Second Edition

Quantum Physics: An Overview of a Weird World

Volume II

A Guide to the 21st Century Quantum Revolution

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Volume II

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Introduction

This second volume on the conceptual foundations of quantum physics (QP) is a continuation of Vol. I, which was a bottom-up introduction to the basics that, with its historical approach, focused mainly on 20th-century physics. This volume continues the journey, leading us from the 20th century and into the 21st century.

Our attempt to furnish a 'grand vision' of QP will, also this time, also address a non-academic audience that is willing to make an effort to go beyond the conventional low-level popular science portrayals, as well as a certain academic reader who is looking for the conceptual foundations of QP for which a pragmatic educational system nowadays does not allow. Again, we will try to find a middle-ground compromise between a too-sophisticated academic and mathematical approach that tends to obfuscate behind a plethora of mathematical abstract notions the deeper meaning of the concepts and physical significance of the phenomena involved and a too-simplified and naïve representation of the subject that tends to misrepresent reality as it is. The approach we adopted in the first volume was unique in the sense that it closed a void: We were neither interested in dwelling in too much technical rigor nor in telling hyped stories that the popular science outlets are eagerly seeking. We looked for the hard facts, the experiments, the empiric data that present us with reality as it is while, at the same time, we tried not to fall into the temptation to impress the reader with wild speculations. The aim was, first of all, to deliver these facts so that, once fixed, the reader is enabled to distinguish between sound scientific reasoning and pseudo-scientific blither. As far as possible, we will also maintain this approach here.

However, especially with this second part, which focuses on the modern theories of QP and particle physics and which also takes a look at cosmology, it is impossible to not mention the most recent theories of theoretical physics which, to a large extent, are not a confirmed and fixed scientific truth but, quite the contrary, are still in a development phase that could not go far beyond conjectures, hypothesis, and sometimes wild speculations. This makes this volume necessarily different in character from the previous one. Sometimes this goes so far that the question arises of whether some of these intellectual endeavors can still be considered sound scientific practice or, if a border was crossed where it is difficult to distinguish between reality and phantasy or, as Wolfgang Pauli used to say, one is talking about theories that are *'not even wrong'*. In the first volume, it was relatively easy to restrict our attention to the established scientific truths and solid empiric data that, most of the time (with the exception of the Bohr-Einstein debate and perhaps few others), did not involve personal and too-subjective preferences and could be separated by ideological influences. Meanwhile, the new-millennium theoretical physics is, in large part, plagued by uncertainties and ambiguous theoretical exercises for which scientists will almost certainly have to spend several decades determining whether they have any sound foundation. Contrary to the physics of Einstein, Bohr, Schrödinger, Dirac, or Pauli, which nowadays has been systemized into a clear and coherent descriptive frame, modern theoretical physics that goes beyond the standard model (SM) of particle physics is far from being an established science. There is no consensus on several issues and no one can pretend to have definite answers to many open questions because no established 'right' answer has been confirmed by experiments and is generally accepted by scientists in the field. However, because these are nowadays at the center of most of the modern discussions on the foundations of QP and particle physics, we included them as well. It is, therefore, also unavoidable that the author will add his own perspective, which does not always align with the mainstream perspective.

While this second part builds on the basics of the first volume (making frequent reference to it) and assumes that the reader is acquainted with the main concepts of QP, it can nevertheless be read as a self-contained work if the reader already has an understanding of the subject. Also, this time, whenever a more sophisticated proof is required, the interested and more skilled reader will find it in the appendix. Meanwhile, those who would like to skip some of the in-depth analyses given in the appendix won't lose track of the conceptual foundations necessary for further reading.

The level of complexity alternates. Some chapters are a relatively easy read and ask for almost no mathematical background: the chapters on the interpretations of QM, the introduction to the SM of particle physics, Bose-Einstein condensates (BEC), quantum biology (QB), quantum cosmology ant the last chapter which is of a more philosophical character. Other chapters require more effort from the self-teaching student: the modern experiments of quantum optics in the first chapter, the advanced description of the SM in chapter IV (especially sections 4-8) and the principles of quantum information theory. Chapter VI 1-4 on quantum computing can be considered independent from chapter VI 5-9 on classical and quantum information theory. They have been combined into one chapter simply because both parts deal with quantum-informational aspects. This is especially the case for chapter VII, in which each section can be considered independent reading.

However, unlike with the first volume, the advantage of this treatise is that each chapter can be considered self-contained. If readers do not feel comfortable with the somewhat-more-intense formal approach of some parts they can proceed to the next chapter without losing contact with the subject.

Finally, chapter VIII deviates from the mainly technical character of the previous topics towards an exquisitely philosophical discourse. It takes up, again, from the first volume our quest regarding how QP presents reality to us and whether it can become more understandable from the perspective of philosophical idealism. What we call 'quantum idealism' is, first and foremost, supposed to make us aware of how much our perceptions and even scientific thinking is, nevertheless, conditioned by an unaware and naïve realism that we should transcend. This is a more speculative conclusion that the author offers but wants to not be yet another interpretation of QM per se. Eventually, it could be considered an integrative part of an interpretation of QM.

The fact that chapters are set out in a somewhat-enumerative manner and that several chapters are a standalone part is not an editorial choice. It is precisely this that reflects the uncertain state of affairs of modern theoretical physics, which is affected by many different approaches and, to some degree, disconnected research fields. Each of these reflects the nowadays existing disparate lines of investigation which sometimes aim even at contrasting goals and/or alternating attempts to find something that still has to be found.

However, whatever kind of uncertainties reign in science, they can't stop human curiosity and our innate instinct from knowing more. It is a reason to feel it more necessary to inform, first and foremost, an audience of people who consider themselves to be auto-didacts, self-teaching students, and independent thinkers who would like to go further than what they have learned at school or university and who wonder if – and how much – truth stands behind the mass media’s sensational headlines. On the other hand, one of our main aims is also to increase awareness of the subject, which might help some of the self-educating readers avoid the kind of autodidacticism that much too frequently falls into a practice of 'crackpot science'.

Who else is this book for? For physicists who didn't focus on the foundations of QM (that is, the majority of them) but who would like to complement and refresh the knowledge they received from their dry and strictly formal college education. Indeed, most physicists could profit from this book because it elucidates several concepts and foundational and philosophical aspects of quantum theory (QT) that they almost certainly did not receive during their conventional undergraduate or graduate studies. Philosophers of science who are in control of high school math with some preliminaries in calculus and linear algebra and who have already acquired some basics of quantum mechanics (QM) could equally profit from this second volume as self-contained literature. In addition, engineers, IT students, biologists, chemists, or whatever professional category with similar technical preparation can eventually proceed directly to the reading of this work.

However, it is the author's conviction that if readers take the necessary time and are willing to make an effort to, eventually, go through some parts more than once so that the more complex concepts can sink in, they will have an understanding of several aspects of the foundations and philosophical implications of QP that, in most cases, even physicists don't have.

I. Advanced experimental tests of 'quantum ontology'

This chapter will deal with some of the most notorious and odd quantum optics experiments that have been performed in the last few decades and that further investigate the foundations and ontology of QP. These experiments can be considered as the continuation of Wheeler's delayed choice experiment and the interaction-free Mach Zehnder Interferometer (MZI) experiments presented in Vol. I. In principle, they could complement it as a concluding part. However, the higher level of theoretical and formal sophistication makes it more appropriate to present this information in the present volume, which addresses the advanced reader.

Apart from furnishing an overview of modern state-of-the-art quantum optics experiments, the aim of the following chapters is to further highlight the non-local aspect of quantum mechanics (QM), inviting the reader to abandon the naïve standpoint of a differentiating 'which-way' (or 'which-path') particle perspective, still frequently invoked by professional physicists, and to embrace the more holistic non-separable point of view which takes entanglement and state superposition as quantum phenomena that must be regarded seriously, not just as formal expedients. Along the way, we will also demystify the myth of temporal quantum retro-causality, according to which some experiments supposedly prove that the effect can precede the cause. While, indeed, physics does not explicitly disallow the existence of retro-causal effects, we will show that, at least so far, the delayed choice quantum eraser (DCQE) experiments that seem to suggest 'back from the future' actions can be explained without invoking alternative cause-and-effect orders other than the conventional one.

1. The double crystal experiment of Zou, Wang and Mandel

Let us begin with a quantum optics experiment that is somewhat less known to the public but that is still quite mind-boggling. It was performed by a group of physicists from the University of Rochester in 1991. We will call it the Zou, Wang, Mandl (ZWM) experiment. [1] It sets the stage as an introductory experiment which, apart from being interesting per se, will acquaint us with the ambiguities involved in a which-way ontology that imagines individual particles on deterministic paths that are supposed to be localized in space and time.

Fig. 1 shows the experimental setup. The light source is a *'single-photon source' (*or *'one-photon source'*) coming from an argon ultraviolet laser –

that is, only one photon is heading for spontaneous parametric down-conversion (SPDC) during a time interval no shorter, or eventually longer, than the time of flight through the device of the two entangled photons. Therefore, the device always contains only a couple of photons. This source sends a photon to beamsplitter BS_1, which splits it in a superposition state along two paths. One path leads (after a reflection in a mirror) the photon to a nonlinear crystal (NL_1), after which the SPDC transforms it into two entangled photons with half the wavelength of the original one, called the '*signal photon'* and *'idler photon'*, labeled s_1 and i_1, respectively.

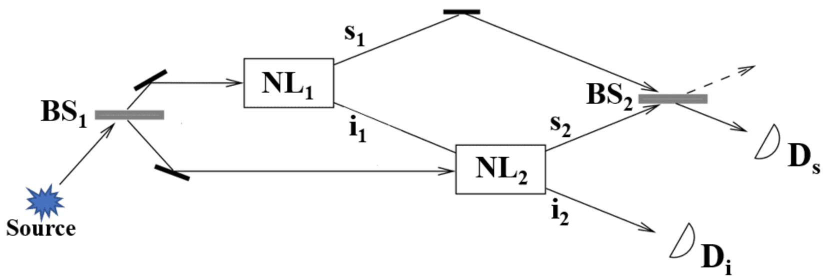


Fig. 1 The experimental setup of the ZWM experiment [1]

Without going into too many details, it may simply be said that by *'nonlinear crystals'*, one indicates a more general class of optical media that can produce entangled photons (one example that we mentioned so far was the beta-barium-borate (BBO) crystals, though there exist several other types of crystals capable of producing entangled photons). They are nonlinear insofar as their physical and optical properties respond non-linearly to the intensity of the electric field of the stimulating light beam.

