Chapter 11: Bohmian Mechanics

Jeffrey A. Barrett

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1 Bohm's theory

Bohmian mechanics (1952) is a no-collapse hidden-variable theory. The quantum mechanical-state is represented by a wave function that evolves according to the linear dynamics. But particles also always have fully determinate positions. And they move in a way that is fully determined by the evolution of the wave function. While it will take a while to explain precisely what this means, one might think of the theory as pure wave mechanics but where the actual particle configuration at a time selects a single effective branch of the total wave function. This selection then, in turn, determines the effective properties of all physical systems.

In its simplest form Bohm's theory is characterized by the following principles:[1]

1. Representation of states: The complete physical state of a system S at time t is given by the wave function $|\psi(q,t)\rangle_S$ over configuration space and a point in configuration space $Q(t)$.

2. Representation of observables: Observations are ultimately measurements of position. The value of a measurement record is determined by the wave function $|\psi(q,t)\rangle_S$ and the configuration $Q(t)$. Specifically, the empirical content of the record is given by the effective wave function selected by the configuration.[2]

3. Interpretation of states: The position of every particle is always determinate and is given by the configuration $Q(t)$.

4. Laws of motion:

   I. Linear dynamics: The wave function evolves in the standard unitary way. In the simplest case this is given by

   $$i\hbar\frac{\partial|\psi(q,t)\rangle_S}{\partial t} = \hat{H}|\psi(q,t)\rangle_S$$

   II. Particle dynamics: Particles move according to

   $$\frac{dQ_k(t)}{dt} = \frac{1}{m_k}\frac{\text{Im }\psi^*(q,t)\nabla_k\psi(q,t)}{\psi^*(q,t)\psi(q,t)}\Big|_{Q(t)}$$

   where m_k is the mass of particle k and Q is the current configuration.

[1] This description of Bohm's theory follows Bell (1987, 127) rather than Bohm's (1952) original quantum-potential description.

[2] Presentations of Bohmian mechanics typically just say something along the lines of the first sentence. We will how the second and third sentences here follow from the details of how measurement works in Bohmian mechanics.

5. Distribution postulate: The prior epistemic probability of the configuration $Q(t_0)$ being in region R of configuration space at an initial time t_0 is given by the standard quantum probability

$$\int_R |\psi(q, t_0)|^2 dq$$

6. Composition: One composes the wave function associated with different systems and properties using the tensor product in the standard way.

Recall that configuration space is a $3N$-dimensional space where N is the number of particles in S. Each point in configuration space, then, determines the three-dimensional position of each particle in S. The usual quantum-mechanical state representing particle positions can be given as a complex-valued function over configuration space. But configuration space plays a more central, conceptual role here.

In Bohmian mechanics, both the wave function $|\psi(q,t)\rangle_S$ and the current particle configuration $Q(t)$ evolve in configuration space. Since the integral of the probability density $|\psi(q,t)|^2$ over configuration space is always one, one might think of probability as a compressible fluid. As the wave function evolves deterministically according to the standard linear dynamics, rule 4I (Bohm), the probability fluid flows about in configuration space just as a high-dimensional, compressible fluid might. The auxiliary particle dynamics, rule 4II (Bohm), characterizes the point representing the full particle configuration $Q(t)$ as being carried along by the probability current in configuration space as if it were a massless particle. The evolution of this point in $3N$-dimensional configuration space, in turn, determines how the N particles of the system move in ordinary three-dimensional space.

This picture of the wave function as a field in configuration space that pushes around the current configuration is crucial to understanding the theory. As John Bell, a strong proponent of Bohmian mechanics, put it:

> *No one can understand this theory until he is willing to think of ψ as a real objective field rather than just a "probability amplitude." Even though it propagates not in 3-space but in $3N$-space.* (1987, 128)[3]

The quantum probabilities specified by rule 5 can be thought of as epistemic. Given the dynamics, if the epistemic probability density for the particle configuration is ever given by the standard quantum probabilities $|\psi(q,t)|^2$, then it will continue to be so until one makes an observation. Since one can think of the configuration as being carried by the probability current, the epistemic probability of the configuration being in a region R changes precisely as the amount of probability fluid in R changes. After a measurement, the posterior epistemic probabilities are given by the standard quantum probabilities conditional on the value of one's record. This distribution is given by the norm-squared of the *effective wave function* given the record.[4] Since the distribution postulate stipulates that one assign a prior probability density $|\psi(q,t_0)|^2$ to the particle configuration

[3]The italics here are Bell's. They indicate the importance he placed on this passage. Because dynamical stories are most naturally told in configuration space in Bohmian mechanics, some proponents of the theory take the real physical world to consist of the full particle configuration and a field represented by the full wave function in configuration space. See, for example, Albert (2013) and (2015). For this variety of wave-function realist, the appearance of ordinary three-dimensional objects occupying locations in three-dimensional space is an emergent illusion, akin to the sort of illusions predicted by GRWr, generated by the evolution of the particle configuration and this high-dimensional field.

[4]See Dürr, D., S. Goldstein, and N. Zanghí (1993) for a discussion of the equivariance of the standard quantum probability distribution.

at time t_0, Bohmian mechanics predicts the standard quantum probabilities for the distribution of particles.[5] One might want to weaken the distribution postulate so that it just says that an initial state is *typical* in the measure over configuration space given by $|\psi(q,t)|^2$, but then, as we saw in the discussion of Everettian quantum mechanics, one would need to add something else to the theory to get from talk of typical states to probabilistic predictions.[6]

In Bohmian mechanics, particle positions are always determinate, and it is this that is supposed to explain experience. For his part, Bell believed that getting the right "positions of things" was both necessary and sufficient to explain experience. He explained how observation works in the theory as follows:

> The fundamental interpretative rule of the model is just that [the particle position] is the real position of the particle at time t, and that observation of position will yield this value. Thus the quantum statistics of position measurements, the probability density [$|\psi(q,t)|^2$] is recovered immediately. But many other measurements reduce to measurements of position. For example, to "measure the spin component σ_x" the particle is allowed to pass through a Stern–Gerlach magnet and we see whether it is deflected up or down, i.e. we observe position at a subsequent time. Thus the quantum statistics of spin measurements are also reproduced, and so on. (1987, 34)

Given this description, one might imagine that the theory explains experience because we directly see where things are—that the real positions of things are simply given, and that we, hence, have immediate epistemic access to those positions. Then, since the theory predicts the standard quantum probabilities for the positions of things, it makes the standard quantum predictions insofar as every measurement is in fact ultimately a measurement of position. Hence, one might suppose, an ontology of *things with positions* immediately explains our experience in the context of the theory.

But observation in Bohmian mechanics is more subtle than this description might suggest. Observing the position of something is an indirect process, and it never quite tells one where the thing is. One cannot *simply see* where an electron is after it passes though a Stern–Gerlach device or at any other time. The issue is not that electrons are small and hard to detect. It is that if one ever did know the precise position of any object, or even just knew it more precisely than allowed by the standard quantum probabilities, then one would be able to predict its future behavior more precisely than the standard quantum probabilities allow. The empirical adequacy of Bohmian mechanics depends on the fact that we *do not* have epistemic access to the precise position of anything.

Determinate particle positions play a role in explaining determinate records, and hence experience, but not by directly representing the empirical content of those records. Rather, determinate positions explain determinate records in Bohmian mechanics by selecting an effective wave function or branch of the quantum-mechanical state.

We will get at what this means in two steps. First, we will consider what the theory predicts regarding the motion of a particle in a spin device of the sort described by Bell. Then we will consider

[5] Note that Bohmian mechanics violates both directions of the standard eigenvalue-eigenstate link. Every particle always has a determinate position even when it is not in an eigenstate of position, and it almost never is. And, as we will see, it is possible for the wave function to represent a particle as being in an eigenstate of one location when the particle is in fact somewhere else.

[6] For this sort of typicality approach in Bohmian mechanics and discussions of it see Dürr, D., S. Goldstein, and N. Zanghí (1992), Callender (2007), Goldstein (2012), and Hemmo and Shenker (2015).

what it means to observe the position of something. This will illustrate how contextual properties like spin work, the nature of measurement records, and how the theory explains experience.

2 basic spin experiments

Consider an x-spin experiment of the sort Bell describes. A few preliminary reflections will help to set up the experiment.

In Bohmian mechanics the precise physical geometry of one's measuring device matters. We will consider a particle passing through a Stern–Gerlach magnet where the inhomogeneous magnetic field is oriented in the x-direction.

For the purpose of describing these experiences, we will suppose that localized wave packets are spherically symmetric with a constant diameter and a uniform probability density. This assumption makes the dynamical stories we tell easier to picture. One can drop this idealizing assumption once one has a basic sense of how the theory works and replace it with something more like realistic gaussian wave packets.

Since configuration space for a single particle is ordinary three-dimensional space, the state of an electron is given by its position in ordinary three-dimensional space and a wave function defined over ordinary three-dimensional space.

