WHEELER'S DELAYED-CHOICE EXPERIMENT MYSTERIES, MISINTERPRETATIONS, COMPLEMENTARITY AND MEASUREMENT

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Master of Science

In
Physics

SCHOOL OF NATURAL SCIENCES

NATIONAL UNIVERSITY

OF

SCIENCES AND TECHNOLOGY

2019

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A thesis submitted to the

National University of Sciences & Technology

In partial fulfillment of the requirement for the degree of

Master of Science

in

FORM TH-4

National University of Sciences & Technology

MS THESIS WORK

We hereby recommend that the dissertation prepared under our supervision by: Mr. Muhammad Usman, Regn No. 00000203307 Titled: "Wheeler's Delayed-Choice Experiment Mysteries, Misinterpretations, Complementarity and Measurement" be accepted in partial fulfillment of the requirements for the award of **MS** degree.

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Acknowledgments

First and foremost, all gratitude and admiration to Allah Almighty, the Most Benevolent and the Most Merciful who blessed me with His countless blessings and kindness to complete my dissertation on time.

For the successful accomplishment of this thesis and my research endeavors, I would like to express my sincere appreciation for the way I was always motivated and supported personally by my Supervisor Dr. Asghar Qadir. Without his academic guidance, technical support, and encouragement this thesis would not have been possible.

I would also like to thank my parents, GEC Member, Dr. Shahid Iqbal and Dr. Aeysha Khalique who helped me greatly to complete this project within the limited time frame. I am grateful to Dr.Azad Siddiqi for useful suggestions and Special thanks to John Ingamells for proof reading.

Abstract

In this dissertation I will review a proposal for using a new symmetric arrangement to the well-known DSE (Double Slit Experiment). In the proposed interferometric situation, we use quantum detectors that will move to a random superposition afterward the interaction with the slits of the DSE. As the quantum detector has a smoothly tunable open option in the proposed interferometric setup so we cover the complete measurement range i.e. from strong to feeble projective situations. It proposes an elective system for weak estimation, in view of data cover from DSE paths. The consequences, although properly in agreement with the quantum standard, raise many questions over the absurdity of the common language for a phenomenon's description in the theory, over the nature of probabilities and separation between the non-projective/projective measurements, and related inappropriate interpretations. Additionally, the consequences impose certain limitations over the hidden variable theories. We also review Wheeler's Delayed Choice Experiment (WDCE) and the supposed experimental test of the experiment. Then we end with a critique of these proposals by comparing the original WDCE and with an explanation of what must be done for an actual test.

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CHAPTER 1: INTRODUCTION

This thesis attempts to review Wheeler's delayed-choice double slit experiment[1](WDCDSE), which tries to demonstrate that whether a quantum entity was a particle or a wave in the double slit experiment (DSE) can be decided after the event by an observer.

The concept of wave particle duality in quantum theory that all quantum entities behave as a wave or a particle but not both at the same time. There have been many scientists in favor of the wave nature while many others have supported the particle nature of the photon. In the early 17th century, Huygens proposed the fundamental theory that light had a wave nature in a medium that supports the wave nature of light. According to Huygens's principle, all points of the wave front of light in a space or in a transparent medium could behave as a source of new wavelets that expand in all directions depending on their velocities. In 1672 Newton proposed the "corpuscular theory of light"[2]. This hypothesis expressed that light is comprised of little distinct particles called corpuscles (little particles). These particles go in an orderly fashion with limited speeds and have dynamic vitality.

Thomas Young's DSE become a new subject for the heated debate. Young deployed mathematical as well as philosophical reasons to show the wave nature of light by combining the principle of elementary wavelets with that of interference. (Young's DSE) is discussed briefly in the next section.) This was some of the research that eventually led to victory for the wave nature of light over the then predominant corpuscular theory.

In 1861, Maxwell's equations promoted the possibility that light is an electromagnetic marvel. The conditions have two significant segments. They relate the electric and magnetic fields to add up to charge and all out flow. At the end of 19th century, light was idea to comprise of influxes of electromagnetic field which proliferated by Maxwell's conditions. In 1900, this parcel started to be addressed because of examinations concerning the hypothesis of blackbody radiation by Max Planck who suggested that light was transmitted or assimilated in discrete quanta of energy.

The theory of light being a particle had completely vanished until the beginning of the 20th century when Albert Einstein[3] revived it through the concept of photons. Since then it has become standard, although questionable, to deal with light in terms of dual behavior. According to this concept, light is made up of small packets of energy known as quanta which are supposed to be particles. A similar but less controversial debate took place because of the de Broglie revolutionary hypothesis of matter wave which proposes that, similarly as photon has particle like properties, similarly in all other material particles and electrons also have wave-like properties. With the expectation of complimentary material particles, De Broglie accepted that the related wave likewise had a frequency $'\nu'$ and wavelength $'\lambda'$ identified with its energy $'E'$ and momentum $'p'$.

He suggested that, similarly as light has both wave-like and particle-like properties, electrons likewise have wave-like properties.

In 1927, Bohr's complementarity principle[4] held that objects had certain pairs of corresponding properties that could not all be observed or measured simultaneously. Bohr implied that it was impossible to be a wave and a particle at the same time. Moreover, Heisenberg[5] implied that objects had certain pairs of corresponding properties that could not be measured or observed simultaneously. According to Bohr the complementarity was a philosophical on the other hand for Heisenberg it was a physical principle. To interrogate the different opinions of Heisenberg and Bohr about the complementarity, it is important to differentiate between individual views of what precisely quantum mechanical measurement is. For Bohr, classical physics and quantum mechanics theory are asymptotically associated by the correspondence principle which says that, we deduce the value of classical mechanics by putting Planck's constant equal to zero ($h \to 0$) in the results of quantum mechanics.

Bohr convinced Heisenberg that the uncertainty principle depended on the deeper concept of complementarity. For Einstein, Bohr's answer was deficient in light of the fact that he would not like to acknowledge quantum mechanics as a hypothesis portraying tiny reality. In the paper Einstein, Podolsky, and Rosen (EPR)[6] must be a definitive endeavor in the discussion with Bohr to demonstrate the inadequacy of quantum hypothesis.

The main query in the double slit experiment (DSE) has been raised how we can detect the path of the passing particles from the slits. For this measurement problem, we discuss here another double slit experiment with quantum detectors[7] related to the path distinguishability, which says that the uncertainty in the position of particle occurs if we do not carry out such a measurement. According to Bohr it was futile to make any declaration about the position of the particle.

This thesis will explore these issues as follows:

In the first chapter, we discuss Young's double slit interferometer, wave particle duality, and the wave and the particle nature of the quantum entity. The next chapter is devoted to a brief discussion of different interpretations of quantum mechanics such as the Copenhagen interpretation, the Einstein Podolsky Rosen Paradox, and the de Broglie-Bohm interpretation. Chapter 3 will deal with DSE with quantum detectors, chapter 4 will take up WDCDSE. The last chapter is conclusion and a critique of these proposals which are explained in chapter 3 and chapter 4 and with an explanation of what must be done for an actual test.

1.2 YOUNG'S DOUBLE SLIT EXPERIMENT (DSE) AND THE WAVE NATURE OF LIGHT

Thomas Young[8] performed a DSE in 1801 to study the interference pattern of light. In modern physics the DSE is used to demonstrate that light and matter can show properties of both classically well-defined waves and particles nature. Young's experiment with light has a place with traditional material science and pre-dates the idea of dual nature i.e. wave and particle. He accepted that he had illustrated that the wave hypothesis of light was right. In the fundamental rendition of this observation, a monochromatic source of light, enlightens a platter punctured by two equal slits, the light waves passing through the slits are make pattern on a screen. The wave idea of light causes that light waves going through the two slits to interfere, producing dark (destructive interference) and bright (constructive interference) bands on the screen.

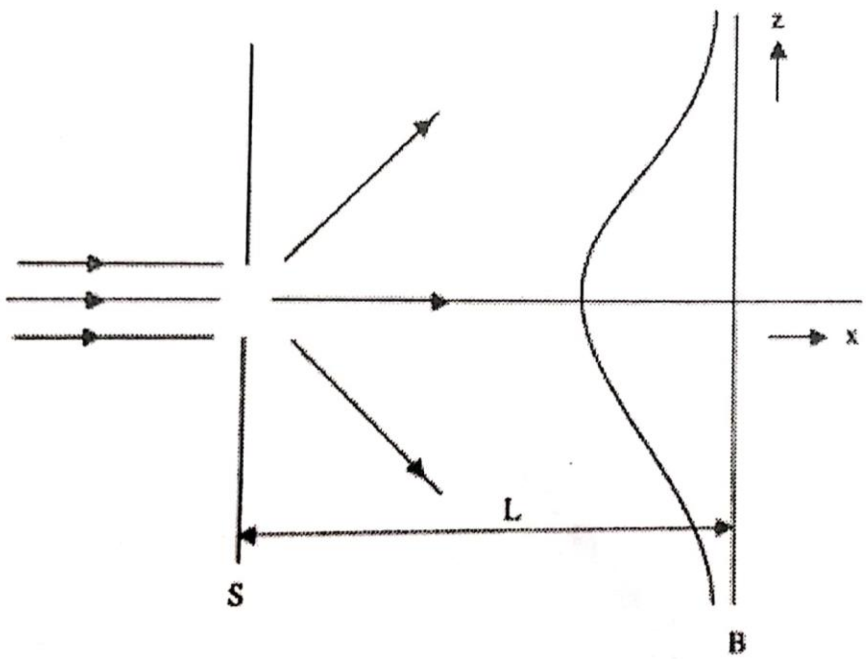

Figure 1. Young's Double Slit Experiment (DSE) through single slit (one slit is closed).

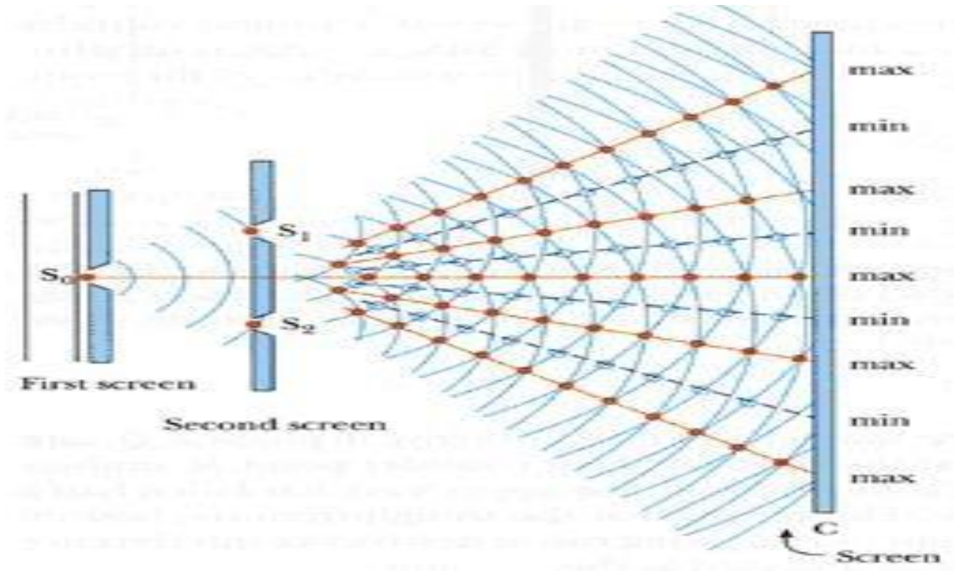

Figure 2**.** Young's Double Slit Experiment through two slits (both slits are open).

