

Quantum tests in collider physics

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TIME vs. REALITY:

A novel quantum effect in $K^0 - \bar{K}^0$ Entanglement

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EXCELENCIA
SEVERO OCHOA



What is THE NOVELTY beyond Entanglement in Quantum Optics ?

➤ $\Delta F = 2$ Mixing ($K^0 - \bar{K}^0, B^0 - \bar{B}^0, \dots$)

➤ CP Violation { Mixing
Mixing - Decay Interference
Decay

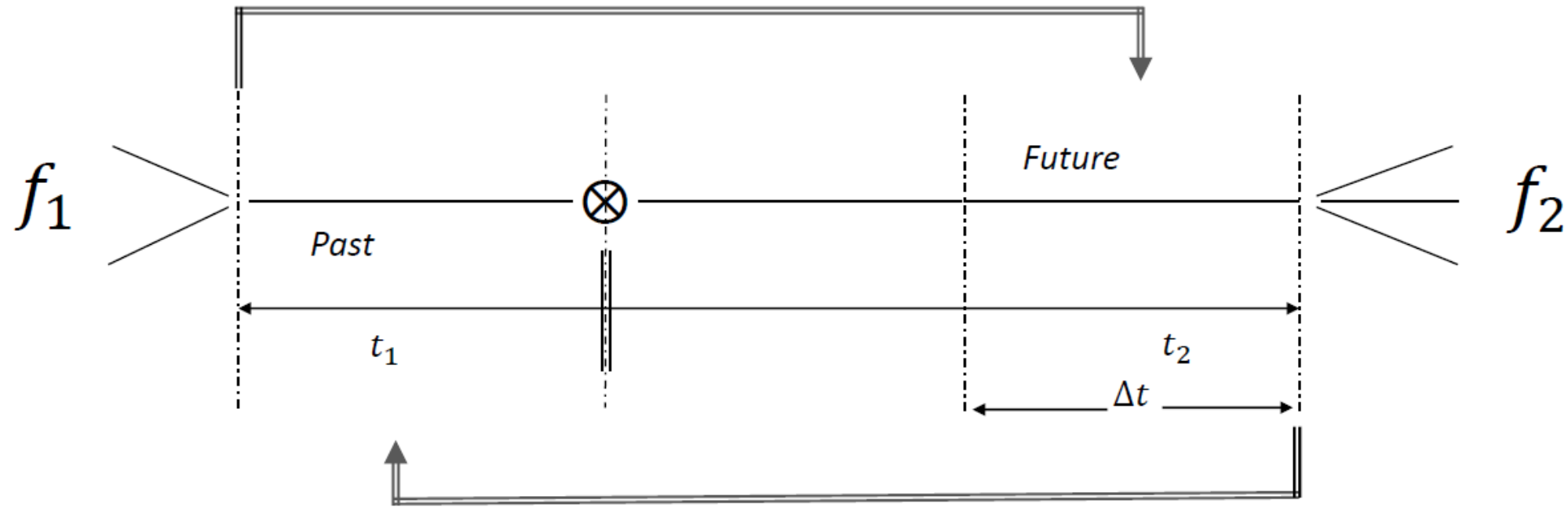
➤ Non-Trivial Time Evolution: Anton Zeilinger
Production \Rightarrow **Entangled** \Rightarrow **Interference** \Rightarrow **Decoherence**

with rich **distinct** information from one or double decay on the three regimes

➤ States with definite Mass and Lifetime $\lambda = M - i\Gamma/2, \quad \Delta M \neq 0, \Delta\Gamma \neq 0$
are those with **definite Time Evolution**.

➤ Existence of B-Factory and Φ -Factory Facilities

- I. **TIME HISTORY** of Entangled System: from Production to its fate
- **TIME REVERSAL** in Δt for unstable particles



II. **POST-TAG** of Past-decayed state: **Entanglement times t_1**

- K_S - TAG

NOVEL EFFECTS

(1) As a **Tool** for the BYPASS of (otherwise) NO-GO THEOREMS

1.1 The Conundrum of **Time Reversal - and CPT** - for Unstable Particles

1.2 What is a K_S experimentally ?

(2) The discovery of new quantum phenomena:

SURVIVING CORRELATION - IN - TIME FROM FUTURE TO PAST

It comes definite **from measurement in the future t_2** , when the system is no-longer entangled, **to the state –depending on t_2 (!?) - of the partner in the past t_1** , before its decay when it was entangled and "unspeakable".

