Can Nature be Intrinsically Probabilistic at Fundamental Level?

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"Can Nature be intrinsically probabilistic at fundamental level?" - The answer cannot be "yes", but ...

Nature cannot be intrinsically probabilistic at its fundamental level, because, if it can be so, then there is no way the classical mechanics can emerge out of quantum mechanics at a single-quantum level. A random phenomenon cannot be described in an absolute sense, but it can be done so with reference to some non-random phenomenon. Therefore, the existence of fundamentally intrinsic probabilistic nature cannot allow the emergence of any kind of non-random phenomenon with respect to which the very existence of the intrinsic probabilistic nature can be defined.

Consider the detection of a quantum particle as shown in FIG. 1. A single-particle source is placed at the center of a hollow spherical detector, emitting a free-particle of mass m - whose quantum mechanical Hamiltonian, $\hat{H}$, and the time-independent Schrödinger wave equation are respectively given by,

$$\hat{H}|\psi >= E|\psi > \quad \Longleftrightarrow \quad \nabla^2\psi + \frac{2mE}{\hbar^2}\psi = 0\,, \tag{1}$$

where, $|\psi>$ is the energy eigenstate, E is the energy eigenvalue, ∇^2 is the 3-Dimensional Laplacian operator, ψ is the Schrödinger wave function, $\hbar = h/(2\pi)$ and h is the Planck constant. The ψ of an emitted particle is "supposed" to be spreading out like a classical spherical wave, hitting the entire inner-surface of the detector, but only a single-particle is observed as a well-localized chunk at some definite location ($\mathbf{r}_p$ in FIG. 1), i.e.,

$$|\psi >= \iiint d^3\mathbf{r}|\mathbf{r}><\mathbf{r}|\psi > \xrightarrow{\text{Observation}} |\mathbf{r}_p><\mathbf{r}_p|\psi >, \tag{2}$$

where, $|\psi>$ is expressed as a superposition of various eigenstates of the position operator $\hat{\mathbf{r}}$, and is inferred to be randomly collapsed to a particular eigenstate, $|\mathbf{r}_p>$, during the observation by the spherical detector; here, $\hat{\mathbf{r}}|\mathbf{r}>=\mathbf{r}|\mathbf{r}>$, the set $\{\mathbf{r} = (r, \theta, \phi) =$ spherical polar coordinates$\}$ contains the position eigenvalues spanning the 3-dimensional

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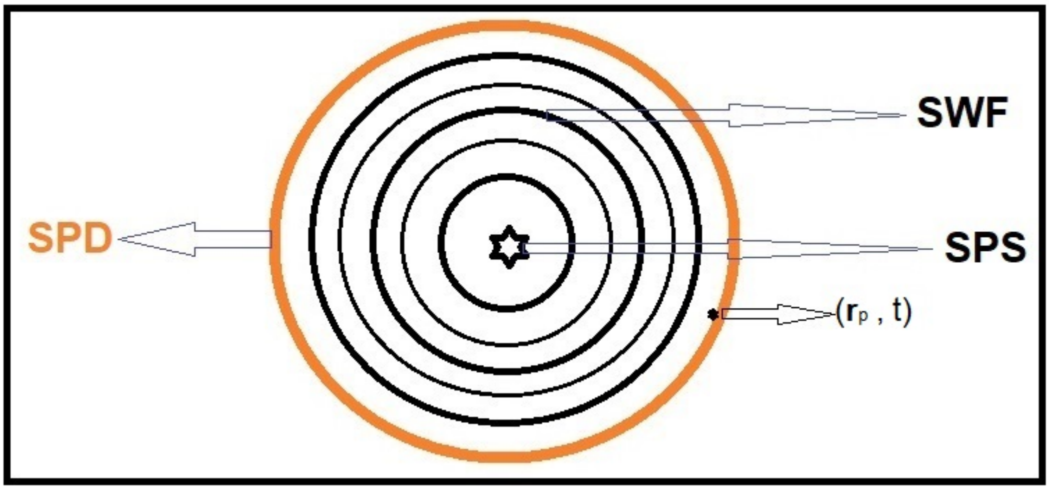

FIG. 1. **Schematic Diagram for the Detection of a Single-particle**: SPS is a single-particle source placed at the center of a hollow spherical particle detector, SPD. When the SPS emits a free-particle of mass m, then its Schrödinger wave function (SWF) - in the position basis representation of the quantum state vector of the emitted particle - "evolves" in the Euclidean space spanned by the set of position eigenvalues. The particle is detected by SPD at a particular spherical polar coordinate $\mathbf{r}_p = (r_p, \theta_p, \phi_p)$ and time t.