For constructive interference, the path difference must be $m\lambda$

$$d \sin\theta = m\lambda, (m=0, \pm1, \pm2, \pm3 \ldots\ldots). \qquad (1.1)$$

For destructive interference, the path difference must be $(2m+1)\frac{\lambda}{2}$ so,

$$d \sin\theta = (2m+1)\frac{\lambda}{2}. \qquad (1.2)$$

The portion of wave fronts incident on the slits behaves as a source of secondary wavelets. The secondary wavelets leaving the slits are coherent. Superposition of these wavelets results in bright and dark bands (fringes) which are observed on the screen. Similarly, in another way we can see that when white light is made incident on a thin oil film, it is partially reflected from the upper surface of the film and partially refracted which is reflected later from the lower surface. Two rays entering the eye cover different paths. Path difference depends upon the following factors:

1) the oil film thickness;
2) the *n* of the material of film;
3) the angle of incidence.

If the thickness of the film is very small (thin film), it causes light to travel more slowly through it. The time taken to get through the film is '$t = dn/c$', '*c*' represents the speed of light, and '*n*' is the symbol of refractive index. The angle 2π represents the full wave length.

1.3 THE PARTICLE INTERPRETATION

The particle view was favored by Einstein. He wanted to conceive of particles as the unified field[9] in space-time which curve the space-time around them. Let us consider the indeterminacy relations in more detail. If we make measurements of the energy of a quantum entity, the values will be distributed about a mean which we call E, with a standard deviation δE, such that

$$\delta E.\delta\tau \geq \frac{\hbar}{2} \tag{1.3}$$

where $\delta\tau$ is the time interval over which the energy measurement is made. Notice that this δE is not the same as ΔE. The usual interpretation of this result holds that the measurement of the energy is not entirely accurate, and the spread of the energy is entirely due to inaccuracy in the measurement. An alternative way to interpret the same result would be to take seriously a suggestion of A. Qadir[10] that energy might be a statistical quantity. We could suppose that energy varies 'randomly' with time so that its average value is E, that is,

$$E(\tau) = E + \varepsilon(\tau) \tag{1.4}$$

where $\varepsilon(\tau)$ has zero average value, but the root means square value of $\varepsilon(\tau)$ is non-zero. It would be reasonable to suppose that the greater the time interval over which the energy measurements are made, the less is the fluctuation $\varepsilon(\tau)$. Assuming the simplest possible relationship between δE and $\delta\tau$ would reduce Eq. (1.4) to equality. If there are further experimental errors in the measurement of E or of τ we get the inequality of equation,

$$\Delta E.\Delta\tau \geq \frac{\hbar}{2}\,. \tag{1.5}$$

We see that there is no problem in the interpretation of the energy indeterminacy relation if we accept the fact that energy is not absolutely conserved but only statistically conserved. Thus, we only need to replace the assumption of the conservation of energy to deal with the energy uncertainty. This assumption automatically leads to the momentum indeterminacy relations.

Due to fluctuation, there is an indeterminacy in the value of energy i.e., δE. From the relativistic formula for energy we have

$$E^2 = P^2c^2 + m^2c^4 \tag{1.6}$$

E represents the energy, m the rest mass and P is the momentum. We have the corresponding indeterminacy due to fluctuations of energy of the momentum being δP, calculated by taking differentials of Eq. (1.6) and keeping the rest mass fixed,

$$\delta P = \left(\frac{E}{Pc^2}\right)\delta E\,. \tag{1.7}$$

Now, according to the special theory of relativity,

$$E = mc^2\,, \tag{1.8}$$

or

$$\frac{P}{E} = \frac{mv}{mc^2} \,. \tag{1.9}$$

This implies that

$$\frac{P}{E} = \frac{v}{c^2} \,. \tag{1.10}$$

Using Eqs (1.3) and (1.7) in Eq. (1.10), we have

$$\delta P. v\delta\tau = \frac{\hbar}{2} \,. \tag{1.11}$$

Since the spatial interval, δx, traveled by the particle in time $\delta\tau$ is just $v\delta\tau$, we obtain the momentum indeterminacy relation

$$\delta P. \delta x \geq \frac{\hbar}{2} \,. \tag{1.12}$$

It can be verified that these wave functions are periodic in time and space with periods τ and λ given by $\tau = h/E$ and $\lambda = h/P$, hence showing that $E = hv$.

Now we would except those particles for which $E(\tau)$ happens to be enough for them to go through the region to appear on the other side of barrier. However, the average energy of the particles would remain the same. Using Eq. (1.3), we can determine what fraction of the beam of particles can be expected to 'jump over' the potential barrier for a given height and thickness of the barrier and verify that it gives the usual predictions of quantum mechanics. This interpretation never runs into a problem with the EPR paradox discussed in next chapter. Thus, the wave function associated with the individual particle represents all possible phase-space configurations with their associated probabilities. The wave function gives more than the particle since it includes other possibilities not, in statistic, realized.

1.4 WAVE PARTICLE DUALITY

The particle and wave view have the advantage of retaining the philosophical and conceptual aspects of the pre-quantum era of physics, and thus seems not to require a change in the way of thinking. The quantum aspect is brought in by requiring a quantum of action via the quantum rules.

$$\Delta E = hv \tag{1.13}$$

Where ΔE is the energy exchange for an oscillator of frequency v.

$$\Delta P_{\Phi} = \frac{h}{2\pi} = \hbar \tag{1.14}$$

Where 'ΔP_{Φ}' is the momentum exchange for systems of angular periodicity = 2π.

$$\varDelta P_x = \frac{h}{L} \tag{1.15}$$

Where '$\varDelta P_{\mathrm{x}}$' is the momentum exchange[6] for the system of linear periodicity 'L'. The Heisenberg uncertainty relation shows,

$$\varDelta X_i \varDelta P_j \geq \frac{\hbar}{2}\delta_{ij}\,. \tag{1.16}$$

In equation (1.16) the indeterminacy relations expressed are taken to come from the interaction of the microscopic objects with microscopic measuring devices with the limit to the accuracy coming from the quantum of actions embodied in equations (1.13)– (1.15). As before there is no well-defined interpretation based on the particle and wave view of nature, but many interpretations with this view as a common denominator. We shall single out Land's interpretation for discussion. Many of the remarks made here (or approximately modified remarks) would be pertinent for the other interpretations based on this view.

Lande[11] takes the basic assumption that all physical laws are essentially statistical in nature. He bases his assumptions on two considerations. Firstly, he claims that even in classical physics we cannot take exact predictions; for example, if ideal balls are dropped 'dead center' on a knife-edge they would fall to one side or the other in an unpredictable (for the individual balls) fashion. Secondly, he argues, statistics could only work if there were essentially no causality to start with but if things had been deterministic at some stage in the development of the universe, they must remain deterministic, since it would take the equivalent of a Maxwell demon acting in reverse to mix things up sufficiently. We need to understand his picture of the preparation of states and their measurement.

In general, for any wave and particle interpretation, there is a problem of explaining the wave or particle nature of a quantum entity. Thus, if we consider a very weak source with a screen with slits (like DSE) to diffract the light and a screen made of photon counters to observe the diffraction pattern, we would not see spots on the screen which gradually merge together to form bright and dark diffraction fringes as would be expected. It would be very difficult to explain why this pattern, which demonstrates the wave nature of the light, appears while the electron diffraction experiment merely shows the statistical cooperation of the particles in a wave-like manner. Similarly, it could be maintained that when photons strike electrons out of metal, it is a particle-like behavior of the wave, but when electrons strike other electrons out of metal it, demonstrates their particle nature.

As we discussed earlier, the measuring quantum entity within the nuclear space can show itself either as a wave or a particle. Bohr's unique thought of 'complementarity,' was that the so-called dual nature of light, has played an important part. Bohr's original concept was that the altered images should correspond to different, joint limited measurement arguments. Thus, in one experiment, i.e., the DSE in which it cannot be experimental through which slit it pass in this context, it behaves as a wave.

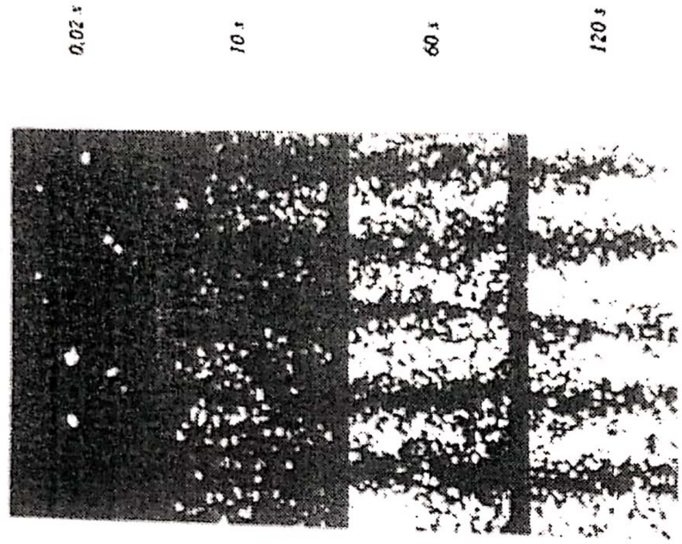

Figure 3. Gradual development of an interference pattern

In later publications, Bohr[12] utilizes the wave-particle duality for presenting and clarifying the perfect of totally unrelated estimation contentions. Without a doubt the simple openness of the distributions has contributed obviously to setting up the possibility this is Bohr's view. It is suspicious, in any case, regardless of whether Bohr, in his verifiable record of his conversation with Einstein on the establishment of quantum mechanics, watched the important artfulness in introducing his thoughts on wave particle duality. It ought to be noticed that the continuous advancement of the obstruction design, as evident in the above figure, was not watched tentatively until 1958 for light[13] and 1959 for electrons[13]. Prior to that time, complementarity was an exceptionally alluring thought in light of the fact that the wave molecule duality was a representation of complementarity, and without question enlivened Bohr's considering complementarity.

CHAPTER 2: INTERPRETATIONS

2.1 INTRODUCTION

In this chapter, we will introduce the Copenhagen interpretation and discuss the meanings of complementarity and completeness in a broader sense. We will then introduce the EPR experiment on this experiment what Bohm says in Bohmian interpretations. At the end of chapter, we will discuss the Bohr–Einstein debates on the same problem.

2.1.1 THE COPENHAGEN INTERPRETATION

The main idea of the Copenhagen or 'orthodox' clarification was developed by Niels Bohr and Werner Heisenberg. The main components are:

1) the complementarity principle;
2) the correspondence principle;
3) the completeness of quantum mechanics.

Regarding the completeness of quantum mechanics, the Bohr's victory in the debate over Einstein for a long time the Copenhagen interpretation was the dominant interpretation in the quantum world.

Bohr's idea was not always formulated with clarity; Bohr had never attempt to state an explicit definition of the interpretation, which is why, unfortunately, there is no proper definition of what the main features of Copenhagen interpretation is. Bohr wrote many eassys[14] in which he established his thoughts regarding the meaning of quantum mechanics[14]. Bohr's approach was more philosophical and conceptual regarding to the queries present by the atomic physics. while in the opinion of Dirac and Neumann[15] it had more mathematical attitudes toward quantum mechanics added extra fundamentals do not present in the tactics of Bohr and Heisenberg. Human consciousness also creates an issue. So, several variations of the Copenhagen interpretation exist, and it is not always easy to be deduced which one is the conventional.

