Chapter 13

Challenging the Newtoniam worldview 2: Quantum Theory

13.1 Homework

Readings – DV 24-28 + 29 (Conclusion)

Further readings:

- David Albert *Quantum mechanics and experience*: easy, clear,

- John Norton, *Eintein for Everyone*, ebook: `http://www.pitt.edu/~jdnorton/teaching/HPS_0410/chapters/index.html`

Study Questions – Give a short answer to the following questions:

1. Explain the distinction between empirical facts, theory, and interpretation
2. What is characteristic of a particle-behavior? What is characteristic of a wave-behavior?
3. Explain how a two slits experiment and a beam splitter experiment help us determine whether a phenomenon is a wave or a particle. Can we determine whether quantum objects are waves or particles in this way?
4. Explain DeWitt's following statement:"Any particular wave can be produced by adding together appropriate members of any family of waves"
5. How do we get predictions from the wave function of a quantum system? (you can explain with the DeWitt's analogy in terms of family members)
6. What is a vector? a vector space?
7. What is an operator? an eigenvector? an eigenvalue?
8. Explain what it means when we say that the state of a quantum system is represented by a superposition of states.
9. What is the measurement problem?

10. Explain the thought experiment: “Schödinger’s cat”. What does this thought experiment is supposed to get us think about?
11. What is the idea behind the notion of “hidden variable interpretations”?
12. Which interpretation is adding a “projection postulate” (or “collapse postulate”)to the formalism of quantum theory? What does the projection postulate say?
13. According to the standard (or orthodox) interpretation, does the wave function describe the way things are outside of measurement? Is there a way for us to know what is really going on outside of measurement outcomes?
14. Are there clear ways in which one can define what physical processes count as measurements in the orthodox interpretation?
15. How does Bohm’s theory (BT) solve the measurement problem? Which property is definite in BT?
16. How does the Many World Interpretations (MWI) solve the measurement problem? What does the wave function represent in the MWI?
17. For which reasons could one prefer adopting BT over MWI? For which reasons could one prefer adopting MWI over BT?
18. What did EPR want to show? Explain their reasoning.
19. Explain what Bell’s theorem shows.
20. What did Aspect’s experiment show?
21. Do the results of Aspect’s experiment force us to admit that there is a form of causal non-locality in the world? Do they force us to admit that there is a form of informational non-locality in the world?
22. Does the success of relativity theory appeal for a revision of core conceptual belief of the Newtonian worldview? Does the success of quantum theory appeal for a revision of core conceptual beliefs in the Newtonian worldview? Explain.

13.2 Introduction

In this chapter, our goal is to:

- Understand what old conceptual beliefs of our worldview quantum facts force us to put into doubt
- Understand the difference between theory and interpretation
- Understand that several options are open concerning the interpretation of quantum theory

- Understand, for each of these options:
  1. which classical conceptual beliefs are kept (because deemed essential)
  2. which classical conceptual beliefs are abandoned
  3. how sucessful and / or promising the option is
  4. what problems are remaining

13.3 Distinction facts / theory / interpretations

Distinction facts / theory / interpretation – I refine a little bit on DeWitt's characterizations:

Facts – Empirical data – outcomes observed.

Quantum facts :

- Definition: the outcomes of experiments with quantum entities

- Surprising but not controversial

- What is a matter of controversy then? the theory which can account for these facts, and most of all the interpretations of the theory

Physical theory – T – A physical theory consists primarily in a mathematical apparatus, the so-called formalism, F. That said, the formalism alone does not suffice to constitute a *physical* theory. The formalism comes with some basic correspondence rules, CR, which tell us how to apply the formalism to certain *physical* situations, thus allowing us to make some empirical predictions.

Thus, we have $T = F + CR$

Quantum theory :

- Definition: the mathematical formalism + Basic correspondence rules

- Used to generate predictions

- Enormously successful

Interpretation – I – Whereas physical theories usually come with some basic correspondence rules, they do not come with a complete interpretation. To provide a physical theory with an interpretation is to give a story of what the world could be like if the theory were true. An interpretation I is primarily an ontological framework for the formalism. An interpretation tells us what entities and what physical quantities correspond to the mathematical constructions of the formalism. A constraint on acceptable interpretations is that they are able to recover the appearance of the world to us, even when it may seem strikingly at odds with the proposed fundamental ontology.

Different interpretations of the same formalism are, by definition, empirically equivalent. We do not have definitive criteria for choosing between consistent interpretations which are compatible with all the empirical predictions of a theory.

Interpreted theory – IT – An interpreted theory is a physical theory provided with an interpretation. This is to say, an interpreted theory consists in 1. a formalism, 2. some basic correspondence rules, and 3. an interpretation.

Thus, we have: $IT = F + CR + I$.

Interpretations of Quantum Theory :

- Definition: An interpretation is an answer to the question what the world could be like if quantum theory was true? or: What sort of reality is consistent with the theory?

⟶ *It is essential to understand the difference between what we use to represent (mostly mathematical theories in physics) and what is represented.* Most often, we are not even aware of the fact that we interpret the formalism. Any scientific theory is a *representation* of a domain (some part of the world out there). Any representation must be interpreted.

