An extension of “Popper’s experiment” can test interpretations of quantum mechanics

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Abstract
Karl Popper proposed a way to test whether a proposed relation of a quantum-mechanical state to perceived reality in the Copenhagen interpretation (CI) of quantum mechanics - namely that the state of a particle is merely an expression of “what is known” about the system - is in agreement with all experimental facts. A conceptual flaw in Popper’s proposal is identified and an improved version of his experiment (called “Extension step 1”) - which fully serves its original purpose - is suggested. The main purpose of this paper is to suggest to perform this experiment. The results of this experiment predicted under the alternative assumptions that the CI - together with the above connection of the state function with reality - or the “many-worlds” interpretation (MWI) is correct are shown to be identical. Only after a further modification (called “Extension step 2”) - the use of an ion isolated from the macroscopic environment as particle detector - the predictions using the respective interpretations become qualitatively different. This is because “what is known” by a human observer H can fail as a basis for the prediction of the statistical distribution of measurement results within the MWI in special cases: The temporal evolution of a system un-entangled with H - like the isolated ion - can depend on another system’s state components that are entangled with states orthogonal to H. Thus - within the CI - for H they are “known not to exist”. Yet H can infer their existence by studying the evolution of the ion.

1 Introduction - aims and plan of the paper
A considerable number of “contemporary” (i.e. writing within the last decade) authors

\[ \text{They will be represented below by B.-G.Englert-M.O.Scully- H.Walther, L.Mandel, A.Peres, R.Peierls, W.G.Unruh and A.Zeilinger} \]
its roots in the “Copenhagen interpretation” formulated by Bohr, Heisenberg, Pauli and others. A central idea of this approach is that the quantum-mechanical state function$^2$ faithfully and exclusively represents our knowledge of a system. I will try to formulate the standard interpretation (called “CI” for brevity below) more precisely in section 2.1 and clarify its relation to the historical Copenhagen interpretation in section 2.2.

“Popper’s thought experiment”, was proposed by the philosopher K.R. Popper $^3$ $^4$ $^5$. It aims to experimentally test the relation of a quantum-mechanical state to observed reality as described in the previous paragraph. Popper’s work is reviewed in section 4.1. His own expectation for the outcome of the experiment and his ideas for the interpretation of quantum mechanics are not the subject of the present paper.

Popper’s proposal contains two flaws, one technical (section 4.2) the other conceptual (section 4.3). Recently Kim and Shih found an ingenious method to avoid the former (section 4.2.1). The latter can be avoided by slightly modifying Kim and Shih’s experimental set-up, as proposed here for the first time (Extension step 1, sections 4.3.1, 4.4). Thus modified - but not in its original form - Popper’s experiment will serve its original purpose. It is the primary aim of this paper to propose to perform this technically feasible (see section 5.1) experiment.

Section 4.5 discusses the predictions of the “many-worlds interpretation” (MWI) - an alternative to the CI (section 3) - for this set-up and concludes that they are the same as the ones of the CI. Based on similar results some authors concluded that all alternative interpretations which leave the standard mathematical quantum-mechanical formalism unaltered (like CI and MWI) give rise to the same phenomenological predictions under all circumstances$^1$ $^2$. If this were true the question which of these alternative interpretations is “correct” would be a purely philosophical one. It is a secondary aim of this paper to prove this contention wrong.

To this end I discuss a further extension of “Popper’s experiment” in section 5, and describe the expected results of this experiment both in the CI and MWI (Extension step 2). The respective results are qualitatively different. Section 5.1 discusses the considerable technical difficulties when experimentally realising this modified experiment. Finally, in section 6 I summarise the main conclusions of the present paper. Sections in small font provide mainly quotes to substantiate my understanding of the “standard view”, they can be skipped without damage to the understanding of the paper.

$^2$Below the denotations “state function” is used interchangeably with “wavefunction” and “density matrix”.

