Realism in the Realized Popper’s Experiment

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July 11, 2021

Abstract

The realization of Karl Popper’s experiment by Shih and Kim (published 1999) produced the result that Popper hoped for: no “action at a distance” on one photon of an entangled pair when a measurement is made on the other photon. This experimental result is interpretable in local realistic terms: each photon has a definite position and transverse momentum most of the time; the position measurement on one photon (localization in a slit) disturbs the transverse momentum of that photon in a non-predictable way in accordance with the uncertainty principle; however, there is no effect on the other photon (the photon that is not in a slit) no action at a distance. The position measurement (localization within a slit) of the one photon destroys the coherence (entanglement) between the photons; i.e. decoherence occurs. This can be understood physically as an electromagnetic interaction between the photon in the slit and the electrons of the atoms in the surface of the solid that forms the slit.

For an individual entangled pair, the detected position of the other (not in a slit) photon is the data for the calculation of the transverse momenta of both photons of this pair; for the photon interacting with the slit this calculation produces its momentum as it enters the slit (just before the interaction takes place), but its momentum after the localization (as it emerges from the slit) is not easily calculable because it depends upon the structure of the electromagnetic field of the photon, upon how this interacts with the atomic electrons in the surface of the slit, and upon the impact parameter of the incident photon with the centerline of the slit; this impact parameter is different for every incident photon, being a statistical aspect of the beam of photons produced by the experimental arrangement. This complex physical interaction is subsumed in the statistics of the uncertainty principle.

This realistic (albeit retrodictive) interpretation of the Shih-Kim realization of what Popper called his “crucial experiment” is in accord with Bohr’s original concept of the nature of the uncertainty principle, as being an inevitable effect of the disturbance of the measured system by the measuring apparatus. These experimental results are also in accord with the proposition of Einstein, Podolski and Rosen’s 1935 paper: that quantum mechanics provides only a statistical, physically incomplete, theory of microscopic physical processes.
1 Popper’s Concept of the Crucial Experiment

Karl Popper was a philosopher who was deeply concerned with the interpretation of quantum mechanics since its inception in 1925. In a book originally published in 1956 he proposed an experiment which he described as “an extension of the Einstein-Podolsky-Rosen argument” [1, pp.ix,27-30]. In summary: two photons are emitted simultaneously from a source that is mid-way between (and colinear with) two slits A and B; the coincident diffraction pattern is observed beyond each slit twice: once with both slits present, and again with one slit (slit B) “wide open”.

Popper (in common with Einstein, Podolsky and Rosen and with the proponents of the Copenhagen interpretation of quantum mechanics) believed that quantum theory predicts that localization of a photon within slit A will not only cause it to diffract in accordance with Heisenberg’s uncertainty relation, but will also cause the other particle at the location of slit B to diffract by the same angle - regardless of whether slit B is present or not. Such spatially separated correlations would violate the causality principle of Special Relativity; i.e. that physical interactions cannot travel faster than the speed of light; thus Einstein called them “spooky actions at a distance” [5].

Popper was “inclined to predict” [1, p.29] that in an actual experimental test, the photon at the location of the absent slit B would not diffract (“scatter”) when its partner photon (with which it is in an entangled state) is localized within slit A. He emphasized that “this does not mean that quantum mechanics (say, Schrödinger’s formalism) is undermined”; only that “Heisenberg’s claim is undermined that his formulæ are applicable to all kinds of indirect measurements”.

Popper [1, p.62] notes that Heisenberg agreed that retrodictive values of the position and the momentum can be known by knowing the position of a particle (e.g. as it passes through a small slit) followed by a measurement of the momentum of the particle after it has passed through the slit - from the position in the detection plane where it is located. Feynman has also emphasized that the uncertainty principle does not exclude retrodictive inferences about the simultaneous position and momentum of a particle [7, Vol.3,Ch.2,pp.2-3], but the uncertainty principle does exclude precise prediction of both position or momentum. This view that retrodictions of classical particle trajectories are consistent with quantum mechanics, is inconsistent with Bohm’s interpretation (Bohmian mechanics) in which the particle follows a non-classical trajectory under the influence of the “quantum potential” [18].

