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Quantum Physics rapidly explained to my nephew

(rapidly because he never has time)

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-ABSTRACT-

A young man and his old uncle have a discussion about Quantum Mechanics. In a first part, the main scientific events in the domain, at the dawn of the 20th century, are recalled. Then the consequences of these main discoveries are examined, from the point of view of the necessary changes in our former thinking habits, based on "traditional" physics and associated interpretations. The growing place taken by modern physics, due to its contribution to the progress of technologies is acknowledged. A significant example of impact of quantum physics on our daily life is given, which is the most recent evolution of the International System of Units. In appendix, a more detailed technical description about this example is given, concerning the domain of electrical metrology.

***KEYWORDS**: PLANCK constant, undetermination principle, exclusion principle, boson of HIGGS, standard model, International System of Units, electrical metrology*

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I. INTRODUCTION

Science imposes rigour, but does not forbid humour

Romain : We were lucky enough, a few years ago, to make together a visit of CERN in Geneva, at the exact time of the experimental discovery of the HIGGS boson.
I remain interrogative about what I saw then. Do you think it would be possible to render quantum physics understandable for those who have openness and curiosity, but not-so-comprehensive scientific background ?

Jean-Pierre : Precisely, our discussion may have for goal to examine this subject, and therefore we shall try to make things simpler by means of an historical approach.

Fig. 1 : the authors

II. A BIT OF HISTORY

R. : So, would it be sensible to situate, at a given moment of science history, the start point of quantum physics ?
JP. : Well, I would be tempted to set this start point in 1900, not only because such date would be easy to remember, but mostly because it corresponds to some landmark publications of German physicist Max PLANCK.
PLANCK gave the decisive kick-off to the discipline at a time where he was studying the radiation of the black body, and the associated "*ultraviolet disaster*", one of the two basic problems which still resisted to the analysis of physicists at the end of the 19th century, along with the question of the invariance of light speed. He came to the conclusion that energy was not a continuous entity, but on the contrary packed in some sort of little grains, the quanta.
The so-called PLANCK equation is still considered as one of the main stones of the edifice of modern physics. This equation is written

$$E = h\nu \quad (1)$$

where **E** is an energy, **ν** is a frequency (the inverse of a time) and **h** is a constant present in nature, today called the PLANCK's constant (also frequently noted as $\hbar = h / 2\pi$).

About the general start, it would be fair to attribute also a special role to Ludwig BOLTZMANN, who issued a successful theory for heat diffusion in gases ; he did this at a time (1870) where very little was yet known about the intimate structure of matter, in terms of atoms and particles. BOLTZMANN's theory was based on a statistical interpretation, and practically he became a source of inspiration for the pioneers of quantum physics [1].
So we know today that we are confronted to a set of 3 "frontiers" of the universe :

- PLANCK's constant **h,** associated to the smallest possible quantity of energy
- BOLTZMANN's constant $\mathbf{k_B}$ associated to the smallest possible quantity of information or entropy,
- and light speed in vacuum **c** representing the maximum possible speed for matter and waves.

R. : Education makes us generally familiar with the three main branches of classical physics, and its emerging figures, NEWTON for mechanics, MAXWELL for electromagnetism, CARNOT for heat, ... But when speaking of modern physics, how do you explain that EINSTEIN is generally referred to, whereas Max PLANCK is often ignored ?
JP. : here, just have a look at this speaking photograph (picture below)
Exchanges of ideas between scientists has not begun with the Internet and social networks.
The first half of the 20th century was a period of permanent and strong political tensions, two world wars are enough to prove it ; but it was also a period of intense activity of the scientific community, which efficiently cooperated on an international basis.

