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The Microcosm: The World of Quantum Mechanics

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Those who are not shocked when they first come across quantum theory cannot possibly have understood it.

– Niels Bohr

Levels of Reality: ***The world may be considered at three different levels.***

From ancient times, the division of the world into a macrocosm and a microcosm has been a feature in many cultures. There are references to it in Pythagorean and Platonic thought[1]. In a classical Hindu worldview, there is an external physical world which is called *Shivaloka*, and an inner world of consciousness called *Antarloka*[2]. The idea of the microcosm and macrocosm was also popular in medieval alchemy where the microcosm was imagined to be more complex than the macrocosm, and each was in a state of vibration. Medieval Christian thinkers like Boethius, Robert Fludd and Sir Thomas Browne were among the many who spoke of two such worlds[3].

In the framework of modern science we may consider the world of perceived reality at three different levels. First, there is the level of everyday experiences where objects are visible to the naked eye or through microscopes. The things that we see and feel range from minute specks of dust to huge boulders, lakes and mountains. We may refer to this as the *mesocosm*. Then there is the extra-terrestrial world beyond, of planets and stars and galaxies: very huge compared to objects we see and hold and measure on earth. They cannot be touched and manipulated, but can be studied with the aid of telescopes, concepts and calculations. We may describe them as being in the *macrocosm*. In the mesocosm and macrocosm we are dealing with matter made up of countless trillions and quadrillions of atoms and molecules. We may refer to these as the classical levels of reality. Finally, there is a level which is minute beyond direct observation, where one may consider the physics of individual molecules and atoms and their subunits. This is the microcosm which came to be explored only in the twentieth century.

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[1] Plato speaks of this in his *Republic*.

[2] These are said to have corporeal existence as *pinda* and *anda* as well.

[3] For details see the classic text on this: G P Conger, *Theories of Macrocosms and Microcosms in the History of Philosophy*, New York, 1922.

The study of the laws and properties of the microcosm constitutes what is known as quantum physics. It is an important branch of physics, often regarded as fundamental physics since it explores the very foundations of perceived reality.

The point to note here is that the physical world on our scale consists mostly of material chunks with mass, from the very small to the very large. These are bathed in a sea of radiant energy (electromagnetic waves). More exactly, matter appears as *particles* and (radiant) energy as *waves* in the mesocosm and macrocosm.

Einstein's Formula: ***Matter and energy are essentially equivalent.***

We recall that one of the most influential theories of 20th century physics was the Special Theory of Relativity (STR) developed by Albert Einstein (1873–1955), published in 1905. Among the many revelations of this theory is the intertwining of space and time which form one seamless continuum. Another fundamental consequence of the STR is the essential equivalence of matter and energy. What this means is that matter and energy are different manifestations of a single ultimate entity.

Matter appears as substantial mass, localizable at one point of region of space. It is measured in units of kilograms for example. Energy is insubstantial and experienced in terms of its impact. Energy may be measured in units of joule, for example. We may look upon matter as the static part of the physical world and energy as its dynamic aspect.

There is also strict quantitative equivalence between matter and energy. This statement has two implications. The first is that any given amount of mass (measured in appropriate units) is equivalent to a precise amount of energy, measured in appropriate units. For example, if we measure mass in kilograms and energy in joules, X kilograms of matter would be equivalent to Y joules of energy. This is expressed through what has become the best known formula of physics: $E = mc^2$, where c stands for the speed of light.

The second implication is that, in principle, matter can be converted or transformed into energy, and energy can be converted or transformed into matter. As we saw in the last essay, this actually happens to appreciable degrees in nuclear reactions. This also means that it is possible to extract energy for human needs through nuclear reactions.

Quantum Aspect of Radiation: ***Waves also have a particle aspect*.**

Energy appears in a variety of forms. The most ubiquitous form of energy is radiation: electromagnetic waves of all wavelengths and frequencies. Unlike material particles, waves are not localized, but spread out over regions. They are not inert entities but oscillations. This is how we perceive waves at the classical level of physical reality.