Example: Newton (DW p.259): dropping ball

Another example: space

13.4 Old conceptual beliefs in danger

Here are a few of the belief that may be put in danger by quantum facts, theory and their interpretation:

Continuous quantities – Physical magnitudes can take on a continuous range of values.

Definite values – Any particle has a definite position and momentum at any time, and hence, any particle has a definite trajectory in space-time.

Determinism – The future position and momentum of any particle can be predicted with certainty from its position and momentum at any given time.

Local Interactions – In our mechanistic worldview, physical systems interact locally. It is impossible for a physical system to influence another system at a distance.

The wave / particle distinction – Physical stuff is either a wave or made of particles

- Particle: well-defined locations, individual trajectories

- Waves: spread out, interferences

Wave vs. particle behavior: the two slits experiment:

- Particle pattern: discrete spots and addition in the middle – See Figure 13.1

- Wave pattern: interference – See Figure 13.2 – We are going to focus on this first.

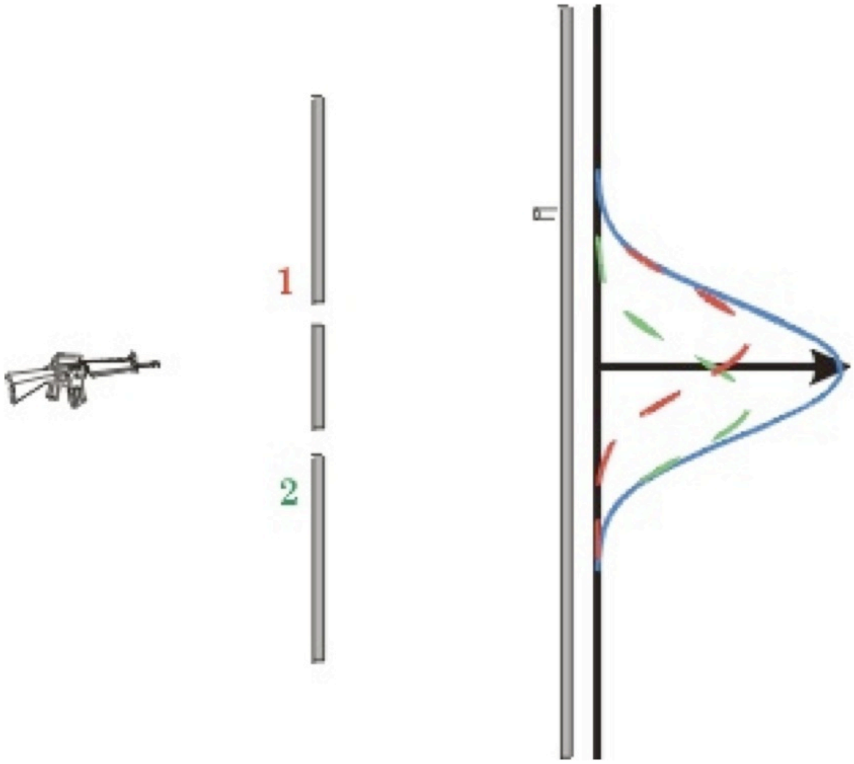

Figure 13.1: Two slits experiment: Particle Behavior (from Prof. DiSalle)

13.5 Quantum Facts

Do quantum systems display a wave behavior or a particle behavior?

Two Slits experiment – with quantum systems

- Basic two-slits apparatus: interferences

- One slit at a time: discrete spots

- Two slits with electron-detectors for each slits (wave should go through both, particles through one only): discrete spots

- Two slits but slower: from discrete spots to interferences !

Beam Splitter experiment – with quantum systems

- Basic splitter: interferences

- Basic splitter, with detectors (wave should go trough both, particles through one only): discrete spots

Definite properties? – (Addition on Dewitt)

- Blue/Red and Round/Square dividers

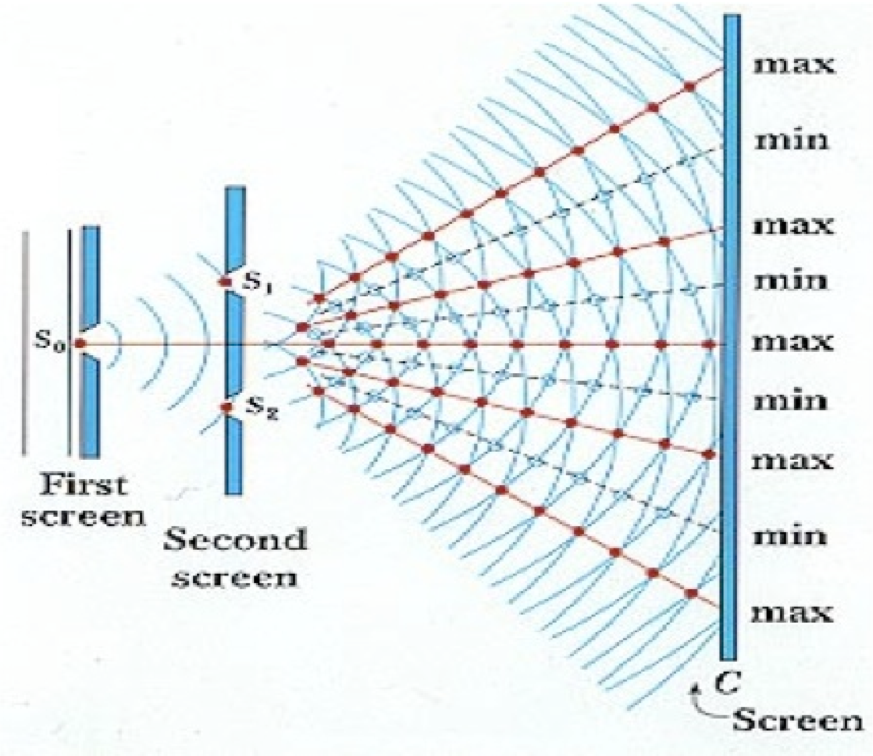

Figure 13.2: Two slits experiment: Wave Behavior (from Prof. DiSalle)