The Copenhagen view of nature comes from the experimental observation that quantum entities, normally regarded as particles or waves, are found to exhibit properties associated with waves or particles. Thus, a beam of electrons can produce different patterns. The wave nature of particles and the particle nature of light can be explained mathematically using De Broglie[16] and Einstein[16] and according to the relation $\lambda = h/p$ and $E = h\nu$, where λ represents the wavelength, h is the symbol Planck's constant, p represents the momentum, and ν is the frequency. Bohr prefers to combine these equations in $E\tau = P\lambda$, thus bringing out the fact that there was no difference in principle between a particle and a wave view. Complete symmetry is found in the way in which the properties of a particle (E, P) correspond to the wave properties (τ, λ) where τ is the time period for the wave.

It was suggested that there is no difference between what we call particle and wave. So, the question arose as to what these quantum entities were? Bohr provided the answer by saying that the question was futile. He based his argument on the philosophical point that the question assumes that we have somehow obtained some knowledge about the entity. The method of obtaining knowledge may prescribe the answer! Thus, the same entity may appear as a wave or a particle condition on the experiment performed. A further point that needed clarification forced those supporting the Copenhagen interpretation to claim that there was no meaning to the question of the existence of a quantum entity except when it can be observed. This may be best understood by considering the phenomenon of tunneling through a potential barrier. Hence the energy of the entity before it enters the barrier is less than the barrier's potential energy. Thus, if we consider the entity inside the potential barrier, it would have total energy less than its potential energy, hence negative kinetic energy. This would imply that the momentum is imaginary. This problem can be resolved with the Copenhagen interpretation by saying that since the entity is not being observed within the potential barrier there is no meaning in the question of whether it exists within the barrier, and hence we cannot even talk of its momentum or wavelength.

Declaring the question of the existence of the entity to be proscribed, unless it refers to the time of observation of the entity, fits the uncertainty principle. According to Heisenberg's uncertainty principle[5],

$$\Delta x . \Delta p_x = \frac{\hbar}{2} . \qquad (2.1)$$

The Copenhagen interpretation takes 'Δp_x' to be the uncertainty in p_x and Δx to be the uncertainty in x. The uncertainties, here, refer to a simultaneous knowledge of both variables. By considering the light of frequency 'E/h' and remembering that for light the momentum is E/C, we get the second Heisenberg uncertainty relation,

$$\Delta E\ \Delta \tau \geq \frac{\hbar}{2}\,. \tag{2.2}$$

Most of the objections to the Copenhagen interpretation were based on a misinterpretation of what it claimed. Some of the most relevant objections, which help to clarify the Copenhagen interpretation, were raised by Einstein. One objection which was satisfactorily answered by Bohr was raised against the interpretation of the first uncertainty relation. Einstein claimed that if we consider the diffraction of the beam of electrons by a double slit, we should be able to determine which slit a particular electron came through, by observing the momentum transfer to the screen containing the slits. However, it can be shown[14] that obtaining adequate information of momentum transfer to investigate the path of electron from the slits would be the exact limit to be able to obtain diffraction patterns. Another objection is that when we have found the probability of an electron passing through a given slit, we use the wave function. However, it was observed that locating the electron at that point was unity and anywhere else the probability was zero. The sudden change of probabilities elsewhere was called the downfall of the wave function. The Copenhagen interpretation avoids this objection by requiring that no signals could be sent by the flop of the wave functions.

In Einstein-Podolsky-Rosen[6] (EPR) the objection to the collapse of the wave function was further investigated. They wanted to illustrate the description of the quantum mechanical description of physical reality was not complete. We will discuss this argument in more detail below. By this statement, they meant that there were objectively definable and measurable (by thought experiment) quantities that were not explained by quantum mechanics. The principle of their argument was that if we allow two systems to interact for some time and then move away from each other, by observing one of the systems, some properties (e.g. position, momentum, etc.) of the other system can be determined, without interfering with the second system. Bohr's reply in defense of the Copenhagen interpretation[12] was that the quantum description, in the Copenhagen interpretation, was the most complete possible interpretation.

Another objection to the completeness of the quantum theory was made by Schrödinger[17]. He pointed out that by linking a microscopic event to another microscopic event the question of observation should become irrelevant. He considered a cat in a box with a mechanism to kill it if an alpha particle strikes a certain region of the box. A source is kept near the box for the period sufficient for it to be as likely that the cat dies as that it survives. The wave function describing the cat by the superposition would be,

$$\psi_{(cat)} = \frac{1}{\sqrt{2}}\left(\psi_{(live\ cat)} + \psi_{(dead\ cat)}\right). \tag{2.3}$$

Now, Schrödinger claims the wave function collapses to either a $live\ cat\ or\ a\ dead\ cat$ when the cat dies or survives but is not dependent on the observation (by means of opening the box) of a live or dead cat.

The whole controversy may be summed up as a discussion of the validity of Wheeler's dictum[18] "*no phenomenon is a phenomenon unless it is an observed phenomenon*". This is the essence of the Copenhagen interpretation which is uncertain.

Wheeler[18] has shown that the Copenhagen interpretation implies a possibility to choose what occurred earlier, by considering a double slit experiment with the screen sufficiently removed from the slits to enable the experimenter to choose whether he wants to observe the photon as a wave or particle, thus determining whether the light interacts with the screen as a particle or as a wave. This basically supports his dictum. However, since macroscopic events do exist independently of the observer, he modified the dictum to read 'no elementary phenomenon', and he prefers to think of the observation as a process.

To sum up, the Copenhagen interpretation starts out like special relativity accepting the observed facts and building the theory around it. As special relativity restricts questions of physical significance to those which are not affected by changes of inertial frames, so the Copenhagen interpretation limits questions to those dealing with an observation, declaring all other questions illegitimate. Whereas the Copenhagen view may be argued to be philosophically sound, it does not provide any clear way of visualizing and understanding phenomena. Bohr maintained that our ideas of visualization and understanding need to be altered as they are tied up with the classical point of view. Even if the various objections to the Copenhagen interpretation can be adequately dealt with, we have to pay a price for this. At the very least, we must give up our old ideas of visualization and understanding, and even of the existence of past events in themselves, apart from trying to explain how elementary an elementary phenomenon is. In addition, there is a restriction of the questions which can be asked.

2.1.2 THE BOHR-EINSTEIN DEBATES

The Bohr-Einstein debates began in spring 1920, when Bohr visited Berlin and met Einstein. The discussion between the two, if viewed from the perspective of later developments, may give the impression that their thinking at that time was quite different from what it was afterwards. According to Einstein's, at that time, a comprehensive concept of light had some way to association adulatory and particulate features. While Bohr, defending the classical wave theory of light, claimed that the 'υ', seeming in the energy '$h\upsilon$' of the quantum, was described on the basis of interference phenomena "which apparently demands their interpretations as a wave composition of light". The Mere particle theory of the photon thus contradicts from its fundamental equation. Bohr stressed the need for a profound contradict with the ideas of classical theory but according to Einstein, though recommending the duality of light, was converted that these two aspects must be linked to each other.

For Bohr, classical mechanics and quantum mechanics, although asymptotically associated by the corresponding principle (which says that by putting $h \rightarrow 0$ in the results of quantum physics we can get the results of classical physics), seemed irreconcilable. On the other hand, Einstein had already suggested[1] in 1909 that Maxwell's equations might yield points like particular explanation in accumulation to waves, an idea which he later (1927) successfully applied to the field equations of universal relativity. Thus, he was a firm believer in a combined casual theory of all physical phenomena.

The conflict among Einstein and Bohr arrived after the disclosure of the Compton Effect. The Compton Effect gave strong support to the particulate theory of light. To meet this challenge in 1992, Bohr wrote with Kramer and Slater, the famous paper "*The Quantum Theory of Radiation*"[19] in which he completely unrestricted Einstein's idea of a quantum structure of radiation, replacing it by a thoroughly probabilistic method based on only statistical preservation of energy and momentum.

Einstein wrote a letter in April 1924 to Born, "Bohr's opinion of radiation interests me very much. But I do not want to let myself be driven to a renunciation of strict causality before there is much stronger resistance against it than up to now. I cannot bear the thought that an electron exposed to a ray should, by its own free decision, chose the moment and the direction in which it wants to jump away. It is true, my attempts to give the quanta palpable shape have failed again and again, but I am not going to give up a long time yet."[20] In another letter dated May 1, 1924, to Paul Ehrenfest, "Einstein listed several reasons why he rejected Bohr's suggestion, the main reason being that a final rejection of strict causality was very hard to tolerate"[20].

In December 1925, Bohr and Einstein met again in Leiden. Ehrenfest, who had been in Leiden since 1912, had friendly relations with both Bohr and Einstein. This time, the debate seems to have focused on an experiment that Einstein proposed in 1921. This experiment was to decide between the adulatory Doppler formulas

$$\nu = v_0(1 + \nu \cos {}^{\theta}\!/_{c}). \tag{2.10}$$

Eq. (2.10) applied to the radiation and quantum theoretical formula E_2-E_1=hv. According to Einstein's theory, the optical beam was expected to suffer a deviation of a few degrees, while passing through a dispersive medium, whereas according to Bohr, it was not[20]. A few weeks later, following Ehrenfest's suggestion that the group velocity rather than the phase velocity should be taken into consideration (since the problem deals with a finite wave train), Einstein revised his theory of the propagation of light through dispersive media. He concluded that the wave theoretical and corpuscular treatments of the problem lead to the same result. Although very little is known about the conversation between Bohr and Einstein in Leiden, it seems certain that Bohr, having meanwhile accepted Einstein's theory of light quanta, put a great deal of emphasis on the difficulties of applying the notions of classical physics to quantum mechanics. In a letter of April 13, 1927, to Einstein, he insisted that the classical concepts only gave the choice of whether they should direct their attention to the continuous or the discontinuous features of the description. At the request of Heisenberg, Bohr enclosed in this letter to Einstein a preprint of Heisenberg's article on the indeterminacy relation. Connecting its contents with their discussion in Leiden, Bohr wrote that, as shown by Heisenberg's analysis, inconsistency can be kept can be away only because the fact that the limitation of our concepts coincides with the limitations of our observational capabilities. A clear indication that the Bohr already make-believe on its complementarity interpretation. Turning to the point of light quanta, Bohr wrote on April 11, 1927: "In view of Heisenberg relation it becomes possible to reconcile the requirement of conservation of energy with the implication of wave theory of light, since according to the character of the description the different aspects of the problem never manifest themselves simultaneously."[21]

2.1.3 THE EINSTEIN-PODOLSKY-ROSEN PARADOX

In the era of Einstein and Bohr, the completeness of quantum mechanics was a very hot topic. The question was whether quantum theory was accepted as a complete theory. Einstein always tried to explain this theory by thought experiments, as opposed to Bohr. As indicated by Einstein, more keen values of q $(position)$ and p $(momentum)$ could be measured for a particle. Einstein's thought experiments were always regret by Bohr because according to Bohr the Einstein did not take into account the impact of measurement devices. Einstein did not want to consider theory as a microscopic reality as it is interacting with measurement devices, that's why Bohr's solution was rejected by Einstein. Einstein thought theory must be independent of the observer and the measurement instrument.

In 1935, a paper was published by EPR the aim of the paper was to prove the incompleteness of quantum mechanics, under the title, "Can Quantum-Mechanical Description of Physical Reality Be Consider Complete." EPR supported their argument by considering that a particle/measured object does not interact with the measurement instrument, that is showing the objective reality rather than observed reality.

