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Quantum Physics and Information

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1.1. Orthodox introduction to quantum physics

"Nobody understands quantum mechanics!" This brilliant catchphrase uttered by Feynman is still true. The dozens of books devoted to this enigmatic science have not yet provided an explanation regarding the quantum world, but the descriptions of these strange experiences as well as these esoteric theories are nonetheless pleasant to read, provided that we are equipped with a minimum of mathematical baggage to travel without much difficulty in a universe that refuses to reveal its secrets. That being said, classical mechanics are hardly easier to understand when they are spiced up with abstract notions such as the configuration space, the Lagrangian or the Poisson bracket [SUS 15]. Electromagnetism is even less accessible. If the world of quantum mechanics is difficult to understand, it naturally follows that introducing this science to a wider audience constitutes a real challenge for physicists, especially considering that physicists do not fully grasp the strangeness of the quantum world. How is it possible to teach quantum mechanics if nobody understands it?

The first book that explained the physical and mathematical principles of quantum mechanics was published by Dirac in 1930. Reading this text, we are struck by the clear and elegant presentation of early quantum mechanics, a few years old at that time. Historians of science have suggested that Dirac might have been affected by a certain kind of autism, which might explain his ability to capture the principles of these new mechanics early on and to expose them with undeniable elegance, together with a very platonic aesthetic concern. Dirac exposed the basic quantum mechanics, including the relativistic equation of the electron. In 1930, the great enigma of quantum entanglement was not known and specialists were satisfied with the orthodox interpretation acquired after bitter controversy during the Solvay Congress of 1927.

A presentation of quantum mechanics should also include the so-called orthodox interpretation. Quantum mechanics are integrated by two blocks. In the first place, the preparation of the experiment described in the form of a superposition of states, each described by a complex function, ψ_1, ψ_2, ψ_N, etc. The notation system uses the column vector (bra) or the line vector (ket), symbolized by a | bar, respectively followed or preceded by > or <; each state corresponds to an observable[1]. Let us imagine an experiment with two observable colors, red and blue. The system is described by an addition of the two vectors; each vector is assigned a coefficient whose square corresponds to the probability that the observable associated with its state may actually appear in the experiment. One of the requirements is that the sum of the squares equals one.

$$\text{State vector} = \sqrt{1/3}\ |\ \psi\text{-red} > + \sqrt{2/3}\ |\ \psi\text{-blue} >$$

– This state vector indicates that there is a one in three chance for red to appear and two chances out of three chances for blue to appear. When there is no observation, the wave function is supposed to obey a deterministic equation established by Schrödinger. Evolution is continuous in time and deterministic. When a measurement is made, there is a collapse or a reduction in the state vector. The measurement is discontinuous and indeterministic because we cannot know in advance if it is red or blue that will pop out of the “quantum roulette”.

– The orthodox interpretation states two things:

1) First, the wave function (or vector) describing the system does not correspond to a physical reality of the world (be it objective or not). It is merely a mathematical tool for calculating what is

1 In physics, an *observable* (noun) is a dynamic variable that can be measured.

observable and the probability associated with each measure. In my example, the wave function indicates that the moment when the experiment is performed, blue and red will be able to manifest with one-third and two-thirds probabilities. However, the wave function does not assign any property to the system, which is neither blue, nor red, nor purple. In fact, the wave function does not have a “color” in the space of quantum vectors. In other words, we know nothing about the system in terms of the characters or phenomena present in our world.

2) Second, once the experiment is launched and the measurement made, thanks to the detectors of our world, we know perfectly well whether it is the red or the blue that will be expressed. The orthodox interpretation separates the description of the system when nobody is trying to make an observation and what occurs if an observation is made and the wave function is reduced (in order to express red or blue). According to Bohr, the quantum experiment might require two descriptions: an independent one (purely quantum and made of wave functions with no real counterpart) and a classical one, including the laboratory and its devices. The whole enigma can be reduced to what happens when we move from the “unreal” quantum stage “$\sqrt{1} / 3 \mid \psi\text{-red}> + \sqrt{2} / 3 \mid \psi\text{-blue}>$” to the classic “blue” or “red” stage. Besides, the orthodox interpretation postulates that we know nothing about a system until we have measured anything. And therefore the most complete description of the system, that of the wave functions, is not expected to belong to the field of the natural knowledge of things. Only “blue” or “red” signals belong to our material universe, which can be known by performing an experiment.