R. FOWLER
A. PICCARD E. HENRIOT P. EHRENFEST E. HERZEN T. DE DONDER **E. SCHRÖDINGER** E. VERSCHAFFELT **W. PAULI** **W. HEISENBERG** L. BRILLOUIN
P. DEBYE M KNUDSEN W.L. BRAGG H. KRAMER **P. DIRAC** A. COMPTON **L. DE BROGLIE** **M. BORN** **N. BOHR**
I. LANGMUIR **M. PLANCK** M. CURIE H. LORENTZ **A. EINSTEIN** P. LANGEVIN C. GUYE C. WILSON O. RICHARDSON

Figure 2 : the participants to the 1927 Solvay congress in Brussels

Most scientists of that time, famous today, such as EINSTEIN, BORN, SCHRÖDINGER, PAULI, DE BROGLIE, DIRAC, and others ... communicated frequently with one another. Scientific progress was as much a collective one than an individual one.

For his own, Albert **EINSTEIN** become notorious at the time he published a set of 4 major scientific publications. In the mind of the public, EINSTEIN remains the father of relativity, with two main steps : special relativity in 1905 (which has linked together space and time), and general relativity, taking into account gravitation, in 1916. In parallel he also devoted much research efforts to quantum mechanics.
One can situate at this time the structuring of the "tree of modern physics", with its two main branches, growing in parallel and uninterruptedly since, relativity and quanta. These are two independent topics ; but they have in common to concretise human attempts towards a better understanding of the laws of nature. And above all, they

represent the two main branches mentioned above. Among the two branches, the one is oriented to a micro-scale world (the quanta), i.e. atomic particles, and the other is rather oriented to an astronomic-scale world (relativity), i.e. astrophysics.
R. : I would have said that the result of all these discoveries was the inverse of the expectation, I mean by that : around 1900, before the advent of quantum physics, minds were excessively quiet, "*there remains nothing significant to discover in physics*" ; this opinion reflecting perhaps some sort of ignorance. And now, we master quantum physics, but our minds remains definitely troubled, and we have lost our unlimited confidence in our capacity to understand reality.
JP. : We cannot dispute the fact that quantum physics forces us to accept uncomfortable new concepts and visions of reality.

To come back to EINSTEIN, he not only worked on relativity, but also investigated much on the nature of light ; he started from PLANCK's results, and concluded that light could be considered as made of light grains, the photons ; in other terms light appeared to be quantified. Before him, it was admitted that light was just a particular electromagnetic wave, conforming to Maxwell's equations, its wave nature enabling to interpret interferences and diffraction.
EINSTEIN got his Nobel Prize in 1921 due to his works on the photoelectric effect, i.e. work belonging to the "second branch", quantum physics, and not to relativity ; but his public image remains attached to his formula for mass/energy equivalence

$$E = m c^2 \qquad (2)$$

where **E** is once more an energy, **m** a mass, and **c** the speed of light in vacuum
R. : in that context of intense, continuous, and exciting progress, rich in new physical concepts, who came next ?
JP. : in a short period of time, a considerable amount of discoveries took place. Only 15 years separate for instance the BOHR atom model (1913), and the introduction of special relativity in quantum physics by Paul DIRAC (1928). The progress was global and resulted as much from frequent and fruitful exchanges between physicists, as from their individual, even though very personal, contributions.
We need here to introduce Niels **BOHR**, a Danish physicist. BOHR took early the lead of a school of thought attached to the name of his residence town, Copenhagen.
Prior to BOHR theory, the available atom models of THOMSON and RUTHERFORD, comparable to planets and satellites spinning around, showed diverse weaknesses, such as instability.

BOHR could remedy to this, he proposed a descriptive model of the atom compatible with quanta theory. In this model, the energy levels of the electrons spinning around the atom nucleus are quantized ; in other terms they can only take a finite set of values ; an electron cannot crash into the nucleus.
The existence of the electron particle was experimentally confirmed around 1906.
With his thesis work dated 1924, Louis DE BROGLIE brought a synthesis between the two possible visions of light, wave and corpuscle, and introduced the general concept of wave of matter : for any particle can be defined an associated wave, of wavelength $\lambda = h / p$ ($p = m v$, impulse momentum)

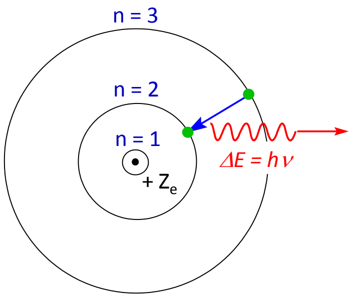

Figure 3 : sample of a BOHR-SOMMERFELD atom representation, with a state transition of a electron giving birth to a photon