Bohr show the keen interest in the EPR problem as they were thought-provoking his philosophy of complementarity. The main features of Complementarity had always position and momentum. There were two main points given by EPR[6] in their paper. In the quantum mechanics, with two physical parameters explained by non-commuting functions, the knowledge of one depends upon the knowledge of the other, moreover:

1: the explanation of reality given by the wave function in quantum theory is not comprehensive, or

2: two physical quantities such that their operators do not commute, these two quantities cannot have simultaneous reality.

Two queries can be asked, in order to judge the success of physical theory.

1: Is this theory correct?

2: Is the explanation given by the theory complete?

EPR made a statement which could be called a condition of completeness: "Every element of the physical must have a counterpart in the physical theory. The later question can be answered as soon as we are able to decide what the elements of physical reality are."

To illustrate the idea of physical reality, consider a particle having a single degree of freedom. The fundamental concept of the theory is the state vector which is the function of variables chosen to describe.

If ψ is wave function and the Eigen function of the operator 'A' then

$$A\psi = a\,\psi \tag{2.4}$$

where 'a' is just a number known as the Eigen value of the operator A. The physical quantity A has a certain value whenever the wave function is ψ. Consider an example where

$$\psi = e^{[(2\pi i/h)px]}. \tag{2.5}$$

Where 'h' is the Planck's constant, operator 'P' can be defined as

$$P = \left(\frac{h}{2\pi i}\right)\frac{d}{dx}\,. \tag{2.6}$$

$$P\,\psi = p\,\psi\,. \tag{2.7}$$

The momentum certainly has the value 'p'. So, we can say that the momentum of the particle in the given state is real. If Eq. (2.1) does not hold, we cannot say anything about the physical quantity A having a particular value. Consider the position coordinate of a particle. What we see is

$$q\,\psi = x\,\psi \neq a\psi. \tag{2.8}$$

The relative measurement of the quadrature will give us a result between a and b. Consider the equation below,

$$P\,(a,b) = \int_a^b \psi' \psi dx = \int_a^b dx = b - a. \tag{2.9}$$

As probability is independent of 'a' but depends upon the difference between 'b-a' what we can say is that all the values of the quadrature have equal probability.

A definite value can be obtained by direct measurement. Such a measurement disturbs the system or particle and its state. What we can say is that when the momentum of a particle is measured, we will lose information about the position coordinates. As written in EPR[6]: "When the momentum of the particle is known its coordinate has no physical reality." Moreover, two operators corresponding to two physical quantities *A* and *B* do not commute *AB≠BA*, then the knowledge of one disturbs the knowledge of the others. From this we can say that "the quantum mechanical description of reality given by the wave function is not complete, or if the operator does not commute the two physical quantities cannot have simultaneous reality".

EPR proved that two non-commuting physical quantities can have simultaneous reality by keeping in mind that wave function gives the complete description of the physical reality. This proof leads to huge amount of literature. This proof was a challenge to Bohr's philosophy of complementarity.

2.1.4 THE DE BROGLIE-BOHM INTERPRETATION

The de Broglie-Bohm Interpretation is also known as pilot wave theory or Bohmian Mechanics. Bohm's Interpretation is one of the interpretations of quantum mechanics. The theory suggests that along with the wave function there is a guiding equation that tells us about the evolution in time. This theory is non-local and deterministic. The position coordinate depends upon the value of the guiding equation which depends upon the wave function of the system.

This theory was originally given by De-Broglie[22] in 1927, but de Broglie gave up this thought and Bohm later presented his interpretation. Bohmian mechanics gives an answer for the measurement problem which originated in the topic of the interpretation of quantum mechanics in the Copenhagen interpretation.

The non-local character of Bohm’s theory has had a large influence on the foundation of quantum mechanics by inducing that nature is non-local at quantum level and theory must be non-local fundamentally to be correct. The theory can be understood easily: if we consider a particle, the motion of that particle is governed by a wave leading the particle. Let us imagines a drop of water on a drum that is vibrating. Because of the vibration the particle follows the wave that is being originated by the vibration of the drum. This phenomenon can be visualized easily. Bohm’s theory gives an answer to the old question about the trajectory of the particle when it passes through the famous Young double slit apparatus. What this theory suggests is that the wave associated with a particle passes through both slits and, based on the interference, the particle will decide which path to follow.

Bohm’s theory was rejected when he first introduced it in 1952 because at that time physics was under the influence of empiricism/Logical positivism. For this reason, Bohm’s theory was named “The Casual Interpretation of quantum mechanics”. The main drawback of this theory is that it does not give results at relativistic speeds. Calculation of the particle trajectories was performed for few physical situations. There are other objections to this theory but one of the main reasons for its failure is that experimental physicists did not work on it . As a result, they did not propose any experiments which could have shown that the theory would tell us more about reality than quantum mechanics.

CHAPTER 3: THE DOUBLE SLIT EXPERIMENT WITH QUANTUM DETECTORS

Introduction

In the first chapter, I discussed Young's double slit experiment. Now I will use that experiment with some modifications to describe the path followed by the particle. For this purpose, I will use different schemes. In the first scheme, I will put a quantum non-demolition detector in front of one of the slits of the Young double slit apparatus. In the second scheme I will place another quantum detector along with the first one and will try to explain the wave function of the particle. In the third scheme, I will put four detectors in front of slits. The diagram for this will be explained later in the chapter. I begin the chapter with the simplest scheme.

3.1 Arrangement 1

This proposition is very straightforward and is based on a double slit interferometer that's connected to one non-demolition quantum detector. A quantum detector is placed such that it is coupled to and is influenced by both arms of the interferometer. I assume that the detector goes from an initial state to a superposition state whose amplitudes depend upon the strength of the interaction with the particle or, more generally, with a quantum entity.

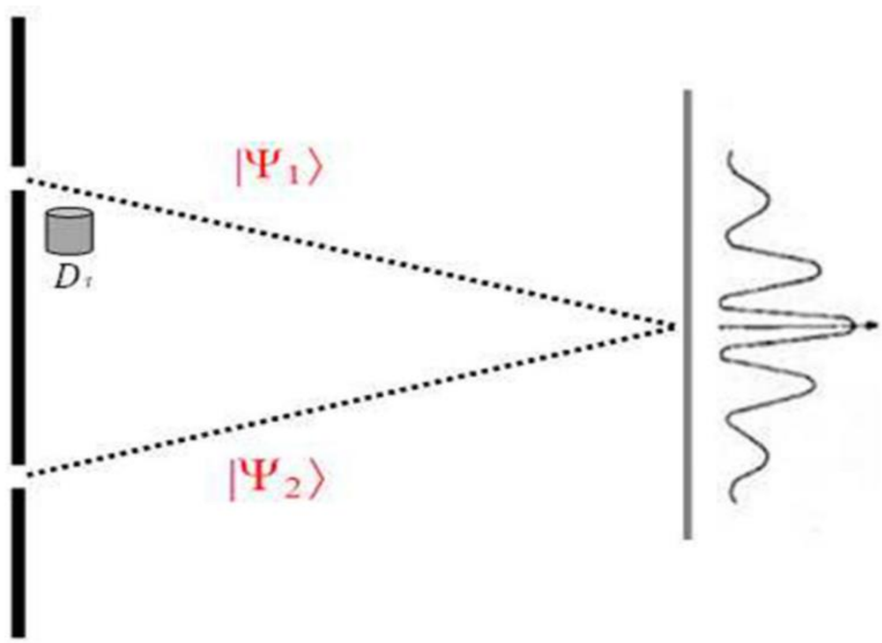

Figure 4. DSE set-up with a single non-demolition Quantum Detector[7].

As shown in Figure 4, the detector is set near to path 1 so that it will be more affected by the path 1 of the interferometer. The wave function of the quantum entity will pass through both the slits simultaneously, designated as $l\Psi_1>$ and $l\Psi_2>$. One cannot anticipate with certainty that detector clicks are due to a particle coming from path 1 or path 2. The initial state of the system is written as,

$$\left|\Psi_{(0)}\right\rangle = \frac{1}{\sqrt{2}}(|\Psi_1\rangle + |\Psi_2\rangle) \otimes \left|0_{D_1}\right\rangle. \tag{3.1}$$

This state evolves to the state,

$$\left|\Psi_{(t)}\right\rangle = \frac{1}{\sqrt{2}}\left[|\Psi_1\rangle \otimes \left(\alpha_1\left|0_{D_1}\right\rangle + \beta_1\left|1_{D_1}\right\rangle\right) + |\Psi_2\rangle \otimes \left(\alpha_2\left|0_{D_1}\right\rangle + \beta_2\left|1_{D_1}\right\rangle\right)\right]. \tag{3.2}$$

Here, α_1 and α_2 correspond to the reflected probability amplitudes making the cases when the quantum entity transfers along slit 1 or slit 2. In the case when no tunneling occurs in the detector we see the no reflected probabilities, so the detector fails to click. Similarly, β_1 and β_2 are the tunneling amplitudes corresponding to the single particle split wave packets $|\Psi_1\rangle$ and $|\Psi_2\rangle$ passing through slit 1 and slit 2, respectively. As the detector is non-demolition it does not absorb the quantum entity in general. Further, the detector is supposed to be affected by both paths (path 1 and path 2). Here the value of the set of probability amplitudes (α_1,β_1) and (α_2,β_2) depends on the location and the distance of the detector V from the interferometric path 1 and path 2 and can be adjust as required. We take the values as

$$\alpha_1 = \sqrt{\left(\frac{1}{\eta}\right)_1}, \beta_1 = \sqrt{\left(\frac{\eta-1}{\eta}\right)_1}, \alpha_2 = \sqrt{\left(\frac{\eta-1}{\eta}\right)_2}, \beta_2 = \sqrt{\left(\frac{1}{\eta}\right)_2} \tag{3.3}$$

Here we take η to be a positive real number, corresponding to probability amplitudes. So, it is also assumed to be real for the sake of simplicity. Now it is easy to notice that $\alpha_1 << \alpha_2$ and $\beta_1 >> \beta_2$ because the detector D_1 is closer to path 1 than to path 2. After placing the values of α_1 and α_2, $\beta 1$ and β_2 in the equation we get

$$|\Psi(t)> = \frac{1}{\sqrt{2}}\begin{bmatrix} \left(\sqrt{\left(\frac{1}{\eta}\right)_1}|\Psi_1\rangle + \sqrt{\left(\frac{\eta-1}{\eta}\right)_2}|\Psi_2\rangle\right) \otimes \left|0_{D_1}\right\rangle + \\ \left(\sqrt{\left(\frac{\eta-1}{\eta}\right)_1}|\Psi_1\rangle + \sqrt{\left(\frac{1}{\eta}\right)_2}|\Psi_2\rangle\right) \otimes \left|1_{D_1}\right\rangle \end{bmatrix}. \tag{3.4}$$

From the above equation, we see that we can acquire increasingly precise information on which path is being taken by increasing the value of η, that is, by changing the position of detector D_1 closer and closer path 1.

