Phase-Shifted Bell States and Potential Implications in the understanding of 'Spooky action at a Distance'

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Abstract

This paper conveys briefly and concisely what could be the implications of the Einstein-Bohr debate when we consider the results of Phase-Shifted EPR-Bell states from a study conducted in Maarten Hoogerland's Lab in the Dodd-Walls Centre for Photonics and Quantum Technologies, University of Auckland, New Zealand (2018-2024). The results of this study were presented at the first Biological Physics and Meaning Mini Conference on 'QUANTUM MECHANICS, THE MEASUREMENT PROBLEM AND HUMAN CONSCIOUSNESS' (Feb. 2024). Here, I also examine the nature of correlated pairs of photons produced by Spontaneous Parametric Down-Conversion (SPDC) Type II, when the photon of one path is altered with a Quarter Wave Plate (QWP), shifting the polarization from linear to elliptical or circular. As stated in the above-mentioned study, surprisingly, some of these Phase Shifted Bell states (correlated pairs) produce no violation of the Clauser, Horne, Shimony and Holt (CHSH) inequality, raising yet again a question mark on the meaning of 'entanglement' when understood as 'spooky action at a distance', in the context of the formalism of Quantum Mechanics and the different associated interpretations. If 'spooky action at a distance' is ruled out from physical systems and we consider new more general stochastic laws, then we open the way for a more interesting future physics on the side of Einstein and realism that, under some regimes, may manifest as nonlocality in terms of information structures. Perhaps, religious, spiritual and mystical experience (RSME) may have a place in physics and the sciences in general, as *experienced information and meaning* within physical restrictions in a classically consciously experienced lived life in spacetime.

Keywords: Bell Experiment, Phase-Shifted Bell States, Entanglement, SPDC Type II, CHSH Inequality, Quantum Mechanics.

Introduction

Based on the work of John Bell in relationship to the ideas of Einstein, Podolsky and Rosen (EPR), traditional EPR-Bell states are predicted to violate the CHSH inequality (Bell, 1987; Einstein, Podolsky, & Rosen, 1935). However, what if other kinds of maximally 'entangled' states, different than the traditional ones already mentioned here, would be predicted to show no violations of the

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CHSH inequality. How would we interpret such predictions, when it is well known that violation of the CHSH inequality is the hallmark of 'entanglement' understood as 'spooky action at a distance'.

Einstein complained about the idea of 'spooky action at a distance', while Bohr contested such complaint in favor of the predictions of quantum mechanics (QM) in his famous paper 'Can Quantum-Mechanical Description of Physical Reality be Considered Complete?' (1935), bearing the same title as the Einstein, Podolsky, & Rosen (1935) paper. Bell provided a mathematical and statistical framework that led to the ruling out of local realism (Bell, 1987) and Clauser and Shimony gave an experimental framework to test the equivalent of Bell inequality (Clauser & Shimony, 1978). Later, experiments were conducted by Kwiat, et al. (1995) that showed violations for all four EPR-Bell states with great precision, using a Beta Barium Borate (BBO) crystal to perform SPDC Type II.

While plagued with different interpretations, QM predictions have been verified in multiple experiments and labs with great precision. The notion of 'entanglement' is derived from the QM formalism itself, where the wave function $|\psi\rangle = \frac{1}{\sqrt{2}}(|H_1, V_2\rangle + e^{i\alpha}|V_1, H_2\rangle)$, is said to collapse to one of the two entangled states after measurement, something that has been put in question. However, other formalisms and models have been proposed, leading to the same predictions of QM, yet ruling out 'spooky action at a distance', by invoking, for example, Markovian versions of Quantum Electrodynamics, non-local pilot wave or Bohmian theories, that would also violate CHSH inequality (Werbos, 2015). Also, toy models invoking super determinism have recently been proposed (Sandro & Hossenfelder, 2022).