Finally, as we have seen, the wave packet associated with an electron can be represented as a tensor product of a spin component and a position component. In Bohmian mechanics, one might think of the position component as describing the *density of the probability fluid* and the spin component as characterizing the *flavor of the wave packet.*

We will first consider how the electron's wave function behaves, then how the electron itself moves. Suppose that the electron's initial wave packet is $|{\uparrow_x}\rangle_e|0\rangle_e$ (as in figure 1A). This might be

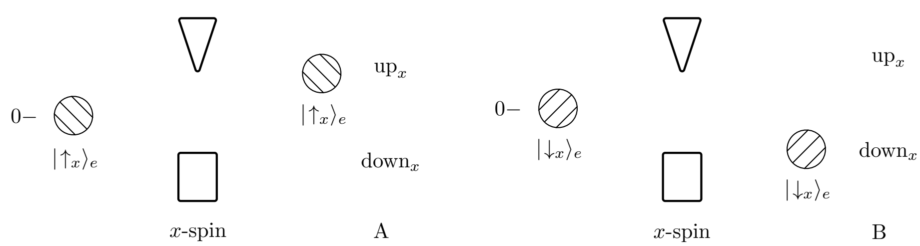

Figure 1: how the wave function is deflected by Stern-Gerlach magnets

thought of as representing an x-spin-up-flavored spherically-symmetric, three-dimensional droplet of probability fluid in region 0. The spin flavor of the wave packet determines how it will move in the x-spin device. Given the standard setup of the x-spin device, the x-spin-up-flavored wave packet $|{\uparrow_x}\rangle_e|0\rangle_e$ would be deflected up to region up$_x$ and hence evolve to $|{\uparrow_x}\rangle_e|\text{up}_x\rangle_e$. In contrast, the x-spin-down-flavored packet $|{\downarrow_x}\rangle_e|0\rangle_e$ would be deflected down to region down$_x$ and hence evolve to $|{\downarrow_x}\rangle_e|\text{down}_x\rangle_e$ (as in figure 1B).

The distribution postulate tells us that the initial position of the electron is determined by the standard quantum probabilities. In this case that means that the electron is inside its associated wave packet with probability one. Since we are supposing that the probability density is uniform in the packet, the electron has an equal probability of being in the *top half* and *bottom half* of its spherical wave packet on this side view, and an equal probability of being in the *right half* and *left* *half* if one were looking at the wave packet from a top-down perspective, etc. Further, by volume, the electron has an equal chance of being in the top half of the *top half* and the bottom half of the *top half* and an equal chance of being in the top half of the *bottom half* and the bottom half of the *bottom half* of the wave packet, etc. In short, while we know with probability one that the electron is in its associated wave packet, we do not know where it is in that wave packet beyond the probability densities given by the wave function.

Suppose that the electron happens to begin in the *top half* of an x-spin-up-flavored wave packet as indicated in figure 2. Given the standard setup, the wave packet will evolve from $|\uparrow_x\rangle_e|0\rangle_e$ to

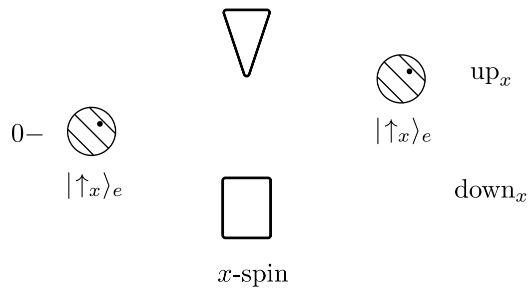

Figure 2: how the wave function moves the electron

$|\uparrow_x\rangle_e|\text{up}_x\rangle_e$. For its part, the electron with move as if it were a massless particle being pushed along by the probability current in configuration space. Since, for a single particle, configuration space is just ordinary three-dimensional space, the electron will be carried by its wave packet to region up$_x$ as the wave packet itself moves there. And if the electron's initial wave packet were $|\downarrow_x\rangle_e|0\rangle_e$, the wave packet would evolve to $|\downarrow_x\rangle_e|\text{down}_x\rangle_e$ carrying the electron along with it to region down$_x$.

What it means for an electron to be x-spin up on this account is that it is associated with an x-spin-up-flavored wave packet. Such an electron moves like an x-spin up particle because its x-spin-up-flavored wave packet moves as one would expect an x-spin up particle to move and carries the electron along with it. Spin properties are not intrinsic. Rather, they are contextual properties that particles have by virtue of their being associated with a particular flavor of wave packet.[7]

Now consider how a z-spin up wave packet would behave in an x-spin device. Suppose again that the wave packet starts in region 0. Since

$$\begin{gathered}|\uparrow_x\rangle_e|0\rangle_e\\ \downarrow\\ |\uparrow_x\rangle_e|\text{up}_x\rangle_e\end{gathered}$$

and since

$$\begin{gathered}|\downarrow_x\rangle_e|0\rangle_e\\ \downarrow\\ |\downarrow_x\rangle_e|\text{down}_x\rangle_e\end{gathered}$$

[7]Most of the usual physical properties one might consider are *contextual* in Bohmian mechanics. Contextual properties are not robust intrinsic properties. Part of what this means is that the value of the contextual property one gets on measurement depends on precisely how one performs the measurement. But since Bohmian mechanics makes the standard quantum statistical predictions for measurement outcomes, that most properties are contextual poses no empirical problem whatsoever for the theory.

by the linearity of the wave function dynamics

$$
\begin{gathered}
|\uparrow_z\rangle_e|0\rangle_e = \\
\frac{1}{\sqrt{2}}|\uparrow_x\rangle_e|0\rangle_e + \frac{1}{\sqrt{2}}|\downarrow_x\rangle_e|0\rangle_e \\
\downarrow \\
\frac{1}{\sqrt{2}}|\uparrow_x\rangle_e|\mathrm{up}_x\rangle_e + \frac{1}{\sqrt{2}}|\downarrow_x\rangle_e|\mathrm{down}_x\rangle_e
\end{gathered}
$$

This means that the initial z-spin up wave packet $|\uparrow_z\rangle_e|0\rangle_e$ *will split symmetrically* into two x-spin-flavored wave packets. The x-spin-up-flavored wave packet $|\uparrow_x\rangle_e|\mathrm{up}_x\rangle_e$ will end up in region up_x and the x-spin-down-flavored wave packet $|\downarrow_x\rangle_e|\mathrm{down}_x\rangle_e$ will end up in region down_x (as in figure 3).

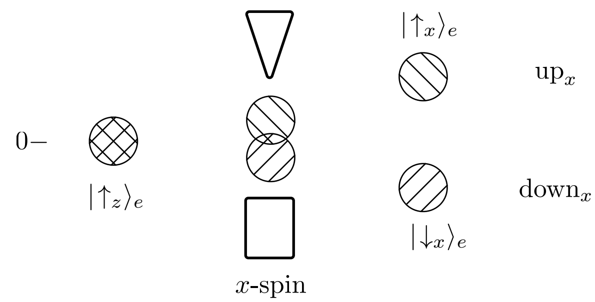

Figure 3: how a z-spin wave function evolves in an x-spin device

Suppose that the electron starts located in the *top half* of the initial z-spin up wave packet as illustrated in figure 4. As that wave packet moves toward the magnetic field, it will carry the

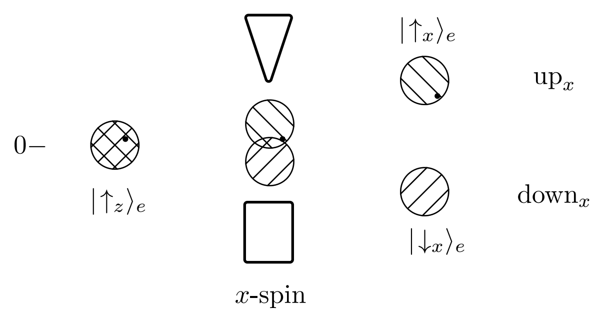

Figure 4: how an (initially) z-spin electron moves in an x-spin device

electron to the right. Since the wave packets have uniform probability density, when the x-spin up and x-spin down wave packets begin to split, the electron will initially feel no probability currents in the up or down direction. It will just continue moving directly to the right. But as the x-spin packets move apart, the electron will eventually only feel the probability current from one of the two packets. When this happens the motion of the electron will be fully determined by the motion of that wave packet.

Because of the symmetry of the wave packets and how they come apart in the x-spin device, the probability current in the x-direction on the plane that is perpendicular to the x-direction and through the middle of the initial wave packet will always be zero. An electron that starts in the *top half* of the initial z-spin up wave packet will end up in the x-spin up wave packet and will be deflected toward region up_x. And it will continue to act like an x-spin up electron as long as it remains associated with the x-spin-up-flavored wave packet. In this case, the electron's *effective wave function* will be $|\uparrow_x\rangle_e|\text{up}_x\rangle_e$. Similarly, if an electron started in the *bottom half* of the initial z-spin up wave packet, it would end up in the x-spin down wave packet and be deflected toward region down_x. And it would continue to act like an x-spin down electron as long as it remained associated with the x-spin-down-flavored wave packet. In this case, the electron's effective wave function will be $|\downarrow_x\rangle_e|\text{down}_x\rangle_e$.

The evolution of the electron's wave function and position are fully deterministic. The theory predicts the standard quantum probabilities as epistemic probabilities. We do not know where the electron will end up since we do not know where it started. By the distribution postulate, the probability of the electron initially being in the *top half* and the probability of it being in the *bottom half* of the initial z-spin wave packet are each 1/2, so the probability of it ending up x-spin up and the probability of it ending up x-spin down are also each 1/2. This is why a z-spin up electron has an equal probability of ending up x-spin up or x-spin down in an x-spin device. The story for an electron initially associated with a z-spin down wave packet proceeds along precisely the same lines.

On the idealized assumptions we are making, an electron that started precisely in the center of the initial z-spin wave packet would end up stranded in a region of zero wave function support since it would never feel any probability currents in the x-direction. One direction of the eigenvalue-eigenstate link is routinely violated by the theory since particles always have exact determinate positions while their wave functions are rarely if ever precise eigenstates of position. This shows one way that the other direction might be violated.

