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Would Bohr be born if Bohm were born before Born?

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I discuss a hypothetical historical context in which a Bohm-like deterministic interpretation of the Schrödinger equation is proposed before the Born probabilistic interpretation and argue that in such a context the Copenhagen (Bohr) interpretation would probably have not achieved great popularity among physicists.
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I. INTRODUCTION

Is this the real life
Is this just fantasy
Caught in a landslide
No escape from reality
(Freddie Mercury, "Boh(e)mian Rhapsody")

The Copenhagen interpretation of quantum mechanics was the first interpretation of quantum mechanics that achieved significant recognition among physicists. It was proposed very early by the developers of quantum mechanics, especially Bohr and Heisenberg.[1] Later, many other interpretations of quantum mechanics were proposed, such as the statistical ensemble interpretation,[2] the Bohm (pilot wave) interpretation,[3] the Nelson (stochastic dynamics) interpretation,[4] the Ghirardi-Rimini-Weber (spontaneous collapse) interpretation,[5] the quantum logic interpretation,[6] the information theoretic interpretation,[7] the consistent histories interpretation,[8] the many-world (relative state) interpretation,[9] and the relational interpretation.[10] All of these interpretations are consistent with experiment, as well as with the pragmatic and minimal "shut-up-and-calculate interpretation."

Apart from the latter interpretation, the Copenhagen interpretation still is the dominate one. Is this dominance because this interpretation is the simplest, the most viable, and the most natural? Or is it because of the inertia of physicists who do not want to waste much time on irrelevant interpretational issues, so that it is easier for them to (uncritically) accept the interpretation to which they were first exposed? I believe that the second answer is closer to reality. To support this answer I argue in the following that if some historical circumstances had been slightly different, it would have been very likely that the Bohm deterministic interpretation would have been proposed and accepted first. Consequently, this interpretation would be dominant today.[11]

For the sake of easier reading, in the next section I will not use the conditional, but present an alternative hypothetical history of quantum mechanics as if it really happened.[12] Although a prior knowledge of the Bohm deterministic interpretation is not required, I suggest that readers unfamiliar with this interpretation read the original paper[3] or a recent pedagogical review.[13] For a comparison with other formulations of quantum mechanics, I recommend also Ref. 14.

II. AN ALTERNATIVE HISTORY OF QUANTUM MECHANICS

When Schrödinger discovered his wave equation, the task was to find an interpretation of it. The most obvious interpretation—that electrons are simply waves—was not consistent because it was known that electrons behave as pointlike particles in many experiments. It also was known that electrons obey some wavelike properties. What was the most natural interpretation of such a dualistic behavior of electrons? The notion of naturalness is highly subjective and strongly depends on personal knowledge, prejudices, and current paradigms. At that time, classical deterministic physics was well understood and accepted, so it was the most natural to first propose an interpretation that maximally resembles the known principles of classical mechanics. In particular, classical mechanics contains only real quantities, so it was strange that the Schrödinger equation describes a complex wave. Consequently, it was natural to rewrite the Schrödinger equation in terms of real quantities only. The simplest way to do so was to write the complex wave function ψ in the polar form $\psi = Re^{i\phi}$ and then to write the complex Schrödinger equation as a set of two (coupled) real equations for $R(\mathbf{x},t)$ and $\phi(\mathbf{x},t)$. Such a simple mathematical manipulation did not immediately reveal the physical interpretation of R and ϕ. Fortunately, a physical interpretation was revealed after an additional mathematical transformation

$$\phi(\mathbf{x},t) = \frac{S(\mathbf{x},t)}{\hbar}, \tag{1}$$

where S is a new function. The Schrödinger equation for ψ rewritten in terms of R and S turns out to look remarkably similar to some equations very familiar from classical mechanics. One equation is similar to the classical Hamilton-Jacobi equation for the function $S(\mathbf{x},t)$, differing from it only by a transformation

$$V(\mathbf{x},t) \to V(\mathbf{x},t) + Q(\mathbf{x},t), \tag{2}$$

where V is the potential and

$$Q \equiv -\frac{\hbar^2}{2m}\frac{\nabla^2 R}{R}. \tag{3}$$

The other equation looks exactly like the continuity equation

$$\frac{\partial\rho}{\partial t} + \boldsymbol{\nabla}(\rho\mathbf{v}) = 0 \tag{4}$$

for the density $\rho \equiv R^2$, with the Hamilton-Jacobi velocity

$$\mathbf{v} = \frac{\boldsymbol{\nabla} S}{m}. \tag{5}$$

Thus the most natural interpretation of the phase of the wave function seemed to be a quantum version of the Hamilton-Jacobi function that determines the velocity of a pointlike particle. But what was ρ? Because one of the equations looks just like the continuity equation, it was first proposed that ρ was the density of the particles. This interpretation meant that the Schrödinger equation describes a fluid consisting of a large number of particles. The forces on these particles depend not only on the potential V, but also on the density ρ through the quantum potential (3) in which $R=\sqrt{\rho}$.[15]