$^3$No general proof for this claim is given in these references.
2 The “Copenhagen” interpretation as formulated by modern authors

In this section I summarise the “standard” interpretation of quantum mechanics given by many modern authors in order to understand its predictions for Popper’s experiment. This “standard view” is based on the historical “Copenhagen interpretation” (and therefore abbreviated as “CI” in this article) but the authors quoted below (with the exception of Zeilinger) do not explicitly call it like this. More than in deep insights of a philosophical nature (which was a central point for the founding fathers) they seem to be interested primarily in a simple and unique set of rules that make the mathematical formalism of quantum mechanics work in accordance with experience.

Typical statements are:

“This minimalistic interpretation of state vectors is “forced upon us by the abundance of empirical facts that show that quantum mechanics works” (Englert et al. in Ref.[6], p.328, sec. VI, l.14). “Minimalistic” is meant in the sense of a renunciation of an understanding of the state function as something existing independently of our minds.

“...when you refer to the Copenhagen interpretation what you really mean is quantum mechanics.” (Peierls in Ref.[7], p.71, l.8).

2.1 Summary of CI interpretation

If at a time t=0 a “measurement” is performed on a complete set of commuting observables A,B,C... of a physical system, the results obtained (i.e. non-degenerate eigenvalues a_n,b_n,c_n ...) define a unique eigenvector Ψ of all observables. Ψ(t=0) is called the “state vector” and is a complete description of the system’s state. This operation is called “preparation” of the system. The temporal evolution of Ψ is defined by deterministic equations of motion, e.g. Schrödinger’s equation for nonrelativistic electrons or QED for photons. When an observable A is measured at a later time t>0 the probability P to obtain an eigenvalue a_n is

\[ P(a_n) = \sum_{i=1}^{g_n} |<u_i|^\Psi|^2 \]

here g_n is the degree of degeneracy of a_n and the <u_i are the eigenvectors associated with the eigenvalue a_n. The state function is thus the unequivocal basis for prediction of statistical results of future measurements.

2.1.1 Relation of the state function to observed reality

“Measurement” is defined here as “knowledge obtained by observations” (Peierls in Ref.[8], p.778, l.34). “The most fundamental statement of quantum mechanics is that the state vector ... represents our knowledge of the system”[8](Peierls’s emphasis, p.778, l.20). This
definition of the state vector is emphasised by all authors. Englert et al. \[6\] (p.328, IV., l.7) explain their “minimalistic interpretation” of the state vector - mentioned above - like this: “The state vector Ψ(x) serves the sole purpose of summarising concisely our knowledge about the ... system; in conjunction with the known dynamics it enables us to make correct predictions about the statistical properties of future measurements.” Unruh\[9\](p.883, left column, l.22) describes the state vector in its “usual epistemological role” as “a device within the theory to incorporate our knowledge of the world, without it in itself corresponding to anything in the real world.” Zeilinger\[10\] writes (p.3, l.10): “In the Copenhagen interpretation the state function is only our way of representing that part of our knowledge of the system which is needed for calculating future probabilities for specific measurement results.” Mandel\[11\] - based on the results of quantum-optical experiments - and Peres\[12\] define the nature of the “knowledge” more precisely: Mandel states: “the state reflects not what is actually known about the system, but what is knowable, in principle, with the help of auxiliary measurements that do not disturb the original experiment.” In order to not contradict the previous authors and to avoid counterfactual reasoning I suggest to clarify Mandel’s wording to: “...not only what is actually known about the system, but also what is knowable...”. Peres makes clear that the knowledge is not the knowledge of a system existing independently of the observer when he replaces “knowledge of the system” by “knowledge of the preparation of the system”. There are eminent contemporary advocates of the “standard interpretation” (e.g. Asher Peres in Ref.\[13\]) who avoid to use the above understanding of “state function” all together, but they do not criticise it as incorrect.

2.1.2 Whose knowledge is relevant?

Because information cannot spread with velocities exceeding c “what is knowable, in principle with the help of auxiliary measurements” about a certain system can be different for observers at space-like distances. Thus the state function of a given system can be different for these observers. Which state function then has to be used for the prediction of the statistical properties of future measurements? Peierls\[8\] gave the following answer: “Each (observer) has to use his or her state function.”(p.779, right column, l.11). In other words: *The knowledge relevant for experimental outcomes is the one of the observer performing a measurement of the state function representing the knowledge.* This answer seems very natural, because any alternative potentially violates causality.