The other path after BS_1 leads the photon to another nonlinear crystal (NL_2), which transforms it into two entangled signal and idler photons, s_2 and i_2. One of the most important details to fix in our minds is how the idler photon i_1 of the first crystal is sent through the second crystal NL_2. In fact, if a light beam is sent at an appropriate angle, no entangled photons are produced. The crystal behaves only as a transparent medium, just like a piece of glass with low absorption. This allows for interference between the two idler photons i_1 and i_2, which can be measured at the 'idler detector' D_i. Meanwhile, on the upper stage of this optical device, the two signal photons, s_1 and s_2, are led to converge onto the second beamsplitter BS_2, where they will interfere as well. This latter interference can be measured at one side of the beamsplitter by a 'signal-detector' D_s by slightly displacing beamsplitter BS_2 from its position or inclination and changing the relative optical lengths of the two optical paths involved. (This requires very precise mechanical control on the order of less than a micrometer.) A coincidence counter (not their reflections, one can equate $|\nwarrow\rangle = -|\searrow\rangle$ and we can rewrite the vertical polarization as:

$$|\uparrow\rangle = \frac{1}{\sqrt{2}}\,|\nearrow\rangle - \frac{1}{\sqrt{2}}\,|\searrow\rangle.$$

Adopting this alternative representation, one can highlight the anti-symmetric components. Let us use degrees instead of arrows and define the angles relative to the horizontal x-reference axis. Then we can rewrite the two polarization vectors as:

$$|H\rangle = \frac{1}{\sqrt{2}}|45°\rangle + \frac{1}{\sqrt{2}}|-45°\rangle, \quad \textit{Eq. 3}$$

$$|V\rangle = \frac{1}{\sqrt{2}}|45°\rangle - \frac{1}{\sqrt{2}}|-45°\rangle. \quad \textit{Eq. 4}$$

Expressing the same quantum state of the system in the 45° diagonal basis, that is, inserting these into Eq. 2, it 'splits' into the sum of two terms:

$$|\Psi\rangle = \frac{|45°\rangle_{S_1} + |45°\rangle_{S_2}}{2} + \frac{|-45°\rangle_{S_1} - |-45°\rangle_{S_2}}{2} \quad \textit{Eq. 5}$$

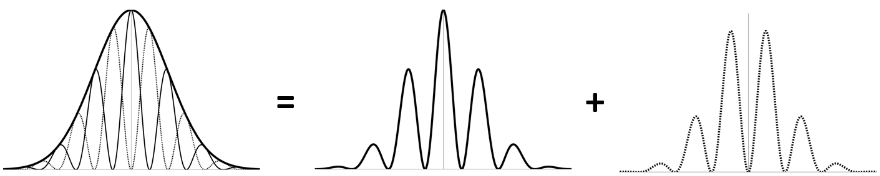


Fig. 11 Graphical representation of Eq. 5.

The first right-hand side term of Eq. *5* represents the symmetric wavefunction while the second one represents the anti-symmetric. We know now the significance of that negative signature of the second term as indicating an anti-symmetric wavefunction (see also Bosons, Fermions, and Pauli's exclusion principle in Vol. I). The $\frac{1}{2}$ coefficients tell us that there is a 25% probability of obtaining one or the other outcome instead of 50%. This is because a diagonal polarizer filtering horizontal or vertical polarized photons will block 50% of them.

What we have done is create a change of the eigenvectors basis from the H/V to the 45°/-45° basis. (There are much more rigorous and formally precise quantum algebraic methods with matrix and group representations by which to do this than what we have tentatively done here, but this should not come as entirely new information; it is, in essence, the same operation we completed in Vol. I in the chapters on spinors or the superposition principle.) One represents the very same quantum state in a different eigenbasis – or, to put it in a more intuitive language, we are 'looking' at the state of the quantum system no longer along the horizontal and vertical

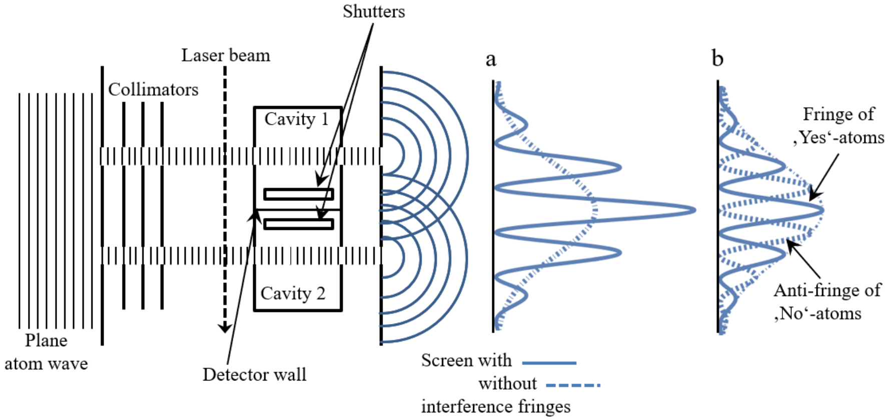


Fig. 13 Experimental setup of the SEW experiment.

Labeling the atom's path-state through cavity 1 and cavity 2 as $|\Psi_1\rangle_a$ and $|\Psi_2\rangle_a$ and labeling the photon being stored in cavity 1 and cavity 2 as $|1{,}0\rangle_\gamma$ and $|0{,}1\rangle_\gamma$, the entangled state between the atom and the cavities is:

$$|\Psi\rangle = \frac{|\Psi_1\rangle_a\,|1{,}0\rangle_\gamma + |\Psi_2\rangle_a\,|0{,}1\rangle_\gamma}{\sqrt{2}}.$$

If we chose to keep the shutters closed, the photon emitted by the atom in whatever cavity is not absrbed by the detector wall, and we can read out whether the atom left its photon in cavity 1 or cavity 2. Because the two cavities are placed in front of each slit, the apparatus with closed shutters is capable of telling us where an atom has gone through, by controlling in which cavity the photon has been stored. Therefore, we can extract information about the atom's which-way, which implies that no interference fringes can appear on the screen. (One again obtains the dashed line in graph (a) of Fig. 13).

If, instead, we chose to open the shutters and let the photon that the atom emitted during its passage in one of the cavities be absorbed by the detector walls, or simply be 'removed', then the 'memory of passage' (the which-way information) could be said to be 'erased'. That is, we have built a quantum eraser.

Consider that in this case (for quantum mechanical reasons too long to be discussed here), for an ideal photon detector having 100% efficiency, the probability that the detector wall will absorb the photon in both cavities is only 50%. (In the remaining cases, the photon remains unchanged and bounces back and forth in the cavity.) Let us label the atoms for the case of open shutters where the photodetector in the micromaser cavity clicked as a 'yes-atom', while those atoms where no photocount is observed in the

4. The delayed quantum erasure experiment of Walborn et al.

About then years later, in 2001, yet another overall combination of a double-slit delayed quantum eraser experiment was performed by a Brazilian group (Walborn et al. [8]). It might be instructive to dwell further on these experiments to overcome doubts about any supposed retro-causality in QP. It can also be considered the photonic replica and continuation of the SEW experiment.

Fig. 14 illustrates how photons from an argon laser (at 351 nm wavelength) are focused by a lens and sent through a BBO crystal to create, via a SPDC, a couple of entangled photons.

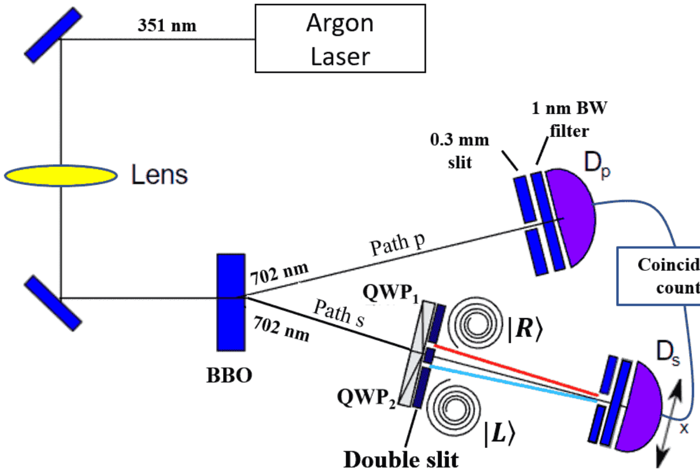


Fig. 14 The which-way experiment with entangled photons: version I.

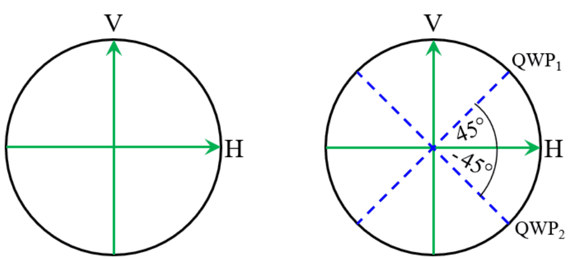


Fig. 15 Polarization diagrams for experiment version I.
Left: for path p. Right: for path s.

Because the total energy must be conserved, the wavelength of the two down-converted photons must be twice as much as the original one (or equivalently, they have half the frequency of the incoming photon, of course, due to Planck's relation between the energy and frequency). Therefore, the slits, quantum entanglement, a delayed choice quantum erasure (well, not really as we will see), and an interaction free which-way measurement. A sketch of the experimental setup is shown in Fig. 22.

An argon pump laser beam (351 nm wavelength, ultraviolet light) shines on a double slit behind which a BBO crystal generates a pair of entangled type-II orthogonally polarized photons (702 nm wavelength each) by SPDC at regions A and B (0.7 mm center separation). As usual, the light beam is a single-photon source. The signal-photon, that which goes through the lens focusing on detector D_0, and the idler-photon that which travels towards the prism. Detector D_0 scans with a step motor along the perpendicular axis of the path of the incoming signal photon (as shown by the arrows at D_0 in Fig. 22) counting each photon cumulatively in order to reconstruct the interference pattern (that is, the fringes or the bell-shaped intensity curves).

