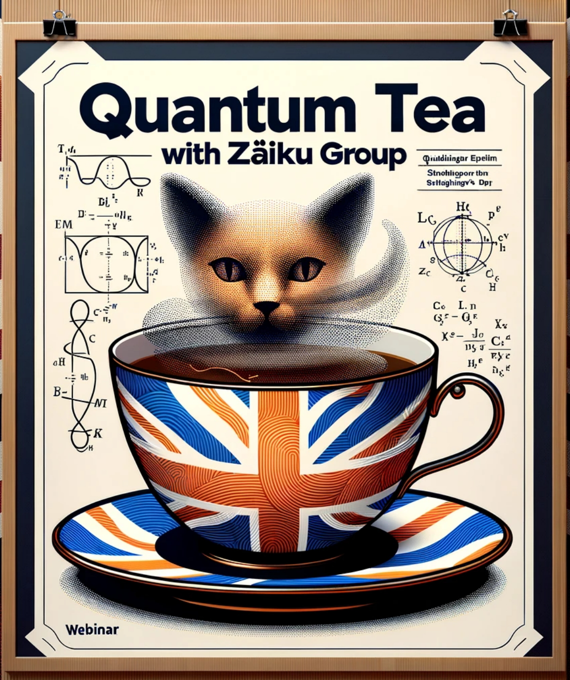

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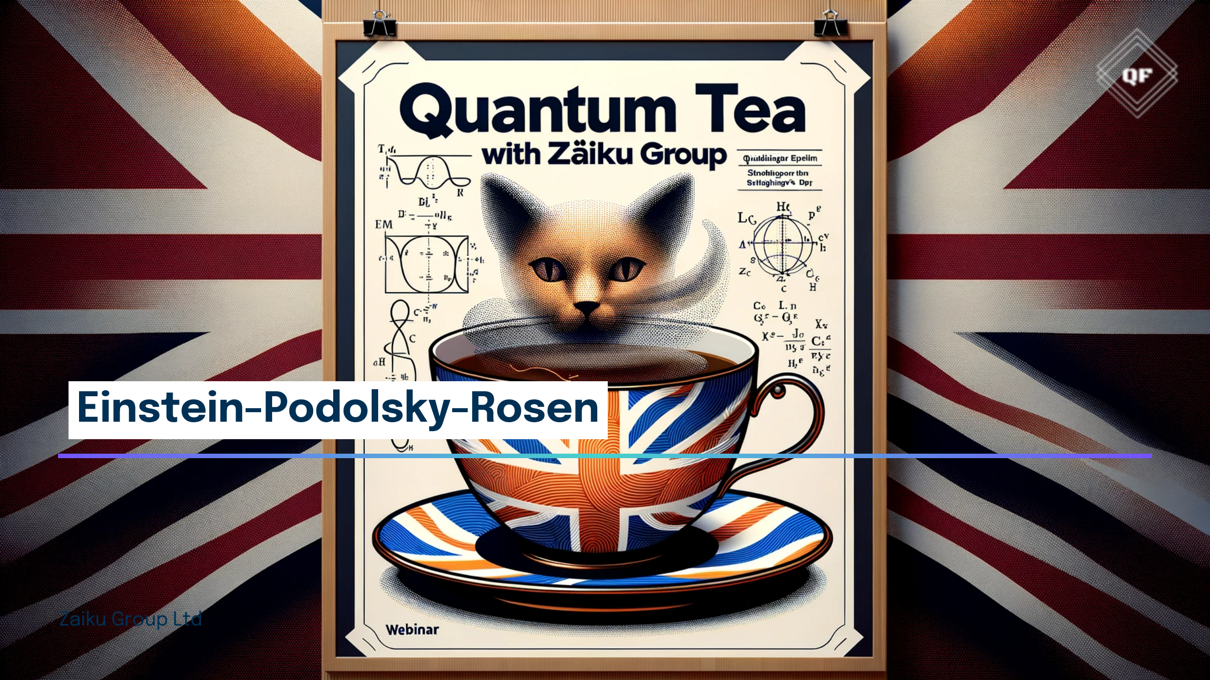
Quantum Formalism

Overview

1. Einstein-Podolsky-Rosen



Einstein-Podolsky-Rosen

- Ψ) Following the uncertainty principle, if two observables do not commute, we can't know their eigenvalues with maximum precision simultaneously
- Ψ) When measuring one of these observables, the wave function collapses to the eigenstate that corresponds to the value measured
- Ψ) The quantity associated with the other observable is undetermined and without physical reality
- Ψ) We know that the individual terms of a superposition represent potentialities and in this case, we can only talk about the probability of finding a certain value to this other observable
- Ψ) Einstein wanted to show that this determination was not fundamental $\Longrightarrow$ The quantities relatives to two observables that do not commute between them would have an objective and simultaneous reality
- Ψ) The conclusion was that the wave function did not have a complete description of the physical system

Ψ) To prove this, Einstein needed to attack the uncertainty principle proposing experiments where quantities associated with observables that do not commute could be measured simultaneously with high precision

MAY 15, 1935 PHYSICAL REVIEW VOLUME 47

Can Quantum-Mechanical Description of Physical Reality Be Considered Complete?