Exp A: 1. Blue / Red: select the red ones. 2. Blue/Red: they all turn red

Exp. B: Same with Hard / Soft – same result

Exp. C: 1. Blue/Red: select the red ones. 2. Hard/Soft: select the soft ones. 3. Blue/Red: half red, half blue

Exp. D: Same but with Hard/Soft firs – same result

Conclusion – Surprising? Yes, but not unpredictable

- Rule of thumb for particle / wave: depends on detection: if detected before interference, then particle-behavior; but if detected after interference, then waves-behavior

- Notice that we are not saying: they are particles / waves, but they display particle / waves *behavior*.

- Rule of thumb for properties: counter to zero every time you check on another (incompatible) property

- Again: these outcomes are well predictable, The problem arises only when we try to *interpret* them, that is, when we try to tell the story of what underlying reality is producing these outcomes.

13.6 Quantum Theory

13.6.1 Descriptive Overview

Two types of math – Wave math / Particle Math

QT: wave math – Quantum theory is "a wave sort of mathematics, and it is used in the same way that other mathematics are used in physics. In particular, given the current state of a system, one can use the mathematics of quantum theory to make prediction about what attributes of the system might be observed, and to make predictions about what state the system will be in at a future time" (248-249)

Why do we hear the theory is strange? :

1. *Probabilistic predictions only*: the formalism does not tell you which specific outcome is to going to occur. It only allows you to predict a probability distribution over possible outcomes

That is: it gives you a range of possible outcomes + the probabilities associated with each of them

That said, other physical theories share that feature: this is not brand new!

2. *No consensus at the interpretative level*: controversy about how to tie up the formalism with the world. No controversy on the basic correspondence rules. The problem is when we ask: what kind of world lies behind such phenomena?

About the probabilities, for example: the probabilities in all other statistical theories are understood as reflecting our ignorance, i.e. as *epistemic* probabilities. It is only because we lack a full specification of the situation that we have only probabilistic predictions.

Example: dice

The problem is that quantum probabilities are not easily understood this way: they may be better understood as reflecting a form of randomness at the fundamental level, i.e. *objective chances.*

Note: The fact that only the interpretations are controversial implies that there is a problem only for the realist, not for the instrumentalist, who can use the theory to generate predictions.

13.6.2 A little more math

Introduction on waves and wave math :

- Waves come in families (wind vs. string for example)

- Family A: $A = \{a_1, a_2, ...a_3\}$

- Law of addition: “Any particular wave can be produced by adding together appropriate members of any family of waves” .

- Examples:

*within a family: two cords of a guitar at a time

*from various families: guitar + electronic devise reproducing wave of second cord

- Consequence: *Given the equation of a particular wave, we can* decompose *this equation in various ways.*

For example, a given sound can be seen as the sum of the waves of 2 guitar cords, or of 2 electronic waves

Application to quantum systems :

(1) State of a quantum system: wave function – a wave equation

(2) Each type of measurement = 1 family or decomposition

(3) In order to make predictions, we decompose the wave function within the family of the measurement concerned.

Explanation of the three above :

(1) – For example, an electron is *represented in the formalism by a wave function*

(2) and (3) –

*Back to our sound:

What would we need to add together if we’d like to make that sound with guitars?

What would we need to add together if we’d like to make that sound with electronic piano?

Then you can get something like

$$|sound(guitar) >= (lots)|1st >= (little)|3rd >$$

*For the electron:

What would we need to add together if we’d like to make that wave with positions?

What would we need to add together if we’d like to make that wave with momenta?

What would we need to add together if we’d like to make that wave with spins?

*Trickier: how to generate the prediction from the sum obtained?

Let’s say you came up with:

$$|electron(position) >= (lots)|left > +(little)|right >$$

Compare with:

$$|USpresident(elections)>=(49)|Obama>+(47)|McCain>$$

Then your prediction is: you have lots of chance to observe the electron on the left, and little chance to observe the electron on the right

13.6.3 Even more math

Disclaimer – We'll describe the maths only for pure states and quantities with discrete (i.e. non-continuous) spectrum. That should be enough !

Mathematical formulation of (1), (2) and (3) above :

(1) State of a quantum system : a vector in a Hilbert space

(2) Each type of measurement : a particular operator in the Hilbert space

(3) Generation of predictions: decomposition of the wave function as a sum of eigenstates with eigenvalues associated.

Vectors and Vector spaces :

- A vector: orientation, direction and length

- Vector space: example of the 2-dimensional vector space over the real numbers. An example of a vector is: $(3, 4)$

An important property of vector space is that if you combine two vectors, you obtain a vector, and conversely, any vector can be decomposed as a sum of vectors – here is a crucial similarity with wave-maths!

