THE DOUBLE SLIT EXPERIMENT AND THE MACH-ZEHNDER INTERFEROMETER

SCHOOL ON PARADOXES IN QUANTUM PHYSICS

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BELGIUM

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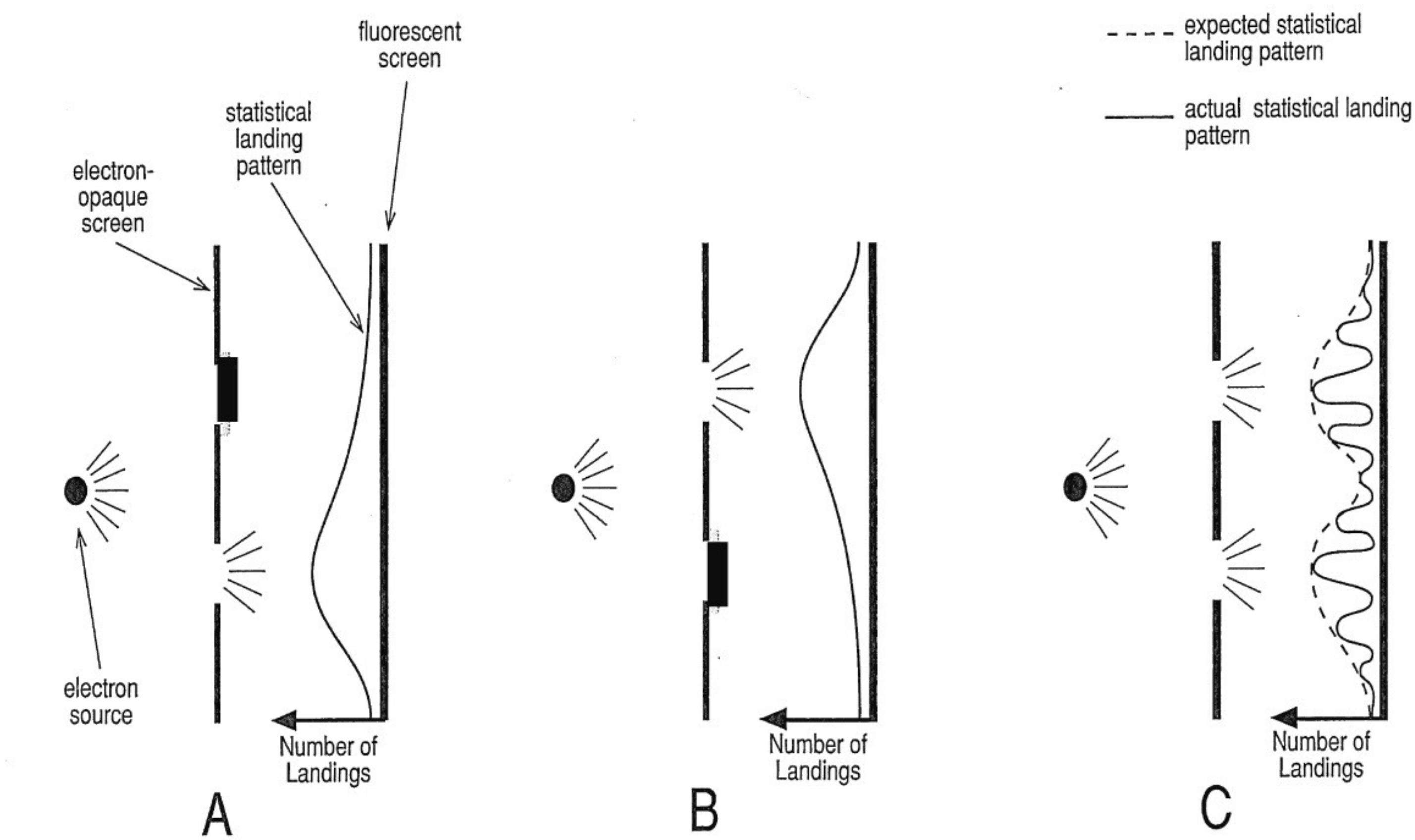
THE DOUBLE SLIT EXPERIMENT.

REMINDER:



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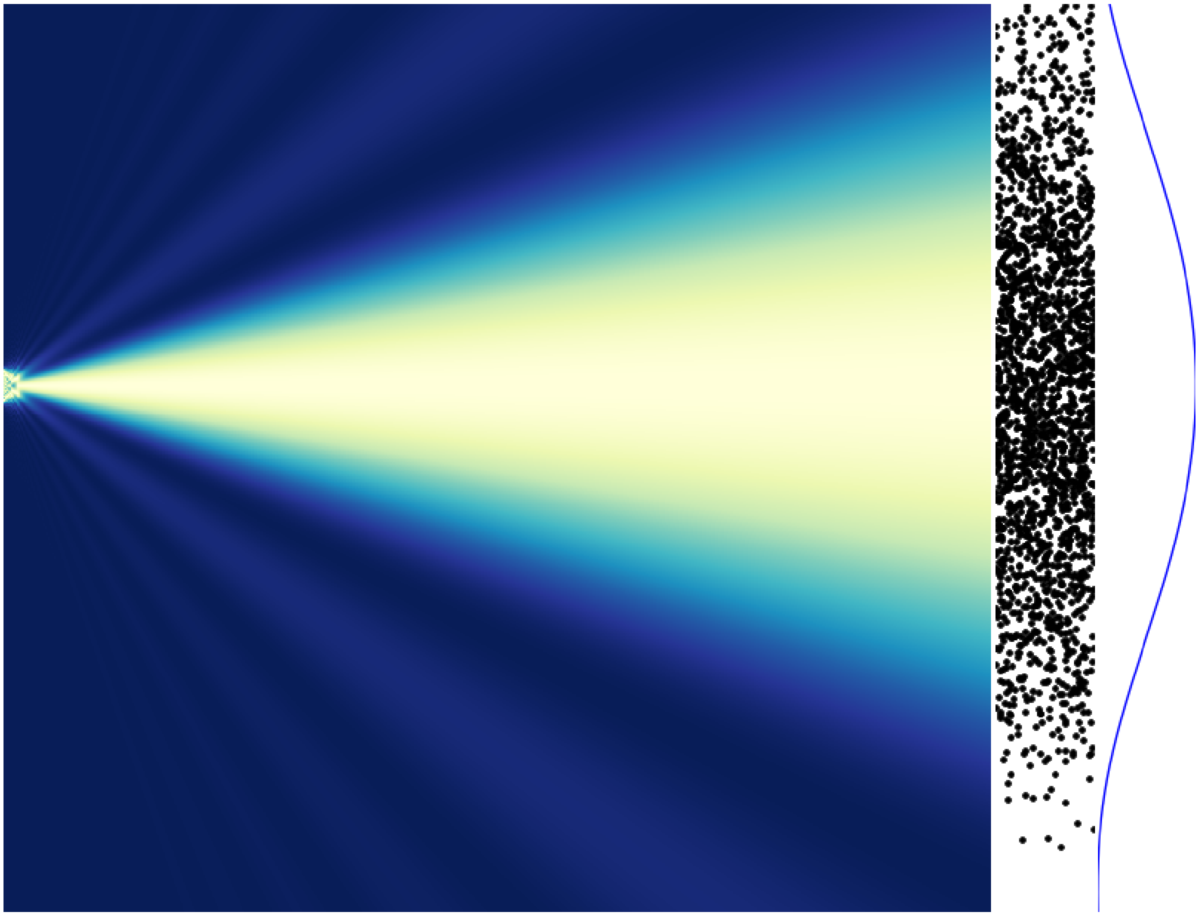
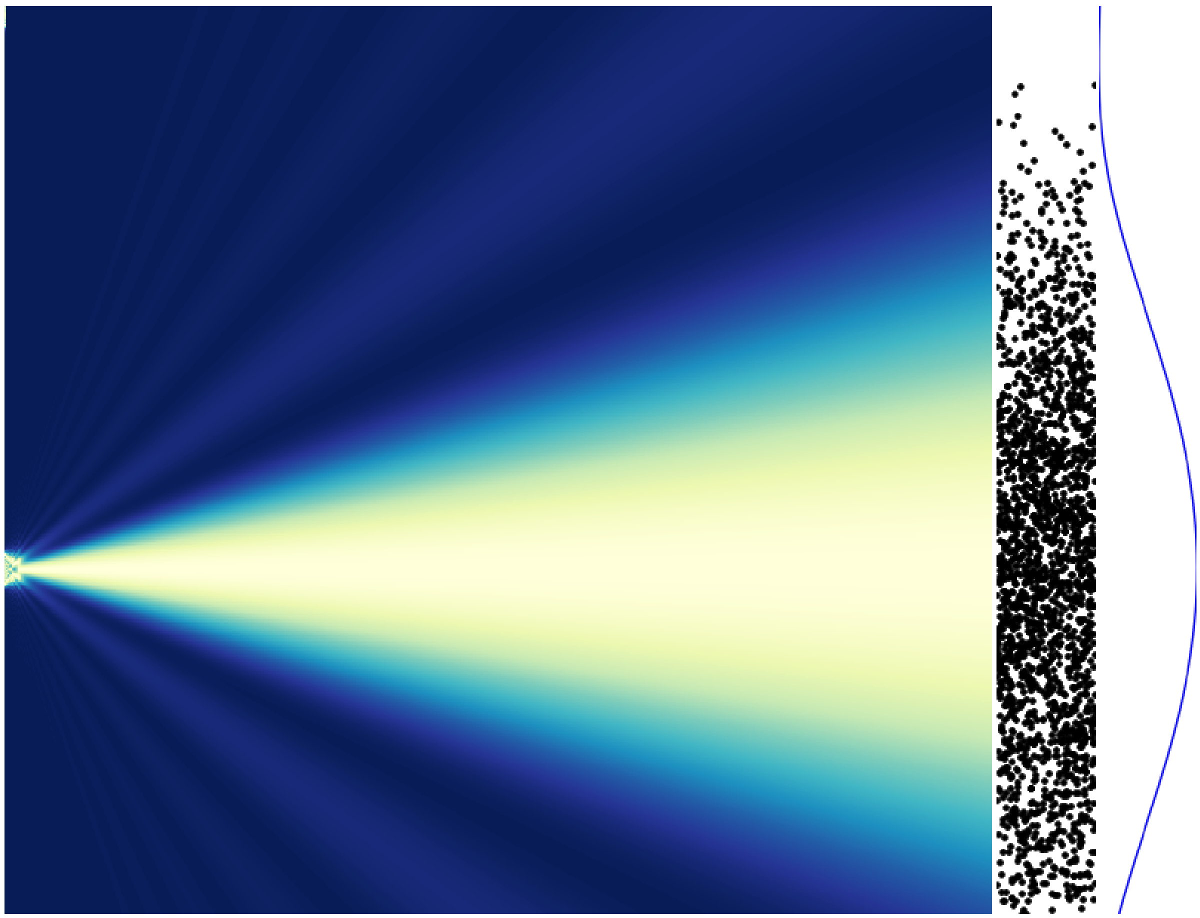
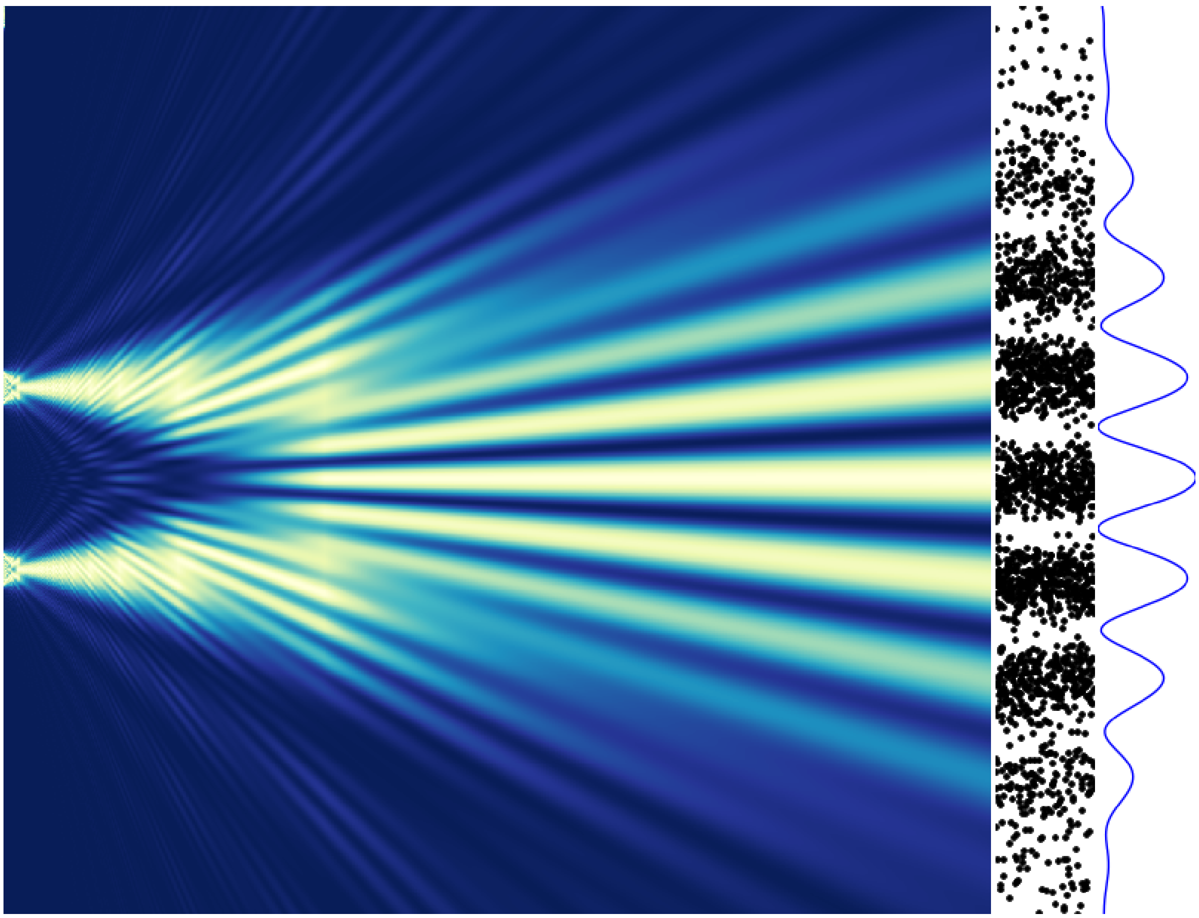


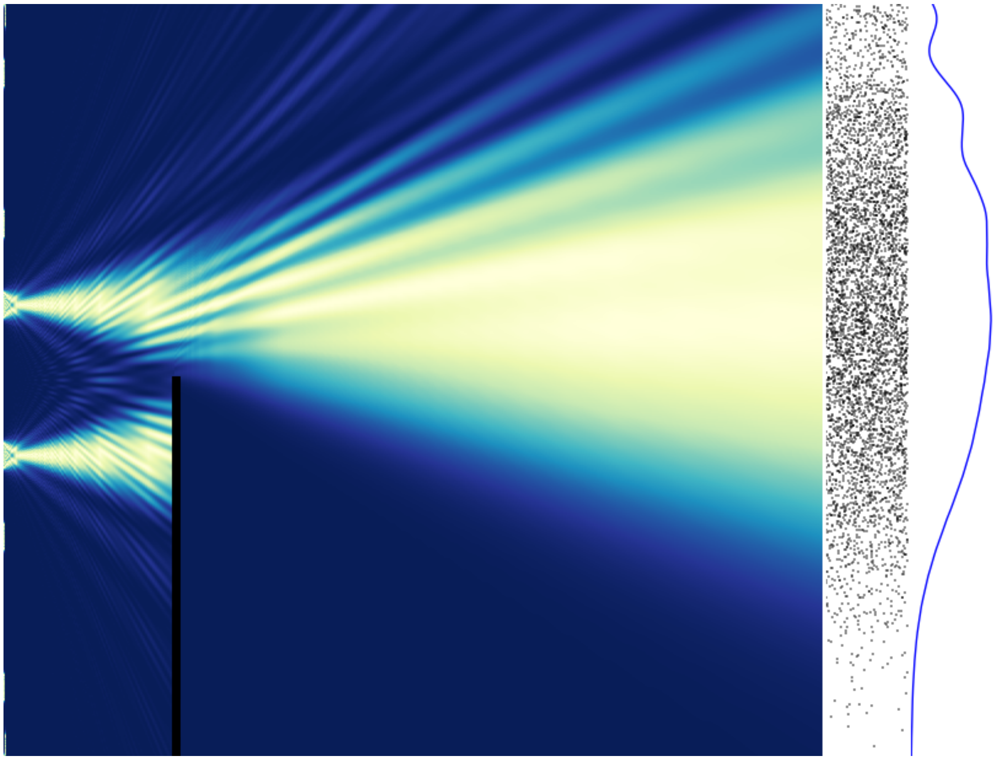
INTENSITY OF THE FLOW OF PARTICLES WHEN ONLY THE UPPER SLIT IS OPEN



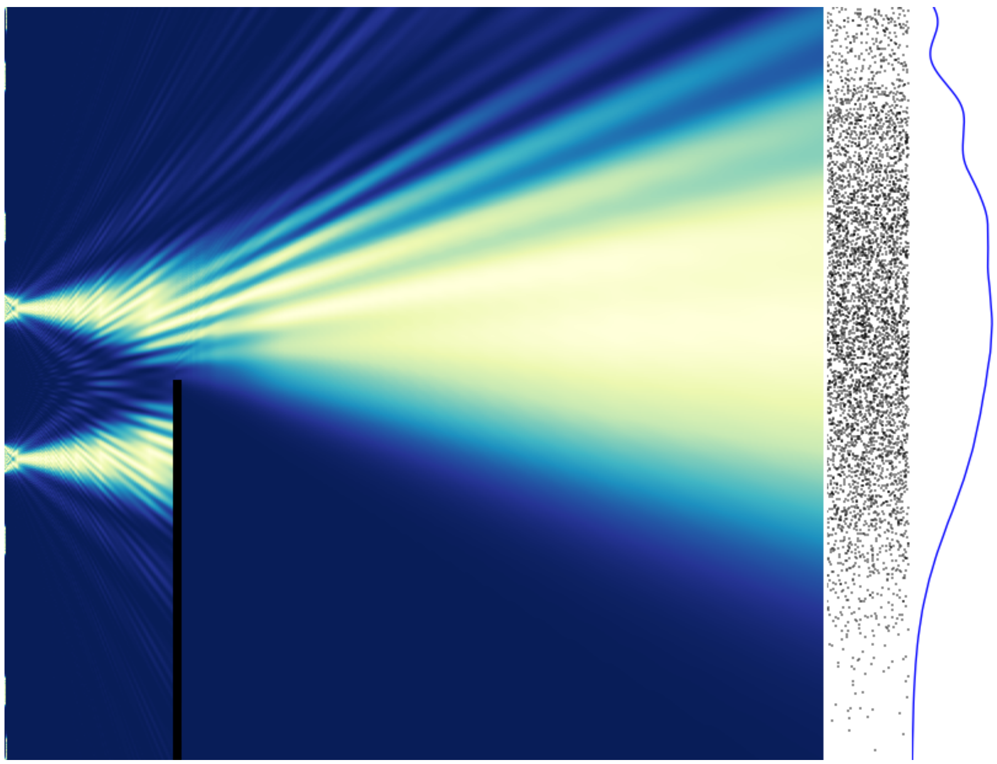
INTENSITY OF THE FLOW OF PARTICLES WHEN ONLY THE LOWER SLIT IS OPEN



INTENSITY OF THE FLOW OF PARTICLES WHEN BOTH SLITS ARE OPEN



The mystery thickens if one puts a detector behind one of the slits, say the lower one, that would allow us to determine whether the particle goes through that slit. Then, the interference pattern disappears!



