Title: Lecture - Quantum Foundations, PHYS 639

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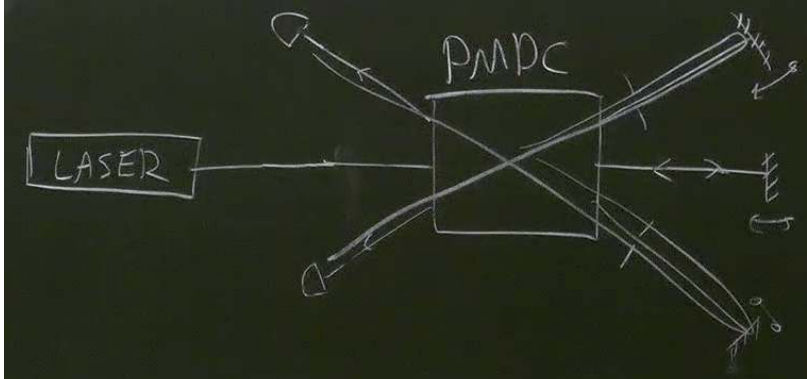
Collection/Series: Quantum Foundations (Elective), PHYS 639, January 6 - February 5, 2025

Subject: Quantum Foundations

Date: January 20, 2025 - 11:30 AM

URL: https://pirsa.org/25010043

The Tirol cross



$$|\alpha\rangle_s|0\rangle_a|0\rangle_b + \epsilon|\alpha\rangle|1\rangle|1\rangle +$$

$$|\alpha\rangle_s|0\rangle_a|0\rangle_b + c|\alpha\rangle|1\rangle|1\rangle + ce^{i\theta}|\alpha\rangle|1\rangle|1\rangle$$

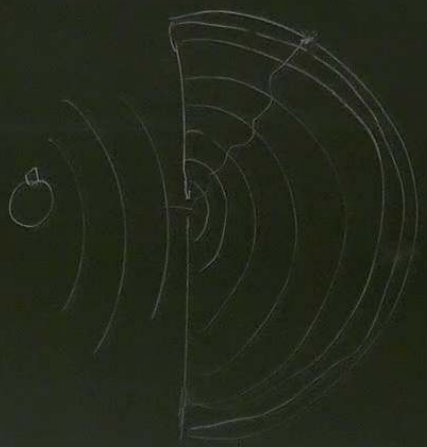
$$|c+c|^2 = 4|c|^2$$

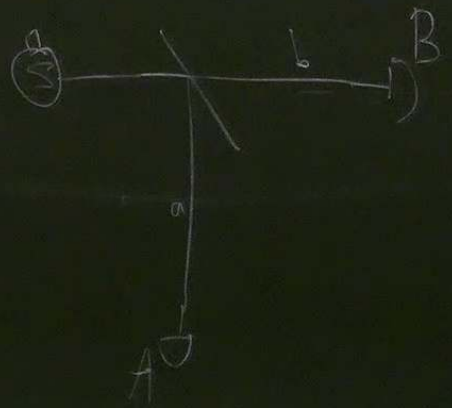
EPR 1935

Einstein 1927

completeness

locality





Def'n.

Completeness: "every element of physical reality (epr) must have a counterpart in the physical theory"

ψ-completeness: All elements of physical reality follow from the quantum state

$[A=\alpha]_a$ is an epr iff $\langle\psi|\hat{P}_{(A=\alpha)_a}|\psi\rangle = 1$

Suff. cond. for the existence of an epr: If, without in any way disturbi

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"If, without in any way disturbi
probability equal to unity)
exists an element of physic

certainty $\Leftrightarrow$ prob $= 1$

If prob$\left((A=\alpha)_a \,|\, (B=\right.$

$\left[\lim_{N\to\infty} \frac{N-100}{N} = 1 \;\middle|\; \text{QBism}\right]$

and if it measurement B does

then $\exists$ an epr $[A=\alpha]_a$ for

Suff. cond. for the existence of an epr

certainty $\Leftrightarrow$ prob $= 1$

$$\lim_{N\to\infty} \frac{N-100}{N} = 1$$

QRISM

"If, without in any way disturbing a sy
probability equal to unity) the v
exists an element of physical reali

If $\text{prob}\left((A=\alpha)_a \,\middle|\, (B=\beta)_b\right) =$

and if if measurement B does not dis
then $\exists$ an epr $[A=\alpha]_a$ for a e

"If, without in any way disturbing a system, we can predict with certainty (i.e. probability equal to unity) the value of a physical quantity, then there exists an element of physical reality corresponding to this quantity"

If $\text{prob}\left((A=\alpha)_a \,\middle|\, (B=\beta)_b \right) = 1$

and if if measurement B does not disturb a

then $\exists$ an epr $[A=\alpha]_a$ for a even when we don't measure B

Locality A system is undisturbed by choices made at spacelike separation from it.

