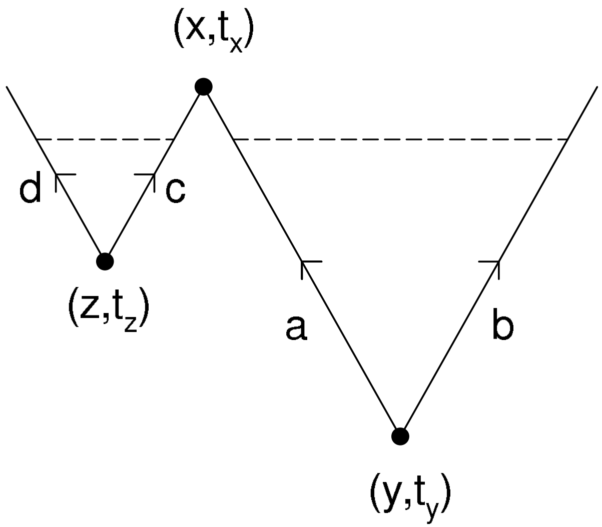
$$\begin{aligned}
|\Psi_{dcab}(t)\rangle &= M'(t-t_z)M(t)|\Psi_-\rangle_{dc}|\Psi_-\rangle_{ab} \\
&= \frac{M'(t-t_z)M(t)}{2}(|\Psi_+\rangle_{ca}|\Psi_+\rangle_{db} - |\Psi_-\rangle_{ca}|\Psi_-\rangle_{db} \\
&\quad -|K^0\bar{K}^0\rangle_{ca}|\bar{K}^0\bar{K}^0\rangle_{db} - |\bar{K}^0\bar{K}^0\rangle_{ca}|K^0K^0\rangle_{db}).
\end{aligned}$$

Collision

Let c and a collide at t_x



Spacetime diagram:



Detection

Collision:

$$
\begin{aligned}
|\Psi_{dcab}(t_x+0)\rangle \;=\; & \tfrac{M'(t_x-t_z)M(t_x)}{2}(\mathcal{S}|\Psi_+\rangle_{ca}|\Psi_+\rangle_{db} \\
& -\mathcal{S}|\Psi_-\rangle_{ca}|\Psi_-\rangle_{db} \\
& -\mathcal{S}|K^0K^0\rangle_{ca}|\bar{K}^0\bar{K}^0\rangle_{db} \\
& -\mathcal{S}|\bar{K}^0\bar{K}^0\rangle_{ca}|K^0K^0\rangle_{db}).
\end{aligned}
$$

In detecting outgoing particles from the collision, c and a are projected to: $\mathcal{S}|\Psi_+\rangle_{ca}$, $\mathcal{S}|\Psi_-\rangle_{ca}$, $\mathcal{S}|K^0K^0\rangle_{ca}$ or $\mathcal{S}|\bar{K}^0\bar{K}^0\rangle_{ca}$. Correspondingly d and b are projected to: $|\Psi_+\rangle_{ca}$, $|\Psi_-\rangle_{ca}$, $|K^0K^0\rangle_{ca}$ and $|\bar{K}^0\bar{K}^0\rangle_{ca}$, respectively, each with probability $|M'(t_x-t_z)M(t_x)|^2/4$. .

The projection result is revealed by P, S and I of the outcomes of $c-a$ collision, according to which b and d are retained or abandoned.

Verification scheme (1)

- Measure the S asymmetry of b and d

$$A(t) = [p_{diff}(t) - p_{same}(t)]/[p_{diff}(t) + p_{same}(t)]$$

$p_{diff}(t)$ $(p_{same}(t))$:
probability to have different (same) strangeness values

- Many runs are needed.
- No entanglement swapping (all runs are considered): A(t)=0
- Entanglement swapping succeeds (consider those runs in which c-a project to $\mathcal{S}|\Psi_-\rangle_{ca}$: A(t)=1

Verification scheme (2)

- Measure the CP asymmetry of b and d

$$A(t) = [p_{diff}(t) - p_{same}(t)]/[p_{diff}(t) + p_{same}(t)]$$

$p_{diff}(t)$ $(p_{same}(t))$:
probability to have different (same) values of CP.

- Many runs (events) are needed.
- No entanglement swapping (all runs are considered): A(t)=-1
- Entanglement swapping succeeds (consider those runs in which c-a project to $\mathcal{S}|\Psi_-\rangle_{ca}$: A(t)=1

Summary

- The neutral kaon whose state is to be teleported collides with an EPR member. The detection of the outgoing particles of the collision completes the projection to an eigenstate of P, S and I, which is conserved in the collision.
- This basis is different from Bell basis, as used in the original teleportation scheme.
- Conditioned on the projection, teleportation can be made stochastically.
- Verification can be made based on strangeness measurements or CP measurements. The latter is better.
- Entanglement swapping can also be done.

A new feature

- In conventional implementations of teleportation, it is only the “sole” (state), rather than the “body” (matter), that is teleported.

- But in particle physics, as demonstrated in the present scheme, the “body” (particle) itself becomes a kind of “sole” (state of the quantum field), and is teleported.

Conclusion

- Quantum information can be discussed in the setting of particle physics.
- Like that QI stimulates researches on quantum coherence in other areas, similar works could be done for particle physics.
- Such studies could reveal some new features unavailable in nonrelativistic regime, and deep connections between matter and information, provide new insights on particle physics!

Thank you for your attention!