While the orthodox interpretation has been accepted by the majority of physicists, other interpretations have been offered. For example, many-worlds theory assumes that if we observe blue during a reduction of the wave function, then the universe splits in two, with a double in which red is observed, except that we do not have the means to go and check what happens in the split universe and verify if red has appeared there. It is nonetheless possible to conduct such a precise experiment that we are able to observe blue and red superimposed in a system for an infinitesimal period of time. This is the decoherence experience that was achieved in the 1990s and recently won a Nobel Prize for Serge Haroche and David Wineland. Decoherence does not change a word to the orthodox interpretation, but it does question the link between our classical world and the quantum world. In fact, it arouses bold speculations about the measurement process that could take place much like a natural selection of observables, from which derives the concept of "quantum Darwinism" (that we will explore in Chapter 4). Scientists who want to know what occurs during the measurement instance are similar to the spectators of a prestidigitation act, wishing to go behind the scenes in order to understand how the magic trick is carried out. They want to go beyond the horizon and lift the sails. If primordial matter is a quantum gum, then nature unfolds as if it were chewing multicolored gum. Then, the experiment consists of extracting red or blue bubble gums that stick to our extended matter and color it. Why and how? This enigma is not solved yet.

There is a more classic image that can help us to represent this strange wave function and its reduction at the moment when it is measured. Let us imagine a football game. Zidane is in possession of the ball. He can choose between four possibilities: either to keep it, to pass it to a winger, to pass it to a forward or to a fullback. The match is filmed but it suddenly stops. The wave function that determines the experiment is defined like this, assuming that each possibility is equiprobable.

$$\psi\text{-Zidane} = \tfrac{1}{2}\,|\,\text{to keep it} > + \tfrac{1}{2}\,|\,\text{pass it to winger} > + \tfrac{1}{2}\,|\,\text{forward} > + \tfrac{1}{2}\,|\,\text{full back} >$$

In order to find out how this continues, we have to resume the film. A few seconds after the retransmission was interrupted, we then see Zidane's choice. The operation for reducing the wave function took place in Zidane's brain. However, the picture is misleading. The description of the system by ψ-Zidane deals with classical situations, not with quantum waves. These are classic probabilities we are referring to, as in a game of dice. The terrain where wave reduction takes place is a classic, macroscopic scenario, whereas in the quantum world, if this "terrain" is a reality, it is partly out of our classical scene. Besides, the evolution of ψ-Zidane's brain wave function depends on the information collected by Zidane. If the forward player is marked by an opposing defender, but the opposing winger progressively stops marking, the wave function necessarily changes; the probability of passing the ball forward decreases while that of passing the ball to the winger increases. In quantum world, such an eventuality is inconceivable because as long as the system does not exchange information, the evolution of the wave function remains independent from what is going on in our classical world and obeys Schrödinger's equation.

The orthodox interpretation has been discussed in thousands of articles. It suggests a limitation of natural knowledge, that is, it draws a horizon of knowledge, a concept cleverly introduced by Gonseth. Experimenting with decoherence has slightly pushed this horizon, as occurred with the recent works of Humphrey Maris, who detected phenomena that may be interpreted as a fission of the wave function under extreme conditions, those of superfluid helium (see Chapter 2, section 2.4). Thus, quantum description in terms of complex waves corresponds to an element of the physical world under exceptional conditions. In a totally different context, quantum entanglement has equally pushed the horizon of knowledge. In a device containing two intertwined "elements", a measurement on one of them makes it possible to obtain information about the second one. In other words, global information is contained in the part (see Chapter 3).