The value of η increases when we move the detector closer to either path or investigate the coupling strength of the quantum detector(s). Moreover, we see the weak values resulting from the weak measurements when the detector is almost at the midpoint between the two paths. The case for $\eta = 0$ corresponds to indeterminacy, whereas for η =*1* it corresponds to the projective measurement. As stated earlier, the coupling increases as η increases beyond η =*2* and the measurement again approach the projective situation as η approaches infinity. This case covers the range (*2*, ∞). Now, by using the Greenberger-Englert relationship we can calculate the value of *P* and *V*, where *P* is denoted by path distinguishability and *V* is the visibility of the corresponding fringe with the various values for η. As we know, it is in Greenberger-Englert relationship, that we can first calculate visibility mathematically.

$$V = 2\left|\frac{C_A . C_B}{(C_A)^2 + (C_B)^2}\right|, \tag{3.5}$$

$$V = 2\left|\frac{\sqrt{\frac{1}{\eta}} . \sqrt{\frac{\eta - 1}{\eta}}}{\frac{1}{\eta} + \frac{\eta - 1}{\eta}}\right|,$$

$$V = 2\left|\frac{\sqrt{\eta - 1}}{\eta}\right|.$$

Now, we have to calculate path distinguishability *P*.

$$P = \left|\frac{(C_A)^2 - (C_B)^2}{(C)^2 + (C_B)^2}\right|, \tag{3.6}$$

$$P = \left|\frac{\frac{\eta - 1}{\eta} + \frac{1}{\eta}}{\frac{\eta - 1}{\eta} - \frac{1}{\eta}}\right|,$$

$$P = \left|\frac{\eta - 2}{\eta}\right| = \left|\frac{2 - \eta}{\eta}\right|. \tag{3.7}$$

It satisfies the $P^2 + V^2 \leq 1$

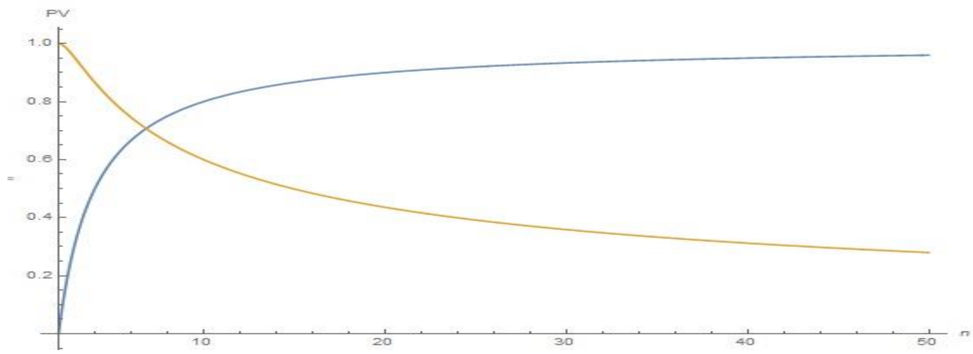

Figure 5. Fringe visibility *V* and path distinguishability *P* for various interferometer-plotted coupling strengths of the detector

The plot in the figure demonstrates the validity of complementarity under this setup.

3.2 Arrangement 2

With just a slight modification to the set-up already described in the previous section (scheme 1), here we simply add another quantum detector D_2, similar to D_1 in the vicinity of path 2 of the interferometer.

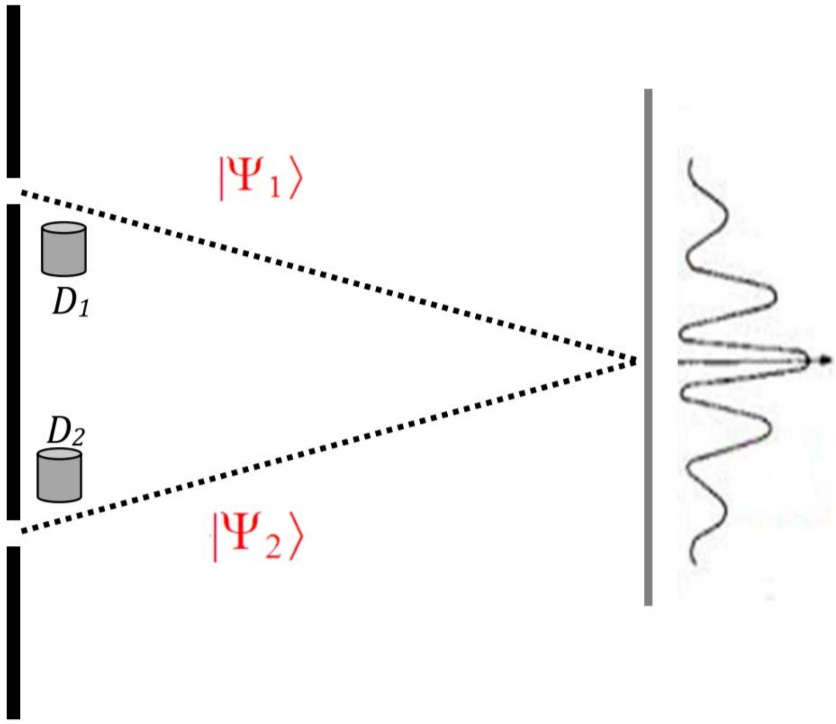

Figure 6. DSE set-up with two quantum detectors[7].

It is clear in Figure 6 that the detector D_1 is coupled relatively strongly to path 1, whereas detector D_2 is more affected by the wave packet component traversing through path 2 with the coupling strengths at almost the same level in the initial state.

$$|\Psi_{(0)}\rangle = \frac{1}{\sqrt{2}}(|\Psi_1\rangle + |\Psi_2\rangle) \otimes |0_{D_1}\rangle \otimes |0_{D_2}\rangle. \tag{3.8}$$

After interaction,

$$|\Psi_{(t)}\rangle = \frac{1}{\sqrt{2}}\begin{bmatrix} |\Psi_1\rangle \otimes \left(\alpha_1{}^{D_1}|0_{D_1}\rangle + \beta_1{}^{D_1}|1_{D_1}\rangle\right) \otimes \left(\alpha_1{}^{D_2}|0_{D_2}\rangle + \beta_2{}^{D_2}|1_{D_2}\rangle\right) \\ +|\Psi_2\rangle \otimes \left(\alpha_2{}^{D_1}|0_{D_1}\rangle + \beta_2{}^{D_1}|0_{D_1}\rangle\right) \otimes \left(\alpha_2{}^{D_2}|0_{D_2}\rangle + \beta_2{}^{D_2}|1_{D_2}\rangle\right) \end{bmatrix}. \tag{3.9}$$

Here, ${\alpha_1}^{D_1}$ and ${\alpha_1}^{D_2}$ denote the probability amplitudes for non-detection cases at the detectors D_1 and D_2, that is, $(\left|0_{D_1}\right\rangle, \left|0_{D_2}\right\rangle)$, whereas, ${\beta_1}^{D_1}$ and ${\beta_1}^{D_2}$ are the corresponding probability amplitudes when the detectors detect the quantum entity, that is, $(\left|1_{D_1}\right\rangle, \left|1_{D_2}\right\rangle)$. Similarly ${\alpha_2}^{D_1}$ and ${\alpha_2}^{D_2}$ denote the probability amplitudes for non-detection cases at the detectors D_1 and D_2, that is, $(\left|0_{D_1}\right\rangle, \left|0_{D_2}\right\rangle)$ and the quantum entity goes through path 2, whereas ${\beta_2}^{D_1}$ and ${\beta_2}^{D_2}$ are the corresponding probability amplitudes when the detectors detect the quantum entity, that is, $(\left|1_{D_1}\right\rangle, \left|1_{D_2}\right\rangle)$. Following the earlier arrangement, we may take these probability amplitudes to be real, as follows:

$$ {\alpha_1}^{D_1} = \sqrt{\left(\frac{1}{\eta}\right)_1}, {\beta_1}^{D_1} = \sqrt{\left(\frac{\eta-1}{\eta}\right)_1}, {\alpha_2}^{D_1} = \sqrt{\left(\frac{\eta-1}{\eta}\right)_2}, {\beta_2}^{D_1} = \sqrt{\left(\frac{1}{\eta}\right)_2} $$

and

$$ {\alpha_1}^{D_2} = \sqrt{\left(\frac{\mathcal{M}-1}{\mathcal{M}}\right)_1}, {\beta_1}^{D_2} = \sqrt{\left(\frac{1}{\mathcal{M}}\right)_1}, {\alpha_2}^{D_2} = \sqrt{\left(\frac{1}{\mathcal{M}}\right)_2}, {\beta_2}^{D_2} = \sqrt{\left(\frac{\mathcal{M}-1}{\mathcal{M}}\right)_2} $$

substituting these expressions in the equation so we get

$$ \left|\Psi_{(t)}\right\rangle = \frac{1}{\sqrt{2}} \begin{bmatrix} \left(\sqrt{\left(\frac{1}{\eta}\right)_1 \left(\frac{\mathcal{M}-1}{\mathcal{M}}\right)_1} \left|\Psi_1\right\rangle + \sqrt{\left(\frac{\eta-1}{\eta}\right)_2 \left(\frac{1}{\mathcal{M}}\right)_2} \left|\Psi_2\right\rangle\right) \otimes \left|0_{D_1}, 0_{D_2}\right\rangle \\ + \left(\sqrt{\left(\frac{\eta-1}{\eta}\right)_1 \left(\frac{1}{\mathcal{M}}\right)_1} \left|\Psi_1\right\rangle + \sqrt{\left(\frac{1}{\eta}\right)_2 \left(\frac{\mathcal{M}-1}{\mathcal{M}}\right)_2} \left|\Psi_2\right\rangle\right) \otimes \left|1_{D_1}, 1_{D_2}\right\rangle \\ + \left(\sqrt{\left(\frac{1}{\eta}\right)_1 \left(\frac{1}{\mathcal{M}}\right)_1} \left|\Psi_1\right\rangle + \sqrt{\left(\frac{\eta-1}{\eta}\right)_2 \left(\frac{\mathcal{M}-1}{\mathcal{M}}\right)_2} \left|\Psi_2\right\rangle\right) \otimes \left|0_{D_1}, 1_{D_2}\right\rangle \\ + \left(\sqrt{\left(\frac{\eta-1}{\eta}\right)_1 \left(\frac{\mathcal{M}-1}{\mathcal{M}}\right)_1} \left|\Psi_1\right\rangle + \sqrt{\left(\frac{1}{\eta}\right)_2 \left(\frac{1}{\mathcal{M}}\right)_2} \left|\Psi_2\right\rangle\right) \otimes \left|1_{D_1}, 0_{D_2}\right\rangle \end{bmatrix}. \tag{3.10} $$

Here we can see that the interaction of both arms of an interferometer with each detector and the information overlap resulting from the interaction subsequently yields a detection pattern, that is, no detector excitation or tunneling $\left|0_{D_1}, 0_{D_2}\right\rangle$, along with both the detectors excitation $\left|1_{D_1}, 1_{D_2}\right\rangle$ or any detector clicks $\left|0_{D_1}, 1_{D_2}\right\rangle, \left|1_{D_1}, 0_{D_2}\right\rangle$ as detected by the corresponding probabilities.