Now consider what happens if we change the inhomogeneous magnetic field so that the x-spin up wave packet $|\uparrow_x\rangle_e|0\rangle_e$ is deflected toward region down_x and the x-spin down wave packet is deflected toward region up_x (as in figure 5).[8] If the electron begins in the *top half* of the initial

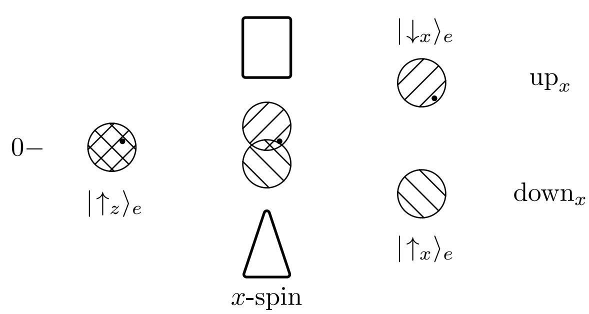

Figure 5: the contextuality of spin results

z-spin up wave packet, it will again be deflected toward region up_x, but now this means that it is associated with the x-spin *down* wave packet. Hence the electron will behave like an x-spin down electron. So for a given initial state of the electron, the details of how we set up the x-spin device

[8]This can be done by either flipping the field gradient or by exchanging the poles on the magnets.

determines its resulting x-spin. But, however one sets up the device, the epistemic probability of getting each of the two possible x-spin results is 1/2.

Back to the original setup, let's consider more precisely how the electron moves in figure 4. Since the two x-spin wave packets that make up the initial z-spin wave packet are separating in the x-direction before the electron itself starts to move in the x-direction, the relative position of the electron in its final wave packet is different from its relative position in its initial wave packet. More specifically, if the electron starts in the top half of the *top half* of its initial z-spin up wave packet, it will end up in the *top half* of its final x-spin up wave packet. But if it starts in the bottom half of the *top half* of its initial wave packet, it will end up in the *bottom half* of its final x-spin up wave packet. Similarly, if the electron starts in the top half of the *bottom half* of its initial wave packet, it will end up in the *top half* of its final x-spin down wave packet. And if it starts in the bottom half of the *bottom half* of its initial wave packet, it will end up in the *bottom half* of its final x-spin down wave packet.[9]

The electron in figure 4 starts in the bottom half of the *top half* of its its initial wave packet, so it ends up in the *bottom half* of its final x-spin up wave packet. This shift in the relative position of the electron in its wave packet is critically important to the probabilistic predictions of the theory. It is what explains why one cannot predict the motion of the electron in a *second* x-spin device *after* it passes through an intervening z-spin device.

Suppose we send a z-spin up electron through an x-spin device and suppose that the electron begins in the bottom half of the *top half* of its initial wave packet (as in figure 6). From our

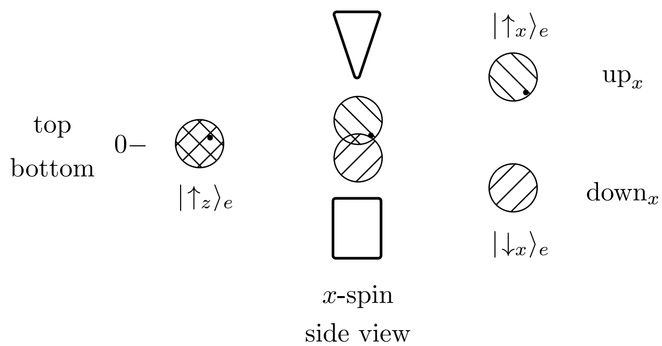

Figure 6: alternating spin measurements (initial side view)

side-view perspective, the electron will end up in the *bottom half* of the resulting x-spin up wave packet and will be deflected with this wave packet up to up_x. If we immediately send the electron through a second x-spin device, it would again be deflected in the x-spin up direction. Indeed, as long as it is associated with the x-spin up wave packet, it will act like an x-spin up electron.

But suppose we send this x-spin up electron through a z-spin device before sending it through a second x-spin device (as in figure 7). Since the magnetic field of the z-spin device is at a right angle to the magnetic field of the x-spin device, consider the motion of the wave packet and electron from the top-down perspective. The z-spin device splits the initial x-spin up wave packet into a z-spin up packet that is deflected left to region up_z and a z-spin down packet that is deflected right

[9]For more realistic wave packets where the probability density is neither uniform nor bounded, the electron's motion is more complicated, but the idea is the same. In that case, one would think of the electron's relative position in terms of its position relative to the total probability of the wave packet.

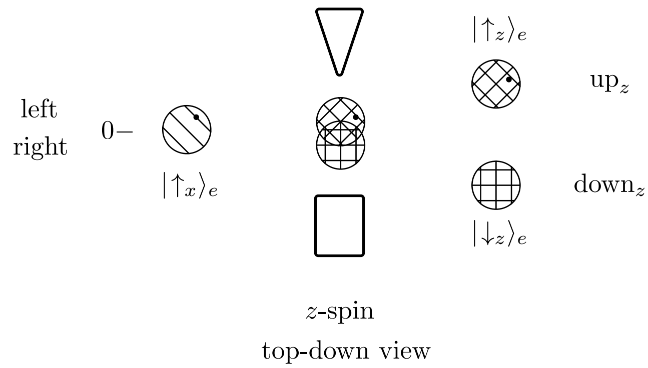

Figure 7: alternating spin measurements (top-down view)

to region down$_z$. What matters for the electron's motion here is whether it starts in the *left half* or *right half* of the initial x-spin up packet. If it starts in the *left half* (as in figure 7), then it is carried by the z-spin up wave packet to region up$_z$.

Now suppose we send this z-spin up electron through a *second* x-spin device (as in figure 8). Returning to the side view, the electron is still in the *bottom half* of the wave packet where it was

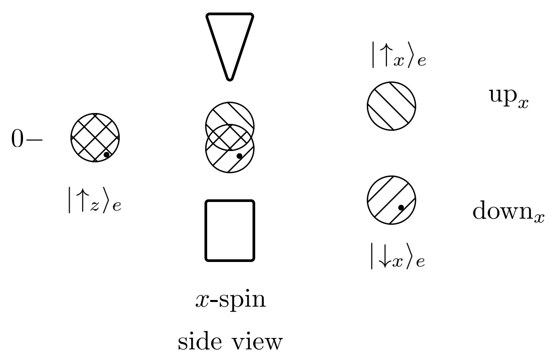

Figure 8: alternating spin measurements (final side view)

left after its x-position was shifted by the first x-spin device. The second x-spin device will split the z-spin wave packet into an x-spin up wave packet and an x-spin down wave packet, but this time the electron will be deflected down because it is in the *bottom half* of the z-spin up packet—because that is where it was left after passing through the first x-spin device as it started in the bottom half of the *top half* of the initial z-spin wave packet at the very beginning of the experiment (as in figure 6). By the distribution postulate, the electron had an equal chance of starting in the top half of the *top half* or the bottom half of the *top half* of the initial wave packet by volume, so the probability that it will end up with each of the possible x-spins after the second x-spin device is 1/2. The shift in the position of the electron *relative to its wave packet* that was produced by the first x-spin device is why it behaves randomly in a second x-spin device *after* passing through an intervening z-spin device.

3 interference and the two-path experiment

Bohmian mechanics explains interference effects by predicting how interactions between wave packets in configuration space affect the motions of particles. Considering precisely how this works will also help to set up the discussion of what it means to *observe the position of a particle* in the theory.

Consider the two-path experiment with x-spin. Since there is only one particle, configuration space is ordinary three-dimensional space. We will describe the evolution of the electron's wave function (as in figure 9). We will then consider what this means for the motion of the electron.

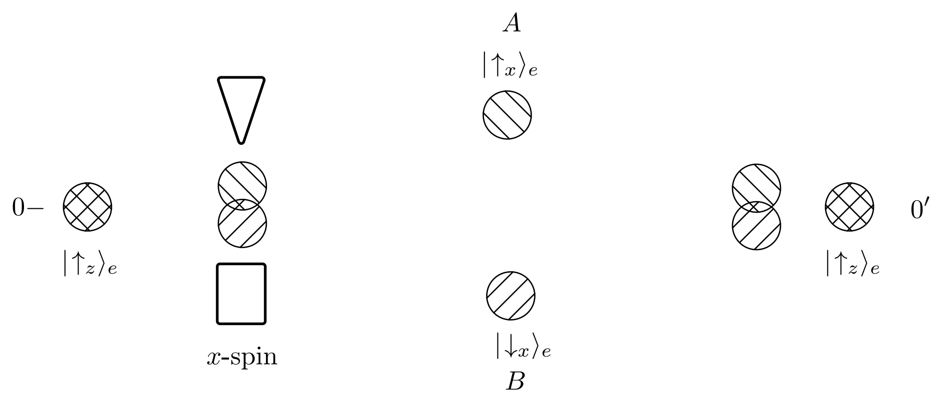

Figure 9: how the wave function evolves in the two-path experiment

An initial x-spin up wave packet in the two-path experiment would evolve as follows:

$$\begin{gathered} |\uparrow_x\rangle_e|0\rangle_e \\ \downarrow \\ |\uparrow_x\rangle_e|A\rangle_e \\ \downarrow \\ |\uparrow_x\rangle_e|0'\rangle_e \end{gathered}$$

and the probability currents generated by the motion of the wave packet would carry an electron associated with it from region 0 along path A to region $0'$. Similarly, an initial x-spin down wave packet would evolve as follows:

$$\begin{gathered} |\downarrow_x\rangle_e|0\rangle_e \\ \downarrow \\ |\downarrow_x\rangle_e|B\rangle_e \\ \downarrow \\ |\downarrow_x\rangle_e|0'\rangle_e \end{gathered}$$

carrying an associated electron from region 0 along path B to region $0'$.