And that is true even if one considers only the events where the detector *does not* detect a particle; which means that, in order that the interference pattern disappears, it is enough that *we are able to know* through which slit the particle went (here, through the upper one), simply by checking that it does not go through the other slit.

This is sometimes expressed by saying that, if we *look* or if we *know* through which slit the particle went, then it behaves like a particle (no interference pattern), but if we do not know through which slit it went, it behaves like a wave.

One often describes these phenomena by saying that the particle goes through both slits when they are both open and through one slit otherwise. But what does it mean for a particle to go through two slits whose separation is far greater than the size of that particle? And how does the electron, while moving towards the wall with the slits, ”know” whether one or both slits will be open, so as to know whether it should behave as a wave or as a particle?

This double-slit experiment is an example of what Niels Bohr called "complementarity": we can either check through which slit the particle went, when both slits are open, and then the particle behaves as a particle (no interference pattern), or we can ignore which slit the particle went through, and then the particle behaves as a wave. But we cannot combine both pictures into a single coherent whole.

Note that "complementary" is used here in a non-habitual fashion, as Roderich explained yesterday: the word usually means that two pictures, say of a person viewed from the front and from the back, may "complement" each other in the sense that they yield a more precise image of that person. But one must stress that, for Bohr, the wave description and the particle one are "complementary" in the sense that they *exclude* each other.

In any case, these "ways of speaking" do not cast much light on what is really going on.

It should be emphasized that, in principle, the experiment is done by sending one particle at a time, so that no explanation can possibly be based on interactions between particles.

That the double-slit experiment is mysterious is acknowledged by most physicists. For example, in a standard textbook of quantum mechanics, written by two famous Soviet physicists, Lev Landau and Evgeny Lifshitz, one reads:

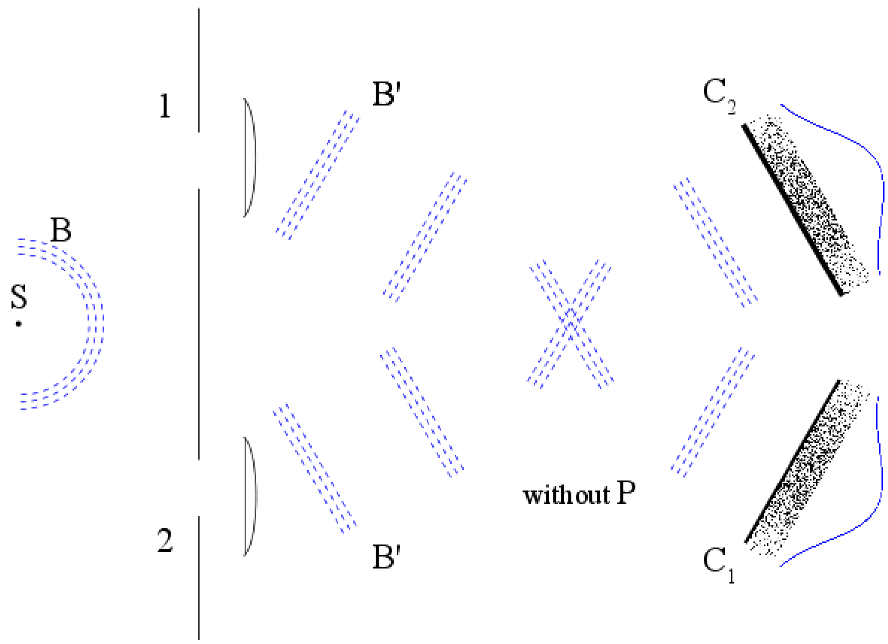
> It is clear that [the results of the double-slit experiment] can in no way be reconciled with the idea that electrons move in paths. [...] In quantum mechanics there is no such concept as the path of a particle.
>
> Lev Landau and Evgeny Lifshitz

And, after describing the double-slit phenomenon, Richard Feynman wrote:

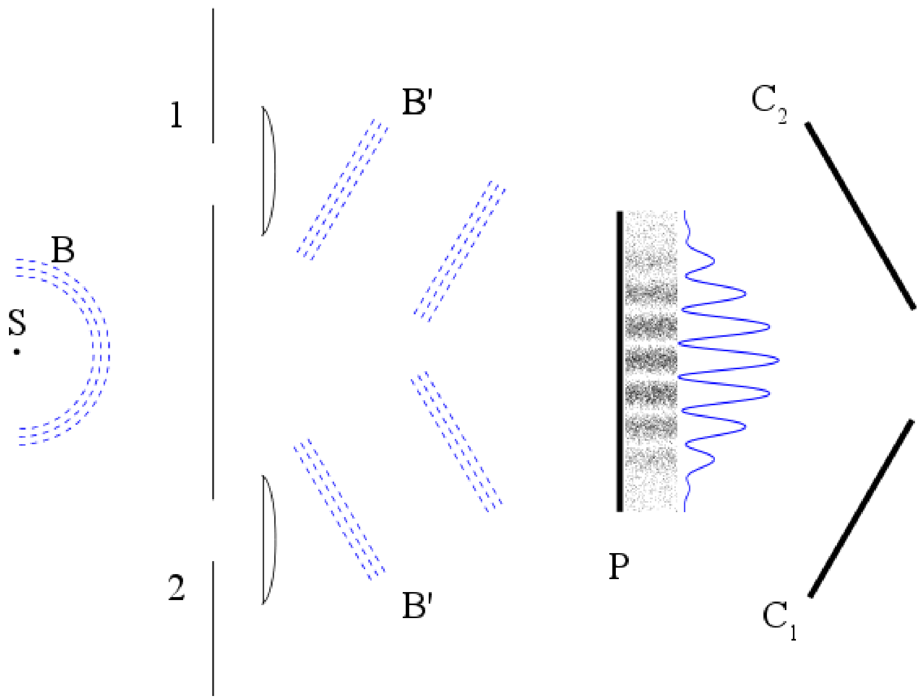
> Nobody knows any machinery. Nobody can give you a deeper explanation of this phenomenon than I have given; that is, a description of it.
>
> Richard Feynman

THE DELAYED-CHOICE DOUBLE SLIT EXPERIMENT

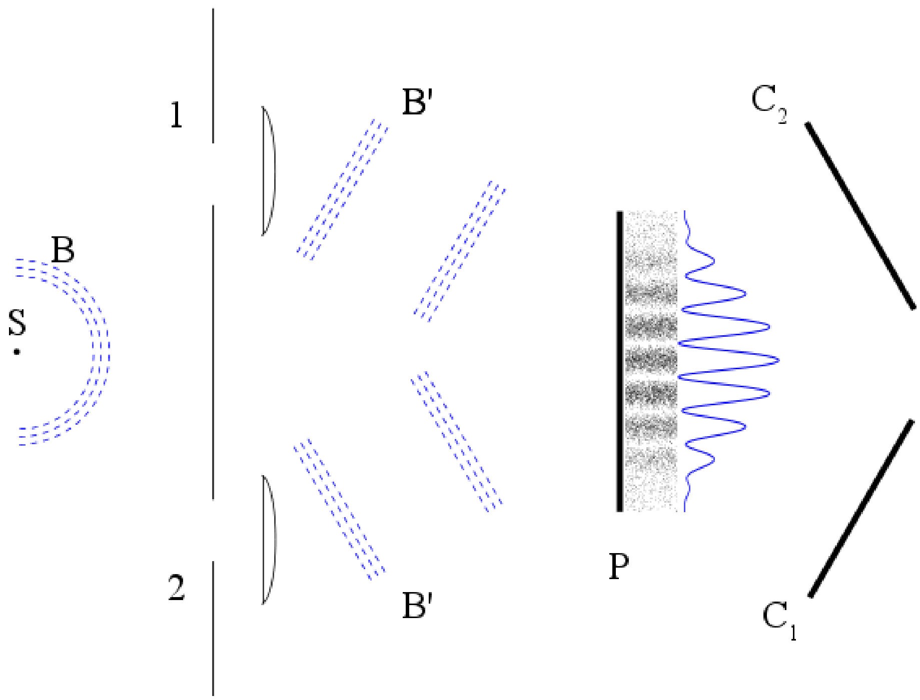
The American physicist John Wheeler invented a clever experiment, called the "delayed-choice" experiment, that makes the mystery of interferences even more troubling.



One can modify the double-slit experiment as follows: insert lenses behind the slits that will focus the two sets of incoming particles toward two counters C_1 and C_2 that may detect them. If one detects the particle on one of those counters, one will be tempted to conclude that the particle went through the upper slit if counter C_2 detects it, and that it went through the lower slit if counter C_1 detects it.



But one can also insert a detection plate in the region where what appears to be the particles trajectories cross each other (the plate is denoted by P in that figure). Then, one will see an interference pattern, and according to the standard way of speaking, one will say that the particle went through both slits.



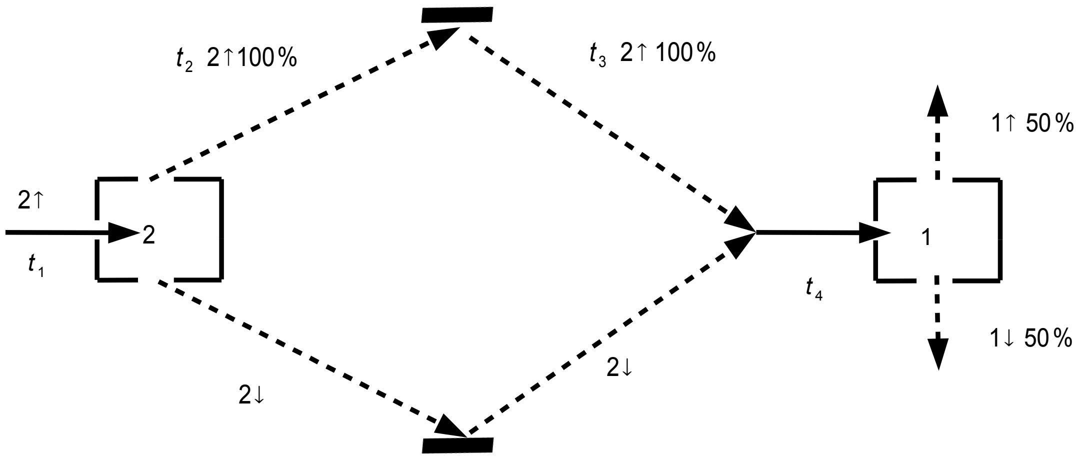
But one can choose to insert the detection plate *after* the passage of the beams through the slits. So, it looks like we can decide whether the particle went through both slits or through only one of them by inserting or not the detection plate after the particle had supposedly decided to go through one slit or both!

This is the basis of the claim by Wheeler, that "the past is not really the past until it has been registered".

Moreover, Wheeler invented an ingenious scheme where such "experiments" would not take place in the laboratory, but on a cosmic scale: light sent by distant quasars can pass on either side of a galaxy. The experiment here concerns photons instead of electrons, since light is composed of the former, but the phenomena are similar in both cases. The two sides of the galaxy are like the two slits here. Then, when the photon reaches the Earth, one can choose to either put some equivalent of the detection plate or not put it: if we do not put it, we can detect on which side of the galaxy the light went, and, if we do put it, we can "observe" that it went on both sides at once.

If we accept Wheeler's reasoning, this implies that we could decide *now*, by choosing which kind of experiment to perform on the light coming from distant quasars, what happened billions of years ago! In other words, the choices we are making now do not only "create reality", but they also "create" the past. If this were true, it would give us, humans, a more fantastic role in Nature than what most of science fiction can imagine.

MACH-ZEHNDER INTERFEROMETER



2 paths, one for the $2\uparrow$,

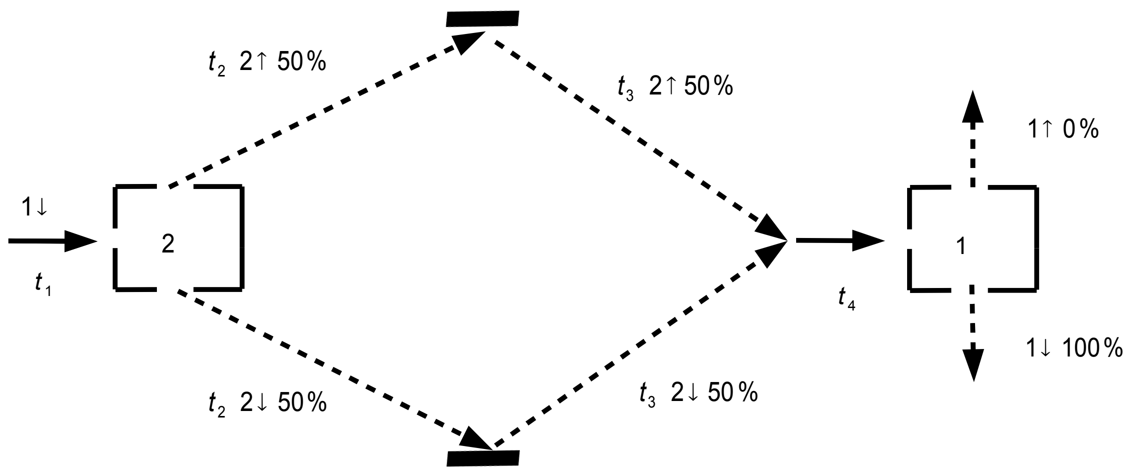
the other for the $2\downarrow$

If one starts with $|2\uparrow\rangle$:

100 % one path ($2\uparrow$)

after box 1 : 50 % $|1\uparrow\rangle$, 50 % $|1\downarrow\rangle$

If one starts with $|2\downarrow\rangle$: same thing 100 % one path ($2\downarrow$)



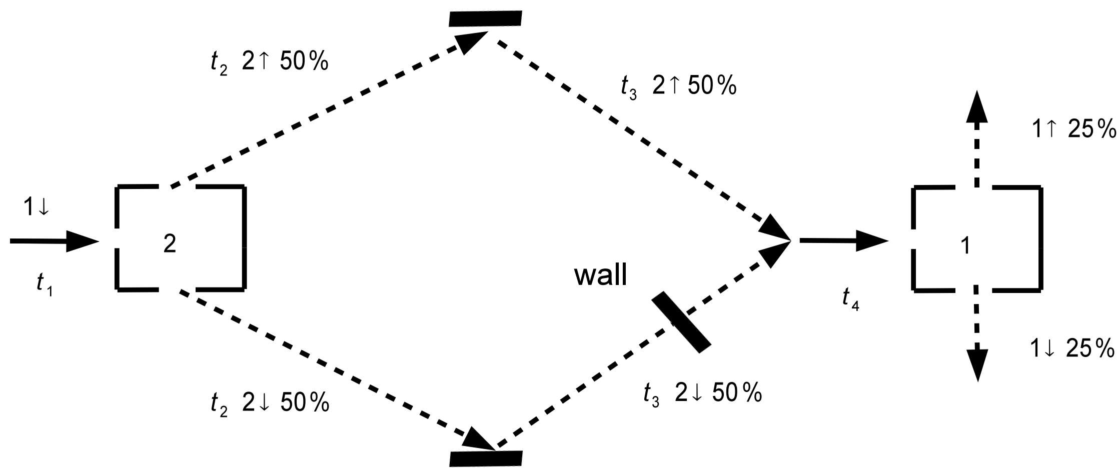
If one starts with $|1\downarrow\rangle$

50 % one path $(2\uparrow)$

50 % the other path $(2\downarrow)$

After box 1 100 % $|1\downarrow\rangle$

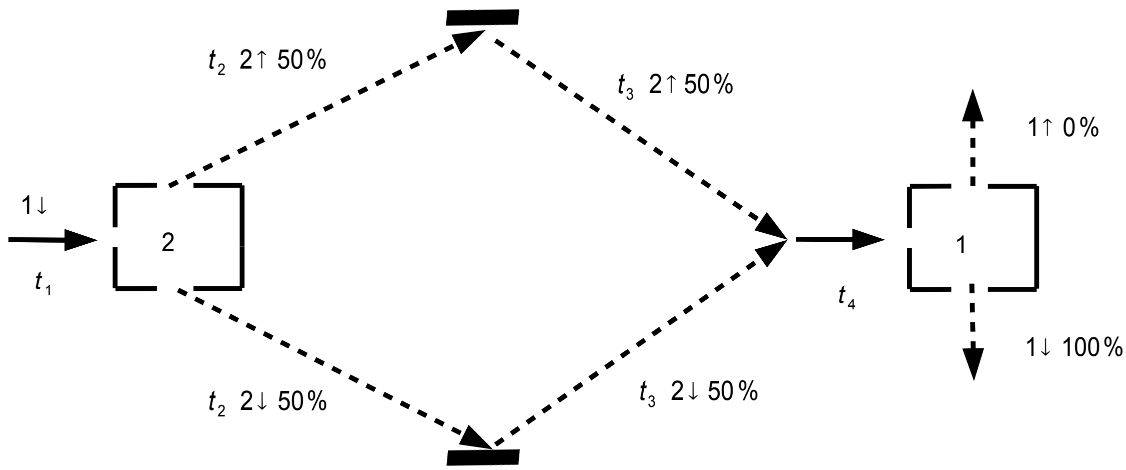
INSERT A WALL ALONG ONE PATH



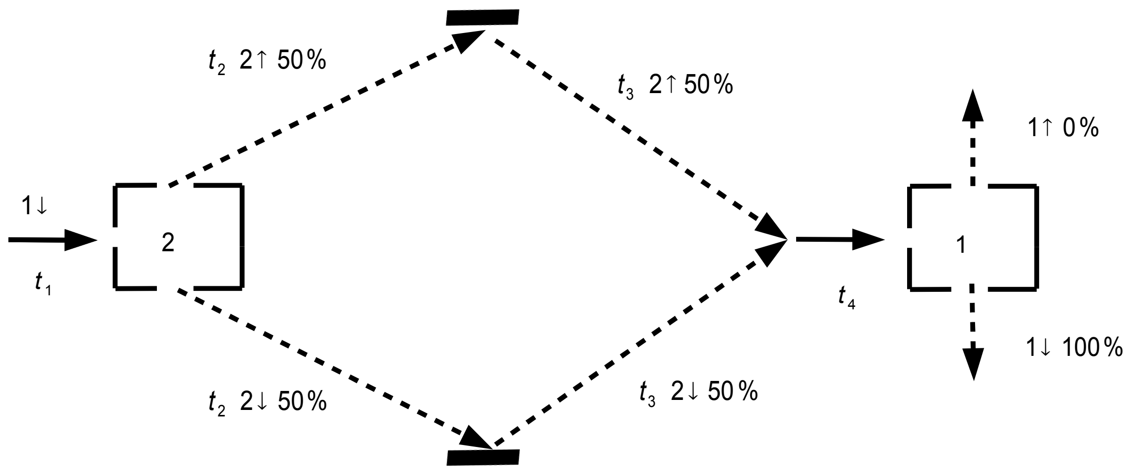
1. 50 % fewer particles.