Although this interpretation seemed appealing, it was very soon realized that it was not consistent with experiment. It could not explain why only one localized particle at a single position was often observed. Thus, ρ could not be the density of a fluid. It seemed that ρ (or R) must be an independent continuous field, qualitatively similar to an electromagnetic or a gravitational field, which influences the motion of a particle. But why does ρ satisfy the continuity equation? Physicists could not answer this question, but they were able to identify a physical consequence of the continuity equation. To understand this consequence, consider a statistical ensemble of particles with the probability distribution of particle positions equal to some function $p(\mathbf{x},t)$. Assume also that, for some reason, the initial distribution at $t=0$ coincides with the function ρ at $t=0$. Then the continuity equation implies that

$$p(\mathbf{x},t)=\rho(\mathbf{x},t) \tag{6}$$

at any t. But why should these two functions coincide initially? Although nobody was able to present a very convincing explanation, some heuristic arguments were found based on statistical arguments.[16] These arguments suggested that, in typical experiments, ρ could be equal to the measured probability density of the particle positions. Such a prediction agrees with experiment. Because this prediction was derived from the assumption that each particle has a velocity determined by Eq. (5), it was concluded that Eq. (5) is confirmed by experiment. Thus, this interpretation became widely accepted and received the status of the "orthodox" interpretation.[17]

Not everybody was satisfied with this interpretation. In particular, Born objected that there was no direct experimental evidence for the particle velocities as given by Eq. (5), so this assumption was questioned by him. As an alternative, he proposed a different interpretation. In his interpretation, the equality (6) was a fundamental postulate. Thus, he avoided a need for the particle velocities to be given by Eq. (5). However, his interpretation has not been widely accepted. The arguments against the Born interpretation were the following: This *ad hoc* postulate could not explain why the probability density was given by ρ. Also, a theory in which the probabilistic interpretation was one of the fundamental postulates was completely against all current knowledge about the fundamental laws of physics. The classical deterministic laws were well established, so it was more natural to accept a deterministic interpretation of quantum mechanics that differs from classical mechanics less radically. And it was observed that if Born's arguments suggest that quantum mechanics is to be interpreted probabilistically, then we could use analogous arguments to conclude that even classical mechanics should be interpreted probabilistically,[18] which seemed absurd.

Although Born's purely probabilistic interpretation was not considered very appealing, mainly due to the overwhelming mechanistic view of physics of that time, it was appreciated by some positivists that such an interpretation should not be excluded. The Born interpretation was quite radical, but still acceptable as a possible alternative. His interpretation seemed to match well with a more abstract formulation of quantum mechanics (which started with the Heisenberg matrix formulation of quantum mechanics proposed before the Schrödinger equation, and was further developed by Dirac, who formulated the transformation theory of quantum states and operators, and by von Neumann, who developed the Hilbert-space formulation), in which Eq. (5) did not seem very natural.

One version of the Born interpretation was much more radical—too radical to be taken seriously. This new interpretation was suggested by Bohr, who was already known for proposing the Bohr model of the hydrogen atom in which electrons move circularly at discrete distances from the nucleus. A much better model of the hydrogen atom [based on the Schrödinger equation and particle trajectories that Eq. (5) predicts] was known, so the Bohr model was no longer considered that important, although it still enjoyed a certain respect. Because the model by which Bohr achieved respect among physicists was based on particle trajectories, it was a surprise when Bohr proposed that particle trajectories did not exist at all. But this proposal was not the most radical part of his interpretation. The most radical part was that it did not make sense to talk about particle properties unless these properties were measured. An immediate argument against such a proposal was classical mechanics, in which particle properties existed even without measurements. Bohr argued that there was a separation between the microscopic quantum world and the macroscopic classical world, so that the measurement-independent properties made sense only in the latter. Bohr never explained how and where this separation took place. He introduced no new equation, and his arguments were considered pure philosophy, not physics. Although his arguments were partially inspired by the widely accepted Heisenberg uncertainty relations, the orthodox interpretation of the uncertainty relations (expressing practical limitations on experiments, rather than the properties of nature itself) seemed more viable. Thus, it is not a surprise that his interpretation has never been taken seriously and was soon forgotten. (Much later it was found that the mechanism of decoherence through the interaction with the environment provides a sort of dynamical separation between "classical" and "quantum" worlds, but this separation is not exactly what Bohr suggested.[19])