When we approach a heated surface we experience the radiant heat from it. When this common experience was studied systematically, experimentally, and quantitatively, and when one tried to account for the observed details in mathematical and theoretical terms, a most remarkable aspect of radiation was uncovered: namely, that radiant energy has a particle aspect. This discovery was made by Max Planck in 1900[4]. In other words, though radiation has a wave aspect at the classical level, deep down at the atomic level it appears and disappears as microcosmic bundles of energy. More precisely, each of these little energy bundles carries an amount of energy proportional to the frequency of the wave[5]. In other words, radiation of higher frequency means photons carrying more energy. For example, a gamma ray photon carries far more energy than a microwave photon, because the frequency of the former is much greater. The particle-units of radiation are referred to as *quanta*[6] of energy.

Whenever we are dealing with a microcosmic process, i.e., one in which individual atomic particles are involved, we should take this aspect of radiant energy into account. There are many such processes which occur in the microcosm whose effects can be observed and measured[7].

This knowledge about the ultimate nature of radiation could never have been made without the probing methodology of modern science that uses instruments, precise measurements, and mathematics. This fact must be stressed and brought to the notice of commentators on modern science who equate and confuse modern scientific results with ancient philosophical insights.

Wave Aspect of Particles: ***Particles in the microcosm also have a wave aspect.***

Now let us briefly review what we have seen thus far about the architecture of the material universe.

(a) In the classical world matter appears as particles and (radiant) energy as waves.
(b) Energy has a wave as well as a particle aspect.
(c) The particle aspect of waves becomes more manifest in the microcosm.

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[4] For a good history of this discovery, see M J Klein, 'Max Planck and the Beginnings of Quantum Theory', *Archive for History of Exact Sciences*, Vol.1, pp.459–470, 1962.

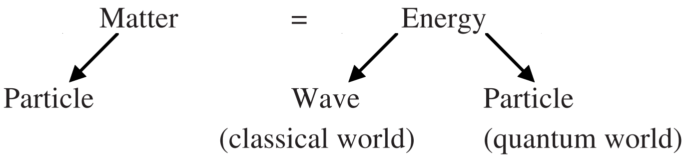
[5] In quantitative terms, the amount of energy in a quantum of radiation of frequency n is given by $E = hn$, where h is a universal constant known as *Planck's constant*. Its numerical value is about 6.63×10^{-34}J.s.

[6] The word quantum is a Latin word, meaning *how much* of something. Ever since this word entered common vocabulary it has been extrapolated and misused in a number of ways, as in *quantum healing*, *quantum leap*, etc., by non-physicists who like to show they are knowledgeable about modern science.

[7] These include the photoelectric effect, the Compton effect, the Raman effect, etc.

(d) Matter and energy are equivalent.

We may represent these in a diagram as follows:



When we reflect on the statements (a) to (b) and see the diagram above, we are inclined to add two more items to make the nature of physical reality more symmetrical and complete:

(e) Matter has a particle as well as a wave aspect.
(f) The wave aspect of matter becomes more manifest in the microcosm.

Indeed these two were the central ideas in a doctoral dissertation submitted by Louis de Broglie (1892–1987) in 1924[8]. The so-called de Broglie hypothesis was that every particle has a wave aspect. More exactly, with every particle of mass m moving with a velocity v, that is, a momentum $p = mv$, is associated a wave whose wavelength λ is inversely proportional to its momentum[9].

Because of the extreme smallness of the value of h, the waves associated with ordinary matter are imperceptibly small. For the de Broglie waves to have any appreciable wavelength at all, the corresponding momentum must be extremely small. This would imply very small masses, as with protons and electrons. For example, an electron moving with a speed of 3×10^6 m/s has a momentum of about 2.7×10^{-27} kg.m/s. We can compute the corresponding de Broglie wavelength to be 2.3×10^{-10} m. This is of the order of X-ray wavelengths. However, matter waves are not EM waves.

Recall that the most important properties of waves are interference and diffraction. Therefore, if waves are associated with particles, then it must be possible to produce diffraction and interference with particles also. This has been verified by experiments. By sending beams of electrons through slits and crystals, interference patterns (such as those obtained with light and X-rays) have been observed. The wavelengths of particle waves as determined from such

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[8] It was my privilege to have done my doctoral work under the supervision of Louis de Broglie. He was an extremely gentle, modest, and kind person of great charm and erudition. He inspired me to study the history of science and its humanistic dimensions.

