No qualms about quantum theory

views from the past millennium

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Menu

– What is a physical theory?

– What are the preexisting concepts in quantum theory?

– Probabilities for what?

– Is quantum evolution reversible?

– What is state reduction? Do wave functions collapse?

– Is there instant action at a distant?

– Is quantum theory nonlocal?

– Where is Heisenberg's cut?

– How many interpretations do we need?

– Is there a measurement problem?

Physical theories

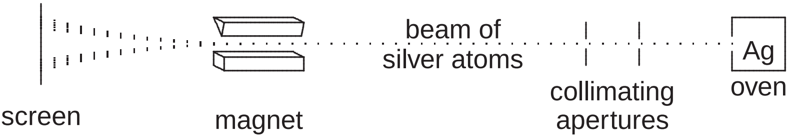
A physical theory has three defining constituents:
– the physical phenomena
– the mathematical formalism
– the interpretation, which links the formalism with the phenomena

and it relies on preexisting concepts.

All physical theories are local theories with local interactions and local conservation laws.

Events

Quantum mechanics can be used to predict probabilities — probabilities for what? For events!



Events

– are localized in space and in time (by short-range interactions); events are linked by particles, so that a causal history evolves and the space-time structure acquires meaning

– are irreversible; events leave a document behind, which can be amplified to bring the event to human attention

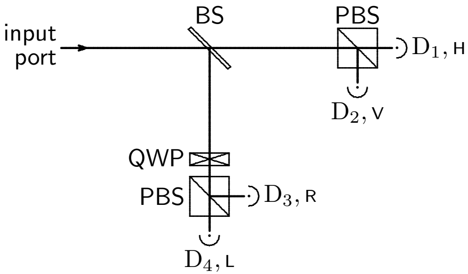
– are randomly realized

Recommended reading:

R. Haag, Commun. Math. Phys. **132** (1990) 245–257; Found. Phys. **43** (2013) 1295

A polarization measurement

A single-photon polarization measurement



What is the probability p_k that the kth detector will click? According to Born's rule, it is $p_k = \mathrm{tr}\{\Pi_k \rho\}$ where ρ is the statistical operator for the polarization of the incoming photon and Π_k is the probability operator for the kth detector.

The Π_ks make up a probability-operator measurement (POM), *vulgo* a positive-operator-valued measure (POVM):

$$\Pi_k \geq 0\,, \qquad \sum_{k=0}^{4} \Pi_k = 1\,, \qquad \Pi_0 = \text{no-click probability.}$$

A polarization measurement

Change of the photon state before→after the polarization measurement:

$$\rho^{(in)} = \begin{pmatrix} |V\rangle & |H\rangle \end{pmatrix} \begin{pmatrix} \rho_{VV} & \rho_{VH} \\ \rho_{HV} & \rho_{HH} \end{pmatrix} \begin{pmatrix} \langle V| \\ \langle H| \end{pmatrix} \longrightarrow \rho^{(\mathrm{out})} = |\mathrm{vac}\rangle\langle\mathrm{vac}| \,.$$

Kraus operators for the probability operators, $\Pi_k = A_k A_k^\dagger$:

$$A_1 = |H\rangle\sqrt{\eta_1}\langle\mathrm{vac}| \,, \quad A_2 = |V\rangle\sqrt{\eta_2}\langle\mathrm{vac}| \,,$$
$$A_3 = |R\rangle\sqrt{\eta_3}\langle\mathrm{vac}| \,, \quad A_4 = |L\rangle\sqrt{\eta_4}\langle\mathrm{vac}| \,,$$

with detection efficiencies $\eta_1, \ldots, \eta_4$.

Before→after: $$\rho^{(in)} \longrightarrow \rho^{(\mathrm{out})} = \frac{A_k^\dagger \rho^{(in)} A_k}{p_k} \,.$$

What about the popular textbook “axiom” After the measurement the system is in an eigenstate of the measured observable. ?
It’s mathematical over-idealization, but real life is different.

Murky Interpretation?

From the Introduction to a recent paper:

It is remarkable, that a century after the discovery of quantum mechanics, it seems that we are no closer to a consensus about its interpretation, than we were in the beginning. The collapse of the quantum state at the process of measurement which appears in all textbooks of quantum theory does not have an unambiguous definition and a reasonable explanation.