As a result, these considerations open a dialogue with nature: in fact, what is matter from the quantum point of view? Having elaborated this question in other papers, I suggest some elements of response by refocusing on the notion of information, which will be a common thread in this work. Primordial quantum matter "produces" or "contains" information that can be communicated to the experimenter by means of a technological interface. Therefore, following the previous example, the information content is provided by a wave function that looks like this: $\sqrt{1} / 3 \mid \psi\text{-red}> + \sqrt{2} / 3 \mid \psi\text{-blue}>$. The information communicated corresponds to one of the observables, red or blue. In other words, it is quantum gum that sticks and is introduced into the technological device. It is in a similar fashion that hidden impressionist matter projects a few tiny drops of paint, if we look close enough. By nature, quantum physics is a dynamic. However, it is a dynamic of communications, not of mechanics with forces and is arranged in a geometrical extent, like that of Newton or Lagrange.

1.2. Quantum states or how nature communicates with physicists

Let us start with a general idea that is applicable to every physical experience; two notions are always present: state and measurement. In a sense, a state is like a "dynamic and kinematic inventory". With variables and equations that determine dynamics and kinematics, that is, the arrangement of forces and the movement of particles. A measurement is a number obtained during observation. It may be a speed, a position, an angle, a mass, a trajectory, a translational or torsion force, kinetic momentum, a particle detected with a spin, etc. The analysis of the "epistemological work" around the notions of state and measurement makes it possible to highlight the irreducible difference between classical physics and quantum dynamics.

Firstly, the definition of a quantum system or a quantum state with wave functions is completely different from the descriptions used in mechanics. Second, we have to be aware that while in classical mechanics the notions used for describing the state of a system are also implemented for describing observations (speed, angles and positions); in quantum mechanics, this is no longer the case. I will now illustrate with the example of a function defined as the Lagrangian in classical mechanics. To calculate it, we have to subtract the kinetic energy from the potential energy and its formula can be summarized as $L = L(p, q)$. In this formula, it is sufficient to know the potential and six parameters, three for p, the position, and three for q, the impulse, the latter being calculated from m mass and dp/dt speed. In a way, the Lagrangian sums up the state of the system, as it evolves along a trajectory by obeying the principle of least action. It is clear that the parameters used for describing the state are also the parameters used in experimental measurement (mass, speed and position). If we now consider a quantum state described by the formula:

$$\Psi = \sqrt{1/3}\ |\ \psi\text{-red} > + \sqrt{2/3}\ |\ \psi\text{-blue} >.$$

We find that $|\ \psi\text{-red}>$ and $|\ \psi\text{-blue}>$ are mathematical formulas that do not describe real things in the experience. On the contrary, the observables, red and blue, are “real”. In classical mechanics, the evolution of the system is calculated from the Lagrangian, whereas in quantum mechanics, it is the Ψ wave function that evolves by “obeying” the Schrödinger equation which is applicable as long as the system is not observed (that is, disturbed). This is what makes quantum physics strange, since the evolution of the system concerns something that is not observable, and what is more something which does not correspond to a physical reality. When observation is carried out, the classical rules of determinism are no longer valid.

The link between the two domains is neither intuitive nor trivial. The world of observations is deduced from that of the states by means of rather esoteric mathematical operations. Man and higher animals are naturally “conceived” for perceiving macroscopic classical things, force, figures, position, temperature, but not quantum phenomena. Scientists have had to develop an arsenal of mathematical and technological tools to describe and observe quantum systems. In the quantum experiment, every observation modifies the state of the observed system. On the contrary, in classical physics, the observed system is considered independent from the observer. The modification of the quantum state is interpreted as a two-way communication. In other words, the exchange of information is reciprocal up to such an extent that when the matter communicates information to us, we also communicate information to the matter, which has in this way been a recipient of our influence. Let us recall that the notion of influence over a system or a thing is one criterion used for characterizing and for defining the ambiguous and ambivalent notion of information in the physical sense. How do we extract this information? Let us take the example of the system described by:

$$\Psi = \sqrt{1/3}\ |\ \psi\text{-red} > + \sqrt{2/3}\ |\ \psi\text{-blue} >.$$

To go from the state vector to the observable, we apply an operator to the vectors, which are then transformed. Given a C operator (which will be called “color operator”), this has a very special property, found in all quantum physics operators, namely that it is Hermitian. This means that if it acts upon a state vector, the result is a multiplication of this vector by a number that is real and not complex. And this is convenient because a real number may correspond to an experimental measurement. Let us write the application of an operator to the proper vector corresponding to red:

$$C \mid \psi\text{-red} > = \text{Red} \mid \psi\text{-red} >.$$

We can do the same for the other proper vector:

$$C \mid \psi\text{-blue} > = \text{Blue} \mid \psi\text{-blue} >.$$

Color operator C makes it possible to extract two observable properties from the system described by Ψ, which are red and blue. This operation should be interpreted as taken from the formal viewpoint of objective information from a world which is not objective itself, that of state vectors Ψ. What is so particular about a Hermitian operator? In linear algebra, a Hermitian operator is defined as a self-adjoint endomorphism. This means that the C operator and its designated assistant indicated by a *dagger* (or C^+, read C cross) match, which gives the formula $C = C^{dagger}$. Quantum operators are often matrices. Obtaining an assistant requires two operations, transposition and conjugation. Transposition refers to tilting the matrix around its diagonal. It is as if we were turning a metal square using its diagonal axis. In a matrix, the terms are noted with two indices which designate the row and the column. Transposition leads to reversing the indices. For example, the element placed in the third row, second column moves towards the second row, third column: thus the transposed c_{32} is equal to c_{23}. On the contrary, conjugation refers to reversing the sign of the imaginary part of a complex number. For instance, if c = 7 + 3i, then its conjugate is written with an asterisk, in such a way that c* equals 7 − 3i. Thus, we have the formula: $c_{32}* = c23$, and more generally, $c_{ab}* = c_{ba}$. The elements of the diagonal have no imaginary part and are real.

Given a square matrix with $c_{21} = 1 + i$; if we want the adjoint matrix to be identical to the initial matrix, then $c_{12} = 1 - i$. The other two coefficients are in the diagonal and must be real numbers, as for example $c_{11} = 3$ $c_{22} = 4$. This results in the following matrix:

$$\begin{matrix} 3 & 1 - i \\ 1 + i & 4. \end{matrix}$$

Therefore, let us now imagine the square matrix as a piece of metal whose shape is square and where each term is represented with a surface corresponding to the whole part. Now, this part is deformed with a bump (or a hollow) whose height (or depth) corresponds to the complex part. The sign of the imaginary number (positive or negative) determines whether it is a hump or a hollow. In our example, the hump of coefficient $c_{21} = 1 + i$ mirrors the hollow, which is associated with $c_{12} = 1 - i$. Hence, if we turn around the metal square choosing its diagonal as rotation axis, then what is a bump with a certain height becomes a hollow with a certain equivalent depth, and as a conclusion, rotation does not change the shape of the metal square.

Are Hermitian matrices simple calculation tools or do they have anything to say in regard to this rather enigmatic matter that we can conceive as vibrating quantum? If we assume that quantum states are in the image of structured vibrating gums, then the shape of the operator describes a process capable of making a reversal operation look like a gum element from an interior place towards another crossing point in the quantum interface and an extension in our macroscopic extended universe. Quantum gum communicates by spreading over the extended world and, conversely, with the symmetry of reversal we may think that the information of our world is transmitted to matter. If this matter could "observe" what is going on, it would see the same observable that we see at the laboratory. As if it looked at us through a mirror.

The Hermitian character of the operator reveals a symmetric property that characterizes "quantum nature". By symmetry, we mean an operation makes an object move without changing its shape. This symmetric reversal might explain why we perceive things with our sight. Therefore, the thesis of the visible world that fixes itself on the retina after passing through the lens and that the brain recomposes is a fable. Sensitive vision can be explained through quantum physics, to which the principles of extended macroscopic order are added. We will note a coincidence: the geometric tensors of general relativity are 4×4 matrices but with real terms; these can be reversed, taking the diagonal as axis of rotation without them changing their shape.