Popper also notes that momentum values are usually inferred from two sequential position measurements; in this regard he concurs with Heisenberg, who wrote [1, p.62]:

“The . . . most fundamental method of measuring velocity [or momentum] depends on the determination of position at two different times . . . it is possible to determine with any desired degree of accuracy the velocity [or momentum] before the second measurement was made”

The whole of Popper’s rebuttal of what he calls “the great quantum muddle” is very inciteful [1, pp.50-64]: he emphasizes that while predictions of future events (such the
trajectory of an individual particle) are only statistical with statistics limited by the Uncertainty Principle, that precise retrodiction of past events (the positions and momenta of the particle along its trajectory) are not only possible - “they are tests of the theory” [1, p.63,last line]. Indeed precise inferences of particle positions and momenta are widely used in the analysis of observations in high-energy particle accelerators, by which the modern plethora of “fundamental particles” have been discovered. This is emphasized by another quote from Popper [1, p.39]:

“my assertion [is] that most physicists who honestly believe in the Copenhagen interpretation do not pay any attention to it in actual practice”.

1.1 Measurements: Selections and Interactions

Popper distinguished between two types of measurements on particles:

Selective Measurements simply select particles from a larger ensemble of particles; e.g. a slit selects those particles in a beam (larger than the slit) that happen to collide with the selecting screen within the slit, rather than on either side of it (when they will be absorbed or reflected).

Interactive Measurements disturb the physical state of the particle; e.g. when a particle is absorbed within the emulsion of a photographic detecting plate, or within a photo-multiplier detector.

However, selection (location of a particle’s position) by a slit, may subsequently (after the moment of selection) lead to an interaction with the slit that causes the momentum of the particle to change in an unpredictable way, because the precise trajectory of the particle as it passes through, and interacts with the slit, cannot be known in principle; determination of its trajectory would inevitably involve disturbing its trajectory; this is the essence of the Uncertainty Principle interpreted as a disturbance of the particle in which the action involved cannot be smaller than Planck’s constant - the quantum of action. Reflections at a mirror do change the direction of the momentum of a photon in a predictable way, but they do not change the magnitude of its momentum. Whether reflection at a mirror should be regarded as a measurement is a moot point. Selective reflection or transmission in a beam splitter is also in this category of apparently non-interactive changes in momentum. The deflections of an electron in a Stern-Gerlach apparatus [18, pp.404-416] also appear to be a momentum-changing, but otherwise non-interactive “measurement”.

Studies by Bell and others [11], have concluded that any realistic interpretation of quantum mechanics must involve an essential non-locality of physical interactions. In this regard it is salutory to reflect that Planck’s constant is a constant of Action, and that the nature of action (momentum×distance, energy×times) is intrinsically non-local (regardless of quantization) because one of its factors (distance or time) is an extension in space or time. Likewise angular momentum, with the same physical dimensions as action, being an attribute of rotational motion is classically a property of an extended object.

3 “action” in the physical sense as momentum×displacement or energy×time
2 The Real Experiment of Shih and Kim

Yoon-Ho Kim and Yanhua Shih carried out a modern realization of Popper’s experiment; their report was published almost simultaneously three times \([2,3,4]\).\(^4\) Other experiments that don’t confirm the widely held interpretation of quantum mechanics have also been reported \([9]\); in his book John Bell wrote \([11\text{ p.} 60]\):

“Of course, any such disagreement, if confirmed, is of the utmost importance”

2.1 Quotes from Kim and Shih’s Paper

These quotations are drawn from \([2\text{ §1.pp.}1849-1950]\):

- Karl Popper believed that:
  
  “the quantum formalism could and should be interpreted realistically . . . the same view as Einstein”.

- Popper’s thought experiment was designed to show
  
  “that a particle can have both precise position and momentum at the same time”.

- The experiment is
  
  “a correlation measurement of an entangled two-particle system”.

- Popper’s thought experiment is strikingly similar to the Einstein, Podolski, Rosen \(\text{gedanken}\) experiment (EPR) proposed in 1935 \([8]\); Popper also thought of it “in the early 1930s” \([2\text{ p.} 1849]\), but unlike EPR (which became part of the folklore of physics) Popper’s \(\text{gedanken}\) experiment was remembered by only a few physicists, perhaps because it wasn’t published in a scientific periodical.

- In the realization of Popper’s experiment
  
  “it is astonishing to see that the experimental results agree with Popper’s prediction”.

