The Many-Worlds Interpretation

Lev Vaidman
A tale of a single world universe

Quantum states of all macroscopic objects are Localized Wave Packets all the time

\[
\Psi_{\text{UNIVERSE}}(\vec{r}_1, \vec{r}_2, \ldots, \vec{r}_N, t) = \psi^1(\vec{r}_1) \psi^2(\vec{r}_2) \ldots \psi^N(\vec{r}_N)
\]

\[
\Psi_{\text{WORLD}} = \psi^{i}_{\text{CM}}(\vec{r}_1^{CM}) \phi^{i}_{\text{rel}}(\vec{r}_{1i} - \vec{r}_{1j}) \psi^{2}_{\text{CM}}(\vec{r}_2^{CM}) \phi^{2}_{\text{rel}}(\vec{r}_{2i} - \vec{r}_{2j}) \ldots \psi^{M}_{\text{CM}}(\vec{r}_M^{CM}) \phi^{M}_{\text{rel}}(\vec{r}_{Mi} - \vec{r}_{Mj}) \Phi^{\text{REST}}
\]

\[ \Rightarrow \rho(\vec{r}) \]

\[ \rho(\vec{r}) \text{ of a cat!} \]

TRIVIAL experience \[ \Leftrightarrow \]

Almost the same as in

Textbook collapse

GRW-Pearle Collapse (mass density)

Bohmian trajectories

Laplacian Determinism
Two worlds universe
Two worlds universe

This is a multiple worlds universe
Two worlds universe
Two worlds universe

One world does not disturb the other
Two worlds universe

One world does not disturb the other
Two worlds universe
One world does not disturb the other
Two worlds universe

One world does not disturb the other
Two worlds universe

Preferred basis: \( \{ |A\rangle, |B\rangle \} \) or \( \left\{ \frac{|A\rangle+|B\rangle}{\sqrt{2}}, \frac{|A\rangle-|B\rangle}{\sqrt{2}} \right\} = \{ |+\rangle, |-\rangle \} \)
Two worlds universe

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Two worlds universe

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STABILITY

\[ |A\rangle |R\rangle_{MD_A} |R\rangle_{MD_B} |R\rangle_{ENV} \rightarrow |A\rangle |V\rangle_{MD_A} |R\rangle_{MD_B} |R\rangle_{ENV} \]
Two worlds universe

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\[ |A\rangle |R\rangle_{MDA} |R\rangle_{MDB} |R\rangle_{ENV} \]
\[ \rightarrow |A\rangle |V\rangle_{MDA} |R\rangle_{MDB} |R\rangle_{ENV} \]
\[ \rightarrow |A\rangle |V\rangle_{MDA} |R\rangle_{MDB} |A\rangle_{ENV} \]

\[ |B\rangle |R\rangle_{MDA} |R\rangle_{MDB} |R\rangle_{ENV} \]
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\( \rightarrow |B\rangle |R\rangle_{MDA} |V\rangle_{MDB} |R\rangle_{ENV} \)
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STABILITY

\( |A\rangle |R\rangle_{MD_A} |R\rangle_{MD_B} |R\rangle_{ENV} \)
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\( \rightarrow |A\rangle |V\rangle_{MD_A} |R\rangle_{MD_B} |A\rangle_{ENV} \)

\( |B\rangle |R\rangle_{MD_A} |R\rangle_{MD_B} |R\rangle_{ENV} \)
\( \rightarrow |B\rangle |R\rangle_{MD_A} |V\rangle_{MD_B} |R\rangle_{ENV} \)
\( \rightarrow |B\rangle |R\rangle_{MD_A} |V\rangle_{MD_B} |B\rangle_{ENV} \)
Two worlds universe

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STABILITY

$|A\rangle |R\rangle_{MD A} |R\rangle_{MD B} |R\rangle_{ENV}\n\rightarrow |A\rangle |V\rangle_{MD A} |R\rangle_{MD B} |R\rangle_{ENV}\n\rightarrow |A\rangle |V\rangle_{MD A} |R\rangle_{MD B} |A\rangle_{ENV}$

$|B\rangle |R\rangle_{MD A} |R\rangle_{MD B} |R\rangle_{ENV}\n\rightarrow |B\rangle |R\rangle_{MD A} |V\rangle_{MD B} |R\rangle_{ENV}\n\rightarrow |B\rangle |R\rangle_{MD A} |V\rangle_{MD B} |B\rangle_{ENV}$

$|+\rangle |R\rangle_{MD A} |R\rangle_{MD B} |R\rangle_{ENV}$
Two worlds universe

