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Two Experiments from the Perspective of the Structural Probability Theory

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Abstract

Current literature presents about a dozen probability (P) interpretations: frequentist, Bayesian etc. Each one illustrates a partial aspect of indeterminism and turns out to be incompatible with the others on the logical plane. Basically, every model of P deals with a specific relation of P with the world and this fragmentary theorization inevitably has negative impact on quantum physics which is intrinsically indeterministic.

Popper believed that the base issues of quantum mechanics cannot be untangled unless the unified probability theory is set up. So, we have conducted an attempt to integrate all the probability models and used the theoretical results to interpret quantum duality, wave collapse and measurement.

The entire work, published in a recent book, exceeds the limits of this paper. Here we put forward a summary that concisely recalls the main definitions and five theorems out fifteen that have been proved. Finally, these theoretical tools will be used to discuss a thought experiment of Einstein and the Wheeler experiment.

This proposal has the following features: (1) It addresses classical and quantum issues using the same theorems; (2) It develops a quantum interpretation that agrees with intuition and refutes disputable and bizarre views.

Keywords: Probability theory, Quantum dualism, Wave collapse, Quantum measurement, Einstein's thought experiment, Experiment with the interferometer

1 Introduction

Since its origin, the probability domain has shown two widely different strands of research. On the one hand, mathematicians solved *application problems* with success. On the other hand, *theoretical investigations* began somewhat late; they have waded with difficulty and come up with constructions that are characterized by striking differences and raise endless controversy. Alan Hájek recognizes that the leading probability theories named *classical, axiomatic, logical, evidential, subjective, Bayesian, frequency, propensity* and *best-system* present irreconcilable features [1].

Probabilists share various mathematical achievements; they do not quarrel about the equations to calculate rather they dispute about the interpretation of *P*, that are the relationships of *P* with the *physical reality*; therefore, the opposed answers inevitably hinder the progress of *quantum physics* which is intrinsically indeterminate. As examples, we mention the unresolved contrasts between the *ensemble* and the *quantum-Bayesian interpretations* directly inspired by the frequentist and subjectivist schools. We also recall the issues raised by the probability meanings of the wavefunction.

There are quantum scientists who underestimate the difficulties emerging in the probability domain in the last three centuries. Some hold that the debates are nothing more than philosophical disputes; others are inclined to adopt each probability theory depending on the specific situation [2]. In reality, quantum mechanics (QM) is intrinsically bound to indeterminism [3] and pragmatic remedies cannot answer the fundamental questions. Karl Popper [4] was convinced that the issues met in the foundations of QM are not physical, but mathematical. He developed the theory of propensity primarily to provide effective support for quantum physicists.

We have made an attempt to gather all the probability models inside a consistent frame named *structural theory*; its scope is to go beyond the present intellectual deadlock. Two theorems begin to demonstrate the boundaries of the frequentist and the subjective views [5]. Article [6] illustrates the *theorems of continuity* and *discontinuity* describing the behavior of a single random outcome and [7][8][9] apply them to QM.

The present paper concisely recollects the mentioned theorems and appends the *theorem of reduction* (TR). Eventually, the results are used to interpret the Einstein and Wheeler experiments.

2 The Structural Theory in Brief

Let us begin with the following pair of remarks, and then we shall go through some steps.

2.1 Each master, say Ramsey, von Mises, de Finetti etc., presents a single model of probability (or two models at most) and rejects other solutions. Instead, this inquiry began with the idea that every model of *P* proves to be useful in a specific range of applications. For example, the Bayesians and subjectivists are concerned with decisions making; the frequentists deal with repeated occurrences; the logicians focus on deductive reasonings etc.

2.2 The variety of topics treated suggests formulating accurately the argument A calculated by P(A); it is necessary the thorough model of A in order to deduce the properties of P(A) from A. This duty is not so easy since most authors assume that the event is a subset of outcomes [10] and neglect that the initial conditions characterize random and determinate outcomes. Moreover, the set model does not fit with the probabilities expressed by sentences. It is necessary to underscore that the set model tacitly holds that *events and outcomes have the same nature*, whereas modern literature shows how the former is the process that brings forth the latter. The event and the result are close but widely differ [11][12].