\(^4\)The triple publication may have occurred because the paper was thought to be of such fundamental importance that it should reach the widest possible audience, or perhaps it was a result of simultaneous submissions in anticipation of the predisposition of journal editors and their referees against accepting an experimental result that is in disagreement with the prevailing beliefs of the majority of physicists.
2.2 Experimental Parameters

- the source is a CW\(^5\) argon-ion laser producing highly monochromatic ultra-violet radiation of wavelength, \(\lambda = 351.1\) nm.
- a pair of coherent (i.e. entangled) visible photons are produced by Spontaneous Parametric Down-Conversion (SPDC) in a BBO crystal.\(^6\)
- the length of the BBO crystal = 3 mm.
- the diameter of the photon beam = 3 mm.
- the wavelength of both of the entangled photons = 702.2 nanometers (nm).
- the two photons emerge from the BBO crystal in the same direction; they are separated by a polarizing beam-splitter, which directs them in different directions.
- the width of slit A and of slit B (when present) = 0.16 mm.
- the diameter of the avalanche photodiode detectors (D1 and D2) = 0.18 mm.
- the distance from the SPDC source (the BBO crystal) to slit A was 1255 mm.
- the distance (optical path length) from the SPDC source to slit B was 1245 mm.
- the difference of 10 mm between these path lengths may be due to the presence of the lens LS in the path to slit A; the two optical path lengths (from the BBO crystal to D1 and to D2) are presumably the same in order to achieve the coincident detection that is an essential feature of the measurements.
- the distance (optical path length) from slit B to detector D2 was 500 mm.
- During the measurements, D1 was in a fixed position (not scanned along the \(y\)-axis) close to a collection lens (of 25 mm focal length) with the lens close to slit A; this lens was designed to direct every photon passing through slit A into detector D1.
- a lens (focal length=\(f=500\) mm) is placed in the path of the photon going towards slit A and detector D1; slit A is \(2f\) from the lens, and the plane of slit B (regardless of whether slit B is actually present) is also \(2f\) from the lens as measured from the lens, back along the path of the slit A photon to the BBO crystal, and then forwards from the BBO crystal along the path of the photon going towards slit B.

In their report \[2\] Fig.4,p.1854 they say that this makes a “ghost image” of slit A at slit B (regardless of whether slit B is present or “wide open”). The significance of this is not clearly explained, although it was presumably essential to the successful execution of the experiment; they do, however, cite a previous publication as containing an explanation of the principle of the ghost image \[10\].

On the other hand, Angelides claims that:\(^7\)

\(^5\)CW = continuous wave
\(^6\)BBO = \(\beta\) barium borate
\(^7\)Personal communication by email, April 2002.
The presence of the lens (LS) before slit A is redundant, despite the Kim-Shih claim that:

“The use of LS is to achieve a ‘ghost image’ of slit A at screen B”.

It is true that if light were being emitted through slit A towards the lens LS, and then reflected in the beam-splitter back to the BBO crystal, and then reflected out of the crystal back to the beam splitter, and then onwards towards screen (slit) B, that the real image of slit A at screen B would be the same size as slit A, because slit A and screen B are equidistant from the lens LS at twice its focal length. However, since in fact light is not radiating in this direction in the actual experiment, the significance of the “ghost image” achieved by the lens LS is unclear and controversial; it is not involved in the subsequent analysis here.

### 2.3 Classical Theory of Diffraction

The relative light intensity beyond a single slit in a screen is given from the classical theory of diffraction \[12\] pp.214-216 by:

\[
\text{relative intensity} = \left( \frac{\sin \left( \frac{\pi sy}{\lambda D} \right)}{\frac{\pi sy}{\lambda D}} \right)^2
\]

where \(s\) is the slit width, \(\lambda\) is the wavelength of the light, \(D\) is the distance of the observing plane\(^8\) from the screen containing the slit,\(^9\) and \(y\) is the displacement in the observing plane from the axis of the incident beam (the \(x\)-axis). Graphs of the peaks and troughs generated by \[11\] are given in \[12\] pp.215,223. The central maximum (relative intensity = 1) occurs when \(y = 0\).\(^{10}\)

The first minimum (zero intensity) occurs when:

\[
\left( \frac{\pi sy}{\lambda D} \right) = \pi \quad \Rightarrow \quad y = \frac{\lambda D}{s}
\]

For \(\lambda = 702.2\) nm, \(s = 0.16\)mm, and \(D = 500\) mm, this produces:

\[
y = \frac{702.2 \times 10^{-9} \times 500 \times 10^{-3}}{0.16 \times 10^{-3}} = 2.194375 \text{ mm}
\]

which is the value (2.2 mm) evident from the experimental Figure 5 \[2\] p.1855.

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\(^8\)the scanning plane of photon-detector D2 in this experiment

\(^9\)The observing plane and the slit-screen are parallel; they are perpendicular to the incident light beam.

