3. Quantum Paradoxes

‘How wonderful that we have met with a paradox. Now we have some hope of making progress.’. Bohr [Ph.D thesis, Eric G. Cavalcanti, 2008].

3.1 Introduction

There are several occasions when this word ‘paradox’ invariably appears in this work on the thesis. ‘Para’ for our purpose may be taken as ‘beyond’ or ‘apart from’. Further ‘doxa’ in Greek means glory, opinion. So ‘paradox’ is a noun meaning: Seemingly absurd, though perhaps actually well-founded statement, self-contradictory or essentially absurd statement, phenomenon or thing conflicting with pre-conceived notion of what is reasonable or possible. According to Richard Feynman, the doyen of physics, a paradox is a situation which gives one answer when analyzed in one way and another, particular answer, when analyzed in a different manner, so that we are left in somewhat of a quandary, perplexed state or practical dilemma as to actually what should happen. Feynman opines that, of course, in physics there are never any real paradoxes because there is only one way (and that is the right way, naturally). So in physics a paradox is perhaps only confusion in our own understanding of the actual situation. Paradox means apparently untrue, though perhaps actually, ultimately a well-framed situation. It can also be self-contradictory or essentially illogical account. There is no dearth of paradoxes and mysteries in nature. Thus paradox is one of the most interesting topics to go into seriously.

To paraphrase John G. Cramer, QM is a ‘museum of mysteries’. For example, the de Broglie, and Schrödinger’s cat, Wigner’s friend and Herbert paradoxes are some of them, which we shall describe and discuss in the sections that follow. The EPR paradox being the forerunner of the deliberations on Bell type inequalities, both of them will be discussed in the next chapters. Whether a paradox is used as a
euphemism for contradiction or absurdity is for one to scrutinize. We would examine if they are really apparent, or lead to a stalemate situation. Ideally one would genuinely love to be in a paradox-free situation or resolve all the existing ones, if possible. We come across many apparent absurdities in QM and are always in a dilemma whether to use the localized particle or the non-local wave metaphors.

The success of QM is unprecedented and unsurpassed. Indeed, QM is the greatest intellectual achievement of the 20th century. Nobody doubts about its practical utility and success. But when it comes to the problems of interpretation of the wave function, $\psi$, and about the reality that it describes many different versions, interpretations and their variations emerge. The 80 year old debate still is relevant more than ever. Certainly, no academic debate ever in the history of mankind has attained so much prominence. It can aptly be called the debate of the last millennium. The quantum enigma continues to puzzle even the greatest minds in science. Hence it is worthwhile and rewarding to take a careful, concentrated study of the various aspects associated with the quantum paradoxes.

To paraphrase Richard Feynman, the central mystery of quantum is that of the double-slit. According to him if one can come to terms with the double-slit experiments, then one will be at home with QM [Feynman, 1964]. We see that the wave-particle duality is at the heart of the mystery that shrouds the double-slit experiment. The Schrödinger’s cat paradox also can be described in terms of the double-slit experiment. We shall discuss about refinement of this when we describe about the Mach Zehnder interferometer and associated experiments including Wheeler’s delayed choice experiment, Vaidman bomb [Elitzur and Vaidman, 1993] etc. Following E.C.G. Sudarshan, a particle can be defined as one which has no further structure or it can be neglected for the phenomenon that we talk about. In that sense Earth, Sun etc. are treated like a particle (point mass) in the Kepler’s equation. It is not the big or small size that really matters as size is only relative. Had we been much smaller than a proton then protons would be big
like Earth for us. In this chapter the mysteries of wave-particle duality and that of measurement are considered. More of the notorious measurement problem will be dealt with in the next chapter on EPR paradox.