2.3 First stage – These considerations led us to go beyond the set model and adopt he *triad* or *structure* **E** [13][14] that is equipped with the elements i and e linked by the relationship r:

$$\mathbf{E} = (i, r, e). \tag{1}$$

Namely, given the initial conditions i, the event occurs through r which carries out the output e. The event is something that happens, will happen or hypothetically happens, and $P(\mathbf{E})$ quantifies this capability whose size varies between two extremes:

$$1 \leq P(\mathbf{E}) \leq 0 \tag{2}$$

Ordinarily, the occurrence of **E** is established by means of e; hence the event and its outcome share the same probability value:

$$P(\mathbf{E}) = P(e) \tag{3}$$

This paper means to address physical issues, so we locate (1) in the time scale; **E** starts at the instant $t_o = 0$ and finishes at t_e that is the delivery time of e. When the event repeats t_e is the time of the last outcome. We obtain the *time intervals* T_1 with $0 < t < t_e$, and T_2 with $t \geq t_e$.
We define the *determinate status* $e^{(D)}$ of the result when $P(e)$ or the frequency $F(e)$ are integers; and the *indeterminate status* $e^{(I)}$ when they are decimal:

$$P(e) = 0 \text{ OR } 1; \quad F(e) = 0 \text{ OR } 1. \tag{4a}$$
$$0 < P(e) < 1; \quad 0 < F(e) < 1. \tag{4b}$$

Structure (1) allows to state the event $\mathbf{E_1}$ that occurs only once and *the long-term event* $\mathbf{E_\infty}$ that repeats indefinitely also called *collective* by von Mises. The unlimited series of single events that have independent and identically distributed outcomes, make $\mathbf{E_\infty}$ and its outcome:

$$\mathbf{E}_\infty = (\mathbf{E}_{\mathbf{11}}, \mathbf{E}_{\mathbf{12}}, \mathbf{E}_{\mathbf{13}}, \ldots), \tag{5a}$$
$$e_{\boldsymbol{\infty}}^{(I)} = (e_{\mathbf{1}1}^{(I)}, e_{\mathbf{1}2}^{(I)}, e_{\mathbf{1}3}^{(I)}, \ldots). \tag{5b}$$

2.4 Second stage – Testing is supreme in science, hence we have to discuss the testability of probability. *The theorem of large numbers* (TLN) proves that the relative frequency approaches the probability when the number of trials tends to infinity:

$$F(\mathbf{E_n}) \xrightarrow{a.s.} P(\mathbf{E_\infty}), \qquad as\ n \to \infty. \tag{6}$$

The theorem of a single number (TSN) demonstrates that probability does not match with the relative frequency in a single trial:

$$F(\mathbf{E_1}) \neq P(\mathbf{E_1}). \tag{7}$$

This means that $P(\mathbf{E_\infty})$ can be tested while $P(\mathbf{E_1})$ cannot be directly controlled with experiments; all that remains is to employ special techniques for testing, as usual in several scientific fields when test cannot be arranged.
TLN is the law of large number in the Borel form, which we place apart from the strong and weak forms of the law of large numbers. In fact, the latter give the account of *the statistical convergence of empirical data toward the expected value.* TLN focuses on *the experimental validation of probability* and ensures that it can be checked when the event repeats.

2.5 Third stage – The theorem of single number highlights the strange behavior of *P* in the physical world, so we carefully examine this argument. We shall inspect the random outcome step by step; that is, in the stages T_1 and T_2.

The corollary of initial conditions (CIC), on the basis of (3), proves that if **E** is random then also the outcome is random in T_1:

$$e = e^{(I)}, \qquad 0 \le t < t_e. \tag{8}$$

Perhaps CIC sounds trivial now; it will provide theoretical assistance later.
Supposing (8) true, the following pair of theorems describes the outcomes in T_2. *The theorem of continuity* (TC) proves that the outcome e_∞ keeps the indeterminate status in T_1 and T_2:

$$e_\infty = e_\infty^{(I)}, \qquad 0 \le t\ . \tag{9}$$

For example, the lotto runs 100,000 times. At the end of T_1, 100,000 extracted numbers make a statistical distribution which demonstrates that every number keeps the indeterminate state in T_1 and T_2.
The theorem of discontinuity (TD) holds that the outcome e_1 of $\mathbf{E_1}$ switches from the indeterminate to the determinate status at the end of T_1:

$$e_1^{(I)} \to e_1^{(D)}, \qquad t = t_e. \tag{10}$$

For example, the operator of the lotto draws number 67. This number was uncertain before the extraction and becomes determinate as soon as it is drawn:

$$67_{\mathbf{1}}^{(I)} \rightarrow 67_{\mathbf{1}}^{(D)}, \qquad t = t_{67}.$$

2.6 Fourth stage - Suppose that $\mathbf{E_1}$ has N alternative outcomes:

$$e_{\mathbf{1}} = (e_{11} \text{ OR } e_{12} \text{ OR } e_{13} \text{ OR } \ldots \text{ OR } e_{1N}). \tag{11}$$

