Primal structure of Quantum Mechanics - A critique and an alternative

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Abstract
The basic premise of Quantum Mechanics, embodied in the doctrine of wave-particle duality, assigns both, a particle and a wave structure to the physical entities. The classical laws describing the motion of a particle and the evolution of a wave are assumed to be correct. Gauge Mechanics treats the discrete entities as particles, and their motion is described by an extension of the corresponding classical laws. Quantum mechanical interpretations of various observations and their implications, including some issues that are usually ignored, are presented and compared here with the gauge mechanical descriptions. The considerations are confined mainly to the conceptual foundations and the internal consistency of these theories. Although no major differences between their predictions have yet been noticed, some deviations are expected, which are indicated. These cases may provide the testing grounds for further investigations.

1 Introduction
Early physicists, in their attempts to understand the behaviour of material bodies in motion, treated them as particles, i.e., as materially isolated, discrete entities that may be idealized as mathematical points. While these structural properties completely characterize a particle, they give no indication of the laws governing its motion. The motion of a particle was studied by observing the evolution of its position with respect to time. Initially, this resulted in the so called empirical laws, and then in Newton’s laws of motion, which were further adjusted in conformity with the relativistic formulation. These classical laws were found to describe the motion of particles encompassing a large range, within the limits of the accuracy of the measuring devices. However, this success does not establish their finality, as is the case with all the physical theories.

In a double slit experiment, photons, electrons and other similar physical entities encounter a barrier with two slits enabling them to pass through, and then they land on a distant screen. On the screen they are known to arrive as isolated, discrete entities with small extension, that is, as particles, essentially by definition. Now, if

A. the observed entity is a particle at all space-time points, and
B. the classical laws describing the motion of a particle are valid,
then a large number of them, arriving as a collection or individually, should cluster in two separate or overlapping regions on the screen. However, a large number of the entities identified as particles, arriving as a collection or individually, are observed to cluster about several locations, with very few in between, when the separation between the slits and the screen is sufficiently large [1 pp.2-5]. Thus, if A and B are both true, we encounter a contradiction. Hence,

C. A is not true or B is not true.

To be precise, C holds if one of the following three mutually exclusive statements is valid:

C1. A is not true but B is true.
C2. A is true but B is not true.
C3. A is not true and B is not true.

Quantum Mechanics developed essentially out of the premise C1., supplemented with the assumption that these entities are waves at some space-time points, embodied in the orthodox or the Copenhagen interpretation. As is well known, various interpretations of Quantum Mechanics were developed to overcome the consequent difficulties. Notable among them are the probability interpretations [2,3,4 pp.38-44], the pilot wave interpretation, which evolved into Bohmian Mechanics [5], and the many worlds view [6]. These alternative views attempt to eliminate C1. as the founding premise of the theory, to some extent. Also, a number of alternative formulations of mechanics have been attempted [7] and there are variations on the original interpretations.

These attempts were motivated by the fact that a violation of A alone is sufficient to create some inconsistencies, which are compounded by the assumption of the wave nature. Thus, a theory based on C3. would also suffer from such difficulties. Although it is not of primary importance, C3. is also a stronger statement than either of the other two. Therefore, it would not be desirable to make C3. the basis of mechanics, unless a satisfactory theory cannot be based on either of the others.

Recently, a new formulation, Gauge Mechanics [8], was developed with C2. as its premise, supplemented with new laws of motion replacing the classical ones. The laws of motion for a particle were developed by extending the classical, by a process of completion in the framework of Weyl’s gauge transformations. Thus, this formulation bypasses the quantum mechanical and the related developments. The world view presented by this theory is at variance with the others, and some of its predictions appear to differ slightly from those of Quantum Mechanics [8,9]. No major quantitative departures or phenomenological differences have yet been noticed, and several quantum mechanical equations have been deduced, as approximations, from this formulation[8,10].

In the present note, some experimental observations are examined as interpreted by the quantum and the gauge mechanical formulations. The focus here is on the logical consistency of their conceptual foundations. Some of this material has been discussed in great detail in literature, particularly dealing with Quantum Mechanics, but it is scattered. We attempt to present a comprehensive picture but concentrate mainly on the basic concepts, some of which are usually lost in the details. Also, some relevant points that are frequently ignored, are
discussed here. This comparison shows that Gauge Mechanics eliminates the troubling aspects of various interpretations of Quantum Mechanics. Since adequate observations and calculations are lacking presently, a precise conclusion is not possible but the estimated deviations in the predictions, whenever they exist, are also favourable to Gauge Mechanics.

2 Quantum Mechanics

To develop a theory founded on the premise C1., a supplementary assumption is needed concerning the structure of these entities. Violation of \( A \) at all space-time points is excluded as it would contradict the observation of them as particles on the screen, and also at the source which is established by other observations. Therefore, a non-particle structure can only be assumed at some space-time points.

