Bell state measurement locally explained

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Abstract

Entangled quantum systems can connect to the environment by means of a Bell state measurement. This is true for instance for teleportation and entanglement swapping. While the results are well understood it is not quite clear if they involve nonlocal action or if they are determined in advance. Models based on the fact that the partners of an entangled pair have the same value of a statistical parameter do not apply here. Therefore, in this work a model is presented which reproduces the quantum mechanical predictions, but is not based on common statistical parameters. It refutes Bell's theorem. The manuscript is a contribution to understanding the coupling of entangled systems with their environment. Since the coupling systems do not have to be connected by common statistical parameters, there is no need to look for them in further work. The manuscript is thus a step forward towards a complete theory describing quantum physical reality as thought possible by Einstein, Podolsky and Rosen.

Keywords: Bell's theorem, entanglement swapping, teleportation, hidden variables, EPR

1. Introduction

Entanglement swapping allows particles that were not previously in contact to become entangled. This entanglement can be accomplished using Bell state measurements [1]. Many physicists are convinced that this process is non-local. This conviction is ultimately based on the assumption of Bell's theorem validity [2]. It states that quantum mechanics cannot be local because it cannot be described by local realistic models with hidden variables. A detailed description of the literature and arguments regarding Bell's theorem can be found in [3]. Bell's theorem was refuted by a local contextual model with hidden variables [4] which correctly predicts quantum mechanical expectation values with polarization-entangled particles. This model is based on the fact that both members of an entangled pair are connected by a common hidden parameter.

However, assuming a common value of a hidden parameter for the members of an entangled pair, as also proposed by Bell [5], cannot explain phenomena such as entanglement swapping and teleportation [6-9]. When photons that did not interact before become entangled by entanglement swapping they cannot have a common parameter with a statistical distribution.

With the locally realistic model [4], Bell's theorem was formally refuted. It correctly reproduces the quantum mechanical expectation values of entangled particles. However, it remains unsatisfactory that well-known phenomena such as entanglement swapping and teleportation cannot be explained in this way. The added value of the model presented in this paper is that this shortcoming has been addressed. With a model that not only predicts the quantum mechanical correlations with entangled photons but also explains teleportation and entanglement swapping, the understanding of the physical correlations also increases. To circumvent the difficulties mentioned above, we introduce a model in which the indistinguishability of the entangled photons explains the physical states, as in [4], but in which the photon pairs do not share the value of a statistical parameter. The question then arises as to how the photons on side B get information regarding the position of the polarizer on side A without communication. This information comes first from the mixing ratio of the horizontally and vertically polarized photons from the constituent initial states (see model assumption MA2), which contribute to the selection, and second from the initial conditions and the conservation of angular momentum (see model assumption MA3), which couple both sides.

The reader is assumed to be familiar with the Bell states $\Psi+$, $\Phi-$, $\Phi+$ *and* $\Phi-$ the definition of which can be found in the literature [1]. For each Bell state, we show what a selection of photons by a polarizer on one side means for the state on the other side. The results are listed in Table 1. From this, expectation values for correlation measurements on entangled photons and the states for entanglement swapping and teleportation are derived.

2. A new model for polarization entangled photons with local hidden variables

2.1 Model overview

In polarization measurements, photons can choose one of two perpendicular exits of the polarizer. A model with hidden variable must describe which of these two possible exits a photon will take. Four model assumptions are introduced, which are outlined and then described in italics:

MA1 introduces the statistical parameter λ which controls the polarizer exit that a photon will take. This model assumption is the same as MA1 in [4].

MA2 describes the polarization of a selection of photons from an entangled pair. This is a new model assumption.

MA3 describes the coupling of photons from an entangled pair. This is a new model assumption.

MA4 states that photons carry the complete set of the hidden variable after a measurement. This model assumption is the same as MA4 in [4].

Figure 1 shows the coordinate systems and nomenclature of the experiments with polarization entangled photons.