R. : I suspect the curiosity of scientists could not remain limited to a description of atoms and particles, even though satisfactory. I mean they should have wanted to know about particles behaviour in space, their speed, position, and interactions with local fields such as electromagnetic fields.
JP. : at this stage we find **SCHRÖDINGER**, who established (1926) an elegant analytical, non-relativistic model, enabling us to calculate these desired quantities, location and speed, as a consequence of environmental conditions, i.e. the presence of distant force fields.
The equation is written in a bi-dimensional space, where the main parameter is called the wave function $\Psi(r, t)$, with ***r*** position, ***t*** time, and ***i*** being the unit of the second dimension :

$$H \; \Psi = i \hbar \, (\partial\Psi/\partial t) \qquad (3)$$

R. : my dear uncle, are you kidding ? I could agree on Max PLANCK's law, I could agree on EINSTEIN's formula, as bearing a reasonably complicated formalism. But don't you think that, while introducing SCHRÖDINGER's equation, with its partial derivative $\partial\Psi/\partial t$ and algebraic hamiltonian operator H, all that in the complex plane, you are going a bit too far ?

JP. : on the contrary, SCHRÖDINGER's equation was much appreciated by physicists as being simple, or at least more simple compared with something which came just after, the matrix formalism developed by Werner HEISENBERG (1927).

SCHRODINGER's equation is quite similar to the wave propagation equation used in classical electromagnetism ; physicists were much more familiar with this, and in the same time it is a wave-oriented representation of phenomena, whereas Heisenberg formalism is a corpuscle-oriented representation.

■ *We must have some principles*

HEISENBERG is today rather known for his **uncertainty principle**, also named undetermination principle. According to this principle, it is not possible to know simultaneously the speed of a particle represented by its impulse momentum **p,** and its position represented by **x**, in such a way that

$$\Delta p \cdot \Delta x \geq h / 4\pi \qquad (4)$$

equation where we again find the unavoidable PLANCK constant.

HEISENBERG's uncertainty has nothing to deal with measurement uncertainties, familiar to metrologists, and which take into account the imperfections of a measurement system.

It represents the definitive impossibility to know exactly at the same time **p** and **x**, due to their probabilistic nature.

To tell more about SCHRÖDINGER, his reputation among the public does not result from his equation, but mostly from his "*cat*".

Presenting his famous cat problem, SCHRÖDINGER wanted to bring a contribution to the debate on one of the main consequences of quantum physics, also one of the most difficult to accept, which is the **state superposition principle**.

According to this principle, statements about particle location or speed must obey to probabilistic considerations, which implies that a given statement : "*the particle is here*" may be at the same time true and false. This principle, transposed at man's scale by SCHRÖDINGER, through an ingenious experimental setup (including a cat, but fortunately fictitious), leads to apparently inacceptable results, i.e. the cat may be at the same time dead and alive.

Figure 4 : Noisette - the cat of the author - is perfectly healthy and alive, and totally indifferent to thought experiences about quantum physics, such as Schrödinger's

R. : do you still have in reserve many other frustrating principles ?

JP. : well, it remains to me Wolfgang PAULI's **exclusion principle**, but this last one cannot be honestly considered as frustrating.

PAULI completed the BOHR-SOMMERFELD atom model, which already included the three quantic numbers, **n**, **k**, and **m**, to describe the physical state of the electrons [2]. He added a fourth number called spin, with a only two possible values +1/2 and -1/2. His exclusion principle tells that two different electrons within an atom cannot have the same set of 4 quantic numbers.

This property is common to all fermion-type particles, category to which electrons belong.

Thus electrons around the atomic nucleus organize themselves in a sort of cloud according to PAULI's principle.

About our capability to accept disturbing ideas, the superposition principle obviously belongs to the class of the hardest ones, along with the wave-particle duality, the uncertainty principle of HEISENBERG, and the impossibility to travel faster than the speed of light in vacuum **c**. NEWTON's mechanics postulates that gravitation forces act instantaneously, this is not compatible with special relativity, which excludes supraluminic speeds for the information transfer.