A classical wave in a double slit experiment is divided in two at the slits, which interfere with each other as a pair, transmitting energy to the screen continuously that is distributed in a similar pattern as the observed density built by the arrival of a large number of the discrete entities. This similarity provided the basis for the founding assumption of Quantum Mechanics that what is observed as a particle on the screen, travels as a wave, which was forged into the doctrine of the wave-particle duality. The equivalence is established by

\[
\lambda = \frac{2\pi}{p}
\]

where \( \lambda \) is the wavelength of the wave and \( p \) is the momentum of the particle, in natural units, i.e., with Planck’s constant equal to \( 2\pi \).

Even if the history of the formation of the density distribution on the screen is ignored, the existence of such a pattern is not sufficient to establish that it was produced by a wave. Therefore, to have this conjecture as a viable basis of a theory, further evidence is needed, even if one is inclined to set the following difficulty aside for the time being.

Since these entities are observed as particles at some space-time points, the violation of \( A \) requires an abrupt transformation of a non-particle into a particle on the screen, in fact, whenever an observation is made. If a compelling evidence of these entities being waves is found, then this issue could be considered, likely with some insight provided by the observations.

The matter of the accuracy of the prediction of this assumption, in case of the original double slit experiment, has rarely been raised, but obviously, it is relevant. A coherent wave, split in two at the slits, must interfere to produce points of zero intensity between the two consecutive maxima. Observed minimum intensity differs significantly from zero. Explanations, for example, in terms of the diffusion caused by the interaction between the observed entities and the atoms on the screen, are suspiciously qualitative. Thus, to settle this issue, appears to require more careful measurements.

The predictions based on the rules of Quantum Mechanics are quite accurate for a large class of phenomena, within the limits of the measuring devices. In fact, the success of Quantum Mechanical rules in describing the observations and in the new developments, has been its strongest defence. However, this does not establish complete accuracy of the quantum calculations in all situations, and of course the issue of its conceptual foundations remains open, no matter how accurate and encompassing the descriptions may be.

Weak conceptual foundations of Quantum Mechanics inspired numerous experiments, including some thought experiments. These will be stated and discussed in a later section, on the background of some interpretations of Quantum Mechanics outlined below.

The original, Copenhagen interpretation is essentially the wave-particle duality doctrine, that these entities have a dual personality. The transformation from a wave to a particle is
assumed to be the result of the collapse of the wave-function, caused by an act of observation, even non-intrusive. This interpretation introduces unwarranted discontinuities, no mechanism or characterization for this process has been conceived and it assigns an unreasonable role to an act of measurement, that of a creator of the outcome. These are the sources of various difficulties with Quantum Mechanics [6]. The reverse process, termed the quantum eraser, presumably undoes the effect of a collapse [11].

According to the probability interpretation proposed by Schrödinger [2], a physical system has no objective meaning prior to a measurement, and the associated wavefunction $\psi$, characterizes it completely. The probability density, given by $|\psi|^2$, is fundamental and provides a complete description of an individual. The statistical interpretation suggested by Born [3,4 pp.38-44] is essentially the same except that it is non-committal about the meaning of a system prior to a measurement, and thus an individual is described entirely in terms of a statistical concept. Both of the views hold that a probabilistic assertion can be a complete description, and retain discontinuous changes in the wavefunctions as a part of the formalism. These interpretations attempt to eliminate C1. as the basic premise by considering the structural properties somewhat irrelevant [12].

The pilot wave interpretation, originally proposed by De Broglie and developed by Bohm [5] is based on the polar representation of the wavefunction, originally used by Madelung [13]. The wavefunction $\psi$ may be expressed as $\psi = \sqrt{\sigma} \exp(iS)$. Substitution in the Schrödinger equation then yields the following, coupled set of equations:

$$\frac{\partial \sigma}{\partial t} + \nabla \cdot \left( \frac{\sigma \nabla S}{m} \right) = 0 \quad (1)$$

$$\frac{\partial S}{\partial t} + \frac{(\nabla S)^2}{(2m)} + V - \nabla^2 \sqrt{\sigma}/(2m\sqrt{\sigma}) = 0 \quad (2)$$

The picture that emerges, from (1), is that the probability density $\sigma$, evolves as a classical fluid with velocity $(\sigma \nabla S/m)$. Eq. (2) differs from the Hamilton-Jacobi equation by the last term, called the quantum potential, that depends on the state of the particle, and impacts upon the trajectory.