[9] As a formula, we have the de Broglie relationship $p = h/\lambda$, where h is Planck's constant.

experiments have confirmed with remarkable precision the de Broglie formula[10]. The property has also been applied in the construction of electron-microscopes[11]. This double characteristic of particles and waves, namely, their possible manifestations in two different forms, is referred to as *wave particle duality*.

It may be noted in passing that de Broglie's idea seemed so outrageous that his professors hesitated to award him a doctoral degree. But when they showed his thesis to Einstein, he (Einstein) whole-heartedly endorsed it[12].

The Schrödinger Equation: ***The evolution of microcosmic entities can be studied in terms of a (matter-) wave equation.***

The laws of motion that govern the changes in the positions and momenta of material bodies are expressed in mathematical relations known as Newton's equations of motion. Similarly, the evolution of waves, i.e., the manner in which the amplitude of a wave changes from point to point and from instant to instant is mathematically described by what is called the wave equation[13].

Since matter has a wave aspect, it is possible to find a wave equation for matter waves. Such a matter-wave equation, known as the Schrödinger equation (SE) was derived soon after de Broglie's thesis was published[14].

The SE plays a fundamental role in quantum physics, exactly as Newton's equations do in classical physics. In other words, when one considers the evolution of particles that are subjected to forces at the atomic (microcosmic) level, one has to take the SE as the starting point. By applying this equation, physicists have solved a variety of problems at the atomic level. In order to understand the full import of the SE and to apply it meaningfully, one needs to master a reasonable level of higher mathematics.

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[10] The diffraction of electrons at the surface of nickel crystals was experimentally demonstrated first by the celebrated experiments of Clinton Joseph Davisson and Lester Germer in 1927 at the Bell Labs. This gave empirical support for the de Broglie hypothesis.

[11] The first electron microscope was constructed by Ernest Ruska in 1932. It can magnify microscopic entities some 10 million times more than optical microscopes.

[12] Tony Hey and Patrick Walters, *The Quantum Universe*, Cambridge University Press, Cambridge, 1987.

[13] The wave equation was first derived by Jean le Rond d'Alembert in 1747. For details see, V V Raman, 'Jean le Rond D'Alembert (1717–1787)', *Indian Journal of History of Science*, Vol.19, No.3, 1984.

[14] One form of the Schrödinger equation is: $i\hbar\frac{\partial\Psi}{\partial t} = -\frac{\hbar^2}{2m}\left(\frac{\partial^2\Psi}{\partial x^2} + \frac{\partial^2\Psi}{\partial y^2} + \frac{\partial^2\Psi}{\partial z^2}\right) + V(x,y,z,t)\Psi$

For a historical background, see V V Raman and Paul Forman, Why was It Schrödinger who developed de Broglie's Ideas? *Historical Studies in the Physical Sciences*, Vol.1, pp.291–314, 1969.

Planck's constant h appears explicitly in the SE. Hence this equation is of significance only at the microcosmic level. In the classical world to which we are normally accustomed, the SE is of no direct relevance whatsoever. It is like the law of some alien land which does not affect us, but which we must somehow know if we are to understand the behavior of the people there.

In classical mechanics, one often studies the motion of a body or of a system of bodies under the action of well-defined external forces. In the quantum world, on the other hand, it is more fruitful to consider, not the forces, but the potential energies due to the force fields that influence the behavior of the particles or the system.

The amplitude of the matter-wave is represented by the symbol Ψ (pronounce: *psi*). In simple terms, Ψ stands for the amplitude of the matter-wave. It appears in the SE exactly as the wave amplitude appears in the classical wave equation.

Quantum States: *Quantum entities can be simultaneously in different states until they are detected.*

When one solves the SE, one finds a set of solutions for the differential equation. Each of these states refers to the energy, position, momentum, spin, etc., that a quantum entity can have. These possible states are referred to as the *eigenstates* of the quantum entity[15]. The most significant find of quantum physics is that a microcosmic entity exists in *all these states simultaneously* until an observation is made. This is quite contrary to anything in the world on our scale. This is a totally new concept in physics.

We may envision this through an analogy. Consider a coin. We may regard its two sides (head and tail) as its two possible (eigen) states. When the coin is flung in the air it may be said to be in both its states of head and tail simultaneously. But when it falls to the ground, an observation has been made, and it is found to be in only one of its allowed states.