1.3. Particles, information, evolution

Quantum dynamics can be described by means of an epistemological triplet: state vectors, operators and observables. State vectors define overlapping "quantum states" when these are not observed. In his treatise on quantum mechanics, Feynman has stated that any state in the world could be described as an overlapping of basic states and we wonder which are these basic states that exist in innumerable situations, as for example in the spinning of an electron or a proton. These examples bring us back to natural order, that is, to physical order. If the three elements of the triplet wave, operator and observable triplet are no more than mathematical forms, then the experience of the world and the quantum experience lie upon a natural physical substratum that we call matter and which manifests itself in an extended field of expression. If we assume that the states of the world constitute basic information, then the particles act as the medium for expressing such information. This conception brings us back to Aristotelian hylemorphism with a form–matter duality which, in the quantum world, becomes the principle of a duality between quantum states and particles, understanding that a particle (in terms of mass or energy) belongs to the material pole. Quantum neohylemorphism as studied in my thesis [DUG 96] will be exposed in Chapter 2.

Hence, I interpreted fundamental quantum matter as an overlapping of information arranged in a certain order. This information is formally extracted by operators and can be found in experiments in the form of observables. We can reasonably think that the "material particle" is the physical element that performs this extraction, which updates information in our world. In this way, basic states are somehow the DNA equivalent to the primordial material world. The operator works as a quantum code expression system, in the same way as the genetic code is expressed in RNAs. Observables would then correspond to proteins translated from RNA. Thus, quantum dynamics is the science that describes the expression and communication of information by means of a matter that takes part in experimentation as a set of particles with defined features.

Quantum physics teaches us that states evolve over time. While the triplet "vector, operator and observable" is complete for describing quantum measurement, time evolution concerns the state vector. This evolution is shown by the Schrödinger equation ($H\ \Psi = E\ \Psi$). In classical mechanics, energy is the state variable as this is preserved through time (see Noether's theorem). The energy makes it possible to calculate the classical Hamiltonian. In quantum mechanics, the Hamiltonian is not an amount but an H operator whose proper value determines the E energy that the system "consumes" when it is observed. Let us nonetheless recall that in Heisenberg and Jordan's *Matrix mechanics*, it is the observable that evolves over time (see Chapter 2), which finally changes nothing because the two versions are equivalent.

The evolution operator noted as U is unitary. The result of applying a U operator and then its auxiliary leads to the same state. In other words, the multiplication of the two operators is the identity operator. $U \times U^{dagger} = I$. With one important consequence: the "logical" relation between two states is preserved by time [SUS 16]. This property presents a similarity with a Liouville theorem that states the conservation of the number of configurations over time for an irreversible dynamic system or even another Liouville theorem on the conservation of the space volume between phases. As a unitary operator, Liouville's theorem and many other things are connected to the issue of information conservation. As soon as we approach the question of information, the links between quantum mechanics and other physics become more precise and this is also the case of the AdS/CFT[2] correspondence in quantum gravity.

2 Anti de-Sitter/Conformal Field Theory (AdS/CFT).

We will stick to the idea of order in how basic quantum states are arranged, that is, an information order of "fundamental matter". This is what makes it possible to propose a universal principle. In a classical system, the state variable preserved in time is energy, provided that this system does not exchange energy with the environment. *In a quantum system, it is information that is preserved*. Then, the evolution operator has a dual role. It determines the evolution of quantum states while it preserves the order of information and it makes it possible to calculate the energy associated with each state. In other words, an expressed state manifests itself as information extracted by an operator and also from a different angle, with energy necessary for its expression in the material world. This is what makes it possible to envision equivalence between information and energy.

1.4. Interpretation of Pauli's exclusion principle

One of the strangest properties of the quantum world is explained by Pauli's exclusion principle. Two particles cannot simultaneously occupy the same state characterized by quantum numbers and a level of energy. This principle concerns the particles having a half-integer spin, which is the case for the electron, the proton and the neutron, particles that have a spin equal to ½. These particles are called fermions. Thus, a set of indistinguishable particles, placed under conditions where the quantum effects are effective, are placed on the energy levels foreseen by the description of the system and the calculations. This starts with the lowest energy states. This principle elegantly explains the properties of atoms in the context of quantum chemistry (see Chapters 2 and 5). The electrons only have to "place" themselves on each orbital with their energy and a shape is calculated using three quantum numbers.

