Quantum Mechanics (QM)

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Abstract

Quantum Mechanics originated at the beginning of the 20th Century in order to explain the behaviour of the microscopic world. In this paper QM will be briefly described and the topic of retrocausality introduced.

1. The double slit experiment: light as a wave

On 24 November 1803 Thomas Young presented, at the Royal Society of London, the double slit experiment demonstrating that light is a wave:

"*The experiment I am about to relate (…) may be repeated with great ease, whenever the sun shines, and without any other apparatus than is at hand to every one*".

Young's experiment was very simple in design: a narrow ray of sunlight shines through a pinhole in a cardboard, the light then goes through two pinholes in a second cardboard, and then ends on a white flat surface creating patterns of lines, light and dark. (Fig. 1) which Young explained as a consequence of the interference among light waves. White lines (constructive interference) are shown when light waves add up, whereas dark lines (destructive interference) are shown when they do not add up.

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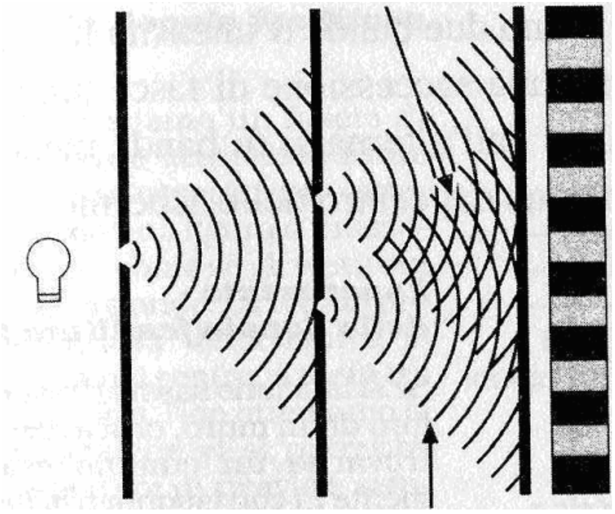

Fig. 1 – *Thomas Young's double slit experiment*

Young's experiment was generally accepted as the demonstration of the fact that light propagates as waves. If light would have been made of particles, the interference pattern would not have shown up, but only two well localized dots of light would have been observed in association to the pinholes of the cardboard. Instead, in the double slit experiment, the brightest line is located between the two pinholes, in what would have been expected to be a dark area (Fig. 2).

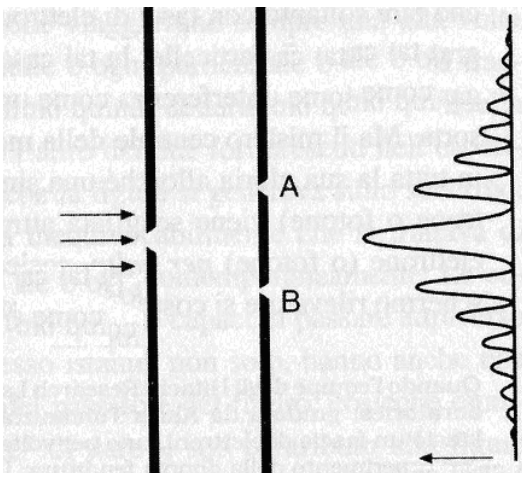

Fig. 2 – *Light patterns in Young's experiment*

Young's experiment has been considered the fundamental demonstration of the wave properties of light until Quantum Mechanics started to disclose the dual nature of matter: waves and particles at the same time.

2. The birth of Quantum Mechanics

At the end of the 18th Century Lord Rayleigh and Sir James Jeans tried to extend the equipartition theorem of classical statistical mechanics in order to describe thermal radiations.

> In classical statistical mechanics, the equipartition theorem is a general formula that relates the temperature of a system with its average energies. The idea is that energy is shared equally among its various forms.