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$|B\rangle |R\rangle_{MD_A} |R\rangle_{MD_B} |R\rangle_{ENV}$
$\rightarrow |B\rangle |R\rangle_{MD_A} |V\rangle_{MD_B} |R\rangle_{ENV}$
$\rightarrow |B\rangle |R\rangle_{MD_A} |V\rangle_{MD_B} |B\rangle_{ENV}$

$|+\rangle |R\rangle_{MD_A} |R\rangle_{MD_B} |R\rangle_{ENV}$
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STABILITY

\[ |A\rangle |R\rangle_{MD_A} |R\rangle_{MD_B} |R\rangle_{ENV} \]
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\[ \rightarrow |B\rangle |R\rangle_{MD_A} |V\rangle_{MD_B} |R\rangle_{ENV} \]
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\[ |+\rangle |R\rangle_{MD_A} |R\rangle_{MD_B} |R\rangle_{ENV} \]
\[ \rightarrow |A\rangle |V\rangle_{MD_A} |R\rangle_{MD_B} + |B\rangle |R\rangle_{MD_A} |V\rangle_{MD_B} \frac{1}{\sqrt{2}} |R\rangle_{ENV} \]
Two worlds universe

Preferred basis: \( \{ |A\rangle, |B\rangle \} \) or
\[
\left\{ \frac{|A\rangle + |B\rangle}{\sqrt{2}}, \frac{|A\rangle - |B\rangle}{\sqrt{2}} \right\} = \{ |+\rangle, |-\rangle \}
\]

STABILITY

\[ A \]

\[ B \]

\[ \begin{align*}
|A\rangle |R\rangle_{MDA} |R\rangle_{MDB} |R\rangle_{ENV} \\
\rightarrow |A\rangle |V\rangle_{MDA} |R\rangle_{MDB} |R\rangle_{ENV} \\
\rightarrow |A\rangle |V\rangle_{MDA} |R\rangle_{MDB} |A\rangle_{ENV} \\
|B\rangle |R\rangle_{MDA} |R\rangle_{MDB} |R\rangle_{ENV} \\
\rightarrow |B\rangle |R\rangle_{MDA} |V\rangle_{MDB} |R\rangle_{ENV} \\
\rightarrow |B\rangle |R\rangle_{MDA} |V\rangle_{MDB} |B\rangle_{ENV} \\
|+\rangle |R\rangle_{MDA} |R\rangle_{MDB} |R\rangle_{ENV} \\
\rightarrow \left| \frac{A\rangle |V\rangle_{MDA} |R\rangle_{MDB} + |B\rangle |R\rangle_{MDA} |V\rangle_{MDB}}{\sqrt{2}} \right| R\rangle_{ENV} \\
\rightarrow \left| \frac{A\rangle |V\rangle_{MDA} |R\rangle_{MDB} + |B\rangle |R\rangle_{MDA} |V\rangle_{MDB}}{\sqrt{2}} \right| B\rangle_{ENV}
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\[ |+\rangle |R\rangle_{MDA} |R\rangle_{MDB} |R\rangle_{ENV} \]
\[ \rightarrow \frac{|A\rangle |V\rangle_{MDA} |R\rangle_{MDB} + |B\rangle |R\rangle_{MDA} |V\rangle_{MDB}}{\sqrt{2}} |R\rangle_{ENV} \]
\[ \rightarrow \frac{|A\rangle |V\rangle_{MDA} |R\rangle_{MDB} |A\rangle_{ENV} + |B\rangle |R\rangle_{MDA} |V\rangle_{MDB} |B\rangle_{ENV}}{\sqrt{2}} \]

\[ \frac{|V\rangle_{MDA} |R\rangle_{MDB} |A\rangle_{ENV} + |R\rangle_{MDA} |V\rangle_{MDB} |B\rangle_{ENV}}{2} + \frac{|V\rangle_{MDA} |R\rangle_{MDB} |A\rangle_{ENV} - |R\rangle_{MDA} |V\rangle_{MDB} |B\rangle_{ENV}}{2} \]
What is “a world” in the many-worlds picture?

experience $i \iff$ world $i \iff \Psi_i(r_1, r_2, \ldots, r_N, t)$

$\Psi_i = \psi_i^{\text{OBJECT}_1} \psi_i^{\text{OBJECT}_2} \ldots \psi_i^{\text{OBJECT}_K} \phi_i^{\text{REST}}$

$\psi_i^{\text{OBJECT}}$ is a Localized Wave Packet for a period of time

A world consist of:
- "classical" macroscopic objects rapidly measured by the environment,
What is “a world” in the many-worlds picture?