2. After box 1: without the wall, 100 % of those that take 2 ↑ are $|1\downarrow\rangle$. Same for those that take the path 2 ↓.

If one blocks 2 ↓, it cannot affect the particles that take path 2 ↑. So, one should have 100 % $|1\downarrow\rangle$ (out of the remaining 50 %) ? NO : 25 % $|1\downarrow\rangle$ 25 % $|1\uparrow\rangle$! One acts in a certain way on the particles that take one path by blocking *the path that they do NOT take !*



This leads to an apparent *dead end*. Let us go back to the experiment without the wall, sending particles that are $|1\downarrow\rangle$. What does each particle do?



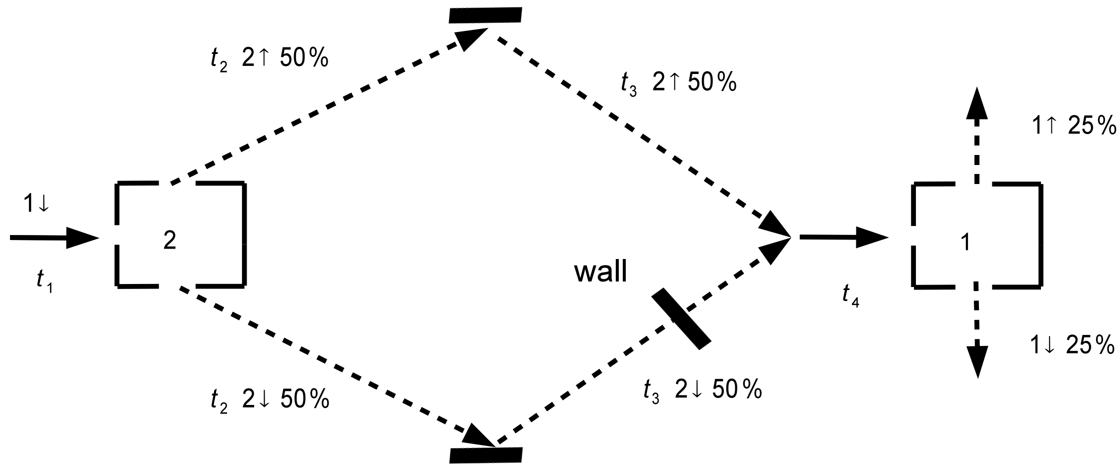
- Does it take path $2\uparrow$? No because if it did, one would have 25% $|1\uparrow\rangle$, 25% $|1\downarrow\rangle$ at box 1, as one sees when one puts a wall blocking the path $2\downarrow$.
- The path $2\downarrow$? No, for the same reason.
- Both paths? No, one always finds the particle along one of the paths if one tries to measure it.
- Neither of the paths? No, if both paths are blocked, no detection happens at the box on the right.

This phenomenon is similar to what happens in the double slit experiment, because whether one path is open or not seems to influence the behavior of the particles following the other path.

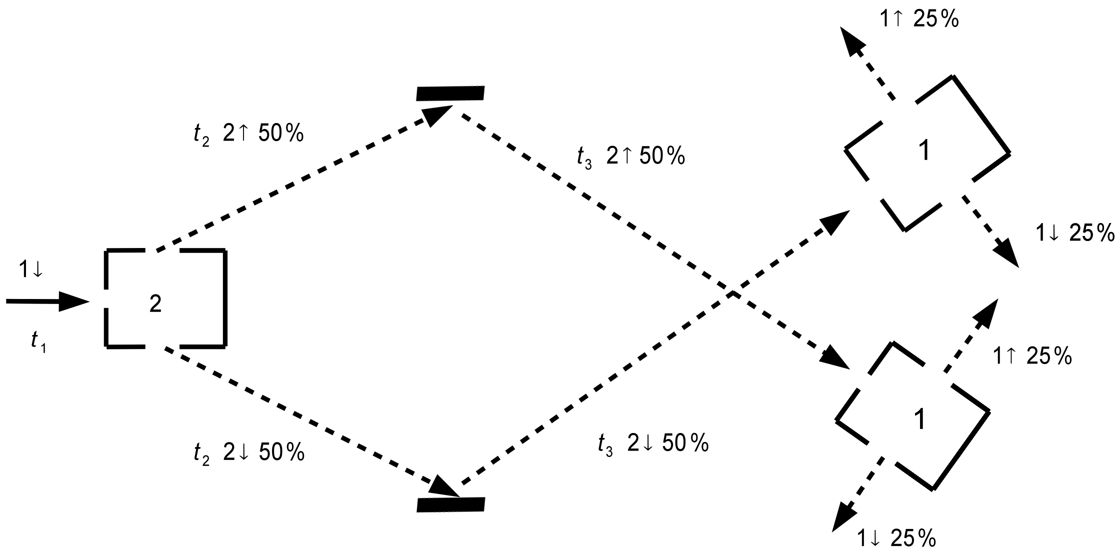
This is the essence of the (first) quantum mystery!

Again, in principle, these experiments are done by sending one particle at a time, so that no explanation can possibly be based on interactions between particles.

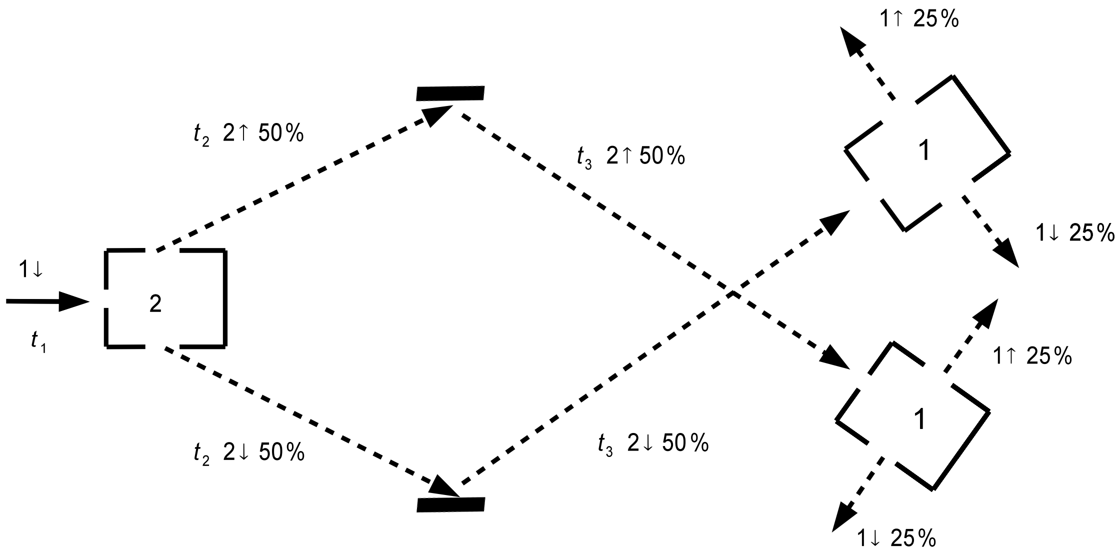
The way this experiment is usually described is by saying that the particle "follows both paths if they are both open" and only one path if one of them is blocked. But how does the particle know ahead of time, whether both paths are open or not?



One may also do a "delayed-choice" version of that experiment, that is, introducing the wall *after* the passage of the particle through the box 2 on the left measuring the spin in direction 2 (we can imagine both paths to be very long or put the wall just before the horizontal arrow on the right).



Alternatively, one could remove the box on the right while the particle is in flight and, then, there would be no recombination of the paths and the particle would continue its trajectory.



The particles following the path 2 $\uparrow$ continue (apparently) downwards and those following the path 2 $\downarrow$ continue (apparently) upwards. If we then measure the spin in direction 1, along any of these paths, we get 25% $|1\uparrow\rangle$, 25% $|1\downarrow\rangle$ in each case. Indeed, we have, along each path, particles that are only $|2\uparrow\rangle$ or $|2\downarrow\rangle$, and are measured in direction 1.

Another paradoxical consequence of the experiment described here is the Elitzur–Vaidman bomb-testing mechanism. Suppose that we have a stock of bombs, some of which are active and some of which are duds. We want to find out which is which, but an active bomb will explode if it is hit by only one particle. On the other hand, by definition, a dud is totally insensitive to being hit by one or more particles, so that it does not affect those particles in any way. How could we tell, by classical means, which bombs are active without exploding them? There seems to be no way to do that.

But there is a trick, based on the Mach–Zehnder interferometer (see the Appendix), that allows to identify at least a fraction of the active bombs as being active without exploding them.

WHAT HAPPENS IN ORTHODOX (COPENHAGEN) QUANTUM MECHANICS?

NOT CLEAR WHAT IT MEANS: MINIMALIST INTERPRETATION; IT GIVES RULES TO PREDICT RESULTS OF MEASUREMENTS.

States are represented by vectors in $\mathbb{C}^2$

$$| 1 \uparrow> = \begin{pmatrix} 1 \\ 0 \end{pmatrix}$$

$$| 1 \downarrow> = \begin{pmatrix} 0 \\ 1 \end{pmatrix}$$

$$| 2 \uparrow> = \frac{1}{\sqrt{2}} \begin{pmatrix} 1 \\ 1 \end{pmatrix}$$

$$| 2 \downarrow> = \frac{1}{\sqrt{2}} \begin{pmatrix} 1 \\ -1 \end{pmatrix}$$

So

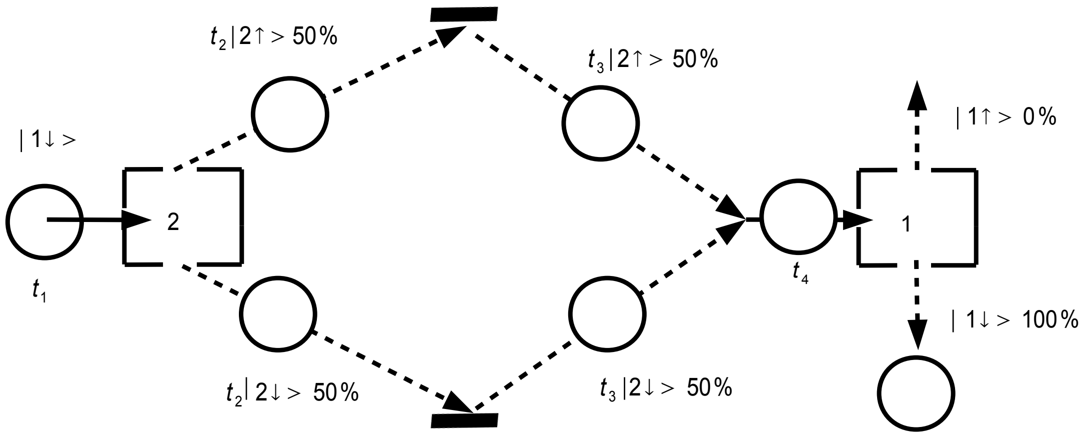
$$| 2 \uparrow > \;\; = \frac{1}{\sqrt{2}} \left(| 1 \uparrow > \; + | 1 \downarrow > \right)$$

$$| 2 \downarrow > = \frac{1}{\sqrt{2}} \left(| 1 \uparrow > \; - | 1 \downarrow > \right)$$

$$| 1 \uparrow > \;\; = \frac{1}{\sqrt{2}} \left(| 2 \uparrow > \; + | 2 \downarrow > \right)$$

$$| 1 \downarrow > \; = \frac{1}{\sqrt{2}} \left(| 2 \uparrow > \; - | 2 \downarrow > \right)$$

How does it work?



At t_1,

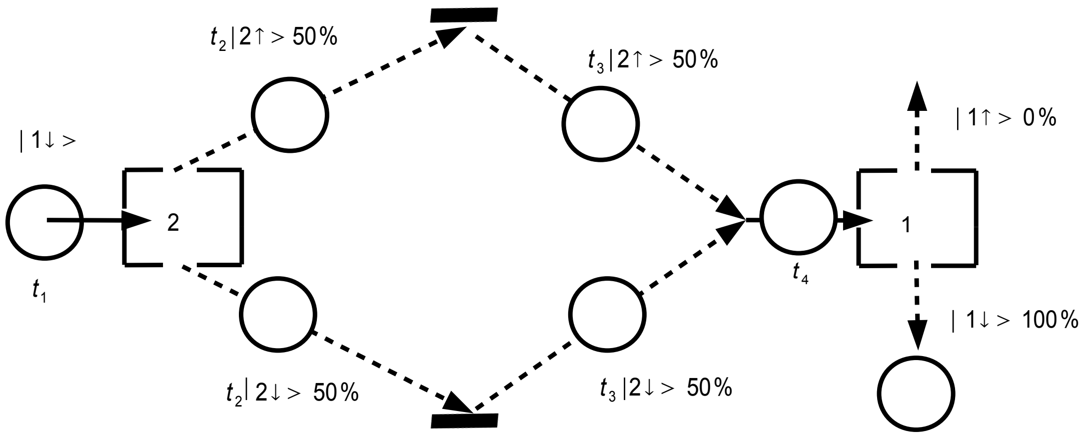
$$| 1 \downarrow> = \frac{1}{\sqrt{2}} (| 2 \uparrow> \ - | 2 \downarrow>).$$

At t_2 and t_3,

$$\frac{1}{\sqrt{2}}(| 2 \uparrow> \ | \mathrm{path2} \uparrow> -| 2 \downarrow> \ | \ \mathrm{path2} \downarrow>)$$

$| \ \mathrm{path2} \ \uparrow>$, $|\mathrm{path2} \ \downarrow>$ are wave functions $\Psi(x,t)$ that belong, for each t, to $L^2(\mathbb{R}^3)$ and evolve in time.

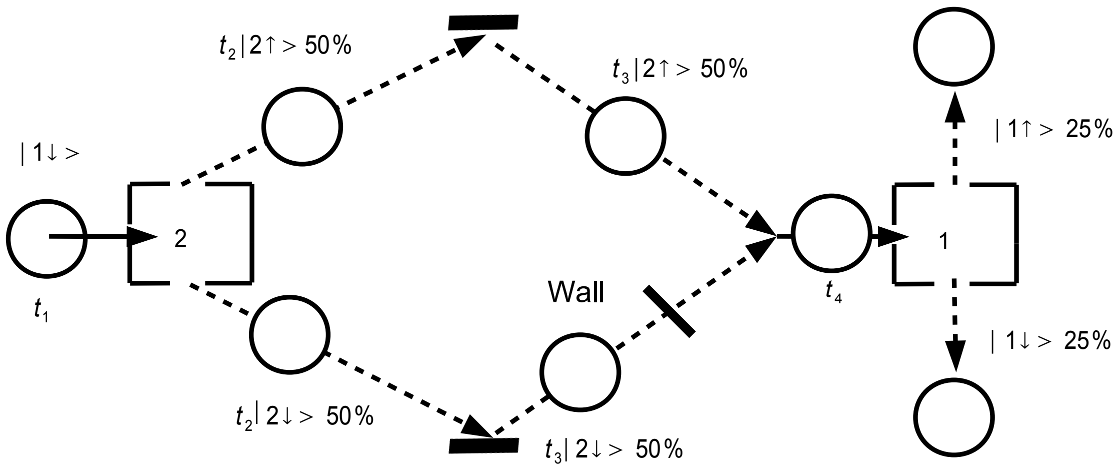
They are represented by disks that are the support of wave functions moving along the corresponding paths.



At t_4,

$$= \frac{1}{\sqrt{2}}(|\,2\uparrow> \; - |\,2\downarrow>) \,|\,\text{path} \rightarrow>$$

$$= |\,1\downarrow> \; |\,\text{path} \rightarrow> \rightarrow 100\%\; 1\downarrow .$$



Blocking path 2 $\downarrow$ IS A MEASUREMENT, SO IT COLLAPSES THE STATE:

at t_3, after the wall

$|$ state $> \rightarrow |2\uparrow>\ |$ path $2\uparrow>$

At t_4,

$= \frac{1}{\sqrt{2}}(|1\uparrow> + |1\downarrow>)\ |$ path $\rightarrow>$.

So, after the box $\rightarrow$ 25 % $\uparrow$ 25 % $\downarrow$.

Here the essential role of "measurement" and thus of "observation" enters.

THAT's IT ! NOTHING MORE NEEDS TO BE SAID: WE JUST PREDICT RESULTS OF MEASUREMENTS AND THAT IS ALL WHAT SCIENCE IS ABOUT.