Particles placed in quantum conditions are distributed obeying a statistical law, Fermi–Dirac statistics, when it comes to fermions. Whole-spin particles such as photons obey another statistic, Bose–Einstein statistics. That is why they are called bosons; these "particles" can massively occupy the same state, in this case the one with the lowest energy. Fermi–Dirac statistics, formulated in a relativistic context, are often introduced as the successful expression of Pauli's exclusion principle. Sometimes the exclusion principle is not considered a fundamental element of quantum physics, although it may have intrigued more than one scientist, including Feynman who speculated in his treatise on physics about what might happen at the level of the atom in the absence of this principle. Although this speculation may possess heuristic value, it does not reveal the secrets of fermions, regardless of the fact that they exist as objects.

In 1929, Pauli's principle experienced a singular episode when Dirac formulated the relativistic wave equation for ½ spin particles, especially for the electron. Dirac's results astonished the specialists of the quantum world. In fact, Dirac's equation is oversized because only two components of the state vector used are useful for describing the electron. What to do about the other two? The most surprising feature was the emergence of negative energy solutions supposed to describe electrons with a positive electrical charge. At first, Dirac rejected these solutions as non-physical, but when he later coupled the electron with an electromagnetic field, he observed that this electron could switch to a negative energy state. This led him to consider that the universe is composed of positive and negative states. As a result, a strange conception of matter ensued, with quantum states occupied by electrons or not occupied at all, which were defined as vacant or holes.

In the 1930s, negative energy states were a curiosity provisionally solved by applying Pauli's principle. Dirac assumed that these states were all occupied and that, by virtue of the principle of exclusion, positive-energy electrons, those of our real world, could not topple over into the already filled negative holes. These explanations are now over and Dirac's Sea Hypothesis no longer appears in modern physics textbooks for fear of making students more confused. Nevertheless, some of Dirac's work has opened paths that may not have been thoroughly explored. The combination of Dirac's Sea, Pauli's Principle and the coupling of this sea to the electromagnetic field provide precious knowledge about "fundamental matter".

It is commonly accepted that particles and atoms are the elementary constituents of matter. However, a complete analysis of quantum dynamics makes it possible to envision another possibility for gaining access to fundamental elements. These are the basic quantum states or, more exactly, the elementary information contained in fundamental matter. Let us suppose that quantum information carried by one state is the fundamental element of the real. Explaining the world no longer needs the formulation of Pauli's principle because it is not the electrons that occupy a state but it is the "states" that achieve themselves in the form of an electron, which is the empirical element indirectly accessible to experience. Let us imagine a stock of information as a set of letters, a, b, c, d, and so on. These states are now achieved by electrons and are designated as A, B, C, D, etc. The exclusion principle is then a principle of multiplicity and differentiation. The idea that an electron occupying a state is actually a mental experiment, which does not necessarily have any physical meaning. What is fundamental is the information carried by the state and the energy that enables its realization. The electrical charge means that the information that goes through the range is quantified and responds to precise constraints.

The electron is an interface that enables the communication of quantum information. The existence of the charge reveals the universal rules that govern communication. We may think the same thing about mass. It is the interaction with the electromagnetic field that provides the "hole" with the features of the electron, whose existence cannot be separated from the field. It is as if visible information manifested itself through a universal material medium, in the image of a flat screen with pixels. In this metaphor, the electron would then be like a natural pixel broadcasting quantum information.

1.5. State vectors, science of orientations

Physics textbooks use two definitions for the same notion: the wave function and the state vector, constituted by a linear addition of complex vectors. The notion of vector contains a precise meaning in terms of mathematical formalism because a vector is not a simple collection of numbers, but it possesses an orientation. Nevertheless, this orientation of quantum vectors is not covered by our study, featuring spatial coordinates and time.