Two ways to generalize the simple vector space above :

1. We can imagine a vector space with 3, 4, 5, ... an infinity of dimensions
2. Complex numbers instead of real numbers

Complex numbers $x = a + bi$, with $i = \sqrt{-1}$

Hilbert space :

Dewitt: a vector space with some specific properties

The properties are

1. Inner product – allows notion of distance and projections

$$< x|y >= |x||y| \cos \alpha$$

2. Completion: nothing missing – no hole

Example: compare rational number with real numbers : The real numbers are constructed in filling the rational numbers' holes

Operators :

An operator is just a function that transforms a vector into another vector

Eigenvector and eigenvalues :

Some operators are associated with a family of vectors (called eigenvectors) such that when applied to its eigenvector, the operator just "adds some length" to the eigenvector:

$O|v>= 3|v>$

v is then an eigenvector, and 3 is the eigenvalue

Projection operators and decompositions :

In QM, each type of measurement is associated with a particular *projection operator*.

Projection: we all know what it is.

A projection operator is just an operator which projects a vector onto another.

Now, here is how we can link all the information we just got about vectors and operators to measurements in QM:

- Take an operator (a family of measurement like spin for example) with eigenvectors and associated eigenvalues

Operator momentum ($Momentum$): eigenvectors: —fast¿, —slow¿ (only two, well distinct possibilities)

- It is possible to construe this operator as a sum of projection operators, one projection for each eigenvector:

$$Speed = Proj_{onto|fast>} + Proj_{onto|slow>}$$

- It is then possible to get the decomposition of a vector / wave function of a quantum system:

$$Speed|electron >= Proj_{onto|fast>}|electron > + Proj_{onto|slow>}|electron >$$

$$|electron(Speed) >= (lots)|fast > +(little)|slow >$$

We can have various decompositions of the vector corresponding to the quantum system (just like for the waves before). We could have:

$$|electron(Position) >= (lots)|right > +(little)|left >$$

$$|electron(Spin) >= (lots)|up > +(little)|up >$$

From there, you should be able to guess what predictions we are able to generate.

Evolution :

The Shrödinger Equation allows to compute, given the state of the system at a certain time, the state of the system at a later time.

IMPORTANT NOTE: the Schrödinger equation is perfectly *deterministic*. No chance involved.

13.6.4 Conclusion

Quantum Theory:

- No problem for accounting for the empirical facts: perfect predictions
- The problem is: what kind of world is lying behind these phenomena? what could be the world like of the theory is true?

  That is, the problem of interpretation

13.7 Interpretations of quantum theory

13.7.1 Introduction

It so happens that classical theories of physics can be interpreted as describing the world as made of local interactions between physical systems with determinate properties. Quantum mechanics is famously recalcitrant to any interpretations in such terms. The result is that, even if quantum physics is one of the most empirically well confirmed and most successful theories, it is still a matter of controversy of what the theory is *really about*.

It is often taken that this situation is not a problem because all we ask from quantum theory is that it makes correct predictions about quantum phenomena, not that it gives us any kind of fundamental account of the quantum domain. This is to say that standard quantum mechanics equipped with the so-called orthodox interpretation is not a fundamental theory. Given that only fundamental theories can be considered from a realist point of view, one has to admit a quasi-instrumentalist view on quantum mechanics if one accepts the orthodox interpretation.

Many philosophers and physicists however do not content themselves with such a quasi-instrumentalist view. Physicists and philosophers have developed interpretations for quantum mechanics as well as alternative theories for the quantum domain and interpretations for those theories. Providing an interpretation of theory is to indicate what the world might be like if the theory is true.

Two main problematic features:

1. Superposition ($\longrightarrow$ Measurement Problem)

2. Entanglement ($\longrightarrow$ EPR-Bell and non-locality)

In this section, we deal with the problem of superposition, which leads to the measurement problem. Many quantum systems are described by the formalism of quantum mechanics as a weighted sum of different states corresponding to possible observable outcomes. How to interpret such a sum is sill a matter of controversy.

In Section 13.7.2, we begin by demonstrating that orthodox quantum mechanics does not qualify as a good candidate for a fundamental theory because of the measurement problem. That said, orthodox quantum mechanics is but one of many theories that we have today for the quantum domain. There are other coherent and empirically adequate alternative accounts of quantum phenomena, and we shall briefly describe three of them. Each of them give a different solution to the measurement problem. We shall describe these three alternatives in Section 13.7.3.

13.7.2 Orthodox quantum mechanics and the measurement problem

The orthodox interpretation

From its inception, the interpretation of quantum mechanics has been the object of debate. It is well known that Einstein and Shrödinger opposed the so-called "Copenhagen interpretation"[1] usually associated with Bohr and Heisenberg. Further, it is well known that the debate raged within the Bohr Institute. At least as usually understood, followers of Bohr defended a roughly neo-kantian view and Heisenberg defended a roughly positivist view.[2] Von Neumann provided a rigorous axiomatization of the theory that was and has been accepted by most working physicists.[3] This framework provided a minimal interpretation is what we shall call "orthodox quantum mechanics".[4]

In orthodox quantum mechanics:

- The possible physical states of a system are represented by unit-length vectors (up to an overall phase factor) in the appropriate Hilbert space. The physical state at a time is represented by a single vector (or ray) in the Hilbert space.
- Physical properties that one might observe of a system are represented by projection operators in the Hilbert space.