WE DON'T HAVE TO SPEAK ABOUT TRAJECTORIES OR ANY OTHER QUANTUM REALITY BEYOND WHAT IS DIRECTLY OBSERVABLE!

EXERCICE: UNDERSTAND THAT SCIENCE NEEDS TO FIGURE OUT HOW THESE EXPERIMENTS WORK.

HINT: WHAT EINSTEIN SAID TO HEISENBERG IN 1926.

> [...] it is quite wrong to try founding a theory on observable magnitudes alone. In reality the very opposite happens. It is the theory which decides what we can observe. You must appreciate that observation is a very complicated process. The phenomenon under observation produces certain events in our measuring apparatus. As a result, further processes take place in the apparatus, which eventually and by complicated paths produce sense impressions and help us to fix the effects in our consciousness.

Along this whole path [...] we must be able to tell how Nature functions [...] before we can claim to have observed anything at all. Only theory, that is, knowledge of natural laws, enables us to deduce the underlying phenomena from our sense impressions. When we claim that we can observe something new, [...] we nevertheless assume that the existing laws — covering the whole path from the phenomenon to our consciousness — function in such a way that we can rely upon them and hence speak of 'observations'.

When it comes to observation, you behave as if everything can be left as it was, that is, as if you could use the old descriptive language. In that case, however, you will also have to say: in a cloud chamber we can observe the path of an electron. At the same time, you claim that there are no electron paths inside the atom. This is obvious nonsense [. . .].

Albert Einstein speaking to Werner Heisenberg

WHAT HAPPENS IN THE DE BROGLIE-BOHM THEORY ?

We saw yesterday that the de Broglie-Bohm theory is a theory of matter in motion. Particles do follow trajectories and are guided in their motion by the wave function, which evolves according to the usual Schrdinger's equation, at all times, whether one measures something or not.

Double slit experiment: numerical solution in the de Broglie-Bohm theory.

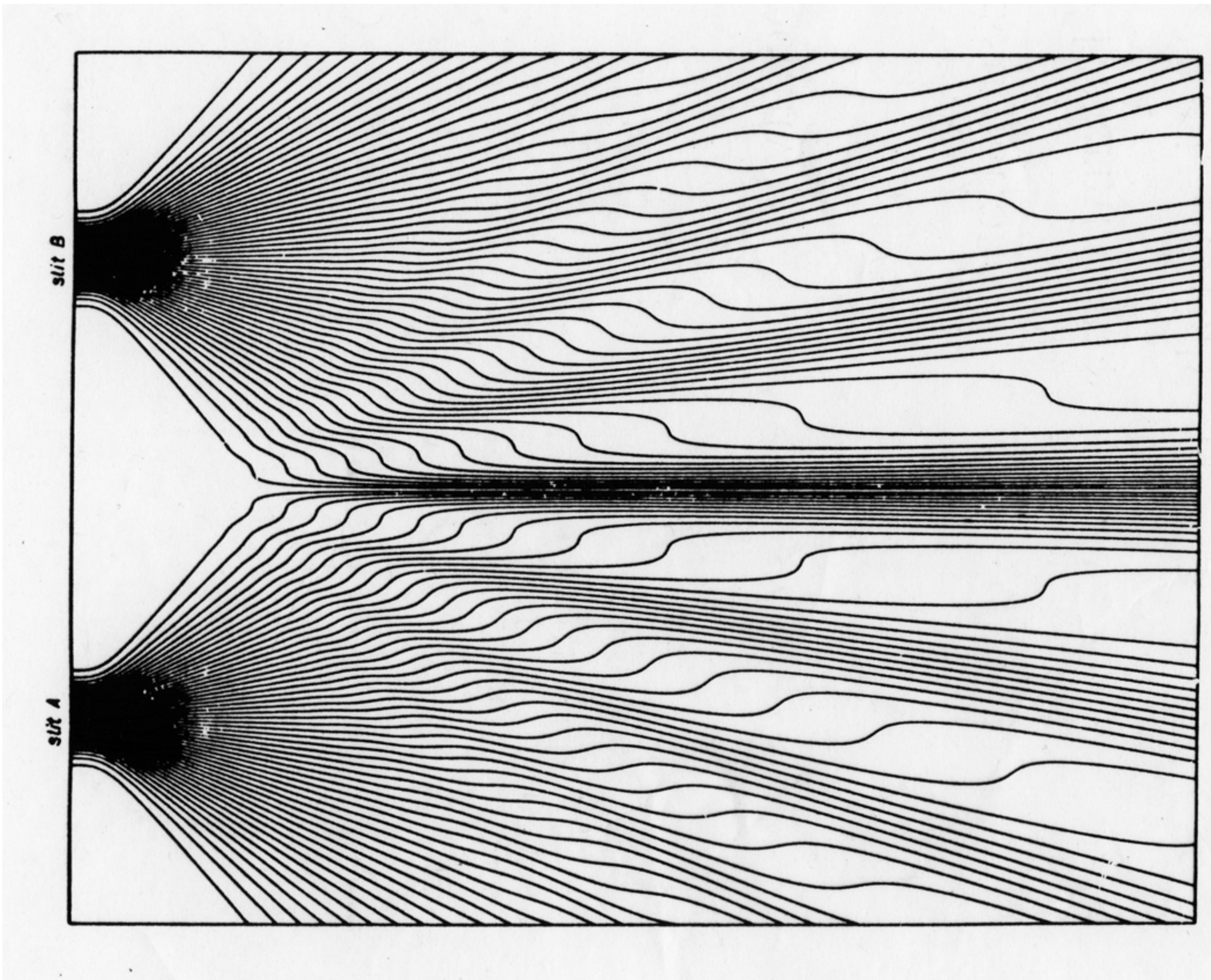
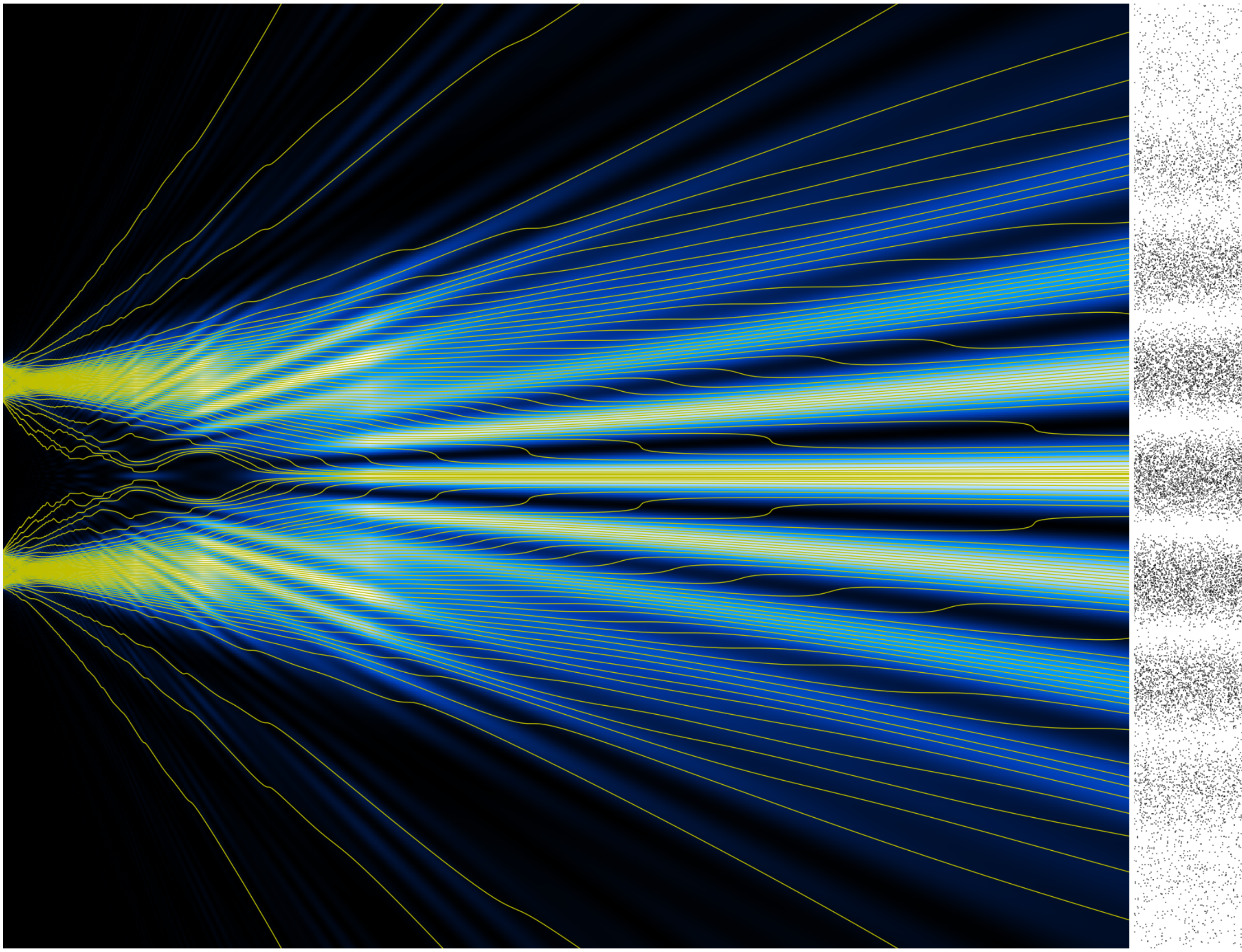


Figure 9.3 Trajectories for two Gaussian slits with a Gaussian distribution of initial positions at the slits.

Motion *in vacuum* highly *non classical*!! Note that one can determine a posteriori through which hole that particle went !



INTENSITY OF THE FLOW OF PARTICLES WHEN BOTH SLITS ARE OPEN WITH ONE HUNDRED TRAJECTORIES SIMULATED

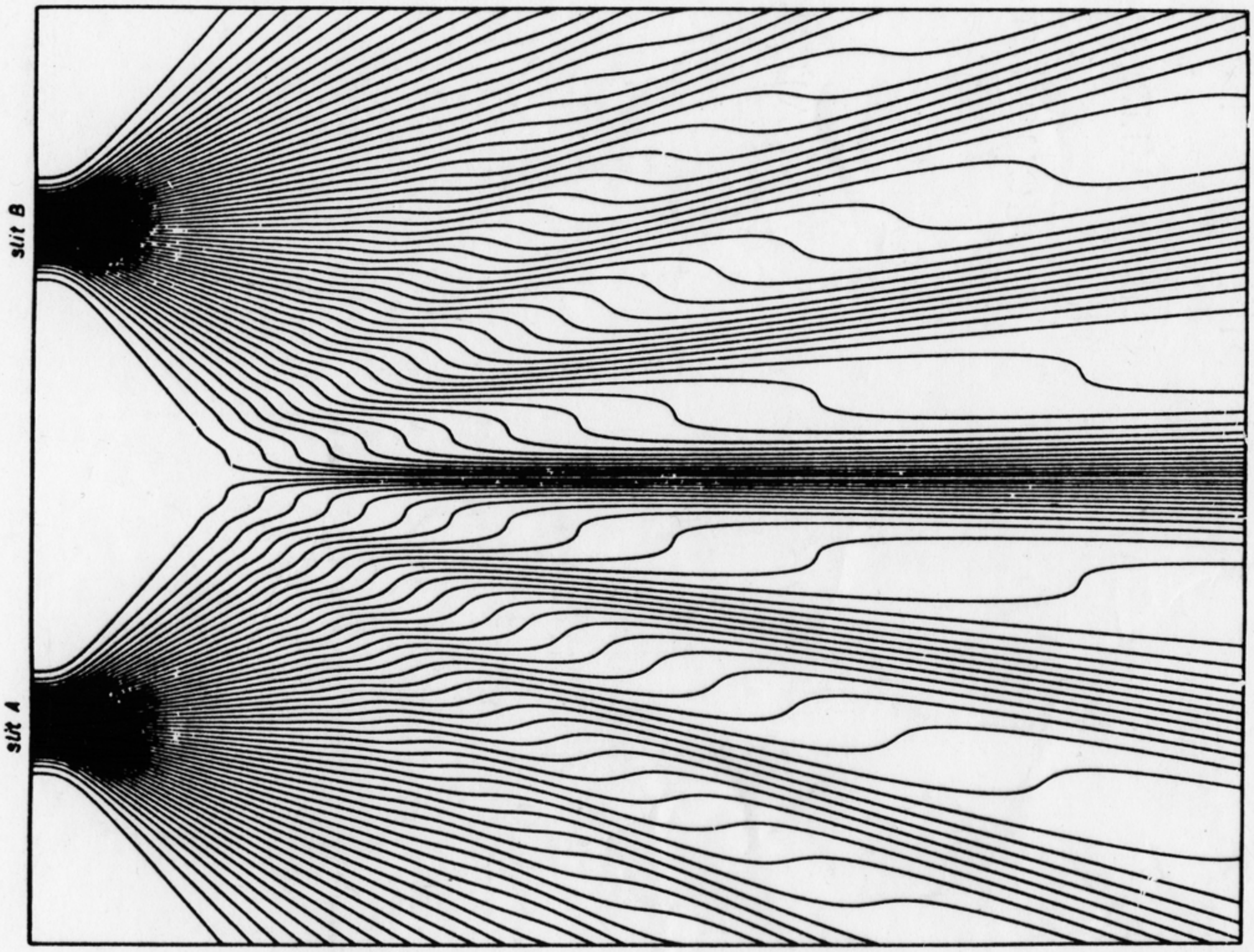
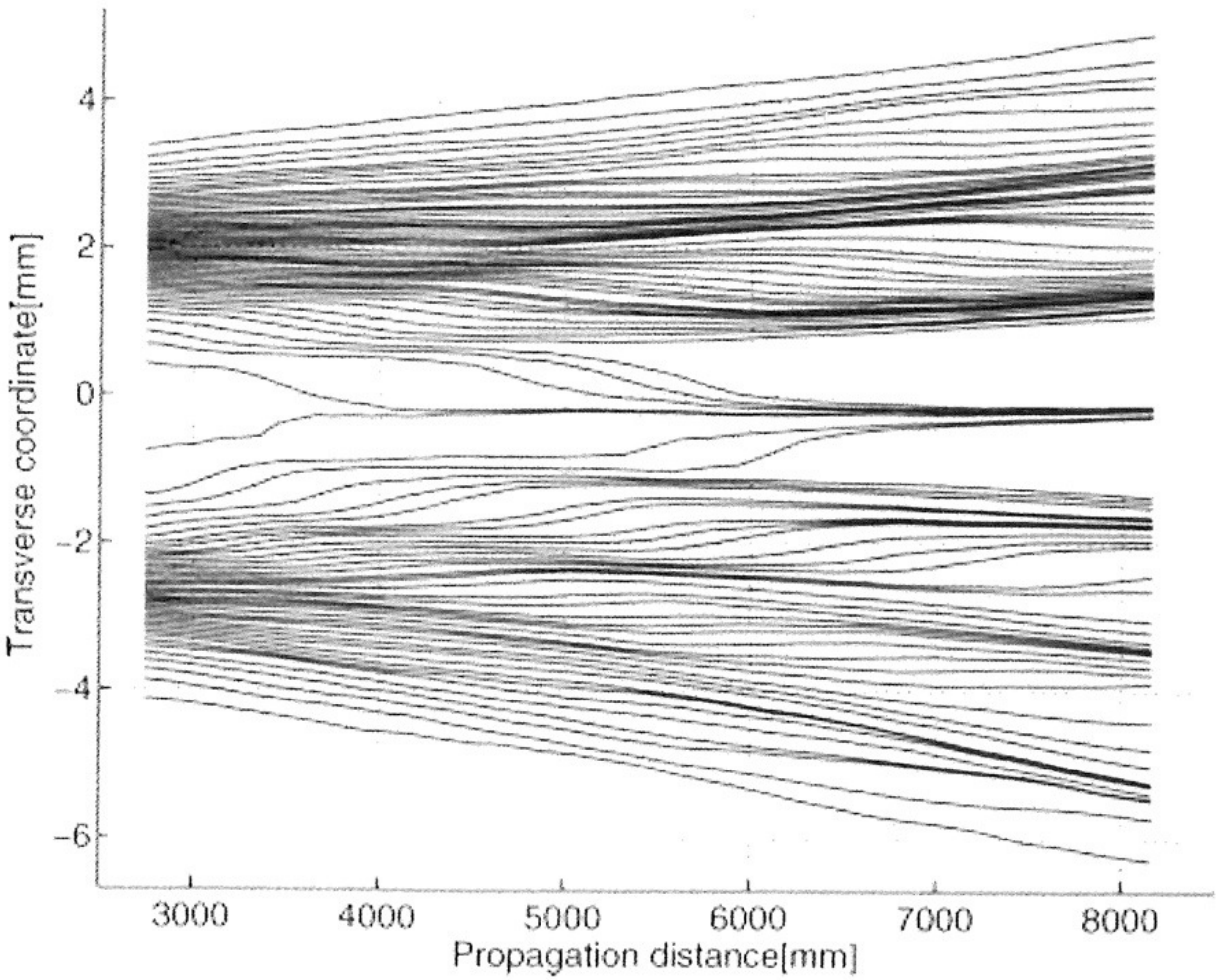
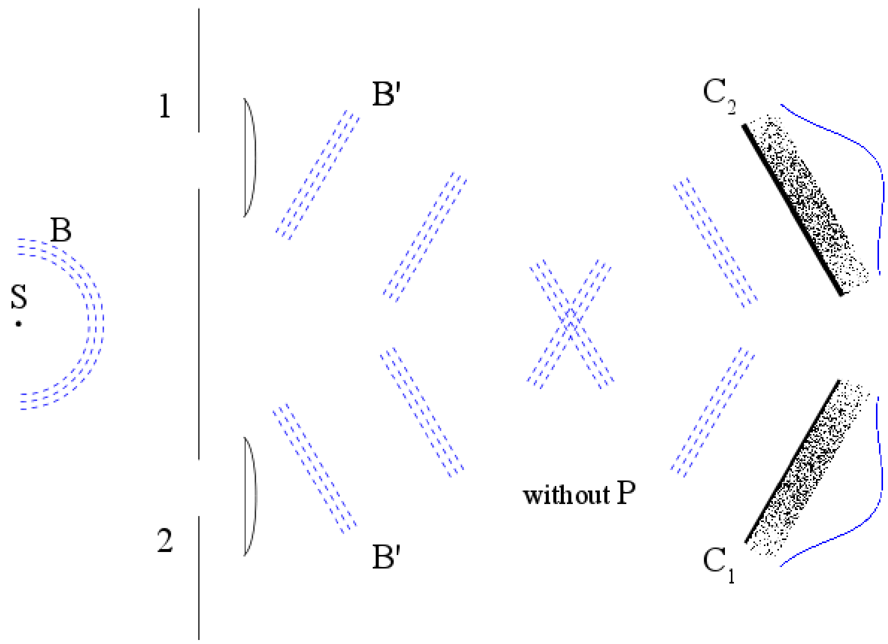


Figure 9.3 Trajectories for two Gaussian slits with a Gaussian distribution of initial positions at the slits.