R. : Would the state superposition principle apply to quantum physics itself ?

JP. : I don't see your point

R. : Well, quantum physics seems to me at the same time understandable, and non-understandable ...

JP. : well, let us speak rather now of two other major figures, Paul DIRAC and Max BORN.
Although not as much notorious as some others, DIRAC , had a considerable contribution to a whole set of subjects.
First, he demonstrated the equivalence of the HEISENBERG matrix model and the SCHRÖDINGER wave model (1928) ; secondly, he successfully introduced general relativity into quantum physics. Discovering negative solutions in the equation

$$E^2 = m^2 c^4 + p^2 c^2 \quad (5)$$

more general than the famous equation (2), while taking into account the possibly non-null impulse momentum **p** of the particle, he came to interpretations which further led to the hypothesis of positive electrons, a concept later generalised as anti-matter [3]. Lastly, imagining the possible quantification of the electromagnetic field, he initiated the approach called quantum electrodynamics.

It was BORN who developed the probabilistic interpretation of quantum physics, which he first published in 1926. Starting from SCHRÖDINGER's equation, which is a wave equation, he could interpret the behaviour of particles, for instance during their collisions, in terms of probability density. More precisely, a presence probability of a particle is proportional to $|\Psi|^2$, where Ψ is the wave function.
BORN's idea was in fact highly innovative : it completely upsets the concepts of hazard, determinism, and causality of conventional physics. Random results of a given quantic experience are not due to our ignorance of initial conditions ; on the contrary it is intrinsic, i.e. probabilistic, and finally unavoidable.
R. : was there always unanimity on those controversial questions ?
JP. : no ; EINSTEIN, and also SCHRÖDINGER, were much reluctant about BORN's theory. Hence SCHRÖDINGER's cat experiment, as already mentioned. On the contrary, the theory was easily accepted by BOHR and close physicists, gathering around the "*Copenhagen interpretation*" [4]
EINSTEIN and BORN were true friends ; despite their distant conceptions of quantum physics, they maintained over a long period written exchanges. The archiving and compilation of their more than 100 letters, constitute a great chance for us to read, and an exciting mix of intimate family news and deep physical reflections (including a few, but not to many equations) [5].

III. QUANTUM PHYSICS RECENT AND ACTUAL

R. : is the domain today quite active as in the blooming period of 1920 ?
JP. : activity in the domain has never ceased, although discoveries, because of their complexity and number, are less easier to popularise ; and consequently it is the same for their authors.
We will arbitrarily limit ourselves to two exceptions, Richard **FEYNMAN** and Stephen **HAWKING.**

FEYNMAN had a major contribution to modern physics, through his works on quantum electrodynamics, following those of DIRAC, from 1940 and during some 30 years.
FEYNMAN was a very attaching figure, having strong human qualities, and unfortunately numerous dramatic events in his personal life. As a teacher, he was especially attached to the diffusion of science, effort which is still accessible for us today thanks, among other things, to his famous lectures [6].
Just think of this : using conventional physics, no one ever seems troubled by the fact that distant forces can move objects without any contact with them, may they be gravitational forces, magnetic forces, or electrical forces. Finally, we accept extraordinary phenomena simply because we are accustomed to them, we hardly remark them.

We "explain" this, speaking of "*fields*" : electromagnetic field, gravitation field. To be honest, the notion of field is very efficient, since it allows easy calculations of the forces in play. But this is only a model, and FEYNMAN just postulated that fields DO NOT exist ; instead of them, particles move and interact. He developed a well-known graphical formalism to describe the various existing interactions