Another prominent physicist who criticized the orthodox interpretation of quantum mechanics was Einstein. He liked the determinism of orthodox quantum mechanics (despite the fact that he made contributions to the probabilistic descriptions of quantum processes such as spontaneous emission and photoelectric effect), but there was something else that bothered him. To see what, consider a system containing N particles with positions $\mathbf{x}_1,\ldots,\mathbf{x}_N$ described by a wave function $\psi(\mathbf{x}_1,\ldots,\mathbf{x}_N,t)$. The N-particle analog of Eq. (3) is a nonlocal function of the form $Q(\mathbf{x}_1,\ldots,\mathbf{x}_N,t)$. In general it is a nonlocal function, that is, not of the form $Q_1(\mathbf{x}_1,t)+\cdots+Q_N(\mathbf{x}_N,t)$, provided that the system exhibits entanglement, that is, that the wave function is not of the form $\psi_1(\mathbf{x}_1,t)\cdots\psi_N(\mathbf{x}_N,t)$. Such a nonlocal Q is interpreted as a nonlocal potential that determines the forces on particles which depend on the instantaneous positions of all the other particles. This interpretation implies that entangled spatially separated particles must communicate instantaneously. Einstein argued that such instantaneous communication contradicts the theory of relativity, because no signal can exceed the velocity of light. Orthodox quantum physicists admitted that this contradiction with the theory of relativity is a problem, but they soon found a solution. They observed that the geometric formulation of relativity does not really exclude superluminal velocities, unless some additional properties of matter are assumed. Thus, they introduced the notion of tachyons,[20] hypothetical particles that can move faster than light and still obey the geometrical principles of relativity. Einstein admitted that tachyons are consistent with relativity, but he objected that this consistency is not sufficient to solve the problem of instantaneous communication. If the communication is instantaneous, then it can be so only in one reference frame. Consequently, there must be a preferred reference frame with respect to which the communication is instantaneous, which again contradicts the principle of relativity according to which all reference frames enjoy the same rights. At that time orthodox quantum physicists understood relativity sufficiently well to appreciate that Einstein was right. On the other hand, the theory of relativity was sufficiently young, so that it did not seem too heretical to modify or reinterpret the theory of relativity. It was observed that with a preferred foliation of spacetime specified by a fixed timelike vector n^{μ} we can still write all quantum equations in a relativistic covariant form. It was also observed that, in analogy to nonrelativistic fluids, relativity might correspond only to a low-energy approximation of a theory with a fundamental preferred time.[21] Thus, it was clear that the preferred foliation of spacetime does not necessarily contradict the theory of relativity (both special and general), provided that the theory of relativity is viewed as an effective theory. At first Einstein was not very happy with the idea that the theory of relativity might not be as fundamental as he thought. Nevertheless, he finally accepted that quantum mechanics is irreducibly nonlocal when he was confronted with the rigorous proof that, in quantum mechanics, the assumption of reality existing without measurements is not compatible with locality.[22]

A new crisis for orthodox quantum mechanics arose with the development of quantum field theory. Classical fields are objects very different from particles. Because quantum field theory seemed to be more fundamental than particle quantum mechanics, it seemed natural to replace the quantum particle trajectories by quantum time-dependent field configurations. There were two problems with such a replacement. First, from the time-dependent fields, it is not possible to reproduce the trajectories of the particles. Also the idea of time-dependent fields does not seem to work for fermionic (anticommuting) fields. Still, the agreement with experiment was not ruined, because all measurable predictions of quantum field theory were predictions for the properties of particles. Therefore, it seemed natural to interpret quantum field theory not as a theory of new, more fundamental objects (the fields), but as a more accurate effective theory of particles in which fields play only an auxiliary role. The divergences typical of quantum field theory reinforced the view that quantum field theory cannot be the final theory, but only an effective one.