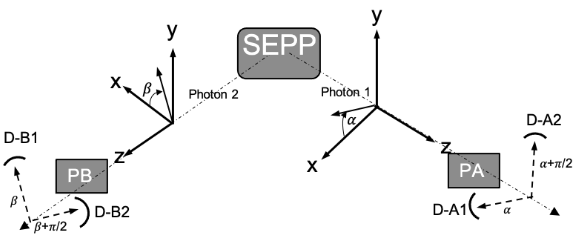

Figure 1: The SEPP (source of entangled photon pairs) emits entangled photons propagating towards the adjustable polarizers PA and PB and detectors DA-1 and DA-2 on wing A and DB-1 and DB-2 on wing B. A coincidence measuring device (not seen in the picture) encounters matching events. The polarization angles are defined in the x–y-plane, which is perpendicular to the propagation direction of the photons. The coordinate systems are left-handed with the z-axis in propagation direction for each wing, with the x-axis in horizontal and the y-axis in vertical direction.

2.2 Model assumptions

Model assumption MA1: *The statistical parameter λ, uniformly distributed between 0 and 1, controls which of the two polarizer exits the photon will take. Given the polarizer setting α and the photon polarization φ we define $\delta = \alpha - \varphi$ as the difference between the polarizer setting and the polarization of the photon. The function $A(\delta,\lambda)$ indicates which polarizer exit the photon will take.*

$A(\delta,\lambda)$ can have values +1 and -1. For $0 \le \delta < \pi/2$, we define
$A(\delta,\lambda) = +1$ *for* $0 \le \lambda \le \cos^2(\delta)$, (1)
meaning the photon takes polarizer exit α and

$A(\delta,\lambda) = -1$ *for* $\cos^2(\delta) < \lambda \le 1$, (2)
meaning the photon takes polarizer exit $\alpha+ \pi/2$. MA1 is valid for single photons as well as for each wing of entangled photons.

The case $\pi/2 \le \delta < \pi$ is covered referring to the other exit of the polarizer. Then equation (2) applies and the range of values of λ for positive results is $\cos^2(\delta) < \lambda \le 1$. The case $\delta < 0$ is covered by reversing the polarizer direction by 180°. Thus, $-\pi \le \delta < -\pi/2$ is equivalent to $0 \le \delta < \pi/2$ and $-\pi/2 \le \delta < 0$ is equivalent to $\pi/2 \le \delta < \pi$.

Thus $A(\delta,\lambda) = +1$
for $0 \le \delta < \pi/2$ and $0 \le \lambda \le \cos^2(\delta)$, (3.1)
for $-\pi/2 \le \delta < 0$ and $\cos^2(\delta) < \lambda \le 1$, (3.2)
for $\pi/2 \le \delta < \pi$ and $\cos^2(\delta) < \lambda \le 1$, (3.3)
for $-\pi \le \delta < -\pi/2$, and $0 \le \lambda \le \cos^2(\delta)$ and (3.4)
$A(\delta,\lambda) = -1$ otherwise. (3.5)

Model assumption MA2: *If the fractions of horizontally and vertically polarized photons from the entangled state contributing to a photon stream selected by a polarizer are $\cos^2(\alpha)$ and $\sin^2(\alpha)$ respectively, obtain a common polarization of α or $-\alpha$, because of the indistinguishability of the photons.*

The fractions of horizontally and vertically polarized photons that leave a polarizer exit α are $\cos^2(\alpha)$ and $\sin^2(\alpha)$ respectively. This makes up for the common polarization. The selection comprises all photons that take the same polarizer exit. Photons with polarization α and $\alpha+\pi/2$ come in equal shares, due to symmetry reasons. MA2 accounts for the fact that the polarization of photons from the entangled state is undefined because of their indistinguishability, but is changed and re-defined by entanglement. Thus, the photons of a selection cannot be distinguished by their polarization. This argument has already been made in [4] but only for photon pairs with common hidden variables. MA2 is a contextual assumption, because the polarization of a selection coincides with the setting of a polarizer. However, this is a local realistic assumption, because it assigns a real value to the physical quantity polarization. MA2 leaves open whether the polarization of a selection is positive or negative. To distinguish this we use the initial conditions taking into account the conservation of angular momentum. This leads to