The electric field is given by a vector. Spherical symmetry states that when two points M and M' are diametrically opposed to the source of the field located at S at an equal distance, then the electric vector E_M is equal to $-E_{M'}$. If we take a turn traversed by a current of electric charges, a magnetic field is generated and the plane on which is the turn is a plane of symmetry for this field B. Nevertheless, there is no inversion: vector $B_M = B_{M'}$. Physicists say of the electric field that it is polar or even that it is true. Which means that if we transform a physical reality with a reflective symmetry (of the mirror type), then a vector is transformed into its opposite. The same goes for a speed vector. You see yourself in a mirror and you note that as you move towards the mirror, your image moves towards you and it seems to move in the opposite direction. On the contrary, the magnetic field does not obey this inversion by parity, in such a way that it is considered as an axial vector or a pseudovector.

If we consider a complex vector and represent it in an Argand plane, then the parity transformation becomes evident. In the Argand plane, the horizontal axis represents the real part and the vertical axis represents the imaginary part of the complex vector. For example, $2 + 2i$ is represented by a vector whose length is equal to $2.\sqrt{2}$ and whose orientation is 45 degrees upwards. If we perform a reversal, considering the horizontal axis as symmetry, then we obtain the same vector, except that its orientation will be 45 degrees downwards. This vector is actually the conjugate vector of the previous one, $2 - 2i$. These few remarks reveal the important role of orientation in quantum physics, as well as in electrodynamics and magnetism. Matter is not only displayed in a certain manner, but is also oriented. What is more, this orientation is associated with the communications that quantum matter establishes. Orientation in the quantum sense belongs to the physics of elementary communication, and should not be confused with orientation of mass in the context of a physics of arrangements, such as the rotation of a spinning top or a planet in the cosmos.

Orientation is practically universal in the quantum world. Orientation could be found in the electric and magnetic vectors, describing realities at the confines of the classical world. In the universe of "particles", orientation was introduced as spinning, awkwardly defined as intrinsic kinetic momentum. Spinning actually designates the orientation adopted by a fermion. Pauli matrices constitute a basis for spin states which correspond to three axes, x, y and z. When the atomic electrons are represented on the orbitals, they successively occupy the levels in pairs of two, one with a spin whose representation is an arrow pointing downwards and the other with the arrow pointing upwards. I suggest that these opposing spins (in sign and direction) refer to quantum communications in opposite directions, from the manifested world towards fundamental matter (overlapping quantum information, if you will) and from this fundamental matter towards the manifested world. This can be expressed using Nicolas de Cues's terms, *explicatio* and *complicatio*. Complex fundamental matter can be explained, as it unfolds in order to communicate with the world. To be even more graphic, I use the notions of quantum expression and quantum impression. Expression is communication, impression is information. In order to complete the description, I propose the notion of compressed or even zipped information so as to designate the world of basic states formalized by state vectors.

The dynamics of orientations is explicit thanks to three Pauli matrices that enable us to describe the spin operators associated with the internal rotations of the electron. These matrices are designated with the letter σ, and three indices corresponding to orientations in space assigned to them: $\sigma_1 = \sigma_x$; $\sigma_2 = \sigma_y$; $\sigma_3 = \sigma_z$. I suggest imagining a fly moving in front of a window as if observed by an individual at a certain distance, on the ordinate axis (y-axis). The σx matrix corresponds to the flight of the fly on the window along the horizontal axis. The σz matrix corresponds to the same scan on the vertical axis. Finally, σy, located in the axis of the observer, corresponds to the movement of the fly from one side of the window to the other. Thus, the electron appears as a microwave of a communicating interface that can cover the three directions of space. Therefore, orientation is specific to communication as facilitated by "quantum matter", be it in the sense of reception or in the sense of expression.