### 3.2 Quantum Riddles

#### 3.2.1 Wave-Particle Duality

The quantum particles exhibit both the wave nature and particle nature with diverse and mutually not accommodating properties. Particles are localized while waves are spread out. Waves exhibit periodicity, have frequency and wavelength and therefore exhibit properties like interference and polarizations, whereas particles do not have those features but have more or less well-defined position, momentum and so on. Waves and particles are definitely different in ever so many clear, visible ways. But still both of these diverse set of attributes manifest together.

#### 3.2.2 Double-Slit Experiment

Double-slit experiment can be done using ‘particles’, like photons or electrons. Interference will occur only as long as the route of the particle is not being monitored [Feynman,1964, 1968]. The ‘which way’ detection will erase the interference pattern and we get the classical pattern (denoted by (b) in figure 3.1) according to the equation (3.1), else we would get the interference pattern (c) of figure 3.1 as per equation (3.2). The complementarity principle due to Bohr works very well.

\[
\psi_1^2 + \psi_2^2 = P_1 + P_2 = |\psi_1|^2 + |\psi_2|^2 \quad \text{(Pattern a) Classical, (3.1)}
\]

\[
P_{12} = |\psi_1 + \psi_2|^2 \quad \text{(Pattern c) Interference pattern. (3.2)}
\]

bigger entity, The superposition experiment can be realized on bigger entities other than photons or electrons. In fact recent experiments have been performed with not

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\(^k\) Lecture given by E.C.G. Sudarshan at the Workshop on ‘Frontiers in Quantum Mechanics and Consciousness’, 2009, SVYASA University, Bangalore.
only atoms but with very big molecules like Fullerenes (containing 60 carbon atoms) [Zeilinger, 2005b]. Bose-Einstein condensates [George Greenstein and Arthur Zanjoc, 2007] were also used to demonstrate the interference phenomenon. Hence it is not the size that really matters but the fact that the particles themselves should not ‘get detected’ on the way. Once they get detected the ‘trajectories’ will be formed and the very nature of the experiment will become quite different.

![Figure 3.1 The famous double-slit experiment](image)

### 3.2.3 Mach Zehnder Interferometer

Experiments using Mach Zehnder interferometer can be used to demonstrate the quantum enigma most vividly. The figures 3.2a and 3.2b caricature almost the essence of the whole idea. The semi-silvered\(^1\) beam splitters, S-1&2 reflect 50% of the light and transmits the other 50% falling on it. The intensity of the source can be adjusted to be so low that it emits only one photon at a time; the two parts of the experiment are depicted in fig 3.2a & 3.2b. Detectors D1 and D2 of figure 3.2a will never click simultaneously. That is, if D1 clicks, D2 will not click and vice versa which can be verified by connecting both detectors to a coincidence counter. Ideally the two detectors can even be in far away places like even two different galaxies. The correlation between D1 and D2 can easily be explained by the particle picture as perhaps the photon (‘particle’) has decided to go to one of the

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\(^1\) These days the thickness of the plates is adjusted to do the job more efficiently. The technical details are secondary to the present discussions and therefore omitted.
detectors at the time of reflection at the first beam splitter-1. If we now adopt the wave picture, then it would require that the detection at one of the places collapses non-locally the entire wave function that goes to other detector which can be well-separated.

![Figure 3.2a](image1.png)  ![Figure 3.2b](image2.png)

Mach Zhender interferometer Experiment to prove non-locality and wave-particle duality

