BOHR'S COMPLEMENTARITY AND AFSHAR'S EXPERIMENT: A NON-DUALISTIC STUDY AT THE SINGLE-QUANTUM LEVEL

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Abstract - *Using a newly proposed 'wave-particle non-dualistic interpretation' of the quantum formalism, Bohr's principle of complementarity is analyzed in the context of the single-slit diffraction and the Afshar's experiments - at the single-quantum level. The fundamental flaw in the Afshar's argument is explicitly pointed out.*

Key Words: Copenhagen Interpretation of Quantum Mechanics, Principle of Complementarity, Wave-Particle Duality, Non-Duality, Born's Rule, Afshar's Experiment

1. INTRODUCTION

Bohr's principle of complementarity (PC) [1–3] states that any given application of classical concepts precludes the simultaneous use of other classical concepts which in a different connection are equally necessary for the elucidation of the phenomena. Let's elucidate the same using wave-particle duality [4–7]: According to the wave-particle duality, a quantum behaves particle-like while observing, but, wave-like in the absence of observation, suggesting an inference that the same quantum possesses both the behaviors simultaneously. However, observation of one behavior excludes the simultaneous observation of the other. Which behavior becomes observable depends on the experimental configuration. Notice that, here, the PC is simply stitching both the classical natures, wave and particle, together. No physical mechanism is provided for such a stitching using the quantum formalism. Also, how wave nature makes instantaneous transition to the particle nature during the observation is unclear. The Afshar's experiment [8, 9] (Fig. 1) is a variant of the Young's double-slit experiment designed to verify the validity of the PC. A laser beam passing through the pinholes 1 and 2 undergoes superposition and forms an interference pattern on a vertical screen, if present. A vertical grid of thin wires (VT) is placed instead of the screen such that the wires lie exactly in the regions of dark fringes

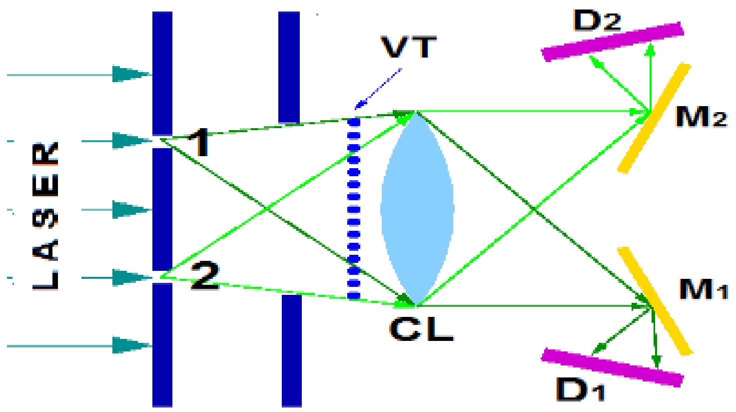

Fig-1: Diagram of Afshar's experiment:

A laser beam, passing through two closely spaced circular pinholes 1 and 2, is refocused by a convex lens, CL, such that the images of pinhole 1 and 2 fall on the photon-detectors D1 and D2 , respectively. When pinhole-2 (pinhole-1) is blocked, then a photon passing through pinhole-1 (pinhole-2) is detected by D1 (D2). A vertical grid of thin wires, VT, is placed just before the CL, in the region of interference due to the pinholes 1 and 2 so that the wires lie in the dark fringes. M1 and M2 are two totally reflecting mirrors.