Speaking in general, $\mathbf{E_1}$ can adopt different techniques, namely it can make e_{11}, e_{12}… ready using various procedures during T_1. For example, the event prepares the outputs step by step, or creates them by assembling pre-packaged components, or amasses partial results and so on.
A noteworthy kind of events handles e_{11}, e_{21}, e_{31}… e_N all together during the interval T_1. This situation is typical of the games of chance whose outcomes are potentially ready since the beginning of the game. We use the angle brackets ⟨ ⟩ to specify that all the possible outcomes *superpose* because *in principle all are available during* T_1:

$$\langle e_{11}^{(I)}, e_{12}^{(I)}, e_{13}^{(I)}, \ldots, e_{1N}^{(I)} \rangle, \qquad t < t_e. \tag{12}$$

For example, the roulette wheel includes the numbers from 0 to 36. All of them are available for extraction during the rotation of the wheel, that is to say, the numbers superpose in T_1.
The theorem of reduction (TR) demonstrates that the ensemble of possible outcomes (12) decreases in size when the experiment is over. *If* $\mathbf{E_1}$ *has N superposed outcomes, they reduce to just one determinate outcome at the end of* T_1:

$$\langle e_{11}^{(I)}, e_{12}^{(I)}, e_{13}^{(I)}, \ldots e_{1h}^{(I)} \ldots, e_{1N}^{(I)} \rangle \rightarrow [e_{1h}^{(D)}],$$
$$\text{where } h = \text{any of } 1,2\ldots N;\ t = t_e. \tag{13}$$

More precisely, the result $e_{h\mathbf{1}}$ becomes certain while all the other potential outcomes become impossible and vanish at t_e:

$$[0 < P(e_{1h}) < 1] \rightarrow [F(e_{1h}) = 1],$$
$$\text{where } h = \text{any of } 1, 2 \ldots N.$$
$$[0 < P(e_{1k}) < 1] \rightarrow [F(e_{1k}) = 0],$$
$$\text{where } k = 1, 2..(h-1),(h+1),\ldots N; \tag{14}$$

2.7 The theorems of a single number, discontinuity and reduction progressively provide details about $\mathbf{E_1}$: TSN proves that the single event cannot be tested; TD specifies that the random outcome of $\mathbf{E_1}$ collapses at $t = t_e$ and TR demonstrates how only one potential outcome becomes certain, and the remnants disappear.

2 Applications in Quantum Physics

The following sections apply the structural theory of probability to QM.

3.1 We assume the *quantization* and *wave/particle principles,* that is to say, the *quantum ξ is a discrete portion of energy and eventually of matter that behaves either as a particle or a wave.*

We are forced to use a probability distribution function to describe the two physical states because ξ cannot be subdivided at will. Let $P(\xi \in r)$ is the probability of finding ξ in the point $r = (x,y,z)$ of the Euclidean space Σ at the generic time. Definitions (4a) and (4b) lead us to conclude: *the quantum ξ is a particle when it has the determinate status $\xi^{(D)}$; ξ is a wave when it has the indeterminate status $\xi^{(I)}$.* In consequence of these definitions, $\xi^{(D)}$ leads to the universal distribution that is the Dirac function with $P(\xi \in r) = 1$ in a point and zero elsewhere. The wave $\xi^{(I)}$ is described by various probability distributions which depend on specific physical constraints. Several quantum theorists agree that $|\Psi|^2$ provides the exact distribution in each case.

3.2 Let us focus on the simplest physical phenomenon that consists of *one or more quanta flying freely without interferences*. We also exclude entanglement, spinning, relativity and other quantum effects. Definition (1) leads us to formalize the free flight as the structure $\mathbf{E}_\xi = (i,\ moving,\ \xi)$ where the ergodic source is the initial element i, and the dynamical relation yields the outcome ξ. The movement is random since it is triggered by an ergodic source and does not provide a precise trajectory. When something interposes, the free flight of ξ finishes. The movement occurs during T_1 and closes in t_ξ, when ξ is measured or is affected in another manner. The interval T_2 lasts only one instant because we assume the measurement process is destructive.