Note also the presence of a nodal line: by symmetry of Ψ, the velocity is tangent to the middle line; thus, particles cannot cross it.

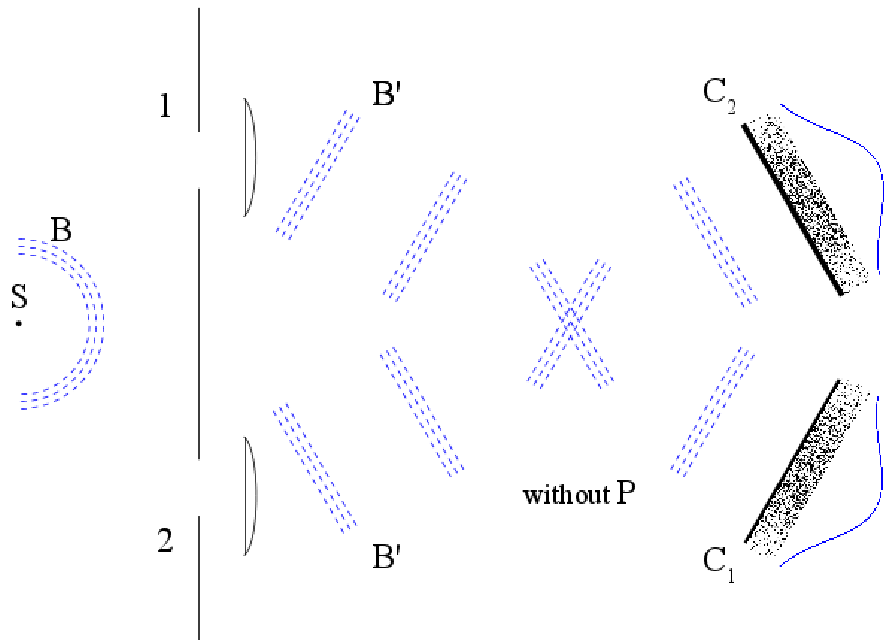
Related experiment (Science, june 2011).





WARNING

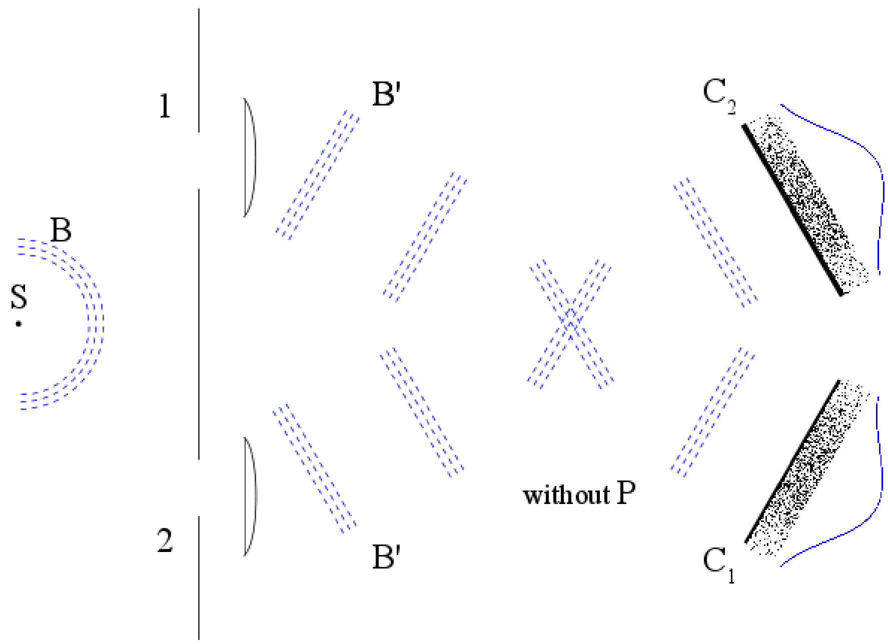
In the de Broglie-Bohm theory if a particle goes through the upper slit, it is detected at C_2 and if it goes through the lower slit, it is detected at C_1.



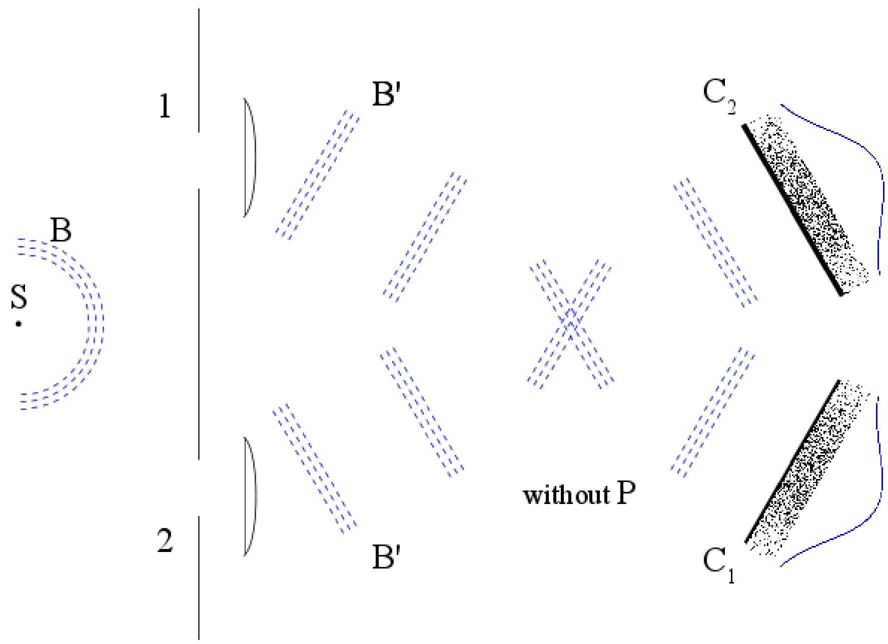
WHY?

Because there is again a nodal line in the middle of the figure that the particles cannot cross.

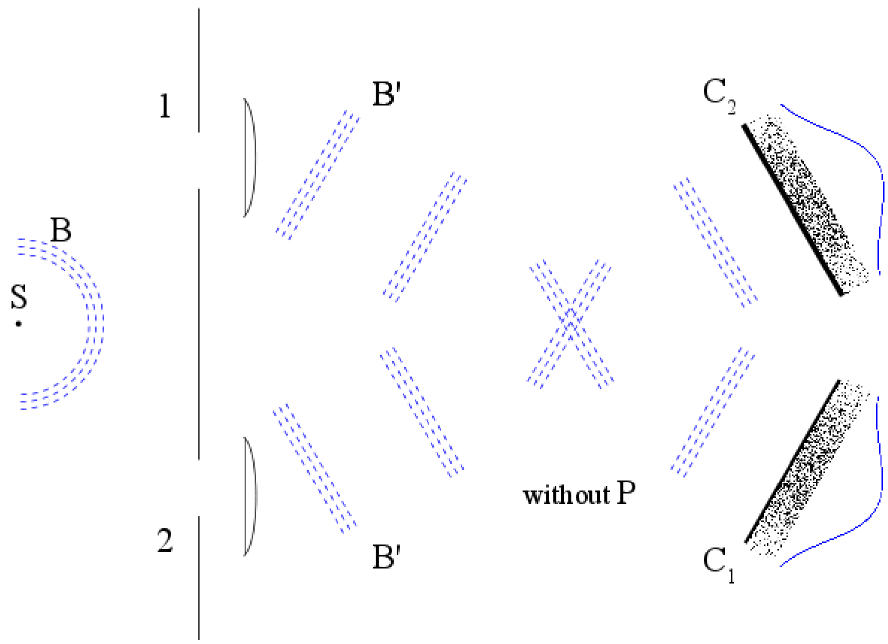
The wave functions evolve as in the figure: the part that goes through the upper slit, goes towards C_1 and the part that goes through the lower slit goes towards C_2.



But the particles, since they cannot cross the line in the middle of the figure, bounce back against that line and "switch horses" so to speak: if a particle goes through the upper slit, it starts being guided by the part of the wave function that goes through the upper slit, but, when both parts of the wave function cross, it becomes guided by the part of the wave function that went through the lower slit.

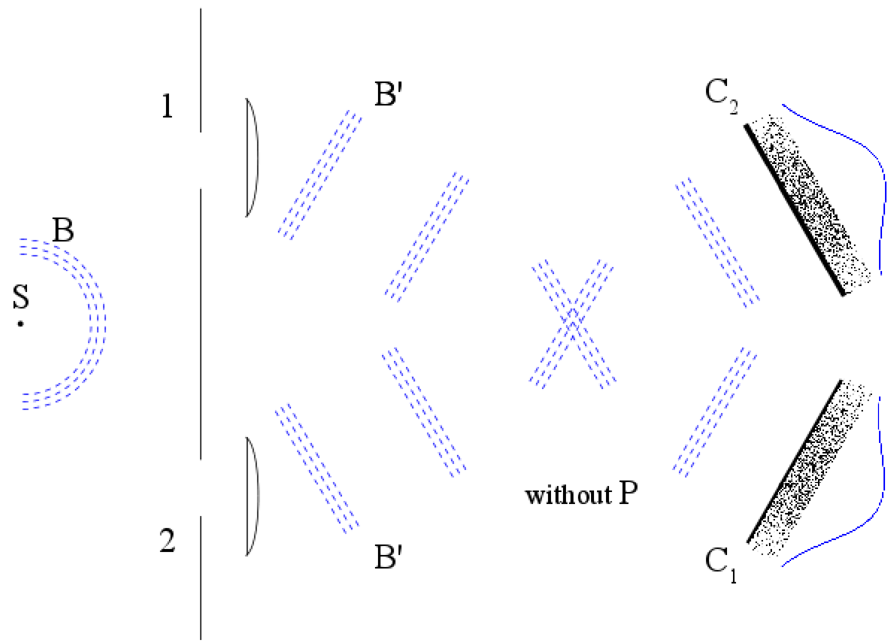


Wheeler thinks that one can tell through which slit the particle went (the upper one if it is detected at C_1 and the lower one if it is detected at C_2).



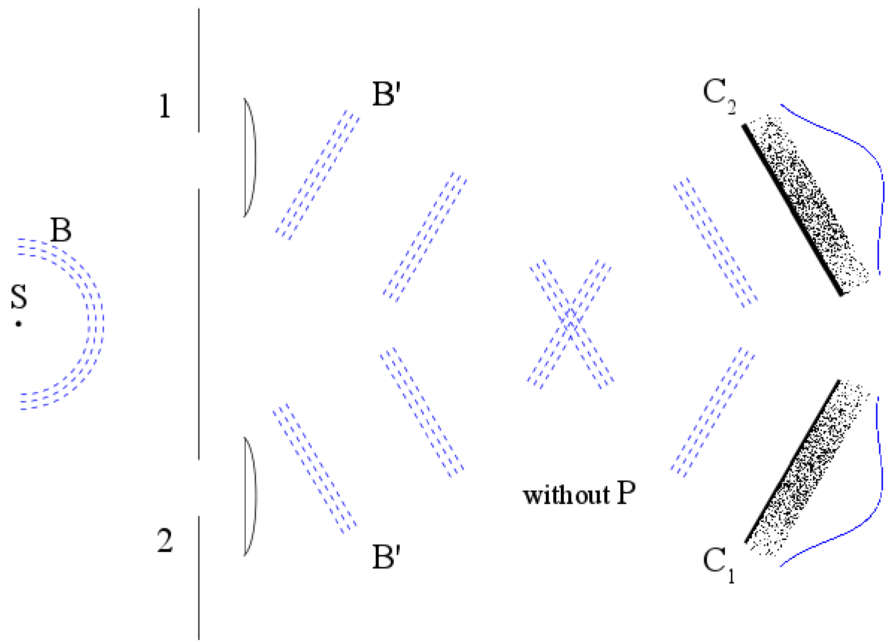
This is an instance of what Tumulka in his lectures (p. 26) calls **Wheeler's fallacy**:

> If one assumes that there are no particle trajectories in the quantum world, as one usually does in orthodox quantum mechanics, then it would seem natural to say that there is no fact about which slit the electron went through, given that there was no attempt to detect the electron while passing a slit.



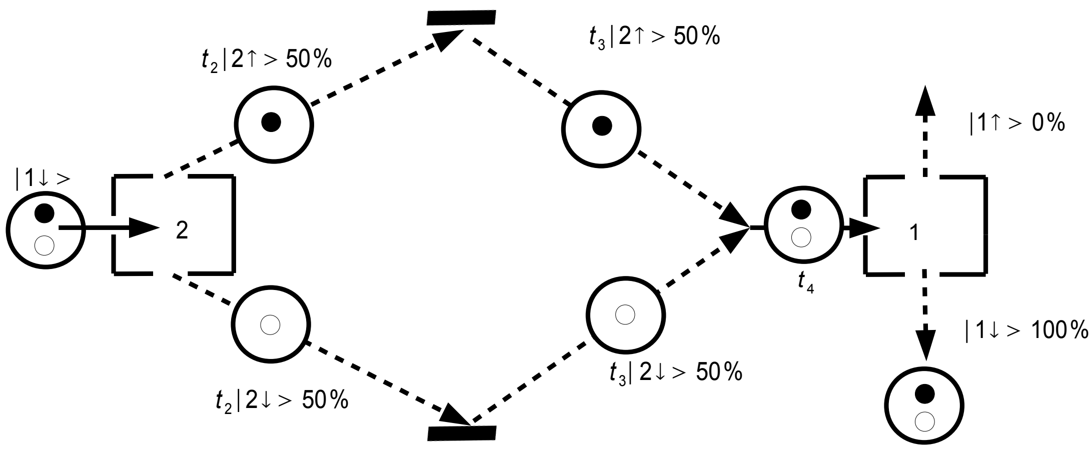
Surprising it is, then, that Wheeler claims that the detection on the far- away screen reveals which slit it took! How can anything reveal which slit the electron took if the electron didn't take a slit?

Roderich Tumulka



Moreover, in a theory where **there are trajectories** , such as the de Broglie-Bohm one, the particle does go through one slit and one can tell through which one it went by looking where it is finally detected (through the upper one if it is detected at C_2 and through the lower one if it is detected at C_1), but it is the opposite of Wheeler's conclusion.

The Mach-Zehnder experiment in the de Broglie-Bohm theory.



at t_1

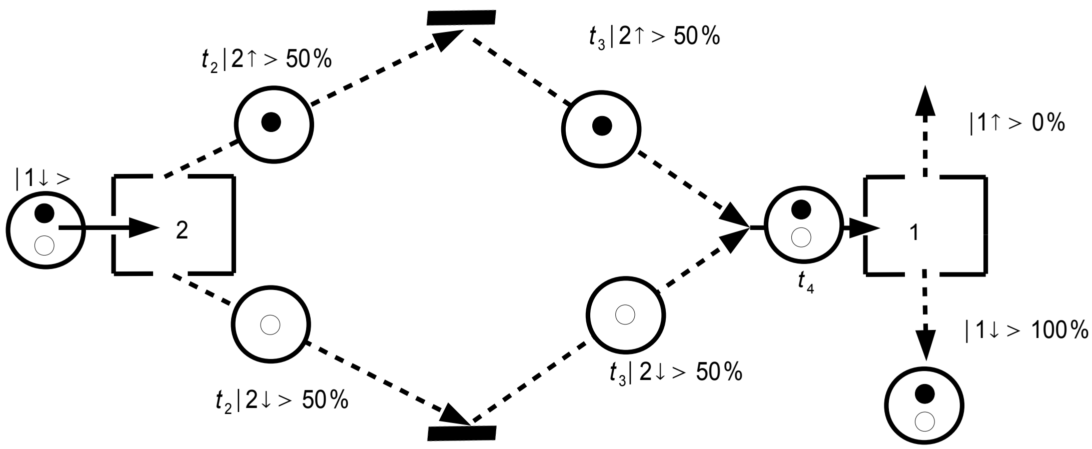
$$| 1 \downarrow> = \frac{1}{\sqrt{2}} (| 2 \uparrow> \ - | 2 \downarrow>)$$

at t_2 and t_3

$$\frac{1}{\sqrt{2}}(| 2 \uparrow> \ | \text{path2} \uparrow> -| 2 \downarrow> \ | \ \text{path2} \downarrow>)$$

The particle follows a unique path, but the wave goes through both paths (as in the double slit experiment)

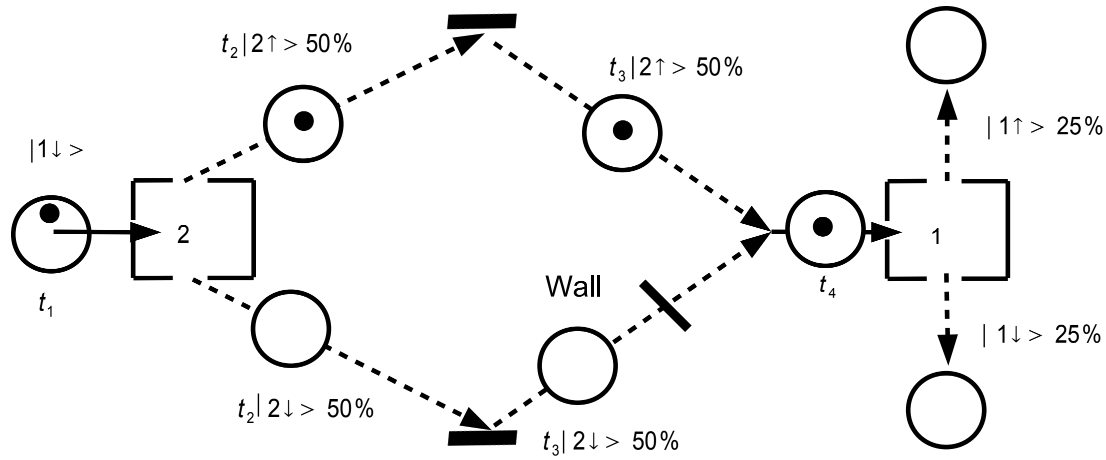
The particle is always guided by the part of the wave function in the support of which it finds itself.



at t_4

$$= \frac{1}{\sqrt{2}}(| 2 \uparrow> \ - | 2 \downarrow>) \ | \text{path} \rightarrow>$$

$$= | 1 \downarrow> \ | \text{path} \rightarrow> \rightarrow 100\% \ 1 \downarrow$$



Blocking path $2\downarrow$ will change the wave function:

at t_3 after the wall:

$\rightarrow |2\uparrow> \ \ |\ \text{path}\ 2\uparrow>$

Since the particle is guided by the part of the wave function in the support of which it finds itself:

at t_4 :

$= \frac{1}{\sqrt{2}}\,(|1\uparrow> + |1\downarrow>)\ |\ \text{path}\ \rightarrow>$

after box 1 $\rightarrow$ 25 % $\uparrow$ 25 % $\downarrow$.