The Madelung equations provided the foundation for what has come to be known as Bohmian mechanics [5], which is equivalent to Quantum Mechanics except for a variation in the interpretation. In the previous interpretations, a particle has no objective meaning or the issue is irrelevant, and thus, there is no concept of its trajectories. Instead, the probabilities are considered sufficient to describe the behaviour of a particle. Bohmian mechanics interprets the system as a particle following a trajectory, determined by the Bohmian field, which flows as a classical fluid. Since this is a coupled set of equations, the trajectory and the field flow, both affect each other. Thus, Bohmian mechanics interprets Quantum Mechanics so that A is preserved. The classical law of motion for particles is replaced by the one determined by the Madelung equations, equivalently, Quantum Mechanics, involving the Bohmian field, as if a particle floats in it. In this formulation, particle and wave are made available at all times acting according to their respective classical characters. Whichever is suitable for a given situation may then be invoked without forcing a transformation of one into the other. In case of the double slit experiment, according to this view, the particle passes through one slit or the other and the wave, through both, and the probability of a particle existing in a space-time region is determined by the wave.

Dalton [14] has developed a model with the particle floating in the fluid. This formulation overlaps with the Bohmian view, but there is a basic difference: The trajectory is determined by a fundamental force that coordinates the particle motion with the wave, in a limit.
Everett’s "Relative State” formulation [6], commonly known as the many worlds interpretation, was developed in an attempt to eliminate the discontinuous change resulting from an act of measurement. This was done by considering the original system and the measuring device as the subsystems of a larger system. The measured state of the observed subsystem depends on the state of the observing subsystem. The view presented is that a physical system is composed of many states, each one in a world of its own. Which state it is observed in, depends on the world the observer enters. The concept of the collapse of a wavefunction is avoided by introducing many copies of the world where a laboratory and the observer exist. All of the other aspects of the quantum mechanical formulation are maintained.

All of these formulations maintain the equivalence of the probability density and \(|\psi|^2\), and thus the wavefunctions differing by a phase factor are physically indistinguishable.

A common feature of all the above interpretations is that each one addresses a part of the complete set of difficulties associated with Quantum Mechanics. In some cases, a troubling concept has been replaced by another, requiring further explanations. For this reason, the interest in each has varied with time.

3 Gauge Mechanics

The gauge mechanical formulation is based on the premise C2. from the outset. This requires that the classical laws of motion for a particle must be modified. The classical laws describe a large class of phenomena quite accurately. Therefore, they must be approximations to the more accurate ones. Thus, their extension should be an appropriate route to the more accurate laws. Gauge Mechanics is founded on an extension of the classical, Hamilton’s action principle.

So far, the formulation is restricted to the particles of non-zero rest mass, ignoring the spin. Thus, the following considerations are strictly applicable only to such cases, although some reasonable conjectures are possible for the others. An extension to the particles of zero rest mass appears to be straightforward but the case of spinors requires additional developments.

3.1 The gauge mechanical principle

The concept of the gauge transformations was developed by Weyl, motivated by the observation that only the ratios, not the absolute values of the elements of the metric tensor in a space are physically determinable. Weyl proposed that this makes it impossible to attach an absolute meaning to the length of a rigid measuring rod. The gauge group element associated with a general curve is defined in terms of the change in the rod as it is transported along the curve. The force field at a point in a space equipped with a gauge field, e.g., the electromagnetic, may be defined in terms of the change in the length, as the rod is transported along an infinitesimal closed curve about the point.

The classical trajectory for a particle is defined by Hamilton’s action principle, i.e., by the requirement that the action about it be stationary. This is expressed as \(\delta S = 0\), up to the first order as a trajectory is varied, which is equivalent to \(exp(\alpha S_{ABA}(\rho_c)) \approx 1\) up to the first order in the area enclosed by an arbitrary closed curve \(\rho_c\), in a small neighbourhood. Each curve \(\rho_c\), is defined as the union of a path \(\rho'\) from A to B, and the inverted path \(\rho\) from B to A, and \(\alpha\) is a constant. The gauge mechanical principle extends the action principle by requiring the equivalence exactly, and includes all the curves into consideration. Thus, the gauge mechanical,
or the physical, paths are the continuous solutions of

$$\kappa(B) \exp(\alpha S_{BA}(\rho)) \kappa^{-1}(A) = 1$$  \hspace{1cm} (3)

As explained in [8], $\kappa$ represents the state of the system, and remains constant for a free particle, which may be considered an extension of Newton’s first law. The value of $\alpha$ was also determined from the motion of the free particles, to be equal to $i$. It is clear that this approach bypasses the quantum mechanical and the related developments completely.

The gauge mechanical principle describes motion in terms of the general gauge group elements while the action principle defines it in terms of the force field [8]. In addition to the metaphysical arguments given above, it will be indicated in the next section that the Aharonov-Bohm effect presents a compelling experimental motivation for building mechanics in terms of the gauge group elements, instead of the field. Although of a motivational value, these arguments are inconsequential for the validity of (3) as the principle describing the motion of particles. It is sufficient that this prescription describes the experimental observations in a logically consistent manner.