3.3 TLN and TSN require to distinguish the *single wave* or *wavelet* $\xi_{\mathbf{1}}^{(I)}$ from the *intense wave* or *radiation* $\xi_{\boldsymbol{\infty}}^{(I)}$ which includes innumerable wavelets due to (5b):

$$\xi_{\boldsymbol{\infty}}^{(I)} = (\xi_{\mathbf{1}1}^{(I)}, \xi_{\mathbf{1}2}^{(I)}, \xi_{\mathbf{1}3}^{(I)}, \dots). \qquad (15)$$

The theorems (6) and (7) prove that the probability of $\xi_{\boldsymbol{\infty}}^{(I)}$, namely the radiation, can be tested while the probability of the wavelet cannot be, this conclusion does not exclude that $\xi_{\mathbf{1}}^{(I)}$ can be checked through indirect experimental control.

3.4 The movement $\mathbf{E}_\xi$ is random and the corollary of initial conditions (8) proves that also the result is random; namely the ergodic source casts waves. The theorem of continuity (9) implies that *the radiation* (15) *keeps the indeterminate status in T_2* and is consistent with TLN. The theorem of discontinuity (10) specifies that *the sensor which should detect the wavelet $\xi_{\mathbf{1}}^{(I)}$ fails because $\xi_{\mathbf{1}}^{(I)}$ collapses in t_ξ, and the sensor perceives a particle.*

3.5 The theorem of reduction (TR) adds further details in the following manner. Suppose the sensor #1 is placed at the point $r_1 = (x_1,y_1,z_1)$ of Σ and is able to perceive the first potential outcome $\xi_{11}^{(I)}$ of the free movement**.** If the operator places the sensor #2 in $r_2 = (x_2,y_2,z_2)$, he determines the second potential outcome $\xi_{12}^{(I)}$ and so forth. When the operator arranges N distinct sensors, the following potential outcomes: $\xi_{11}^{(I)}, \xi_{12}^{(I)},\ldots, \xi_{1N}^{(I)}$ are available in T_1; N possible outcomes superpose according to definition (12):

$$\langle \xi_{11}^{(I)}, \xi_{12}^{(I)}, \ldots , \xi_{1N}^{(I)} \rangle, \qquad t < t_\xi. \tag{16}$$

The reader can note how the concept of superposition illustrated here has nothing to do with the quantum superposition illustrated in the current literature.
The theorem of reduction asserts that the set of results (16) drops-down to just one deterministic result. All the superposing results collapse namely ξ_{1h} becomes a particle, while the remaining potential result vanish:

$$\langle \xi_{1}^{(I)}, \xi_{21}^{(I)}, \xi_{13}^{(I)} \ldots \xi_{1h}^{(I)} \ldots \xi_{1N}^{(I)} \rangle \rightarrow \xi_{1h}^{(D)}, \quad \text{where } h = \text{any of } 1,2,\ldots N;\ t = t_x. \tag{17}$$

In a more explicit way:

$$[0 < P[\xi_{h1} \in (x,y,z)] < 1] \rightarrow [F[\xi_{h1} \in (x,y,z)] = 1], \quad \text{where } h = \text{any of } 1, 2,..N;\ t=t_\xi. \tag{18}$$

$$[0 < P[\xi_{k1} \in (x,y,z)] < 1] \rightarrow [F[\xi_{k1} \in (x,y,z)] = 0], \quad \text{where } k = 1, 2..(h\text{-}1),(h+1),..N;\ t=t_\xi. \tag{19}$$

The change of $\xi_{h1}^{(I)}$ which becomes $\xi_{h1}^{(D)}$, and the dissolution of the other potential outcomes are phenomena consistent with the quantization principle which denies the arbitrary subdivision of the quantum.
The theorem of reduction does not admit spatial limitations, namely the potential results can be very far away from each other and confirm the non-locality property of quantum mechanics. If the potential results are light year distant, they do not contradict the special theory of relativity since there is no information career.
Two experiments corroborate the predictions of the present theory: the first is a straightforward thought-experiment, the second experiment is much more complicated.