Hence wave-picture apparently does not fit in here. In order to avoid this proposed collapse, say, one may stick to particle picture. But it will be shown that this is not possible if we consider the second part of the experiment which demonstrates the superposition aspect by means of interference. The ‘spooky’, ‘instantaneous’ influence can be appreciated more, if we contrast this situation with the next part. The picture will be completed only then. This becomes more bizarre when we consider that in SRT the concept of simultaneity as well as the order of events in two space-like separated events is reference frame dependent and hence the word ‘instantaneous’ also cannot have any usual meaning, if at all. As for the second part, consider two more mirrors that reflect the two ‘parts’ of light. They are then made to interfere using the beam-splitter-2 (semi-silvered mirror or phase-plate) kept in their path as shown in figure 3.2b. The path difference between the photons can be adjusted in such a way that either the waves interfere destructively along D1. Therefore no photons will be detected by D1 in which case only the detector D2 will register photons. Moreover by adjusting the path difference continuously the correlations between D1 and D2 can be shown to be wavy, clearly showing the wave nature. Without the second beam-splitter-2 in place both the detectors would
trigger but not simultaneously. This means that the photon would have taken either path-1 or path-2, but not both. Clearly, unlike in the earlier case, particle picture does not fit in here, whereas wave picture does not fit in the earlier scenario. In other words, the first part of the experiment (fig.3.2a) can only be explained by particle paradigm and second part (fig.3.2b) by the wave picture. Wave aspect or the particle aspect both cannot be simultaneously observed as per Bohr’s complementarity principle [Folse,1964], which so far has been experimentally vindicated several times and the contrary examples not found yet. It is not surprising altogether as the non-local and local aspects are mutually exclusive.

3.2.4 Wheeler’s Delayed Choice Experiment

In the above experiment, the introduction of the second beam-splitter-2 influences the photon ‘decide’ not to take one of the paths but both of them. This introduction can be delayed after the light underwent reflection at the first beam-splitter-1 which was suggested by John Wheeler adding more mystery of the whole thing. Non-locality is clearly demonstrated by the Wheeler’s delayed choice experiment. This experiment has been realized in the laboratory. In the delayed choice experiment the photon’s reflection or transmission at the first beam-splitter-1 is influenced, but not completely determined by the presence of the second semi-silvered mirror far away from the first.

The quantum cosmologist, Wheeler extended this argument of ‘retro-influence’ to the cosmic level. The splitting of the photon beams by massive objects like a galaxy or a cluster of them (often called gravitational lensing) causes what was observationally found as Einstein ring. Hence if it is true that the placing of the second semi-silvered mirror influences the decision of the photon in a retrospective way, logical consistency would require that the entire historical course of the universe in some way is affected by our observation at present. This is an extreme extrapolation of the above experimental situation in the Wheeler’s delayed choice.

According to wheeler, we are in a sort of participatory universe wherein we, the observers are the central figures. The problem here is not of forming a
complete mental picture alone but it puts one into a logically tight corner similar to that of the EPR situation (see chapter-4)- a non-local and retro influence with its bizarre ontological possibilities. The delayed choice experiment demonstrates clearly the instantaneous and even retro influence in quantum.

![Figure 3.3 The Cosmic Mach Zehnder interferometer](image)

A dramatization of this situation can be seen in the Wheeler’s illustration in which a photon traveling all the way far away from a very distant quasar for several billions of years only to encounter the mirrors and detectors on Earth to be waiting for it to be detected (see fig.3.3) [Penrose, 2004]. Light from a far away quasar is split by the gravitational lensing. Whether the photon takes both the paths or either of path-1 or path-2 is decided by the observer on earth by placing a beam-splitter or not. We have a case of ‘retro-influence’ not retro-causality. This makes QM co-exist peacefully with SRT.

### 3.3 de Broglie Paradox

Let us regard the surface of the walls of a box as perfectly reflecting and that this box can be divided into two parts, box-1 and box-2 by a smoothly sliding partition [Selleri.F and Tarozzi .G, 1981] and also imagine that the box contains a single electron and initially the partitioning wall is not introduced, as in upper part of figure-3.4. Then in the beginning the wave function $\psi(x,y,z,t)$ is confined to the volume, $V$ of the whole box. The probability density of observing the electron in
any small elemental volume $dV$ around the point $P(x,y,z)$ at time $t$ is $|\psi(x,y,z,t)|^2 dV$.