It is asymmetric compared to the correlation from past to future.

If EPR → Spooky Action at a Distance → Bell Theorem → end of Hidden Variables and proof of "Lack of Local Realism" → Quantum Information,

then → What about the novel correlation - in - time ? → **Spooky Action to the Past** →???

OUTLINE

- **Entangled** two-body C=- neutral meson system
 - Time Evolution and **“Survival”** probability: the Total Width
 - The state $|K_{\rightarrow f}\rangle$ not decaying to f. **The K_L tag**
 - The Conundrum of **Time Reversal** –and CPT- **for Unstable Particles:**
NO-GO and its Bypass (in 1999): **The Conceptual Basis**
-
- From the observation of second decay f_2 at t_2 to the partner state before its decay at t_1 . **SURPRISE of the “initial” state depending on t_2 .**
 - **The K_s tag**
 - **Conclusion: An epistemological open question**

ENTANGLED C = - neutral meson system

➤ Actually existing at DAΦNE with $\Phi \rightarrow K^0 \bar{K}^0$,

at BABAR and BELLE with $\Upsilon(4S) \rightarrow B^0 \bar{B}^0$

$$C\mathcal{P} = + \Rightarrow |i(t=0)\rangle = \frac{1}{\sqrt{2}} \{ |K^0\rangle |\bar{K}^0\rangle - |\bar{K}^0\rangle |K^0\rangle \}$$

with particle 1 decaying at t_1 , particle 2 decaying at $t_2 > t_1$

➤ Even With Mixing, $|i(t)\rangle$ **does not generate any $K^0 K^0$, nor $\bar{K}^0 \bar{K}^0$** , due to antisymmetry (not valid for symmetric C=+ !)

➤ Time Evolution \rightarrow definite in terms of **non-orthogonal eigenstates of the non-normal Hamiltonian**

$$|K_{S,L}\rangle \propto [(1 + \epsilon_{S,L}) |K^0\rangle \pm (1 - \epsilon_{S,L}) |\bar{K}^0\rangle],$$

$$\mathcal{CP} \rightarrow \langle K_S | K_L \rangle \simeq \epsilon_L + \epsilon_S^*,$$

$$\epsilon = (\epsilon_S + \epsilon_L)/2 \rightarrow \mathcal{T}, \quad \delta = (\epsilon_S - \epsilon_L)/2 \rightarrow \mathcal{CPT}$$



quantum
entanglement

TIME EVOLUTION $|i(t)\rangle$

➤ The entangled state is **non-separable** in parts:

(i) "which is which" is not defined;

(ii) the two parts are not definite: any two linearly independent combinations.

Only the state $|i\rangle$ is definite: **the state of each part is "unspeakable"**.

➤ The time evolution, written as

$$|i(t=0)\rangle = N/\sqrt{2} \{ |K_S\rangle |K_L\rangle - |K_L\rangle |K_S\rangle \}, \quad |N|^2 = (1 - |\langle K_S|K_L\rangle|^2)^{-1} \Rightarrow |i(t)\rangle = e^{-i(\lambda_S+\lambda_L)t} |i(t=0)\rangle$$

The Survival Probability $P(t_1) = \|i(t=t_1)\|^2 = e^{-\Gamma t_1}$, **Total Width** $\Gamma = \Gamma_S + \Gamma_L$

$|i(t)\rangle$ is unaltered, it remains the same: NO INTEREST BEFORE THE FIRST DECAY.
The considered observable has been the **Double Decay Rate Intensity** $I(f_1, f_2; \Delta t)$!

➤ **Careful!** $P(t_1)$ iff nothing else is observed in the future

➤ **How to inquire in the "unspeakable" regime ?**

FIRST DECAY $f_1 \rightarrow$ TAGGING AND FILTERING

- Any state can decay to f , **but** that with zero probability

$$|K_{\rightarrow f}\rangle = N_{\rightarrow f} [|K_L\rangle - \eta_f |K_S\rangle]; \quad \eta_f = \frac{\langle f | T | K_L \rangle}{\langle f | T | K_S \rangle}$$