Experience $i$ $\iff$ World $i$ $\iff$ $\Psi_i(r_1, r_2, \ldots, r_N, t)$

$$\Psi_i = \psi_i^{\text{OBJECT}} \psi_i^{\text{OBJECT}_2} \ldots \psi_i^{\text{OBJECT}_K} \phi_i^{\text{REST}}$$

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A world consists of:
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- quantum objects measured only occasionally (at world splitting events),
What is “a world” in the many-worlds picture?

experience \( i \) \( \iff \) world \( i \) \( \iff \) \( \Psi_i(\vec{r}_1, \vec{r}_2, \ldots, \vec{r}_N, t) \)

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A world consist of:
- "classical" macroscopic objects rapidly measured by the environment,
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Many worlds universe

Single Slit
Diffraction
Pattern

Photons in this area are diffracted and show a smooth curve centered on screen

Photon Source
Diffraction Slit

Film Strip
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Many worlds universe

Locality and strength of the interaction to numerous particles ensure stability of all worlds.
The tree of worlds
The tree of worlds
The tree of worlds
Test of the MWI
Test of the MWI
Test of the MWI
Test of the MWI
Test of the MWI

Diagram:

- A
- B
Test of the MWI
Test of the MWI
The tree of worlds
Test of the MWI
Test of the MWI
Do we experience amplitude?

\[ |\Psi_i\rangle = \sqrt{\frac{3}{4}} |\Psi_A\rangle + \sqrt{\frac{1}{4}} |\Psi_B\rangle \quad ? \quad |\Psi_i\rangle = \sqrt{\frac{1}{4}} |\Psi_A\rangle + \sqrt{\frac{3}{4}} |\Psi_B\rangle \]

Experience world B  \iff  Experience world B
Do we experience amplitude?

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Experience world B \(\iff\) Experience world B
Probability

Probability is the likelihood or chance that something is the case or will happen.

Wikipedia
**Probability**

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Wikipedia

‘Interpreting probability’ is a commonly used but misleading name for a worthy enterprise. The so-called ‘interpretations of probability’ would be better called ‘analyses of various concepts of probability’

SEP
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SEP

The classical probability of an event is simply the fraction of the total number of possibilities in which the event occurs.
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The Logical probability: the possibilities may be assigned unequal weights, and probabilities can be computed whatever the evidence may be, symmetrically balanced or not.
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Frequency Interpretation: the probability of an attribute A in a finite reference class B is the relative frequency of actual occurrences of A within B.
The classical probability of an event is simply the fraction of the total number of possibilities in which the event occurs.

The Logical probability: the possibilities may be assigned unequal weights, and probabilities can be computed whatever the evidence may be, symmetrically balanced or not.

Frequency Interpretation: the probability of an attribute A in a finite reference class B is the relative frequency of actual occurrences of A within B.

Propensity Interpretation: disposition, or tendency of a given type of physical
Subjective probability

degrees of confidence, or credences, or “partial” beliefs of suitable agents.
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The betting interpretation, de Finetti:
Your degree of belief in $E$ is $p$ iff $p$ units of utility is the price at which you would buy or sell a bet that pays 1 unit of utility if $E$, 0 if not $E$. 
Classical Many Worlds
Teleportation
Teleportation
Classical teleportation
Classical teleportation
symmetry \implies p = 1
Probability of something to happen – A or B?
Probability of something to happen – $A$ or $B$?
Probability of something to happen – A or B?
Probability of something to happen – A or B?
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Probability of something to happen – A or B?
Probability of something to happen – A or B?

Here: A and B

There is nothing to be ignorant about, everything is known.
Probability of something to happen – A or B?

Here: A and B

There is nothing to be ignorant about, everything is known.

No ignorance, no randomness

NO PROBABILITY
Probability of something to happen – A or B?

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But a good reason to bet!

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Probability of something to happen – \(A\) or \(B\)?

Here: \(A\) and \(B\)

There is nothing to be ignorant about, everything is known.