Present extension assigns infinitely many, equally likely, paths to a particle in motion. A particle may follow any one of the allowed paths on the basis of random selection. Thus, while there is a definite trajectory that a particle follows, it cannot be determined before or after the event, since it is selected on a random basis, even though from a precisely defined collection, indicating the existence of an objective reality coupled with randomness, from the outset, which is confirmed by the later considerations. It should be noted that, there are infinitely many trajectories that are excluded from the collection of the particle paths.

Being an extension, the present approach to the formulation of mechanics is similar to Hamilton’s, which was itself motivated by Fermat’s principle of stationary time for the light rays. All of these formulations prescribe a principle to assign geometrical trajectories to the entities under consideration, and thus assume that it can be idealised as a point, or at least, a central point can be assigned representing it in a geometrical setting. Einstein’s formulation of the motion of a particle in a gravitational field falls within the same class. The present approach is geometrical in nature as are various other theories in physics, including the above, and the modern ones related to the fields and the fundamental particles.

3.2 Physical paths

The solutions of (3) fall within two distinct classes: monotonic and non-monotonic, defined by the respective property of the evolution parameter, which is taken to be the proper time with the curves being in the Minkowski manifold. The non-relativistic description is treated as the limiting form of the relativistic. Along a curve such that all but one coordinate are constant, a monotonic classical trajectory is physical if and only if its length is an integral multiple of $2\pi/p$, with $p$ being the momentum. Each point on the surface of a sphere with radius $2\pi/p$ is reachable along such paths from a point source at the centre. The next surface is formed as the envelop of the spheres with the same radius with centres at all points of the original sphere. This parallels Huygenes’ construction for the propagation of a classical wave. A particle can reach other points also, but along non-classical physical paths. It was also shown in [8] that a non-monotonic physical trajectory can be treated as a pair of two monotonic ones, which will also be called the correlated paths.

According to some elementary estimates, the physical paths cluster close to the classical, physical trajectories. As an example, consider a non-relativistic particle moving along x-axis,
from time $t = 0$ to $T$. Let $\rho$ be a classical trajectory with $x(0) = 0$ and action $S(\rho) = (2\pi n - \omega)$, where $n$ is an integer. It is clear that $\rho$ is physical if and only if $\omega = 0$. It can be shown that there is a physical path $\hat{\rho}$ in a small neighbourhood of $\rho$ with $\rho(0) = \hat{\rho}(0)$ and $\rho(T) = \hat{\rho}(T)$. Consider a physical path $\tilde{\rho}$ with $S(\tilde{\rho}) = 2\pi n$, in an $\xi$ neighbourhood of $\hat{\rho}$ with $\xi(0) = 0$. Standard manipulations and estimates yield that $\xi(T) \simeq [a\bar{\xi}^2 + b\bar{\xi}\sqrt{\omega}]$, where $a, b$ are positive constants and $\xi$ is an average value of $\xi$ [9]. The density of such paths ending close to the end point $\rho(T)$ is directly proportional to $[1/\xi(T)] \simeq [a\bar{\xi}^2 + b\bar{\xi}\sqrt{\omega}]^{-1}$. Thus, there is a considerably high density of allowed paths, and hence of the particles, about the classical, physical paths than the others. These estimates are extendable to the case of the non-monotonic solutions with the same conclusion.

3.3 The double slit experiment

As discussed above, the quantum mechanical formulation developed from attempts to reconcile what has been considered the mysterious behaviour of the microscopic entities in a double slit experiment. This was done by assigning to each item a dual structural character, that of a particle and a wave, fused together. Classical laws describing the time evolutions of the particles and the waves were assumed to be correct, each one applicable according to the operative structure of the entity. Gauge Mechanics, on the other hand, considers the observationally determined structural character definitive, and the classically unexpected behaviour, indicative of the inadequacy of the classical laws of motion for a particle. For this to be a viable theory, therefore, the behaviour of these entities, now treated as particles, in the double slit experiment should be deducible from the extended laws. This deduction is outlined below.

In this case, the identical particles encounter two slits, at $A$ and $A'$, and are collected on a distant screen at a point $B$. Gauge mechanically, each particle passes through one of the slits. Because of this arrangement, most of the contribution to the density on the screen results from the non-monotonic solutions of (3), i.e., the solutions of

$$\exp [i(S_{BA}(\rho) - S_{BA'}(\rho'))] = \kappa(A')\kappa^{-1}(A)$$

(4)

If $A$ and $A'$ are physically equivalent, $\kappa(A) = \kappa(A')$. From the estimates indicated in Sec. 3.2., it follows that most of the physical paths are concentrated about the trajectories defined by

$$S_{BA}(\rho_s) - S_{BA'}(\rho'_s) = 2\pi n$$

(5)

where the subscript $s$ indicates that the action is stationary and $n$ is an integer. As a consequence, the particles cluster about the locations $B$ defined by (5), in agreement with the observed fact [1 pp.2-5]. With $\Delta r$ being the difference in the path lengths of $\rho_s(AB)$ and $\rho'_s(A'B)$, (5) reduces to $\Delta r = 2\pi n/p$.