![Figure 3.4 de Broglie Paradox](image)

We now slide the partition so as to divide the box into two parts Box-1 and Box-2 of volume $V_1$ and $V_2$, respectively after which the two parts are taken far apart. In principle there is no limit to this separation. The particle inside the box has not been observed after the box was divided into two. If $\psi_1(x,y,z,t)$ and $\psi_2(x,y,z,t)$ be the wave functions defined in volume $V_1$ and $V_2$ of Box-1 and Box-2, respectively, then the corresponding probabilities of finding the particle in the two boxes are given by:

\[ P_1 = \int_{V_1} |\psi_1^*(x,y,z,t)\psi_1(x,y,z,t)|^2 dV = \int_{V_1} |\psi_1(x,y,z,t)|^2 dV, \quad (3.3) \]

\[ P_2 = \int_{V_2} |\psi_2^*(x,y,z,t)\psi_2(x,y,z,t)|^2 dV = \int_{V_2} |\psi_2(x,y,z,t)|^2 dV. \quad (3.4) \]

Obviously the total probability is $P = P_1 + P_2 = 1$. By observing box-1 (say at time $t = t_o$) we can predict with certainty the outcome inside box -2 at that time. If the electron is found in box -1, then

\[ P_1 = 1, P_2 = 0 \quad \text{and} \quad \psi_2(x,y,z,t) = 0. \quad (3.5) \]

Instead, if the electron is not found in Box-2, then

\[ P_1 = 0, P_2 = 1 \quad \text{and} \quad \psi_1(x,y,z,t) = 0. \quad (3.6) \]
Observation of the electron in one box, far away, collapses the wave function of
the other box non-locally and instantaneously. The order of events which are
space-like separated could be reversed in some suitably different inertial frames of
reference [Einstein,1907]. SRT rejects the absoluteness of simultaneity itself. For
space-like separated regions the concept of simultaneity is meaningless. As we
shall see later this forms one of the grounds for rejecting the space-time picture in
QM. The repudiation of space-time frame is tantamount to infringement of the
principles of locality and causality as SRT mingles locality and causality into local
causality. That is, quantum indeterminacy *ipso facto* is break down of local-
causality at least at the micro-level. We may return to this point a few times to
examine it from different point of view.

Now, from a purely classical point of view it may seem ridiculous to have
talked about the non-local collapse and quantum jumps. It might even look like
wondering at a paradox created by the artifacts of wrong assumptions and then
wondering at its consequences. One might argue that after all if we put a ball in
one of the two boxes and open one of them then we immediately come to know
about the other and hence there is apparently no question of non-locality or any
paradox in here. The trouble is only when we adopt the wave picture in this case.
One is entitled to have a particle picture and adhere to it throughout. But it is not
possible to be consistent in all the cases considered. The interference experiments
cannot be explained by the particle paradigm. That is, it is not possible to stick to
only one picture throughout. Similar predicament is experienced in the paradoxes
described below which are not resolved satisfactorily till date in spite of having
several of propositions. All the various interpretations of QM have certain
queerness about them. It is to be underscored that the general consensus is that the
quantum mechanical wave-function is non-local.

As per the standard orthodox interpretation of QM, the dynamical variables do
not have any reality or cannot be assigned a definite value before the actual
observation, being in a state of superposition of possibilities with various
probabilities. Thus there seem to be non-local influences on separated quantum
systems. Yet, one cannot use it for faster than light (FTL) messaging due to the inherent quantum indeterminacy or randomness of the outcome of measurement. Nature seems to be conspiring against exploiting the non-local effect for super luminal communications. The non-local correlation in this case of de Broglie experiment is that one never observes the particle in both the boxes. As told earlier, assuming classical particle scenario one can easily explain it. Nevertheless, the wave nature of particles defies such an explanation. What is it that makes an object such that it behaves like a particle at certain times and wave at other times? The answer seems to be rather elusive.