A. EINSTEIN, B. PODOLSKY AND N. ROSEN, *Institute for Advanced Study, Princeton, New Jersey*

(Received March 25, 1935)

In a complete theory there is an element corresponding to each element of reality. A sufficient condition for the reality of a physical quantity is the possibility of predicting it with certainty, without disturbing the system. In quantum mechanics in the case of two physical quantities described by non-commuting operators, the knowledge of one precludes the knowledge of the other. Then either (1) the description of reality given by the wave function in quantum mechanics is not complete or (2) these two quantities cannot have simultaneous reality. Consideration of the problem of making predictions concerning a system on the basis of measurements made on another system that had previously interacted with it leads to the result that if (1) is false then (2) is also false. One is thus led to conclude that the description of reality as given by a wave function is not complete.

In summary, the authors followed two definitions

(1) A theory is complete if every element of the physical reality must have a counterpart in the physical theory

(2) If, without in any way disturbing a system, we can predict with certainty (*i. e.*, with probability equal to unity) the value of a physical reality corresponding to this physical quantity

We will not use the experiment suggested by EPR here. It is more didact to study the one proposed by Bohm [2] where a particle with total spin null, decays in two particles of spin $1/2$ with opposed velocities.

Correlations in Spin-Singlet States

- Consider a two-electron system in a spin singlet state (total spin zero)
- The ket state can be written as

$$|\psi_z\rangle = \frac{1}{\sqrt{2}} \left(|z_+\rangle_A \otimes |z_-\rangle_B - |z_-\rangle_A \otimes |z_+\rangle_B\right)$$

where we have explicitly indicated the quantization direction.

Remember that

$|z_+\rangle_A \otimes |z_-\rangle_B \Rightarrow$ Electron A with spin-up state, Electron B with spin-down state
$|z_-\rangle_A \otimes |z_+\rangle_B \Rightarrow$ Electron A with spin-down state, Electron B with spin-up state

Correlations in Spin-Singlet States

- Ψ) Suppose we measure the spin component of one of the electrons. There is a $50-50$ chance of getting either up or down because the composite system may be $|z_+\rangle_A \otimes |z_-\rangle_B$ or $|z_-\rangle_A \otimes |z_+\rangle_B$ with equal probabilities.
- Ψ) If one of the components of electron A is shown to be in the spin-up state, the other is necessarily in the spin-down state, and vice-versa
- Ψ) When the spin component of electron A is shown to be up, the measurement apparatus has selected the first (red) term

$$|\psi_z\rangle = \frac{1}{\sqrt{2}}\left(|z_+\rangle_A \otimes |z_-\rangle_B - |z_-\rangle_A \otimes |z_+\rangle_B\right)$$

- Ψ) A subsequent measurement of the spin component of electron B must ascertain that the state ket of the composite system is given by $|z_+\rangle_A \otimes |z_-\rangle_B$

Correlations in Spin-Singlet States

- Ψ) It is remarkable that this kind of correlation can persist even if the two particles are well separated and have ceased to interact provided as they fly apart, there is no change in their spin states
- Ψ) To reply to the EPR argument Bohr wrote a paper seven-page response to this question.

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Can Quantum-Mechanical Description of Physical Reality be Considered Complete?

N. Bohr, *Institute for Theoretical Physics, University, Copenhagen*

(Received July 13, 1935)

It is shown that a certain "criterion of physical reality" formulated in a recent article with the above title by A. Einstein, B. Podolsky and N. Rosen contains an essential ambiguity when it is applied to quantum phenomena. In this connection a viewpoint termed "complementarity" is explained from which quantum-mechanical description of physical phenomena would seem to fulfill, within its scope, all rational demands of completeness.

Bohr Response

- He admits that there is no ”mechanical disturbance” in Region B due to the actions carried out in Region A
- He states that “there is essentially the question of an influence on the very conditions which define the possible types of predictions regarding the future behavior of the system” (in B)
- He questions the applicability of question 2 to the case considered
- Bohr is thus connecting the notion of physical reality only to what can be predicted about system B, and making this prediction depends on what is done in A.
- In this way, he tries to conserve mechanical locality but introduces a kind of “action at a distance” since he attributed the term ”physical reality” to what we know about the system.

Bohr Response

Ψ) Thus, Bohr removed from the notion of physical reality the reference to the parts of nature that exist and we can or cannot know, and limited himself to only the parts that we can know, therefore being subject to the choice of experiments that will be carried out.

Ψ) In summary, this orthodox interpretation of the spin-singlet case says,

- A measurement is a selective process $\Longrightarrow$ When S_z of particle A is measured to be positive

$$|\psi_z\rangle = \frac{1}{\sqrt{2}}\left(|z_+\rangle_A \otimes |z_-\rangle_B - |z_-\rangle_A \otimes |z_+\rangle_B\right)$$

  then the component $|z_+\rangle_A \otimes |z_-\rangle_B$ is selected
- A subsequent measurement of the other particle (B) merely ascertains that the system is still in $|z_+\rangle_A \otimes |z_-\rangle_B$

Bohr Response

- We must accept that a measurement of what appears to be a part of the system is to be regarded as a measurement of the whole system
- This type of response was rejected in the EPR paper "...one would not arrive at our conclusion if one insisted that two or more physical quantities can be regarded as simultaneous elements of reality *only when they can be simultaneously measured or predicted*"
- An impasse of a metaphysical nature was thus reached. It took almost 30 years for this impasse to be translated into physical terms, which could be verified in the laboratory...

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