If one combines both waves, one gets a different result than if one blocks one of them.

The wave function is "physical" because of its "guiding" property -it is not simply a "probability amplitude".

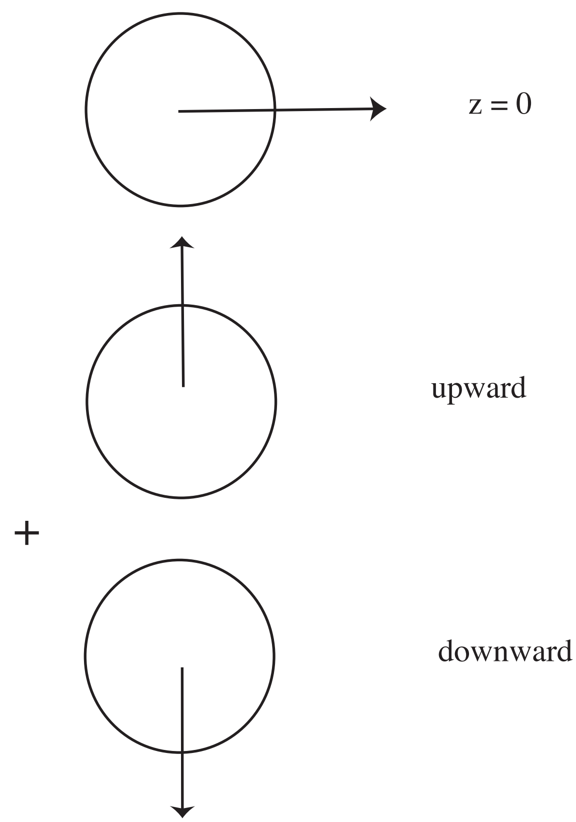
The upshot is that there is no problem whatsoever in the de Broglie-Bohm theory with the double slit experiment or the Mach-Zehnder interferometer or with the delayed-choices versions of them.

WHAT HAPPENS IN THE SPONTANEOUS COLLAPSE MODELS ?

In what follows I will rely on Tumulka's lectures.

I cannot understand the pure wave function ontology.

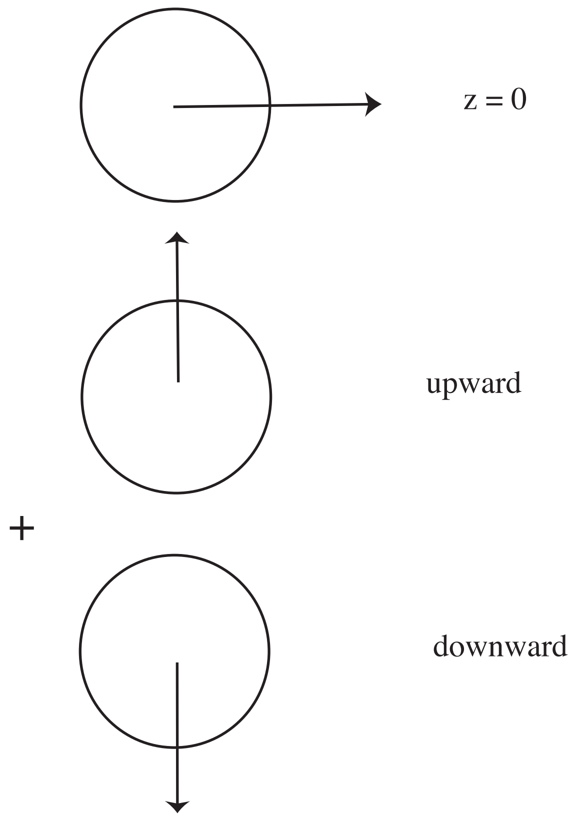
YOU may think you are a vector in a Hilbert space, **but I am not!**.



By the way, there was a big mistake when I spoke yesterday of the state:

$$\frac{1}{\sqrt{2}}\begin{pmatrix}1\\0\end{pmatrix}\varphi^{\uparrow}(z)+\frac{1}{\sqrt{2}}\begin{pmatrix}0\\1\end{pmatrix}\varphi^{\downarrow}(z)\ ,$$

"where $\varphi^{\uparrow}(z)$ and $\varphi^{\downarrow}(z)$ correspond to the last two pictures in the figure, i.e., the pointer pointing upward or downward."



Because I identified $\varphi^{\uparrow}(z)$ and $\varphi^{\downarrow}(z)$ with pointers in the real, three dimensional, space.

But $\varphi^{\uparrow}(z)$ and $\varphi^{\downarrow}(z)$ are in principle functions defined on a high dimensional space $\mathbb{R}^{3N}$ where N is the number of particles in the pointer (the variable z representing their center of mass).

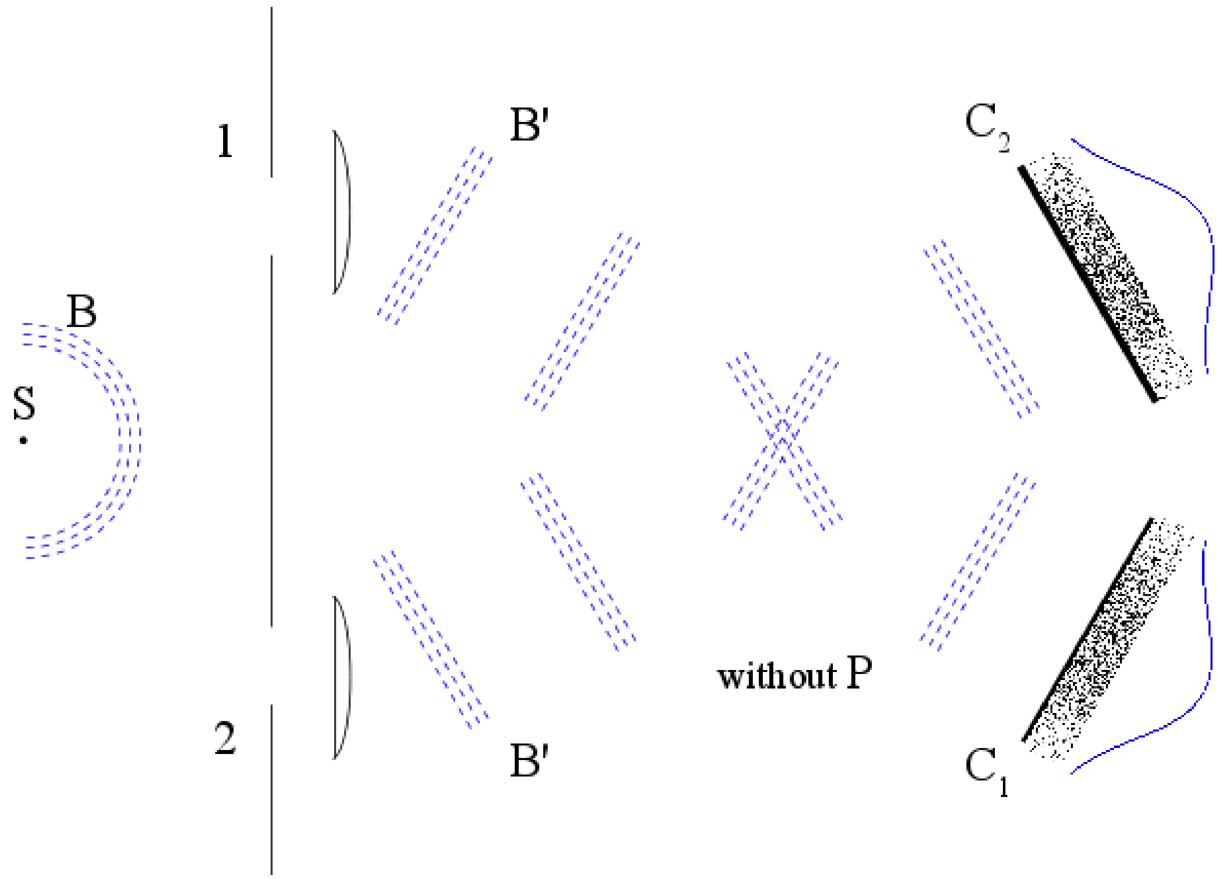
THESE ARE NOT AT ALL THE SAME THINGS!

But, as a de Broglie-Bohmian, I have an ontology: the pointers are made of particles located in $\mathbb{R}^3$. So, from my point of view, there was no real problem.

Now, let us consider spontaneous collapses with an ontology, and let it be the matter density one: GRW_m.

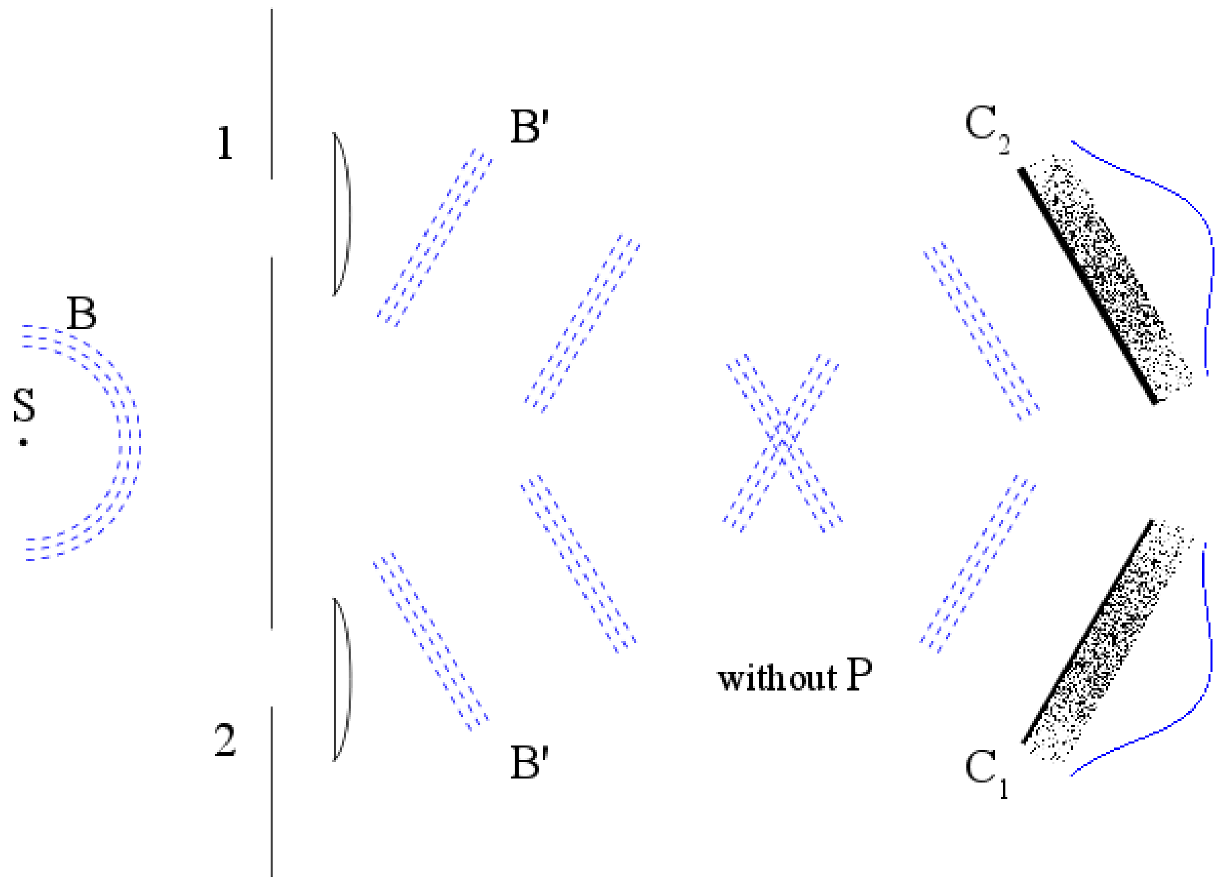
There $|\Psi(x,t)|^2$ is (roughly) the local density of matter at x and at time t.

What happens in GRW$_m$ in this picture?



There is a half electron going through the upper slit and a half electron going through the lower one.

The half electron going through the upper slit goes towards C_1 and the half electron going through the lower one goes towards C_2.

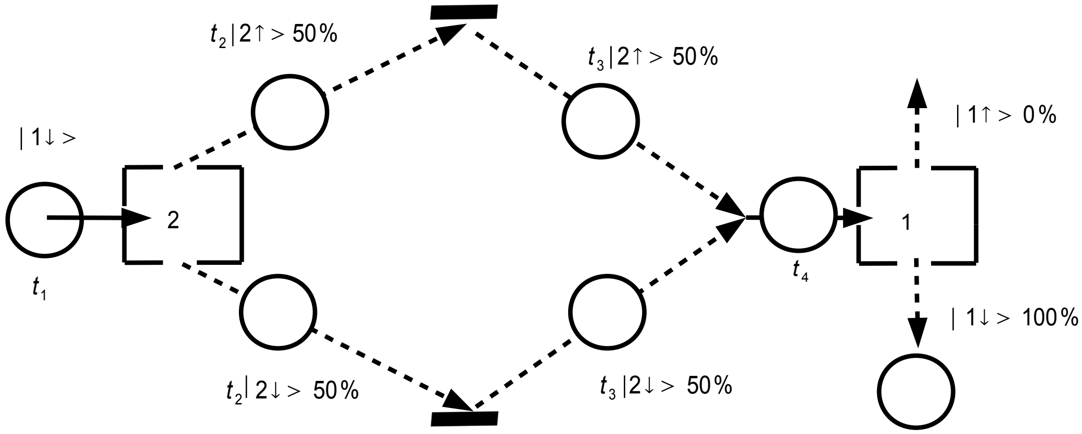


The probability of a collapse during all this is minuscule.

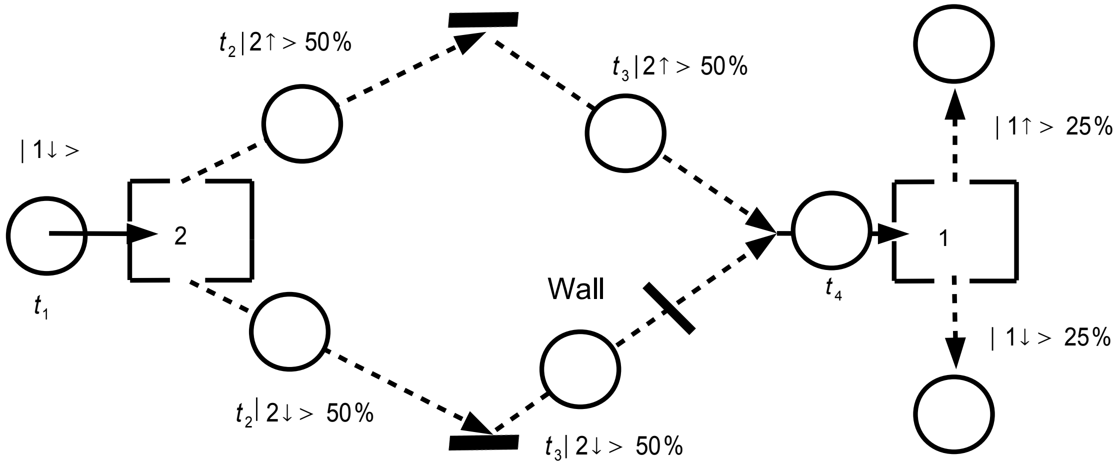
Then, at C_1 and C_2 there are detectors, namely macroscopic objects, and collapses are extremely frequent.

Let's say that the first collapse occurs at C_1.

Then, the half electron at C_2 gets "killed" and a full electron appears (instantaneously!) at C_1.

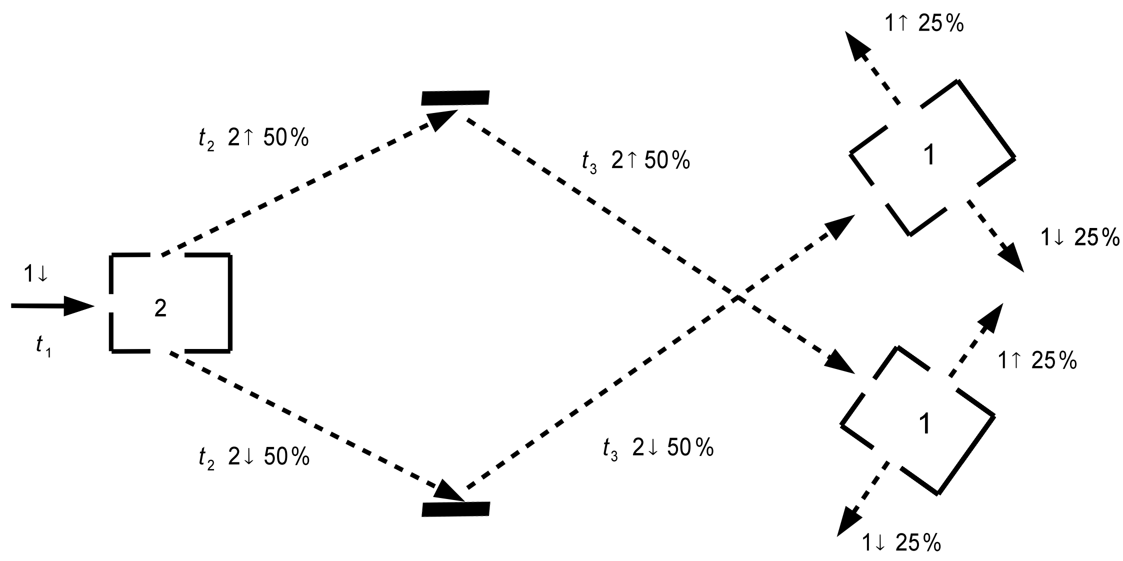


Same thing in the Mach-Zehnder experiment: there is a half electron following each route and when the paths recombine, it becomes a full electron.