‘All this leads to a rather elementary conclusion: de Broglie’s paradox exists only for people who insist on a realistic (particles exist objectively) and rationalistic (space-time is not an illusion of our senses and it is possible to talk about electron localization.) philosophy’ [F.Selleri and G. Tarozzi, 1981].

### 3.4 Schrödinger’s Cat Paradox

The essence of the measurement problem is most vividly depicted by the Schrödinger’s cat paradox. This is the most famous of all quantum mechanical paradoxes. The superposition of two quantum states $\phi_1$ and $\phi_2$ can be represented by the equation,

$$
\psi = \frac{1}{\sqrt{2}} (\phi_1 + \phi_2).
$$

Equation (3.7) depicts the strange quantum superposition state. A particle or a quantum system can be in such a superposition state. More exactly it is in a state which is a linear combination of two or more possibilities. By classical logic one may say either ‘YES’ or ‘NO’, never both at the same time where the two possibilities are mutually exclusive. Schrödinger cat state is a state before observation which is not actualized by measurement. According to Bohr’s version of Copenhagen Interpretation (CI) the value of a dynamical variable of a physical system can only be in relation to an experimental set up (see chapter-6). In
philosophical terms it could be interpreted as the reality of dynamical variable is manifested by the act of actual observation. Schrödinger was averse to the CI. ‘*If one has to live with this darn quantum jumps, then I feel sorry that I had anything to do with it*’-Schrödinger [Bell, 1987].

Schrödinger conceived the following idealized situation to illustrate the apparent absurdity of the concept of this quantum superposition state mentioned above and the postulate of collapse of the wave function by observation. This paradox has defied proper and completely satisfactory explanation until now creating a stalemate situation. The quantum states can be a superposition of the possible states or corresponding wave functions. When observation takes place, state vector reduction (which means ‘collapsing’ into a definite state/outcome) occurs. This aspect of QM remains a paradox even today. The situation is akin to that in the de Broglie paradox.

A cat is placed inside a closed box along with a sealed bottle of cyanide. There is a certain radioactive material inside the box in a bottle which has a 50% chance of decay [John Gribbin, 1996]. The decay would trigger a mechanism that would break the bottle with a 50% chance as it is linked to the above decay process (a quantum mechanical process). If the bottle is broken then the cat would definitely be killed instantaneously. This contraption of Schrödinger is only one of the many
ways of linking a quantum process to an observable macro process that has a
definite outcome (on observation).

A physicist looking at the outside of the box will definitely not know if the cat is
dead or not. But if the box is opened he is certain to find the cat either dead or alive
but not in a ‘superposition state of suspended animation’ (i.e., dead and alive at the
same time). So opening of the box and the ‘act of observing’ is supposed to take
the state to either ‘alive or dead’ state. That is, the observation collapses the wave
function to one of the two states mentioned above. The circumstance here is akin to
the de Broglie case discussed above as far as the collapse is concerned. But
Schrödinger’s cat is more vivid in that it also emphasizes the linear combination
aspect of a state before observation. It was meant to be a direct attack on the
Copenhagen notion of quantum reality. Since then, in physics literature
Schrödinger’s cat had become a metaphor to represent superposition states in QM
which is quite distinct from the classical mixture. The state of the cat is entangled
quantum mechanically to that of the radioactive state. Hence we can describe it
with a total quantum state, which is a linear combination of the two possible states.
Now the total wave function is
\[ \psi = \frac{1}{\sqrt{2}} \left( \psi_{\text{alive}} + \psi_{\text{dead}} \right) . \]  

The laboratory versions of Schrödinger’s cat consist of particles or even group of
molecules these days. Such states were realized in the laboratory using \( C_{60} \)
molecules (Bucky balls) and even Bose-Einstein condensates [George Greenstein

Schrödinger’s cat points to a very important point. It was supposed that the
certain superposition states existed only at the micro-level and not at the macro-
level. If we consider the macro-level, every measurement seems to yield definite
values like those in a typically classical state. Due to statistical reasons the
infringement of causality becomes insignificant at the macro realm which is not so
in the micro phenomena. What Schrödinger wanted to demonstrate was that it was
possible to link and amplify the micro-level events to the macro level by some
suitable device. It is only a question of technological sophistication to amplify these micro-level problems connected with reality to the macro status. Hence causality violations or issue of reality cannot be neglected by dubbing them to be only micro affair.