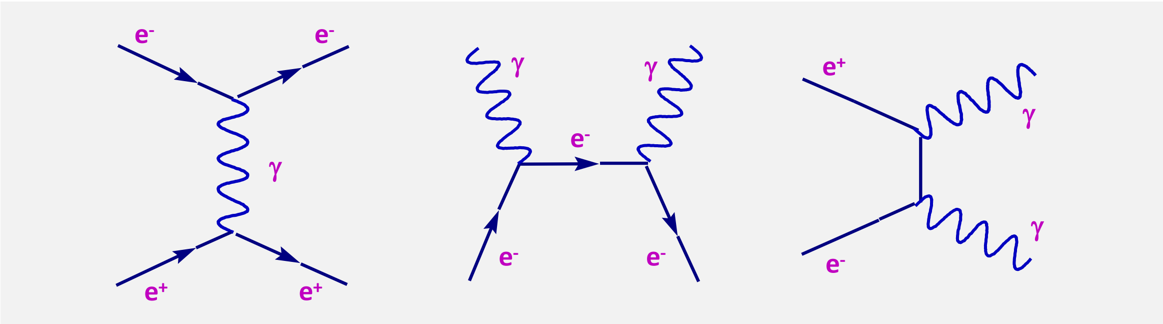

Figure 5 : a few samples of Feynman diagrams, used to represent interactions between atomic or subatomic particles ; the horizontal axis represents time, the vertical axis represents space ; from left to right electron/positron interaction, electron/photon interaction, electron/positron annihilation with photons emission

One attributes to FEYNMAN the judgment that "*a six year old child could understand quantum physics*". True or not, he was a very original mind, even a bit eccentric. Among other achievements, he could explain the dramatic failure of the 10^{th} flight of the space shuttle Challenger, thanks to his exceptional physical intuition.

Lastly, he also generalised the action principle, well-known of mechanical engineers, to quantum mechanics.

Hawking was one of the most prominent theoretical physicists of the 20th century. During his long and active career, despite a severe disabling illness (amyotrophic lateral sclerosis "ALS"), he brought a lot of new and stimulating ideas, due to his deep understanding of physics ; he thus could set out a theory of cosmology explained by a union of the general relativity and quantum mechanics. He also strongly contributed to popularise modern physics, with books such as [7]. He was engaged in the life of his contemporary world from a political point of view.

We shall retain especially his contribution about the radiation of black holes, and his vision of a non-bordered universe.

IV. THE IMPACT ON OUR DAILY LIFE

R. : Finally, does quantum physics, or more generally modern physics, interact with our daily life ?

JP. : the answer is yes, although we are often inattentive to it.

As widespread applications, we may think for instance to electricity production by means of photovoltaic panels, or to the multiple uses of lasers, in computers, in leisure video and audio systems. The whole industry of electronic components makes a very wide use of quantum mechanics. The Light Emitting Diode (LED) is a component today omnipresent is lighting systems, communication systems ...

More generally, modern physics is present in our daily lives. Some consequences of the general relativity theory (EINSTEIN 1916) such as the curvature of space-time are to be referenced, to allow a sufficient accuracy of the Global Positioning System (GPS) within our mobile phones.

V. A RECENT APPLICATION : THE LAST REVISION OF THE INTERNATIONAL SYSTEM OF UNITS

A significant event has occurred in November 2018, perhaps not enough emphasised by the media, which is a revision of the International System of Units (S I). Such an event occurs periodically, but only every 4 or 5 years, and the last one had consequences we must speak of.

The International System of Units relies in practical on some international institutions, such as the Conférence Générale des Poids et Mesures (CGPM) and the Bureau International des Poids et Mesures (BIPM), located in Sèvres (France). CGPM takes the form of an assembly of delegates of the world's countries. This assembly works on a democratic mode and validates by votes the scientific projects submitted to it.

Here, it should be underlined that the last meeting of CGPM in November 2018 unanimously voted in favour of the introduction of quantum mechanics in the definition of 3 among 7 of the system's base measurement units [8]

These units are :

- the kilogram (symbol kg), unit of mass
now referenced to Planck constant **h**

- the kelvin (symbol K), unit of temperature
now referenced to Boltzmann constant $\mathbf{k_B}$

- the ampere (symbol A), unit of electrical current intensity,
now referenced to **e**, the elementary electric charge

To be comprehensive, the mole (symbol mol), unit of matter quantity, also received a new definition (not quantic), being now referenced to Avogadro constant $\mathbf{N_A}$
(*see the Appendix for the use of **e** as a quantum parameter*)