\(^{10}\)\(y = 0\) is the point in the observing plane where the undiffracted photons of the incident beam meet it.
2.3.1 Diffraction in terms of the Uncertainty Relation

Insertion of the de Broglie relation:
\[ \lambda = \frac{h}{P} \]

into (2) produces a form that resembles the Uncertainty Relation:
\[ yP = \frac{hD}{s} \]  \hspace{1cm} (4)

where \( s \) is the slit width and \( P \) is the momentum of a photon diffracted towards the first minimum in the diffraction pattern; \( y \) is the displacement from the \( x \)-axis of the first minimum on the screen, the screen being at distance \( D \) from the plane of the slit. This formula (4) has been presented by Feynman as a simple “derivation” of the Uncertainty Relation; in this context (4) is re-interpreted as:
\[ \Delta y \Delta P_y = \frac{hD}{s} \]  \hspace{1cm} (5)

in which \( \Delta y \) is the “uncertainty” in the position of the photon in the \( y \) direction, and \( \Delta P_y \) is the “uncertainty” in the \( y \) component of the photon’s momentum. Thus the position of the first minimum in the diffraction pattern \( (y \text{ in eqn.}(4)) \) is identified with the spread of a beam of photons after it passes through a slit of width \( s \). This is relevant to the interpretation of the two experimental curves in Figure 5 of [2] (below).

2.4 Momenta and Uncertainty Products

The product of the uncertainties in the position and momentum of the photons is calculated as follows:

2.4.1 Photon Properties

The two photons are emitted at the same time from a small volume\(^{11} \) surrounding the point \( \{x=0, y=0\} \).\(^{12} \) They have a wavelength of 702.2 nm, and hence the energy of each photon is:
\[ E = h\nu = \frac{hc}{\lambda} = 6.626176 \times 10^{-34} \times 2.997925 \times 10^8/(702.2 \times 10^{-9}) \]
\[ = 2.82893 \times 10^{-19} \text{ Joules} \]  \hspace{1cm} (6)

Thus the momentum of each photon in the direction of propagation is given by:
\[ P = h\nu/c = \frac{E}{c} = 2.82893 \times 10^{-19}/2.997925 \times 10^8 \]
\[ = 9.43631 \times 10^{-28} \text{ Kg.metre/sec} \]  \hspace{1cm} (7)

and the dynamic mass of each photon is
\[ M = \frac{P}{c} = 9.43631 \times 10^{-28}/2.997925 \times 10^8 \]
\[ = 3.14761 \times 10^{-36} \text{ Kg} \]  \hspace{1cm} (8)

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\(^{11}\)From the experimental data (\[^{12}\] the source is a cylinder 3 mm in diameter and 3 mm long.

\(^{12}\)The line connecting the two slits is designated the \( x \) axis by Shih and Kim.
2.4.2 Transverse Momentum: Slit B Present

From Kim and Shih’s Figure 5, when slit B is present the photons emerging from slit B are deflected (diffracted) up to about 2.0 mm over a distance (from the slit) of 500 mm; a feature of the wider curve of the experimental results [2, Fig.5, p.1855] is a diffraction minimum at \( y = 2.2 \) mm with one data point showing the onset of the second diffraction maximum; this is predicted by the classical theory of diffraction (eqn. 2 in §2.3 above).

In view of (4) it is appropriate to work out the momentum of photons diffracted towards the first minimum in the observed diffraction pattern; i.e. those diffracted to reach detector D2 at \( y = 2.2 \) mm. The length of the path from slit B to the first minimum is:

\[
D' = \sqrt{D^2 + y^2} = \sqrt{500^2 + 2.2^2} = 500.00484 \text{ mm} \approx 500 \text{ mm}
\]  

(9)

The time taken for the photon to travel this distance is \( 0.500/c = 1.667 \times 10^{-9} \) seconds. In this time it travels 2.2 mm in the \( y \) direction; i.e. its speed in the \( y \) direction is:

\[
v_y = 0.0022/1.667 \times 10^{-9} = 1.3191 \times 10^6 \text{ metre/sec}
\]  

(10)

and hence its transverse momentum (in the \( y \) direction) is:

\[
P_y = M v_y = 3.14761 \times 10^{-36} \times 1.3191 \times 10^6 = 4.1520 \times 10^{-30} \text{ Kg.metre/sec}
\]

Multiplication of this transverse momentum by the slit width of 0.16 mm produces a position-momentum uncertainty product of:

\[
\Delta y \Delta P_y = 0.00016 \times 4.1520 \times 10^{-30} = 6.643 \times 10^{-34} \text{ Joule.sec}
\]  

(11)

which is Planck’s constant: \( h = 6.62617 \times 10^{-34} \text{ Joule.sec} \)

within the two decimal digit precision of the data: i.e. a slit width of 0.16 ± 0.005 mm and an observed diffraction minimum at 2.2 ± 0.05 mm. This result exemplifies Feynman’s derivation of the uncertainty principle given above in [2.3.1] specifically equation (5).