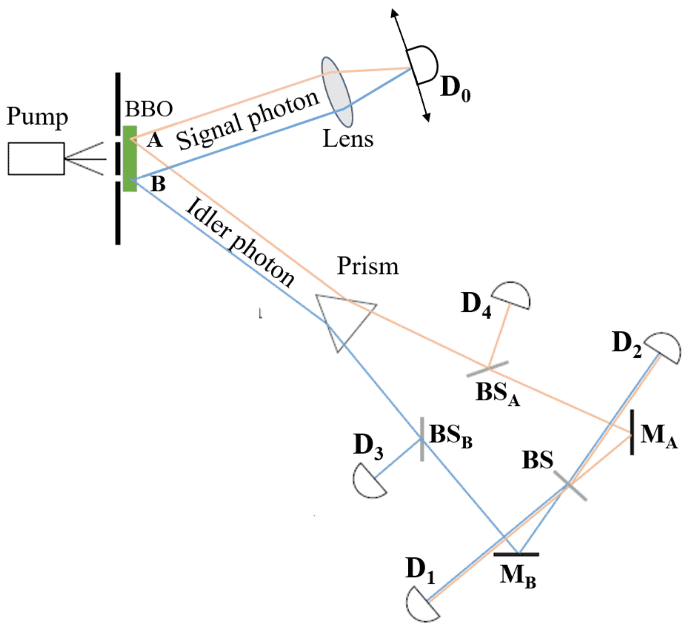


Fig. 22 The delayed choice quantum eraser of Kim et al. [9]

The prism (a *'Glan-Thompson prism'*) has the peculiarity of splitting orthogonally polarized beams. Because regions A and B determine two mutually orthogonal polarizations, the splitting prism sends the idler-photon towards beamsplitter BS_A if it has a horizontal (vertical) polarization or towards beamsplitter BS_B if it has a vertical (horizontal) polarization. Therefore, in the event (50% chance) that this photon, according to its polarization, is deflected towards detectors D_3 or D_4, one can determine the which-path from region A or B, respectively. However, if, instead, it is

II. Interpretations of Quantum Mechanics

You will have realized that while QP is a rigorous and exact science, it has no clear accepted ontology. Formally, everything is consistent but it relies on no particular models of reality. Its power resides precisely in the fact that it is a mathematically complete theory that can predict the outcome of experiments with high precision, successfully describing all the quantum processes of the real world. After all, this is what science is primarily about. Models, interpretations, ontological questions, and philosophical speculations are sometimes added but only as tolerated addenda, not as necessary ingredients of a scientific theory. This quickly led physicists to realize that it is easier to restrict oneself to the calculations and to follow the '*shut up and calculate*' approach without bothering much about the ontological model of the quantum world. And because the mathematics involved in learning and using consistently modern QT takes a huge amount of time, most physicists do not allow themselves to go beyond that.

However, as we have discussed previously, some famous physicists were an exception to this approach. For example, while Einstein wasn't satisfied with mere calculations, he also didn't try to construct a new worldview emerging from the quantum phenomena. Rather, he simply hoped that some form of deterministic local realism could be saved. As you know, this attempt ended in failure and, particularly because it became clear that QM violates Bell's inequalities, today almost no one follows Einstein's path. Most physicists (still) stick to the Copenhagen interpretation of QM, which we already discussed and that, in any case, doesn't appear to be an 'interpretation' at all but, rather, simply a working attitude that discourages speculation beyond the empirical facts and its rigorous formalization. For this reason we have not considered the Copenhagen interpretation here, we already discussed it in Vol. I.

Other physicists, philosophers, and mathematicians have tried hard to build models of reality which are compatible with the current structure of QM. In the following sections, we will take a look at few of these interpretations but the description will necessarily be somewhat superficial and incomplete, as it is impossible to do justice to each of them with only a few pages. Nowadays, one can count about two dozen different interpretations of QM, and it would be impossible to illustrate them all in detail. But precisley this proliferation of interpretations demonstrates the controversial nature of this issue. Additionally, you will by no means find a solution to the quarrel here. How the weird world of QP is to be correctly interpreted remains a widely debated and unresolved question and is still more a matter of personal taste and preference than a real scientific matter. The aim of this chapter is therefore only to give you an intuitive glimpse into a few mainstream interpretations of QP out of many, so that you will be able to proceed further and judge for yourself whether you believe that one or the other theory merits more or less attention.

With that said, at the end of this chapter the author feels authorized to present a somewhat biased concluding remark to clarify why he isn't at all passionate about what are called 'interpretations' of QM. I added this chapter only out of completeness but feel that physics is not going in the right direction by insisting so much on creating such a profusion of diverse interpretations.

1. The de Broglie-Bohm pilot wave interpretation

The '*de Broglie-Bohm interpretation*', also called the '*Bohm pilot-wave theory*' or '*Bohmian mechanics*' (BM), is probably the most notorious and, in a certain sense, most surprising interpretation of QM. It was proposed by L. de Broglie way back in 1927. He presented it at a conference attended by W. Pauli, who pointed out some apparent inconsistencies to which de Broglie could not reply in a satisfying manner. The story goes that de Broglie perceived this as a publicly humiliating experience and soon gave up further attempts to develop the theory. In 1952, however, D. Bohm rediscovered and took up de Broglie's idea, showing how Pauli's objections were unwarranted. An interesting historical anecdote that could be a lesson, especially for young researchers: Never be intimidated by authority!

The key characteristic of this approach to QM is that BM can recover classical determinism, though at the cost of local realism. QM must be at least a non-local theory or a non-deterministic theory or both, as the violation of Bell's inequality and its related theorem clearly tell us. In fact, Bell's theorem does not necessarily give away determinism and hidden variables. A non-local but deterministic theory is still allowed. This is precisely what Bohm strived for, successfully. Bell *"saw the impossible done,"* as he commented, referring to BM, and later embraced the reality model that it suggests.

In BM, one still conceives of classical particles, that is, point-like entities as our intuition suggests, as little pinpointed physical objects (with or without an inner structure) that have a definite actual position following a deterministic trajectory. This aspect makes the approach so appealing to many physicists, who are uneasy about giving up a classical Laplacian hidden variable determinism.

But how can particles exhibit the interference phenomenon that QP so ubiquitously displays? De Broglie's groundbreaking idea was to separate the particles from the wavefunction as two different categories of reality. The former has precise initial conditions (position and velocities in a 3D space, the Universe, which otherwise have no meaning on their own. In relativity, it is already known that time passes by with different speeds for different observers, or that clocks tick faster in space than they do on Earth (as in any gravitational field). Moreover, relativity tells us that notions like simultaneity, speed, and a particle's position in space have no absolute value and meaning. Rather, they must be determined relative to a reference system. Similarly, in RQM, the state of a quantum system can be relative to the observer's state of motion or position or to other physical parameters characterizing it. Two different observers may see a quantum system in opposite states—for example, for one, it is in a superposition state whereas for the other, it is in an eigenstate. The very notion of 'state' becomes a relative notion that depends on the relation between the observed object and the measurement instrument. The wavefunction or state vector describes a correlation between two objects. It makes no sense to speak of a state of one or the other system if not in comparison to each other or to some reference object and quantum state. For example, it is meaningless to state that a physical process—say, the speed of light—is fast. One must always specify a reference process against which it can be measured. RQM is still in its infancy but seems to capture something essential that our subjectivity, based on an instinctive way of perceiving and understanding the world, seems to miss or unconsciously posit as granted.

8. On the proliferation of the interpretations of quantum mechanics

Lots of other interpretations were not mentioned here (such as the consistent histories, ensemble, modal interpretation, QBism, and many others). The author, however, does not feel it instructive to discuss each of them or to dwell further on those that have already been mentioned. So far, I have tried to focus mainly on the facts and experiments and, in this chapter, on laying out the different interpretations of QM, seeking to avoid being too biased by favoring a personal point of view. However, having delivered the basics and main concepts of the foundations of QP, I can finally engage in some gossip.

The simple fact that there is such a proliferation of quantum interpretations, most of which (with few exceptions) have no contact with each other, speaks volumes: There is actually zero consensus among physicists on how to interpret QP at all! Everyone sees something different and, of course, pretends that his/her interpretation or theory is that which best captures the meaning and/or ontology of quantum phenomena. There is

III. The standard model: an introduction

1. Quantum Field Theory

We now have a sufficient background with which to discuss the SM of particle physics and the lines of research that seek to build a unified theory of fundamental forces and that scientists are currently investigating. It builds upon classical mechanics, statistical mechanics, and especially the theory of relativity and QM.

The enhanced version of QM is '*quantum field theory*' (QFT). The bad news is that its description is much too complicated to be summarized in a brief semi-popular science description here. It is covered in books with hundreds of pages that are full of calculations. The good news, however, is that its conceptual foundations are not very different from those of classical QM, which allows us to highlight its basics.

QFT extends the quantum laws of classical QP, which is still a non-relativistic theory, to that of '*special relativity*' (SR). Most importantly, QFT rests entirely on the notion of a '*relativistic quantum field*.'

In non-relativistic QM, the wave-particle duality, together with all the experiments on quantum-ontology that we illustrated in the previous volume and in this volume, made it amply clear how misplaced the concept of a point-particle is. However, so far, one could still stick with the point-particle idea by making calculations without bothering much about philosophical subtleties. In relativistic QM, however, it turns out that even this is no longer allowed. If one insists on the image of the single point-particle moving throughout space and time, nothing really works and one has come to terms with contradictions with the theory of relativity.

For example, trying to extend non-relativistic QM to relativistic QM leads to the violation of unitarity and causality, which means that there is a non-zero probability that a particle can propagate from a position A to a position B faster than light. Moreover, while in classical QM the number of particles is conserved (think of the incoming and outcoming particles in a scattering process, such as the Compton scattering), for high-energy relativistic quantum scattering processes, the number and even type of particles may no longer be conserved. For example, a high-energy collision between an electron and a proton will scatter the electron but transform the proton into many outgoing pion particles. (We will describe and classify the 'exotic' particles as pions, muons, kaons, etc. later.) This is in line with Einstein's mass-energy equivalence, $E=mc^2$. Energy must be conserved but the kinetic energy of the colliding particles can also be transformed into mass. Therefore, the number and type of particles are generally not conserved quantities in QFT.

These differences between QFT and classical QM must be taken into account if one wants to avoid inconsistencies. This forced physicists to give up the classical wavefunction description of particles by replacing it with the 'quantum field' concept.

If one extends the concept of a discreet point-like particle of classical QM to that of a continuous field extended in space and time, everything behaves fine. In QFT, the fundamental entity is not a particle but a field. What we visualize as a particle is the excitation of a field. To each kind of particle one associates just a quantum field which obeys a relativistic wave equation, that is, an extension of the Schrödinger equation to SR. A photon, an electron, or a muon is described by its photon, electron, and muon field, respectively. The photon, electron, or muon is an elementary quantum excitation of the EM field, the electron field, or the muon field. These fields are represented as vibrating ‘ripples’ in some region of space-time. Each ripple is thought of as an ‘excitation’ or a ‘displacement’ from the ground state which varies in time. (As an analogy, in 1D you can think of something like small vibrating strings while, in 2D, you can think of a vibrating membrane and extend this to a 3D space.) The simplest version of a quantum field is the ‘*scalar field*.’ This is a mathematical scalar function which defines, for every space coordinate $x = (x_1, x_2, x_3)$ and for every instant in time t, a scalar function $\phi(x,t)$. It is just a number linked to a coordinate in space at time t. To provide an example with which we are familiar, recall the standing modes in the black body cavity discussed in Vol. I. It can be thought of as a 1D transverse vibration of a string, which can be described by a scalar field $\phi(x,t)$ that measures the displacement of each point from equilibrium, at time t, of a small element of string around a point x.