So, if the electron begins associated with a z-spin up wave packet, by the linearity of the dynamics, the wave function will evolve as follows:

$$\begin{array}{c} |{\uparrow_z}\rangle_e|0\rangle_e = \\ \frac{1}{\sqrt{2}}|{\uparrow_x}\rangle_e|0\rangle_e + \frac{1}{\sqrt{2}}|{\downarrow_x}\rangle_e|0\rangle_e \\ \downarrow \\ \frac{1}{\sqrt{2}}|{\uparrow_x}\rangle_e|A\rangle_e + \frac{1}{\sqrt{2}}|{\downarrow_x}\rangle_e|B_x\rangle_e \\ \downarrow \\ \frac{1}{\sqrt{2}}|{\uparrow_x}\rangle_e|0'\rangle_e + \frac{1}{\sqrt{2}}|{\downarrow_x}\rangle_e|0'\rangle_e \\ = |{\uparrow_z}\rangle_e|0'\rangle_e \end{array}$$

Here the initial wave packet *splits* and the x-spin up packet travels path A to region $0'$ and the x-spin down packet travels path B to region $0'$. The trajectory of the electron depends on its position in the initial z-spin up packet.

If the electron is in the *top half* of the initial z-spin up wave packet (as in figure 10), it will be carried by the x-spin up wave packet along path A, and it will behave like an x-spin up electron as long as it is associated with an x-spin-up-flavored wave packet. Meanwhile, the empty x-spin

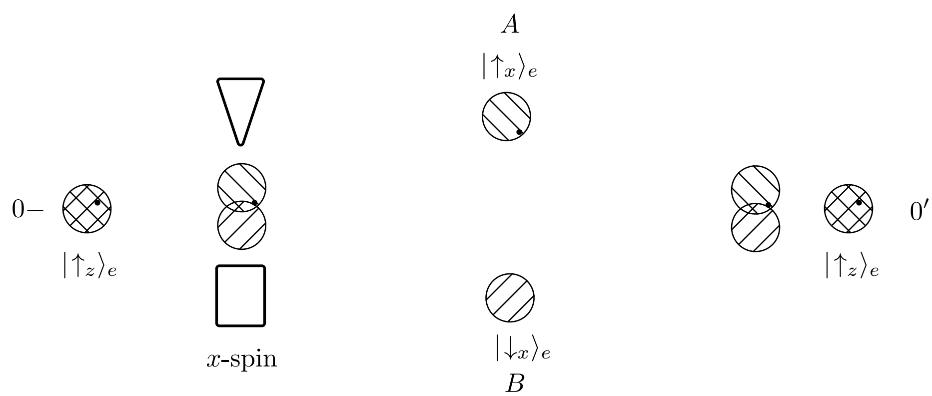

Figure 10: how the electron moves in the Bohmian two-path experiment

down wave packet travels path B to region $0'$. If the two wave packets come together in the same symmetric way that they came apart, the electron will again be associated with a z-spin up wave packet and will thus act like a z-spin up particle. It will also go back to its initial relative position in its wave packet. And if the electron starts in the *bottom half* of the initial z-spin up wave packet it will travel path B, act like an x-spin down electron along the way, then act like a z-spin up electron again when the two wave packets come together in region $0'$. This is how a z-spin up particle exhibits a determinate x-spin if one checks it while it is on path A or B but returns to acting z-spin up in region $0'$.

This story is very different from the one we told in the context of the standard theory. It is also very different from the one that one would tell in Wigner's theory, GRW, or a decohering-worlds theory. In those theories, the electron is in a superposition of traveling path A and traveling path B and hence does not determinately travel either path. Here the electron determinately travels precisely one of the two paths and the wave function travels both. We know that the wave function travels both paths because of the interference effect that produces z-spin up dispositions in region $0'$, what happens when we block one of the paths, and the effect of a total-of-nothing box on either path.

If a barrier gently blocks the path that the electron travels, then it will stop the wave packet that guides the electron and hence stop the electron. If one checks the spin of the blocked electron, one will find that it exhibits the x-spin property matching the wave-packet flavor associated with that path. A barrier on the path that the electron does not travel will stop the empty wave packet that takes that path. The electron and the wave packet that guides it will get to region $0'$, but it will not meet up with the wave packet that was blocked on the other path, so it will continue to be associated with a wave packet with the determinate x-spin flavor matching the path the electron took and hence continue to act like an x-spin up or an x-spin down particle (as the case may be) when it gets to region $0'$. The same thing would happen if one or the other of the two x-spin wave packets were slowed down or diverted or if one path were longer than the other or if anything else happened to prevent the two packets from overlapping at the same time in region $0'$. One only gets the interference effect of having a z-spin up electron in region $0'$ if the two x-spin wave packets come together at the same place and time so that the electron is again associated with a z-spin-up-flavored wave packet.

Placing a total-of-nothing device on one of the two paths does not change the spin flavor of the wave packet that goes through it, but it changes the spin flavor of the final wave packet in region $0'$ from z-spin up to z-spin down when the two x-spin wave packets come together. Note that here, as in the basic two-path experiment, the empty wave packet only makes an empirical difference if it comes to overlap the actual particle configuration (here the position of the electron) and hence changes the effective wave function of the system (here the electron's effective wave packet). Understanding the role of the effective wave function is the key to understanding how measurement works in the theory.

4 measurements and records

In order to consider what it means to *measure the position* of the electron in the theory, we will introduce a second system to record the result of the measurement. A measuring device in Bohmian mechanics is just a physical system that produces a position record of a property of a system by correlating that property with the position of the record. In the simplest case, one might record the position of one particle in the position of another. But even with just two particles, one can no longer tell the dynamical story in ordinary three-dimensional space as both the composite system's wave function and configuration live in six-dimensional configuration space. Understanding how observation works in Bohmian mechanics requires a dynamical story in configuration space.

Suppose we set things up in the two-path experiment so that the path traveled by the electron e is recorded in the position of a particle p. To this end, we might, as earlier, put particle p in region a and arrange its interaction with e so that p moves from region a to region b if and only if e takes path B. Since particles only move in response to the changes in the wave function, one characterizes the interaction between the two particles by saying how the wave function of the composite system evolves.

Given the recording dispositions that we want for p, if e starts x-spin up (as in figure 11.11), we want the composite system to evolve as follows:

$$\begin{array}{c}|{\uparrow_x}\rangle_e|0\rangle_e|a\rangle_p\\ \downarrow\\ |{\uparrow_x}\rangle_e|A\rangle_e|a\rangle_p\\ \downarrow\\ |{\uparrow_x}\rangle_e|A\rangle_e|a\rangle_p\\ \downarrow\\ |{\uparrow_x}\rangle_e|0'\rangle_e|a\rangle_p\end{array}$$

And, just slightly more interestingly, if e starts x-spin down (as in figure 11.13), we want the composite system to evolve as follows:

$$\begin{array}{c}|{\downarrow_x}\rangle_e|0\rangle_e|a\rangle_p\\ \downarrow\\ |{\downarrow_x}\rangle_e|B\rangle_e|a\rangle_p\\ \downarrow\\ |{\downarrow_x}\rangle_e|B\rangle_e|b\rangle_p\\ \downarrow\\ |{\downarrow_x}\rangle_e|0'\rangle_e|b\rangle_p\end{array}$$

Consider how the two-particle configuration evolves, and hence how the ordinary positions of the two particles evolve, in each of these cases. The coordinates that matter most to the dynamical story are e's x-position and p's x-position, so those are the coordinates we will track in the figures. We will consider the two simple cases first.

Suppose that the two-particle configuration starts associated with the wave packet $|{\uparrow_x}\rangle_e|0\rangle_e|a\rangle_p$ (as in figure 11). This puts the electron e starting in region 0 and particle p starting in region a. The

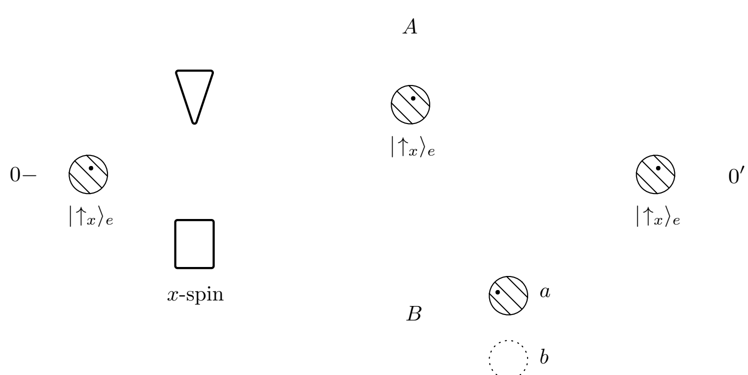

Figure 11: an x-spin up electron in the two-path experiment with a recording particle

interaction between the two particles can be seen in configuration space as illustrated in figure 12. As the wave packet evolves in configuration space, the probability current pushes the two-particle configuration in such a way that e moves from the center position in region 0 up along path A

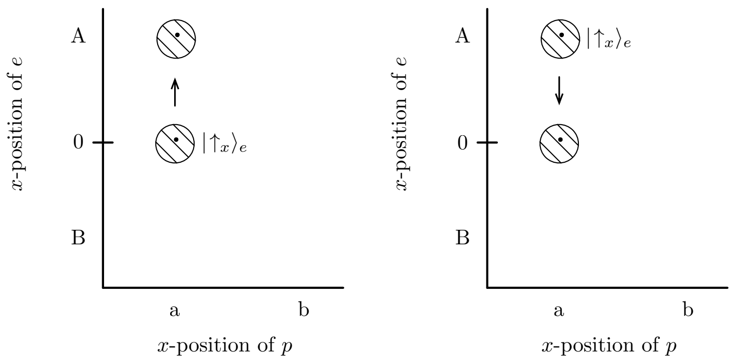

Figure 12: an x-spin up electron and recording particle in configuration space

then back down to the center at region $0'$. Since there are no probability currents in particle p's x-direction (or any of its other coordinates) it simply stays where it is. In this case, the recording particle p does not move at all, reliably indicating that e took path A and is effectively x-spin up.