### 3.5 Wigner’s Friend Paradox

Wigner’s friend experiment is an extension of Schrödinger’s cat to demonstrate an additional aspect. Wigner considered the case when a conscious person (say, his friend) is included as part of the equipment in the previous Schrödinger’s cat experiment. This person will be in superposition of different state vectors corresponding to possible outcomes until he interacts with the observer, say, by asking him questions [Wigner, 1962, 1965]. He wanted to show that the ‘reduction of state vector’ can be by any one endowed with consciousness. The question is whether the Schrödinger’s cat has enough degree of consciousness to reduce it or it is at the lower end of it so that it will go into superposition state like other inanimate objects. Wigner suggested that the observer’s awareness of the state of the cat might change or reduce the state to either alive or dead. The assumption of Wigner was that the wave function, $\psi$, is a property of the object. The act of observation affecting the wave function $\psi$ directly leads to the philosophy of solipsism\textsuperscript{m} [Amit Goswami, 1995].

Wigner considers the following paradox. He asks his friend to observe (equivalent to taking measurement) the cat on his behalf. His friend observes at a time $t_f$ and Wigner asks him about it after some time, say $t_o$. As he becomes aware of the result the wavefunction $\psi$ changes from a state of super-position depicting indefiniteness to a definite state at $t_o$. So he assumes that throughout the interval between his friend’s observation and becoming aware the system was in a state of indecisiveness. Yet his friend says that he was sure of the state of the object at $t_f$. The paradox lies in the following. Both of the acts, his friend’s observation and the

\textsuperscript{m} The doctrine that “I” or the SELF alone exists.
subsequent asking by him should not give two different results for time of reduction of state of the cat. To resolve this Wigner suggested that an interaction between living minds and inanimate nature would cause the reduction of state [Alastair Rae, 1995]. To prove the point further he argued that when mind can be influenced by the environment, the mind of the observer will be able to affect the surroundings in a similar way. The symmetry of the law similar to action and reaction is invoked here.

## 3.6 Herbert’s Paradox

Herbert in 1982 proposed a *gedanken* experiment to suggest that non-local communication might be a possibility. It is basically a modification of the Freedman-Clauser apparatus to test the Bell’s inequality (chapter-5). As depicted in figure (3.6), a source produces entangled EPR pairs of photons.

![Figure 3.6 The experimental set up to demonstrate Herbert's paradox](image)

A and B are the two arms of the interferometer. At the end of the arm B a semi-silvered mirror splits the beam. The laser ‘gain tube’ is to ‘clone’ photon 2. The PP Beam splitters are to allow different polarization measurements on the cloned photons of B. The detectors marked H, V and H/R are analyzers to measure the horizontal, vertical and circular polarizations of the photons.
The photons travel from each other to space-like separated regions along the arms A and B. A laser ‘gain tube’ amplifier is added to the arm B of this apparatus. Notwithstanding the ‘no-clone theorem’ [Wooters and Zurek, 1982], the laser-gain tube would then ‘clone’ the photon from the source by a process of stimulated emission, making several copies of the say state vector $|B_i\rangle$ of photon B. There is nothing that would prevent from determining this state of polarization exactly. There are beam splitters to divert these several ‘cloned’ editions of photons. Now, multiple measurements can be made with polarimeters set along several axes to divulge the type of polarization measurement which was performed on the photon in the state $|A_i\rangle$ in the arm A. For instance, it can very easily be determined whether it is a linear or circularly polarized photon A. This would apparently allow one at A to send a message to another at B across a space-like interval for example by encoding a message in the time structure of the measurements done, say, in a binary code of 0 and 1. That means superluminal communication would then be possible against stringent stricture of SRT.