While there is a qualitative agreement between the gauge mechanical prediction of the density distribution and that obtained from the assumption of the wave-particle duality, the quantitative agreement, although close, is not exact. In particular, it can be shown that gauge mechanically the minimum density on the screen differs significantly from zero, in contradistinction with Quantum Mechanics. However, a close agreement between the two provided the basis for the deduction of a slightly modified form of Feynman’s path integral formalism of Quantum Mechanics, as an approximation, from the gauge mechanical formulation [8]. This modification requires that only the contribution from the physical paths be retained in computing the probabilities, while Feynman’s original formulation retains contribution from all trajectories. This
modification played a crucial role in the derivation of some Quantum Mechanical equations, particularly, the Klein-Gordon equation. Wavefunction in this derivation appears as a convenient auxiliary quantity. It should be noted that, while the indicated derivation is instructive, the original gauge mechanical equations should be used for its more accurate predictions, which do not involve the wavefunctions.

4 Discussion

In this section we examine the world view presented by the above formulations by considering some relevant experimental observations and the related matters. To avoid repetition, various interpretations of Quantum Mechanics are discussed only when they provide some additional insight. The world view presented by them is mostly contained in the comments made in Sec.2., that are easily applied to most of the phenomenological situations. The gauge mechanical descriptions are confined to a general exposure that is sufficient for the present purpose. Further details, particularly the computational, are available elsewhere, as indicated.

4.1 The double slit experiment – Effect of observation

The conjecture of the wave-particle duality generated an obvious interest in finding some convincing experimental evidence of these entities being waves in some space-time regions. The double slit experiment presents a natural setting for such observations. Whether an observed entity encounters the slits as a particle or a wave, can be determined by observing just before it encounters the slits. A particle would enter a slit as a whole, but a wave would divide itself and enter both slits. To be precise, consider the case of an electron. One may use light to detect it. If a photon is scattered close to a slit, then the electron is entering it as a particle. If a reasonably high frequency radiation is used in this experiment, then an electron is found to enter one slit, as a complete particle. After a large number of the electrons have reached the screen, they are found to cluster in two overlapping regions, which is radically different from the case when they were not watched. That is, if the electrons are watched, they demonstrate particle structure and travel according to the classical laws of motion for a particle: both $A$ and $B$ appear to be the correct assumptions.

This experiment may be performed with lower frequency radiation to reduce the impact of the observation on the electron. If the frequency is very low, the interference like distribution on the screen is maintained. At these frequencies, one cannot determine which slit the electron passes through. To be consistent with Quantum Mechanics, a photon cannot be localized with better precision than its wavelength. At a low frequency, the photon may have scattered at any point in a region including both slits. Thus, if the electrons cannot be determined to have passed through one of the slits as particles, they appear to pass through both slits as waves.

The density distributions on the screen, as the frequency of the observing photons is altered gradually, appears to be unavailable. According to the wave-particle duality, the distribution should change little as the frequency is reduced, and change abruptly to an interference like pattern as the wavelength becomes large enough to cover both slits. That is, there is a critical level of intrusion to cause the collapse of the wave. Bohmian mechanics avoids the concept of collapse, but the particle gets disentangled from the Bohmian field in a discontinuous manner. In the many worlds view, which world the observing device enters depends discontinuously on the level of intrusion it creates.
As indicated in Sec. 3.3., gauge mechanically, the existence of an interference like pattern requires that \( \delta \kappa = (\kappa(A) - \kappa(A')) = 0 \). The solutions of (4) depend continuously on \( \delta \kappa \), and thus, the pattern on the screen should change continuously with its value. It can be shown that for sufficiently large value of \( |\delta \kappa| \), most of the contribution to the density on the screen results from the monotonic solutions of (3), which yields a classical particle like distribution \[8,9\]. An intrusive observation alters the value of \( \delta \kappa \) which can be determined or estimated with the same degree of accuracy as the available details of the interaction \[9\]. In the above experiment, the pattern on the screen should change continuously with respect to the momentum imparted by the colliding photon to the electron, from one type to the other.

4.2 The uncertainty principle

The uncertainty principle may be deduced from the above observation and the assumption of the wave-particle duality, as follows. The bulk of the argument, briefly outlined here, is the same as in ref. 1, pp. 9-13.

Since the point of arrival of an individual particle on the screen does not enable one to determine which slit it may have passed through, its momentum \( p \) has an uncertainty of \( \delta p \), given by \( (\delta p/p) \simeq (\delta r/d) \), where \( d \) is the separation between the two consecutive maxima on the screen. Here, \( \delta r = \Delta r \) for \( n = 1 \) as defined in Sec. 3.3. A determination of \( p \) and position with an accuracy of \( \delta p \) and \( d/2 \) respectively, would enable one to construct the distribution that is observed for a collection of the undisturbed particles, which is prohibited by the observed behaviour of the electrons when watched with photons with this precision. Hence, \( \delta p \delta x \geq p \delta r/2 \).