Suppose that the configuration starts associated with the wave packet $|\downarrow_x\rangle_e|0\rangle_e|a\rangle_p$ (as in figure 13). Again, e starts in region 0 and p starts in region a. As the wave packet evolves in configuration

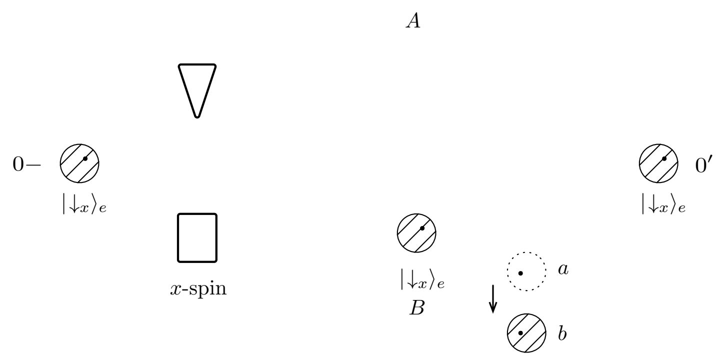

Figure 13: an x-spin down electron with a recording particle

space (as in figure 14), the probability current pushes the two-particle configuration in such a way that e moves from region 0 down along path B, then p moves from region a to region b, then e moves back up to the center at region $0'$. In this case, the recording particle p moves from region a to region b, reliably indicating that e took path B and is effectively x-spin down.

Now consider what happens when the configuration starts associated with the wave packet $|\uparrow_z\rangle_e|0\rangle_e|a\rangle_p$ (as in figure 15). By the linearity of the dynamics, the wave function of the composite

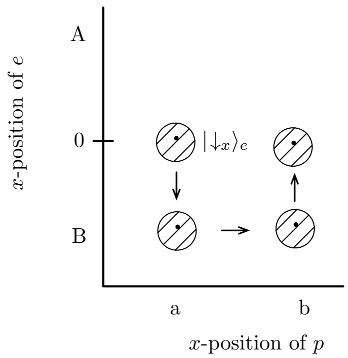

Figure 14: the x-spin down electron and recording particle in configuration space

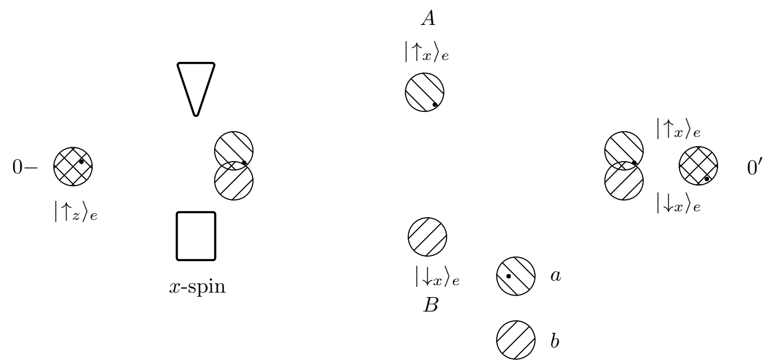

Figure 15: a z-spin up electron in the top half with a recording particle

system evolves in configuration space as follows:

$$
\begin{gathered}
|\uparrow_z\rangle_e|0\rangle_e|a\rangle_p = \\
\frac{1}{\sqrt{2}}|\uparrow_x\rangle_e|0\rangle_e|a\rangle_p + \frac{1}{\sqrt{2}}|\downarrow_x\rangle_e|0\rangle_e|a\rangle_p \\
\downarrow \\
\frac{1}{\sqrt{2}}|\uparrow_x\rangle_e|A\rangle_e|a\rangle_p + \frac{1}{\sqrt{2}}|\downarrow_x\rangle_e|B\rangle_e|a\rangle_p \\
\downarrow \\
\frac{1}{\sqrt{2}}|\uparrow_x\rangle_e|A\rangle_e|a\rangle_p + \frac{1}{\sqrt{2}}|\downarrow_x\rangle_e|B\rangle_e|b\rangle_p \\
\downarrow \\
\frac{1}{\sqrt{2}}|\uparrow_x\rangle_e|0'\rangle_e|a\rangle_p + \frac{1}{\sqrt{2}}|\downarrow_x\rangle_e|0'\rangle_e|b\rangle_p
\end{gathered}
$$

Note that, unlike the situation with just one particle, the final wave packet here is not z-spin up flavored.

Here the x-spin device splits the initial wave packet in configuration space. Consider two cases.

In figure 15 the two-particle configuration begins in the *top half* of the configuration wave packet in e's x-position. On the auxiliary dynamics, the two-particle configuration will be carried along by the probability current in configuration space as if it were a massless particle. By symmetry considerations just like those in the single particle case, this means that the configuration will be picked up by the x-spin-up-flavored wave packet. And this means that e will take path A and will end up effectively x-spin up and p will not move from region a (as in figure 16). Here p reliably

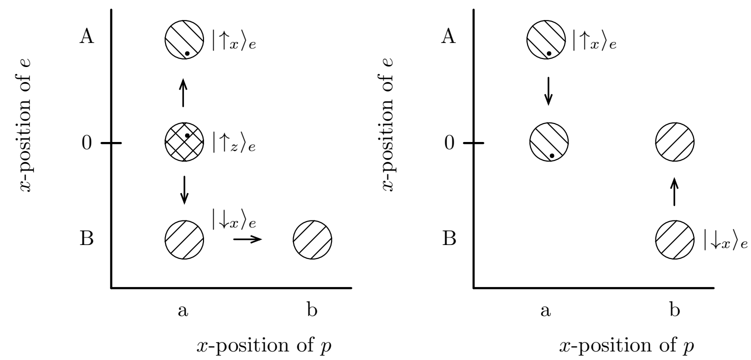

Figure 16: a z-spin up electron with a recording particle in configuration space

records that e took path A.

Now suppose instead that the configuration begins in the *bottom half* of the wave packet in e's x-position (as in figure 17). Here this means that the configuration will be picked up by the x-spin-

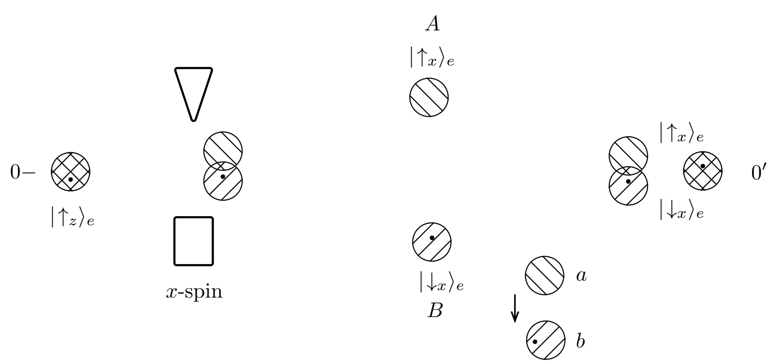

Figure 17: a z-spin up electron in the bottom half of its wave packet with a recording particle

down-flavored wave packet, which means that particle e will take path B and will end up effectively x-spin down and particle p will move from region a to region b (as in figure 18). Here p reliably records that e took path B.

Note that while the two x-spin wave packets end up in the same region of three-dimensional space, *they do not overlap in configuration space.* Hence the configuration remains associated with the x-spin-up-flavored wave packet in the first case (as in figures 15 and 16) and with the x-spin-down-flavored wave packet in the second case (as in figures 17 and 18). The position of particle p reliably records *both* the path taken by e in each case and that the electron ends up effectively x-spin

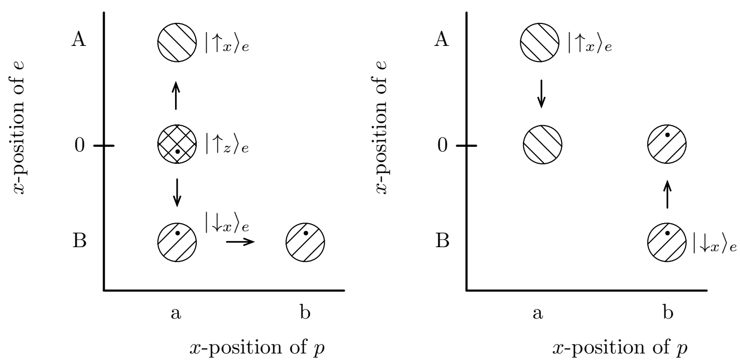

Figure 18: a z-spin up electron in the bottom half of its wave packet with a recording particle in configuration space

up in the first case and effectively x-spin down in the second. More precisely, the record in the first case tells us that the *effective wave function* for the two particles is $|\uparrow_x\rangle_e|0'\rangle_e|a\rangle_p$ and the record in the second case tells us that the *effective wave function* for the two particles is $|\downarrow_x\rangle_e|0'\rangle_e|b\rangle_p$.

It is in this precise sense that the value of a measurement record in Bohmian mechanics indicates the branch of the wave function selected by the actual configuration. The *content* of the record is given by *the effective wave function of the composite system*. To be sure, the value of the record tells one something about the actual configuration that one did not already know, but it never tells one precisely where any particle is. If one knew anything more regarding the positions of particles than what is given by the effective wave function, then one would be able to make empirical predictions that violate the standard quantum probabilities.

5 surreal trajectories and decoherence

The very existence of a position record can significantly affect the behavior of the measured system. Consider the same two-path experimental setup with the recording particle p but this time we will allow the wave packets to pass through each other in region $0'$ so that the x-spin down wave packet continues to region A' and the x-spin up wave packet continues to region B'. The electron starts associated with a z-spin up wave packet in region 0 and the recording particle starts in region a with positions as indicated in figure 19.