4 Einstein's Thought Experiment

Einstein presented a thought experiment at the 1927 Solvay Conference, which we examine in the simplest version [15][16].
Suppose the plane wave is incident on a diaphragm with a single aperture, behind which lies a large, hemispherical detection screen (Figure 1). With a sufficiently narrow aperture, the incident quantum wave will diffract, resulting in essentially spherical waves propagating toward the screen. The spherical wave can be detected at points **a, b** and **c**. If detector **b** perceives the wave that collapses, how can

detectors **a** and **c** be informed about this collapse?

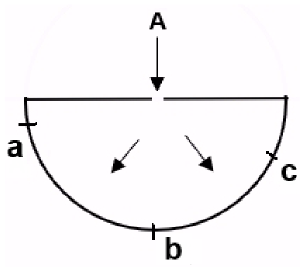

Figure 1. Schematic of Einstein thought experiment

The wavelet $\xi_{\mathbf{1}}^{(I)}$ can be detected by the receptors **a, b** or **c,** hence $\xi_{\mathbf{a1}}^{(I)}$, $\xi_{\mathbf{b1}}^{(I)}$ and $\xi_{\mathbf{c1}}^{(I)}$ are the potential results that comply with the superposition hypothesis (16):

$$\langle \xi_{\mathbf{a1}}^{(I)}, \xi_{\mathbf{b1}}^{(I)}, \xi_{\mathbf{c1}}^{(I)} \rangle. \tag{20}$$

Suppose **b** perceives the wavelet, the theorem of reduction (18) and (19) forecasts the following transitions:

$$\begin{aligned} &[0 < P(\xi_{\mathbf{b1}}) < 1] \rightarrow [F(\xi_{\mathbf{b1}}) = 1\}, \\ &[0 < P(\xi_{\mathbf{a1}}) < 1] \rightarrow [F(\xi_{\mathbf{a1}}) = 0], \\ &[0 < P(\xi_{\mathbf{c1}}) < 1] \rightarrow [F(\xi_{\mathbf{c1}}) = 0], \qquad t = t_{\xi}. \end{aligned} \tag{21}$$

This means that $\xi_{\mathbf{b1}}^{(I)}$ switches to $\xi_{\mathbf{b1}}^{(D)}$, the statuses $\xi_{\mathbf{a1}}^{(I)}$ and $\xi_{\mathbf{c1}}^{(I)}$ vanish and therefore the detectors **a** and **c** 'do not need to be informed'. The incoming $\xi_{\mathbf{1}}^{(I)}$ behaves as a whole respect to the three sensors and corroborates the previsions supplied by TR. This thought experiment has not space limits and makes explicit the non-locality property of QM.

5 Wheeler's Experiment

The experimental device consists of a Mach-Zehnder interferometer where the laser **A** emits a large number of photons, one by one [17]. The beam-splitter BS_{in} subdivides the incoming beam into two equal parts that the mirrors M_H and M_K redirect toward the detectors D_H and D_K respectively. When a detector perceives a photon, it shows a dot and also sends a click.

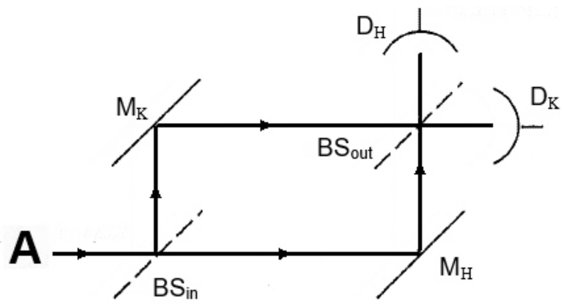

Figure 2. Schematic of the experiment
with Mach-Zehnder interferometer (close configuration)

5.1 This experiment includes two configurations but the first turns out to be rather trivial. We focus on the second configuration where the operator places the device BS_{out}, which works like a semi-transparent mirror for D_H and D_K (Figure 2).
Figure 3 shows the black and grey dots describing two discrete interference patterns on BS_{out} that D_H and D_K view. The clicks of D_H and D_K never occur at the same time.

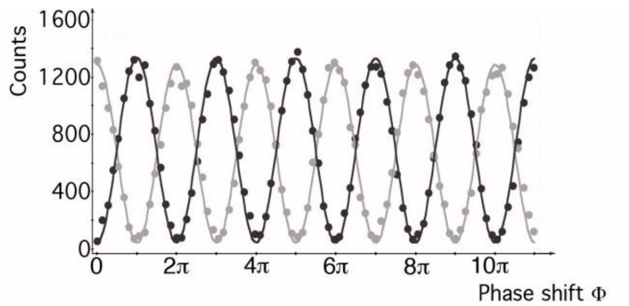

Figure 3. Results of the second configuration of the experiment [From [16]].