Model assumption MA3: *Each Bell state is a mixture of indistinguishable constituent photon pairs in equal shares whose components have the same polarization 0° or 90° for Φ+ and Φ- and an offset of π/2 for Ψ+ and Ψ-. The constituent photon pairs make up the initial state.*

The coupling of a selection on wing A with polarization α and the corresponding selection of the partner photons on wing B with polarization β is a relation between the normalized signs of the polarizations on both sides and is given

For Ψ+ and Φ+ as $\mathrm{sign}'(\alpha)_1 = \mathrm{sign}'(\beta)_2$, *and* (4.1)

for Ψ- and Φ- as $\mathrm{sign}'(\alpha)_1 = -\,\mathrm{sign}'(\beta)_2$, (4.2)

where the normalized sign' is given by

$\mathrm{sign}'(\alpha) = \mathrm{sign}(\alpha)$ *for* $-\pi/2 \le \alpha \le \pi/2$ *and*

$\mathrm{sign}'(\alpha) = \mathrm{sign}(\alpha-\pi)$ *for* $\pi/2 \le \alpha \le 3\pi/2$ *and*

$\mathrm{sign}'(\alpha) = \mathrm{sign}(\alpha-2\pi)$ *for* $3\pi/2 \le \alpha \le 2\pi$, (5)

with α and α-π denoting the same polarization and the suffixes 1 and 2 denote the sides.

From equation (5) we obtain

$$\mathrm{sign}'(\alpha) = -\,\mathrm{sign}'(\alpha+\pi/2) = \mathrm{sign}'(-\alpha-\pi/2). \quad (6)$$

Model assumption MA4: *Photons having left a polarizer exit α have polarization α with λ evenly distributed in the range* $0 \le \lambda \le 1$.

MA4 emphasizes that photons carry the full set of hidden variables after leaving the polarizer.

2.3 Predicting measurement results for single photons

Using equations (3.1 or 3.4), a photon with polarization φ is found behind the exit α of a polarizer with probability

$$P_\delta = \boxed{\int_0^{\cos^2(\delta)} d\lambda} = \cos^2(\delta), \quad (7)$$

where $\delta = \alpha - \varphi$ with $0 \le \delta < \pi/2$ or $-\pi \le \delta < -\pi/2$.

Using equations (3.2 or 3.3) for $-\pi/2 \le \delta < 0$ or $\pi/2 \le \delta < \pi$ we refer to the other exit of the polarizer and have, with $\vartheta^* = \delta - \pi/2$

$$P_\delta = \boxed{\int_{\cos^2(\delta*)}^1 d\lambda} = 1-\cos^2(\vartheta^*) = \cos^2(\vartheta), \text{ as well.} \quad (8)$$

With $\delta = \alpha - \varphi$ we obtain the same P_δ for a photon in state cos(φ)*|H> + sin(φ)*|V> by projection onto cos(α)*<H| + sin(α)*<V| according to QM (i.e., Born's rule).

2.4 Conclusions from the model assumptions

MA2 has the consequence that the selection by a polarizer in position α on one side corresponds to a selection with polarization α+π/2 or -α-π/2 on the other side.(for Ψ+ or Ψ-) This can be seen from the following consideration: According to equations (7,8) a polarizer PA set to α selects a fraction of $\cos^2(\alpha)$ of horizontally polarized photons 1 and a fraction of $\sin^2(\alpha)$ of vertically polarized photons 1. This means that partner photons 2 are also selected, but with perpendicular polarization, resulting in a selected fraction of $\cos^2(\alpha) = \sin^2(\alpha+\pi/2)$ of vertically polarized photons 2 and a selected fraction of $\sin^2(\alpha) = \cos^2(\alpha+\pi/2)$ of horizontally polarized photons 2. Due to MA2 the polarization of the selected photons 2 is α+ π/2 or -α- π/2.