2.2 Is this “modern Copenhagen interpretation” the same as the one of the founding fathers?

A complete analysis of the Copenhagen interpretation’s history is beyond the scope of the present paper which tries to make possible an experimental test of the CI as defined by contemporary physicists. However it is important to ask whether the principal architects of the Copenhagen interpretation (Bohr, Heisenberg and Pauli among others) shared the unequivocal view expressed above by representative modern authors that the quantum-mechanical state function is merely an expression of our knowledge of the system. D.Mermin
- who has studied the original writings in great depth (especially those of Bohr) - concluded recently[p.3,l.4]: “...those who maintain, unambiguously with Heisenberg and presumably with Bohr, that the state function is nothing more than a concise encapsulation of our knowledge.” Pauli repeatedly stressed the observer dependent character of physical laws that follows from such a view of the state function; e.g. in a letter to Bohr he wrote[in ref.28]: “...I see the unpredictable change of the state through the individual observation ... as a rejection of the idea of the detachment of the observer of the course of physical events outside himself.” I conclude that the writings of the founding fathers at least do not contradict the modern CI view.

3 The “many-worlds” interpretation

The conceptually simplest alternative interpretation to the CI is Everett’s “many-worlds” interpretation[15, 16, 17, 18, 2] that proposes to plainly accept the mathematical formalism as an exact description of an objective observer-independent reality. In particular the state function exists as an element of reality completely independent of any observer. It can be shown that a necessary consequence of these strong but natural assumptions is that after each quantum measurement “branches” with independently existing observers form - each of which observes ones of the quantum mechanically possible results. Proponents of the MWI suggest to take these “bizarre” consequences from the equations of quantum mechanics serious, in the same way as Einstein’s “bizarre” conclusions from Maxwell’s equations (such as time dilation) were taken serious before their direct experimental confirmation. Understanding whether CI or MWI establishes the correct correspondence between perceived world and theory is one of the most profound questions of physics. As an example within the MWI quantum mechanics is a deterministic theory whereas within the CI chance plays a fundamental role in nature.

4 Popper’s experiment

4.1 The original proposal (fig. [4])

Let a point source S - located at rest in the middle on the connecting line between two slits A and B - decay into two entangled particles, e.g. positronium decaying into two photons, or a photon being down converted into an “idler” and a “signal” photon. The position in y of the particle propagating towards slit A (particle 1) is determined with the slit A. If one of the detectors behind slit A fires, the position in y is known with a precision $\Delta y = d_{\text{slit}}$, where $d_{\text{slit}}$ is the slit width. According to the uncertainty relation the momentum of this particle can then only be known with a precision $\Delta p_y = h/d_{\text{slit}}$. In other words: diffraction takes place at slit A. The dimensions of the setup are chosen such, that - as a consequence of the increased momentum spread - all counters on the left side (rather than only the one located behind slit A on the connecting line with slit B) fire with equal probability when the
A particle passes through the slit.

**Figure 1:** Popper’s experiment as originally proposed (from Ref.[19]). A pair of entangled particles is emitted from a point source S. In panel A slits are placed on both sides of S and diffraction takes place as a result of the localisation at the respective slits. All counters in the figure fire in repetitions of the experiment. Panel B is the experiment proposed: Particle 1 is localised in a slit. As a results of momentum conservation particle 2 is also localised in spite of the absence of a slit at its side[20]. Does the knowledge of its position, gained by Alice’s observation of particle 1 lead to an increased momentum scatter, i.e. “virtual diffraction”? Do all counters on the right side continue to fire in repetitions of the experiment?