When applied to waves the equipartition theorem predicted that a body would emit radiations with infinite power, as it would all concentrate in the ultraviolet wavelength. This prediction was named the "ultraviolet catastrophe", but fortunately it was not observed in nature. This paradox was solved on 14 December 1900 when Max Planck presented a work, at the German Physical Society, according to which energy is quantized. Planck assumed that energy does not grow or diminish in a continuous way, but according to multiples of a basic quantum, which Planck defined as the frequency of the body (v) and a basic constant which is now known to be equal to $6{,}6262 \cdot 10^{-34}$ joule·seconds and which is now named Planck's constant. Planck described thermal radiations as composed of packets (quantum), some small others larger according to the frequency of the body. Below the quantum level, thermal radiation disappeared, avoiding in this way the formation of infinite peaks of radiation and solving in this way the ultraviolet catastrophe paradox.

December 14 1900 is now remembered as the starting date of quantum mechanics.

3. The photoelectric effect and light as particles: the photons

When light or electromagnetic radiation reach a metal, electrons are emitted, this is named the photoelectric effect. The electrons of the photoelectric effect can be measured, and these measurements show that:

- until a specific threshold is reached the metal does not emit any electrons;
- above the specific threshold electrons are emitted, and their energy remains constant;
- the energy of the electrons increases only if the frequency of light is raised.

Classical light theory was not able to justify these behaviours, for example:

- Why does the intensity of light not increase the energy of the electron emitted by the metal?
- Why does the frequency effect the energy of the electrons?
- Why electrons are not emitted below a specific threshold?

In 1905 Einstein answered these questions using Planck's constant and suggested that light, previously considered an electromagnetic wave, could be described as quantum packets of energy, particles which are now called photons.

Einstein's interpretation of the photoelectric effect played a key role in the development of quantum mechanics, as it treated light as particles, instead of waves, opening the way to the duality wave/particles.

The experimental proof of Einstein's interpretation was given in 1915 by Robert Millikan who, ironically, had been trying, for 10 years, to prove that Einstein's interpretation was wrong. In his experiments Millikan discovered that all the alternative theories did not pass the experimental test, whereas only Einstein's interpretation was shown to be correct. Several years later Millikan commented: “*I spent ten years of my life testing that 1905 equation of Einstein’s and contrary to all my expectations I was compelled in 1915 to assert its unambiguous experimental verification in spite of it unreasonableness since it seemed to violate everything that we knew about the interference of light.*”

4. The double slit experiment and the dual nature of matter: waves and particles

Young’s experiment can now be performed using single electrons. Electrons used in a double slit experiment produce an interference pattern and therefore behave as waves, but at their arrival they give place to a point of light, behaving as particles. Do electrons travel as waves and arrive as particles?

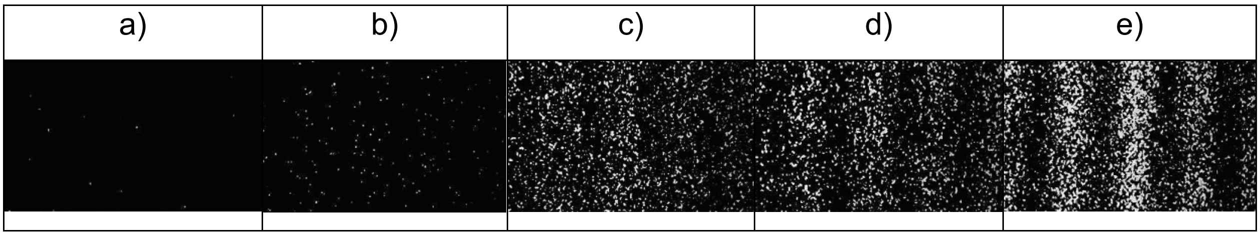

Fig. 3 – *Double slit experiment using electrons*
a) 10 electrons; b) 100 electrons; c) 3.000 electrons; d) 20.000; e) 70.000 electrons.

If electrons were particles we could conclude that they would go through one of the two slits, but the interference patters shows that they behave as waves going through the two slits at the same time. Quantum entities seem to be capable of going through the two slits at the same time and know how to contribute to the interference pattern.