The theorems of this paper lead to the following interpretation, which has nothing in common with the literature.

5.2 The laser **A** is an ergodic source, and the corollary of initial conditions concludes that every incoming photon is a wavelet:

$$\xi_{\mathbf{1}} = \xi_{\mathbf{1}}^{(I)}, \qquad 0 \le t < t_{\xi}. \qquad (22)$$

Because **A** casts several photons one by one, there are two effects occurring simultaneously. Effect ***A*]** involves all the wavelets that make a stream; ***B*]** involves every individual wavelet.

***A*]** Definition (15) holds that a large number of incoming photons make the radiation $\xi_{\infty}^{(I)}$, thus, the patterns shown in Figure 3 are made by the stream of wavelets. More precisely, the beam-splitter BS_{in} makes $\xi_{H\mathbf{1}}^{(I)}$ and $\xi_{K\mathbf{1}}^{(I)}$ that are coherent secondary waves of each photon. The device BS_{out}, which works like a

semi-transparent mirror, recombines $\xi_{H\mathbf{1}}^{(I)}$ and $\xi_{K\mathbf{1}}^{(I)}$ that cause constructive and destructive interferences, and make visible the overall radiation. The patterns are double because of the geometrical distance between D_H and D_K which creates distinct perspectives and distinct patterns on BS_{out}.
This interpretation agrees with TLN and TC ensuring how the wave $\xi_{\infty}^{(I)}$ can be controlled with experiments.

***B*]** The secondary waves $\xi_{H\mathbf{1}}^{(I)}$ and $\xi_{K\mathbf{1}}^{(I)}$ emitted by BS_{out} and perceivable by D_H and by D_K are the *potential results* of the experiment, they superpose in agreement with definition (16):

$$\langle \xi_{H\mathbf{1}}^{(I)}, \xi_{K\mathbf{1}}^{(I)} \rangle, \qquad t < t_\xi. \qquad (23)$$

The theorem of reduction forecasts that one potential outcome becomes a particle, while the other potential outcome vanishes. There is no distance-action, both the potential results switch as they are part of the unique wavelet:

$$[0 < P(\xi_{X\mathbf{1}}) < 1] \rightarrow [P(\xi_{X\mathbf{1}}) = 1], \quad \text{where X = either H or K; } t=t_\xi.$$
$$[0 < P(\xi_{Y\mathbf{1}}) < 1] \rightarrow [P(\xi_{Y\mathbf{1}}) = 0], \quad \text{where } Y \neq X \text{ ; } t=t_\xi. \qquad (24)$$

The single dots in Figure 3 and the clicks which never overlap, corroborate (24).

In summary, the incoming wavelets make a long-term event (= effect ***A***) and behave as superposed outcomes (= effect ***B***). This experiment turns out to be somewhat complex because of the overlapping effects ***A*** and ***B***, and the four theorems that govern these effects: CIC, TR, TLN, and TC.

6 Conclusion

This paper is a draft that introduces the *structural theory of probability* aiming to show how the multiple and seemingly incompatible aspects of $P(\mathbf{E})$ can coexist in point of logic because they refer to different events; specifically, the frequentists and subjectivist probability models are dealt using a unique tool that is the algebraic structure (1). This work spends much energy to disentangle probability issues; in return, it addresses classical and quantum issues using uniform mathematical instruments.

The *probability-based interpretation of quantum mechanics* deriving from the structural theory:

- Formulates the wave/ particle duality by means of P.
- Examines the free flight of quanta which is not affected by external forces or agents.

- Proves different theorems which explain the behavior of the single wave and that of the radiation.

The probability-based interpretation demonstrates that:

- Both the flow of quanta and the single wavelet are real even if the latter cannot be directly tested.
- The wavelet collapses when the free flight terminates.
- A free movement terminates because something interferes. Measurement is the principal but not exclusive factor of interference.
- *N* detectors result in *N* potential outcomes. Only one becomes determinate, the others vanish.

In current literature some experiments seem paradoxical, and the current theories lead to counterintuitive and weird explanations. Physicists invoke unusual concepts, such as the retro-causality and the delayed choice which raise a lot of discussion. The present framework puts forward explanations that are consistent with classical mechanics and intuition [9].

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