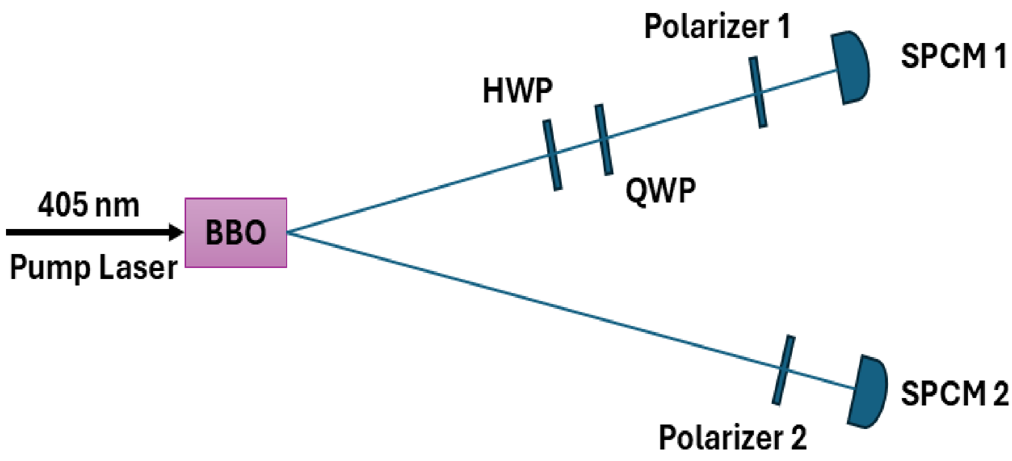
In a recent study published by Davis, Jackman, Leonhardt, Werbos & Hoogerland (2024) it was proposed that a new family of Phase-Shifted EPR-Bell states can be prepared to test for the violations of the CHSH inequality of correlated photons generated via SPDC Type II. In this study it is clearly shown with high precision that both the traditional EPR-Bell states and the Phase-Shifted EPR-Bell states show violations of the CHSH inequality. However, for a subset of this new family of EPR-Bell states no violations are observed.

Even though these results are predicted by QM, together with these novel experimental results confirming such predictions, these are very surprising results, since these correlated states show no 'entanglement' according to the hallmark of the violation of the CHSH inequality.

In the following section, I briefly describe some relevant features of the study.

Phase-Shifted EPR-Bell States

The experimental schematic is shown in Picture 1, where a laser pump of ~405 nm goes through a BBO crystal and performs a SPDC Type II, where pairs of correlated 810 nm photons arriving at the same time (within a window of 10 ns apart) are targeted, and the number of coincidences per second is recorded with the aid of a coincidence detector and a computer program running in a PC.



Picture 1. Shows the schematics of the experimental setting, where arm 1 contains a Half Wave Plate (HWP), a Quarter Wave Plate (QWP), Polarizer 1 and a Single Photon Counting Module (SPCM 1). Arm 2 contains Polarizer 2 and SPCM 2.

Coincidence counts are computed for an exhaustive set of angles θ_1 and θ_2, as shown in the following example in Table 1, and they are used to compute the parameter S, that if greater than 2 and less than $2\sqrt{2}$, indicates that the CHSH has been violated and therefore the correlated pairs are said to be 'entangled'.

Table 1. Shows coincidence counts for different combinations of angles $\boldsymbol{\theta_1}$ and $\boldsymbol{\theta_2}$, for polarizers 1 and 2.

$\boldsymbol{\theta_1/\theta_2}$	**0**	**22.5**	**45**	**67.5**	**90**	**112.5**	**135**	**157.5**	**180**
22.5	211	462.5	745.3	907.7	832.4	614.1	321.1	147.5	196
67.5	763.9	833.3	747.8	558.8	362.8	308.3	396.6	578.2	740.4
112.5	865.5	614.4	317	147.2	193.9	446.2	748.1	917.6	867.1
-22.5	358.5	290.2	376.8	568.8	720.1	806.2	718.9	528.6	355.8

Note that in Table 1, angle θ_1 is set to four different values, while θ_2 varies in steps of 22.5^0. However, an experiment could be run where both θ_1 and θ_2 move in steps of 9^0, showing the following qualitive results in Figure 1, for example.

Here the color yellow indicates a high number of coincidences, while dark blue indicates the opposite, a very low number.