As quantum physics made further progress, it became clear that many theories that were considered fundamental turned out to be merely effective theories. Such an effective view of various quantum theories reinforced the dominant paradigm according to which relativity is also an effective, approximate theory. Some relativists still believed that the principle of relativity is a fundamental principle. Consequently, they were not satisfied with the orthodox interpretation of quantum mechanics, which requires a preferred foliation of spacetime. Instead they tried to interpret quantum mechanics in a completely local and relativistic manner. To do so, they were forced to introduce some rather radical views of nature. In one way or another, they were forced to assume that a single objective reality did not exist.[23] Such radical interpretations were not appreciated by mainstream physicists. It did not seem reasonable to overthrow one of the cornerstones not only of physics but of the whole of science (the existence of objective reality) just to save one relatively new theoretical principle (the principle of locality and relativity) for which there existed good evidence that it could be only an approximate principle.[24] Therefore, the deterministic interpretation of quantum mechanics survived as the dominating paradigm, while the probabilistic rules of quantum mechanics, used widely in practical phenomenological calculations, were considered emergent, not fundamental. In fact, it has been found that in some cases, the probabilistic rules cannot be derived in a simple way, so that we are forced to use the fundamental fully deterministic theory explicitly.[25]

III. CONCLUSION

I have argued that in the context of scientific paradigms that were widely accepted when the Schrödinger equation was discovered, it was much more natural to propose and accept the Bohmian deterministic interpretation than the Copenhagen interpretation. If the Bohmian interpretation really had dominated, then it (or a minor modification) would still be dominant. In other words, the answer to the allegoric tongue-twisting question posed in the title of this paper is probably no! This answer does not prove that the Bohmian interpretation is more likely to be correct than another interpretation. The point is that it is surprising that the history of quantum mechanics chose a path in which the Copenhagen interpretation became much more accepted than the Bohmian one. I leave it to the sociologists and historians of science to explain why the history of quantum mechanics chose the path that it did.

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[1] See, for example, the recent book by D. Lindley, *Uncertainty: Einstein, Heisenberg, Bohr, and the Struggle for the Soul of Science* (Doubleday, New York, 2007).

[2] L. E. Ballentine, "The statistical interpretation of quantum mechanics," Rev. Mod. Phys. **42**, 358–381 (1970).

[3] D. Bohm, "A suggested interpretation of the quantum theory in terms of 'hidden variables.' I," Phys. Rev. **85**(2), 166–179 (1952); D. Bohm, "A suggested interpretation of the quantum theory in terms of 'hidden variables.' II," Phys. Rev. **85**(2), 180–193 (1952).

[4] E. Nelson, "Derivation of the Schrödonger equation from Newtonian mechanics," Phys. Rev. **150**, 1079–1085 (1966).

[5] G. C. Ghirardi, A. Rimini, and T. Weber, "Unified dynamics for microscopic and macroscopic systems," Phys. Rev. D **34**, 470–491 (1986).

[6] G. Birkhoff and J. von Neumann, "The logic of quantum mechanics," Ann. Math. **37**, 823–843 (1936).

[7] The information-theoretic interpretation gradually developed from the Copenhagen interpretation, so it is difficult to specify the first paper in which this interpretation was proposed. For a review, see, for example, A. Peres and D. Terno, "Quantum information and relativity theory," Rev. Mod. Phys. **76**, 93–123 (2004).

[8] R. B. Griffiths, "Consistent histories and the interpretation of quantum mechanics," J. Stat. Phys. **36**, 219–272 (1984).

[9] H. Everett, "Relative state interpretation of quantum mechanics," Rev. Mod. Phys. **29**, 454–462 (1957).

[10] C. Rovelli, "Relational quantum mechanics," Int. J. Theor. Phys. **35**, 1637–1678 (1996).

[11] A similar thesis with somewhat different arguments has been advocated by J. T. Cushing, *Quantum Mechanics: Historical Contingency and the Copenhagen Hegemony* (Univ. of Chicago, Chicago, 1994).

[12] Remarks concerning the actual history of quantum mechanics are given in the references.

[13] R. Tumulka, "Understanding Bohmian mechanics: A dialogue," Am. J. Phys. **72**(9), 1220–1226 (2004).

[14] D. F. Styer *et al.*, "Nine formulations of quantum mechanics," Am. J. Phys. **70**(3), 288–297 (2002).

[15] Such an interpretation was proposed in 1926: E. Madelung, "Quantentheorie in hydrodynamischer form," Z. Phys. **40**, 322–326 (1926).

[16] These arguments might have looked similar to those in D. Dürr, S. Goldstein, and N. Zanghì, "Quantum equilibrium and the origin of absolute uncertainty," J. Stat. Phys. **67**, 843–907 (1992); A. Valentini, "Signal-locality, uncertainty, and the subquantum H-theorem," Phys. Lett. A **156**, 5–11 (1991).