It is noteworthy that Kim and Shih report [2 top of p.1856]

“the single detector counting rate of D2 is basically the same as that of the coincidence counts except for a higher counting rate”.

In other words: the outer (wider) diffraction peak\(^{13}\) of Figure 5 of [2] is obtained regardless of whether the coincidence detection circuit is active or not. This observation indicates that this peak is produced by the diffraction of the photons incident upon slit B \textit{regardless} of their entanglement with the photons incident upon slit A; i.e it is a single-photon phenomenon; indeed it is nothing more than the central diffraction maximum predicted by the classical theory of light [12, p.214].

The higher counting rate is explained by the effective size of the source only being about 0.16 mm diameter for coincidence counting, whereas for non-coincidence counting it is the full diameter of the laser beam of 3 mm.

\(^{13}\) the curve for slit B present
2.4.3 Transverse Momentum: Slit B Absent

The inner curve of Figure 5 of [2] is drawn from the experimental coincidence counts obtained when slit B is “wide open”. This shows that the photons are deflected up to 0.9 mm, and that from 0.9 mm to 1.45 mm the detection rate is constant and close to zero.

Interpretation as Diffraction from Ghost slit B

If this inner curve is interpreted in the same way as the outer curve (as in the immediately preceding section), then the “first diffraction minimum” would be at \( y = 0.9 \) mm. The time taken for the photon to travel from the ghost slit B to the detector D2 is the same as when slit B is actually present; i.e. \( 0.500/c = 1.6678 \times 10^{-9} \) seconds.
In this time it travels 0.9 mm in the \( y \) direction; i.e. its speed in the \( y \) direction is:

\[
v_y = \frac{0.0009}{1.6678 \times 10^{-9}} = 5.3963 \times 10^5 \text{metre/sec}
\]  

(12)

and hence its transverse momentum (in the \( y \) direction) is:

\[
P_y = M v_y = 3.14761 \times 10^{-36} \times 5.3963 \times 10^5 = 1.6985 \times 10^{-30} \text{Kg.metre/sec}
\]

Multiplication of this transverse momentum by the slit width of 0.16 mm produces a position-momentum uncertainty product of:

\[
\Delta y \Delta P_y = 0.00016 \times 1.6985 \times 10^{-30} = 2.718 \times 10^{-34} \text{Joule.sec}
\]

(13)

which is smaller than Planck’s constant:

\[
h = 6.626176 \times 10^{-34} \text{Joule.sec}
\]

the ratio being:

\[
2.718 \times 10^{-34}/6.626176 \times 10^{-34} = 0.41
\]

an apparent violation of the uncertainty principle as formulated by Feynman; i.e. a violation of eqn. [4]. For this reason this interpretation must be wrong.

The result vindicates Popper when he wrote that he was [1, p.29]:

“inclined to predict” that in an actual experimental test, the photon at the location of the absent slit B would not diffract (“scatter”) when its partner photon (with which it is in an entangled state) is localized within slit A.

It is also a vindication of Einstein, Podolski, and Rosen, in their inference that such instantaneous\(^{14}\) action at a distance is inconsistent with the causality principle of Special Relativity – that physical effects cannot travel faster than the speed of light. Since this experimental result is consistent with causality, the further inference of EPR (that quantum theory must be incomplete) is also vindicated.

\(^{14}\)or at least superluminal with no upper limit on the speed of transmission
Interpretation as Diffraction from the Source

In this case the photons have traveled a distance of 1245 mm from their source (without encountering any slit). The time taken for the photon to travel 1245 mm along the x axis is $1.245/c = 4.15287 \times 10^{-9}$ seconds. In this time it travels 0.9 mm in the y direction to the “first minimum” in the diffraction pattern; i.e. its speed in the y direction is $0.0009/4.15287 \times 10^{-9} = 2.1672 \times 10^5$ metre/sec, and hence its transverse momentum is:

$$P_y = M v_y = 3.14761 \times 10^{-36} \times 2.1672 \times 10^5 = 6.82142 \times 10^{-31} \text{ Kg.metre/sec}$$

Multiplication of this transverse momentum by the slit width of 0.16 mm produces a position-momentum uncertainty product of:

$$\Delta y \Delta P_y = 0.00016 \times 6.82142 \times 10^{-31}$$

which is smaller than Planck’s constant, the ratio being:

$$1.09142 \times 10^{-34}/6.626176 \times 10^{-34} = 0.1647$$

which is an even greater violation of the Uncertainty Principle (of eqn.5) than when interpreted as diffraction from the ghost slit B.