It is this circumstance that led Einstein to famously and frequently declare that, "God doesn't play dice with the world." By this he meant that it was difficult for him to imagine a God who would be playing dice with the world. But from so many considerations, quantum mechanics seems to suggest that this is precisely what God (or Nature) seems to be doing in the microcosm.

The Ψ-Function and Probability: *The laws in the microcosm are probabilistic laws.*

At the level of electrons and protons, particles evolve with a certain degree of freedom even

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[15] The term eigenstate literally means a state that is characteristic of the system, that is, its own. The prefix *eigen-* in German means one's own. It corresponds to the Sanskrit *sva-*. Thus, for example, the term *svadharma* would be translated as *eigendharma* in German.

under well-defined external conditions; that is to say, their paths are not as rigidly determined as at the classical level. This evolution is governed by laws of probability. In other words, while it is not possible to predict precisely the manner in which a given quantum entity will evolve under specific influences, as with dice, one can predict the outcomes with certain probabilities.

The key point in quantum physics is that the Ψ-function is a measure of that probability. For example, imagine an electron enclosed in a box. If mathematical analysis shows that the value of the corresponding Ψ-function is very large at a particular corner of the box, this would imply that the electron is most probably somewhere in the vicinity of that corner, and that it is least likely to be found in a region where the Ψ-function has a low value. More exactly, what the result tells us is that if we deal with a very large number of similar particles, then in the vast majority of cases, electrons will be near the particular corner at which Ψ takes on a large value, and very few will be in regions where the Ψ value is quite small.

Only in the extreme instance when the Ψ-function takes on the value of 1 at a single point and 0 everywhere else, can one say that the corresponding particle is precisely located at that point. This, however never happens. Generally, the Ψ-function has non-zero values at various points of the region. Therefore, the position of a quantum entity is never fully localized at a single point. Because of this, we have the picture of an electron, for example, as being spread out in the points of the region where Ψ is non-zero. This leads to the view of the electron as a nebulous entity, rather than a concentrated particle.

The Tunnel Effect: ***Classically impossible things can happen in the microcosm.***

Imagine giving a push to a ball on a horizontal surface which has a small mound. Whether the ball will roll over to the other side of the mound or roll back after reaching a distance on the slope depends on the initial (kinetic) energy it was given. If this initial energy is not enough to push it to the top of the mound, the ball simply cannot reach the other side. In the microcosm the situation is different. There, an electron with far less energy than is necessary to overcome such a *potential barrier* can still reach the other aide. It behaves as if there is a tunnel in the mound. This follows from the fact that the Ψ-function turns out to be non-zero even beyond the barrier. This implies the following apparently impossible situation: When a quantum entity is imprisoned within walls which it cannot climb over, there is a finite probability of it going to the other side! This simply cannot occur at the classic level. But it can and does happen in the quantum world without violation of any physical law. This possibility is referred to as the *tunnel effect*[16],

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[16] The phenomenon of quantum tunneling in radioactivity was first suspected by Friedrich Hund in 1927. The concept was further developed by Max Born. See in this context, Eugen Merzbacher, The Early History of Quantum Tunneling, *Physics Today*, Vol.55, No.8, pp.44–49, 2002.

for here the quantum entity seems to seep through an imaginary tunnel. This is a striking instance of how things behave quite differently in the quantum world.

This is not simply a matter of theoretical interest. Quantum tunneling occurs regularly in the microcosm. In radioactivity, for example, alpha particles escape from within atomic nuclei even though they do not have sufficient energy to accomplish this[17]. They are able to do so because of the tunnel effect. Similarly, under appropriate conditions, it is possible for electrons in metal atoms to get out of the binding force even when they have far less energy than their work function. This phenomenon, known as field emission, is utilized in the field emission microscope whose purpose is to study the surface structure of solids.