[...] some radical changes in our classical understanding of reality have to be made; e.g. constructing a physical process of collapse, accepting the existence of parallel worlds, or adding non-local hidden variables.

Rebuttal:

In fact, there is no lack of consensus, because **the interpretation of a physical theory is simply the link between the mathematical symbols and the physical phenomena**, such as $p_k = \mathrm{tr}\left\{\Pi_k \rho\right\}$ (Born's rule). — If you endow the symbols with more meaning than that, you yourself are responsible for the consequences. But **please** don't blame quantum mechanics if it gets you into dire straits.

Nonlocality?

A referee report:

The authors claim that they have a proposal for an experiment that would demonstrate non-locality for a single photon. [. . .] there is no fundamental non-locality in quantum phenomena. Quantum mechanical processes are fundamentally local in the very definite sense that observations in space-like separated regions are independent. Technically speaking, the observables (elements of an operator algebra) of one region commute with all observables of the other region. Rudolf Haag's monograph on *Local Quantum Physics* (Springer, 1992) is recommended reading. All interactions considered in [. . .] are of the usual local kind.

The arbiter's comment:

The reviewer is correct to say that there is no fundamental non-locality in QM [. . .] However, in the present context, the phrase non-local is really a shorthand for "any realistic hidden variable theory capable of reproducing the results would have to be non-local". Workers in the field take this for granted, . . .

Nonlocality?

From the Abstract of a recent paper: “Bell’s 1964 theorem, which states that the predictions of quantum theory cannot be accounted for by any local theory, represents one of the most profound developments in the foundations of physics.”

Fact: All aspects of experiments in the quantum domain are correctly described by quantum theory, which is local.

Fact: Inadequate non-quantum theories succeed in describing some quantum phenomena only if they contain nonlocal elements.

Non sequitur: Quantum mechanics is nonlocal.

Sequitur: The properties of inadequate descriptions are utterly irrelevant.

Two kinds of evolution?

The opening paragraph of a certain paper:

"According to the basic principles of quantum mechanics, there are two ways in which a quantum state $|\psi\rangle$ changes in time. For a closed system the Hamiltonian H determines the time development according to Schrödinger's equation $H|\psi\rangle = i\hbar(\partial/\partial t)|\psi\rangle$, but when a measurement is performed, the state collapses to an eigenstate $|i\rangle$ of the operator Q corresponding to the observed eigenvalue q_i: $Q|i\rangle = q_i|i\rangle$. Prior to the measurement the system is usually in a superposition of the various states satisfying the eigenvalue equation, but immediately after the measurement the system is found (with certainty) in the state consistent with the particular value observed."

From a different source:

"Since the apparatus is very complex in terms of a quantum mechanical description, the collapse of its wavefunction is very fast."

Two kinds of evolution?

Folklore: "According to von Neumann there are two kinds of evolution: unitary evolution between measurements, and sudden collapse at the time of measurement."

Really? Reconsider $p = \operatorname{tr}\{\Pi\rho\}$ where Π and ρ are functions of the dynamical variables $Z(t)$ with, possibly, a parametric time dependence as well, and all such operator-valued functions *evolve* in accordance with Heisenberg's equation of motion,

$$\frac{\mathrm{d}}{\mathrm{d}t} f(Z(t),t) = \frac{\partial}{\partial t} f(Z(t),t) + \frac{1}{\mathrm{i}\hbar}\left[f(Z(t),t), H(Z(t),t)\right].$$

In particular, we have $\frac{\mathrm{d}}{\mathrm{d}t}\rho = 0$: the statistical operator is constant, $\rho(Z(t),t) = \rho(Z(t_0),t_0)$, as it should be because it represents our knowledge about the preparation of the system.

The "sudden collapse" is the state reduction by which we update ρ when we learn something new about the system.

State reduction is not a physical process, it is not *evolution*.

State reduction . . .

. . . is not particular to quantum mechanics. It is a book-keeping device of all statistical formalisms.

My wallet before:

$$	0	1	2	3	4	5	6	7	8	9	10
prob	0	0	0.5	0	0	0	0	0	0	0	0.5

My wallet after:

$$	0	1	2	3	4	5	6	7	8	9	10
prob	0	0	0	0	0	0	0	1	0	0	0

“Der Akt der Registrierung andererseits, der zur Zustandsreduktion führt, ist ja nicht ein physikalischer, sondern sozusagen ein mathematischer Vorgang. Mit der unstetigen Änderung unserer Erkenntnis ändert sich natürlich auch die mathematische Darstellung unserer Kenntnis unstetig.”