The importance of orientation in the quantum world is confirmed by the Compton Effect, often introduced from a mechanistic perspective in physics textbooks. An incident photon comes up against an electron associated with an atom that absorbs a portion of the photon energy and is ejected from the nucleus in the form of an ionized electron, while the photon is launched again, but this time losing a small portion of its energy, which produces a difference between the wavelength of the incident photon and that of the reflected photon. The phenomenon is interpreted as inelastic diffusion. This presupposes an epistemological artifice that is not self-evident because, in principle, a photon has no mass and, therefore, it cannot be involved in a shock. The trick is to consider that, given the very short wavelength of the photon (which is gamma radiation), it can be compared to a corpuscle. In physics textbooks, the incident photon is represented on the horizontal axis, it comes upon an atom, the photon goes upwards with a direction measured by a θ angle, whereas the electron goes downwards with a Φ angle. I suggest interpreting this process as an information exchange. Now, the two angles θ and Φ represent the manifestation of this information exchanged during the process. The shock is of little importance. What is remarkable is the importance of the orientation that is emerging in this quantum experience. As we can see, the Compton Effect marks a clear difference between the mechanical world and the quantum world.

Let us imagine a similar configuration in classical mechanics. The atom is represented by a billiard ball. If we push another billiard ball whose impulse vector meets the mass center of the first ball, then an elastic shock occurs and the second ball acquires the energy of the first and starts moving in the direction of the vector. An inelastic shock occurs if we push a ceramic ball towards the billiard ball. The ball may break into two pieces that will get dispersed. This is the situation found in the Compton diffusion, except that the incident ball is not material; it is a radiation of an almost imperceptible wavelength. Everything happens as if the photon broke the atom by ejecting an electron, except that the photon is not material.

Other research projects will help us confirm the importance of orientation in the physical world with the magnetism that is inseparable from orientation, both in the quantum field as well as in the classical world. In his treatise, the importance of orientation had not escaped Dirac, who evoked the orientation of the radiative emission by the electron which is then transmitted to the photon via polarization. Orientation is present not in a spatial but in a formal sense in the canonical transformations that are specific to quantum mechanics, but not analogous to classical mechanics [DIR 32, p. 95]. A canonical transformation concerns the representation of observables. It is as if the physicist changed his formal view angle so as to represent the system. Finally, orientation appears in the great enigma of neutrinos whose (negative) helicity perfectly translates the oriented character of this "particle". Helicity is to the neutrino what polarization is to the photon. The antineutrino has a positive helicity that makes it the mirror image of a neutrino. In the end, we rejoin the fundamental CPT symmetry[3] of the world of charged particles, except that charge conjugation C does not exist since the neutrino is not charged. Conjugation then takes place at the level of helicity.

1.6. Provisional conclusions on quantum mechanics

In conclusion, quantum physics must be considered as an information science and, more precisely, as a science that describes the fundamental rules that quantum matter obeys, whose fundamental and universal property is to communicate with interfaces and with dynamic exchanges between signals that carry energy and information. Quantum formalism with state vectors, Hilbert spaces and operators describe how the observer extracts information from a fundamental, or even primordial, matter of submerged information.

Quantum physics enhances the importance of orientation, which is the character of a substance that leans on its environment in order to communicate. Quantum physics can only be understood by highlighting its features and by making it even stranger than it is. It is necessary to highlight the characters of the quantum world and not to

3 Charge, Parity and Time reversal symmetry.

try to reduce them while we try to find correspondences with classical and mechanical images, as was done by most physicists who wisely misled themselves by avoiding the realities that this science offers us about the essence and behavior of matter. In his physics class, Feynman explicitly recognized the fact that "quantum mechanics is a different kind of representation theory about the world" and that while correspondences may sometimes exist, these are little more than mnemonic tricks, that is, things for helping us associate ideas [FEY 79, p. 205].

On my behalf, correspondences, be them explicit (like those of Bohr) or implicit (with the primitive notions), are no more than semantic means for speaking about a world that is completely strange to us. Using these notions helps us to say things, but in reality, these things do not exist. For instance, the notions of particles and waves, respectively derived from mechanical physics and the mechanical field, are not relevant in the quantum world. No more than these strong or weak forces so common in textbooks and books for the general public. At most, we can speak about interaction.