Now, by putting $\mathcal{M} = \eta$ we make the symmetric placing of both detectors mean that the distance of detector 1 from slit 1 is exactly equal to the distance of slit 2 of the interferometer from detector 2. Ignoring the subscripts designating the two paths we have,

$$\left\langle\Psi_{(t)}\middle|\Psi_{(t)}\right\rangle = \frac{1}{\sqrt{2}}\times\frac{1}{\sqrt{2}}\left[\begin{array}{c}\left(\sqrt{\left(\frac{\eta-1}{\eta^2}\right)}\times\sqrt{\left(\frac{\eta-1}{\eta^2}\right)}\ \langle\Psi_1|\Psi_1\rangle+\sqrt{\left(\frac{\eta-1}{\eta^2}\right)}\times\sqrt{\left(\frac{\eta-1}{\eta^2}\right)}\ \langle\Psi_2|\Psi_2\rangle\right)\\ +\left(\sqrt{\left(\frac{\eta-1}{\eta^2}\right)}\times\sqrt{\left(\frac{\eta-1}{\eta^2}\right)}\langle\Psi_1|\Psi_1\rangle+\sqrt{\left(\frac{\eta-1}{\eta^2}\right)}\times\sqrt{\left(\frac{\eta-1}{\eta^2}\right)}\langle\Psi_2|\Psi_2\rangle\right)\\ +\left(\sqrt{\left(\frac{1}{\eta^2}\right)}\times\sqrt{\left(\frac{1}{\eta^2}\right)}\ \langle\Psi_1|\Psi_1\rangle+\sqrt{\left(\frac{(\eta-1)^2}{\eta^2}\right)}\times\sqrt{\left(\frac{(\eta-1)^2}{\eta^2}\right)}\ \langle\Psi_2|\Psi_2\rangle\right)\\ +\left(\sqrt{\left(\frac{(\eta-1)^2}{\eta^2}\right)}\times\sqrt{\left(\frac{(\eta-1)^2}{\eta^2}\right)}\ \langle\Psi_1|\Psi_1\rangle+\sqrt{\left(\frac{1}{\eta^2}\right)}\times\sqrt{\left(\frac{1}{\eta^2}\right)}\ \langle\Psi_2|\Psi_2\rangle\right)\end{array}\right],$$

$$\left\langle\Psi_{(t)}\middle|\Psi_{(t)}\right\rangle = \frac{1}{2}\left[\begin{array}{c}\left(\sqrt{\left(\frac{\eta-1}{\eta^2}\right)}\times\sqrt{\left(\frac{\eta-1}{\eta^2}\right)}+\sqrt{\left(\frac{\eta-1}{\eta^2}\right)}\times\sqrt{\left(\frac{\eta-1}{\eta^2}\right)}\right)\\ +\left(\sqrt{\left(\frac{\eta-1}{\eta^2}\right)}\times\sqrt{\left(\frac{\eta-1}{\eta^2}\right)}+\sqrt{\left(\frac{\eta-1}{\eta^2}\right)}\times\sqrt{\left(\frac{\eta-1}{\eta^2}\right)}\right)\\ +\left(\sqrt{\left(\frac{1}{\eta^2}\right)}\times\sqrt{\left(\frac{1}{\eta^2}\right)}+\sqrt{\left(\frac{(\eta-1)^2}{\eta^2}\right)}\times\sqrt{\left(\frac{(\eta-1)^2}{\eta^2}\right)}\right)\\ +\left(\sqrt{\left(\frac{(\eta-1)^2}{\eta^2}\right)}\times\sqrt{\left(\frac{(\eta-1)^2}{\eta^2}\right)}+\sqrt{\left(\frac{1}{\eta^2}\right)}\times\sqrt{\left(\frac{1}{\eta^2}\right)}\right)\end{array}\right],$$

$$\left\langle\Psi_{(t)}\middle|\Psi_{(t)}\right\rangle = \frac{1}{2}\left[\begin{array}{c}\left(\frac{\eta-1}{\eta^2}\right)+\left(\frac{\eta-1}{\eta^2}\right)+\left(\frac{\eta-1}{\eta^2}\right)+\left(\frac{\eta-1}{\eta^2}\right)\\ +\left(\frac{1}{\eta^2}\right)+\left(\frac{1}{\eta^2}\right)+\left(\frac{(\eta-1)^2}{\eta^2}\right)+\left(\frac{(\eta-1)^2}{\eta^2}\right)\end{array}\right],$$

$$\left\langle\Psi_{(t)}\middle|\Psi_{(t)}\right\rangle = \frac{1}{2}\left[\frac{4(\eta-1)+2+2(\eta-1)^2}{\eta^2}\right],$$

$$\left\langle\Psi_{(t)}\middle|\Psi_{(t)}\right\rangle = \frac{1}{2}\left[\frac{4\eta-4+2+2(\eta^2-2\eta+1)}{\eta^2}\right],$$

$$\left\langle\Psi_{(t)}\middle|\Psi_{(t)}\right\rangle = \frac{1}{2}\left[\frac{4\eta-4+2+2\eta^2-4\eta+2}{\eta^2}\right],$$

$$\left\langle\Psi_{(t)}\middle|\Psi_{(t)}\right\rangle = \frac{1}{2}\left[\frac{\eta^2}{\eta^2}\right],$$

$$\left\langle\Psi_{(t)}\middle|\Psi_{(t)}\right\rangle = 1. \tag{3.11}$$

So, Eq. (3.10) is normalized after normalization of the Eq. (3.11) turn into

$$\left|\Psi_{(t)}\right\rangle = \alpha\left(\frac{1}{\sqrt{2}}(|\Psi_1\rangle + |\Psi_2\rangle)\right)\otimes\left|0_{D_1},0_{D_2}\right\rangle + \alpha\left(\frac{1}{\sqrt{2}}(|\Psi_1\rangle + |\Psi_2\rangle)\right)\otimes\left|1_{D_1},1_{D_2}\right\rangle$$

$$+\beta\left(\sqrt{\left(\frac{1}{(\eta-1)^2+1}\right)}|\Psi_1\rangle + \sqrt{\left(\frac{(\eta-1)^2}{(\eta-1)^2+1}\right)}|\Psi_2\rangle\right)\otimes\left|0_{D_1},1_{D_2}\right\rangle$$

$$+\beta\left(\sqrt{\left(\frac{(\eta-1)^2}{(\eta-1)^2+1}\right)}|\Psi_1\rangle + \sqrt{\left(\frac{1}{(\eta-1)^2+1}\right)}|\Psi_2\rangle\right)\otimes\left|1_{D_1},0_{D_2}\right\rangle \qquad (3.12)$$

where

$\alpha = \sqrt{\frac{(\eta^3-3\eta^2+4\eta-2)}{2(\eta^3-2\eta^2+4\eta-2)}}$ $\quad ,\beta = \sqrt{\frac{\eta^2}{2(\eta^3-2\eta^2+4\eta-2)}}$.

Further, we can check that the Eq. 3.12 is normalized by substituting the values α and β

$$\left\langle\Psi_{(t)}\middle|\Psi_{(t)}\right\rangle = \alpha^2\left(\frac{1}{\sqrt{2}}\right)^2(1+1) + \alpha^2\left(\frac{1}{\sqrt{2}}\right)^2(1+1)$$

$$+\beta^2\left[\left(\sqrt{\left(\frac{(\eta-1)^2}{(\eta-1)^2+1}\right)}\right)^2 + \left(\sqrt{\left(\frac{1}{(\eta-1)^2+1}\right)}\right)^2\right]$$

$$+\beta^2\left[\left(\sqrt{\left(\frac{1}{(\eta-1)^2+1}\right)}\right)^2 + \left(\sqrt{\left(\frac{(\eta-1)^2}{(\eta-1)^2+1}\right)}\right)^2\right],$$

$$= 2\alpha^2+\beta^2\left(\frac{2(\eta-1)^2}{(\eta-1)^2+1} + \frac{2}{(\eta-1)^2+1}\right),$$

$$= 2(\alpha^2+\beta^2)\left(\frac{(\eta-1)^2+1}{(\eta-1)^2+1}\right),$$

$$= 2(\alpha^2+\beta^2).$$

Now, finally, we put the values of α and β after simplification

$$= 2\left(\frac{\eta^3 - 3\eta^2 + 4\eta - 2}{2(\eta^3 - 2\eta^2 + 4\eta - 2)} + \frac{\eta^2}{2(\eta^3 - 2\eta^2 + 4\eta - 2)}\right),$$

$$= \frac{\eta^3 - 3\eta^2 + 4\eta - 2 + \eta^2}{\eta^3 - 2\eta^2 + 4\eta - 2},$$

$$\langle \Psi_{(t)} | \Psi_{(t)} \rangle = 1. \tag{3.13}$$

We note that for these states $|0_{D_1}, 0_{D_2}\rangle, |1_{D_1}, 1_{D_2}\rangle$ detections, the probability strangely increases with , that is, with η the coupling strength of the non-demolition quantum detectors such that

$\lim_{n\to\infty} \Pr(|0_{D_1}, 0_{D_2}\rangle)[|1_{D_1}, 1_{D_2}\rangle] = 1/2$, while it declines consequently for the states conforming to $|0_{D_1}, 1_{D_2}\rangle, |1_{D_1}, 0_{D_2}\rangle$ detection measures and becomes zero when η goes to ∞ (infinity). This clearly marks the situation when detectors are placed in the vicinity of the interferometry paths and register a weak, non-demolition measurement through indirect interaction with a quantum entity passing through the interferometer. A quantum entity leads to the collapse of the state vector as the detectors do not block or absorb it, a situation we encounter for $\eta = 1$ or $\eta \to \infty$ agreeing to the projective measurement.

3.3 Arrangement 3

A further interesting situation arises when we install two additional detectors D_3 and D_4. Firstly, in the state $|0_{D_3}, 0_{D_4}\rangle$, along the interferometric routes after the (D_1, D_2) couple, we see,

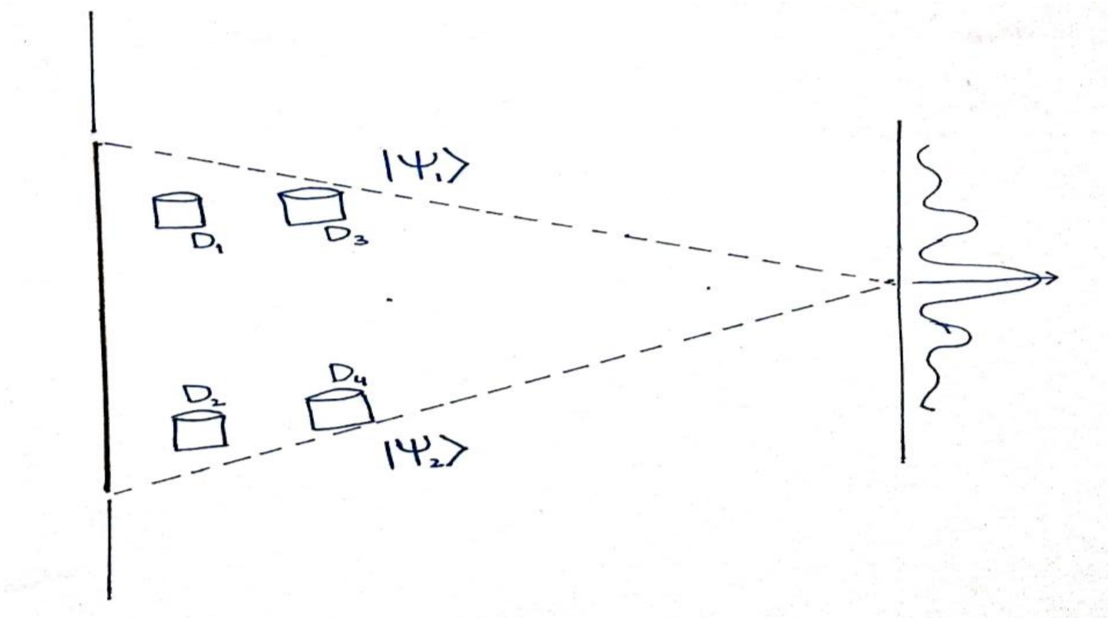

Figure 7. DSE set-up with four non-demolition quantum detectors.