We can prove

$$\left(\begin{matrix}\text{QT}\\ \text{predictions}\end{matrix}\right) \wedge (\psi\text{-completeness}) \wedge \text{locality} \Rightarrow \text{contradiction.}$$

$$\text{prob}\left(\left(A = \begin{matrix} 1 \\ 0 \end{matrix} \right)_a \middle| \left(B = \begin{matrix} 0 \\ 1 \end{matrix} \right)_b \right) = 1$$

(locality) $\Rightarrow$ have an epr

If we perform B and see $B = 0$

then $\exists$ epr $[A = 1]_a$

If we perform B and see $B = 1$

then $\exists$ epr $[A = 0]_a$

$\text{prob}\left(\left(A = \begin{matrix} 1 \\ 0 \end{matrix} \right)_a \middle| \left(B = \begin{matrix} 0 \\ 1 \end{matrix} \right)_b \right) = 1$

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If we perform B and see $B=1$

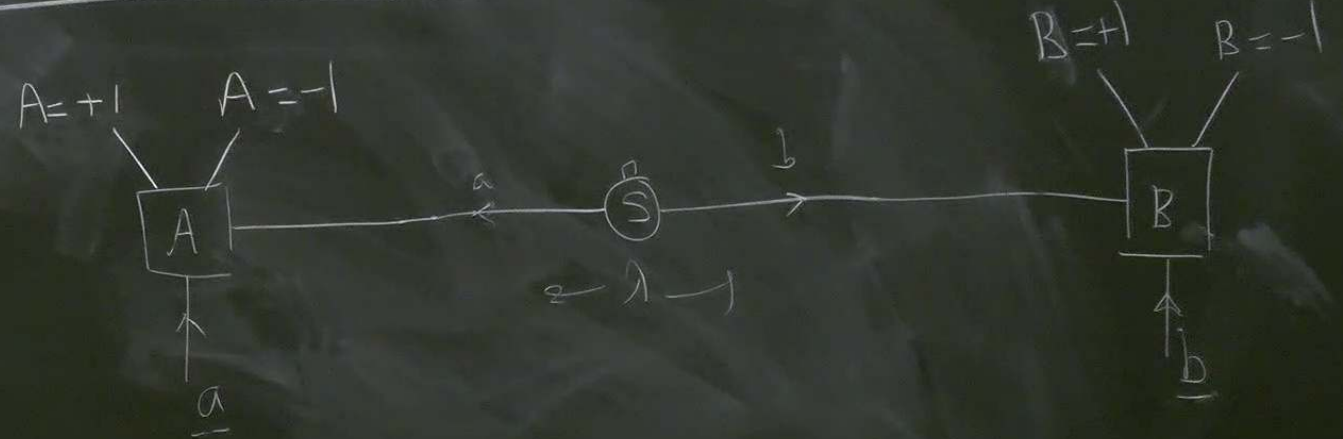
then $\exists$ epr $[A=0]_a$

locality $\Rightarrow$ have an epr $[A=\alpha]_a$ even if we don't perform measure B.

But if $|\psi\rangle = \frac{1}{\sqrt{2}}(|a\rangle + |b\rangle)$

then $\langle \psi | \hat{P}_{A=\alpha} | \psi \rangle = \frac{1}{2}$

J.S. Bell 1964



Introduce λ (hidden variables)