- If you observe the first decay to f_1 at t_1 , projecting $|i(t = t_1)\rangle$ to f_1 , the **living partner** (2) corresponds to the pure state

$$|K^{(2)}(t = t_1)\rangle = |K_{\rightarrow f_1}\rangle \quad \Leftarrow \quad \text{TAG of (2)}$$

This fact was always recognized for “**flavour tag**”: First decay to $l^+(l^-) \rightarrow$ Partner tagged to $\bar{K}^0(K^0)$. **It is, however, valid in general as stated!**

- **What for the decayed state (1)?** The state before decay was undefined. Written as a superposition of $|K_{\rightarrow f}\rangle$ and its orthogonal $|K_{\rightarrow f}^\perp\rangle$

$$\text{Decay to } f_1 \Rightarrow |K_{\rightarrow f_1}^\perp\rangle \quad \text{FILTERED for (1)}$$

Decay Rate given by the **decay probability** to f_1 of $|K_{\rightarrow f_1}^\perp\rangle \equiv$ **FILTERING IDENTITY**

Δt HISTORY OF THE LIVING PARTNER

- The subsequent Δt - evolution of particle (2) and its decay to f_2 are definite from the prepared tagged state.
- For $\Delta t \leq \text{few } \tau_s$, one has an interference pattern, because no decay channel - due to CP Violation - projects either K_S or K_L !
- For long enough Δt , one has Decoherence $K_L \text{ tag} \Leftrightarrow |\eta_1| e^{-\Delta\Gamma\Delta t/2} \ll 1$ with a quantitative purity of the K_L -state
- The observable is the Double Decay Rate, the Intensity $I(f_1, f_2; \Delta t)$. Tagging of the living partner at t_1 and Filtering of its state in its Decay to f_2 at t_2

allows to talk of Δt Transition Probability $P \left(K_{\rightarrow f_1} \xrightarrow{\Delta t} K_{\rightarrow f_2}^\perp \right)$

“independent of the decay” and connected to $I(f_1, f_2; \Delta t)$.