### 3.7 Discussion and Comments

We feel that most of the paradoxes that we come across in QM hint at the problems that we are led to, when we deal with the reality of the wave function and the apparent absurdity of collapse of the wave function. The problem arises when the wave or non-local description is suddenly used to describe the particle or localized aspects or vice versa.

#### 3.7.1 The Quantum Measurement Riddle

We feel these quantum paradoxes are actually due to the fact that we use the particle aspect to explain the wave properties like interference pattern. The interference effect is actually due to wave nature which is non-local while particles have localized behaviour. But how does the wave collapse on observation to a

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n The no-clone theorem of the quantum states is employed in the quantum teleportation and cryptography experiment.
localized particle? This notorious ‘measurement problem’ is sometimes termed as ‘collapse of wave function’ or its analogue in Hilbert space as ‘state vector reduction’. There is much more to the measurement problem than the problems of wave particle duality. What constitutes a quantum measurement? What constitutes a classical instrument? When is a measurement said to be complete? John Bell talks about the misuse and misunderstanding surrounding the notion of measurement and even almost recommended banning this very particular word altogether [Bell, 1990a]. He talks of ‘beables’ instead of ‘measurables’ [Bell, 1976b, 1985]. We discuss more about the measurement problem in section (6.4) of chapter-6.

3.7.2 Quantum Mechanics and Reality

Equations (3.7 and 3.8) represent superposition state which is not surprising, as it is a property of the Euclidian space. The Euclidian space has the property that if a set of bases can be expressed as a linear combination of another set then the latter can be expressed as the linear combination of the former. That is, one set of bases can be expressed in terms of another basis and vice versa (chapter-4). In other words, there is no unique or privileged set of bases. If \( |\psi_1\rangle, |\psi_2\rangle, |\psi_3\rangle, \ldots, |\psi_n\rangle \) represent possible eigen states of a system, then the linear combination of the same as given by

\[
|\Psi\rangle = a_1 |\psi_1\rangle + a_2 |\psi_2\rangle + a_3 |\psi_3\rangle + \ldots + a_n |\psi_n\rangle ,
\]

(3.9)

also represents an eigen-state. If \( \phi_1, \phi_2, \phi_3, \ldots, \phi_n \) are a set of solutions of Schrödinger equation, then a linear combination

\[
\Phi = a_1 \phi_1 + a_2 \phi_2 + a_3 \phi_3 + \ldots + a_n \phi_n
\]

(3.10)

is also a solution to the equation on account of linearity. The postulate of linearity and the corresponding property of the mathematical formulation together justify the superposition principle. The quantum theory is formidable in its formulations. In addition, experimental results have always confirmed the theoretical predictions to a very high degree of accuracy and so far have not been contradicted. The fact
that it is non-intuitive is perhaps due to two reasons. We are used to the classical way of thinking and the non-locality and superposition of states are alien to classical paradigms. Classical world is a world of measurements involving classical instruments. Whether the irreversible process of measurement is due to decoherence effect or not, the basic idea of CI has been the foundation of all the other interpretations about which we shall discuss in the sixth chapter on interpretations. Bohr’s deep insight on QM is really superb, especially at a time when so much of experimental data were not available as we have today.

Some of these questions related to measurement coerce one to talk about the subjective aspects like consciousness and free will. The measurement itself is the problem as such. The above mentioned paradoxes are the compelling features that are clearly on the verge of true subjectivity. Therefore physics, that is supposed to be the most objective of all sciences, unwittingly and inevitably turns to the subjective questions directly related to consciousness, free will and self. We discuss these in some more detail in later chapters. Similar situations arise in cosmology and biology (Appendix-B) also where one can possibly not be at peace without tackling the subjective matters.