The states agreeing to the detection event $\left|0_{D_1}, 0_{D_2}\right\rangle$, which happens with the probability $\frac{\eta^3-3\eta^2+4\eta-2)}{2(\eta^3-2\eta^2+4\eta-2)}$ when exposed to this edited recognition situation, result in the following state

$$\left|\Psi_{(t)}\right\rangle = \upsilon\left(\frac{1}{\sqrt{2}}(|\Psi_1\rangle + |\Psi_2\rangle)\right) \otimes \left|0_{D_3}, 0_{D_4}\right\rangle + \upsilon\left(\frac{1}{\sqrt{2}}(|\Psi_1\rangle + |\Psi_2\rangle)\right) \otimes \left|1_{D_3}, 1_{D_4}\right\rangle$$

$$+\mu\left(\sqrt{\left(\frac{1}{(\eta-1)^2+1}\right)}|\Psi_1\rangle + \sqrt{\left(\frac{(\eta-1)^2}{(\eta-1)^2+1}\right)}|\Psi_2\rangle\right) \otimes \left|0_{D_3}, 1_{D_4}\right\rangle$$

$$+\mu\left(\sqrt{\left(\frac{(\eta-1)^2}{(\eta-1)^2+1}\right)}|\Psi_1\rangle + \sqrt{\left(\frac{1}{(\eta-1)^2+1}\right)}|\Psi_2\rangle\right) \otimes \left|1_{D_3}, 0_{D_4}\right\rangle. \quad (3.14)$$

Here again

$$\upsilon = \sqrt{\frac{(k^3-3k^2+4k-2)}{2(k^3-2k^2+4k-2)}}, \qquad \mu = \sqrt{\frac{k^2}{2(k^3-2k^2+4k-2)}}$$

Where k is just like η and describes the connection assets of the detectors D_3 and D_4. In the similar way, we could similarly inscribe parallel expressions for the states evolving out of the detection choices $|1_{D_1}, 1_{D_2}\rangle$, $|0_{D_1}, 1_{D_2}\rangle$ and $|1_{D_1}, 0_{D_2}\rangle$. For these cases, results will be discussed in the last chapter.

CHAPTER 4: WHEELER'S DELAYED-CHOICE GEDANKEN EXPERIMENT AND IT'S TEST

WDCE is an assumed experiment. It concerns the experimenter's choice with which he will be able to change the past. If he fixed the screen, he saw the particle nature; to view the wave nature he allows screen to move. There are several experiments he tried to perform with this thought experiment. These analyses are endeavors to choose whether light by one way or another 'understands' the experimental device in the DSE, when it is changed by the experimenter's choice and whether it shows its wave nature or particle nature. We would also hope to determine regardless of whether light stays in an uncertain, neither particle nor wave, until measured.

The expectation of these investigations was to test whether, as certain understandings of the hypothesis recommended would happen, every photon *"chose"* regardless of whether it shows the dual nature (wave/particle), and afterward, before the opportunity for the photon to arrive at the location gadget, it makes another adjustment in the framework that would cause it to appear that the photon had *"picked"* to carry on in the contrary path. A few mediators of these analyses state that the photon can be either a wave or a molecule yet not together at similar time. Wheeler's aim was to examine the time-related circumstances under which a photon makes the change among assumed conditions. His work has delivered some snug investigations. He might not have thought about how conceivable it is that different specialists would incline in the direction of determination that a photon holds the two its *"particle nature"* and *"wave nature"* until the time it takes its life. In any case, he himself is by all accounts exceptionally clear on this point. He says:

> "The thing that causes people to argue about when and how the photon learns that the experimental apparatus is in a certain configuration and then changes from wave to particle to fit the demands of the experiment's configuration is the assumption that a photon had some physical form before the astronomers observed it. Either it was a wave or a particle; either it went both ways around the galaxy or only one way. Quantum phenomena are neither waves nor particles but are intrinsically undefined until the moment they are measured."[24]

4.1 WHEELER'S DELAYED-CHOICE GEDANKEN EXPERIMENT USING A MACH-ZEHNDER INTERFEROMETER.

YDSE is accomplish with the particles that are sent one by one through the interferometer is at the temperament of quantum mechanics[23]. It is incompatible with the notion that the marvel of interference be understood as a wave occupy two paths. Several experiments have obsreved the wave particle duality of the light-field by true single-photon interference. To recognize their meaning, consider the single-photon experiment as shown in figure below.

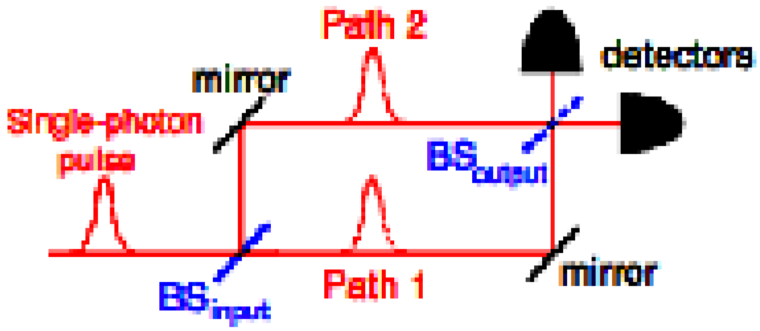

Figure 8. Wheeler's Delayed-Choice Gedanken Experiment with a single-photon pulse in a Mach-Zehnder interferometer[1].

A single-photon pulse is divided by the BS_{input} of a Mach-Zehnder interferometer and pass through it. The BS_{output} of the interferometer can be introduced or removed at will.

In closed arrangement, when BS_{output} is introduced, the single-photon pulse travels by the BS_{input} until BS_{output} remerge the two interfering arms. When the phase shift Φ between the two arms is diverse, interference seems as a modulation of the finding probabilities at output ports 1 and 2 correspondingly as $sin2\Phi$ and $cos2\Phi$. This is the expected result for a wave, and as Wheeler said: "This is the evidence that each arriving light quantum has arrived by both routes."[1]

In open configuration, when BS_{output} is removed, if one uses true single-photon light, individually detector D_1 or D_2 on the output ports is then related with a given path of the interferometer. In this situation, Wheeler pointed out: "Either one counter goes off, or the other. Thus, the photon has traveled only one route."[24] These two configurations, or similar experiments, support Bohr's statement that "the behavior of a quantum system is determined by the type of measurement performed on it"[25].

Two opposite measurements are measured here; the consistent experimental settings are jointly limited, that is, the BS_{output} cannot be instantaneously introduced or removed. In experiments where the choice of an inserted or removed BS_{output} is made long in advance, one could settle Bohr's complementarity with Einstein's local beginning of physical reality, which holds that the objects have a certain pair of complementary properties which cannot be observed or measured simultaneously (wave and particle related properties). When the photon enters the interferometry, it could have received some hidden information on the chosen experimental formation and could then adjust its behavior accordingly[1]. J. A. Wheeler proposed the DCGE in which the choice as to which property will be observed is made later the photon has passed the

BS_{input}. "Thus, one decides the photon shall have come by one route or by both routes after it has already done its travel."[1]

4.2 WHEELER'S DELAYED-CHOICE GEDANKEN EXPERIMENT (WDCGE) BY USING A QUANTUM RANDOM NUMBER GENERATOR.

The acknowledgment of such a DCE is a plan near WDCGE performed by using a Mach-Zehnder interferometer as described in the above section (Figure 8). Now the choice to remove or insert the BS_{output} is decided randomly by using a $QRNG$. The $QRNG$ is situated near to the BS_{output}, and far enough from the BS_{input} so that no data about the decision can arrive at the photon earlier it goes through the BS_{input}.

For the single-photon source nitrogen-vacancy $(N-V)$ color center in a diamond nanocrystal is centered on pulsed, optically excited photoluminescence. Such photoluminescent centers can be dealt with individually using confocal microscopy at the single-emitter level and have exposed unrivaled effectiveness and photostability at room temperature. In order to achieve the demanded relativistic departure condition, we use $48-meter$ long divergence interferometer with two spatially detached paths. Linearly polarized single photons, from the eigenpolarizations of polarizing beam-splitter BS_{input} at 45°, are divided into two mechanisms that travel along detached paths. The choice to recombine or not the two paths of the interferometer is completed in two steps.

1) Symmetrically two beams captivated and spatially isolated, are covered by a polarizing beam-splitter $BS^{/}$, however can in any case be expressly distinguished by their polarization.
2) The decision among the two arrangements, open or shut, is composed with the quick electro-optical modulator (EOM) trailed by a Wollaston crystal.

Note also:

- At the point when the value of voltage is zero that is, V_o to EOM, the circumstance relates to the removal of BS_{output}, (open configuration of the first case) the two paths remain uncombined, and each detector D_1 and D_2 is related with a precise path, respectively path 1 or path 2.
- At the point when half-wave voltage, that is, V_π, is applied to EOM (closed configuration of first cause), the two orthogonally polarized beams are recombined by Wollaston prism, which have traveled along different paths.

The space-like division among the decision of the measurement and the section of the photon at the BS_{input} is accomplished utilizing a home-fabricated quick driver fit for exchanging among V_o and V_π within $40\,ns$. Moreover, the EOM exchanging is chosen arbitrarily continuously by the $QRNG$ situated near to the output of the interferometer, 48 $meters$ from BS_{input}.

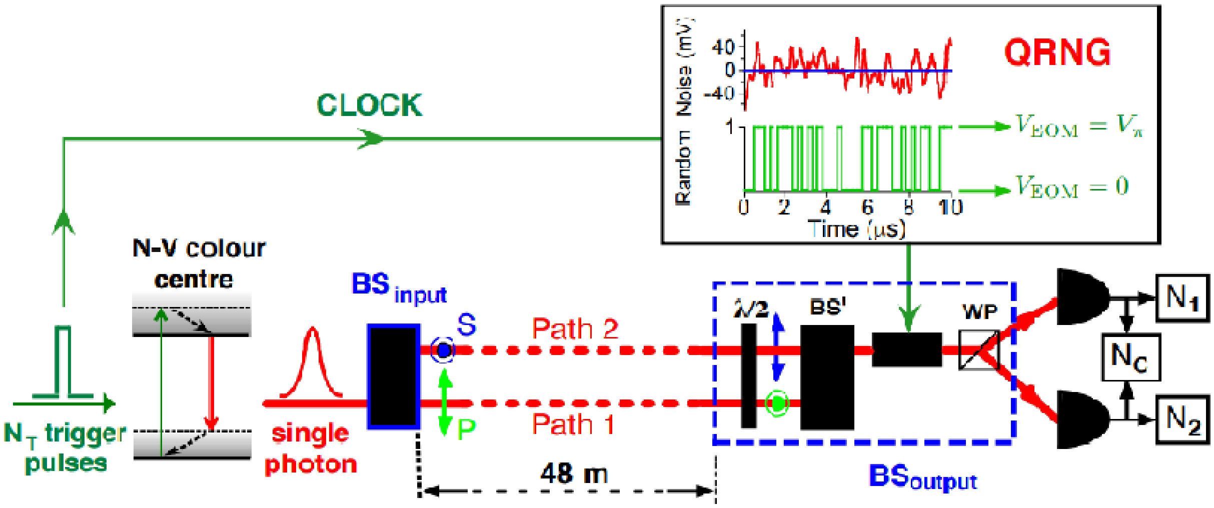

Figure 9 .Test of Wheeler's Delayed-Choice Gedanken Experiment using a single-photon pulse by usnig a QRNG and an EOM[1].