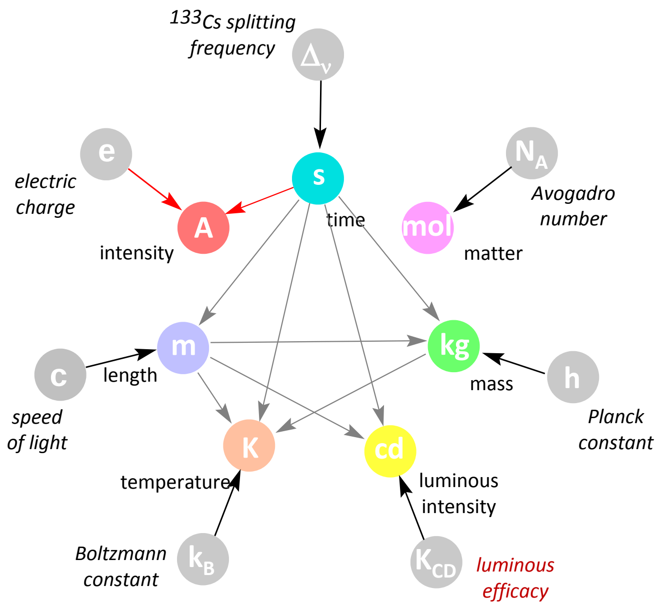

Figure 6 : new configuration of the international System of units, based on 7 natural constants, and on the use of quantum physics [9]

Let us recall that the 3 other units of the system already had received "advanced" definitions
- the second (symbol s), for time, relies on an atomic process, a state transition frequency in the caesium atom (in other terms on atomic clocks)
- the metre (symbol m), for length, is derived from the second, through the speed of light in vacuum **c**, and
- the candela (symbol cd), for luminous intensity, remains derived from geometrical measurements, energy measurements, and from statistics on human sensitivity

It is remarkable to observe that in this framework, the quasi-venerated International Prototype of the Kilogram (familiar name IPK), created in 1889, jealously kept and surveyed in Sèvres (France) at BIPM, will disappear, replaced by ... the PLANCK constant !
An other interesting consequence of this revision is that the metre becomes in some way no longer necessary ; the metre corresponds to the distance travelled by light in approximately 3,335 nanoseconds. However the practical use of the metre will likely not disappear.

VI. TO FINISH : A GOAL FOR CURRENT RESEARCH

R. : this is an endless process. Each time a theoretical problem receives a satisfactory solution, immediately new theoretical questions are raised.
JP. : there is obviously a dramatic change since the 19^{th} century, and its belief in a comprehensive knowledge of physics. Today, Internet sites provides lists of hundreds of problems still to solve in physics. A short list of them would include primarily black holes, dark matter, dark energy, ...
We are going to privilege only one of these, but not the least : the question of quantic gravity.
The goal of finding a "*new coherent description of the world*" is since some time under course. Previous research, during the second half of the 20^{th} century, has already led to a satisfactory unifying theory for three of the four distant interactions present in nature. This theory is called the **standard model**, and takes into account the nuclear force, present in the nucleus of atoms, the electromagnetic force, and the weak interaction due to beta radioactivity.
In this respect, the experimental confirmation of the Higgs boson by the experiments at CERN has been a significant success for this theory.

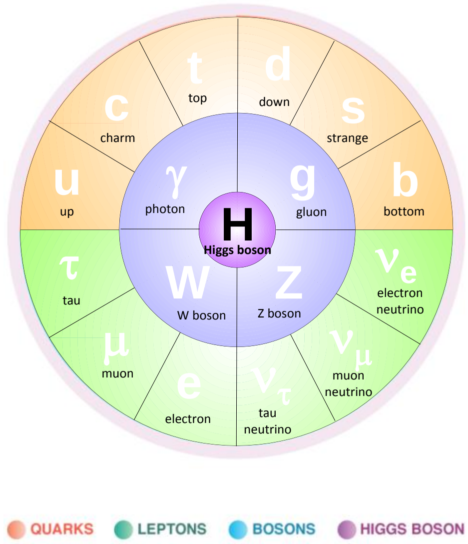

Figure 7 : arrangement of the basic particles present in the standard model

In this diagram :