The electrons rushing through a conductor as an electric current may sometimes tunnel through an insulator and appear on the other side. It must be clearly understood that the electrons are not actually penetrating through the insulator. The insulator is in no way affected by the process. They simply manage to come to the other side in a manner which, from the classical point of view, is nothing short of magic. Recently, it has been shown that tunneling of electrons can even take place through vacuum. This possibility has been exploited in a device known as the scanning tunneling microscope which also provides the investigator with detailed information on the surface structure of materials. Again, in suitable combinations of semiconductors (called p–n junctions), electrons tunnel through the forbidden band from the valence band into the conduction band. This is the basis of tunnel diodes which are extensively used in solid state electronics[17].

The Heisenberg Principle of Uncertainty: ***There are limits to the precision with which we can measure in the microcosm.***

Another important consequence of the wave aspect of matter is that it is impossible to specify simultaneously with absolute precision both the position and momentum of a quantum entity. To see how this comes about, consider the case where the position and velocity of an automobile are measured from a helicopter by the use of radar. These data can be obtained to any desired degree of precision (on our scale) by bouncing back EM waves (photons) from the moving automobile. In the process the automobile's motion is not affected.

Now suppose that we wish to measure the position and velocity (momentum) of an electron. Here again we will have to use a photon for the task. However, when the photon hits the electron, the latter will be disturbed significantly. As a result, the information brought in by the reflected photon will not be accurate. In the very process of measurement, the state of the observed system

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[17] All this is part of what one studies in courses on electronics and solid state physics.

is disturbed. This interaction between the observer and the observed is inevitable with quantum systems: this is at the root of our inability to get absolute precision.

The impossibility, even in principle, of measuring simultaneously and with absolute precision both the position and momentum of a quantum entity is an example of what is known as *Heisenberg's principle of uncertainty* (or *indeterminacy*)[18]. The Heisenberg principle becomes relevant and significant only in the microcosm.

We can explain why electrons are not found within atomic nuclei by invoking the Heisenberg principle. The diameter of the nucleus is of the order of 10^{-14} m. Taking this as the uncertainty in the position of the electron, one may calculate the uncertainty in its momentum. When this is done, the momentum uncertainty turns out to be of an enormous order. In fact, it corresponds to an electron with kinetic energy of about 20,000,000 eV. Ordinarily, electrons have only a few eV of energy in an atom. Therefore, with this much energy, an electron will fly off the nucleus. This is why nuclei cannot and do not contain electrons.

Indeterminacy in Energy and Time: ***The energy conservation principle does not strictly hold in the microcosm.***

There are other pairs of such physically observable quantities which are also subject to the Heisenberg principle. Such pairs are known as *conjugate observables*[19]. Energy and time are two such, i.e., if we measure the energy of a quantum system during a given time interval, the uncertainties in these quantities are also restricted[20]. This implies that during sufficiently short time intervals, there can be violation of the energy conservation principle. For very small values of uncertainty in time, there can be large uncertainties in energy. It is thus possible in the quantum world for masses (or energy) to appear out of and disappear into nowhere during extremely short time intervals.

Consider, for example, an atom in which an electron has been excited to a higher level. We recall that when the electron jumps back to its initial state, it will radiate a photon. Now suppose that the excited state lasts for a period of 10^{-8}s. This corresponds to the uncertainty in time. Therefore, the energy of the emitted photon will be imprecise by an amount of about 10^{-26} J. This is equivalent to an uncertainty in the frequency of about 10^7 Hz. In fact, in fundamental

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[18] In mathematical terms one would say that the product of the errors in the measurement of the position and of the momentum of a quantum entity are of the order of Planck's constant: $\Delta x \, \Delta p \approx h$ (≈ means is of the order of h).

[19] In mathematical jargon, conjugate variables form Fourier-transform duals. They are analyzed in harmonic analysis and in the theory of topological groups. In quantum mechanics their significance arose in the context of the Heisenberg principle.

[20] $\Delta E \Delta t \approx h$ (is of the order of h), where E and t stand for energy and time respectively.

interactions such as between two protons in a nucleus, for example, new masses arise and disappear causing the so-called strong field. More generally in the substratum of the physical universe zillions of such particles arise and vanish continuously, sustaining the universe. These are known as virtual particles. Real particles conserve matter–energy. They also take finite time to go from point to point. Virtual particles don't conserve matter–energy. Their role is to link particles through interactive forces. That is why we say that the universe is bubbling everywhere with imperceptible virtual particles.