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[1] The name comes from the Institute for Theoretical Physics which Niels Bohr was the director in the twenties – it was later renamed the Niels Bohr Institute. Under his direction, the Copenhagen Institute was a major center of research for the formulation, development and interpretation of quantum mechanics.

[2] It is not the place here to give a precise account of these debates. For more details, see [**?**] and references therein.

[3] [**?**].

[4] Note that we are not attempting to describe the so-called "Copenhagen Interpretation" of quantum mechanics.

- Ascription of properties : Eigenstate - eigenvalue link : a system has the property corresponding to a given eigenvalue of a given observable if and only if its quantum state is an eigenstate of the observable (more generally, if the corresponding eigenprojection is given probability 1 by the quantum state). It is indeterminate otherwise.

- The dynamics is determined by the Schrödinger equation as long as no measurement is completed (linear, deterministic evolution depending only on the energy of the system)

- The dynamics is governed by the reduction postulate (with the Born rule for the probabilities) in case of measurement – quantum jump: radical non-linear, indeterministic, and irreversible discontinuity in the evolution.

So, the theory does not indicate which state a system is going to collapse to upon measurement. In other words, the theory does not tell which definite property is going to be observed after a measurement. That said, the theory gives the probabilities associated with the various possible outcomes – by the Born Rule. The Born rule states that when a state is written in the measurement basis, the probabilities of certain measurement results are given by the square of the complex coefficients of the basis vectors corresponding to those results.

It should be stressed that the projection postulate and the Born rule are uncontroversial as practical rules. Orthodox quantum mechanics is one of our best empirically confirmed theories. Difficulties only emerge if one tries to interpret orthodox quantum mechanics as a fundamental theory.

The measurement problem

In this subsection, we explain why orthodox quantum mechanics cannot be taken to be a fundamental theory. There are at least two necessary criteria for a theory to be considered as a candidate for a fundamental theory. A first criterion is that the theory gives a dynamical account of all physical processes and interactions in its domain. In the case of quantum mechanics, this includes measurement interactions. A second criterion is that the theory saves the phenomena. This is simply to say that a theory can be considered fundamental only if it rightly predicts what we observe. No claim is made here that these criteria are sufficient for a theory to be considered fundamental. These two criteria are minimal desiderata for a theory to be a candidate fundamental theory, and a fortiori for a theory to be considered as a (structurally, approximately etc., according to your own preferences in the debate over scientific realism) true description of the world. Orthodox quantum mechanics as characterized above cannot be a fundamental theory because it does not provide a dynamical account of measurement interactions.

Orthodox quantum mechanics indeed distinguishes between two types of evolution:
- Shrödinger equation and,
- the projection postulate.

The problem is that it does not give any answer to the following questions:

1. What does it mean to put the notion of measurement at centre stage within axiomatization? And first and foremost, what qualifies as a measurement? The interpretation

does not provide any condition, either necessary or sufficient, to define the legitimate application of one or the other type of dynamical evolution.

In Bell's evocative words (1989):

> It would seem that the theory is exclusively concerned about 'results of measurement' and has nothing to say about anything else. What exactly qualifies some physical systems to play the role of 'measurer'? Was the wave function waiting to jump for thousands of millions of years until a single celled living creature appeared? Or did it have to wait a little longer, for some better qualified system...with a PhD? If the theory is to apply to anything but highly idealized laboratory operations, are we not obliged to admit that more or less 'measurement like' processes are going on more or less all the time, more or less everywhere? Do we not have jumping all the time?[5]

2. Problem of consistency

   No other physical theory takes measurement processes to belong to a special kind of interaction. You can usually give an account of measurement processes just as any other physical interaction. A measurement process is just a physical interaction between a given system and the measurement apparatus. For example, consider a solution of cold water in which you put a heated steel ball. Now, imagine that you measure the evolution of the temperature of the water in that situation in putting a thermometer in it. You have a theory, laws to give an account of such an evolution. But the same laws could give an account of how the thermometer is measuring the temperature of the water. Well this is just what is not possible to do within the orthodox interpretation of quantum mechanics: *if one takes the measurement process as an interaction, and consequently applies the deterministic evolution to it (given the e/e link), what you get contradicts the reduction postulate.*

Let us consider the following quotes by David Albert :

> The dynamics and the postulate of collapse are flatly in contradiction with one another ... the postulate of collapse seems to be right about what happens when we make measurements, and the dynamics seems to be bizarrely wrong about what happens when we make measurements, and yet the dynamics seems to be right about what happens whenever we aren't making measurements; and so the whole thing is very confusing; and the problem of what to do about all this has come to be called "the problem of measurement(1992).

A natural move is to include measurement processes in the domain which is governed by the Schrödinger equation. This is how the measurement problem emerges.

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[5] [**?**].

If we apply the Schrödinger dynamics to a measurement, that is, is we treat a measurement process just as any other physical interaction, then we get into trouble:

Consider that we start with a system in a superposition state between being french and american. Imagine that we measure such state with a special apparatus, the possible outcomes being : that a glass is filled with beer if the system is measured american, and with a nice bordeaux if the system is measured as being french.