According to Richard Feynman: “*Double slit experiment is a phenomenon which is impossible, absolutely impossible, to explain in any classical way, and which has in it the heart of quantum mechanics. In reality, it contains the only mystery, the peculiarities of quantum mechanics.*” (Feynman 1977)

5. Copenhagen Interpretation

The interpretation of Copenhagen was formulated by Niels Bohr and Werner Heisenberg in 1927 during a joint work in Copenhagen, and explains the double slit experiment in the following way:

- Electrons leave the electronic cannon as particles;
- They dissolve into waves of superposed probabilities, in a superposition of states;
- The waves go through both slits and interfere creating a new state of superposition;
- The observation screen, performing a measurement, forces the waves to collapse into particles, in a well defined point of the screen;
- Electrons start again to dissolve into waves, just after the measurement.

Essential components of the Copenhagen interpretation are:

- The Uncertainty principle formulated by Heisenberg, according to which a quantum entity cannot have a precisely defined moment and place at the same time.
- The Complementarity principle which states that a single quantum mechanical entity can either behave as a particle or as a wave, but never simultaneously as both; that a stronger manifestation of the particle nature leads to a weaker manifestation of the wave nature and vice versa..
- Schrödinger's wave equation, reinterpreted as the probability that the electron (or any other quantum mechanical entity) is found in a specific place.
- The superposition of states, according to which all the waves are superposed together until a measurement is not performed.
- The collapse of the wave function which is caused by the observation and the act of measuring.

According to the interpretation of Copenhagen consciousness, through the exercise of observation, forces the wave function to collapse into a particle. This interpretation states that the existence of the electron in one of the two slits, independently from observation, does not have any real meaning. Electrons seem to exist only when they are observed. Reality is therefore created, at least in part, by the observer.

When Erwin Schrödinger discovered how his wave function had been reinterpreted into a probability function with mystical implications, he commented: *"I don't like it, and I am sorry I ever had anything to do with it".* Einstein immediately refused the interpretation of Copenhagen stating that the use of the observer, of consciousness and probability proved the incompleteness of the interpretation. According to Einstein a scientific theory had to use causality: "God does not play dice with the universe!"

6. EPR

In 1924 Pauli discovered that electrons have a spin, and that in a specific orbit only two electrons, with opposite spins, can find place (Pauli's exclusion principle). According to this principle any couple of electrons, which shared the same orbit, remain entangled showing opposite spins independently from their distance. According to Einstein, causality is always local and information can only travel at speeds lower or equal to the speed of light, never faster. Starting from these assumptions Einstein refused the idea that information relative to the spin of entangled electrons could travel faster than light. In 1934, he formulated these considerations in the EPR paradox (named after the initials of Einsten-Podolsky-Rosen) which remained unanswered for more than 50 years.

7. Aspect's experiment

EPR had been presented as a conceptual experiment, in order to demonstrate the absurdity of the interpretation of Copenhagen, raising a logical contradiction. No one expected that the EPR experiment could be really performed.

In 1952 David Bohm suggested to replace electrons with photons in the EPR experiment, and in 1964 John Bell showed that the change introduced by Bohm opened the way to the possibility of a real experiment. At that times even Bell did not believe that the experiment could be performed, but 20 years later several groups had developed the precision of measurements required and in 1982 Alain Aspect published the results of an experiment which showed that Einstein was wrong and that non-locality was real.

Aspect's experiment measured the polarization of photons. It is possible to force an atom to produce two entangled photons, which go in opposite directions. Each photon, of an entangled pair, have opposite polarization. The interpretation of Copenhagen predicts than when the measurement is performed on one photon it instantaneously determines the state of the second photon. This is what Einstein named "a spooky action at a distance".