The Principle of Complementarity: *In many instances more clarity in one aspect means more blur in another.*

One may extend the implications of the Heisenberg principle to other contexts also. For example, if we wish to study the behavior of little children we have to let them lose to interact among themselves. The moment we observe them, it will affect their behavior. Extrapolations like this began soon after Heisenberg's principle was published. In 1927, Niels Bohr formulated his famous *principle of complementarity*[21]. It is an insightful interpretation of de Broglie's wave–particle duality. It simply says that with microcosmic entities, the more precise we are in the description/apprehension of the particle aspect of an entity, the more fuzzy its wave aspect becomes, and vice versa. This duality may be extended to other domains as well[22]. In this context we may introduce the notion of *conjugate realms*: Consider two different realms in which we are engaged[23]. Call these C_1 and C_2. Let M and L stand for more and less respectively. Then we may state the principle of complementarity as: the more clearly we recognize one realm the less clear the other will become:

$$\mathrm{M\,C_1 \rightarrow L\,C_2 \ \ and\ \ L\,C_1 \rightarrow M\,C_2}.$$

Complementarity may be taken to imply that it is impossible to obtain complete knowledge, understanding, and insight into aspects of two conjugate realms at the same time. We may describe them as *epistemic conjugate realms*. Thus, the *mechanistic approach* to a biological system and the *vitalistic approach* are complementary approaches. So are art criticism and art appreciation, the *outsider's understanding* of a culture and the *insider's experience* of a culture, the *emotional response* to a problem and *logical response* to it: all these are examples of epistemic conjugate realms.

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[21] Niels Bohr, The Quantum Postulate and the Recent Development of Atomic Theory, *Nature,* Vol.121, pp.580–590, 1928. See also, Bohr's *Atomic theory and the description of nature*, Ox Bow Press, Conn. 1987).

[22] For an excellent discussion on this, see Abraham Pais, *Niels Bohr's Times*: *in Physics, Philosophy, and Polity*, Clarendon Press, Oxford, Ch.19, 1991.

[23] This discussion is based on the paper 'Conjugate Realms' by V V Raman, presented at a conference on Generalized Quantum Theory, Frankfurt am Oder, Berlin, July 6, 2010.

Sometimes conjugate realms may be philosophically, doctrinally, and practically opposed to each other. These may be called *negative conjugate realms*. Examples of these are: *Historical approach* to scriptures and *religious approach*; free enterprise and socialism; *conservative* and *liberal* ideologies in politics, *scientific understanding* of the human condition and the *religious*. Epistemic conjugate realms can enrich us and it is possible to move from one to the other. On the other hand, negative conjugate realms, being mutually opposed, often lead to conflicts. In this case it is possible to go into extreme states in each of the conjugate realms. The value in this analysis of complementarity lies in that it enables us to better understand why there are different perspectives on issues. As with Heisenberg's principle there are built-in constraints in the world of ideas and understandings that we simply cannot overcome. This may be seen as a macrocosmic (human-level) reflection of what obtains in the microcosm.

Subject–Object Interaction: *There are limits to our measurable knowledge.*

The uncertainty principle sets an inerasable limit to the precision with which we can know the conjugate states of microcosmic systems. This built-in incompleteness in our full understanding has made us realize that we cannot comprehend the physical world in its ultimate entirety. This should not be mistaken as an expression of the practical difficulties involved in the construction of very precise instruments. It has always been known, for example, that the world is much too vast and complex for the human mind to grasp in its entirety, and that it requires superhuman powers to track it down in all its myriad details. But these limitations arise from time and energy constraints, not out of anything intrinsic in the nature of the world itself.

To give an analogy between the two kinds of limitations, no human being can possibly read every page of all the books in all the libraries of the world. Yet, if we assume that a person has an indefinite amount of time and energy available, this can be accomplished, at least in principle. On the other hand, it is impossible, even in principle, for anybody to ice skate on the surface of the sun. In this case, the impossibility arises because of the very laws of nature (there can be no ice at 5000 degrees). Likewise, Heisenberg's principle states in effect that there is a law of nature which sets limitations in our efforts to explore the quantitative details of the world at the microcosmic level.