From equations (4.1) and (6) we obtain for Ψ+ the polarization -α- π/2 of the partner photon 2 with the same normalized sign as that of the polarization α. For Ψ- we obtain the polarization α+ π/2 of partner photon 2 with an opposite normalized sign of the polarization α in accordance with equation (4.2).

For Φ+ and Φ- we find that the selection by a polarizer in position α on one side corresponds to a selection with polarization α or -α on the other side. Again a polarizer PA set to α selects a fraction of $\cos^2(\alpha)$ of horizontally polarized photons 1 and a fraction of $\sin^2(\alpha)$ of vertically polarized photons 1. This means that partner photons 2 are also selected, but in this case with the same polarization, resulting in a selected fraction of $\cos^2(\alpha)$ of horizontally polarized photons 2 and a selected fraction of $\sin^2(\alpha)$ of vertically polarized photons 2. Due to MA2 the polarization of the selected photons 2 is α or -α.

According to equation (4.1) we obtain the polarization of the partner photons 2 of α for Φ+ as $\mathrm{sign}'(\alpha)_1 = \mathrm{sign}'(\alpha)_2$ and of -α for Φ- as $\mathrm{sign}'(\alpha)_1 = -\,\mathrm{sign}'(-\alpha)_2$ in accordance with equation (4.2). The results for all four Bell states are presented in Table 1.

Bell state	A	B
Ψ-:	α	α + π/2
Φ+	α	α
Ψ+	α	-α -π/2
Φ-	α	-α

Table 1: polarization of partner photons 2 at wing B for different Bell states for a selection of photons 1 with a polarizer set to α at wing A.

The Bell states Ψ- and Φ+ are known to be rotationally invariant. The same applies to the states Ψ+ and Φ- as well if the coordinate system on wing B is changed from left- to right-handed. In this case, the polarization values for Ψ+ and Φ- in column B in Table 1 change sign, so that the difference between A and B is constant and therefore independent of α. Model assumption MA3 reproduces the conservation of spin angular momentum. This is shown in the quantum formalism.

Let |R> and |L> denote the state of the right and left polarized photons, respectively. These are related to the spin direction. The connection to the linear polarization is given by

$$|R\rangle = 1/\sqrt{2} *(|H\rangle + i|V\rangle) \text{ and}$$

$$|L\rangle = 1/\sqrt{2} *(|H\rangle - i|V\rangle) \text{ with} \tag{9}$$

$$|H\rangle = 1/\sqrt{2} *(|R\rangle + |L\rangle) \text{ and}$$

$$|V\rangle = -i/\sqrt{2} *(|R\rangle - |L\rangle). \tag{10}$$

This provides for the four Bell states with the suffixes A and B denoting the wings of the entangled states.

$$\mathbf{\Phi}{+}= 1/\sqrt{2} *(|H_A\rangle|H_B\rangle + |V_A\rangle|V_B\rangle)$$

$$= 1/\sqrt{2} *(|R_A\rangle|L_B\rangle + |L_A\rangle|R_B\rangle), \tag{11}$$

$$\mathbf{\Psi}^- = 1/\sqrt{2} *(|H_A\rangle|V_B\rangle - |V_A\rangle|H_B\rangle)$$

$$= i/\sqrt{2} *(|R_A\rangle|L_B\rangle - |L_A\rangle|R_B\rangle), \tag{12}$$

$$\mathbf{\Phi}{-} = 1/\sqrt{2} *(|H_A\rangle|H_B\rangle - |V_A\rangle|V_B\rangle)$$

$$= 1/\sqrt{2} *(|R_A\rangle|R_B\rangle + |L_A\rangle|L_B\rangle), \tag{13}$$

$$\mathbf{\Psi}^+ = 1/\sqrt{2} *(|H_A\rangle|V_B\rangle + |V_A\rangle|H_B\rangle)$$

$$= -i/\sqrt{2} *(|R_A\rangle|R_B\rangle - |L_A\rangle|L_B\rangle), \tag{14}$$

For **Φ**+ and **Ψ**- the total spin of the photon pairs vanishes because left and right polarization cancel. This also applies to **Φ**- and **Ψ**+ if the coordinate system on wing B is rotated by 180°, i.e. the photons exit the source in the opposite direction.