Aspect measured the polarization of photons according to an angle which he could regulate. According to non-locality changing the angle with which the polarization of a photon is measured would instantaneously change the measurement effected on the second entangled photon. The experiment was conducted on series of entangled pairs of photons. Bell theorem stated that if locality is true, the measurements of polarization performed on the photons moving through the first apparatus, which could be regulated changing the angle, should always be higher than the measurements performed on the second set of entangled photons (Bell's inequality theorem). Aspect obtained opposite results violating Bell's theorem and showing that non-locality is real. Einstein's good sense lost the competition against the unreasonableness of quantum mechanics. Aspect's experiment, proved that in nature instantaneous correlations, where information propagates faster than the speed of light, are real and possible.

8. Wheeler's delayed choice experiment

When, in a double-slit experiment, a detector is used to measure which slit the photon goes through, the interference pattern disappears.

In 1978 John Archibald Wheeler proposed a variation of the double-slit experiment in which the detectors could be activated after the passage of the photon through the slits. In the delayed choice experiment the detector is located between the slits and the screen on which the interference pattern is observed. Quantum theory tells that when the detectors are turned on the interference pattern disappears, forcing the waves to collapse and the photons to go through the slits as particles. This should happen also if the detection is activated after the transition of the photons through the slits.

The delayed choice experiment became possible thanks to the speed of computers which can choose randomly when to activate the detectors between the double slit and the screen. The result is that this choice effects the way in which the photon has gone through the slit (wave/particle), and that this effect operates backwards in time. The first two experiments which verified this model were performed independently in the 1980s in the University of Maryland and Munich, Germany. These experiments showed that the decision to activate the detectors affected the nature of photons backwards in time.

Wheeler, noted that it is possible to devise a double slit experiment at the cosmic level using light coming from quasars and a galaxy which operates as a gravitational lens on the way to Earth. This light would generate an interference pattern showing that light has travelled as waves. But if a measurement would be performed before the screen on which the interference pattern takes form, the pattern would dissolve and the photons would change from waves into particles. In other words our choice on how to measure the light coming from a quasar influences the nature of the light (particle/quasar) emitted 10 billion years ago. According to Wheeler this experiment would show that retrocausal effects operate at the quantum level.

9. The transactional interpretation

The transactional interpretation of quantum mechanics was presented in 1986 by John Cramer, physicist of the Washington State University. In this interpretation the formalism of quantum mechanics remains the same, but the difference is how this formalism is interpreted. Cramer was inspired by the absorber-emitter model developed by Wheeler and Feynmen which used the dual solution of Maxwell's equation. As is well known also the generalization of Schrödinger's wave equation into a relativistic invariant equation (Klein-Gordon 1926) has two solutions, one positive, which describes waves which propagate forward in time, and one negative, which describes waves which propagate backward in time. This dual solution allows to explain in a simple way the dual nature of matter (particles and waves), non locality and all the other mysteries of quantum mechanics and permits to unite quantum mechanics with relativity.

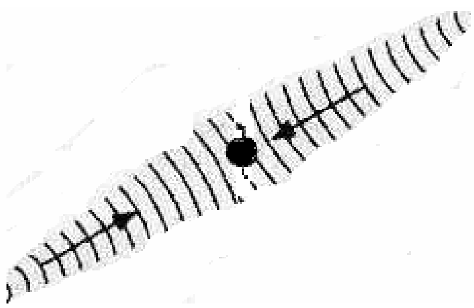

Fig. 4 – *Transactional Interpretation*

The transaction between retarded waves, coming from the past, and advanced waves, coming from the future, gives birth to a quantum entity with dual properties wave/particle. The wave property is a consequence of the interference between retarded and advanced waves, the particle property is a consequence of the point in space where the transaction takes place.

The transactional interpretation requires that waves can really travel backward in time. This assertion is counterintuitive, as we are accustomed to the fact that causes precede effects. It is important to underline that the transactional interpretation takes into account special relativity, which describes time as a dimension of space, in a way which is totally different from our intuitive logic. The interpretation of Copenhagen, instead, treats time in a classical

Newtonian way, and this is why it required the introduction of consciousness, in a mystical way, as a means to solve the contradictions which it was encountering.

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