Euclidean space and the subscript p in $\mathbf{r}_p$ stands for "particle". If the particle is described only by the wave function and nothing else, then such a description naturally leads to draw an inference, purely based on the experimental outcomes, that the delocalized wave "somehow" collapses to a localized particle, which is the well-known "wave function collapse" in Copenhagen interpretation (CI) [1–5]. The probability for such a collapse is given by the Born rule:

$$< \psi|\psi >= \iiint d^3\mathbf{r} < \psi|\mathbf{r} >< \mathbf{r}|\psi > \xrightarrow{\text{Observation}} | < \mathbf{r}_p|\psi > |^2, \tag{3}$$

where, $| < \mathbf{r}_p|\psi > |^2$ is the probability density for the observation of the particle in an infinitesimal volume around $\mathbf{r}_p = (r_p, \theta_p, \phi_p)$, such that, the repeated measurements on identically prepared initial states yield,

$$< \psi|\psi >= \iiint d^3\mathbf{r}_p \; | < \mathbf{r}_p|\psi > |^2 = 1, \tag{4}$$

where, $\mathbf{r}_p$ is treated as a continuous variable in the limit of infinite number of particles. The Eqs. (2), (3) and (4) comprise the essence of CI. Notice that there is no direct and further irreducible equation for probability density like the Schrödinger equation for wave function, implying the absence of probability for a single-quantum event in quantum mechanics.

From Born's probabilistic interpretation [6] - "*The wave function determines only the probability that a particle - which brings with itself energy and momentum - takes a path; but no energy and no momentum pertains to the wave*" - clearly a given particle does take some particular path, though, that path cannot be predicted a priori except probabilistically. If some parameter like hidden-variable exists, determining the path taken by the particle, then automatically the Born interpretation can be recast as, "*The parameter determines only the path a particle - which brings with itself energy and momentum - takes; but no energy and no momentum pertains to the wave*". Therefore, if the probability is kept aside for a moment, then the natural picture evident in Born's interpretation is as follows: analogous to a test particle moving in the curved space-time of general theory of relativity, the quantum-particle moves along a definite path in the wave function. Instead of this naturally available Born's picture in quantum formalism, the CI contains wave-particle duality along with wave function collapse occurring according to the Born rule. "How does the emitted particle from the single-particle source transform itself into wave function and again does collapse back to the particle at some unpredictable location upon observation?" is known as the "measurement problem", which has no reasonable solution either within the quantum formalism or within the known Universe, if the wave function alone is used for the description of quantum phenomenon.

Notice that, there are other aspects to be consider along with the wave function for the non-paradoxical description of quantum mechanics:

1. The unavoidable particle nature - characterized by the mass parameter m in Eq. (1) - carrying the energy eigenvalue E [7].

2. The global-phase factor, which associates any quantum state, cannot be ignored at the single-quantum level [8–15] by simply claiming, "It won't change any probabilities and hence, any physics at all".

3. The nature of boundary conditions to be imposed to the wave function in accordance with the quantum formalism [8–15].

By considering all these aspects, including the Born's picture, a new interpretation - "The wave-particle non-dualistic interpretation of quantum mechanics at a single-quantum level"

- is worked out [8–15]. Most importantly, in this new interpretation, there is no need to introduce any external hidden-variables, but the global-pahse associating a given quantum state vector naturally serves such purpose, facilitating to the derivation of Born's rule as a limiting case of the relative frequency of detection. Also, the conundrum appearing in Dirac's statement [16], "*Questions about what decides whether the photon is to go through or not and how it changes its direction of polarization when it does go through cannot be investigated by experiment and should be regarded as outside the domain of science*", can be resolved using the same global-phase [15], may be because, the hearts of both Born's interpretation and Dirac's statement are one and the same.

In conclusion, if wave function alone is used in describing any quantum phenomenon, then the notion of 'Nature being intrinsically probabilistic' and also, the measurement problem cannot be avoided. The global-phase associating any quantum state vector, the unavoidable presence of particle nature due to the mass parameter in Schrödinger wave equation and the boundary conditions to be imposed to the wave function in accordance with the quantum formalism cannot be ignored at the individual quantum level. The global-phase depends on the quantum state of the source with respect to the rest of the Universe at the moment of particle-emission and hence, appears to be occurring randomly, though, it need not be so in principle. In other words, its occurrence can be deterministic from Nature's perspective, but uncertain and random from observer's perspective. In this regard, it is important to reconsider the notion of "space" of quantum mechanics [17], in order to make use of the global-phase parameter as a "kind" of hidden-variable.

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