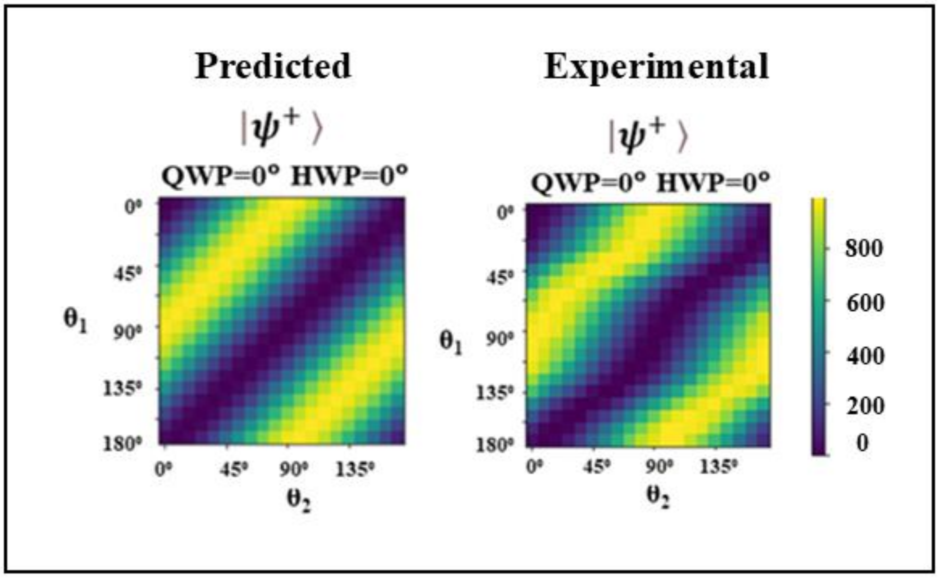


Figure 1. Shows predicted and experimental coincidence counts in 2D surf plots at angles $\boldsymbol{\theta_1}$ and $\boldsymbol{\theta_2}$, for polarizers 1 and 2 when the system is prepared in $|\boldsymbol{\psi}^{+}\rangle = \frac{\mathbf{1}}{\sqrt{\mathbf{2}}}(|\mathbf{H_1}, \mathbf{V_2}\rangle + |\mathbf{V_1}, \mathbf{H_2}\rangle)$.

The way in which the Phase Shifted EPR-Bell States are obtained is by changing the angle θ_{QWP} of the QWP. θ_{QWP} can be used to change the angle α in the wave function $|\psi\rangle = \frac{1}{\sqrt{2}}(|H_1, V_2\rangle + e^{i\alpha}|V_1, H_2\rangle)$ to prepare linear, elliptical or circularly polarized light in arm 1 of the experiment, as shown in Figure 2.

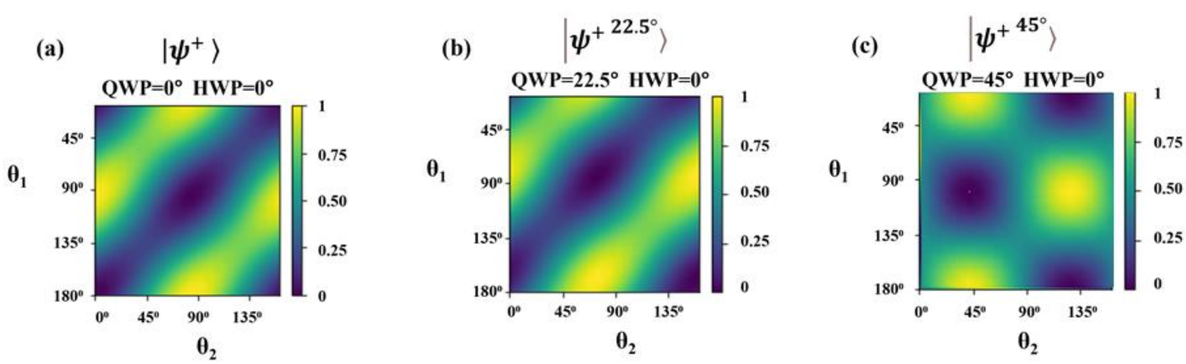


Figure 2. Shows three landscapes associated with three different Phase Shifted EPR-Bell states: $|\boldsymbol{\psi}^{+}\rangle, |\boldsymbol{\psi}^{+22.5^0}\rangle$ **and** $|\boldsymbol{\psi}^{+45^0}\rangle$, where the predicted normalized coincidence counts are shown in 2D surf plots at angles $\boldsymbol{\theta_1}$ and $\boldsymbol{\theta_2}$, for polarizers 1 and 2.

The predicted normalized results show a shifted landscape behavior when the QWP angle is set at 22.5º, when compared to the traditional EPR-Bell States, as well as a very new and surprising behavior when the QWP angle is set at 45º, as shown in Figure 2. These predictions are confirmed experimentally in (Davis et al., 2024), and it must be noted that the parameter S shows different results for each of these states.

The reader must note that if we set θ_{QWP} at 45º, we would prepare the system in the following state $\left|\psi^{45^0}\right\rangle = \frac{1}{\sqrt{2}}(|L_1, V_2\rangle + |R_1, H_2\rangle)$. Considering that $|L_1\rangle = |H_1\rangle + i|V_1\rangle$ and $|R_1\rangle = |H_1\rangle - i|V_1\rangle$, then the resulting state is:

$$\left|\psi^{45^0}\right\rangle = \frac{1}{2}(|H_1, V_2\rangle + i|V_1, V_2\rangle + |H_1, H_2\rangle - i|V_1, H_2\rangle).$$

This state turns out to be very relevant!

General Results

The following results are a close approximation derived from (Davis et al., 2024). The reader is highly advised to read the full study which contains a robust analysis and display of the results.