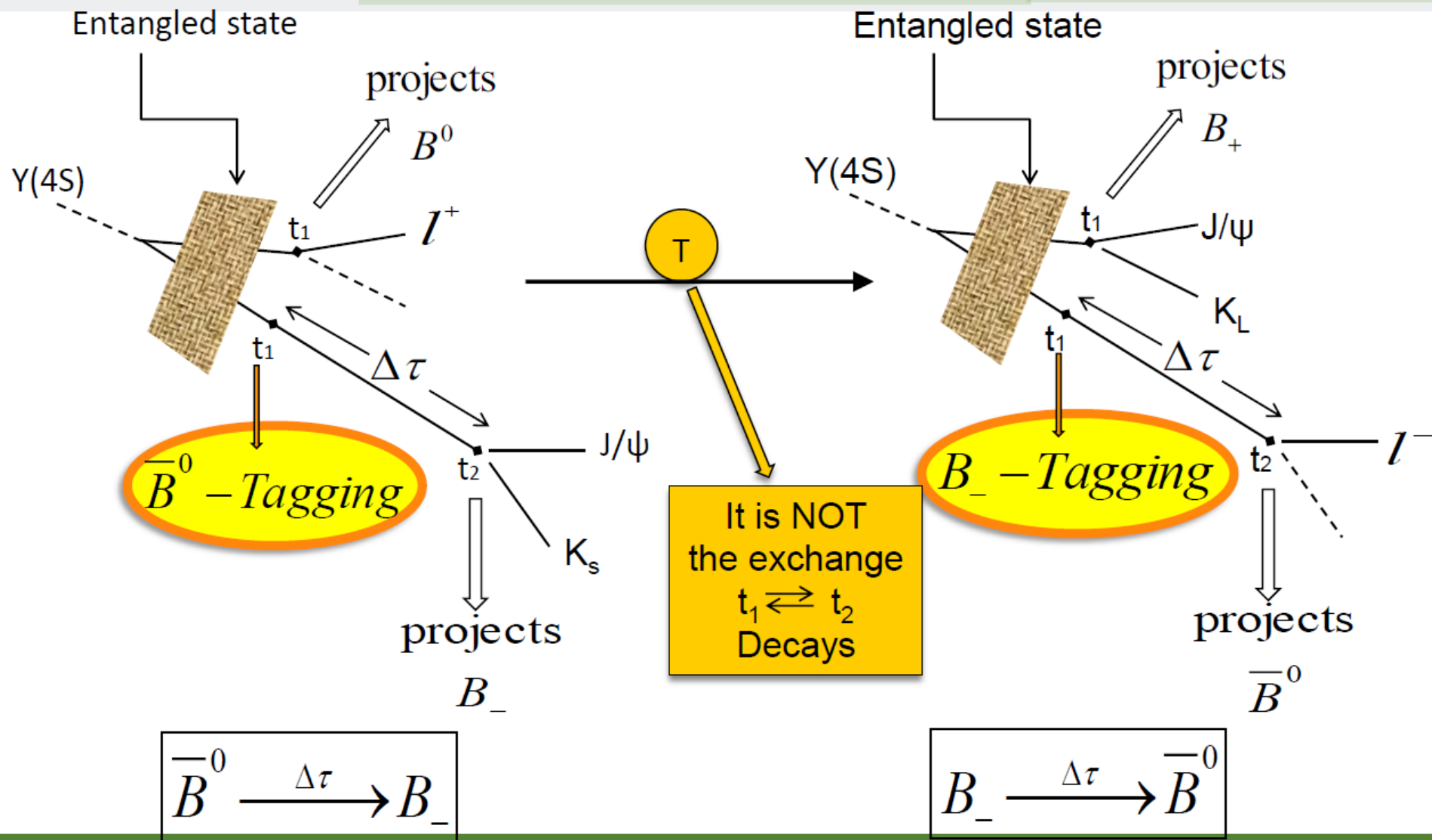
TR-ASYMMETRY: CONCEPTUAL BASIS FOR BYPASSING NO-GO

- Neutral Mesons $K^0 - \bar{K}^0$, $B^0 - \bar{B}^0$ are UNSTABLE and the Decay is irreversible.
- **T and CPT, ANTIUNITARITY!** , need however the exchange of initial and final states →NO-GO.
L. Wolfenstein, PRL 1999 : "The T-reverse of a decaying state is not a physical state".
- **BYPASS** M. C. Banuls, J. B., PLB 1999, NPB 2000 → Do not include the Decay Products in your Asymmetry, write it in terms of Meson States and the Decay should not be an essential ingredient for getting a non-vanishing value:
 - 1) Use the Decay as a **Quantum Filtering Measurement** of the Meson State ONLY:
Orthogonal to Non-Decay State.
 - 2) **Quantum ENTANGLEMENT: Quantum Information** from the First Decay to the (still alive) Partner for the Preparation of the initial Meson State: Non-Decay State **if Antisymmetric entangled system.**
 - 3) The test of Symmetries is made in the Time Evolution of the Partner
from the first to the second decay.
L. Wolfenstein, IJMP E 1999: "It appears to be a true TRV Effect"

WHAT IS T-TRANSFORMATION EXPERIMENTALLY ?

The problem is in the preparation and filtering of the appropriate initial and final meson states for a T-test in transitions

J.B., Martinez Vidal, Villanueva, JHEP 2012, COVER PAGE RMP vol. 87 (2015)



POST-TAG TO THE PAST DECAYED STATE

➤ In the entangled $|i(t)\rangle$ state, there is no privilege of one of the decay times →
Study the implications of observing the second decay to f_2 at time t_2

➤ The partner $K^{(1)}(t = t_2)$ is tagged

$$|K^{(1)}(t = t_2)\rangle = N_1\{\eta_2|K_S\rangle - |K_L\rangle\}$$

which has not been observed! But it decayed at time $t_1 < t_2$

Fixing the observation (η_2, t_2) and evolving t_1 from $t_1=0$ to $t_1=t_2$, **its past state had to be**

$$|K^{(1)}(t = 0)\rangle = N[\eta_2 e^{-i\lambda_L t_2}|K_S\rangle - e^{-i\lambda_S t_2}|K_L\rangle]$$

➤ **DOUBLE SURPRISE!** Not only there is a **post-tag of the initial state**,
it depends on when the second decay will be observed.