“The act of registration, which prompts the state reduction, is after all not a physical but a mathematical operation. When there is a sudden change in our knowledge, there is of course also a sudden change in the mathematical description of our knowledge.”
(W. Heisenberg as cited by R. Renninger, translated by B.E.)

Irreversible quantum evolution

1D motion along the x axis: the Schrödinger equation

$$\mathrm{i}\hbar\frac{\partial}{\partial t}\psi(x,t) = \left(-\frac{\hbar^2}{2m}\frac{\partial^2}{\partial x^2} + V(x)\right)\psi(x,t)$$

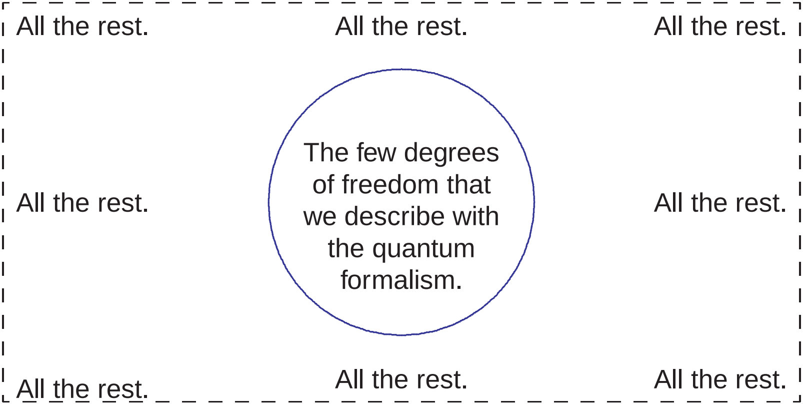
is also obeyed by $\psi(x, 2T - t)^*$.

The argument: "The sequence (i) start with $\psi(x, t = 0)$; (ii) evolve with the SE to time $t = T$; (iii) switch from $\psi(x, T)$ to $\psi(x, T)^*$; (iv) evolve with the SE to time $t = 2T$; (v) perform another complex conjugation; and so (vi) arrive at $\psi(x, 2T) = \psi(x, 0)$, thereby exactly reversing the earlier evolution in step (ii)."

seems to show that the quantum evolution can be reversed. In fact, however, it cannot because no physical process implements steps (iii) and (v).

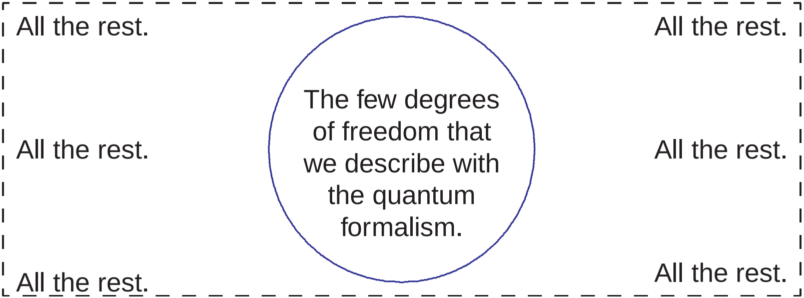
From $t = 0$ to $t = T$: $\mathrm{e}^{-\mathrm{i}H_1 T}$; from $t = T$ to $t = 2T$: $\mathrm{e}^{-\mathrm{i}H_2 T}$. Can't we have $H_2 = -H_1$? No, because both Hs must be bounded from below.

The Heisenberg cut



The cut is needed. By its nature, it cannot be precise.

Decoherence



The degrees of freedom on the quantum side of the cut are not completely isolated from “all the rest” but our model description does not take that into account. As a consequence, long-term predictions are unavoidably imprecise and lack finer details, in particular those of delicate phase relations — there is “decoherence” in our description of the quantum phenomena.

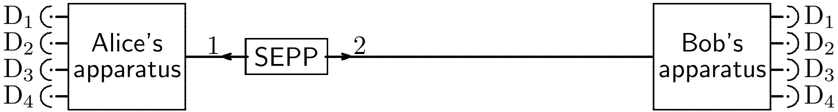
Action at a distance?