Non-Diffractive Interpretation

The inner curve of Figure 5 of [2] does not display a discernable diffraction minimum. There are in fact 5 data points ($y = 1.0 - 1.45$ mm) all of which have the same (very small) value; this suggests that the origin of this peak is not diffraction through a slit.

It is noteworthy that Kim and Shih report [2 p.1856,2nd¶]

“the single detector counting rate of D2 keeps constant in the entire scanning range”

In other words: when the coincidence circuit is switched off D2 detects the same count rate at all values of $y$ at which it was placed (presumable from $y = 0$ to $y = 1.45$ mm); this would be a horizontal straight line if added to Figure 5 of [2]. This measurement was simply seeing the beam from the source towards D2 with a uniform intensity over the scanning range of $\approx 3$ mm ($y = \pm 1.5$ mm).

Kim and Shih also report [2 p.1856,2nd¶]:

“the width of the pattern is found to be much narrower than the actual size of the diverging SPDC beam at D2”

15 This multiplication by a slit width of 0.16 mm is dubious because the diffraction is assumed to originate in the source (the BBO crystal) rather than at the ghost image of slit A.

16 Unlike the wider curve
The alternative, plausible cause of this narrow peak is a convolution of the finite size of the source,\textsuperscript{17} with the geometry of possible coincidences.

Further clarification on the origin of this peak depends upon experimental details which are not available in the publications; in this regard it is a pity that raw data (such as actual, observed counting rates) were not included in the published reports of the experiment.

3 A Retrodictive Realist Account

- A pair of photons produced by SPDC is in an entangled state from the moment of generation until one of them enters a slit; entanglement means that their positions and momenta are correlated; knowledge of the position of one photon allows one to infer the position of the other photon; likewise for their momenta.

- When one photon enters a slit it interacts with that slit and this destroys the coherence (entanglement) between them; i.e. decoherence occurs. The interaction can be attributed to the photon being some kind of localized electromagnetic wave, which interacts with the electrons in the surface of the solid that forms the slit. That photons are localized waves is supported experimentally by the production of laser pulses as short (in time) as two optical periods; thus the photon cannot be longer than two wavelengths along its direction of propagation.

- Measurement of the diffracted position ($y$ coordinate) of a photon (coincidence detection by D2) with slit B absent, allows one to calculate not only the momentum vector of this photon as it travels from the source to D2, but also the momentum of the other photon as it travels from the source to slit A; however when this latter photon enters slit A its interaction with the walls of the slit causes it to diffract at an angle which is predictable only statistically - in accord with the uncertainty principle.

- Thus coincidence measurements with slit B absent provide the positions of both photons (from the detection of a photon having passed through slit A) with a precision equal to the width of slit A. Likewise the measurement of the deflected position ($y$ coordinate) of a photon by D2 allows one to calculate the momentum vectors of both photons of the entangled pair – during their trajectories from the source to the plane of slit A (for one photon), and from the source to the scanning plane of D2 for the other photon. These \textit{in principle}, precise, retrodictive calculations of the trajectories of both photons are unfortunately limited in precision by the actual experimental results because of the relatively large size of the non-point source.\textsuperscript{18}

- It is especially noteworthy that individual events\textsuperscript{19} are not limited by the uncertainty principle: any diffraction of a photon to a position of D2 smaller than the $y$-coordinate of the first diffraction minimum will yield a position-momentum product that is smaller than Planck’s constant – even when slit B is present. In particular,

\textsuperscript{17}a cylinder 3 mm diameter and 3 mm long
\textsuperscript{18}a cylinder 3 mm diameter and 3 mm long
\textsuperscript{19}the generation and detection of a particular entangled photon pair
the most probable diffraction angle (to the top of the central peak) yields a transverse momentum of zero, which when multiplied by the uncertainty in its position (the slit width of 0.16 mm) yields an uncertainty product of zero!

This realist interpretation is in accord with the *consistent histories* interpretation of quantum mechanics [19, 20]; as the term “history” implies, it as a retrodictive realism. However, experimental physics is largely concerned with retrodictively interpreting the results of measurements; hence as Feynman [7] and Holland [18] have noted, quantum mechanics does not preclude the precise *retrodictive* description of past events in terms of the classical coordinates and momenta of particles; it only precludes predictions.

The long standing controversy over “hidden variables” [13] must now be seen as a “red herring”, for the “hidden variables” in this realization of Popper’s experiment are the precise location of the source of an individual photon pair within the BBO crystal, and the impact parameter of each photon with the slit that it passes through. These “hidden variables” would more accurately be described as “uncontrollable parameters” of an individual two-photon event; an essential, statistical uncertainty arising from the experimental arrangement.