In order to guarantee momentum conservation the particles are emitted back to back[20]. As a consequence when particle 1 passed through slit A, particle 2 must have passed through slit B. Both particles experience an increased momentum scatter (diffraction) and all counters on both sides fire in repetitions of the experiment (panel a. in fig 1). Popper’s question was: what happens if one removes slit B (panel b. in fig 1)? The expectation of the CI seems to be (here - as an introduction to the basic question - I faithfully repeat Popper’s argument which is not entirely correct, see sections 4.2 and 4.3 below): As soon as the experimenter “Alice” - reading the detectors behind slit A - knows that particle 1 passed through slit A (i.e. after it passed the x position of slit A) she knows that particle 2 is localised within slit B; slit B still acts as a “virtual slit”. Because the state function is “what is known about the preparation of the system” one has to use the localised state of particle 2 to predict the statistics of the results of the measurement with counters on the right side. The “preparation” is Alice’s test whether particle 1 passes slit A. Thus an increased momentum spread is expected at the virtual slit for all those particles 2 which are detected in the detectors at the right in coincidence with a detection of particle 1 after
slit A. This coincidence requirement is assumed hold in all arguments of this manuscript. “Virtual diffraction” is expected to take place in exactly the same way as before with the presence of a physical slit B, and all detector behind slit B can fire. Mere knowledge can change the unitary evolution of photon 2. It is the change of unitary evolution caused by state preparation, which makes Poppers experiment qualitatively different from previous similar experiments.

Popper thought that this result would not obtain in a really performed experiment, for reasons that are not of interest here.

4.2 First technical flaw in the original proposal - the position determination via entanglement is less precise than the direct one

In 1987 Collett and Loudon\[21, 22, 23\] pointed out an elementary oversight in Popper’s setup of fig 1. The source S has to obey the uncertainty relation and therefore if one localises S with a small spatial region (as necessary for a point source) its y-momentum component becomes uncertain. The particles are then no longer always emitted back to back. They showed that as a result of this, for any source size a localisation of particle 1 within slit A does not imply a localisation of particle 2 within the “virtual slit B”, but only within a much broader region. The authors did not imply that this fact makes Popper’s test impossible in principle, some years later Collett published a proposal for a completely different experiment which would realise Popper’s idea\[25\].

4.2.1 The solution of Kim and Shih (fig. 2a)

Kim and Shih (KS)\[19\] recently demonstrated the feasibility of experimentally performing “Popper’s experiment” for the first time. In their experiment (fig. 2a, a simplified version of fig.2 in their publication) two entangled photons “1” and “2” (this they call a “biphoton”) are produced via parametric down conversion of a pump photon in the beta barium borate “BBO” crystal. Photons 1 and 2 are entangled because they obey “phase-matching conditions”, i.e. their energies and momenta have to add up to the pump photon’s values of these parameters.

Via the introduction of an optical lens in the path of photon 1, KS ensured that if photon 1 is known to be localised within slit A (i.e. detector D1 clicked), the phase matching conditions localise the quantum state of photon 2 within slit B of equal size. This is true even if it is not known from where in BBO crystal the photons were emitted. Even when choosing the emission region in the BBO crystal sufficiently large to avoid Collett and Loudon’s criticism, the localisation of particle 2 within a virtual slit B - after it is known that particle 1 passed through slit A - can be ensured with arbitrary precision.

Detector D2 is located at a distance a behind a virtual slit B. It is movable in y direction - perpendicular to the direction of photon propagation x - and measures the y-momentum spread \( p_y \) of the quantum state of photon 2 with total momentum \( p \) via the
relation \( p_y = y \times p/a \). A quantum state of photon 2 localised within a “virtual slit” of size \( d_{\text{slit}} \) has a momentum spread of \( \Delta p_{\text{slit}} \approx \hbar / d_{\text{slit}} \) according to Heisenberg’s uncertainty relation. Experimentally KS did not find this, i.e. the momentum spread of photon 2 was not increased according to the uncertainty relation.