First consider how the electron behaves if there is no interaction whatsoever between e and p *and hence no measurement record is made of the path traveled by the electron.* Since the two particles start in separable states and since they do not interact, we could just consider how e's state evolves in ordinary three-dimensional space, but we will keep the two-particle configuration space representation for the purpose of comparison.

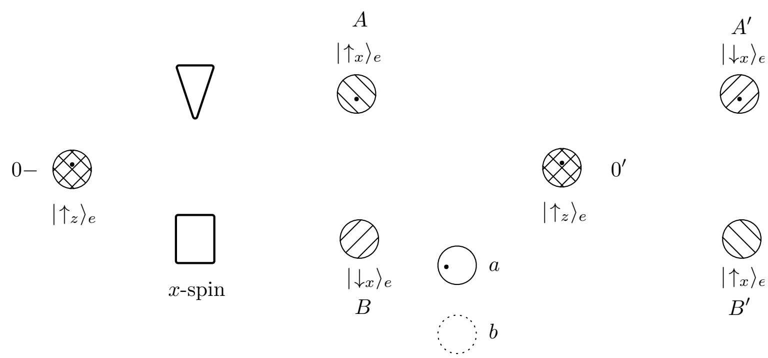

Figure 19: electron trajectory if there is *no interaction* between e and p

Here the wave function of the composite system evolves as follows:

$$
\begin{gathered}
|\uparrow_z\rangle_e|0\rangle_e|a\rangle_p = \\
\frac{1}{\sqrt{2}}|\uparrow_x\rangle_e|0\rangle_e|a\rangle_p + \frac{1}{\sqrt{2}}|\downarrow_x\rangle_e|0\rangle_e|a\rangle_p \\
\downarrow \\
\frac{1}{\sqrt{2}}|\uparrow_x\rangle_e|A\rangle_e|a\rangle_p + \frac{1}{\sqrt{2}}|\downarrow_x\rangle_e|B\rangle_e|a\rangle_p \\
\downarrow \\
\frac{1}{\sqrt{2}}|\uparrow_x\rangle_e|A\rangle_e|a\rangle_p + \frac{1}{\sqrt{2}}|\downarrow_x\rangle_e|B\rangle_e|a\rangle_p \\
\downarrow \\
\frac{1}{\sqrt{2}}|\uparrow_x\rangle_e|0'\rangle_e|a\rangle_p + \frac{1}{\sqrt{2}}|\downarrow_x\rangle_e|0'\rangle_e|a\rangle_p \\
= |\downarrow_z\rangle_e|0'\rangle_e|a\rangle_p \\
\downarrow \\
\frac{1}{\sqrt{2}}|\uparrow_x\rangle_e|B'\rangle_e|a\rangle_p + \frac{1}{\sqrt{2}}|\downarrow_x\rangle_e|A'\rangle_e|a\rangle_p
\end{gathered}
$$

The initial wave packet splits, but since there is no correlation between e's position and spin and p's position, the state ends up separable in region $0'$.

Since there is no interaction, the recording particle p does not move at all and no record is made. In configuration space the evolution looks like figure 20. The electron, however, does a number of curious things on this trajectory.

The electron starts in the bottom half of the *top half* of its wave packet, so when the wave packet splits, it ends up in the *bottom half* of the x-spin up wave packet and is carried along path A by the associated probability currents. But since there is no interaction with p, the two x-spin wave packets end up overlapping in configuration space when they reach region $0'$. This produces a z-spin up wave packet in region $0'$. And the probability current shifts e's relative position in its wave packet back to where it started at the beginning of the experiment as the x-spin wave packets come together. The x-spin wave packets then *pass through each other* in region $0'$. Since e is in the *top*

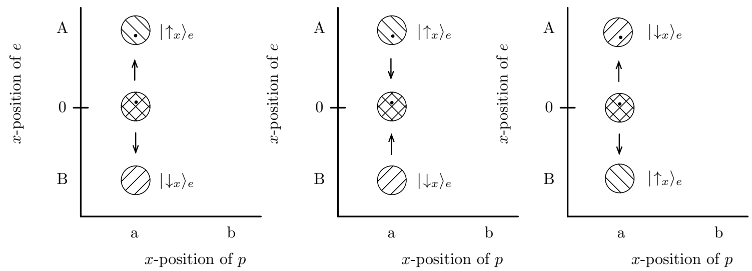

Figure 20: the electron's surreal trajectory in configuration space

half of the wave packet again, it gets picked up by the wave packet headed toward region A' again, but this time it is the x-spin *down* packet. The electron is carried to region A' by the associated probability current and ends up effectively x-spin down.

Here the electron follows what is sometimes called a *surreal trajectory*.[10] It starts z-spin up in region 0, becomes x-spin up while passing through the magnets, travels along path A, becomes z-spin up again in region $0'$, bounces out of this *classically field-free* region, becomes x-spin down, and ends up in region A'. This bouncing behavior and the spontaneous change in spin in region $0'$, which contains no classical fields whatsoever, violates both conservation of momentum and conservation of angular momentum. That we never see anything like this was once given as an argument against Bohmian mechanics.[11] But the theory itself explains why we never see such bounces.

To see the electron bounce, one would need to see that it was initially on path A *then* see that it ends up in region A'. But if one sees it on path A, then the theory predicts that the electron *does not bounce*. It is the measurement record of it being on path A that keeps it from bouncing.

Consider the experiment again, but this time we will allow p to record the position of e. In this

[10]Englert, Scully, Süssmann, and Walther (1992) argue that surreal trajectories pose an empirical problem for Bohmian mechanics in as much as such trajectories are never seen. But, as we will see, the theory itself explains why they are never seen. In short, they go away whenever one looks for them. A more recent line of argument against Bohmian mechanics is given by Frauchiger and Renner (2018). They use an extended version of the Wigner's friend story to argue that Bohmian mechanics violates the standard quantum predictions (something they call assumption Q). Their argument, however, involves a misunderstanding of how state preparation and measurement work in a no-collapse theory like Bohmian mechanics. In brief, as Lazarovici and Hubert (2018) show, Frauchiger and Renner do not keep track of the full quantum state of the systems involved in their story.

[11]Englert et al. (1992) thought that this was a serious problem for Bohmian mechanics since we never in fact see such trajectories. Bohmian mechanics, however, predicts that one would never see such trajectories since measurement records in position prevent such behavior.

case, the wave function of the composite system evolves as follows:

$$
\begin{gathered}
|{\uparrow_z}\rangle_e |0\rangle_e |a\rangle_p = \\
\frac{1}{\sqrt{2}}|{\uparrow_x}\rangle_e |0\rangle_e |a\rangle_p + \frac{1}{\sqrt{2}}|{\downarrow_x}\rangle_e |0\rangle_e |a\rangle_p \\
\downarrow \\
\frac{1}{\sqrt{2}}|{\uparrow_x}\rangle_e |A\rangle_e |a\rangle_p + \frac{1}{\sqrt{2}}|{\downarrow_x}\rangle_e |B\rangle_e |a\rangle_p \\
\downarrow \\
\frac{1}{\sqrt{2}}|{\uparrow_x}\rangle_e |A\rangle_e |a\rangle_p + \frac{1}{\sqrt{2}}|{\downarrow_x}\rangle_e |B\rangle_e |b\rangle_p \\
\downarrow \\
\frac{1}{\sqrt{2}}|{\uparrow_x}\rangle_e |0'\rangle_e |a\rangle_p + \frac{1}{\sqrt{2}}|{\downarrow_x}\rangle_e |0'\rangle_e |b\rangle_p \\
\downarrow \\
\frac{1}{\sqrt{2}}|{\uparrow_x}\rangle_e |B'\rangle_e |a\rangle_p + \frac{1}{\sqrt{2}}|{\downarrow_x}\rangle_e |A'\rangle_e |b\rangle_p
\end{gathered}
$$

Because of the correlation between e's position and spin and p's position, this dynamical story involves *both* particles in an essential way, so it must be told in configuration space (as in figure 21).

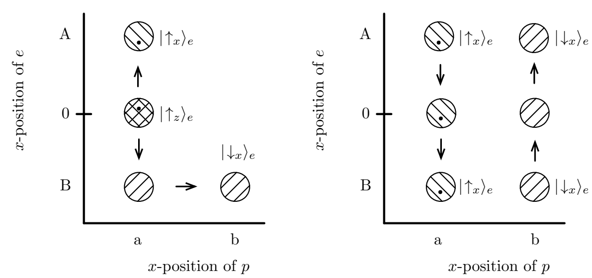

Figure 21: the effect of a measurement record in configuration space

Since the two-particle configuration starts in the *top half* of the wave packet in e's x-direction, it becomes associated with the x-spin up wave packet when the z-spin wave packet splits in configuration space (as in figure 21). The two-particle configuration is then carried by the probability current in configuration space in such a way that the electron travels along path A and p stays in region a. But this time when the electron enters region $0'$, the two wave packets do not overlap in configuration space and hence do not produce a z-spin up wave packet. This is because the interaction where p records e's position shifts the x-spin down wave packet in configuration space in p's x-direction so that the two wave packets miss each other. But, since they miss each other, the two-particle configuration only feels the probability current from the x-spin up wave packet and is carried to region B' in e's x-direction, which means that e moves through region $0'$ *without bouncing* and ends up effectively in region B' and still effectively x-spin up. And the electron will continue to behave like an x-spin up particle as long as the configuration selects an effective wave function that is x-spin-up-flavored for e.