A recent news item:
Quantum theory makes the distinctive prediction that non-local correlations are instant: for example, a measurement of the polarization of one of a pair of quantum-entangled photons should immediately set the polarization of the other, no matter how far the photons are apart, without either photon's polarization being in any way predetermined.

Rebuttal: I told you: "you yourself are responsible for the consequences", I really did.

Here: Don't make the mistake of regarding the statistical operator (or the wave function for that matter) as a physical object. There is Alice's statistical operator for Bob's photon, and there is Bob's statistical operator for Bob's photon, and they can very well be different and both correct.

Alice and Bob



The source of entangled photon pairs emits entangled photons in a state described by the ket $\big(|\text{VH}\rangle - |\text{HV}\rangle\big)/\sqrt{2}$.

Bob's statistical operator for his photon: $\rho_2^{(\mathrm{B})} = \frac{1}{2}\big(|\text{V}\rangle\langle\text{V}| + |\text{H}\rangle\langle\text{H}|\big)$.

This is also Alice's statistical operator for Bob's photon before she has measured her photon.

Her statistical operator for his photon, after she found her photon with polarization H: $\rho_2^{(\mathrm{A})} = |\text{V}\rangle\langle\text{V}|$.

Note: Both Alice's $\rho_2^{(\mathrm{A})}$ and Bob's $\rho_2^{(\mathrm{B})}$ are equally correct statistical operators for the same photon on Bob's side.

The "measurement problem": Schrödinger's ~~cat~~ coin

Before (time t_0): spin-$\frac{1}{2}$ atom with $|\rightarrow\rangle = \frac{1}{\sqrt{2}}(|\uparrow\rangle + |\downarrow\rangle)$;
coin on the edge, $|\mathrm{E}\rangle$

After (time t_1): coin shows head or tail, $|\mathrm{H}\rangle$ or $|\mathrm{T}\rangle$

Total state ket: $|\ \rangle = |\rightarrow\ \mathrm{E}, t_0\rangle = \frac{1}{\sqrt{2}}(|\uparrow\ \mathrm{H}, t_1\rangle + |\downarrow\ \mathrm{T}, t_1\rangle)$

$$= \frac{1}{2}(|\rightarrow\ \mathrm{H}, t_1\rangle + |\leftarrow\ \mathrm{H}, t_1\rangle + |\rightarrow\ \mathrm{T}, t_1\rangle - |\leftarrow\ \mathrm{T}, t_1\rangle)$$

The problem: So, why do we never observe the coin in the superposition states $\frac{1}{\sqrt{2}}(|\mathrm{H}\rangle \pm |\mathrm{T}\rangle)$?

Answer: Because you wouldn't know how to recognize them; the cross terms are ineffective (G. Süßmann 1958, A. Peres 1980, ...); the phenomenology is that of the mixture $\rho(t_1) = \frac{1}{2}(|\uparrow\ \mathrm{H}, t_1\rangle\langle\uparrow\ \mathrm{H}, t_1| + |\downarrow\ \mathrm{T}, t_1\rangle\langle\downarrow\ \mathrm{T}, t_1|)$.

A dogmatist interjects: "But, in principle, I could ... Dirac, von Neumann ... one-to-one correspondence ..."

Reply: "No, you cannot. — Incidentally, did we mention that the kets $|\mathrm{E}\rangle$, $|\mathrm{H}\rangle$, and $|\mathrm{T}\rangle$ are frivolously meaningless in the first place?"

Questions and answers

Is quantum theory well defined? Yes, it is.

Is the interpretation of quantum theory clear? Yes, it is.

Is quantum theory local? Yes, it is.

Is quantum evolution reversible? No, it isn't.

Do wave functions collapse? No, they don't; *you* reduce the state.

Is there instant action at a distance? No, there isn't.

Where is Heisenberg's cut? Where you put it.

Is Schrödinger's cat half dead and half alive? No, it isn't.

Is there a "measurement problem"? No, there isn't.

Take-home message

Quantum theory is a well-defined local theory with a clear interpretation. No “measurement problem” or any other foundational matters are waiting to be settled.

The foundations have been laid, and laid well, by the founding fathers — Planck, Einstein, Bohr, Heisenberg, Schrödinger, Born, Dirac, and others.

There are the physical phenomena, and there is our description of the physical phenomena — don’t confuse one with the other and you’ll be fine.

THANK YOU