### 4.3 Second conceptual flaw in the original proposal - the localisation via entanglement is not knowable to the observer performing the momentum-spread determination

When trying to find the correct prediction of the CI for both Popper’s and KS’s setup we run into the problem explained in section 2.1.2. When the observer “Bob” behind the virtual slit B performs the measurement of particle 2’s momentum spread it is in principle still not knowable for him - for obvious causality reasons - whether particle 1 passed though slit A. According to the definition in section 2.1.1 his state function is thus still the original, unlocalised one. According to the discussion in section 2.1.2 - in spite of the fact that the observer “Alice” near slit A already knows that the particle passed the slit - one expects no increased momentum spread in the CI. **This** is the reason why the experimental result of KS is accordance with the CI and why one expects no increased momentum spread.
also for Popper’s original setup. This is in agreement with the point of view of Peres[24] and KS who argued that no increased momentum spread is expected for Popper’s original setup. The uncertainty relation for a particle has to hold for the state function of the observer measuring its position and momentum i.e. the one relevant for the prediction of experimental results. Therefore particle 2, which remains unlocalised for Bob, shows no increased momentum scatter without violating the uncertainty relation, in accordance with the conclusion of KS.

4.3.1 Fixing the last flaw - the “Extension step 1” form of Popper’s experiment (fig.2b)

We search for an experiment in which the following two conditions are fulfilled:
1. The click of detector 1 has to signal the localisation of particle 2 within the virtual slit B.
2. At time when particle 2 reaches detector D2 Bob has to be at a space-time point on the past light-cone of detector 1’s click.
If conditions 1 and 2 are both fulfilled the click of detector 1 makes it knowable to Bob - the observer performing the measurement and whose knowledge is therefore relevant to define the state function (see section 2.1.2) - that the particle is localised within the virtual slit B. According to the quotes in section 2.1.1 by definition the state function - which Bob must use to predict the statistical properties of future measurements - then is spatially localised in this slit. The standard time evolution of quantum mechanics now predicts an enhanced momentum spread of this particle (i.e. the occurrence of virtual diffraction). Only if both conditions at the beginning of this section are fulfilled the CI is tested in the way envisaged by Popper.

Formally the initial photon state \( \Psi_{\text{photon}} \) (the “biphoton” state of the entangled photon pair) is given as the superposition of two states with labels a and b corresponding to the possible measurement results[19]:

\[
\begin{align*}
|\Psi_{\text{photon}}\rangle_{\text{initial}} &= |\Psi_a\rangle + |\Psi_b\rangle = |\Psi_{i1}\rangle + |\Psi_{i2}\rangle + |\Psi_{o1}\rangle + |\Psi_{o2}\rangle.
\end{align*}
\]

Here label 1 (2) correspond to photon 1 (2) and i (o) to a state in which the photon localised inside (outside) the physical (for particle 1) or virtual (for particle 2) slit position. To find the particle state after the measurement of particle 1 (the “click” of detector 1) I project the particle state onto the eigenstate of the position:

\[
|\Psi_{\text{photon}}\rangle_{\text{after click of detector 1}} = |\Psi_{i1}\rangle + |\Psi_{i2}\rangle.
\]

Such state clearly evolves into the well known diffraction pattern of a single slit with size d in the far field (where the localisation probability is proportional to \( \sin^2(x)/x^2 \) with \( x=\phi \)

\footnote{Because of the small relative velocities of Bob,Alice and the experimental setup the usual nonrelativistic notion of temporal coincidence can be used.}
k \cdot d$, where $k$ is the wave number of the particle and $\phi$ the angle with respect to the slit center).

Fig. 2b shows a setup slightly modified from the one of KS to fulfill both conditions ("Extension step 1"). The basic setup, the focal length of the lens and the optical path-lengths “BBO to slit A and B” remains exactly the same as in KS’s performed experiment. The physical slit A and the virtual slit B are exchanged together with detectors and particle labels. A plane mirror is introduced behind the lens which deflects the optical path of photon 2. Instead of slit A a plane mirror MA which size is equal to the slit width of slit A. Only photons reflected from this mirror can hit D1, therefore a click in D1 signals that the photon was localised within the slit width.

Condition 1 is fulfilled because the optical path “BBO - lens - plane mirror - virtual slit B” has the same length as the one “BBO - Mirror MA - D1”, i.e. a click of D1 signals the localisation of photon 2 within the virtual slit B. To fulfill condition 1 quantitatively it is important to ensure that photons not hitting mirror MA are not absorbed before photons reflected are absorbed by D1. Otherwise a close inspection of the absorbing matter would make it “in principle knowable” that the photon 1 hit MA before photon 2 reaches slit B. Condition 2 is fulfilled because the optical path “BBO - lens - plane mirror - D2” is longer than the one “BBO - Mirror MA - D1 - D2”. This means that the result of the position measurement of photon 1 can be known by Bob - the observer measuring the momentum spread of photon.