In ordinary 3-space this trajectory looks like figure 22.[12] Note that even though p does not

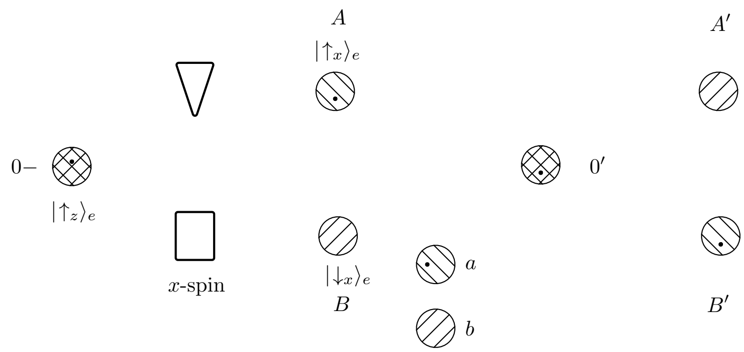

Figure 22: the effect of a measurement record in ordinary space

move in this case, the fact that e took path A and is hence effectively x-spin up is recorded by p being at location a because the interaction between the two particles correlates p's position with both e's position and x-spin as represented by the wave function of the composite system. The two-particle configuration then selects an effective x-spin for e and a *corresponding* record for p. Of course, if the electron begins in the *bottom half* of the initial wave packet, it would take path B and p *would* move to region b indicating that e is in fact on path B.

In either case, *the very existence of the measurement record* prevents the electron from bouncing out of the field-free region $0'$. This is why we never see surreal trajectories. While momentum is not conserved in Bohmian mechanics *observed momentum* is. The existence of the record also provides the electron with *stable* effective spin properties. Here the electron stays x-spin up even when passing through region $0'$.

In order to get interference effects, the wave packets and the two-particle configuration must overlap at the same time *in configuration space*. The only way that this can happen here is if the measurement record is erased by carefully disentangling p's position from e's position *and* x-spin. This would undo the shift in the x-spin down wave packet in p's x-direction. Then one might put the two x-spin wave packets back together in e's position and get back to a z-spin up wave packet and the associated z-spin up interference behavior for e. The degrees of freedom involved here make this difficult to accomplish.

That position records stabilize the physical properties of the object system and lead to classical behavior by destroying interference effects provides an important role for environmental decoherence in Bohmian mechanics. Insofar as interactions between a system and its environment produce (unintentional) position records of the system's properties, they stabilize the properties of the system and promote its classical behavior. Since the properties of a macroscopic system that we think of as classical are typically recorded in the positions of systems in its environment, such systems and properties will indeed behave classically in Bohmian mechanics.

[12]Contrast this with the surreal trajectory (in figure 11.19) when there is no interaction between e and p.

6 how the theory explains experience

We can now say what one sees when one observes the position of a particle in Bohmian mechanics. Suppose that the recording particle p in the two-path experiment moves to region b. This does not tell us precisely where the electron is. It might be anywhere in the wave packet that traveled path B.[13] Rather, it tells us *which wave packet* the configuration (and hence the electron) is associated with. That is, the empirical content of the record, what one can deduce from the value of the record, is given by *the effective wave function selected by the current particle configuration.* This is what an observer has epistemic access to given her measurement record. In this precise sense, this is what she *sees.*

If Bohmian mechanics correctly describes the physical world and if one ever had direct epistemic access to the positions of particles, one would be able to make predictions more precisely than allowed by the standard quantum probabilities. The very empirical adequacy of the theory depends on the fact that one never directly observes the precise position of anything.

Particle positions do not typically by themselves determine the content of a measurement record. Given the contextual nature of measurement, the same particle positions might represent different measurement outcomes by selecting different flavored wave packets. And the wave function does not typically determine the content of a measurement record by itself either. The wave function typically fails to specify any particular outcome. It is the particle configuration and the wave function *together* that determine the value of the record. The effective wave function selected by the particular configuration both determines the empirical content of the record and tracks the dispositional properties of the measured system. For a formulation of quantum mechanics to explain our experience, it needs to characterize something that exhibits the standard quantum statistics and on which one might plausibly take one's one's experience to supervene. In Bohmian mechanics this is the effective wave function selected by the current particle configuration.

7 EPR and relativity

Bohmian mechanics is manifestly incompatible with the constraints of relativity. The dynamics makes essential use of configuration space to explain the standard quantum statistics by means of the correlated motions of distant particles. The very idea of configuration space is incompatible with relativity. The point in configuration space $Q(t)$ represents the positions of all the particles in a system at time t no matter how far apart they may be. To make any sense of this at all one would need to choose a preferred inertial frame, which would violate a basic principle of relativity.

Consider how the theory explains the results of an EPR experiment.[14] Suppose one has two particles e_a and e_b in the EPR state

$$\frac{1}{\sqrt{2}}(|\uparrow_x\rangle_{e_a}|\downarrow_x\rangle_{e_b} + |\downarrow_x\rangle_{e_a}|\uparrow_x\rangle_{e_b}) \tag{7.1}$$

where particle e_a is located at A on Earth with one observer and particle e_b is located at B in orbit about α Centauri with another. The observer at A will measure the x-spin of e_a at noon

[13] Indeed, it could be anywhere where this wave packet provides positive wave function support. And, for more realistic wave packets, that means that it could be virtually anywhere. That said, for a well-designed experiment the electron is probably on (or very nearly on) path B.

[14] This story follows Albert (1992, 156–60).

1 January 2050 (in the laboratory inertial frame) and the observer at B will measure the x-spin measurement of e_b at noon 1 January 2050 plus one second (in the laboratory inertial frame), each on their respective particle. The experimental setup is illustrated in figure 23.

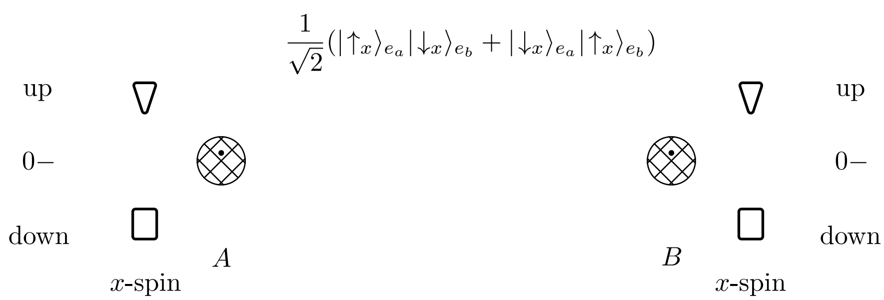

Figure 23: EPR setup

Since these two measurement events are spacelike separated, there is no matter of fact about which is first. There are inertial frames where observer A's measurement is first (as in the laboratory frame) and there are others where B performs her measurement first.

Since the spin properties of the two particles are entangled, we have no choice but to tell the dynamical story in configuration space. The initial state of the two particles is given by an EPR-flavored wave packet in six-dimensional configuration space and a point in that configuration space representing the positions of the two particles. Suppose that the two-particle configuration is such that each particle is in the *top half* of the wave packet in its x-direction (as in figures 11.23 and 11.24). Again, we will just track the x-positions of the two particles in configuration space.

Consider an inertial frame where A's measurement occurs first (as in figure 24). When she

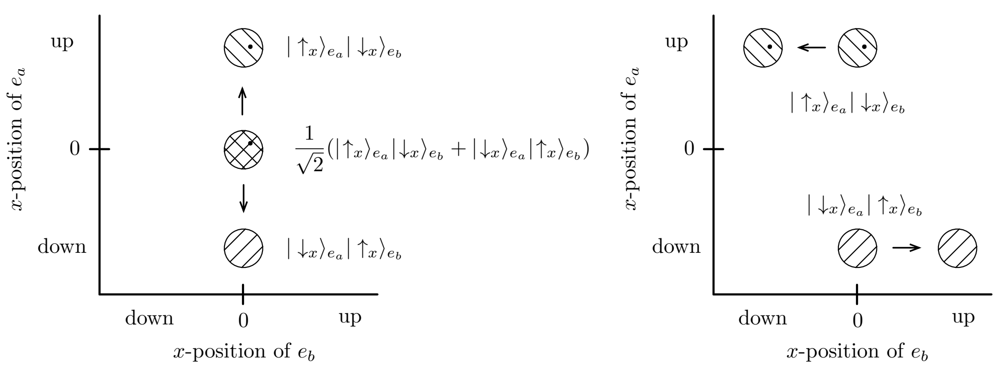

Figure 24: trajectory in configuration space if A's measurement is first

performs her measurement, the linear dynamics requires the initial EPR-flavored wave packet to split in configuration space in e_a's x-direction. Given the usual way of setting up the magnets so that x-spin up wave packets are deflected up and x-spin down wave packets are deflected down, the $|\uparrow_x\rangle_{e_a}|\downarrow_x\rangle_{e_b}$-flavored wave packet is deflected up in e_a's x-direction, and the $|\downarrow_x\rangle_{e_a}|\uparrow_x\rangle_{e_b}$-flavored wave packet is deflected down in e_a's x-direction. Since the two-particle configuration starts in the *top half* of the EPR-flavored wave packet in e_a's x-direction, the configuration ends up associated with the $|\uparrow_x\rangle_{e_a}|\downarrow_x\rangle_{e_b}$ wave packet, which means that e_a is deflected up. When B measures the

x-spin of e_b, the $|{\uparrow_x}\rangle_{e_a}|{\downarrow_x}\rangle_{e_b}$ wave packet is deflected down in e_b's x-direction, and the $|{\downarrow_x}\rangle_{e_a}|{\uparrow_x}\rangle_{e_b}$ wave packet is deflected up in e_b's x-direction. Since the configuration is associated with the $|{\uparrow_x}\rangle_{e_a}|{\downarrow_x}\rangle_{e_b}$ wave packet, e_b is deflected down. In this case, the configuration selects an effective wave function such that e_a ends up effectively an x-spin up electron and e_b ends up effectively an x-spin down electron. That the two electrons exhibit opposite x-spin spins is good since spins are anti-correlated in the EPR state.