And hence the photon flux will not be obstructed appreciably. A convex lens just behind the VT focuses the photon fluxes from pinhole 1 and 2 onto the photon- detectors D1 and D2 , respectively. The same experiment is repeated, now, by blocking alternately either one of the pinhole and registering the corresponding photon flux by the respective detector. The total of registered fluxes by D1 and D2 in the former case is found to be more than the same in the later case. The experiment is again repeated in the absence of the VT by blocking alternately either one of the pinhole. The total registered flux by D1 and D2 is compared with the same total in the initial case where both pinholes were kept open in the presence of the VT and found to be almost the same. Hence, Afshar concluded the existence of an interference pattern at the location of VT by inference but not by the recorded evidence. Therefore, if the interference pattern truly exists, then it implies a photon as wave-like. But the same photon contributed to the image of pinhole, either 1 or 2, at D1 or D2 , respectively, due to the momentum conservation, implying the same photon behaved particle-like. If one uses wave-particle duality, this situation seems to be paradoxical because a given photon has to pass through both the pinholes to form an interference at the grid location but at the same time it has to pass through any one of the pinhole to behave like a particle at either D1 or D2 , in the same given experimental arrangement which is against the PC. Here, we would like to emphasize that the inference about a single photon simultaneously going through both the slits to produce interference itself violates the law of conservation of momentum and is a fundamental drawback in the concept of wave-particle duality which is also the cause for believing the Nature to be intrinsically random, probabilistic and also retrocasual. Wave-particle duality does not contain any paradox but it itself is a paradox.

2. BRIEF SUMMARY OF THE NON-DUALISTIC INTERPRETATION OF QUANTUM MECHANICS

The wave-particle non-duality in quantum mechanics [17, 18] is briefed below:

The Schrodinger wave function is shown to be an instantaneous resonant spacial mode (IRSM) in which a quantum particle flies akin to the case of a test particle in the curved space-time of the general relativity. This picture is unlike any classical wave, though the IRSM obeys the Schrodinger equation. The intensity of a classical wave is proportional to the square of its amplitude. But, such an intensity can't be claimed for the IRSM. If the particle is going to end up on a detector screen, then a dual vector gets excited in the same screen and interacts according to the inner-product which can be found within the quantum formalism. Let the IRSM, say $|\psi\rangle$, gets scattered into some other state, say $|\psi_1\rangle$ at the screen. This process can be described by associating an operator, $\hat{O} = |\psi_1\rangle\langle\psi|$:

$$\hat{O}\,|\psi\rangle = \langle\psi|\psi\rangle\,|\psi_1\rangle \qquad (1)$$

(A remark follows: the time derivative of the unitary evolution operator will be discontinuous at the space-time point of detection but it itself will be continuous).

Therefore, if the scattered state is discarded or it is a null-state, then the particle must have interacted or got absorbed at some location in the region of inner-product, $\langle\psi|\psi\rangle$. Instead of $\hat{O}$, if the IRSM encounters a vector space spanned by discrete orthogonal eigenstates, $|a_i\rangle$; $i = 1, 2, 3, \cdots$, of an operator, $\hat{A}$:

$$|\psi\rangle = \sum_i |a_i\rangle\langle a_i|\psi\rangle, \qquad (2)$$

Then the particle enters into one of the eigenstate, say $|a_p\rangle$, which makes the minimum phase with $|\psi\rangle$. All other empty eigenstates will be present ontologically. During the observation, the IRSM interacts with its excited dual, $\langle\psi|$, in the detector:

$$\langle\psi|\psi\rangle = \sum_i \langle\psi|a_i\rangle\langle a_i|\psi\rangle \to |\langle a_p|\psi\rangle|^2. \qquad (3)$$

The particle will be naturally found in $|a_p\rangle$ with an eigenvalue a_p, since, the remaining orthogonal empty

States have nothing to contribute. This is the underlying physical mechanism of the 'wave function collapse' advocated in the Copenhagen interpretation [5]. Repeating the detection procedure on several particle states with different initial phases yields various eigenvalues, which by normalizing with the total number of particle yields the relative frequency of detection (RFD). In the limit of infinite number of particles, the RFD coincides with $|\langle a_i|\psi\rangle|^2$:

$$\langle\psi|\psi\rangle = \sum_i \langle\psi|a_i\rangle\langle a_i|\psi\rangle = \sum_i |\langle a_i|\psi\rangle|^2 = 1, \qquad (4)$$

which is the well-known Born's rule.