Similarly, Fig. 34 left provides an example of a 2D scalar field for some instant in time.

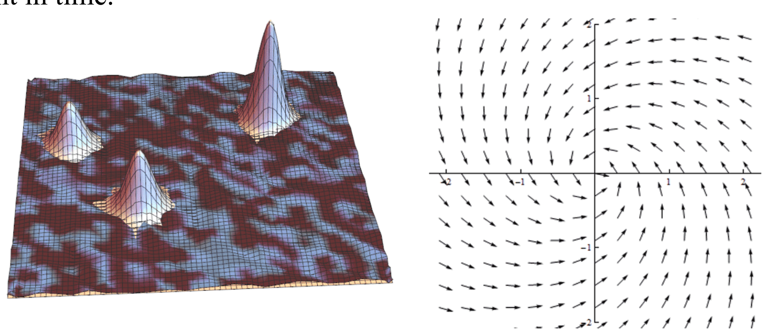


Fig. 34 Left: particles as excitations of a 2D quantum scalar field. Right: a vector field.

energy that fills the empty space of all the cosmos is suggested by the fact that astronomical observations indicate that not only is our Universe expanding but that this expansion is accelerating. Except through the gravitational force, dark matter and dark energy seem to not interact with ordinary matter. Some conjecture about the existence of *'weakly interacting massive particles'* (WIMPs) that make up dark matter—massive particles which, however, are almost undetectable beyond their gravitational observational signature.

Please avoid the frequent misconception of mass being a measure of the 'hardness', 'impenetrability', or 'materiality' of an object. In physics, mass is a measure of inertia–that is, of how difficult it is to accelerate a body. As discussed at length in Vol. I, what causes an object to acquire its macroscopic property of solidity is not its mass but, rather, the microscopic interaction via one or more fundamental forces with other particles. Dark matter might be made of very massive particles and nevertheless traverse entire planets and stars undisturbed, as neutrinos do.

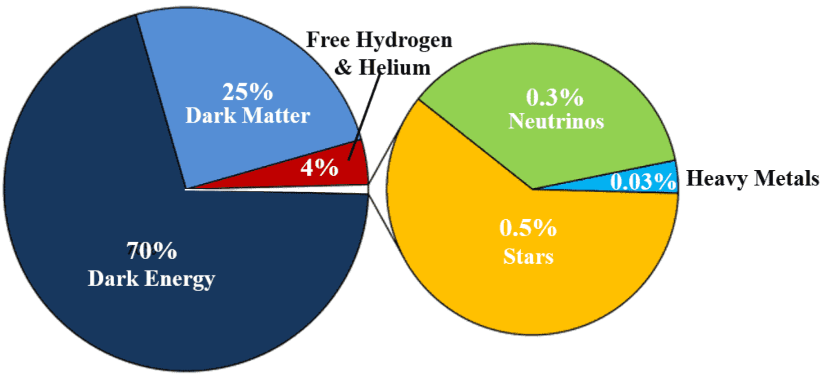


Fig. 41 The relative amount and types of matter in the Universe.

The relative amount of dark energy, dark matter, and visible matter makes the problem clear: The contribution to the mass of the Universe is taken up by the dark energy by more than two-thirds. Then 25% is dark matter, while only about 5% is matter predicted by the SM (and of which only a meager 0.5% is matter in the form of stars and planets).

This can only mean one thing: What we see is only a little scratch on the surface of a Universe which has almost certainly a much more profound and richer structure and content than our limited senses can see, inclusive of our most sophisticated detection instruments, like telescopes, microscopes, or particle accelerators. All of this, put together, clearly tells us that the SM cannot be the whole story.

This was, of course, only a very sketchy outline of the SM. However, it should give you an idea of what we know today about the basic stuff of

IV. More on the standard model: Symmetries, forces, and fields.

1. Symmetries and invariances

In physics, the notions of *'invariance'* and *'symmetry transformation'* play an important role. The two terms are intimately related (and frequently used as synonyms). In general, by invariance (not to be confused with 'covariance', which is a closely related but quite different property of physical laws in relativity), one means the persistence of some physical quantities or features amidst a transformation or change that is described by a symmetry operation. More abstractly (and philosophically), one can also state that symmetries and invariant properties of things are measures of 'objectivity'. If something does not depend on a point of perspective, it is taken to be the 'real' and 'objective' property of things 'out there', independent from our human perceptions. Symmetry transformations change the appearance and perspective without resulting in a real objective change.

Some examples are the following. The simplest case is the rotation of a circle or sphere around an axis that goes through its center; the circle or sphere remains the same (provided that one does not distinguish the points on the circle line or the points on the sphere's surface). This means that the circle or sphere is rotationally invariant under a rotation symmetry transformation. A square rotated by 90° returns to become the same figure, which means that a square is rotationally invariant after a 90° symmetry transformation. Generalizing a bit, one should mention the example of space symmetry as the translation and rotation: If you translate in space and/or rotate an object (say, moving a cube along a straight line and then rotating it by 45°), you won't see the same cube from the same perspective. Something has changed (the visual perspective) but the object itself (the cube) is the very same thing, with the same form, side length, volume, etc. The translation and rotation represent a symmetry transformation, while the invariant quantities are the cube's sides, its volume, and, more generally, its form.

A more specific example related to physics and mathematics is the translation and rotation of a vector without changing its modulus—that is, its length. For example, one can change a particle’s position and direction of motion without changing its speed. This amounts to saying that one shifts and rotates a velocity vector in a coordinate system without changing its length. (Intuitively, simply visualize the displacement and rotation of an arrow.) The rotation is a symmetry transformation acting on a vector, while the invariant quantity is its preserved length.

One can also think of time-translational symmetries. An example is that of an object being invariant in time: It is the same and in the same place today and tomorrow.

These examples might sound a bit trivial but, according to a fundamental theorem called *'Noether's theorem'* (first formulated by the German mathematician Emmy Noether in 1918), it turns out that translational, rotational, and time symmetry lead to the most fundamental principles of Nature—namely, the conservation laws of linear momentum, angular momentum, and energy, respectively. This made it clear that there must be a deep connection between the concept of symmetry and the laws of physics.

These were examples of a *'continuous symmetry transformation'*; however, discontinuous or *'discrete symmetry transformations'* exist. A typical example of a discrete symmetry is the *'reflection symmetry'* (also called *'mirror-', 'radial-',* or *'bilateral symmetry'*): the flipping of a figure along one of its symmetry axes that does not change the figure itself. That Nature has some predilection for symmetries was already clear to Leonardo da Vinci (see the 'Vitruvian man' in Fig. 42 left). Our bodies, as do those of most complex living organisms, have a bilateral symmetry along the vertical head-to-feet axis. Beautiful reflection and rotation symmetries can be observed in snowflakes. Fig. 42 right shows a snowflake that is invariant if its left-right sides are flipped or if it rotates 60° around the perpendicular axis going through its center (a six-fold rotational symmetry).

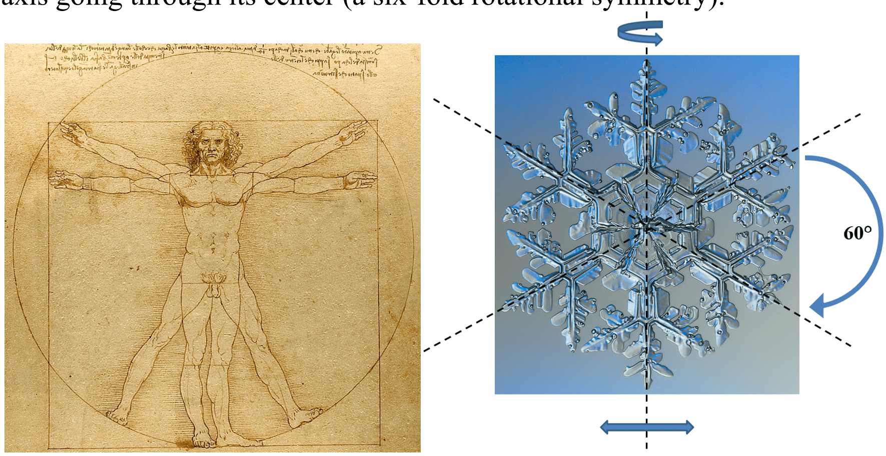


Fig. 42 Left: Leonardo's 'Vitruvian man' showing the human body's reflection symmetry. Right: A snowflake with reflection and rotation symmetry.

Many other examples from Nature can come to our minds, such as sunflowers, the hexagonal honeycombs, the butterfly's wings, etc. There seems to be a deep connection between symmetry and Nature's artwork. Physics showed that symmetries also connect to Nature's laws. To see this, can be related to particles, consider the rotations and reflection transformation of Fig. 44. An equilateral triangle has three different 'particles' attached at its vertices, labeled with a full circle, an empty circle, and a crossed circle, respectively. A 120°, 240°, or 360° rotation of the triangle (the diagrams of the left column in Fig. 44) would leave its shape and orientation invariant. This would also be a symmetry transformation if we do not consider its vertices being labeled by distinguishable particles.

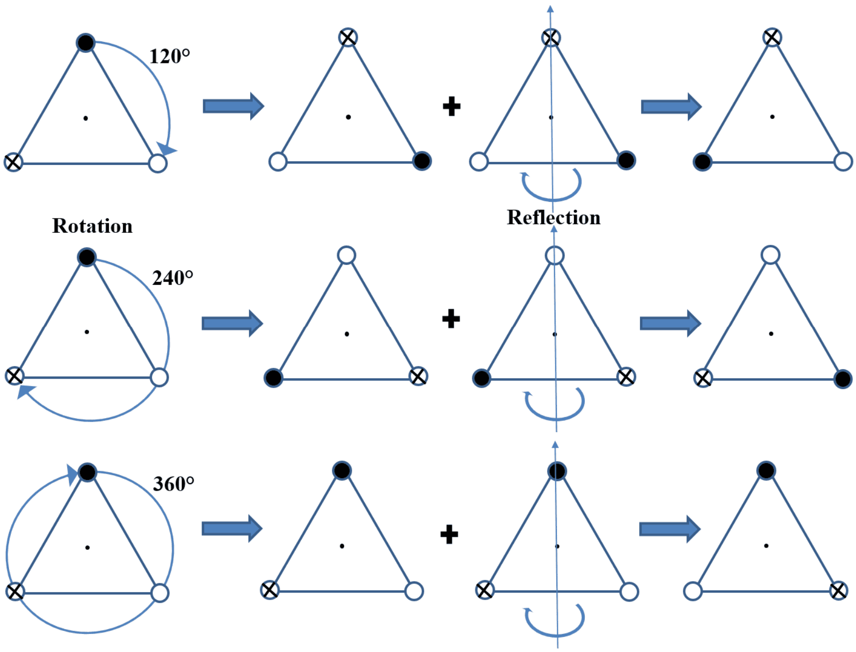


Fig. 44 Rotation plus reflections of an equilateral triangle.