With a wall, when the half electron interacts with the wall, it means that it gets destroyed and its matter density gets transferred to the half electron on the other path, that becomes a full electron.

When the wave functions gets split into two wave functions after t_1, we have again two half electrons until there is a measuring device detecting them (either above or below the box on the right) and again, one half electron jumps so to speak to the other half.



Here again, as in the double slit experiment, we have two half electrons moving towards the two boxes on the right of the picture, and, depending on where the first collapse occurs, one half electron disappears in one box and a full one appears in the other one.

I cannot say that I like this picture of half electrons (remember that I am a fundamentalist de Broglie-Bohmian!), but it "saves the phenomena".

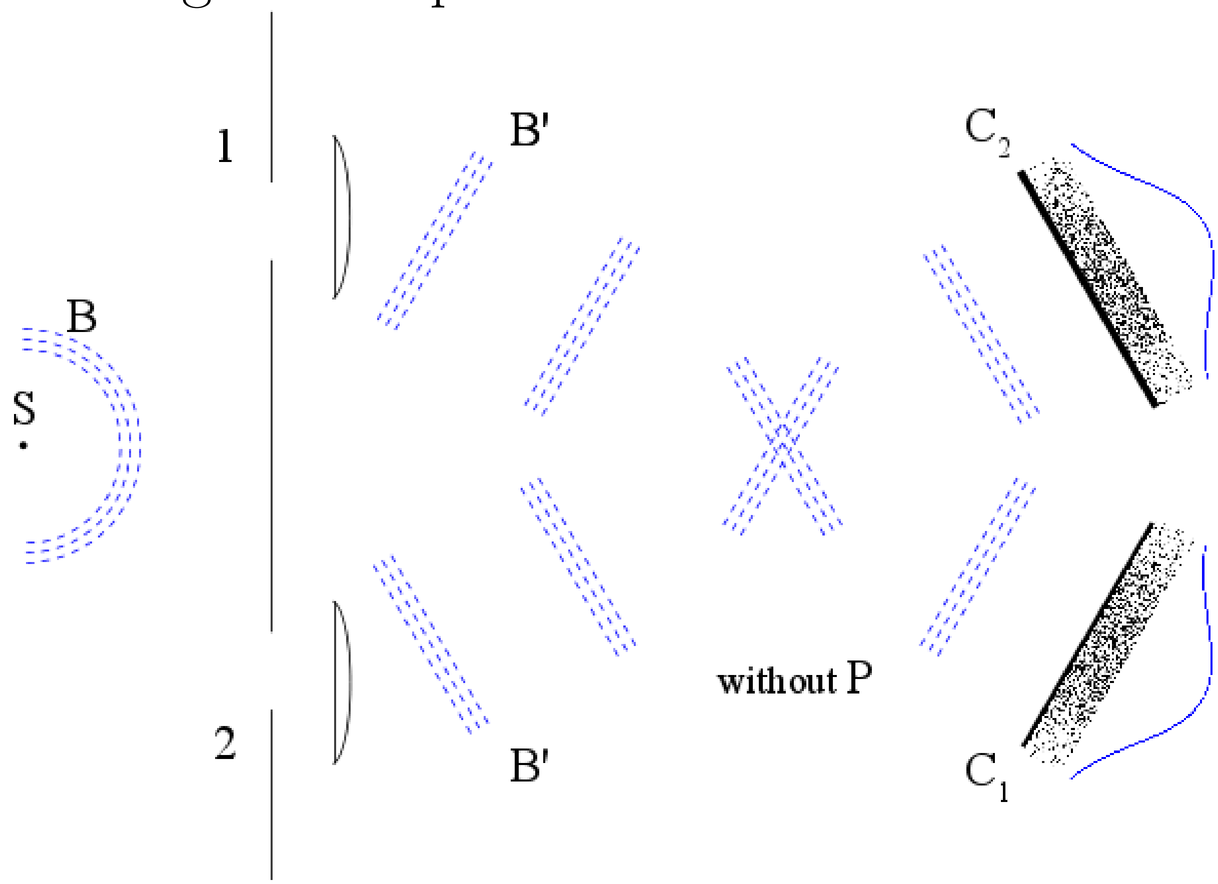
But that alone is a **very weak argument** in favor of a theory (think of brains in a vat)!

WHAT HAPPENS IN THE MANY WORLDS INTERPRETATION ?

Again, we need to add an ontology to the "pure wave function" ontology. Let us consider again the matter density ontology.

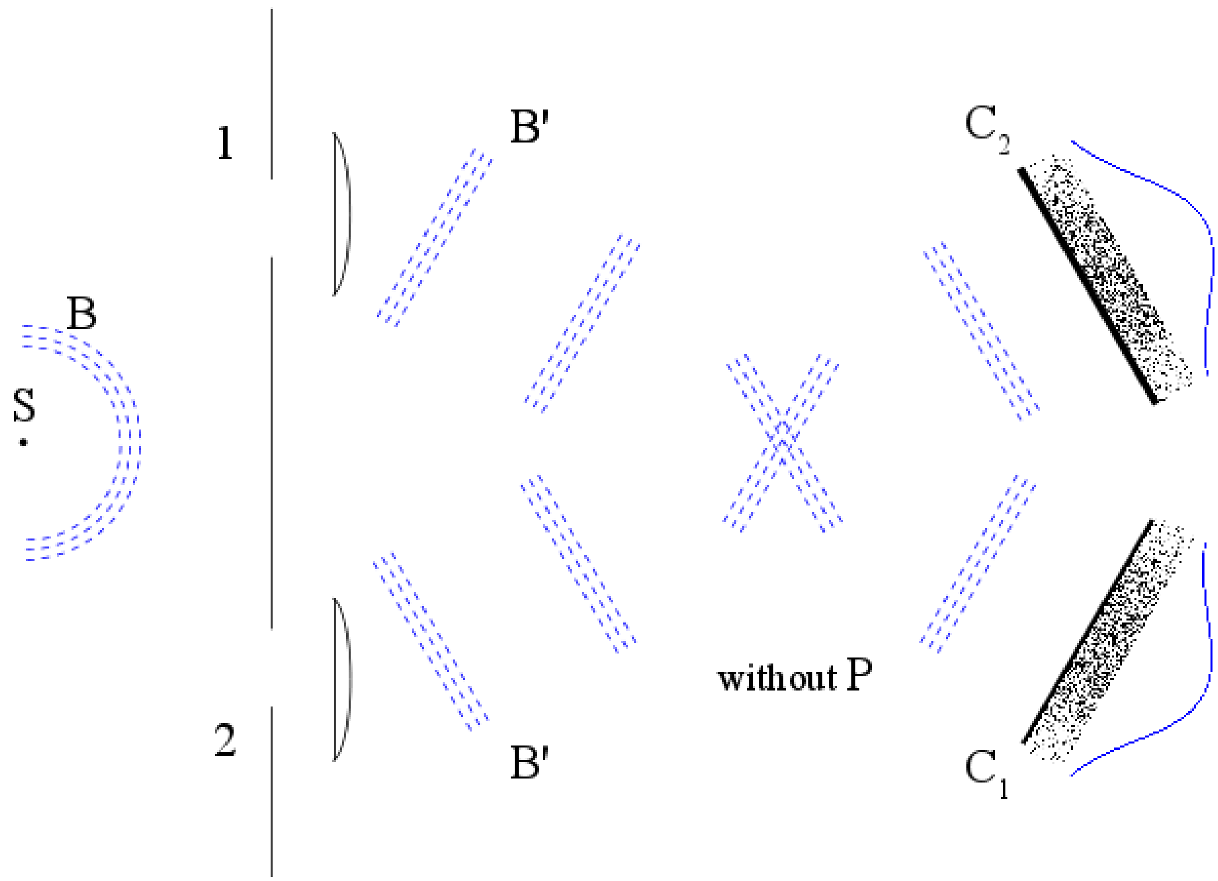
This is what is called "Schrödinger's many worlds", or S_m. There is a continuous matter density given by $|\Psi(x,t)|^2$, but without collapses.

Consider again this picture:



There is again a half electron going through the upper slit and a half electron going through the lower one.

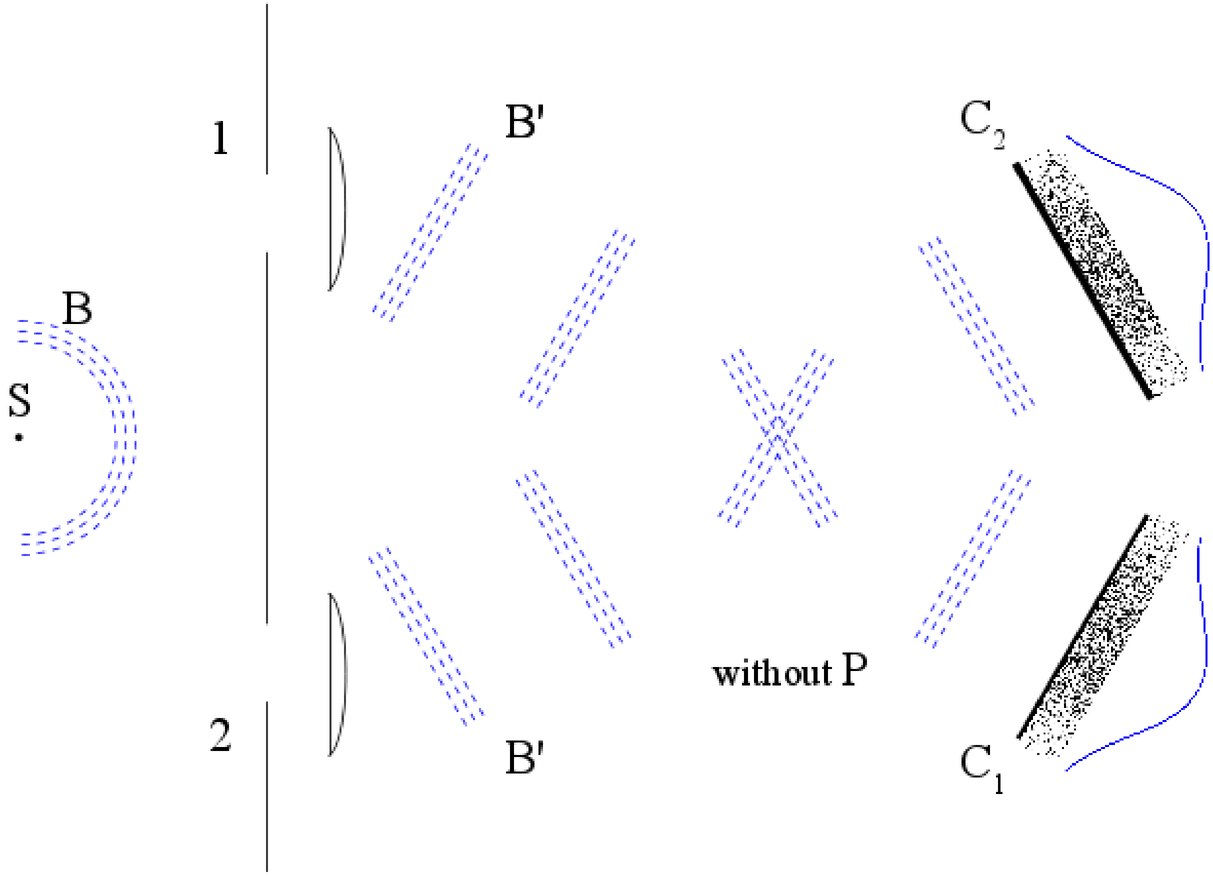
The half electron going through the upper slit goes towards C_1 and the half electron going through the lower one goes towards C_2.



But since there are no collapses, we have the detectors triggered at both C_1 and C_2.

That gives rise to two "worlds": one where the detector C_1 is triggered and one where the detector C_2 is triggered.

If "I" look at the result, I will see only one detector being triggered.



But that is because there are also two "I"'s: one who sees the detector C_1 triggered and one who sees the detector C_2 triggered. Let's call these two "I"'s my **descendants**.

That "multiplication of entities" holds also for the entire Universe.

This multiplication of "I"'s has to be taken literally:

> "I" am an object, such as the Earth, a cat, etc. "I" is defined at a particular time by a complete (classical) description of the state of my body and of my brain. "I" and "Lev" do not refer to the same things (even though my name is Lev). At the present moment there are many different "Lev"s in different worlds (not more than one in each world), but it is meaningless to say that now there is another "I". I have a particular, well defined past: I correspond to a particular "Lev" in 2012, but not to a particular "Lev" in the future: I correspond to a multitude of "Lev"s in 2022."

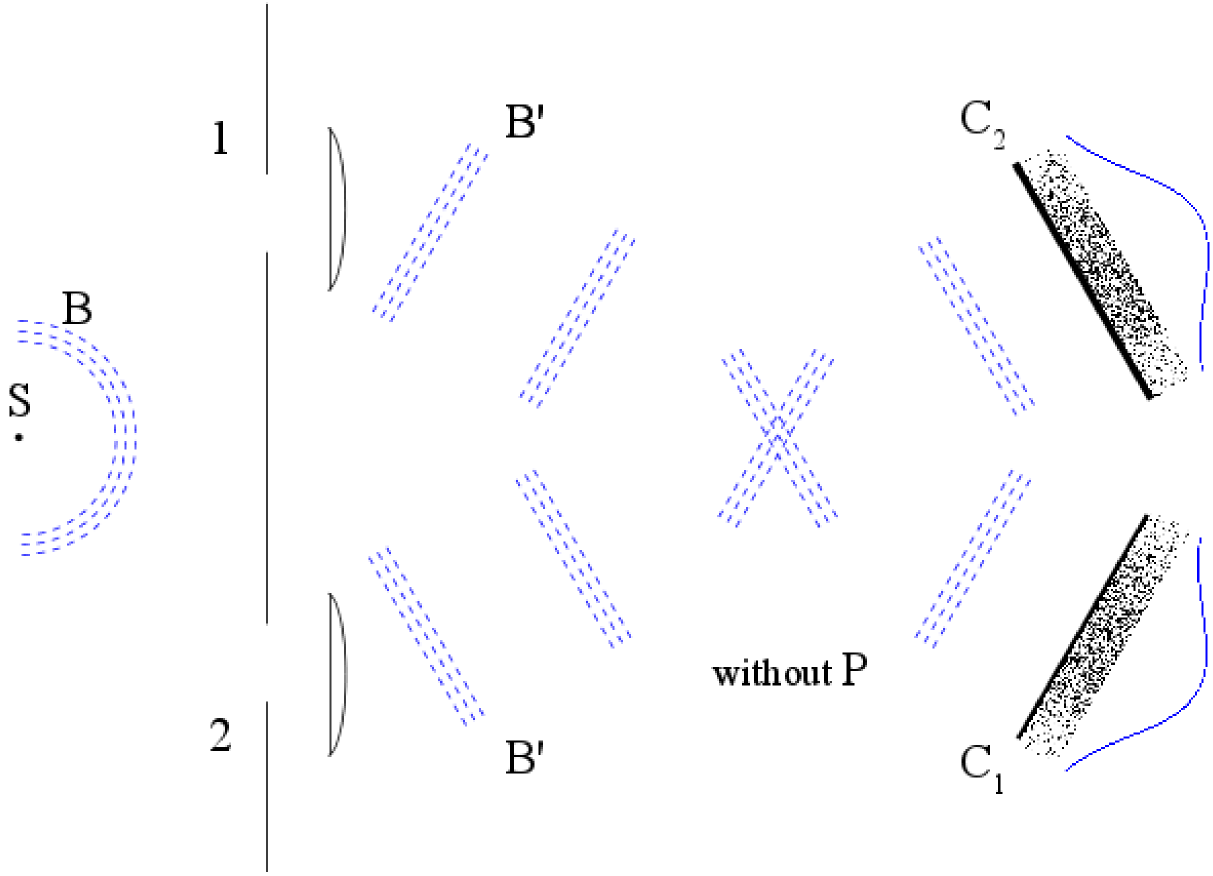
"In the framework of the MWI it is meaningless to ask: Which Lev in 2022 will I be? I will correspond to them all. Every time I perform a quantum experiment (with several possible results) it only seems to me that I obtain a single definite result. Indeed, Lev who obtains this particular result thinks this way. However, this Lev cannot be identified as the only Lev after the experiment. Lev before the experiment corresponds to all "Lev"s obtaining all possible results."