Φ+ and **Ψ**- are rotationally symmetrical. So it also applies

$$\mathbf{\Phi}{+}= 1/\sqrt{2} *(|H'_A\rangle|H'_B\rangle + |V'_A\rangle|V'_B\rangle) \tag{15}$$

for each angle α of a rotation of the coordinate system, with

$$|H'\rangle = \cos(\alpha) *|H\rangle + \sin(\alpha) *|V\rangle \text{ and}$$

$$|V'\rangle = -\sin(\alpha) *|H\rangle + \cos(\alpha) *|V\rangle . \tag{16}$$

Projection onto $\langle H'_A|$ yields

$$\langle H'_A| \mathbf{\Phi}{+}\rangle = |H'_B\rangle = \cos(\alpha) *|H_B\rangle + \sin(\alpha) *|V_B\rangle. \tag{17}$$

So we see that a projection or selection of **Φ**+ by a polarizer PA in position α means the state or polarization of the partner photons in direction α. The projection for **Ψ**- yields

$$\langle H'_A| \mathbf{\Psi}^-\rangle = |V'_B\rangle = -\sin(\alpha) *|H_B\rangle + \cos(\alpha) *|V_B\rangle. \tag{18}$$

This state is orthogonal to α. A projection or selection of **Ψ**- by a polarizer PA in position α results in the direction α + π/2. for the state or polarization of the partner photons.

Φ- and **Ψ**+ are also rotationally symmetrical if the coordinate system on wing B is rotated by 180°, i.e. the photons exit the source in the opposite direction. This means with $|H^*_B\rangle = -|H_B\rangle$ that (19)

$$\mathbf{\Phi}{-} = 1/\sqrt{2} *(-|H_A\rangle|H^*_B\rangle - |V_A\rangle|V_B\rangle). \tag{20}$$

Because of the rotational symmetry also applies

$$\mathbf{\Phi}{-} = 1/\sqrt{2} *(-|H'_A\rangle|H^{*\prime}_B\rangle - |V'_A\rangle|V'_B\rangle) \tag{21}$$

for each angle α of a rotation of the coordinate system, with

|H'> and |V'> given by equation (16) .

Projection onto $\langle H'_A|$ yields

$$\langle H'_A| \mathbf{\Phi}{-}\rangle = -|H^{*\prime}_B\rangle = -(\cos(\alpha) *|H^*_B\rangle + \sin(\alpha) *|V_B\rangle)= \cos(-\alpha) *|H_B\rangle + \sin(-\alpha) *|V_B\rangle. \tag{22}$$

So we see that a projection or selection of **Φ**- by a polarizer PA in position α means the state or polarization of the partner photons in direction -α.

For **Ψ**+ the projection gives

$$\langle H'_A| \mathbf{\Psi}^+\rangle = |V'_B\rangle = -\sin(\alpha) *|H^*_B\rangle + \cos(\alpha) *|V_B\rangle = -\sin(-\alpha) *|H_B\rangle + \cos(-\alpha) *|V_B\rangle. \tag{23}$$

This state is orthogonal to -α. A projection or selection of **Ψ**+ by a polarizer PA in position α results in the direction -α- π/2 for the state or polarization of the partner photons.

This altogether tells us that of the two possibilities given by MA2, only the one given by MA3 is consistent with conservation of angular momentum. For the relationship between the position of the selective polarizer and the polarization of the partner photons, the conservation of the spin angular momentum means the same sign of α on both sides for **Φ**+ and **Ψ**- and the opposite sign for **Φ**- and **Ψ**+ as described in Table 1.