OBSERVABILITY OF “BACK FROM THE FUTURE” EFFECT

- Entanglement times $t_1 < t_2$
- Decay t_1 -time distribution to $f_1 = f_2 = f$, at different fixed t_2

$$\begin{aligned} |\langle f | K^{(1)}(t_1) \rangle|_{t_2}^2 &= \mathcal{N} \left\{ e^{-\Gamma_S t_1} + |\rho|^2 e^{-\Gamma_L t_1} \right. \\ &\quad - 2(\Re \rho) e^{-\Gamma t_1/2} \cos(\Delta m) t_1 \\ &\quad \left. - 2(\Im \rho) e^{-\Gamma t_1/2} \sin(\Delta m) t_1 \right\} ; \\ \Gamma &\equiv \Gamma_S + \Gamma_L ; \\ \text{- QM post-diction } \rho(t_2) &= e^{-i(\lambda_S - \lambda_L)t_2} \end{aligned}$$

- Extract the relative PROBABILITY AMPLITUDE

THE K_S -TAG

- Decoherence is reached for **large Δt before the observation of the second decay**

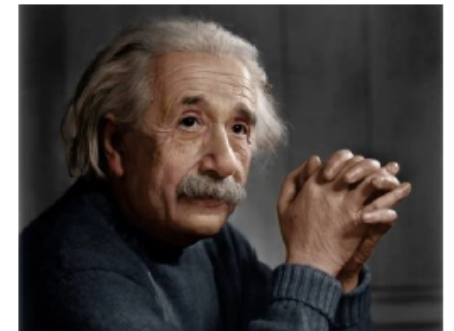
$$e^{-\Delta\Gamma\Delta t/2}/|\eta_2| \ll 1$$

leading to a pure K_S -beam

- Most rewarding: - \mathcal{CP} and $\langle K_L | K_S \rangle \neq 0 \rightarrow$ No decay channel able to tag either K_L or K_S
- After 58 years of CPV: **this POST-TAG condition in times is the only way to study rare K_S -decays.** Compare with 60 year history of K_L decays!
- Example: Difference of charge Asymmetries $A_L - A_S \rightarrow$ Direct test of CPT!

CONCLUSION

- Entanglement in particle anti-particle system $M^0 - \bar{M}^0$
- NOVEL EFFECTS
 - Tools for Particle Physics
 - Quantum Phenomena
- Solution for NO - GO's
 - TR for Unstable Particles
 - K_s - tag
- **POST-TAG of the past-decayed state depending on what and when measurement on the partner in the future.**
- In Classical and Quantum Physics, Time is a parameter to describe the **evolving definite reality, not an observable.**
- With the **surviving correlation-in-time**, Einstein would claim :
“A Spooky Action to the Past”



NO (UNKNOWN) CAUSAL EFFECT

- CAUSAL INFLUENCE says that the cause must precede the effect according to ALL inertial observers, so that for the Post-Tag effect in the entangled K-mesons system –in which there are both time-like and space- like intervals,
 - **If the Interval is time-like**, future is future for all observers → the future to past “influence” is NOT CAUSAL.
 - **If the Interval is space-like**, there could be observers exchanging future and past, BUT the two events could only connect with a signal velocity higher than the speed of light → this “influence” is NOT CAUSAL.
- Then, independent of the space-time interval between the future observation in CM of the second decay and the past state of the partner, **“the Post-Tag correlation in time” effect CANNOT BE A CAUSAL INFLUENCE.**
- Whereas the EPR correlation between observables NEEDS a space-like interval to ensure no causal influence, the Post-Tag effect cannot be a causal influence for ALL cases → no loop-holes. This is an additional argument, besides the fact that TIME IS NOT AN OBSERVABLE, to skate that **the Post-Tag effect goes beyond the EPR correlation.**

FOR PHILOSOPHERS EPISTEMOLOGY

Physics → QM correctly describes the **behaviour of nature when it is observed**

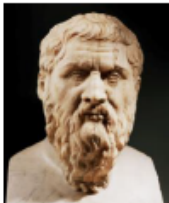
↔ Scientific Methodology

Philosophy → What QM says about nature's reality?

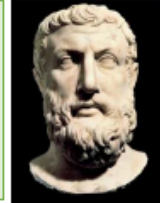
NEW

- Spooky Action at a Distance
 - EPR Correlation-Bell Theorem
 - Lack of Local Realism
- Spooky Action to the Past
 - Surviving Correlation-in-time
 - Lack of Instant Realism

(x,t) is not a definite, separate event ↔ Role of time in QM ?



TIME versus REALITY
Heraclitus vs. Parmenides



**THANK YOU VERY MUCH
FOR YOUR ATTENTION**