However, when the vertices are distinguished, only the 360° rotation is a symmetry transformation. In the 120° and 240° rotations, the orientation of the triangle 'breaks' the invariance and the three 'vertices-particles' find themselves displaced from their original 'state' (the first two diagrams of the second column in Fig. 44). If, to these rotations, we add a reflection along the central vertical axis of this equilateral triangle (third-column diagrams of Fig. 44), the particles and their vertices will end up, in all three cases, in a different state from the initial one, though a 'global invariance' will persist—namely, the shape of the triangles will remain preserved. This toy model should help us understand the symmetries holding in particle physics. In particular, the weak nuclear force can be seen as a force that changes the particles from one to another without changing the overall structure of the theory.

However, scattering experiments in particle accelerators later revealed how these particles are not elementary and must have a sub-particle structure. They must be composed of other particles: The quarks. The SU(3) symmetry governs the quarks and, therefore, the particles composed by it. This insight ignited an enormous theoretical work in group theory applied to particle physics that finally, in 1964, led Murray Gell-Mann to propose an organizational scheme that was based on the SU(3) symmetry groups and that explained the inner structure of all the hadron particles with the quark model. He called it the *'eightfold way'*.

The SU(3) symmetry group relates by an abstract symmetry transformation acting on the quarks and relating one particle to another in a diagram reminiscent of the Dharma wheel of the Buddhist Noble Eightfold Path. As we pointed out in section III 2, the particles composed of quarks—the hadrons—appear in only two classes. First are the baryons, which are composed of three quarks and which are to be distinguished by a 1/2-spin (and of which the proton and neutron are part) or 3/2-spin class (which means that they are both fermion classes), as shown in Fig. 49.

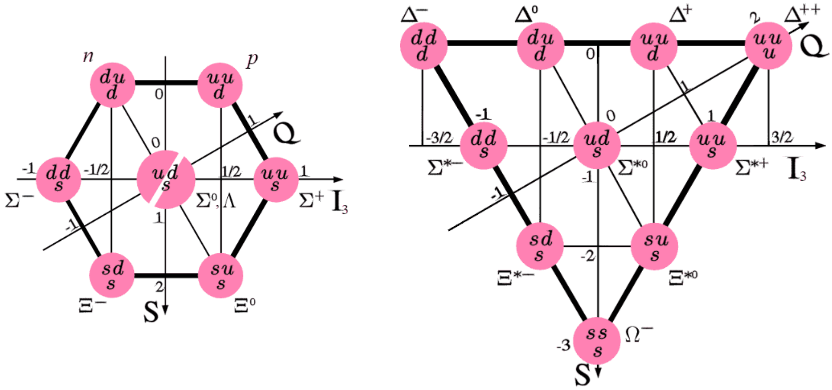


Fig. 49 The baryons (three-quark structure) 1/2- and 3/2-spin family.

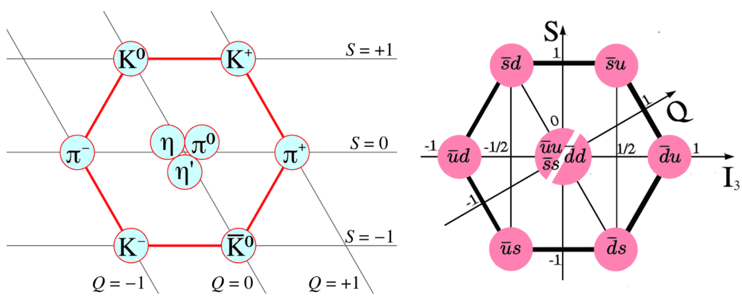


Fig. 50 Mesons (two-quark structure).
Left: Particles' symbol. Right: Internal quark structure.

blue quark as identical because they share the same properties of mass, charge, and spin, except for their color. Fig. 52 shows three equivalent configurations of the neutron (composed of two down and one up quark) by the quark's color exchange.

Inside hadrons, the quarks' color changes continuously due to the gluons' interaction. Gluons change the color of the quarks (but not its flavor—something that the EW force does, as we will see in the next section).

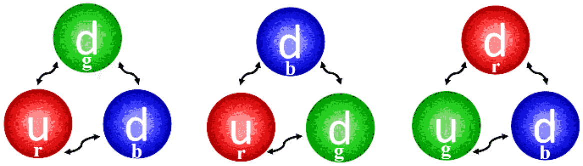


Fig. 52 The neutron: The same flavor quarks change color due to gluon exchange.

One must imagine the strong forces interacting among the quarks inside a neutron (or proton or any other baryon or meson) as an intense gluon field—that is, as a strong force foam that permanently modifies the internal color-state of the quarks (something also called *'quark-gluon plasma'*), even though it does not change the particle's state when seen from a wide field perspective. (Note that in all cases, the overall red-green-blue color combination remains neutral or 'colorless' or a 'white color state'.)

The takeaway message is that imposing a $SU(3)_C$ local gauge invariance on the Dirac Lagrangian leads automatically to the requirement of the existence of the strong nuclear force, described by eight (self-interacting) gluon force fields interacting with fermions, the quarks, and having three color charges. The power of this theoretical approach is that one does not impose but obtains these new fields, once we demand for the SU(3) symmetry to hold.

8. The $SU(2)_L \otimes U(1)_Y$ group of the electroweak unification

The question that remains is: What about the weak nuclear forces? We know that these exist because we know that nuclear decays occur. For example, we know that neutrons in the nuclei decay into protons by emission of an electron, a gamma-ray plus a neutrino (the *'beta-decay'*). Where does the nuclear force responsible for the conversion of a neutron into a proton fit into this picture of symmetries? The EM force mediator particle, the photon, does not change an electron in something else, while a strong interaction force mediator, the gluon, doesn't change the quark's fermions. However, the weak force, besides being responsible for the interaction between quarks and leptons, has the peculiarity of transforming these particles into each other. It

Early Universe electroweak unified forces.

$SU(2)_L \otimes U(1)_y$

Symmetry breaking ↓ shortly after the Big Bang.

$U(1)_y$ $SU(2)_L$

$$A = B\cos(\theta_w) + W_3 \sin(\theta_w) ;$$
$$Z^0 = -B\sin(\theta_w) + W_3\cos(\theta_w) ; \quad \textit{Eq. 32}$$
$$W^{\pm} = \frac{1}{\sqrt{2}}(W_1 \mp iW_2) ;$$

Therefore, what we call 'light' is a gauge field boson that originates from the EW unified theory that preexisted in the first instants shortly after the Big bang in a Universe that was quickly cooling down but, due to a break in symmetry, nowadays manifests itself as a gauge field that is a combination of the W and B gauge fields. This is, finally, the modern description of the EM and weak forces according to the SM of particle physics, also called the *'Weinberg-Salam theory'*.

Returning to Table 2, as mentioned before, the W_i bosons transform the doublets into each other. Because, in this transformation, a negatively charged particle becomes a neutral one, or vice versa, the EW bosons must add or subtract a charge e and, for this reason, are labeled W^+ or W^-, respectively. There must be three such EW bosons, so it follows that there must also be the neutral one—that is, the boson that interacts with all the fermions but without changing the charge, namely, the W^0 EW gauge boson.

Therefore, the weak interaction bosons W_a transform the quarks' flavor. When this occurs for the quark doublets, it leads to the decay of the nuclei. For example, note that the stable atoms of all the Universe are built by the $\binom{u}{d}_L$ quark flavor, as protons and neutrons are built up only by up and down quarks (the protons by two up and one down, the neutron by two down and one up). The weak interaction can transform the up quarks into the down quarks (or vice versa) and transform a proton into a neutron (or a neutron into a proton). This is the main mechanism responsible for the nuclear decay (together with the quantum tunneling effect, as discussed in Vol. I) and it is what physicists mean when they say that the weak nuclear force is responsible for radioactive decay.

The role of the Z^0 boson is not to transmute leptons or quarks; rather, it is responsible for their mutual interaction—that is, scattering. It transfers matter. Obviously, something went terribly wrong. One must conclude that either the theory is simply wrong or something is still missing.

9. The Higgs mechanism and the Higgs boson

This discrepancy between what the EW theory in the above form predicted and the existence of massive bosons led many physicists to believe that the huge and complicated mathematical maze that developed into the SM theory could not be consistent with observations. At about the end of the 1950s and the beginning of the 1960s, the picture arising from the EW theory seemed to be doomed to failure. Until 1964, when Peter Higgs, François Englert, and others came along and saved the entire project from collapsing by pointing out how a symmetry-breaking mechanism of the quantum vacuum state occurring during the Big Bang phase transition could explain how massless particles can acquire mass. This mechanism is nowadays known as the '*Higgs symmetry breaking mechanism'* and is related to the famous Higgs boson.

Their starting point was to consider the vacuum state zero-point energy in the Universe (recall the chapter on the zero-point energy in Vol. I), as it could be in its extremely super-hot state after the first instants of the Big Bang. The quantum vacuum of a particle-less and spin-less quantum field permeating the entire Universe must be described by a complex scalar field ϕ. Therefore, from Eq. 20 we get the simplest massless scalar field Lagrangian density representing a generic vacuum state as:

$$\mathcal{L}(\phi, \partial\phi) = T(\partial\phi) - V(\phi). \quad \textit{Eq. 33}$$

In this context, the Lagrangian no longer describes the dynamics of a particle subjected to a force field but $T(\partial\phi)$ represents a function of the field's time derivative (something that, so to speak, tells us how fast the quantum field fluctuates) while $V(\phi)$ represents the field's ground state quantum potential. The zero-point energy, the ground state of the vacuum we live in (technically speaking, its vacuum expectation value), is the same throughout the Universe but it was not the same in the extreme physical conditions immediately following the Big Bang.

The different magnitudes of the field ϕ in the potential function $V(\phi)$ represent different hypothetical vacuum states at which we can only guess, as there is no known theory at this stage that fixes its precise value. Let us guess and fix the potential as:

$$V(\phi) = -\mu^2\phi^2 = |\mu|^2\phi^2\,, \quad \textit{Eq. 34}$$

where μ is an imaginary parameter. (Its square is negative → $-\mu^2 = |\mu|^2\ is\ positive$.)

V. The long road towards unification

1. In search of quantum gravity

The problem that mid-20th-century physicists had to tackle was the simple fact that we now have two theories which work perfectly and have been experimentally verified several times: the theory of relativity (special and general) and QM. Today, there is no doubt that both theories are correct, at least in their essential parts. They have been confirmed experimentally and are perfectly consistent mathematically. Still, Einstein's relativity and QM are completely different descriptions of reality and present themselves as two complementary understandings. Relativity is a perfectly deterministic theory and, when probabilities are used, it is so only because of our ignorance. In principle, everything can be explained by classical statistical reasoning based on hidden variables. Relativity is a deterministic theory in which point-like particles have definite properties which move on a smooth space-time manifold with perfectly defined trajectories and states, and every correlation and interaction is represented inside the precepts of local realism, that is, the speed of light is a universal and omnipresent limit, a sort of 'dogma' of Mother Nature. On the other hand, QM is intrinsically statistical and a non-local theory (eventually without hidden variables). It does not allow for precise and definite properties; particles behave as waves, have non-local correlations, and can even be in a superposition of states.