4.4 Possible outcomes of Popper’s experiment in the “Extension step 1” form

It is of great importance to actually perform Popper’s experiment with “Extension step 1”. Storey et al. [25] - in a different realisation of Popper’s experiment - expect that virtual diffraction will be observed. The MWI interpretation predicts the same result as discussed in the next subsection. Should an experimental realisation of “Extension step 1” show that no virtual diffraction occurs the relation between “quantum-mechanical state” and “observed reality” proposed in section 2.1.1 and 2.1.2 would be put into doubt. The proposed “Extension step 2” of section 5 would then not be of interest. The further discussion of an extended experiment below assumes that virtual diffraction will be found in “Extension step 1”.

4.5 Analysis of Popper’s experiment within the MWI

The initial state $|\Psi_{\text{initial}}\rangle$ after down conversion of all experiments discussed here can be written as:

\[ |\Psi_{\text{initial}}\rangle = |\Psi_{\text{photon}}\rangle \otimes |M\rangle \otimes |A\rangle \]
Here $|M>$ stands for the state of the “rest of the universe” excluding $|\Psi_{\text{photon}}>$ and $|A>$ but including the measurement device and possibly a human observer. $|A>$ is an ion isolated from the environment in a particle trap. $|A>$ is not used in KS’s and Popper’s experiment “Extension step 1” but will be of importance in the “Extension step 2” version discussed below in section 3. When the position of photon 1 is determined, the biphoton interacts with $|M>$ and entanglement occurs. The entanglement then spreads with a velocity presumably not very different from $c$ in the environment. The final state after entanglement is given as\(^{26}\):

\[
|\Psi_{\text{final}}> = |\Psi_{\text{lab}}> \otimes |A> = (|\Psi_{i1}> |\Psi_{i2}> |M_a> + |\Psi_{o1}> |\Psi_{o2}> |M_b>) \otimes |A>
\]

The MWI assumes that a quantum state is an objective description of reality. Further the localisation of the photon happens upon entanglement of $|M>$ with $|\Psi_{\text{photon}}>$ (an objective physical process) rather than when its position becomes “knowable to an observer” as in the CI. It thus accepts expression (3) as plain reality, i.e. after entanglement (which “for all practical purposes” is irreversible due to the complexity of $|M>$) there are - among other things - two human observers in different “branches” described by $|M_a>$ and $|M_b>$. These observers do not “see” each other because $|M_a>$ and $|M_b>$ do not interfere, due to their entanglement with the states $|\Psi_{i1}> |\Psi_{i2}>$ and $|\Psi_{o1}> |\Psi_{o2}>$, respectively, that are orthogonal in Hilbert space. This is completely analogous to amplitudes of a single atom that do not interfere with each other in a “which-way” experiment, due to their respective entanglement with orthogonal states\(^{27}\). After the photon and $|M>$ are entangled, the observer described by $|M_a>$ only interacts with $|\Psi_{i2}>$. She then measures an increased momentum spread according to the uncertainty relation.

A determination of the momentum spread of photon 2 at a space-time point before entanglement of $|M>$ with $|\Psi_{\text{photon}}>$ took place corresponds to KS’s experiment; performed after this entanglement took place it corresponds to the Popper’s experiment “Extension step 1”.