In Quantum Mechanics, the wave-particle duality associates a wave of wavelength \( \lambda = 2\pi/p \), with a particle with momentum \( p \). The relation \( \delta r = \lambda \) follows from the classical laws of wave propagation. Both relations together yield \( \delta r = 2\pi/p \). Hence, \( \delta p \delta x \geq \pi \).

The interpretations of Quantum Mechanics assume the uncertainty principle as a part of their schemes. In Gauge Mechanics, the relation \( \delta r = 2\pi/p \) follows from (5). Thus, the uncertainty principle follows without invoking any concepts other than the gauge mechanical, and without any reference to the experimental observations. The behaviour of the particles in the double slit experiment is deducible from the basic formulation of Gauge Mechanics. Therefore, the uncertainty principle also is a deduced result.

4.3 The double slit experiment – Delayed choice observation

The impact of an intrusive observation on the behaviour of the electrons, before they enter the slits, can be eliminated completely, by watching them between the slits and the screen, i.e., the delayed choice experiment \[11\]. Again, the electrons are found to pass through one slit or the other, as complete units, and appear to travel according to the classical laws of motion for a particle, if high frequency photons are used to watch. With low frequency photons, they appear to act as waves. The comments concerning the use of intermediate frequency photons, made in Sec. 4.1, apply to this case also. The quantum mechanical understanding of this behaviour creates a paradoxical situation: Each electron knew in advance how it would be observed.

Gauge mechanically, the situation in a delayed choice experiment is identical to 4.1.: A particle passes through one slit or the other. The momentum imparted during an intrusive measurement alters its course in a quantifiable way to result in the expected observation \[9\].
Incidentally, this behaviour, instead of Sec. 4.1, may be invoked in the deduction of the uncertainty principle in Sec. 4.2 [1 p. 7-13].

4.4 The double slit experiment – Effect of screen’s location

In the original double slit experiment, a large number of electrons produce an interference like pattern on a distant screen. If the screen is moved close to the slits, one finds the electrons clustered about two separate locations.

Implications of this observation appear to be minimised in literature by arguing that moving the screen closer to the slits forces an electron to choose between the slits [11], and thus, to behave as a particle. There is no difference between this setup and the same setup with a larger separation. If a particle passes through both slits as a wave, the pattern should be interference-like, which would give no indication of which slit the electron passed through. Thus, no agency has forced an electron to behave as a particle and no additional information has been generated by the experimental setup that would enable one to determine which slit the electron passed through. This information is deducible only from the density distribution on the screen.

Gauge mechanically, it is clear that the paths available to a particle are determined by the experimental setup. Most of the particles passing through each slit would cluster close to the monotonic, classical physical paths. If the screen is close to the slits so that the regions containing the end points of these paths do not overlap, this covers most of the paths. Usual estimates then yield the observed classical particle like behaviour. If these regions overlap, there is a host of correlated paths available, which outnumber the monotonic trajectories. As in Sec. 3.3., this yields an interference like pattern. According to the estimates, the observation on the screen should change gradually as the screen is moved closer to the slits.

4.5 The Aharonov-Bohm effect [15]

In the experimental setup for this case, identical electrons travel from A to C to B, and from A to D to B, shielded from the magnetic field that the closed path $\rho_c(ACBDA)$ encloses. Here B is a point on the screen. As in the case of the double slit experiment, an interference like pattern forms on the screen. This pattern changes continuously with the magnetic flux $F$, repeating the original one for each integer $n$ as $F = \oint_{\rho_c(ACBDA)} \phi_\mu d\mu$, is replaced by $(F + 2\pi n)$. Thus, the pattern changes continuously as the electro-magnetic potential changes from $\phi$ to $\phi'$, repeating itself whenever

$$\exp[i \oint_{\rho_c(ACBDA)} (\phi_\mu - \phi'_\mu) d\mu] = 1$$

i.e., whenever the gauge group elements assigned by them to the curve $\rho_c(ACBDA)$ are equivalent.

All interpretations of Quantum Mechanics equate $|\psi|^2$ with the probability density, which determines all the physically observable quantities. This implies an equivalence of all wavefunctions differing by a phase factor. The Aharonov-Bohm effect shows that the two wavefunctions differing by a phase factor produce a physically measurable effect. This effect was predicted on the basis of the quantum mechanical equations, indicating an incompatibility of the equations with one of its basic assumptions.