And yet, despite being seemingly mutually exclusive, both approaches to physical reality work, are perfectly consistent, and have been experimentally verified with high accuracy. It was assumed that sooner or later one would win out over the other, and physicists are still speculating about which of the two theories should be considered more fundamental.

Will GR prevail, confirming our more intuitive understanding of the world in which objects have well-defined properties with an 'element of reality' which is independent of the fact of whether or not we are observing it, as Einstein would have opted for? Or will QM prove itself to be more 'fundamental' (whatever that might mean) and finally tell us that everything is indeterminate, inherently statistical, and non-local and that reality is contextual?

To date, nobody knows the correct answer for sure, but it might well turn out that neither the former nor the latter is more fundamental. Nature seems to think otherwise. It does not care about our limited understanding which wants to divide up things according to an idea such that one thing or the other thing must be completely true or completely false. It wants us to accept the fact that both things are true at the same time.

On the other hand, if Alice obtains the Bell-state $|\Phi^-\rangle_{AC}$, then Bob knows that he must perform a little operation on his particle, namely, a *'unitary transformation'* which preserves the length of its state vector but changes its phase (we labelled that with the letter U in Bob's box) whereby he must change the sign on the beta coefficient (recall the definition of the unitary operator from Vol. I, chapter on the state vector and Schrödinger equation).

In the third case, if Alice obtains the Bell-state $|\Psi^+\rangle_{AC}$, Bob must perform a unitary transformation whereby the order of the two coefficients, alpha and beta, associated with the states 0 and 1 must be inverted.

Finally, if Alice obtains the Bell-state $|\Psi^-\rangle_{AC}$, Bob will have to invert the coefficients as in the previous operation but must assign a negative signature to alpha.

With this, the quantum teleportation process is complete.

Confused? To clarify some aspects and put things in their proper context, let us note two things.

First, to learn what he must do, Bob has to wait for Alice's call through a classical communication channel. Therefore, it is impossible to realize complete teleportation at a speed faster than light. Bob must still wait until Alice’s message arrives on a line which can, at best, transmit information at the speed of light but not faster, according to the theory of relativity.

Secondly, and most importantly, the question is: What has really been teleported? What happened is that the quantum state of a particle (in our case, particle C) has been copied exactly to the quantum state of another particle (to Bob’s particle B). It is simply an exact information scan, the information which makes up the physical object, that has been teleported, and not the physical object itself. Moreover, this implies the destruction of the quantum state of particle C. It is not a real ‘copy’ because the original quantum state of particle C has been destroyed, as particle C is now entangled with particle A. In fact, there exists a so-called ‘*no-cloning theorem*’ in quantum information technology that forbids the real copying of quantum states from one to another or many particles, maintaining intact the original state. There is no contradiction with the present laws of QM if we recall that this is a ‘copy and destroy’ operation at the same time. Only one particle is left with the original quantum state. So, it must be emphasized that, first, there is no real teleportation of matter but only of the quantum state of one particle to another. Secondly, the original particle's quantum state, which is copied light-years away, will have changed completely.

On the other hand, if you have read up to this point of the book, you should realize that, in QP, the distinction between a particle and the information about its properties and physical state is not entirely clear. To teleport the quantum state of a particle could be considered the teleportation of the particle itself. It is not so clear if we can really distinguish between a material particle and the quantum states that describes that particle. In fact, recall that when two particles are entangled, this means that both particles are with Alice AND Bob at the same time. The entangled duo of particles forms a unique and indistinguishable whole, before measurement. So, when two particles are entangled, where is the matter, the material aspect of the particles? According to QM, we must consider matter at the same time in both places, or even spanned all over space without distinction and real spatial separation, before measurement. At the root of all this is the principle of indistinguishability which is, as we outlined in the section on indistinguishability, much more profound and subtle than the classical conception of indistinguishability. Only at the instant when teleportation occurs (Alice's BSM) does the state vector collapse and we nicely have, again, two particles in two places: matter in two distinct places. So, it is not entirely clear if we are allowed to talk about the teleportation of mere information or if we should consider it, de facto, also a real teleportation of matter itself. The interpretation is up to you.

Of course, this is not mere speculation. Otherwise, we would not mention it here. This kind of quantum teleportation has been realized experimentally with photons. It has been shown how the teleportation of photons could be realized over a distance of 143 km in the Canary Islands. [21] A group of Austrian physicists, under the direction of (the already mentioned) Anton Zeilinger of the University of Vienna, used a laser beam attached to the telescope of an astronomical observatory on one island, which transmitted the photons and signals to another island. But, in principle, QM does allow any distance and any kind of particle quantum teleportation. The important point is that it has been shown that quantum teleportation is not just a sci-fi phantasy but, rather, an established experimental fact.

If we would extrapolate this to a quantum teleportation to larger bodies (say, a human body), this implies that an entire organism would be destroyed completely and rearranged and reconstructed particle by particle for each quantum state elsewhere. The original body, however, would probably have to die and dissolve. Personally, I would not like to undergo this kind of teleportation or 'beaming' process a la Star Trek. And this raises metaphysical questions. Is the teleported body still me? Is the soul, if it exists at all, teleported too? Would that 'I' that makes me feel 'me' be teleported as well?

Obviously, I have no answer and gladly leave these questions to you!

2. Quantum computing

A couple of decades ago, the aim to build *quantum computers* (QC) opened a new and exciting field of research. Quantum computing is based on the idea of using quantum mechanical principles to build a completely new type of computer.

With 'classical computers', one means just those computers that still every one of us uses daily and which are machines that operate on a set of stored strings in form of 'ones' and zeroes', commonly known as 'bits'. These work with registers. A digital register made up of two classical bits can store four digital numbers, namely (0,0), (0,1), (1,0), and (1,1), which we humans can simply label as 0, 1, 2, and 3. If the register is composed of three bits, it can attain eight states—(0,0,0), (0,0,1), (0,1,0), (0,1,1), (1,0,0), (1,0,1), (1,1,0), and (1,1,1)—and could represent the numbers from zero to seven or any other set of symbols (such as letters, punctuations, operators, etc.). In general, a register with n bits can attain 2^n possible distinguishable states. By 'distinguishable', we mean that the register can store one of these states/symbols at a time but not all of them at the same time. Seems obvious, doesn't it?

It was Richard Feynman who, in 1982, first recognized that quantum mechanical phenomena can, in principle, be applied to the building of special kinds of computers capable of performing calculations that classical computers can't, namely, by considering that in QM, bits could also be in a superposition state.

We have already encountered the quantum bit, the qubit, in the chapter on quantum teleportation. It can be practically realized in many ways; for example, with photon polarization, the spins of particles or a nucleus, the two energy states of an atom such as a trapped ion or whatever kind of quantum system can attain only two states (up-down, V/H polarization, on-off, etc.). And we also know very well that, if properly prepared, a single quantum particle (a single qubit) can be in a superposition of states. This implies that a single qubit can be in state 0 and 1 at the same time or, more generally, a quantum register of n entangled particles in superposition forms an overall 'coherent' quantum state that can attain 2^n classical states at the same time.

This makes a quantum register an interesting device because, in contrast to the classical register, it can store all the possible states at once. Of course, once the register is read out, which means we perform a measurement of the qubits, the system 'de-coheres' due to state collapse and displays only one of the possible states, just like its classical counterparts. One might then question: What's the point of having a device that stores many states at the same time if, at the end of the line, we are allowed to read out only one? The trick is to induce interference between the qubits and get a result by coupling another qubit that doesn't take part in the calculation, with the function of the latter being to be read out by collapsing its quantum state but without interacting directly with the quantum register itself. To make this clear, let us proceed step by step.

Building blocks of classical computers are made of logic gates, and QC is no exception. Of course, *quantum logic gates* (QLG) differ from classical ones insofar as they can eventually have bit entries in superpositions and that can be entangled with other gates as well. In very general terms, a QLG is a '*black box*' or '*oracle*'—that is, a device whose internal structure we do not necessarily know, though do know how it acts on N input qubits giving an output according to some logical rules. An important aspect is that QLG must be unitary operators, which means reversible. Given a generic QLG labeled U, its reversibility is formally expressed by $|U|^2 = U{\cdot}U^* = I$ (just as we used to do with the modulus squared of the wavefunction) and which, loosely speaking, means that when applied twice, it outputs the input signal—that is, it works like the identity operator.

For example, one of the simplest gates is the '*negation operator'*, or '*NOT gate'*, which acts like shown in Fig. 64: It inverts the input signal.

Of course, applying it twice will send the quantum states of the qubits $|0\rangle$ and $|1\rangle$ into themselves.

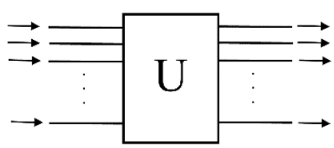


Fig. 63 Every QLG acts like a unitary operator on its input qubits.

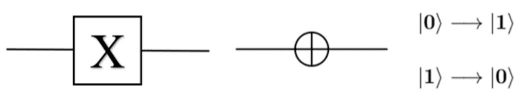


Fig. 64 The quantum NOT gate, its symbols and how it inverts the input.

One of the most genuine quantum gates, which has no classical analogue, is the Hadamard gate. It maps the single qubit basis state into the superposition state vector, as shown in Fig. 65. The *'Hadamard gate'* is responsible for the most fundamental quantum computation: It sets the eigenstates of the qubit into quantum superposition, as shown in Fig. 65.

the concept of randomness logically circular. This has philosophical implications that we will take up in a separate treatise on science, consciousness, and reality.

So far, we have applied information theory to classical systems of Newtonian mechanics. It is time to see how it can also be applied to QP and how that led to profound insights and the fast-developing field of research that is quantum information theory.

6. Quantum information theory

So, what does information theory have to do with QP? To fix the ideas, consider that, if a coin is balanced, the probability of heads or tails showing up is obviously 50%. Shannon information entropy is then:

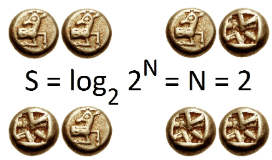


Fig. 77 Two coins have two bits entropy, or two bits storage capacity.

$$S = -\left(\frac{1}{2}\, log_2 \frac{1}{2} + \frac{1}{2}\, log_2 \frac{1}{2}\right) = 1 \text{ bit.}$$

Which states the obvious fact that the system we call 'a coin' can store one bit or, equivalently, it can attain two distinguishable physical states (as $S = log_2 W$, here this implies $W = 2^1 = 2$). Similarly, tossing a two-coin system (N=2) must have two-bit entropy or two-bit storage capacity because it can be in four possible states (heads-heads, heads-tails, tails-heads, or tails-tails), that is, $W = 4 = 2^2 \rightarrow S = 2$.