2.5 Calculating expectation values for photons in singlet state

We have seen above that all selected photons 1 from the singlet state which take PA exit α have polarization α while their partner photons 2 have polarization α+π/2. Seen from the other side we can conclude that if photon 2 leaves polarizer PB at β we have matching events if those photons 2 with polarization β would leave PB with an assumed setting of $\alpha+\pi/2$. Note, that λ is evenly distributed in the value range $0 \leq \lambda \leq 1$ for the photons 2 with polarization β. This can be seen examining the initial states and applying equations (3.1) - (3.4) to horizontally polarized photons and vertically polarized photons. For example, the horizontally polarized photons with $0 \leq \lambda \leq \cos^2(\delta)$ and the vertically polarized photons with $\cos^2(\delta) < \lambda \leq 1$ contribute to a selection with polarization β for $0 \leq \delta < \pi/2$.

Thus, the probability that photons 2 with polarization β would pass PB at $\alpha + \pi/2$ can be obtained by equations (7) and (8), using $\delta = \alpha+\pi/2 - \beta$ thus yielding

$$P_\delta = \cos^2(\delta) = \cos^2(\alpha+\pi/2 - \beta) = \sin^2(\alpha-\beta), \qquad (24)$$

where δ is the angle between the PB polarizer setting β and the polarization $\alpha + \pi/2$ of photons 2 selected by PA.

The expectation value for a joint measurement with photon 1 detected behind detector PA at α and partner photon 2 detected behind detector PB at β is as obtained from [4]

$$E(\alpha,\beta) = \Sigma A^*B^*P_{A,\alpha}{}^*P_{B,\beta|A,\alpha} \text{ for } A,B=+1,-1. \qquad (25)$$

Here $P_{A,\alpha}$ is the unconditional probability to detect (A = 1) or not detect (A = -1) photon 1 at α and $P_{B,\beta|A,\alpha}$ is the conditional probability for photon 2 to have the outcome B at PB set to β if photon 1 has outcome A at PA set to α. With P_δ from equation (24), we get, in particular, that:

$$P_{+1,\beta|+1,\alpha} = P_{-1,\beta|-1,\alpha} = P_\delta \text{ and}$$

$$P_{+1,\beta|-1,\alpha} = P_{-1,\beta|+1,\alpha} = 1 - P_\delta. \qquad (26)$$

The constituent photons of the singlet state with polarization 0° and 90° contribute to the probability $P_{1,\alpha}$ to find a photon 1 at α according to equation (7,8), with fractions $½\cos^2(\alpha)$ and $½\cos^2(\alpha-\pi/2)$ respectively, taking into account that the photons of 0° and 90° contribute in equal shares to the total stream of photons on either wing. Thus,

$$P_{1,\alpha} = ½(\cos^2(\alpha) + \cos^2(\alpha-\pi/2)) = ½ = P_{-1,\alpha}. \qquad (27)$$

With the above definitions, we get, from equations (24)–(27):

$$E(\alpha,\beta) = ½(1^* P_\delta -1^*(1- P_\delta) -1^*(1- P_\delta) +1^* P_\delta) =$$

$$= P_\delta - (1- P_\delta) = \sin^2(\alpha-\beta) - \cos^2(\alpha-\beta) = -\cos(2(\alpha-\beta)), \qquad (28)$$

in accordance with QM. As the expectation value E(α,β) in Equation (28) exactly matches the predictions of quantum physics, it also violates Bell's inequality.

2.6 Applying the model to entanglement swapping

Entanglement swapping uses a protocol in which two wings of different systems, each in singlet state, are entangled by a Bell state measurement of the two remaining wings[1,2,8].

Let AB and CD be the two initial systems in singlet state. Then we define the outer pair AD and the inner pair BC. With a Bell state measurement between B and C we want to entangle A and D. However, this coupling is random in the case of entanglement swapping. Therefore four resulting Bell states are possible. How are these results for the inner pair BC related to the state of the outer pair AD? This is determined by applying table 1 to the pairs of channels. AB and CD are always in state Ψ-. BC is obtained by the Bell state measurement.