Two alternatives have been suggested to reconcile this experimental observation with the quantum mechanical formulation. One suggestion is to re-interpret the wavefunction and the other, to assume action at a distance. Both of these alternatives create additional difficulties.
Also, it raises the issue whether electro-magnetism and other forces, are adequately described by the fields or by the potentials. The view that emerges, from (6), is that the field under-describes and the potential over-describes them. A complete and optimal description is provided by the phase-factors, i.e., the gauge group elements [16].

This experiment could be conducted without any reference to Quantum Mechanics with the same observation, which alone is sufficient to provide a strong motivation for developing a theory of mechanics that would describe the motion of a charged particle in terms of the gauge group elements. Although arrived at by some metaphysical reasoning, the gauge mechanical principle formulates mechanics in terms of the gauge group elements from the outset. Thus the original arguments support and are supported by this observation.

The gauge mechanical description of this effect is straightforward [8,9]. The major facilitators for the passage of the particles in this case are the solutions of

\[ \exp\left[i(S_{ABCD}^{P}(\rho_{c}) - F)\right] = 1 \]  

where \( S_{ABCD}^{P}(\rho_{c}) \) is the free particle part of the action. As in Sec.3.3., this implies a density pattern similar to the case of the double slit experiment, changing continuously with \( F \), repeating the original pattern for each integer \( n \) as \( F \) is replaced by \( (F + 2\pi n) \), in agreement with the experimental observation [15].

4.6 The EPR problem

Einstein, Podolsky and Rosen devised a thought experiment to argue that Quantum Mechanics is an incomplete and inadequate theory [17]. In the experiment, two particles in a bound state break up and travel in opposite directions. The pair is correlated, e.g., both must have equal and opposite momenta. Their relative position is also conserved. An intrusive measurement may be made on one of the particles to determine its momentum with complete accuracy by leaving its position completely undetermined. This determines the momentum of the other particle with complete precision, by the conservation law. Since the measurement can be made in time less than needed for light to travel from one particle to the other, the authors argued that the momentum of the undisturbed particle must have been defined from the beginning. Since Quantum Mechanics is unable to assign this value, it is incomplete and fundamentally inadequate.

Also, the position of the second particle can be determined with complete precision, as a complete indeterminacy in its momentum can be tolerated, which has already been determined exactly. This also determines the exact position of the first particle as the relative position of the two is conserved. Thus, the positions and momenta of both particles are precisely determined, in violation of the uncertainty principle.

Above argument assumes that the information from one particle to the other cannot travel faster than light. Therefore, an alternative to the above scenario is the possibility of passage of signals faster than light, in fact instantaneous, i.e., action at a distance. This non-locality was unacceptable to Einstein.

Above arguments are applicable, not just to the position and momentum, but also to various other physical quantities. There are several alternative measurements that can be made to check if the non-local effects exist. Bell’s inequalities [18] greatly facilitated such tests [19], which have been conducted and non-locality confirmed [see e.g. 20]. Thus, non-locality is an experimental fact, but it can be reconciled with the relativistic assumption of the limiting speed. If the momenta and the positions of the equivalent particles are measured, they are found to...
be randomly distributed. Thus, randomness is also an experimental fact. A faster than light transmission between a pair of correlated particles is possible but it is only the randomness that would be so transmitted. This makes it impossible for a precise signal to travel faster than light.

Such non-local effects are inherent in Quantum Mechanics. In the gauge mechanical terms, this arrangement is essentially equivalent to the double slit experiment. Classical physical paths \( \rho(AB) \) and \( \rho'(AC) \), are defined by

\[
\kappa(B)e^{iS_{BA}(\rho)}e^{-iS_{CA}(\rho')}\kappa^{-1}(C) = 1
\]  

(8)

If the particles travel undisturbed, i.e., \( \kappa(A) = \kappa(B) = \kappa(C) \), then the solutions are given by

\[
e^{i(S_{BA}(\rho) - S_{CA}(\rho'))} = 1
\]  

(9)

If the state of one of the particles is altered by an intrusive measurement, say at \( B \), then \( \kappa(B) \neq \kappa(A) = \kappa(C) \), and hence, the solutions of (8) no longer satisfy (9). The corresponding physical path now is the union of \( \rho(AB) \) and \( \rho''(AC) \neq \rho'(AC) \), compensating for the state change by a multiplicative factor equal to \( e^{i\delta S} \) [21], where \( \delta S \) is the measure of the intrusion.

Gauge mechanically, the positions and the momenta of both of the correlated particles are precisely defined, before and after a measurement. A change occurs as a result of an intrusion which is quantifiable, that is communicated to the undisturbed particle. Thus non-locality is a gauge mechanically predicted effect.

**4.7 Potential barrier**

According to the quantum mechanical view [22], if a particle encounters a classically forbidden barrier, the wave-packet divides itself in two. One part is reflected and the other, passes through. Thus, out of a large collection, most particles are reflected but some tunnel through. As soon as a particle is detected, both parts of the wave-packet disappear, or become inconsequential, depending on the interpretation used. The gauge mechanical description [9] is outlined below.