The solo photon is primary tried utilizing the output detector couple nourishing single and occurrence counters with BS_{output} removed (open configuration). We suppose that a run comparing to $\aleph_T$ trigger pulses applied to the emitter, with $\aleph_1$ (resp. $\aleph_2$) being the interferometer counts spotted by D_1 through slit 1 (respectively by D_2 through slit 2), and $\aleph_C$ the detected chances, corresponding to the joint photodetections on D_1. Any explanation in which wave light is preserved as a classical wave, like semi-classical theory with quantized photodetectors, expects that these numbers of counts must follow the inequality.

$$\alpha = \frac{\aleph_C \times \aleph_T}{\aleph_C \times \aleph_T} \geq 1 \tag{4.1}$$

In the case of open configuration when a single photon pulse passes, we expect each detector D_1 and D_2 to be explicitly associated with the slits of the interferometer. The information parameter is evaluated by blocking one path and measuring the counting rates at D_1 and D_2, to test this case.

The DCE itself is done with the EOM haphazardly exchanged for every photon sent into the interferometer, comparing among open and close arrangements. For every photon, we record the picked arrangement, the identification occasions and the piezoelectric actuator (PZT). The stage move Φ among the two interferometer arms is fluctuated by inclining the subsequent beam-splitter $BS^{/}$ with PZT.

As Wheeler said, since no signal peripatetic at a velocity less than the speed of light can connect these two events, a signal at the speed of light could in fact do so: "We have a strange inversion of the normal order of time. We, now, by moving the mirror in or out have an un-avoidable effect on what we have a right to say about the already history of that photon."[26]

It was found that nature performs in contract with the guesses of quantum mechanics, even in shocking circumstances where a tension with relativity appears. These two experiments, one with a Mach-Zehnder interferometer and the other using the $QRNG$, do not explain Wheeler's original delayed-choice experiment. We will explain in the next chapter how they do not support the original scheme.

CHAPTER 5: RESULTS, DISCUSSION, AND CONCLUSION

The detection pattern yielded by the equation (3.12), at the point when depicted in ordinary language, proposes the accompanying opposing articulations.

1) The quantum entity are not consider the accessible paths ($|0_{D_1}\rangle, |0_{D_2}\rangle$), in any event, for the solid framework-detector interactions, that is, larger η values, but it arrives the screen and show the interference pattern.
2) It passes through the both slits, ($|1_{D_1}\rangle, |1_{D_2}\rangle$), featuring the ancient difficulty of the hypothesis.
   - It may go through slit 1 or slit 2 ($|0_{D_1}\rangle, |1_{D_2}\rangle$). These three cases bound in a reasonable superposition. Moreover, it is noticed that:
   - When there is no click on the detector, operationally like the circumstance we experience while considering the celebrated psychological study known as Einstein's boxes. One generally finds the particle in some case, after opening the boxes.
   - The present proposal, as discussed in chapter 3, additionally unequivocally illustrates, in the middle of the arrangement and the identification, that the substance carries on as an 'incredible smoky mythical beast', in which a quantum entity can go through the two ways.
   - The most perplexing end originates from the articulation (3.14) that is produced a expansion for the additional couple of quantum detectors *(D_3, D_4)*. This mediation, as equation (3.14) delineates unmistakably, whenever a solid ontological probabilistic estimate it reshuffles the earlier probabilities and curiously proposes that, in a specific case, the molecule may immediately and non-locally flip the way, that is, seem to hop from way 1 to way 2 and the other way around because of its cooperation with finder D_3 and D_4. This non-local flipping, if acknowledged, calls for some genuine results.
   - The local-hidden variable theories were not classified.
   - The finding of the present proposal discussed in Chapter 3 is subject to non-local hidden variable theories and De Broglie's pilot-wave standard, which considered that the spatially distinct particle continuously flows, from start to end, accumulated one of the fixed path, but always go together with non-local potential or a pilot wave.
   - In equations (3.12) and (3.14) the values of α, β and υ, μ are not the unique ones they might be:

     $\alpha = \sqrt{\frac{\eta-1}{\eta^2}}$, $\beta = \sqrt{\frac{\eta^2-\eta+1}{\eta^2}}$, $\upsilon = \sqrt{\frac{\mathcal{M}-1}{\mathcal{M}^2}}$, $\mu = \sqrt{\frac{\mathcal{M}^2-\mathcal{M}+1}{\mathcal{M}^2}}$, the equations become

$$|\Psi_{(t)}\rangle = \frac{1}{\sqrt{2}}\begin{bmatrix} \alpha\Big((|\Psi_1\rangle + |\Psi_2\rangle) \otimes |0_{D_1}, 0_{D_2}\rangle + (|\Psi_1\rangle + |\Psi_2\rangle) \otimes |1_{D_1}, 1_{D_2}\rangle\Big) \\ +\beta\Big((|\Psi_1\rangle + |\Psi_2\rangle) \otimes |0_{D_1}, 1_{D_2}\rangle + (|\Psi_1\rangle + |\Psi_2\rangle) \otimes |1_{D_1}, 0_{D_2}\rangle\Big)\end{bmatrix}.$$

Similarly, equation (3.14)

$$\left|\Psi_{(t)}\right\rangle = \frac{1}{\sqrt{2}}\begin{bmatrix} \upsilon\left((|\Psi_1\rangle + |\Psi_2\rangle) \otimes \left|0_{D_3}, 0_{D_4}\right\rangle + (|\Psi_1\rangle + |\Psi_2\rangle) \otimes \left|1_{D_3}, 1_{D_4}\right\rangle\right) \\ +\mu\left((|\Psi_1\rangle + |\Psi_2\rangle) \otimes \left|0_{D_3}, 1_{D_4}\right\rangle + (|\Psi_1\rangle + |\Psi_2\rangle) \otimes \left|1_{D_3}, 0_{D_4}\right\rangle\right) \end{bmatrix}$$

Both equations satisfy, $\left\langle\Psi_{(t)}\middle|\Psi_{(t)}\right\rangle = 1.$

Now in Chapter 4, we discussed the test of WDCE by a Mach-Zehnder interferometer. As we see in the above section two cases are discussed. The photon shows the wave particle duality because in first scenario when photon travels it shows its wave nature while it has to be travel as a particle. Wheeler required to recognize whether the photon decided to become a wave or particle before passing through the slits or after passing through them? But in the proposed Mach-Zehnder interferometer experiment, we cannot answer this.

Another test of WDCE was the use of a QRNG. A coherent single-photon pulses, ejected by a single $N - V$ color center, are sent into two spatially detached way by a piercing beam-splitter BS_{input}. The moveable BS_{output} contains the combination of a half-wave plate, a polarization beam-splitter BS', an EOM, and Wollaston prism. The choice between the measurement configurations, closed or open, is realized by applying a given voltage 0 or V_π to the EOM. The BS_{output} is 48 meters away from the BS_{input}, ensuring the space-like separation between the setting of the chosen experimental arrangement and the entrance of the photon into the interferometer. Here, we face two major problems:

1) the choice between the open or close configuration;
2) the distance between the BS_{input} and BS_{output}.

According to the original scheme proposed by Wheeler, the choice between open and closed configurations (choice of fixed screen or moving) is made by the experimenter. But in the test by the QRNG, the choice is made randomly. There is no concept of experimenter consciousness in this test. With the QRNG, the distance between input and output is only 48 meters, while in calculations we know that the speed of light is $3 \times 10^8 ms^{-1}$ and for decision-making a normal brain needs at least time $0.1s$. According to $s = vt$, we need at least $30{,}000km$ distance between input (slits) and output (screen). So, we need satellite at 30000km or above to perform this experiment or we have to fix the screen (output) on the moon and the input on the earth, which is too difficult. For wave nature, we repeat this open and close configuration millions of times.

REFERENCES

[1] V. Jacques, Ewu, F. Grosshans, et al. "Experimental realization of Wheeler's delayed-choice gedanken experiment." *Science* **315** (2007) 966-968.

[2] E. Frankel. "Corpuscular optics and the wave theory of light: the science and politics of a revolution in physics." *Social Studies Of Science* **6** (1976) 141-184.

[3] L. de Broglie. "A tentative theory of light quanta." *The London, Edinburgh, and Dublin Philosophical Magazine and Journal of Science* **47** (1924) 446-458.

[4] W. Wootters and W. H. Zurek. "Complementarity in the double-slit experiment: Quantum nonseparability and a quantitative statement of Bohr's principle." *Physical Review D* **19** (1979) 473-484.

[5] M. Ozawa. "Universally valid reformulation of the Heisenberg uncertainty principle on noise and disturbance in measurement." *Physical Review A* **67** (2003) 042105.

[6] J. S. Bell. "On the Einstein Podolsky Rosen paradox." *Physics Physique Fizika* **1** (1964) 195-290.

[7] M. Ikram, A. H. Mujtaba and T. Abbas. "Double slit experiment with quantum detectors: mysteries, meanings, misinterpretations and measurement." *Laser Physics Letters* **15** (2017) 015208.

[8] T. Young. "II. The Bakerian Lecture. On the mechanism of the eye." *Philosophical Transactions of the Royal Society of London* **91** (1801) 23-88.

[9] S. A. Fulling. "Nonuniqueness of canonical field quantization in Riemannian space-time." *Physical Review D* **7** (1973) 2850-2862.

[10] A. Qadir, private communication.

[11] F. Reif. *Fundamentals of statistical and thermal physics*, (Waveland Press, 2009).

[12] K. Camilleri. "Bohr, Heisenberg and the divergent views of complementarity." *Studies In History and Philosophy of Science Part B: Studies In History and Philosophy of Modern Physics* **38** (2007) 514-528.

[13] N. Bohr. "On atoms and human knowledge." *Daedalus* **87** (1958) 164-175.

[14] A. Petersen. "The philosophy of Niels Bohr." *Bulletin of the Atomic cientists* **19** (1963) 8-14.

[15] D. Bohm and J. Hiley. "Social Theory as Cartesian science: an auto-critique from a quantum perspective." *Constructivism and international relations: Alexander Wendt and his critics* (2006) 181-219.

[16] D. V. Ahluwalia. "Wave-Particle duality at the Planck scale: Freezing of neutrino oscillations." *Physics Letters A* **275** (2000) 31-35.

[17] C. Monroe, D. Meehkof, et al. "A “Schrödinger cat” superposition state of an atom." *Science* **272** (1996) 1131-1136.

[18] D. L. Hill and J. A. Wheeler. "Nuclear constitution and the interpretation of fission phenomena." *Physical Review* **89** (1953) 1102-1145.

[19] N. Bohr, H. A. Kramers, and J. C. Slater. "The quantum theory of radiation." *The London, Edinburgh, and Dublin Philosophical Magazine and Journal of Science* **47** (1924) 785-802.

[20] A. Calaprice, *The expanded quotable Einstein*, (Princeton University Press, 2000).

[21] N. Bohr. "Discussion with Einstein on epistemological problems in atomic physics." *Niels Bohr Collected Works*. **7**. Elsevier, (1996) 339-381.

[22] A. Valentini. "Perturbations and quantum relaxation." *Foundations of Physics* **49** (2019) 1-23.

[23] J. T. Cushing. "The causal quantum theory program." *Bohmian mechanics and quantum theory: An appraisal. Springer, Dordrecht*, (1996).

[24] A. Narasimhan and M. C. Kafatos. *"Wave particle duality, the observer and retrocausality."* (AIP Publishing LLC, 2017).

[25] H. Zinkernagel. "Niels Bohr on the wave function and the classical/quantum divide." *Studies in History and Philosophy of Science Part B: Studies in History and Philosophy of Modern Physics* **53** (2016) 9-19.

[26] J. J. Bogenstahl, A. Deshpande, et al. *"Proposal for a joint German-British interferometric gravitational wave detector."* (Max-Planck-Institute,1989).