In Table 2 the results obtained for the S parameter when the QWP angle is set at θ_{QWP} equal to 0º, 22.5º and 45º, for a, b and c respectively, as shown in Figure 2, show strong violations of the CHSH inequality for traditional and Phase Shifted EPR-Bell states $\left|\psi^{+\ 0^0}\right\rangle$ *and* $\left|\psi^{+\ 22.5^0}\right\rangle$, while no violations are observed for the state $\left|\psi^{+\ 45^0}\right\rangle$. The reader must also note that surf plots (a) and (b) are similar, yet slightly shifted from each other, while plot (c) shows a very different landscape.

Table 2. Shows the values associated with the $\hat{\mathbf{S}}$ parameter to test for violations of the CHSH inequality obtained from (Davis et al., 2024).

Phase Shifted EPR-Bell states	$\hat{\mathbf{S}}$
$\left|\boldsymbol{\psi}^{+\ 0^0}\right\rangle$	~ -2.78
$\left|\boldsymbol{\psi}^{+\ 22.5^0}\right\rangle$	~ -2.78
$\left|\boldsymbol{\psi}^{+\ 45^0}\right\rangle$	~ -2.02

This result is certainly surprising and merits a deeper exploration and analysis.

Discussion, Future Perspectives and Conclusion

To explain these results several arguments can be made:

1. The fact that the down converted pair of photons are also correlated when we set the QWP at angle θ_{QWP} at 45º, together with the fact that no violations are observed, could indicate

that the notion of 'entanglement' when understood or interpreted as 'spooky action at a distance' based on the formalism of QM, is a flawed interpretation, as Einstein warned us.

2. It could also be that the computation of the S parameter is handicapped, when applied to all possible maximally 'entangled' states, that include some types of Phase-Shifted EPR-Bell States, like $\left|\psi^{+45^0}\right\rangle$. This would indicate that a new form of more general and advanced S parameter computation may be required to account for the violations of the Phase Shifted EPR-Bell states when prepared by setting the QWP at θ_{QWP} at 45º. As was indicated by Kiko Galvez in my recent meeting with him at Colgate University (Oct. 2024), no violations of the CHSH inequality for $\left|\psi^{+45^0}\right\rangle$ may be caused by a mixture of different types of polarization (linear and elliptical or circular), as for example, in the presence of the QWP in only one arm of the experiment, set at θ_{QWP} at 45º. This is depicted by the corresponding wave function $\left|\psi^{45^0}\right\rangle = \frac{1}{\sqrt{2}}(|L_1, V_2\rangle + |R_1, H_2\rangle)$, where L and R indicate left and right circularly polarized light respectively, while H and V stand for horizontal and vertical linearly polarized light.
3. It could also be that the way in which the QWP was set acts as a hidden variable only known by the experimenter.
4. Also, these results may indicate some form of determinism, since the experimenters have shown that they can alter the results at will by shifting from regimes with violations to regimes with no violations of the CHSH inequality, in the face of correlated photons.
5. Other unknown explanations.

In any case, all of these possibilities require careful investigation, and for now, it seems to me, that 'entanglement' understood as 'spooky action at a distance', is a very strong statement without the proper experimental backup, as shown in (Davis et al., 2024), for maximally 'entangled' states, that include some types of Phase-Shifted EPR-Bell States, like $\left|\psi^{+45^0}\right\rangle$, which show no violations of CHSH inequality. Until this is properly explained to fit the notion of 'entanglement' understood as 'spooky action at a distance' for all Phase-Shifted EPR-Bell states, if that ever happens, a more conservative conclusion would be that these states are indeed only correlated, however, in very strange ways. I intend to further explore these results with fellow physicists and collaborators to improve our understanding of this phenomenon.

As a further reflection, I would like to mention Non-Markovian approaches like the one in (Skorobogatov & Svertilov, 1998), and a new more fundamental approach described in (Barandes, 2023) that, if found to be correct, would rule out the notion of 'spooky action at a distance' in physical systems as a valid interpretation of reality. If 'spooky action at a distance' is ruled out from physical systems based on new and more general stochastic laws, then new vistas for conducting physics research are open that remove the mystified views of quantum mechanics, still upheld by many, placing the view of reality again on the side of Einstein, in a way that allows for a new understanding of non-locality in terms of information structures and classical probabilities. This approach also allows us to divorce religious, spiritual and mystical experience (RSME) (Davis, 2009) from 'quantum mystifications', moving such RSME to the realm of physics, cognition, biology and psychology, in order to scientifically study the experience of subjective, willful, volitional mind, as *experienced information and meaning* in memory systems, with physical restrictions in a classically consciously experienced lived life in spacetime.

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