Let us now compare this with a quantum particle with two spin states. Consider it first prepared in an eigenstate – that is, in a definite state. Recall that once a particle that has been prepared is in its eigenstate, it will show up with the same measured value for every measurement – that is, with the same eigenvalue. Say an electron prepared in eigenstate always shows up with certainty in an up-spin ($|\Psi\rangle = |+\rangle, p = 1$) and this is independent of the number of measurements we will make. How many states can such an electron be in? Only one, as it has been prepared to be in that – and only that – state. What is its associated information entropy? Zero, because if $W = 1$, then $S = log_2 1 = 0$. In other words, it has no entropy and no information content (we have no 'ignorance') because there is no 'surprise'. The state of such particles is already known in advance and is always the same. So far, so good.

Now, consider one electron in a spin superposition state, which, as we know all too well, is described by the single state vector (omitting the axis labels) as $|\Psi\rangle = \frac{|+\rangle \pm |-\rangle}{\sqrt{2}}$. The question, again, is: How many states are these? We know that, according to QP, superposition states must be interpreted with a logical AND of being in both eigenstates at the same time. Moreover, It is, therefore, fair to say that a BH is nevertheless an eternal object. However, the evaporation time of a BH with a mass of the order of 10^{11}kg (that is, about the mass of a tiny asteroid) would be about the time corresponding to the age of the Universe (ca. 13.7×10^9 years). This led astrophysicists to speculate that, if such small BHs were formed during the first instants of the Big Bang, we should nowadays detect the footprint-signal of so-called *'primordial black holes'* in its last quantum evaporation phase. So far, no such evidence has been found. This might sound like a falsification of Hawking's theory. However, a possible alternative explanation for the lack of such evidence is that, likely, these BHs did not form during the Big Bang in the first place. However, if, for example, someone smashes two protons against each other with sufficient energy, it is conceivable that they will form a microscopic BH which will evaporate almost instantaneously. This is also what powerful accelerators probably do continuously. There has been some concern, and a wide portrayal by the media, that the LHC could produce a BH that might swallow the entire Earth in a catastrophic doomsday scenario. However, this can't be the case for at least two good reasons. First, the evaporation time of a two-proton mass BH is so small (about $10^{-100}s$!) that it has no time to encounter any particle and do anything; it can't go anywhere. Secondly, much less theoretical but very empiric evidence shows that, above our heads, the atmosphere is permanently bombarded by cosmic rays containing particles that are hundreds of millions of times more energetic than what the LHC can produce. And yet, we are still here! So, there is nothing to fear.

9. The black hole information paradox and the holographic principle

Hawking radiation is interesting in many other respects. One of the things Hawking soon realized is that there must be something fundamentally flawed with our understanding of quantum and/or relativistic phenomena.

Let us focus again on the physical process occurring at the boundary of the EH. According to Hawking's model, here we have virtual entangled particles which are converted near the EH of a BH into real non-entangled particles. Recall what we concluded in section VI 7 about unitarity. A pure state can never spontaneously become a mixed state, as this would violate the time evolution unitarity. If there is no one or nothing that measures and interacts with a pair of entangled particles, QM tells us that these must be described by a single wavefunction which can't collapse entirely on its own to a mixed state of two particles described by the density matrix. Unfortunately, however, this is precisely what, according to our *boundary'*). Unfortunately, in the frame of this holographic principle, the 2+1 dimensional physical reality does not at all contain the force of gravity! Interestingly, however, a couple of years later, the Argentine physicist Juan Maldacena was able to show how this is in line with ST. Under particular conditions, gravity emerges as a lower-dimensional description of a higher-dimensional theory.

Fig. 84 Gerard 't Hooft, Leonard Susskind and Juan Maldacena.

How this could be is a too-long and too-complicated story that would need a separate treatise to be elucidated in the context of ST and QFT. It may, however, be said that a *'duality'* exists between an ST 'living' in a so-called *'anti-de Sitter space'* (AdS) and the conformal field theories (CFT), which describe the known QFT by a scale invariance approach. (The physics of the theory remain invariant at all length scales.) An AdS represents a non-Euclidean Universe in line with GR but with a negatively curved space-time – that is, a decelerating expansion. (Our Universe possesses a positive curvature due to the increasing expanding rate induced by dark energy.)

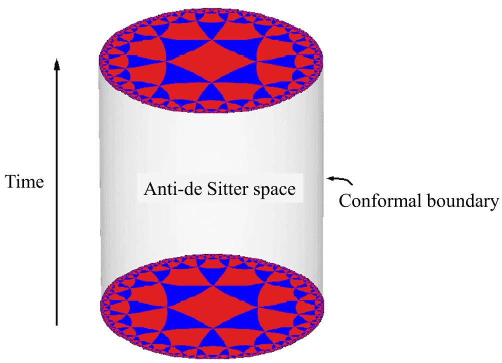


Fig. 85 The 3D AdS space-time looks like a solid cylinder.

Non-Euclidian means that, on the extreme cosmological scales, our classical Euclidian notions of distance no longer hold and must be modified to a hyperbolic space geometry where, for example, triangles and squares look like distorted and stretched objects as in Fig. 85 and with the cylindrical outer conformal boundary infinitely far from any point in the interior. Each fermions nevertheless must pile up in spin-up and spin-down pairs on each energy level (called the *'Fermi energy'* levels E_f) forming a *'Fermi sea'*, bosons instead are free to exist all together in the ground state at the same time, as illustrated in Fig. 87. (Compare this to the last figure of the bosons, fermions, and Pauli's exclusion principle chapter in Vol. I.)

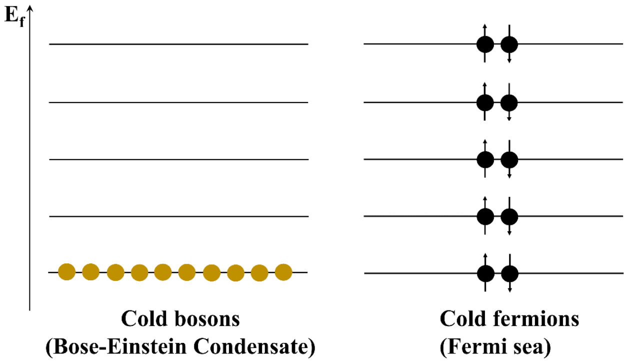


Fig. 87 The different 'condensation forms' for a Boson- and Fermi-gas.

Whereas, we know that for particles, atoms, molecules, or any physical quantum object, the de Broglie relation associates it with a wavelength ($\lambda = \frac{h}{p}$). The lower the temperature, the smaller the momentum (the velocity) of the atoms and the larger their wavelength. Meanwhile, even at only a few degrees Kelvin above absolute zero, the atoms have relatively high impulses and are localized by the de Broglie wavelength. (See Fig. 88 left.)

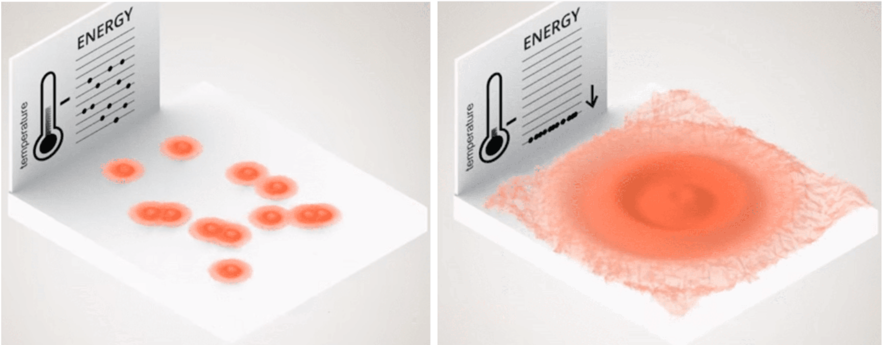
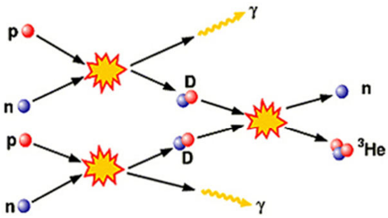


Fig. 88 The coalescence process of bosons into a Bose-Einstein condensate.

However, when the gas is cooled down to a sufficiently low temperature, the wave-packets spread out and overlap each other until they form a unique, undivided gas of atoms, all in the same quantum state and described by a single wave-packet. (See Fig. 88 right.) Therefore, they will not only group themselves into the same energy level but also coalesce into a unique and



$${}^7_4\mathrm{Be} + \mathrm{n}^0 \longrightarrow {}^7_3\,\mathrm{Li} + \mathrm{p}^+$$
$${}^3_2\mathrm{He} + {}^4_2\,\mathrm{He} \longrightarrow {}^7_4\,\mathrm{Be} + \gamma$$
$${}^7_3\mathrm{Li} + \mathrm{p}^+ \longrightarrow {}^4_2\,\mathrm{He} + {}^4_2\,\mathrm{He}$$
$${}^3_2\mathrm{He} + {}^4_2\,\mathrm{He} \longrightarrow {}^7_3\,\mathrm{Li} + \gamma$$
$${}^3_2\mathrm{He} + {}^2_1\,\mathrm{D} \longrightarrow {}^4_2\,\mathrm{He} + \mathrm{p}^+$$
$${}^3_1\mathrm{T} + {}^2_1\,\mathrm{D} \longrightarrow {}^4_2\,\mathrm{He} + \mathrm{n}^0$$
$${}^3_2\mathrm{He} + \mathrm{n}^0 \longrightarrow {}^3_1\,\mathrm{T} + \mathrm{p}^+$$
$${}^2_1\mathrm{D} + {}^2_1\,\mathrm{D} \longrightarrow {}^3_1\,\mathrm{T} + \mathrm{p}^+$$
$${}^2_1\mathrm{D} + {}^2_1\,\mathrm{D} \longrightarrow {}^3_2\,\mathrm{He} + \mathrm{n}^0$$
$${}^2_1\mathrm{D} + \mathrm{p}^+ \longrightarrow {}^3_2\,\mathrm{He} + \gamma$$
$$\mathrm{p}^+ + \mathrm{n}^0 \longrightarrow {}^2_1\,\mathrm{D} + \gamma$$
$$\mathrm{n}^0 \longrightarrow \mathrm{p}^+ + \mathrm{e}^- + \bar{\nu}_e$$

Fig. 92 Left: Pictorial representation of the combined second and fourth reactions. Right: A bottom-up Big Bang nucleosynthesis scheme.