In this case, what the theory predicts is that the system and the apparatus are going to get entangled, and instead of giving out on definite outcome out of the two, the apparatus ends up itself in a superposition state, that is, an indeterminate mixture of beer and wine (which I assume you agree is simply unacceptable).

So: the main point is that the state of superpositon, according to the Shrödinger dynamics, is not reduced, but rather infects the measurement apparatus which gets into a superposition state.

In sum: Due to the linearity of the Schrödinger equation, an interaction between two systems, one of which is in a superposed state, results in a state of superposition for both systems. Importantly, the pointer observable for the measurement device will be in a superposition state. It is uncontroversial that there is no ignorance interpretation for quantum superpositions whereby the system could be viewed as really pointing to one particular outcome, though the formalism does not indicate which.

This is unfortunate because this is simply not what we seem to observe at the macroscopic level. Experiments appear to have determinate outcomes. Just adopting the Schrödinger evolution is thus not enough to show how one can recover the phenomena.

Illustration: Shrödinger's cat

Supposed way out: Decoherence

Given this situation, one can attempt to resolve the problem of recovering the appearances by utilizing the theory of decoherence. Decoherence theory provides a dynamical account for the suppression of interference, at a certain level of description, through spontaneous interaction with the environment, which is in agreement with Schrödinger evolution.

It is rather uncontroversial that decoherence is relevant to why observable properties appear classical to us. It is, however, also uncontroversial that appealing to the theory of decoherence does not solve the measurement problem at the fundamental level.[6] As mentioned above, it does not provide any new dynamics additional to the Schrödinger equation. Hence, by linearity of the Schrödinger evolution, any enlarged system, which includes the apparatus and the environment, ends up in a superposition state.

Thus, even if decoherence theory accounts for classical behavior at the level of the components, it does not suppress the problem that the different components are superposed. By exactly the same argument as the one used in stating the original measurement problem, a macroscopic physical system is represented by a superposition state by the theory, a state for which there is no clear and uncontroversial interpretation. To push the argument a little

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[6] For details on this, see for example [**?**] and [**?**].

bit further, decoherence makes things even worse since not only the apparatus, but also the environment and finally the entire universe can end up being represented by a superposition state.

13.7.3 Three ways of understanding quantum phenomena

From the above, one can see that the measurement problem arises because orthodox quantum mechanics holds the three following claims:

1. the wave function gives a complete description of any physical systems;
2. physical systems have definite properties given by the E-E rule;
3. the wave function evolves linearly and deterministically.

The measurement problem shows that no fundamental theory can include these three claims together. Any theory of the quantum domain has to give up at least one of the above claims in order to qualify as a candidate for a fundamental theory.

There are three different accounts of quantum phenomena that can be distinguished from one another by which feature (1.,2., or 3.) they give up.

- Bohm's theory gives up 1., the idea that the wave function is a complete account of physical systems;
- The Many-Worlds theories give up 2., the idea that physical systems have definite properties at the fundamental level;
- GRW theories[7] give up 3., the idea that the wave function evolves linearly and deterministically.

All three theories mentioned above:

1. Realist: take QM seriously
2. Coherent: solve the measurement problem.

SO: They give three different accounts which are both coherent and empirically equivalent, while suggesting very different worldviews.

These interpretation were developed during the second half of the 20th century, which featured a growing interest in interpretational studies:

- Bohm 1952
- Everett 57

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[7] GRW stands for Ghirardi, Rimini and Weber

- van Fraassen 1973 – Kochen 1985 – Healey 1983 – Dieks 1989
- Ghirardi Rimini Weber (GRW) 1986

None of these has managed neither to supplant nor to be as influential as the orthodox interpretation.

Bohm's theory

A little bit of History

- de Broglie 1927
- Bohm 1952
- Bell
- Dürr, Goldstein, Zanghi 1992
- Hiley, Holland, Valentini ...

In Bohm's theory, one rejects the idea that the wave function be a complete description of physical systems. Bohm's theory supposes that quantum systems are particles and the description of quantum systems by means of a wave function is completed by the specification of configuration of the particles that compose the system, a specification of particle positions. These particles evolve according to the guiding equation, which relates time evolution of the configuration of the particles to the wave function. The wave function as well as the configuration of the particles evolve deterministically.

How well does it work?

- Ontology of particles with definite positions

- All other properties are dispositional (reducible to position)

- The world: deterministic motion of particles

- Appearance of indeterministic collapse: the reduction is a consequence of Bohmian dynamics

- Recovers all the predictions of SQM[8]

How?

The theory has as a consequence that we can never determine the configuration of particles with accuracy greater than standard quantum mechanics. There is always uncertainty associated with the configuration of the particles. This is how probabilities arise in the theory. Because we can never be sure of the actual configuration of a system, we can never know which outcome will occur in measurement situations, despite the fact that systems evolve deterministically.

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[8] According to several authors, this is only an "equillibrium" feature of the theory, and in principle one could have empirical predictions distinct from those of quantum mechanics.