- orange parts are quarks, i.e. matter particles, with spin 1/2
- blue parts are bosons, i.e. interaction particles, with spin 1
- green parts are leptons

all these are fermions

- at centre, the Higgs boson, with spin 0 ; this particle is at the origin of the mass of particles

But the particle named graviton - if ever it exists - associated with the fourth distant force, i.e. gravitation is still to discover.
Despite the observation of gravitational waves in 2016, predicted by EINSTEIN one hundred years ago, we still have no proof that gravitation is of quantic nature [10] [11].
As we have seen, the two big branches of the physics tree, quantum mechanics and relativity, have grown successfully and efficiently each one in its respective domain, in short particles and planets, or in other words, very small-size objects and very high-size objects, these only being sensitive to gravitation.
R. : but is such a synthesis really necessary ?
JP. : in general, situations where quantum physics and general relativity have to intervene simultaneously are not many. But a few ones exist, they concern for instance the understanding of the Big Bang (beginning date of the universe) or the one of the black holes (objects of extreme density distorting the space-time)
R. : what is the expectation of coming out in this area ?
JP. : well, no unemployment is to fear in this domain, specialists speak of some 10 or 20 years of research still necessary.
Among the main tracks towards a unified general model, one may think of the strings theory, the concurrent Loop Quantum Gravity theory both candidates as a Theory of Everything, dear to Stephen HAWKING.

VII. CONCLUSION

Modern physics confirms to us that reality is something excessively complex. We can approach it only with the help of models. And there may be models adapted to the understanding capability of each of us.

In the framework of such a short discussion, it was not possible to evoke but a few basics of the domain. Moreover, this domain continues to broaden its scope and to integrate new theories.

Quantum physics has forced us to accept strange concepts, paradoxical ideas, and uncomfortable principles. This acceptation was however unavoidable, as this physics has shown to be successful in its applications, those concerning electronic components, solid state integrated circuits, lasers, and many others.

One should also note that a recent theory, the theory of decoherence, takes into account the influence of the environment to explain the absence of quantic interferences at the macroscopic scale ; and thus perhaps attenuates the difficulty to accept apparently incompatible visions of reality.

Source of audacious hypotheses jus a century ago, Quantum mechanics is taught today in most universities, mainly based on the "Copenhagen interpretation".

No better conclusion can be proposed than Einstein's formula : "*the most ununderstandable is that the Universe is understandable*".

REFERENCES

[1]. FLAMM D. "*Ludwig Boltzmann, a pioneer of modern physics*", arXiv:physics/9710007 [physics.hist-ph], (1997)
[2]. HENDRY J. "*The Creation of Quantum Mechanics and the Bohr-Pauli Dialogue*", Reidel Publishing Company, (1984)
[3]. ZITO M. "*Dans le tourbillon des particules*", éd. Belin, (2015)
[4]. SHIMONY A. "*Réflexions sur la philosophie de Bohr, Heisenberg et Schrödinger*" in Journal de Physique, Colloque C2, (1981)
[5]. EINSTEIN A., BORN M. "*Correspondance 1916-1955*", éd. Seuil, (1972)
[6]. FEYNMAN R. "*the Feynman lectures volume III Quantum mechanics*", downloadable on the Internet
[7]. HAWKING S. "*Brief answers to the big questions*", (2018)
[8]. BIPM "*The International System of units - Draft of the 9th S I brochure*", (2019)
[9]. FANTON J.P. "*A brief history of metrology : past, present, and future*", Int. J. Metrol. Qual. Eng. 10, 5 (2019)
[10]. CHARDIN G. "*L'insoutenable gravité de l'univers*", éd. Le Pommier, (2018)
[11]. TILLOY A. "*If gravity was not quantic ?*", in Pour la Science, (2018)