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The betting interpretation, de Finetti:

Your degree of belief in \(E\) is \(p\) iff \(p\) units of utility is the price at which you would buy or sell a bet that pays 1 unit of utility if \(E\), 0 if not \(E\).
Measure of existence: Can it be different from 0 and 1?

\[
\begin{align*}
\mu_A &= 0 \\
\mu_B &= 0
\end{align*}
\]

\[
\mu = 1
\]
Measure of existence: Can it be different from 0 and 1?

\[ \mu_A = 1 \]

\[ \mu_B = 1 \]

\[ \mu = 0 \]
Measure of existence: Can it be different from 0 and 1?

\[ \mu_A = 0 \]

\[ \mu = 1 \]

\[ \mu_B = 0 \]
Measure of existence: Can it be different from 0 and 1?

\[ \mu_A = 5 \]
\[ \mu_B = 3 \]

de Finetti readiness to bet is proportional to the measure of existence
Probability Problems of the MWI of QM
Probability Problems of the MWI of QM

Probability given by the number of worlds yields wrong predictions
Probability Problems of the MWI of QM

Probability given by the number of worlds yields wrong predictions

\[ | \Psi \rangle = \sqrt{0.9} \, | \Psi_A \rangle + \sqrt{0.1} \, | \Psi_B \rangle \]
Probability Problems

It seems that it is good to play Russian quantum roulette.
Probability Problems

It seems that it is good to play Russian quantum roulette.
The Probability Problem

In the MWI, there is no meaning for probability
The Probability Problem

In the MWI there is no meaning for probability

There is no randomness and no ignorance

Probability of what?

Probability of something to happen – A or B?

In MWI - A and B

There is nothing to be ignorant about, everything, $|\Psi(t)\rangle$, is known.
The Probability Problem

In the MWI, there is no meaning for probability.

There is no randomness and no ignorance.

Probability of what?

Probability of something to happen – A or B? In MWI - A and B

There is nothing to be ignorant about, everything, $|\Psi(t)\rangle$, is known.

Textbook collapse, GRW – randomness probability.
Add an Observer

Schrödinger:

\[ |\Psi\rangle \rightarrow \sqrt{0.9} \, |\Psi_A\rangle + \sqrt{0.1} \, |\Psi_B\rangle \]
Collapse

Random event: B and not A
Add an Observer

Schrödinger:

\[ |\Psi\rangle \rightarrow \sqrt{0.9} |\Psi_A\rangle + \sqrt{0.1} |\Psi_B\rangle \]
Collapse

Random event: B and not A
Bohmian Mechanics

Ignorance probability: the observer does not know the initial Bohmian position
Many Worlds (Schrödinger):

Probability of what?
Ignorant of what?
MWI: Give up probability
MWI: Give up probability

Probability postulate is replaced by

**Behavior Principle:**
We should care about all our successive worlds in proportion to their measures of existence.

Measure of existence of world $i$: $\mu_i = |\langle \Psi_{\text{UNIVERSE}} | \Psi_{\text{WORLD}_i} \rangle|^2 = |\alpha_i|^2$
MWI: Give up probability

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**Behavior Principle** $\Rightarrow$

I should bet 1:9: Get 1 if A, pay 9 if B
MWI: Give up probability

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**Behavior Principle**

I should bet 1:9 Get 1 if A, pay 9 if B

I should not play Russian quantum roulette
MWI: Give up probability

Probability postulate is replaced by

**Behavior Principle:**
We should care about all our successive worlds in proportion to their measures of existence.

Measure of existence of world

\[ \mu_i = |\langle \Psi_{\text{UNIVERSE}} | \Psi_{\text{WORLD}_i} \rangle|^2 = |\alpha_i|^2 \]

**Behavior Principle**  \[\Rightarrow\]

I should bet 1:9 Get 1 if A, pay 9 if B

I should not play Russian quantum roulette

I should bet as if I have a concept of probability
I should bet as if I have a concept of probability because my decedants have ignorance probability meaning.
I should bet as if I have a concept of probability because my decedants have ignorance probability meaning

\[ \mu_i = |\alpha_i|^2 \] as an ignorance probability measure
Sleeping Pill Experiment

Vaidman (1998) ISPS

Ignorance probability of the descendants A and B
What is the probability that you are in A?
What is the probability that you are in A?

What is the probability that you are in A?
Only $I_A$ and $I_B$ can give this answer.

What is the probability that you are in A?

What is the probability that you are in A?
Since all the descendants yield the same answer we can relate it to me before the experiment. I put my bet for the descendants. They have probability. Thus, my bet is for a probabilistic event. This is the ignorance probability meaning of the measure of existence.
Is there a physical meaning of $\mu_i = |\alpha_i|^2$ of a present world?
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Should $I_A$ behave differently than $I_B$ because $\mu_A = 9\mu_B$?
Is there a physical meaning of \( \mu_i = |\alpha_i|^2 \) of a **present** world?

We put “intelligent bet” according to \( \mu_i = |\alpha_i|^2 \) of **future** worlds.