In short then, Bohm's theory gives us a way to understand the quantum domain as constituted of particles with definite positions and in deterministic motion. One can understand Bell's enthusiasm upon his discovery of the existence of such a theory:

> But in 1952 I saw the impossible done. It was in papers by David Bohm. David Bohm showed explicitly how parameters could indeed be introduced, into nonrelativistic wave mechanics, with the help of which the indeterministic description could be transformed into a deterministic one. More importantly, in my opinion, the subjectivity of the orthodox version, the necessary reference to the 'observer', could be eliminated.[...]
>
> But why then had Born not told me of this 'pilot wave'? If only to point out what was wrong with it? Why did von Neumann not consider it? More extraordinarily, why did people go on producing 'impossibility proofs' after 1952, and as recently as 1978? When even Pauli, Rosenberg, and Heisenberg, could produce no more devastating criticism of Bohm's version than to brand it as 'metaphysical' and 'ideological'? Why is the pilot wave picture ignored in textbooks? Should it not be taught, not as the only way, but as an antidote to the prevailing complacency? To show that vagueness, subjectivity, and indeterminism, are not forced on us by experimental facts, but by deliberate theoretical choice?[9]

Advocates of Bohm-type theories say that the great advantage of these theories is that they make clear *what quantum theory is about.* Indeed, Bohm-type theories are associated with an ontology of particles in deterministic movement. Now, of course, the classical picture of the world is not completely recovered. The most important departure from the classical picture is that Bohm-type theories are contextual and highly non-local: the evolution of any particle depends on the position of all other particles. Also, a serious drawback is that there is no relativistic formulation available for Bohm-type theories. These are the tradeoffs involved in retaining a particle ontology in the quantum domain.

Many Worlds

The central idea of the Many-Worlds interpretations of no-collapse quantum mechanics is to take the wave function seriously. More precisely, it is to accept the wave function and its deterministic evolution as a complete description of any physical system: the wave function is universal and never collapses. In a Many-Worlds interpretation one has to reject the idea that physical systems possess definite properties. It will be recalled that in general, quantum systems are described as having indeterminate properties. The orthodox interpretation via the E-E Rule ensures that some properties have definite values. By contrast, the Many-Worlds interpretations tell us that the world is made of physical systems with no determinate properties at the fundamental level.

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[9] From Bell, [**?**, p. 160]

Given this fundamental ontology, how are we to recover the appearance of determinate properties? The crucial idea of Many-Worlds theories includes observers and measuring devices in our description of any physical situation. The observer is a physical system just as any other one. After a measurement interaction, the state of an observer and the measurement device will be in a superposition state and are entangled: they are no longer capable of independent description. This state is interpreted as a realization of all possible measurement outcomes and an observation of all measurement outcomes as well. Metaphorically, we can think of the world splitting during measurement interactions. In each "world" an observer will appear to see a definite outcome for measurement interactions.

Many-Worlds theories tell us that the world is made of physical systems that lack definite properties at the fundamental level, even though appearances of definite properties emerge at the level of the observer. They give an account of the quantum domain which is local, deterministic and compatible with Relativity(although this is a subtle point). A typical objection to Many-Worlds theories is to suggest that the ontology of worlds is "superfluous". Exactly what counts as superfluous structure is typically in the eye of the beholder, and is a weak objection to the Many-Worlds theories. There is also a problem understanding probabilities in this case. There has been a great deal of interesting work on the matter recently, and the problem of probabilities does not seem incapable of a solution. Hence, Many-Worlds theories seem to be reasonable contenders for fundamental theories.

Collapse Theories

Collapse Theories à la Ghirardi, Rimini and Weber are the third account of quantum phenomena that qualifies as a candidate for a fundamental theory. Collapse Theories give up on the idea of a deterministic and linear evolution of quantum system. The crucial motivation is to take the collapse of the wave function upon measurement as a real physical process. Collapse theories recover definiteness of measurement outcomes by postulating spontaneous collapses of the wave function. The upshot is a world view which is fundamentally indeterministic. Collapse theories replace the deterministic evolution of orthodox quantum mechanics with stochastic evolution where:

1. In clear cut cases of measurement, predictions of the theory approximate those that would be made using the projection postulate on the standard theory;
2. In clear cases of no measurement, dynamics of systems are roughly equivalent to those given by the Shrödinger equation.

Roughly, the quantum mechanical state of a system follows the Schrödinger equation except that it has a probability distribution for *spontaneous* collapse (independently of whether it is measured or not). One can fix such probability distributions together with other factors so that the two conditions above are satisfied. Though not strictly empirically equivalent to standard quantum mechanics, Collapse theories make predictions equivalent to orthodox quantum theory up to our current experimental capacities. Also, it appears that Collapse theories can be given a relativistic formulation. One major drawback of these theories is that energy isn't suitably conserved. That said, these theories are in their infancy, and have no objections that seem insurmountable to date.

13.7.4 Conclusion: A guide for the perplexed

- The usual criticisms against the three above interpretations are :

  1. Against Bohm: Guiding equation is superfluous
  2. Against MWI: The ontology of the worlds is extravagant
  3. Against GRW: the non-linearity and indeterminism is unacceptable

  The problem is: *The orthodox interpretation is simply inconsistent!* All the theory above are consistent, which make them superior!

- How do we choose then?

  - Ontological preferences ? Determinism, Locality, Number of worlds

  - Closeness to what we have now?

  - Compatibility with relativity?

Or.... do we have to choose?