Instead of $\hat{A}$, let's consider the position operator, $\hat{r}$, with orthogonal eigenstates, $|r\rangle$, and continuous eigen values, r (= {x, y, z}):

$$|\psi\rangle = \int dr\, |r\rangle\langle r|\psi\rangle. \qquad (5)$$

The particle naturally enters into the position eigenstate, say $|r_p>< r_p|\psi>$, such that its absolute phase is the same as that of $|\psi>$, i.e., phase$\{< r_p|\psi>\}$ = phase$\{|\psi>\}$. Therefore, the interaction of IRSM with its excited dual, $<\psi|$, in an apparatus is

$$<\psi|\psi> = \int dr <\psi|r><r|\psi> = |<r_p|\psi>|^2 \quad (6)$$

because, except the particle state $|r_p>< r_p|\psi>$, the remaining orthogonal ones, $|r>< r|\psi>$, are empty. Therefore, quantum mechanics is not a probabilistic theory. It can be described at a single quantum level which, anyhow, statistically yields Born's rule for a large number of identical particles. The unavailability of the absolute phase information of the IRSM due to the inner-product interaction forces experiments to observe only RFD. Here, it's worth recollecting the Born Probabilistic Interpretation [5]: "*The wave function determines only the probability that a particle - which brings with itself energy and momentum - takes a path; but no energy and no momentum pertains to the wave*".

Notice that, except for the notion of probability, the above statement is in exact agreement with the spirit of wave-particle non-duality, where, the Schrodinger wave function is shown to be an IRSM [18].

3. BOHR'S COMPLEMENTARITY AND AFSHAR'S EXPERIMENT

3.1 Single-Slit Diffraction and Bohr's Complementarity

Here, we would like to emphasize the case of a single slit experiment where one observes a diffraction pattern which is due to the wave nature. Nevertheless, on the detector screen, one always observes particles landing as a well localized chunks. Therefore, the observation is in terms of particle nature and the overall observed phenomenon, after collecting a large number of particles, reflects an associated wave nature. So, both particle and wave natures along with 'which slit information' are completely available, because there is only one slit. Notice that this is clearly against the PC, if wave and particle natures are regarded as complementary to each other. Further, if one tries to detect whether the particle is really passing through the slit or not, then the diffraction pattern disappears. Therefore, in the absence of observation, one can always infer the particle as going through a particular slit and hence, which slit information need not necessarily account for the particle behavior. Also, when the 'which hole detector' is turned on, the observed intensity on the screen will be that of several superimposed spherical waves whose origins lie at a region where the detector probe interacted with the particles in the vicinity of the slit. The same can be observed as a overlap of two spherical wave intensities in the case of double-slits and here we predict that this can be confirmed by observing the Hanbury-Brown-Twiss effect [19, 20].

3.2 Double-Slit Interference and Afshar's Experiment

From the results obtained, Afshar concluded that his experiment is in direct contradiction with PC. A number of researchers analyzed his experimental setup and interpretation [21–29]; most of them rejected his conclusions in favor of PC and a few accepted as a support for their own interpretations of quantum mechanics.

Now, we consider the results and conclusions of the same experiment for explaining within the non-dualistic inter- pretation of quantum formalism. According to the non-duality, every quantum object moves in its own IRSM which is clearly against the PC and hence Afshar's conclusion is immediately supported. The results of Afshar's experiment is analyzed in the following:

Consider the case of single photons shot at the pinholes 1 and 2 so that any photon is fired only after the registration of the previous photon by any one of the photon-detectors D1 and D2. The photon state, $|S>$, is a superposition of states emanating from the dual pinholes, i.e.,

$$|S> = |S_1> + |S_2> \quad (7)$$

where, $|S_1>$ and $|S_2>$ are from pinholes 1 and 2, respectively. The projector, $\hat{P}_g$, associated with the vertical grid of thin wires is given by

$$\hat{P}_g = \sum_i \int dy_i \; |y_i><y_i|, \quad (8)$$

where, the limits of the integration varies from xi to xi + Δxi. Since the sets of position eigenvalues [xi , xi + Δxi], representing the thickness of the thin wires (here, [,] stands for a closed set, but not a commutator); i = 1, 2, 3, · · · , lie in the dark fringes, the inner-product interaction at the grid surface is given by

$$<S|\hat{P}^{\dagger}_g\hat{P}_g|S> = <S|\hat{P}_g|S> = <S_1|\hat{P}_g|S_1> + <S_2|\hat{P}_g|S_2> + <S_1|\hat{P}_g|S_2> + <S_2|\hat{P}_g|S_1> \approx 0 \quad (9)$$

where, $\hat{P}^{\dagger}_g = \hat{P}_g$, $\hat{P}_g^2 = \hat{P}_g$ and $<S|\hat{P}^{\dagger}_g$ is the excited dual in the grid. Therefore, one has from Eq. (9),

$$< S_1 |\hat{P}_g |S_1 > + < S_2 |\hat{P}_g |S_2 > \approx - < S_1 |\hat{P}_g |S_2 > - < S_2 |\hat{P}_g |S_1 > \quad (10)$$

We know from the Young's double-slit experiment that $< S_1 |\hat{P}_g |S_1 >$ and $< S_2 |\hat{P}_g |S_2 >$ are not independently equal to zero when only either pinhole 1 or 2 is opened but their sum can be exactly canceled by the term in the R.H.S of the Eq. (10), by opening both the slits. Therefore, it's possible to choose the thickness of the thin wires sufficiently small so that the Eq. (9) is satisfied when both the pinholes are opened and at the same time both $< S_1 |\hat{P}_g |S_1 >$ and $< S_2 |\hat{P}_g |S_2 >$ will appreciably reduce the observed intensities, $< S_1 |S_1 >$ and $< S_2 |S_2 >$, at D1 and D2 , when either pinhole-1 or 2 is kept open, respectively; here, $< S_1 |S_1 >$ and $< S_2 |S_2 >$ correspond to the cases without the grid.

Therefore, the results of the Afshar's experiment can be explained within the non-dualistic interpretation of quantum formalism according to which a photon flies in its own IRSM, $|S >$, and hence naturally avoids the regions of dark fringes. Also, any given photon passes through either pinhole 1 or 2 at a given moment and due to momentum conservation, it will be detected either at D1 or D2 , respectively. Therefore, it's true that in this single experimental setup, one can have both the interference pattern at the locations of the thin wires but only a superposed state (i.e., the amplitude but not the intensity) in the spaces between the wires and the information about through which pinhole the photon actually went. In other words, non-duality clearly points out that the inference about the existence of interference in the absence of inner-product interaction is simply wrong (the same was already presented in Ref. [23] by a very natural argument). Nevertheless, it's important to note that, according to the non-duality, the PC is valid even at a single quantum level [18] if and only if one is measuring the eigenvalues of two non-commuting observables but not the wave and particle natures, because, both the wave and particle natures always co-exist which is trivially evident even in the single-slit diffraction experiment, as discussed earlier. Therefore, except for the claim that his experiment invalidates the complementarity inequalities, the rest of Afshar's analysis is in perfect agreement with the non-dualistic interpretation of quantum mechanics.

4. CONCLUSION

Using the newly proposed 'wave-particle non-dualistic interpretation' of the quantum formalism, Bohr's principle of complementarity is analyzed in the context of both the single-slit and the Afshar's experiments at the single-quantum level. This interpretation clearly shows that the wave and particle natures should not be regarded as complementary to each other in the frame work of quantum mechanics though they are, in classical mechanics. All conclusions of Afshar are shown to be true except for the claim that the complementarity inequalities are invalidated. The actual mistake in his conclusion is merely inferring the existence of the complete interference pattern at the plane of vertical grid, which is untruth in the absence of inner-product interaction.

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