$$A(\underline{a}, \lambda) = \pm 1 \qquad B(\underline{b}, \lambda) = \pm 1$$

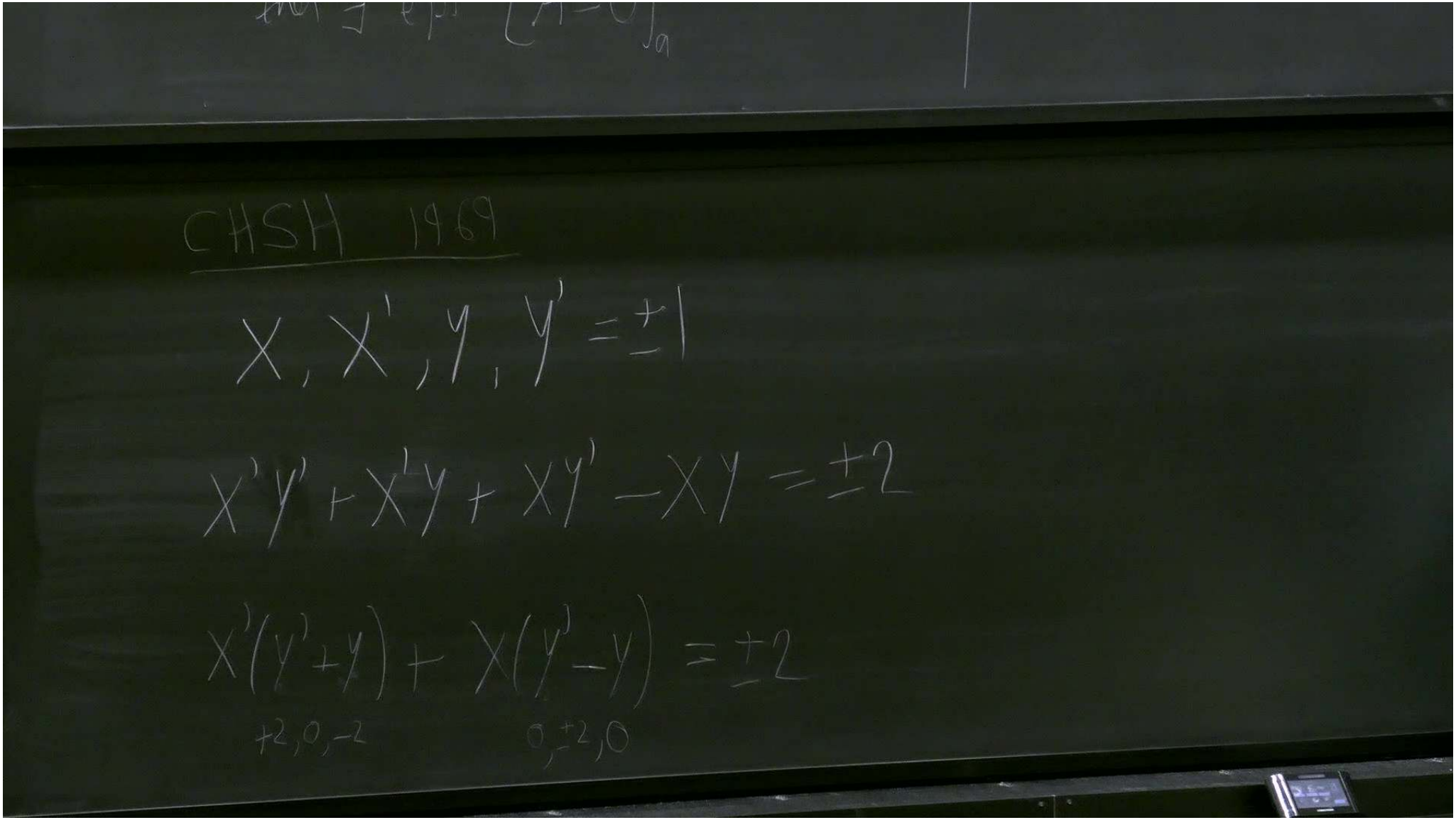
ψ-completeness All elements of [illegible]
quantum state

$[A=\alpha]_a$ is an epr iff $\langle\psi|\hat{P}_{(A=\alpha)_a}|\psi\rangle = 1$

$$E(\underline{a},\underline{b}) = \int_\Gamma A(\underline{a},\lambda)\, B(\underline{b},\lambda)\, \rho(\lambda)\, d\lambda$$

$\rho(\lambda)$ is a distribution over λ

$$\rho(\lambda) \geq 0 \qquad \int_\Gamma \rho(\lambda)\, d\lambda = 1$$


CHSH 1969
$X, X', Y, Y' = \pm 1$
$X'Y' + X'Y + XY' - XY = \pm 2$
$X'(Y' + Y) + X(Y' - Y) = \pm 2$
+2, 0, -2
0, ±2, 0