13.8 EPR-Bell-Aspect and Non-Locality

Please see power-point presentation

13.8.1 Entanglement

Superposition – You remember what superposition is: Some quantum systems are described by the theory in a way that suggest that they are in an "indeterminate" state between two possible states:

$$|Soazig >= (sometimes)|american > +(sometimes)|French >$$

$$|electron >= (sometimes)|spinup > +(sometimes)|spindown >$$

The standard theory does not say anything about which state the system is really in. All it says is that you have a certain probability to measure the system in one of these state.

Entanglement – Two system are entangled when, roughly speaking, they are together in a state of superposition:

$$|Twins>= (sometimes)|Green>_{Bill}\ |Red>_{Bob} + (sometimes)|Red>_{Bill}\ |Green>_{Bob}$$

$$|Twinelectrons>= (sometimes)|Up>_{left}\ |Down>_{right} + (sometimes)|Down>_{left}\ |Up>_{right}$$

What these equations say is that there is

- a certain probability to measure Bill with a Red hat and Bob with a Green hat, and

- a certain probability to measure Bob with a Red hat and Bob with a Green hat.

- but the results are always correlated: if you find one with a red hat, you know the other one's hat is green and vice versa

The standard theory does not say anything about which states the two systems really are in, nor does it say anything about why their behaviors are correlated.

Entangled state are at the core of the EPR argument.

13.8.2 EPR (1935)

EPR: Einstein, Podolski, Rosen wrote an article in 1935, with an argument that *quantum mechanics must be incomplete*[10]

The EPR original argument uses momentum and position for observables. Since Bohm's reconstruction of the argument (in 1951), everybody uses spin instead:

A typical EPR situation involves:

- A measurement set up with two wings, and a source
- On each wing, a measurement apparatus, which can be set to measure one of several observables (incompatible)
- A system at the source, in an entangled state, generally understood as constituted of two parts which travel in opposite directions corresponding to the two wings.

SQM predictions – Standard quantum mechanics predicts that the two systems will display perfect anti-correlations:

While we are in a state of complete ignorance (50%, 50%) about which outcome is going to obtain at each wing taken separately, we are in a state of complete certainty

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[10] Einstein was not happy with the article: Rosen wrote it, and did not write it so well.

on what outcome is to obtain in one wing once we know which outcome obtained in the other wing.

Compare with:

- Bell and Bertlmann's socks (Dr. Bertlmann liked to wear two socks of different color...)

- Two twins in two different classrooms: the green hat and the red hat

Correlations and Causes – We typically think that correlations *need to be explained.* We most often take correlations to be indicative of an underlying causal process:

If one gets sick most often when eating fast food than when eating a meal in accordance with the guidelines of the USDA, one tends to think that there is a causal process which explains the correlation: fat and sugar are hard on the digestive system.

Correlations at a distance – How do we deal with them? What kind of causal picture can explain such situations?

1. Last Minute Interaction: The system on the left let the system on the right know what his outcome is, so that the system on the right acts accordingly.
   ⟶ *The condition of locality prohibits communication. Actual experiments are set up so that such a last minute interaction would have to occur faster than light.*
2. Local Determinate Model: The two systems have left the source with an agreement on how to answer. *The values of the outcomes are predetermined*

These two options seems to be *the only ways to make sense of the correlations*

EPR argument :

(1) Either the values are predetermined, or there is non-locality

(2) Locality is secured by Relativity

(3) So: The values of the systems are predetermined, and SQM, which does not provide these values, is *an incomplete theory.*

13.9 Bell's Theorem (1964) and Aspect's experiment (1982)

Bell's Idea – John Bell took Einstein's challenge seriously: With what kind of "complete" theory could we replace SQM?

In other word, could we answer to EPR's request, in designing a theory (in replacement of SQM) such that

1. would be LOCAL,

2. would ascribe DETERMINATE properties to physical systems, and
3. would recover ALL THE PREDICTIONS of standard quantum mechanics?

Bell's Theorem – Bell managed to show that:

> *Any local determinate theory satisfies some constraints on the statistics of the outcomes. These constraints are called Bell's inequalities.*
>
> This is an amazing achievement: Bell does not suppose any theory, but works in a general framework.
>
> The idea is basically that having determinate values puts constraints on the type of answers that you can give to a set of questions.
>
> See table on power point
>
> Now, it so happens that SQM violates the inequalities !
>
> So the conclusion is:
>
> *No local determinate theory can recover all the predictions of SQM.*
>
> Now, what does the world say? which statistical predictions are the one observed?

Aspect's experiments –

> - Other experiments before Aspect's ones
>
> - Aspect: optical switches – the set up of the measurement apparatuses change randomly while the two systems "travel" from the source
>
> - Results: *The predictions of QM are confirmed !!!*

13.9.1 Guide to the perplexed

Conclusion of the EPR-Bell-Apect adventure :

> Bell's theorem tells us that:
>
> $$Local + Determinate \longrightarrow Inegalities$$
>
> Aspect's experiments (and many others since)
>
> $$Exmpeimer \neg inegalities$$
>
> The conclusion is then: EITHER NON-LOCALITY OR INDETERMINATENESS
>
> This means that *any theory that is compatible with the phenomena must either be non-local or not ascribe determinate properties to physical systems!!*
>
> This puts a constraint on any future quantum theory!

Locality?