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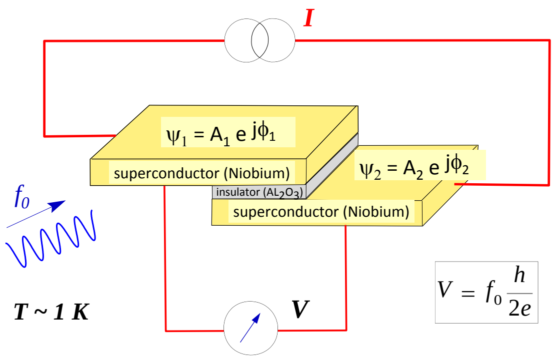
Appendix : a deeper insight into quantum physics applied to electrical metrology

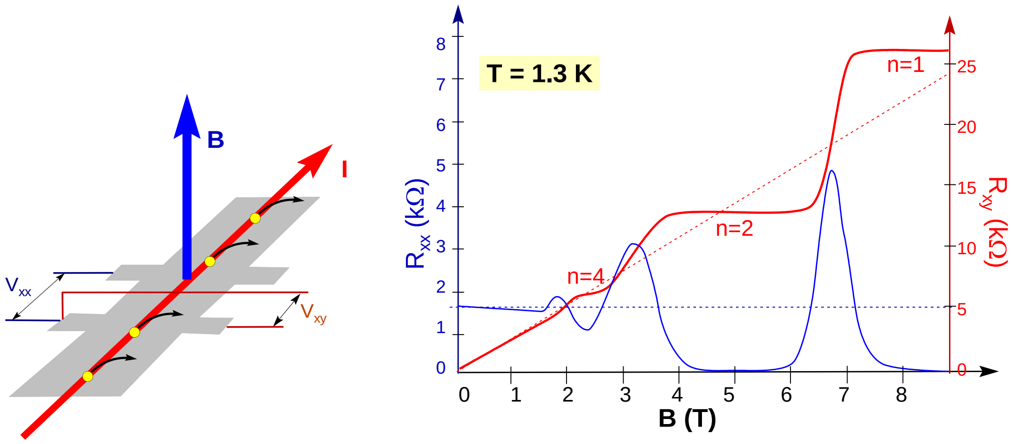
For both scientific and technical activities, electrical metrology needs very accurate references for the two physical parameters voltage and resistance. The associated so-called "derived units" in the International System are the volt V and the ohm Ω, the base electrical parameter being the ampere A.

*1) thus references for the **electrical potential unit**, the volt, can be realised using specific devices : the Josephson junctions (from the name of their inventor Brian JOSEPHSON - around 1960). These devices, placed in adequate physical conditions, i.e. at very low (cryogenic, such as 1 K) temperatures, electrical and electromagnetic conditioning, such as irradiation by an electromagnetic wave at a high frequency f_0, show exceptionally stable and accurate voltage levels, explicitly linked to the reference frequency f_0*
This constitutes the Josephson quantic effect.
The quantity $\Phi_0 = h / 2e$ is the quantum of magnetic flux.
To be usable in practical, Josephson junctions need to be packed in assemblies of numerous junctions, each junction providing only a weak voltage, of the order of 40 µvolt per gigahertz.



Figures 7 and 8 : on left, principle of the measurement of voltage between two electrodes, using the AC Josephson effect
on right : experimental setup at Laboratoire National d'Essais (France) for Comparisons of Currents at Cryogenic temperatures

*2) references for the **electrical resistance unit**, the ohm, can be realised based on the Quantum Hall Effect, also under cryogenic conditions, and under strong magnetic fields. The corresponding quantum effect was discovered by Klaus VON KLITZING around 1990.*
The transverse resistance R_{xy} (or conductance σ_{xy}, which is equivalent) of a given conductor at very low temperatures varies by jumps, and displays a series of extremely stable steps.



$$\sigma_{xy} = \frac{I}{V_{xy}} = n\frac{e^2}{h}$$

<u>Figures 9 and 10 :</u> principle of electrical resistance measurement using the integer Quantum Hall Effect (QHE)

The use of these two techniques, based on quantum mechanics, in electrical metrology allowed to gain several orders of magnitude on the measurements accuracy. They are today currently in use, for instance in National Metrology Institutes throughout the world.