In the framework of the MWI the fact that KS found a momentum spread of photon 2 corresponding to an unlocalised state allows to draw the following nontrivial conclusion “CONCL”. Let the two components $|\Psi_{i1}>$ and $|\Psi_{o1}>$ of a particle 1 be entangled with two components $|\Psi_{i2}>$ and $|\Psi_{o2}>$ of a particle 2 that are orthogonal to each other. In spite of this fact (which precludes the possibility of any interference between the components of particle 1) a system $|M>$ - initially not entangled with either particle - that measures the momentum uncertainty of particle 1 finds the value corresponding to the total state $|\Psi_{i1}> + |\Psi_{o1}>$. 
5 Popper’s experiment “Extension step 2”: an isolated system as detector (fig.2b with a “single ion” as detector D2)

The described absence of interference and the linearity of quantum mechanics - which precludes any other influence of the “branches” \(|M_a\rangle\) and \(|M_b\rangle\) on each other - has led to the view that MWI and CI give rise to the same phenomenology in principle \[2\]. In this case the decision between CI and MWI would forever remain a matter of philosophical taste. This view is erroneous: this equivalence only holds in the approximation that the measurement device is always entangled with its environment. To demonstrate this I now discuss a further modification of Popper’s experiment (“Extension step 2”). Let us assume in the following that photon 1 was found within the slit (first term in eq.(5) \(|M_a\rangle\) describes the subjective observer). Consider the ion in the state \(|A\rangle\) in expression (4) and (5). Its isolation from the environment (e.g. in a particle trap in a good vacuum) prevented its entanglement with the environment for the duration of the experiment. Now this particle is employed as the photon detector D2 for photon 2, i.e. if the ion is found excited the detector has “fired”.

Within the MWI \(|M\rangle\) in eq.(4) and \(|A\rangle\) in eq.(5) have exactly the same status. In particular conclusion “CONCL” above holds. We only replace \(|\Psi_{12}\rangle\) and \(|\Psi_{o2}\rangle\) by \(|\Psi_{12}\rangle\) \(|M_a\rangle\) and \(|\Psi_{o2}\rangle\) \(|M_b\rangle\), respectively, two components which continue to be orthogonal. Therefore \(|A\rangle\) finds the same as \(|M\rangle\) before, i.e. measuring with the “single-ion detector” one finds the small momentum spread as in KS’s experiment even after \(|M\rangle\) became entangled with the biphoton. If this result is ascertained with the ion detector at a y-position where it does not interact with the photon (but would, if the momentum spread were increased to \(\Delta p_{\text{slit}}\)) \(|A\rangle\) does not get entangled in the course of the measurement process via the photon.

I summarise the expectation for Popper’s experiment in the “Extension step 2” form for CI and MWI:

CI: Bob (the observer after slit B) measures an increased momentum spread as expected from the localisation of particle 2 in the virtual slit, which is known to him.

This prediction also holds for all interpretations or modifications of quantum mechanics in which a physical collapse of particle 2’s wavefunction explains its localisation.

MWI: If, and only if, Bob uses a detector which is un-entangled with the biphoton to measure the momentum uncertainty of particle 2 he will find a localised particle 2 with no increased momentum spread.

5.1 Technical possibilities to perform the proposed experiments

KS’s experiment with the “Extension step 1” could be readily performed with relatively small changes in their setup. “Extension step 2” is more difficult, but not out of reach of
present technology. The degree of isolation necessary to prevent an entanglement of a single particle with a macroscopic environment is nothing special for single particles; it has to be ensured in all experiments in which interference phenomena of atoms or neutrons are to be experimentally studied. The observable excitation of single ions - necessary to employ a single ion as photon detector - is routinely practised by some quantum-optics groups (e.g. \cite{28}). Of course such a detector has an exceedingly low efficiency. However, the necessity to produce a very large number of “biphotons” for such a purpose (the single-ion detector has a very low efficiency) does not preclude to perform the experiment with state of the art technology.

6 Summary

After fixing two important shortcomings (i.e. in the setup of Kim and Shih with Extension step 1) Popper’s experiment becomes a test of a non-trivial tenet of the Copenhagen interpretation (CI): that the state function represents our knowledge of a system. The main proposal of this paper is to perform this experiment. An experimental result confirming the above tenet would be strikingly counterintuitive. The very different many-worlds interpretation (MWI) predicts the same result for this experiment. Assuming the confirming result in an actual experiment additional Extension step 2 could be performed - in which the predictions made using CI versus MWI are qualitatively different. Because - in my opinion - both interpretations are logically tenable presently, it is not possible to predict the outcome of an experiment performed in this way.

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after this contains an interview with Popper which deals, among other things, with his experiment.

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