It is especially noteworthy that this interpretation – that each photon has a classical trajectory except when it is interacting with a slit or detector – is inconsistent with the Bohmian interpretation of quantum mechanics [18], because there is no “quantum potential” present to affect the classical trajectories.

4 The Incompleteness of Quantum Mechanics

Notwithstanding developments in the formalism of quantum mechanics [23, 24]:

- the formulation in terms of *Positive, Operator-Valued, Measures* [14, 15] and
- the formulation as a strictly operationist theory [16],

the “measurement problem” remains problematical and essentially unresolved [17, Ch.V, pp.131-137]. Holland [18, pp.328-333] has inferred that

“If we cannot account for the measuring process by applying the usual many-body Schrödinger theory, this implies a massive incompleteness in the quantum mechanical treatment of general natural processes”.

Thus regardless of the question of realism (and of experimental results in accord with realism or otherwise) quantum theory has been recognized to be logically incomplete because it does not describe the actual physical processes involved in making measurements. It is also incomplete because it does not describe individual events, whereas individual events are commonly observed in experimental physics.
Concluding Remarks

The above assertion of a classical, retrodictive and realist interpretation of the realized Popper’s experiment, is not easily extended to the interpretation of some other experiments, notably the various double path experiments that have been conducted.

A plausible, yet tentative, realist interpretation of how a molecule as large as a “bucky ball” (C\(_{60}\)) can “go through 2 slits at the same time and interfere with itself” \(^{21}\) is that every particle is surrounded by a real oscillating field, which manifests itself in the experiments as a wave with an effective wavelength given by the de Broglie relation in terms of the particle’s laboratory-frame momentum.

However, double-path experiments of the Mach-Zender type\(^{20}\) defy any realist interpretation because the two paths are separated by a macroscopic distance thus making the idea that the particle goes along one path while its surrounding wave-field interacts with the other path, implausible; this is especially so when the particle that goes along both paths and interferes with itself is electrically neutral; e.g. the neutron interferometry experiments of Zeilinger et al \(^{22}\). This phenomenon of the self-interference of a wave propagating along widely separated paths is a form of weirdness regardless of quantum mechanics; its most bizarre manifestation is in long-baseline interferometry in radio astronomy, where the two paths are separated by many thousands of miles.

While Popper was correct in regarding his experiment as a “crucial” test of the inconsistency between:

- the presumed non-locality of quantum mechanics manifest by instantaneous actions at a distance, and
- the causality principle of Special Relativity

and while this realization of Popper’s experiment supports the conclusion that the inferences of such instantaneous actions at a distance are the result of incorrect quantum theoretical argument,\(^{21}\) it is nevertheless salutary to recognize that this experimental disproof of instantaneous actions at a distance, does little to resolve the dilemma of double-path interference in locally physical terms.

The zeal with which the completeness of quantum mechanics was defended by Bohr, Heisenberg, and their like-minded peers, can be understood as the enthusiasm of the proponents of a new\(^{22}\) and manifestly successful theory\(^{23}\) which they felt impelled to defend against the skepticism of such distinguished elder physicists as Eddington \(^{25}\) Ch.X,pp.200-229,p.222]. It is salutary to reflect that the papers and letters of the 1930s were written in the midst of the battle to understand and establish quantum mechanics.

It is pity that this justifiable enthusiasm led them to claim more\(^{24}\) than the theory’s ambit of application warranted. The concurrence of the majority of physicists with this undue claim of completeness is understandable, because tacit acceptance of something you

\(^{20}\)as distinct from double-slit experiments

\(^{21}\)because the experiment results do not display the expected actions at a distance

\(^{22}\)new in the 1920s and 1930s

\(^{23}\)Its early successes were the calculations on the hydrogen atom (Schrödinger, 1926), quickly followed by accurate calculations on the helium atom, and the molecules H\(_2^+\) and H\(_2\).

\(^{24}\)that it was a complete theory of the physical world
don’t really understand\textsuperscript{25} is easier than engaging in an intellectual struggle for understanding especially when the topic doesn’t seem to have much relevance to ones daily work. Recall once again Popper’s observation:

\textquote[my assertion [is] that most physicists who honestly believe in the Copenhagen interpretation do not pay any attention to it in actual practice].

This acquiescence in the Copenhagen interpretation is common societal phenomenon arising from the predisposition of a person to agree with his/her companions; it was satirized in the story of the courtiers’ mutual agreement about the splendor of the Emperor’s New Clothes, when in fact the Emperor was naked.

It is ironic that this uncompromising (albeit tacit) advocacy of the completeness of quantum mechanics has now made its advocates the conservative defenders of a proposition that nobody really understands. The statements by Kim and Shih\textsuperscript{2} pp.1858-1859] in defense of quantum theory seem to be motivated by just such an irrational faith.\textsuperscript{26} Thus as other philosophers have noted, youthful rebels turn into conservative bigots in their later years.