This finding of quantum physics has inspired some philosophers and moralists to celebrate it as a recognition of the limitations of science. We should rather celebrate it as yet another triumph of science in that this is also a scientific discovery. Moreover, science has expanded human knowledge in a myriad other domains. Our inability to know simultaneously with 100% precision the position and momentum of an electron need not be a matter for lamentation.

More importantly, what Heisenberg's analysis has revealed is that at the deepest level there is an inevitable interaction between the observer and the observed, between the subject and the object. As Bohr put it[24], "We are spectators as well as actors in the great drama of existence." This alters considerably science's previous view of the world as consisting of an external objective world and an altogether separate subjective world. The Heisenberg principle is a revelation about the world, not a condemnation of science.

Quantum Entanglement: *Everything in the world is interconnected.*

Recall that quantum entities are described and analyzed through the Ψ-function associated with their wave aspect. The waves are spread all around. This means that when two electrons are close together they overlap like two clouds. Moreover, when a quantum entity such as a photon or a particle splits or decays into two different entities, the wave functions of the now separate entities are intrinsically entangled. Their Ψ-function interconnections are sustained when they are separated by a distance. This apparently innocuous statement has deep implications. This means that even entities far apart can influence each other in what may seem like magic from classical perspectives.

To give an example, suppose that a photon splits into two and both move away from each other. Their combined spin would continue to be the same as that of the initial photon. Now each photon will be simultaneously in all the allowed spin states until an observation is made on one of them. When this is done, the spin of the other will be instantaneously determined. In other words, measurement on one photon will affect at once the state of the other which may be far, far away: It is as if information has traveled faster than light[25].

We can give an analogy with two dice, A and B. Suppose that each side of the die A is correlated to a corresponding side of B: Face 1 on A implies Face 1 on B, etc. Now let us throw both dice in the air. They are simultaneously in all the states (sides) until they fall to the ground. According to quantum entanglement, if the die A falls with the side 3 up, say, then B will also fall with the same side up. This would be pure magic in the classical world, but quite normal and expected in the quantum world. Schrödinger, who coined the word, described entanglement[26] as

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[24] Niels Bohr, Discussion with Einstein on Epistemological Problems in Atomic Physics, in P A Schilpp (Ed.), *Albert Einstein: Philosopher-Scientist,* p.236, 1949.

[25] Quantum entanglement is a very complex topic with philosophical, epistemological, and foundational implications (nature of reality) for physics. It has mathematical (John Bell's Theorem), theoretical (non-locality and superluminal transfer of information), and experimental dimensions. For a popular discussion on this, see Gary Zukav, *Dancing Wu Li Masters*, Harper Collins, New York, 2001.

[26] Erwin Schrödinger, Discussion of Probability Relations Between Separated Systems, *Proceedings of the Cambridge Philosophical Society*, Vol.31, 1935.

"the characteristic trait of quantum mechanics, the one that enforces its entire departure from classical lines of thought".

It must be noted that these are perfectly valid and incontrovertible conclusions from the currently accepted framework of quantum mechanics. They have also been experimentally verified. But they are so intriguing and counter-intuitive that the early founders of quantum mechanics did not fully agree with one another on their interpretations. Now, physics has gone from the stage of arguing about their deeper significance as to the nature of reality to one in which possible applications of the results are sought[27].

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[27] The first step in going from theoretical considerations to practical applications of quantum entanglement was taken by David Deutsch in 1985 when he showed that classically impossible computational tasks could be performed using quantum entanglement. See in this context his *The Fabric of Reality*, Penguin, London, 1997.

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Previous Parts:
The World Above: Vol.15, No.10, pp.954–964; No.11, pp.1021–1030, 2010;
The Physical World: Vol.15, No.12, pp.1132–1141, 2010; Vol.16, No.1, pp.76–87, 2011;
On the Nature of Heat: Vol.16, No.2, pp.190–199, 2011;
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M**ore on Light**, Vol.16, No.5, pp.468–479, 2011;
Matter: The Stuff the World is Made of, Vol.16, No.7, pp.670–681, 2011;
More on Matter, Vol.16, No.8, pp.784–793, 2011; No.10, pp.987–998, 2011; No.11, pp.1061–1070, 2011;
More on Force: Vol.17, No.1, pp.83–91;
Waves: No.2, pp.212–224, 2012;
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