[17] This interpretation is known today as the Bohm interpretation, while the status of the orthodox interpretation is enjoyed by a significantly different interpretation. De Broglie proposed the same equation for particle trajectories much earlier than Bohm, but de Broglie did not develop a theory of quantum measurements, so he could not reproduce the predictions of standard quantum mechanics for observables other than particle positions, such as particle momenta. For more historical details see G. Bacciagaluppi and A. Valentini, *Quantum Theory at the Crossroads: Reconsidering the 1927 Solvay Conference* (Cambridge U.P., Cambridge, to be published), arXiv:quant-ph/0609184.

[18] Such arguments might have looked similar to those in H. Nikolić, "Classical mechanics without determinism," Found. Phys. Lett. **19**, 553–566 (2006). In this paper it is shown that classical statistical physics can be represented by a nonlinear modification of the Schrödinger equation, in which classical particle trajectories may be identified with special solitonic solutions. A Bohr-like interpretation of general (not solitonic) solutions suggests that even classical particles might not have trajectories when they are not measured, while a measurement of the previously unknown position may induce an indeterministic wave-function collapse to a solitonic state.

[19] For a review of the theory of decoherence with emphasis on the interpretational issues, see M. Schlosshauer, "Decoherence, the measurement problem, and interpretations of quantum mechanics," Rev. Mod. Phys. **76**, 1267–1305 (2004).

[20] Tachyons were actually introduced in physics somewhat later. See O. M. P. Bilaniuk, V. K. Deshpande, and E. C. G. Sudarshan, "'Meta' relativity," Am. J. Phys. **30**(10), 718–723 (1962); O. M. P. Bilaniuk and E. C. G. Sudarshan, "Particles beyond the light barrier," Phys. Today **22**(5), 43–51 (1969).

[21] It is well known that a wave equation describing the propagation of sound with velocity c_s, in a fluid has the same form as a special-relativistic wave equation describing the propagation of light with the velocity c, in vacuum. Consequently, such a wave equation of sound is invariant with respect to Lorentz transformations in which the velocity c, is replaced by c_s,. A fluid analogy of curved spacetime may also be constructed by introducing an inhomogeneous fluid. For more details, see, for example, M. Visser, "Acoustic black holes: Horizons, ergospheres, and Hawking radiation," Class. Quantum Grav. **15**, 1767–1791 (1998).

[22] This proof is now usually attributed to Bell, although other versions of this proof exist. For a pedagogic review see F. Laloë, "Do we really understand quantum mechanics? Strange correlations, paradoxes, and theorems," Am. J. Phys. **69**(6), 655–701 (2001).

[23] Many of the current interpretations of quantum mechanics mentioned in Sec. I are of this form.

[24] String theory also contains evidence against locality at the fundamental level. Although the theory was originally formulated as a local theory, nonlocal features arise in a surprising and counterintuitive manner. It turns out that string theories defined on different background spacetimes may be mathematically equivalent, which suggests that spacetime is not fundamental. Without a fundamental notion of spacetime, there is no fundamental notion of locality and relativity. It is believed that a more fundamental formulation of string theory should remove locality more explicitly, and known local laws of field theory should emerge as an approximation. See, for example, G. T. Horowitz, "Spacetime in string theory," New J. Phys. **7**, 201–213 (2005); N. Seiberg, "Emergent spacetime," arXiv:hep-th/0601234.

[25] It is known that relativistic quantum mechanics based on the Klein-Gordon equation and quantum field theory does not contain a position operator. Therefore, the conventional interpretation of quantum theory does not have clear predictions for probabilities of particle positions in the relativistic regime. The fundamentally deterministic Bohmian interpretation may lead to clearer predictions, which means that it may be empirically richer than (and thus nonequivalent to) the conventional formulation. For more details, see, for example, H. Nikolić, "Relativistic quantum mechanics and the Bohmian interpretation," Found. Phys. Lett. **18**, 549–561 (2005); H. Nikolić, "Is quantum field theory a genuine quantum theory? Foundational insights on particles and strings," arXiv:0705.3542. Unfortunately, experiments that could confirm or reject such a formulation have not yet been performed. This version of the Bohmian interpretation, which is not empirically equivalent to the conventional interpretation, is considered controversial even among the proponents of the Bohmian interpretation. Nevertheless, in an alternative history of quantum mechanics in which the conventional probabilistic interpretation never became widely accepted, such a fundamentally deterministic Bohmian interpretation might have seemed more natural.