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Should $I_A$ behave differently than $I_B$ because $\mu_A = 9 \mu_B$?
I am from another galaxy. Our technology is 10 million years ahead.
I am from another galaxy. Our technology is 10 million years ahead.

I like betting. Would you like to bet?
Are you ready to bet 1:1? Get 1 if A, pay 1 if B
Are you ready to bet 1:1? Get 1 if A, pay 1 if B

\[ I_B \] should say no! The creature can always win.
Are you ready to bet 1:1? Get 1 if A, pay 1 if B

$I_B$ should say no! The creature can always win.

$I_A$ should say yes! I will have at least 6.4 :3.6 odds to win.
I can do to the neutron what the creature can do to me.
I can do to the neutron what the creature can do to me

Neutron interferometer

\[ \begin{align*}
0.9 & \quad A \\
0.1 & \quad B
\end{align*} \]
I can do to neutron what the creature can do to me

Neutron interferometer
MWI + Decision Theory \[ \Rightarrow \quad p = |\alpha_i|^2 \]
MWI + Decision Theory $\implies p = |\alpha_i|^2$
There is no “real” probability in the MWI

Probability of an event is replaced by measure of existence of the world with this event and probability postulate is replaced by “behavior principle”

Measure of existence of future worlds can be given a meaning as an ignorance probability of the descendents of the observer.

Measure of existence of a present world has a physical meaning as a measure of ability to interfere with parallel worlds
There is no “real” probability in the MWI

Probability of an event is replaced by measure of existence of the world with this event and probability postulate is replaced by “behavior principle”

Measure of existence of future worlds can be given a meaning as an ignorance probability of the descendents of the observer.

Measure of existence of a present world has a physical meaning as a measure of ability to interfere with parallel worlds.
Sleeping Beauty Controversy

Beaty, what is your credence for Tails?  

Elga: $\frac{1}{3}$  
Lewis: $\frac{1}{2}$

Tuesday

Monday

Fair coin $\frac{1}{2} : \frac{1}{2}$
Sleeping Beauty Controversy

Beaty, what is your credence for Tails?

Elga: $\frac{1}{3}$

Lewis: $\frac{1}{2}$

Tuesday

Monday

Fair coin $\frac{1}{2} : \frac{1}{2}$
Sleeping Beauty Controversy

Beaty, what is your credence for Tails?  

Elga: 1/3  
Lewis: 1/2

Tuesday

Monday

Fair coin $\frac{1}{2} : \frac{1}{2}$
Sleeping Beauty Controversy

Beaty, what is your credence for Tails?

Elga: 1/3  
Lewis: 1/2

Tuesday

Monday

Fair coin ½ : ½
Sleeping Beauty Controversy

Beaty, what is your credence for Tails?

Elga: 1/3  
Lewis: 1/2

Tuesday

Monday

Fair coin ½ : ½
Sleeping Beauty Controversy

Beaty, what is your credence for Tails?  

Elga: 1/3  
Lewis: 1/2

Tuesday

Fair coin ½ : ½

Monday
Sleeping Beauty Controversy

Beaty, what is your credence for Tails?  

Elga: $\frac{1}{3}$  
Lewis: $\frac{1}{2}$

Tuesday

Monday

Fair coin $\frac{1}{2} : \frac{1}{2}$
Sleeping Beauty Controversy

Beaty, what is your credence for Tails?  

Elga: 1/3  
Lewis: 1/2

Tuesday

Monday

Fair coin \( \frac{1}{2} : \frac{1}{2} \)
Sleeping Beauty Quantumland

Beaty, what is your credence for Tails?  

MWI: 1/3

Tuesday  

Measure of existence of each world = ½

Monday  

Quantum Fair coin ½ : ½
Interaction-free measurement

A. Elitzur and L. Vaidman

**BOMB:**

explodes when any particle “touches” it

interacts only through explosion
Interaction-free measurement

A. Elitzur and L. Vaidman

BOMB:

explodes when any particle "-touches" it

interacts only through explosion
Interaction-free measurement

A. Elitzur and L. Vaidman

BOMB:

explodes when any particle “touches” it

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Interaction-free measurement
Interaction-free measurement
Interaction-free measurement
Interaction-free measurement
Interaction-free measurement
The Many-Worlds Interpretation is an approach to quantum mechanics according to which, in addition to the world we are aware of directly, there are many other similar worlds which exist in parallel at the same space and time. The existence of the other worlds makes it possible to remove randomness and action at a distance from quantum theory and thus from all physics.