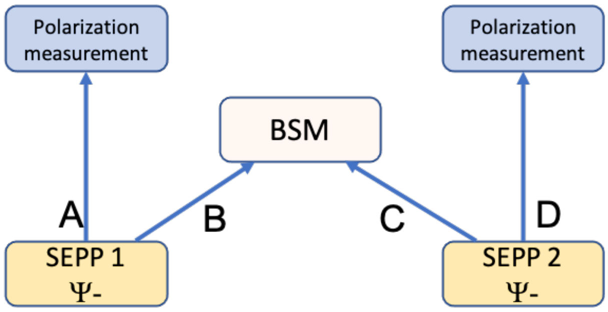

Figure 2: Entanglement swapping entangles wings A and D by a Bell state measurement between B and C.

Thus, we obtained the results of Table 2. Compared with Table 1 we see that the Bell state of the outer pair AD is equal to the measured Bell state of the inner pair BC according to QM [8]. Note that the polarizations $\alpha + \pi$ and α are equal

Bell state	A	B	C	D
Ψ-:	α	α + π/2	α (+ π)	α + π/2
Φ+	α	α + π/2	α + π/2	α (+ π)
Ψ+	α	α + π/2	-α (- π)	-α - π/2
Φ-	α	α + π/2	-α - π/2	-α

Table 2: polarization of the photons of wings B,C and A,D for different Bell states obtained between B and C by applying table 1 with an assumed selection of photons by a polarizer set to α at wing A.

2.7 Applying the model to teleportation

Teleportation uses a protocol in which an unknown state β is transferred to another wing B of a singlet state by Bell state measurement between the unknown β and wing A of the singlet state [9]. Using MA3 and Table 1 we obtain the polarizations at wing A and B. AB are always in the Ψ- state.

The polarization of the pair βA is obtained by measuring the Bell state.

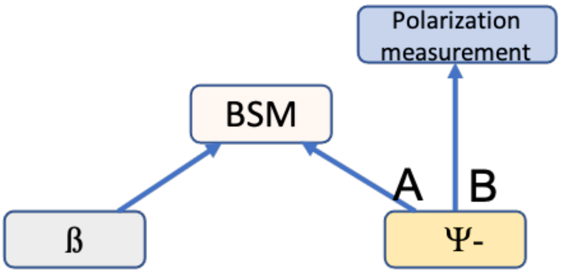

Figure 3: Teleportation of an unknown state ß to a remote wing B by a Bell state measurement between ß and Wing A

Thus, we obtained the results shown in Table 3. The results at wing B can be converted to the state β by simple rotation or mirroring. This result is in accordance with quantum mechanical calculations [9]. Note that the polarizations $\beta + \pi$ and β are equal.

Bell state βA	A	B
Ψ-	$\beta + \pi/2$	$\beta\ (+\ \pi)$
Φ+	β	$\beta + \pi/2$
Ψ+	$-\beta-\pi/2$	$-\beta$
Φ-	$-\beta$	$-\beta + \pi/2$

Table 3: polarization of the photons of wings A and B for different Bell states obtained between the unknown β and wing A.

3. Results, discussion and conclusions

The model presented here is based on the selection of the photons by a polarizer (on one side of a photon pair in a Bell state). Owing to their indistinguishability, the selected photons have a common polarization that depends on the mixing ratio of the constituent horizontally or vertically polarized components. This ratio is the same or inverse on both sides depending on the Bell state. It is physically based on the conservation of spin angular momentum. Accordingly, there is a fixed connection between the polarization of the selection on one side and the corresponding polarization of the partner photons on the other side. These polarizations are present prior to any measurement.

The Bell states were conceived in the model as mixtures of indistinguishable photon pairs. Because the Bell states are entangled they are not separable. This implies that the individual photons of an entangled photon pair have no physical reality. The physical reason for this is their indistinguishability. A Bell state splits into two systems of photon pairs with mutually perpendicular polarizations upon selection by a polarizer. This selection corresponds to a projection in quantum mechanics. By projecting the rotationally symmetric singlet state onto a direction on one side, the state on the other side is also fixed. In the model, this corresponds to the effect of the selection. Until now the problem with quantum physics was that the change of state on the opposite side was considered as a non-local interaction. This was suggested by Bell's theorem but refuted in [4] , and by the model presented. Because a selection on one side implies a corresponding selection on the other side, there is no action associated with a selection.

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