Nobel Prize : Alain Aspect (2022)

During the summer 2022, I had the chance to do an internship - as a physics student - in the Charles Fabry laboratory, in the Quantum Gases group, where Mr. Aspect still works as an emeritus professor. Scientists from the group mostly study ultra cold atoms.

The Nobel Prize was awarded to Alain Aspect for his researches is not about quantum gases though. In the seventies, Mr. Aspect (let me call him Aspect for the sake of shortness) set up an experiment that gave scientific community a somewhat final word[1] to an old debate raised by quantum mechanics : is the world *non-local*?

Question might not be very clear. My first goal here is to recontextualize all the discussion - I'll not expand too much on historical aspects since I want to discuss physics here. Quantum mechanics has started in the early decades of the 20th century. It emphasizes the study of fundamental properties of matter where every particle's attribute seems to lie more on a discrete modelization rather than the continuous vision we had with classical models. This introduces many difficulties to grasp what is derived from quantum mechanics because the world of quanta doesn't behave the way our daily environment does.

Maths behind quantum mechanics described such strange things for us. One of them is quantum entanglement, that could be summarized by a single statement : for two particles that met in the past, for which their states are *entangled* (*i.e.* properties of one of the two particles share some strong links with properties of the other one), playing with one of them acts instantaneously on the other, no matter how far apart they are in space. This contradicts hard with the principle of locality that states that an object is only influenced directly by its immediate surrounding.

Most of what we believe to be true regarding quantum physics is due to the so-called « Copenhagen interpretation ». Physicists who line up with the Copenhagen interpretation have established many principles to understand results of quantum mechanics. That is where our story begins.

The main principle behind Copenhagen interpretation is that, for a quantum system, you can't say whether or not it was in a given state before measuring it (since you don't have any proof of it). This already opposes the classical view of physics where you can derive past and future of a system from equations (called *realism*).

Einstein, Podolsky and Rosen (shortened EPR) were very committed to the « local » view of physics and tried to deny the existence of such things like correlated particles. They had important arguments in their favors. Suppose you take any system composed of two correlated particles, named A and B. Since their properties are kind of related (*entangled*), if you measure a property a_1 of A, you can instantly deduce the property b_1 of B *before* measuring it.

Moreover, Heisenberg's uncertainty principle (who was part of Copenhagen interpretation) stands that the more you precisely measure a property a_1 of A, the less you can say on its conjugate property a_2. But with entangled particles, if you measure a_1 and b_2, you can deduce about a_2 and b_1. That's a thing! Those arguments are wrapped up in what is known as EPR paradox and led EPR to claim whether

> a) Quantum mechanics is incomplete (there exist some *local hidden variable*s that could describe the entire system before measuring it ; EPR embraces this view by rejecting non-locality and non-realism)
>
> b) Measuring both a_1 and b_2 makes no sense (hence agree with Copenhagen interpretation and let place to non-locality)

The debate has been, since, mainly philosophical and no one agreed on an answer. Nonetheless, in the sixties, a theoretical physicist named John Stewart Bell published an article where he described an experiment to settle the question. In fact, the assumption (a) imposes some strong mathematical constrainsts, in particular for a coefficient that we will call the S-parameter. If (a) is true, then $|S| \leq 2$. Furthermore, if quantum mechanics theory is right, S should be equal to 2.70. This has transformed an ontological discussion to an experimentally measurable value, by the use of « Bell's inequalities ».

1. It's not totally true, as we'll discuss it later

Aspect, as a young physicist, had heard about Bell's inequalities and decided to set up the experiment described by John S. Bell. I'll give no further details about the experiment itself but I let you instead with the original article : Proposed experiment to test the nonseparability of quantum mechanics.

After years working on the subject, Aspect's team finally stood up with a very precise result : $S = 2.697 \pm 0.05$[2]. This clearly violates the above Bell's inequality, hence we can reject local hidden variables without any further hesitation. In addition, the given result (within uncertainties) matches the predicted value of S. It reinforces our believes that quantum mechanics is the right theoretical framework to describe matter at the fundamental level.

So, quantum mechanics isn't local : but what does that mean? Plenty of answers could be given. Firstly, quantum mechanics being non-local is kind of different from our world being non-local : quantum mechanics is a *theory*, a *model* we do use to describe nature and all experiments made over the last hundred years have proven quantum mechanics' predictions to be strong enough to keep us sticking with this framework. Under assumptions of quantum mechanics, our world is non-local. Secondly, there are also many different interpretations that contradict each other. Some are testable, some other are not. What can be objectively said about non-locality? Let's take again the statement I gave for explaining correlation and give a physical sense to it.

The main thing is that, for any correlated particles, only one wavefunction describes the entire system. When you measure one of those particles, you can separate the wavefunction of the entire system in two parts and thus the system is determined with very clear states for each particles. Before measuring though, from the Copenhagen interpretation point of view, you can't say particles were in determined states. Therefore, measuring some property a_1 of particle A assesses a « numerical value » to property b_1 of B, even if they are 1 ly apart from each other. But that doesn't mean that particle A sends a signal to particle B though!

This is disturbing. Existences of each particles are so intrinsically tied together. In a more philosophical view, what makes sense to the human mind doesn't have to make any sense for particles. It questions any attempt at anthropomorphism. Concepts of distance or existency for particles seem so abstract for the quantum world. And it is a miracle that matter still has so many apparent properties (mass, size, position, …) we can grasp.

2. Experimental Tests of Realistic Local Theories via Bell's Theorem