Lev Vaidman

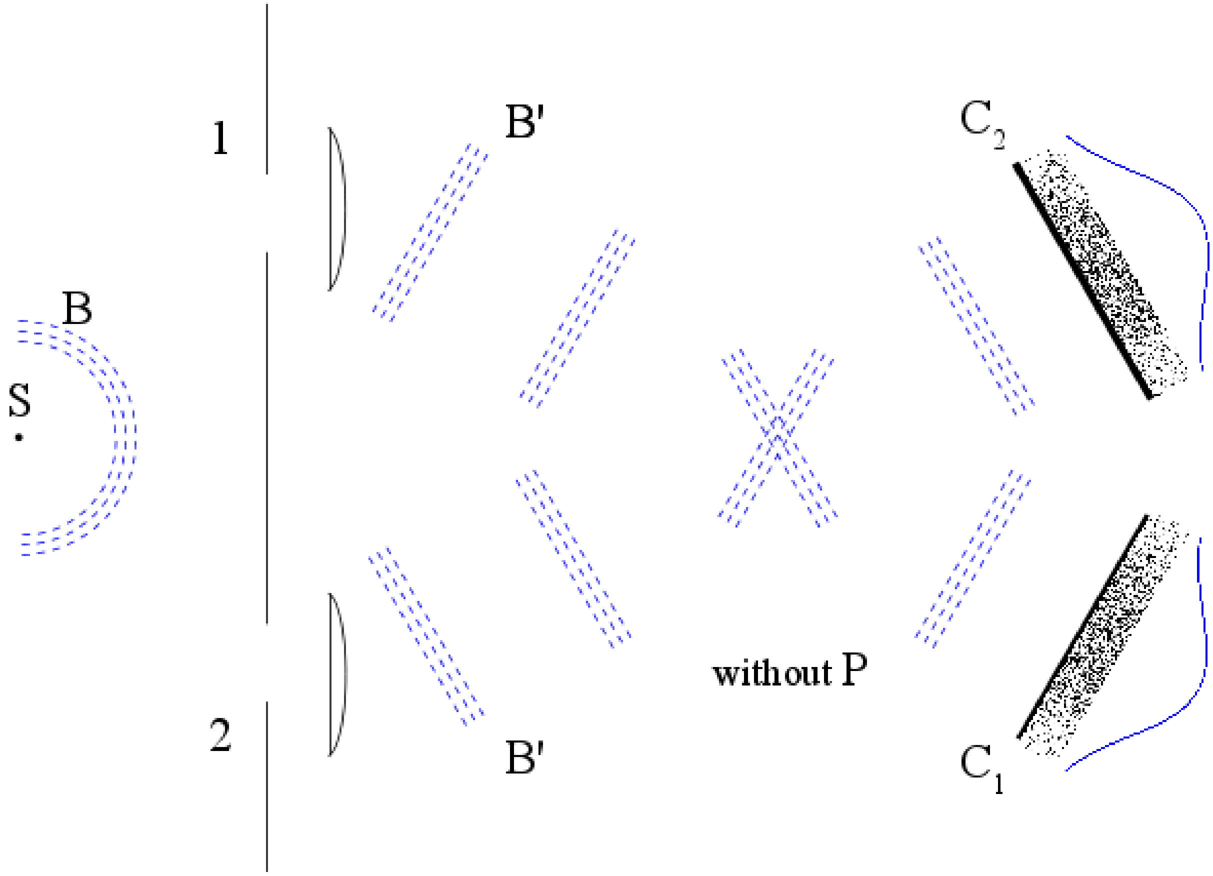
Even supporters of the many worlds interpretation, like Bryce S. DeWitt, admit that this is a bit weird:

> I still recall vividly the shock I experienced on first encountering this multiworld concept. The idea of 10^{100+} slightly imperfect copies of oneself all constantly splitting into further copies, which ultimately become unrecognizable is not so easy to reconcile with common sense.
>
> Bryce S. DeWitt

That last phrase might qualify as being the understatement of the century.

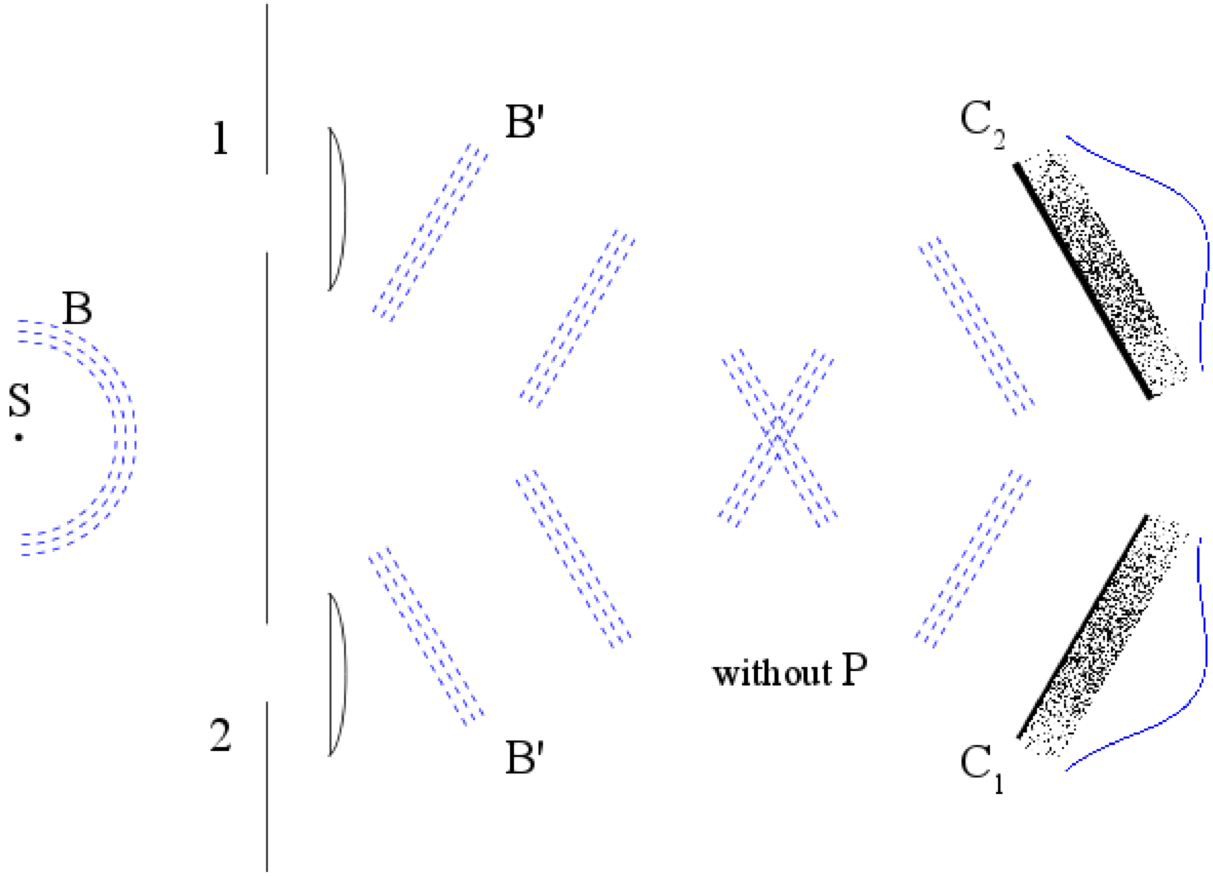


And all this exists in our three dimensional world, but one appeals to decoherence to explain why the two worlds can coexist without interfering with each other.



But the matter density of each of the detector is one half of what it would be if only one slit was open.

And so is the matter density of my descendants and of the rest of the Universe.



But since there is nothing in our world with which one can compare our density, it makes no difference (remember, in this theory, atoms don't exist, it is all a continuous matter density).

However, suppose that there is another experiment where the probability of going through the upper slit and being detected at C_1 is $\frac{1}{3}$ and of going through the lower slit and being detected at C_2 is $\frac{2}{3}$.

Again there will be two worlds, one with C_1 being triggered and a copy of me seeing C_1 being triggered and one with C_2 being triggered and a copy of me seeing C_2 being triggered.

Now repeat that same experiment many times, say N times. After one experiment, I have two descendants, four after two experiments, 2^N after N experiments.

The problem is that, by the law of large numbers, the vast majority of my descendants will have made a sequence of observations where C_1 and C_2 are each triggered approximately an equal number of times ($\sim \frac{N}{2}$).

But that does not fit the Born rule which predicts that one would see C_1 being triggered $\frac{1}{3}$ of the time and C_2 being triggered $\frac{2}{3}$ of the time.

Of course, the matter density of my descendants that will have observed a sequence of C_1 and C_2 being triggered approximately an equal number of times may not be as high as the one of those who see C_1 being triggered $\frac{1}{3}$ of the time and C_2 being triggered $\frac{2}{3}$ of the time.

But if having a matter density $\frac{1}{2}$ as opposed to 1 doesn't make any difference (since there is nothing in a given world with which one can compare it) what difference do these other matter densities make?

By the way, without a matter density (with a "pure wave function ontology") there is no difference whatsoever between those sequences of worlds, unless one assigns (as Everett did) in an *ad hoc* fashion weights to the different histories of worlds so that those satisfying the Born rule have most of the weight.

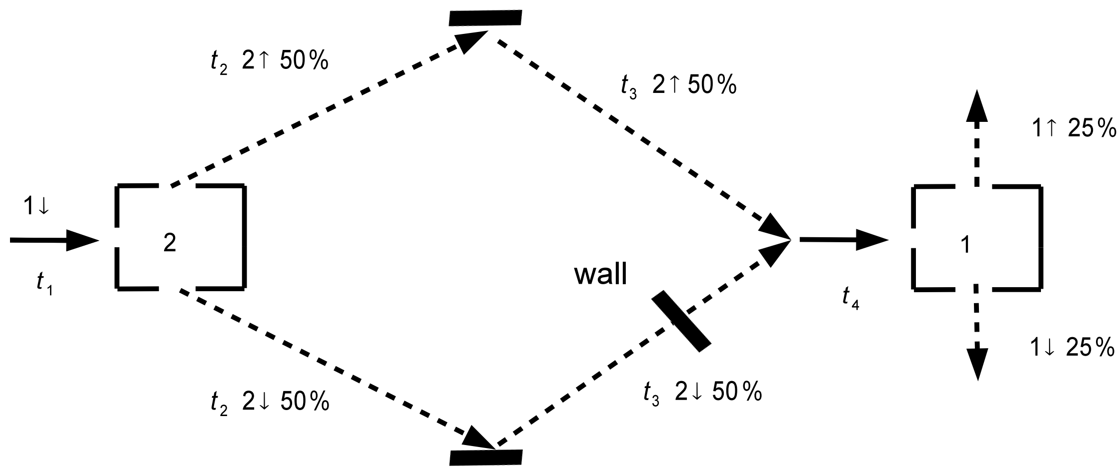
But I don't see what those weights have to do with the actual frequencies of detections at C_1 and C_2 observed by my descendants.

So, I don't really see how the many worlds approach "saves the phenomena".

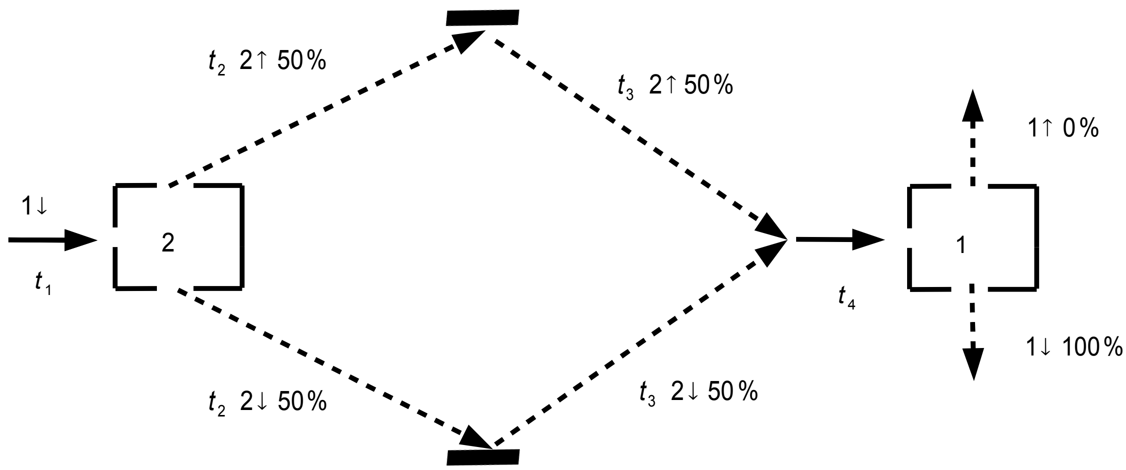
The upshot, it seems to me, is that, of the three “realist” alternatives to Copenhagen, the de Broglie-Bohm theory, GRW and many worlds (with a matter density), the de Broglie-Bohm theory is by far the most reasonable.

In particular, in that theory, we can still “believe” in atoms and whole electrons!

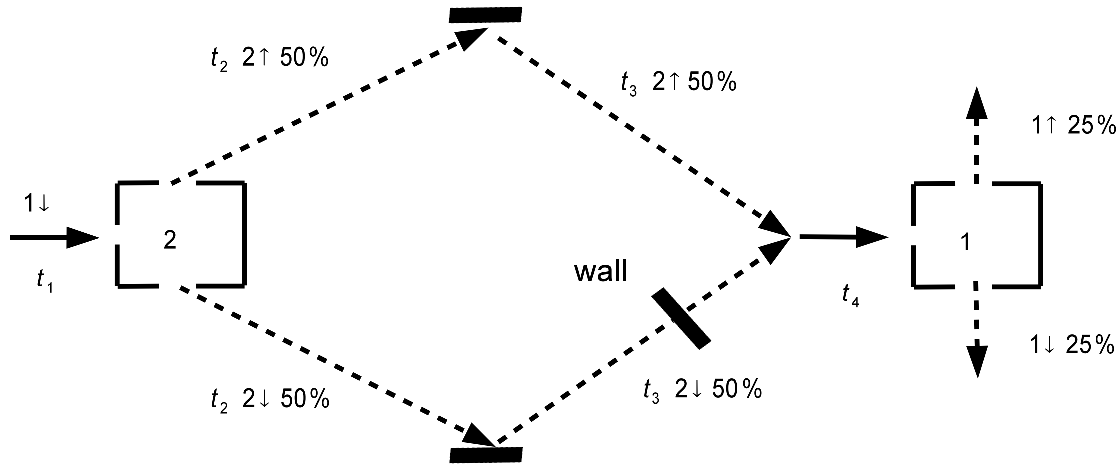
APPENDIX: THE ELITZUR-VAIDMAN BOMB TESTING MECHANISM



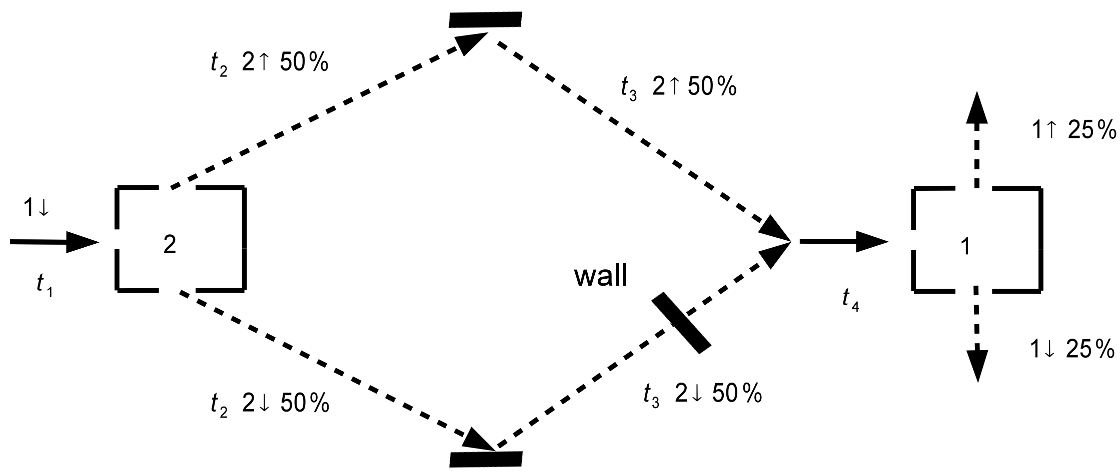
Let us replace the wall by a bomb.



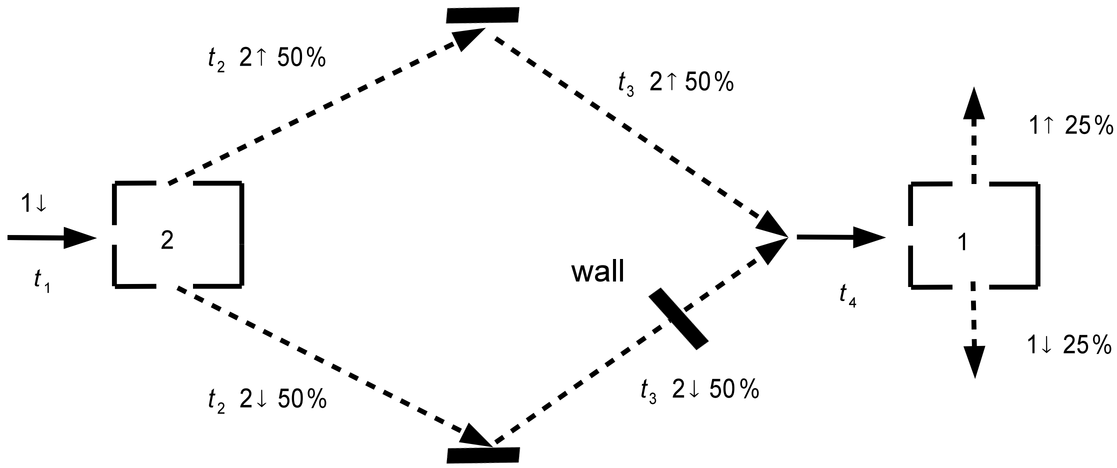
First, suppose that the bomb is a dud. Then, since it is insensitive to the particles, it is as if we had done nothing, i.e., as if we had not put a wall. The particle will behave as if there was no wall and therefore its spin at the box on the right will always be $1\downarrow$ if we measure the spin in direction 1.



On the other hand, if the bomb is active and detects the particle, it explodes and that's it — it is lost. That happens half of the time if the bomb is active. But suppose that the bomb is active and does not explode. This means that the particle took the path $2\uparrow$; if we then measure the spin at the box on the right in direction 1, we will get $1\downarrow$ for half of those particles and $1\uparrow$ for the other half. If we get $1\downarrow$, we cannot conclude anything since that would also happen if the bomb were a dud.



But, if we get $1\uparrow$, then we can be certain that the bomb was *not* a dud since that would *never* happen if the active bomb is replaced by a dud. Since each result $1\downarrow$, $1\uparrow$ happens half of the time (among the 50% that have not exploded), we can identify 25% of our initial stock of bombs as being active without exploding them.



Altogether, half of the active bombs explode and are lost, but a quarter are "saved" (not exploded and known to be active). For the remaining quarter, we don't know. We can then repeat the operation (together with the duds, since we don't know which is which) and identify as active one quarter of that remaining quarter. Repeating the operation many times, we can get as close as we like to a total of one third of the initial stock of bombs as being known to be active and not exploded, since $1/3 = \sum_{n=1}^{\infty}(1/4)^n$.

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