For a relativistic particle, the action along a geodesic line is given by

\[
S_{BA}(\rho_c) = -m\sqrt{t(l)^2 - l^2} - Vt(l)
\]  

(10)

where \( V \), the potential, is zero outside the barrier, and positive inside. Here, \( l \) is the length of the line segment and \( t(l) \) is the classical time taken by the particle in travelling the distance \( l \). For a piecewise geodetic trajectory, the action is given by the sum of the actions on each of the segments. Incidentally, the non-relativistic approximation to this value, with \( V = 0 \), was used to obtain the estimates of Sec. 3.2.

As in Sec.3.2., most of the physical paths are concentrated about the piecewise classical, physical paths. Thus, most of the particles would reflect from a classically forbidden barrier. It is straightforward to check, by direct substitution, that there are physical paths allowing tunnelling with emerging particles having a large spread of velocities, but not exceeding the speed of light [9].

**4.8 Schrödinger’s cat[11,23]**

In this thought experiment, a cat is in a box together with a lump of radio-active material, which may decay releasing a particle that may trigger a hammer, smashing a vial containing cyanide
gas, and killing the cat. According to the Copenhagen interpretation, the cat is both dead and alive until an observation is made, which collapses it in one of the two states. The situation is complicated by the fact that this observation can be non-intrusive. The interpretations that assign a probability to an event are meaningful only if many cats are observed. The many worlds interpretation determines the cat to be dead in one world and alive in the other. What an observer would find depends on which world one enters, which is indeterminable until after the outcome of the observation. In the limit of infinite time, then there is no choice for any observer but to enter the world of the dead cat.

Gauge mechanically, as discussed in Sec. 4.7., there are some paths connecting an interior point of the radio-active material to a point outside, facilitating the passage of a particle to the trigger. By a given time, if a particle has triggered the hammer, the cat is dead, otherwise it is alive. Thus, an objective reality exists, i.e., the cat is either dead or alive, but because of randomness, one cannot determine the state without an observation, which however, has no impact on the state, on the objective reality, only determines it as it exists.

5 Concluding Remarks

The underlying theme in the quantum mechanical formulation of dynamics is that an observationally isolated discrete entity of limited extension, is a self-interacting continuous system of infinite extension, resulting from something oscillating, when not observed. Various paradoxical situations result from this underpinning. The so called quantum mysteries result from the attempts to understand the physical phenomena in terms of the classical concepts: particles travelling according to the classical laws and waves described by the oscillations of the particles, or fields. Objections to the claim of completeness of Quantum Mechanics emanate from its treatment of a single system in terms of the concepts that are pertinent to a statistical collection. A number of interpretations have been developed to reconcile the inconsistencies, e.g., the Copenhagen, the probability, the many worlds and the pilot wave, that evolved into Bohmian mechanics. These interpretations and their limitations are well known. In brief, each one addresses only a part of the difficulties. At times the explanations generate new questions.

Gauge Mechanics is founded upon an extension of the classical laws governing the motion of the localized entities, the particles, without being prejudiced by the quantum mechanical thinking. Since the structural properties of the particles remain intact, the related observations are described in a consistent manner. The extension determines a collection of equally likely trajectories for a particle to follow. Which one of the paths is followed by a particular particle is determined on the basis of random selection. Consequently, each particle has definite properties, e.g., the momentum and the position, but a quantitative plot representing the collection must show a spread, resembling the envelop of a wave packet or something related. An act of an intrusive observation may alter the properties of a particle which is understandable in terms of a physical act of objective and quantifiable nature, but a non-intrusive one only delineates the reality.

Although Gauge Mechanics assigns a probability to an event, it arises out of the statistical behaviour of an ensemble of paths. The randomness in its original formulation is a consequence of the existence of a collection of solution trajectories of the basic equation. A random behaviour of the identical particles is an experimentally observed fact. The non-local effects, which have been experimentally verified, are also described by the gauge mechanical formulation but the view differs fundamentally from the quantum mechanical.
The estimates obtained so far indicate that while there are differences between the quantum mechanical and the corresponding gauge mechanical predictions, they must be small. A more accurate evaluation of the gauge mechanical probabilities requires more intricate analysis. However, satisfactory approximations may be obtained by straightforward numerical computations. Further, a better comparison with the observations requires more careful measurements. A measurable difference, if found, should determine which one of the two theories describes the experimental observations more accurately.

It is clear also, that further analysis is needed for a more complete understanding of the implications of the gauge mechanical formulation. If this theory is found to be more satisfactory than the existing Quantum Mechanics in describing the motion of particles, then the classical laws governing the structure and evolution of waves, and fields in general, must also be examined and adjusted accordingly, if need be.

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