Now consider an inertial frame where B's measurement occurs first (as in figure 25). Here

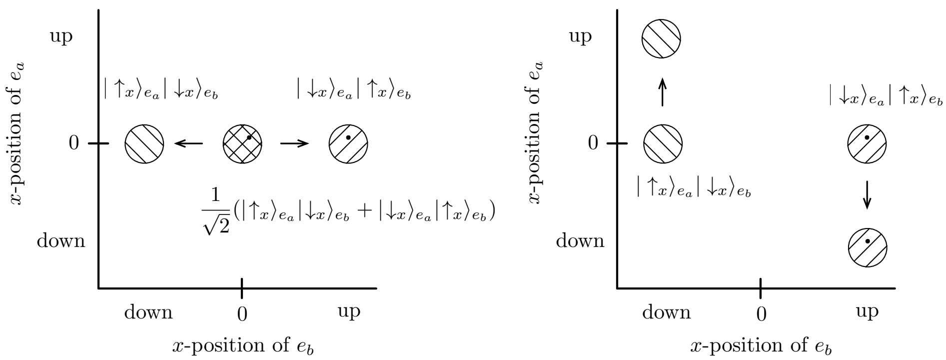

Figure 25: trajectory in configuration space if B's measurement is first

the linear dynamics requires the initial EPR-flavored wave packet to split in configuration space in e_b's x-direction. So the $|{\uparrow_x}\rangle_{e_a}|{\downarrow_x}\rangle_{e_b}$-flavored wave packet is deflected down in e_b's x-direction, and the $|{\downarrow_x}\rangle_{e_a}|{\uparrow_x}\rangle_{e_b}$-flavored wave packet is deflected up in e_b's x-direction. Since the two-particle configuration starts in the *top half* of the wave packet in e_b's x-direction, this time it ends up associated with the $|{\downarrow_x}\rangle_{e_a}|{\uparrow_x}\rangle_{e_b}$ wave packet, so this time e_b is deflected *up*. When A measures the x-spin of e_a, the $|{\uparrow_x}\rangle_{e_a}|{\downarrow_x}\rangle_{e_b}$ wave packet is deflected up in e_a's x-direction, and the $|{\downarrow_x}\rangle_{e_a}|{\uparrow_x}\rangle_{e_b}$ wave packet is deflected down in e_a's x-direction. But now since the configuration is associated with the $|{\downarrow_x}\rangle_{e_a}|{\uparrow_x}\rangle_{e_b}$ wave packet, e_a is deflected *down*. In this case, the configuration selects an effective wave function such that e_a ends up effectively an x-spin down electron and e_b ends up effectively an x-spin up electron. Again, it is good that the x-spins are opposite. But it is not good that the theory predicts *different x-spin results* depending on the temporal order of the measurements at A and B.

Since there is no matter of fact regarding the temporal order of spacelike separated events in special relativity, there can be no physical facts that depend on the temporal order of such events. But the outcomes of EPR measurements *depend on the temporal order of the spacelike separated measurements*. So Bohmian mechanics is dynamically incompatible with relativity. That the dynamical incompatibility between Bohmian mechanics and relativity is not subtle is illustrated by the fact that one would be able to send superluminal messages if one knew the initial particle configuration in the present experiment.

Suppose that observer A performs her measurement first. If she knows that she is making the first measurement and if she knows that the two-particle configuration is in the *top half* of the wave packet in e_a's x-direction, then she would know that e_a will deflect in the up direction no matter how she orients the inhomogeneous magnetic field on her device. This means that (in the standard orientation) her measurement will associate the configuration with the $|{\uparrow_x}\rangle_{e_a}|{\downarrow_x}\rangle_{e_b}$ wave packet. This would make e_a effectively x-spin up and e_b effectively x-spin down. So when observer B gets around to checking her particle (in the standard orientation), it will be deflected down. But by changing the orientation of her field, in just the way we considered when we discussed contextual properties earlier, observer A can arrange things so that the $|{\downarrow_x}\rangle_{e_a}|{\uparrow_x}\rangle_{e_b}$ wave packet is the one that is deflected in the up direction at her end of the experiment. The particle e_a will again be deflected up, but now e_a is effectively x-spin down and e_b is effectively x-spin up. So when observer B gets around to checking her particle, it will be deflected *up*.

The upshot is that observer A can instantaneously control the motion of particle e_b no matter how far away it is if she knows the relative position of e_a in the initial EPR-flavored wave packet. If the distribution postulate is satisfied, then she does not know the relative position of e_a in its wave packet. That said, she is still instantaneously affecting e_b's motion by the field orientation she chooses. It is just that she does not know how.

That Bohmian mechanics is nonlocal in a way that renders it flatly incompatible with relativity is an essential feature of the theory. It uses such nonlocal interactions to get the right anti-correlation statistics here and the right EPR-Bell statistics more generally.

8 virtues and vices

Bohmian mechanics is a no-collapse formulation of quantum mechanics that makes the standard forward-looking probabilistic predictions for the positions of particles. And since it treats measurement interactions precisely the same way that it treats other physical interactions, it resolves the quantum measurement problem by providing a consistent account of nested measurements.

In the context of the Wigner's friend experiment, Bohmian mechanics predicts that the friend, her measuring device, and the particle she is measuring will all evolve according to the linear dynamics. The configuration of the composite system will select an effective wave function that represents a perfectly determinate x-spin result for the friend. Because this is an effective wave function for the entire composite system and since the friend's brain state is correlated with the pointer position which is correlation to the x-spin of the object system, all of the parts of the composite system will behave in a way that is consistent with the result. And if an external observer were ever able to make an A-measurement of the composite system, he would get the result $+1$ with probability one.[15] Inasmuch as the wave function always evolves linearly, Bohmian mechanics is in principle empirically distinguishable from a collapse formulation of quantum mechanics like Wigner's theory or GRW.

One might worry that Bohmian mechanics, unlike pure wave mechanics, commits one to a *particle* ontology. But the Bohmian *approach* can be applied to most any choice of fundamental physical ontology, making the general hidden-variable approach a sort of framework theory. We will see a concrete example of how this works when we discuss Bell's Bohmian field theory in the next chapter. The problem is that while the Bohmian approach can be used to provide a quantum-mechanical dynamics for most any physical observable, we don't know what observable it *should* be talking about.[16] It is in this sense that it encounters a version of the preferred-basis problem.

[15] This is the configuration that would get all of the probability when one correlates the pointer position on an A-measuring device with the A-property of the composite system FMS.

[16] As we will see in the next chapter, the problem is not that one must choose *particle position* to be a privileged physical quantity to make a Bohm-type theory work. The problem, rather, is that one must choose *some privileged physical quantity to be determinate* and that quantity must, by dint of its being determinate, account for *all* of our physical records. Not only do we not know what quantity to choose, but any just right choice for explaining our experience is bound to look ad hoc given the other choices one might have made.

Proponents of Bohmian mechanics often argue that since particles with ordinary three-dimensional positions constitute a primitive ontology, they are precisely the sort of thing that one needs to provide a satisfactory account for experience. But, as we have seen, measuring the position of something in Bohmian mechanics is more subtle than directly seeing its location in ordinary three-dimensional space. Indeed, the theory allows for a plausible argument that the appearance of ordinary things in ordinary three-dimensional space is best understood as a sort of illusion generated by the way the $3N$-dimensional configuration selects an effective component of the wave function in $3N$-dimensional configuration space. Regardless of whether one calls it an illusion, inasmuch as the content of an observer's experience is given by the effective wave function selected by the total configuration of her measuring system, the primitive ontology of particles with ordinary three-dimensional positions is not what explains the observer's experience.

Rather than being directly observable things that single-handedly constitute our manifest image of the world, the particles in Bohmian mechanics play the role of selecting a single branch of the quantum-mechanical state as the effective wave function that is in fact realized on measurement. The content of one's measurement record is given by the effective wave function, which, in turn, provides something on which one's experience might plausibly supervene.[17]

One thing on a different topic before moving on. As mentioned in the discussion of the many-thread formulation (chapter 10), Bohmian mechanics may be thought of as a sort of non-splitting, many-worlds theory. Specifically, to get a Bohmian many-threads theory, fix the wave function for the world at some initial time t_0, then consider a different non-splitting physical world corresponding to each possible initial particle configuration with a history given by how that configuration would evolve under the Bohmian deterministic dynamics.[18] One might take the theory to consist of this set of possible world histories and the measure over this set given by the probability that the distribution postulate assigns to the initial configuration that characterizes each world. These probabilities are the prior probabilities that each possible world is the world we in fact inhabit. One updates by conditioning on what one learns of the actual world. This picture captures the idea that Bohmian mechanics might be thought of as pure wave mechanics with a new variable, the total configuration, that selects the actual branch at each time and hence determines a complete history.

Arguably, the most significant problem with Bohmian mechanics is its manifest dynamical incompatibility with relativity. The theory relies on strongly nonlocal interactions that violate relativistic constraints to explain things like the EPR-Bell statistics. Bell thought that one might lessen the worry over the theory's incompatibility with relativity somewhat by considering a Bohmian field theory. We now turn to that.

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[17] The suggestion here is in contrast to the view that particle configuration is superfluous in Bohmian mechanics and that the theory is hence no better off than pure wave mechanics. See Brown and Wallace (2005) for such an argument. By selecting a *single* effective wave function, the Bohmian particle configuration does something that pure wave mechanics cannot—it provides a precisely *one physical record* as a possible target for experiential supervenience.

[18] See section **??** for a characterization of the many-threads theory.