After some time, they might decay into other nuclei. For example, we can no longer observe ${}^7_4Be$ because it has a mean lifetime of only about 53 days (it decays into ${}^3_2He$) and after 13.7 billion years, nothing is left.

Following Fig. 92 from the bottom-up, one can see how the first reaction describes the decay of a neutron n^0 into a proton p^+ and an electron e^- with the emission of a type of neutrino $\bar{\nu}_e$ (an 'electron neutrino'). The second reaction tells us about the nuclear fusion of one proton p^+ with one neutron n^0, resulting in the nucleation of one deuteron nucleus ${}^2_1D$ plus the emission of energy in the form of a gamma ray γ. Then, as shown in the third reaction line, these deuterium nuclei ${}^2_1D$ fly around in the primordial Universe and quickly encountered another proton p^+, which leads to a fusion process that produces ${}^3_2He$ plus another gamma ray γ, thereby releasing energy. The same ${}^3_2He$ could also be obtained via another reaction, that of the fourth reaction line, with the fusion of two deuterons ${}^2_1D$ plus the release of energetic neutrons n^0. However, there is a certain quantum chance that the reaction of the fifth line takes place – that is, the fusion of two deuterons ${}^2_1D$ could lead to the creation of tritium ${}^3_1T$ instead. The author leaves it to you to interpret the rest of the reaction ladder and see how it leads to the production of the other light elements.

This nucleosynthesis lasted for only three minutes after the Big Bang, which was enough time to produce mostly deuterium, ${}^4_2He$, with small

Vol. I) is yet another triumph of the Big Bang model and assures scientists that the basic mechanisms with which elements were synthesized during the first three minutes after the Big Bang theory are understood. Moreover, it is another nice example of the history of science in which particle physicists studying the microcosm collaborated successfully with astrophysicists investigating the macrocosm. The history of the Universe could be graphically summed up as shown in Fig. 95.

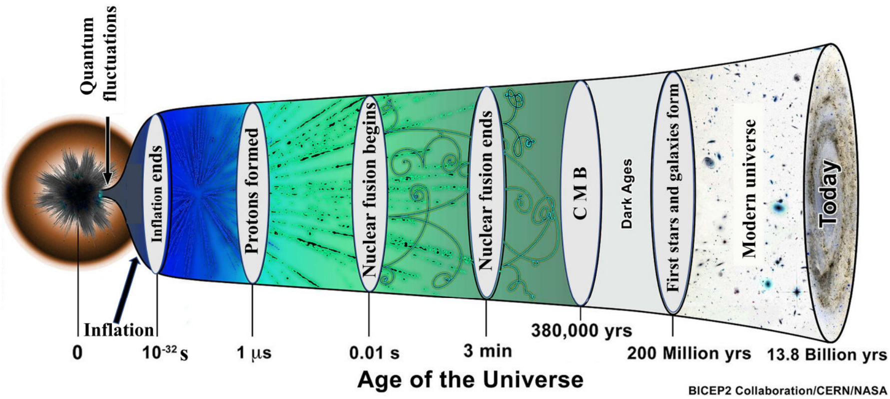


Fig. 95 The creation and expansion of the Universe throughout its different epochs.

During the time between 380,000 years and 200 million years after the Big Bang, the Universe must have been a boring and dark place, as photons were all high-energy light particles invisible to the human eye. However, the temperature after recombination was still about 3000 K. Only at the end of these 200 million years did the Universe cool down sufficiently to form giant hydrogen clouds, which collapsed due to the gravitational pull forming galaxy clusters, galaxies, and stars and where, later on, planets could form.

3. Quantum cosmology and cosmic inflation

Let's now turn our attention to modern quantum cosmology. As you might expect, besides QG, this is still an uncertain and speculative field of research which cannot be summarized in a few pages. We can, however, take a quick glimpse at one of its main representative theories, which is *'inflation cosmology'*.

Apart from the fact that astronomical observations show how galaxies fly apart, indicating that, in the past, the Universe must have been much smaller and with a common origin, there is a very simple reason why the Universe must have been much smaller than it is in its present state: its isotropic and homogeneous distribution of matter and radiation. The almost perfectly uniform CMB radiation and its related Planckian black body spectrum show apart from that of a few scientists and a handful of research institutions. Thus, it has remained very limited in terms of scope, funds, and time. One of the reasons for this is that nobody has been able to come up with a convincing mechanism that could prevent quantum decoherence due to thermal noise and environmental interference. On the other hand, even if one day we discover quantum phenomena influencing or regulating life functions, it would not be clear what this knowledge could be good for. We live in a society driven by pragmatism and utilitarianism. If a relatively small field of research, however interesting and original it might be, isn't seen as useful for some practical and commercial application, it rarely gets funded. Pure science for the sake of knowledge is out of fashion. One can only hope that QB will receive more attention in the coming years. It would be interesting to know for sure whether QM does, or does not, play a role in the development of life. If it does, this could open an entirely new line of research leading to a paradigm shift in biology and potentially also to applications. The history of science shows that pure science can – and, indeed, in most cases does – lead to unexpected applications. Galileo, Newton, Einstein, and Planck, like many other great physicists, were driven primarily by a thirst for knowledge and not by the prospect of applying their discoveries. And yet, without their discoveries, we would still be stuck in the technological middle ages. Despite its inception half a century ago, QB remains a non-mainstream science. One can only hope that this will change soon.

5. Consciousness and quantum mechanics: myth or reality?

It was almost inevitable that the conjecture surrounding QB would sooner or later have been applied to the function of our brains. The human brain is a biological processing unit made of about 100 billion neurons. If QM plays a role in biological cells, and because neurons are nothing other than cells specialized for cognitive functions, it is hard to escape the temptation to extend the potential role of QB to neurons as well.

Moreover, a philosophical problem has plagued philosophers since the 17^{th} century, the time when René Descartes stated, *"cogito, ergo sum"* – namely, a *'mind-body problem'* which ultimately boils down to the problem of consciousness. Nowadays, modern neuroscience dismisses Descartes' ideas about the mind and consciousness. Thinking, being, and perceiving are separate categories that can't be summarized by a slogan. However, what is particularly noteworthy is that the concept of *'consciousness'* continues to elude a definition and clear scientific categorization and explanation.

VIII. Philosophical idealism for quantum physics - Part II

1. Philosophical idealism: the forgotten legacy.

This chapter should not be considered another interpretation of QM. Rather, it is a suggestion for a different approach to the subject and an attempt to point out how our 'human-centric' unaware assumptions regarding the nature of 'reality' and 'objectivity' can deeply mislead us into adopting an anthropomorphic understanding of the world—a misunderstanding and anthropomorphism to which science is not immune. Philosophical idealism may be useful for making us aware of our unconscious assumptions, heightening the philosophical standards which, then, can eventually reflect themselves in the 'modus operandi' with which we pursue science in practice and, only then, eventually, be integrated into new interpretations of QM.

In Vol. I, we briefly outlined that one aspect of the philosophical implications of QP is that it invites us to reconsider the old—but, throughout all history and cultures, always present—doctrine of philosophical idealism. On that occasion, we briefly digressed into neurobiology and resorted to 'allegorical crutches' like Plato's cave, whose function was to clarify why and how we should consider with care any disquisition about the ontology of QM and notions such as 'reality' or the distinctions between what is 'objective' vs. 'subjective'. In particular, we considered epistemological idealism in the form of Kant's transcendental idealism, according to which there exists an indeterminate ontological reality with 'real things' and 'real laws' governing the Universe. However, even these we can infer only from the projections into our conscious experience. The shadow of a stone or a mountain on the cave's wall is permanent and subject to the laws of physics; however, this does not allow us to replace the shadow with the real 'thing-in-itself', as Kant used to call it. Kant thought there must be something which exists independently of us being the cause of our representations of the world that appears to us. Otherwise, these representations and appearances of the world we perceive would arise out of nothing. That's why we are forced to conclude that the things-in-themselves which are the cause of our representations exist, but they are mind-independent or 'transcendental objects'. There is a substratum underlying the phenomenal world, but we can't investigate the true inherent nature of the things-in-themselves and have an objective knowledge of it, because we always start from the representations–that is, from the phenomenon, the symbol.

What we call a 'physical object' is a perceptual and mental construction that appears to us and that science investigates with a more systemized, rigorous, and consensual 'inter-subjective' descriptive discipline. Yet all this does not reveal its intrinsic and inherent nature independent from those perceptions. We must seriously question whether Nature, as appearing to us in the quantum realm, can still be represented by a naïve realism (such as that held by the MWI or in BM) that implicitly assumes our sense-mind representations are faithful reproductions of the physical constitution of external objects as things-in-themselves.

We concluded that we perceive the Universe not as it is-in-itself but necessarily and unavoidably as a conceptual construct arising from innumerable subjective forms of experience in us—forms which the mind first dissects and then, when it is too late, tries to bind together into an object of cognition which is far and completely removed from the reality and intrinsic nature of the object itself.

However, all this does not necessarily imply that reality is ultimately mental (the claim of Berkeley) or that we must confine ourselves to a solipsistic view. Rather, we must conclude that this 'reality' is at least something else, something other than what the human senses or our mechanical measurement devices—through their impressions, sensations, and perceptions—suggest to our minds. The mental act of apprehending and relating to an object a symbolic appearance of it (by a measuring device or via our perceptions, thoughts, and experiences) makes the objects we perceive in us not mental entities in themselves. If we are left with nothing other than mentation in investigating the outer world, this does not imply that the world is mental—or, at least, not only mental.

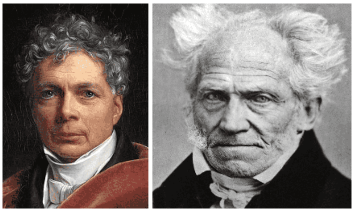


Fig. 100 Friedrich Schelling (1775-1854). Arthur Schopenhauer (1788-1860)

In the 19th century, the German philosopher Friedrich Schelling elevated Kant's transcendental idealism to a monistic ontology in which Nature and Reality have an 'original unity' ('ursprüngliche Einheit'), the Absolute. Nature and Spirit are two complementary parts of a Whole in which the latter struggles to become conscious inside the former. All the properties of things in their form, substance, quantity, and quality are different aspects of an internally differentiated *'primordial totality'* ('ursprüngliche Ganzheit') in its opposites. What we perceive with our senses and translate in our mind as objects, forms, and symbols are only a partial and incomplete one-sided expression of a dynamic Whole. Schelling envisages a 'World-Soul' as the basis of the whole of reality in which we are, so to speak, embedded and forced to distinguish between a subjective mental world tainted by feelings and perceptions in us, contrasted by what we call an 'objective world' outside us.