\textit{fiat lux}

**Acknowledgements**

The support of the Natural Sciences and Engineering Research Council of Canada is gratefully acknowledged.

Thomas Angelides brought the Shih-Kim experiment to the author’s attention at conferences in Baltimore (1999) and Berkeley (2000).

Yanhua Shih provided helpful elaborations of the published accounts of the experimental work and its interpretation (sent to the author by email).

John Sipe of the University of Toronto is thanked for allowing the author to participate in his course, “Current Interpretations of Quantum Mechanics”, given January-April 2002; this stimulated the author’s interest which led to the writing of this article.

Yasaman Soudagar is thanked for bringing John Sipe’s innovative course to the author’s attention.

Marian Kowalski is thanked for many congenial discussions with a kindred spirit believing (like Einstein, Popper, Schrödinger, et al) in the essential simplicity and logicality of individual events in the physical world notwithstanding the limitations on predictive measurements arising from the finite value of Planck’s constant and the inevitably uncontrollable parameters of each experimental arrangement.

\textsuperscript{25}recall Feynman’s edict that “nobody understands quantum mechanics”.

\textsuperscript{26}or perhaps they were included to circumvent, or in response to, a negative evaluation by the journal’s referees
References

[1] Popper, K.R., *Quantum Theory and the Schism in Physics*, Rowan and Littlefield, Totowa, New Jersey, 1982.

[2] Kim, Y-H. and Shih, Y. *Foundations of Physics*, 29, 1849-1961 (1999).

[3] Shih, Y. and Kim, Y-H. *Fortschr.Phys.*, 48, 463-471 (2000).

[4] Shih, Y. and Kim, Y-H. *Optics Communications*, 179, 357-369 (2000).

[5] Pais, Abraham, *Subtle is the Lord: the Science and the Life of Albert Einstein*; Oxford University Press, 1982.

[6] Peat, F.David, *Einstein’s Moon: Bell’s Theorem and the Curious Quest for Quantum Reality*, Contemporary Books, Inc., Chicago, Illinois, 1990.

[7] Feynman, R.P., *Lectures on Physics*, Vol.3, Addison-Wesley, Reading, Massachusetts, 1965.

[8] Einstein, A., Podolsky, B., and Rosen, N., *Phys.Rev.*, 47, 777-780 (1935).

[9] Bell, J.S., *Science*, 177, 880 (1972).

[10] Pittman, T.B., Shih, Y.H., Strekalov, D.V. and Sergienko, A.V., *Phys.Rev A*, 52, R3429 (1995).

[11] Bell, J.S., *Speakable and Unspeakable in Quantum Mechanics*, Cambridge University Press, Cambridge, 1987.

[12] Longhurst, R.S., *Geometrical and Physical Optics*, Longmans Green & Co., London (2nd Edition, 1967).

[13] Belinfante, F.J. *A Survey of Hidden-Variables Theories*, Pergamon Press, Oxford, 1973.

[14] Nielsen, Michael A. and Chuang, Issac L., *Quantum Computation and Quantum Information*, Cambridge University Press, Cambridge, 2000.

[15] Peres, Asher, *Quantum Theory: Concepts and Methods: Fundamental Theories of Physics*; vol.57, Kluwer Academic, Dordrecht, 1993.

[16] Busch, Paul, Grabowski, Marian, and Lahti, Pekka J., *Operational Quantum Physics*, Springer-Verlag, Berlin, 1995.

[17] Busch, Paul, Lahti, Pekka J. and Mittelstaedt, Peter, *The Quantum Theory of Measurement*, Springer-Verlag, Berlin, 1996.

[18] Holland, Peter, *The Quantum Quantum Theory of Motion*, Cambridge University Press, Cambridge, 1993.
[19] Omnès, R., *The Interpretation of Quantum Mechanics*, Princeton University Press, 1994.

[20] Omnès, R., *Rev.Mod.Phys.*, 64, 339 (1992).

[21] Zeilinger *Nature*, circa 1999.

[22] Zeilinger a paper on neutron interferometry circa 1990.

[23] Rae, A.I.M. Quantum Mechanics, 3rd ed.; Institute of Physics Publishing: Bristol, 1992.

[24] Kaempffer, F.A. Concepts in Quantum Mechanics; Academic Press: New York, 1965.

[25] Eddington, Sir Arthur, *The Nature of the Physical World*, University of Michigan Press (Ann Arbor Paperbacks), 1958 - original edition circa 1928.