Delayed Choice with Correlated Photons

O. E. Rössler

Institute for Physical and Theoretical Chemistry, University of Tübingen, Tübingen, West Germany

Z. Naturforsch. **43a**, 110–114 (1988); received November 17, 1987*

A new experiment in the foundations of quantum mechanics is proposed. The existence of correlated photons – first seen by Wheeler – can be taken as a hint to devise a "double-wing" delayed choice experiment in Wheeler's sense. A path choice (polarization choice) measurement made on the one side should then block an interference type measurement made on the other side ("distant choice"). A precondition for the combined measurement to work in theory is that the correlated photons used are of the "prepolarized" (Selleri) rather than the "unpolarized" (Bohm) type. A first EPR experiment involving prepolarized photons was recently performed by Alley and Shih. It may be used as a partial experiment within the proposed experiment.

1. Introduction

Delayed-choice effects [1–3] and Einstein-Podolsky-Rosen [4] correlations are among the most spectacular "holistic" phenomena generated by quantum mechanics [5]. Can they, perhaps, be combined?

In the following, a specific proposal will be presented and discussed.

2. The Experiment

Consider the experiment of Figure 1. The source is marked by a point. There are two polarization splitters, 4 counters, a recombining beamsplitter and a $\lambda/2$ waveplate involved. The experiment is best understood by first looking at the two prototypes contained.

The first subexperiment is obtained by removing the portion enclosed by the two dashed lines on the right of Figure 1. The two right-hand counters are then to be fed directly by the polarization splitter on the right in symmetry to what happens on the left. What remains is a typical EPR experiment with photons (cf. [6]). Such an experiment was, with photons emitted by an atomic Calcium cascade, first convincingly performed by Kocher and Commins [7] and later developed to perfection by Aspect et al. [8]. The predictive accuracy achieved for parallel orientations of the two polarization cubes was 94 per cent [8]. A remaining difference to Aspect's version of the experiment will be discussed in detail in Section 3.

* First reception at March 4, 1987.

Reprint requests to O. E. Rössler, Institute for Physical and Theoretical Chemistry, University of Tübingen, Auf der Morgenstelle 8, 7400 Tübingen, West Germany.

The second subexperiment hidden in Fig. 1 is obtained by removing the part to the left of the source (so that a source emitting correlated photons is no longer needed). What remains is an interferometer of the Mach-Zehnder type. It is unusual only insofar as the first beamsplitter (unlike the recombining one) is not a half-silvered mirror but a polarization splitter. In consequence it is necessary (in order to re-establish interference since perpendicularly polarized light does not interfere) to include a $\lambda/2$ waveplate in one path to reobtain equally polarized light in both paths.

However, this single measure is not enough. It is also necessary now to use previously polarized light (for example, + 45 degrees relative to the polarization splitter) for an input, as is symbolically indicated in the Figure. The reason is that light of the opposite (– 45 degrees) polarization generates the opposite interference pattern. Hence unpolarized light, which contains both components in effect, suffers no net interference [9, 10].

Despite these differences, however, the present "modified" Mach-Zehnder interferometer is as appropriate for use as a delayed-choise device as an ordinary Mach-Zehnder is. In other words, under single-

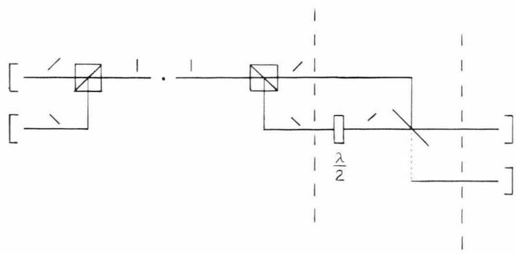

Fig. 1. Delayed choice with correlated photons (compare text).

0932-0784 / 88 / 0200-0110 $ 01.30/0. – Please order a reprint rather than making your own copy.

photon conditions [10], the second (recombining) beamsplitter may be "reinserted" (or not) "at the last moment" [3]. The output (interference or not) then still instantaneously follows the change made in the preparation of the experiment [3, 3a]. See [11, 12] for two recent experimental demonstrations.

Finally, there is the full (combined) experiment of Fig. 1. The combination is expected to display a new phenomenon, "delayed choice at a distance". More specifically, there should be two modes of functioning once more, dependent on preparation. The first applies when the measuring device on the left either is not made use of or is rotated by 45 degrees so that no correlations to the path chosen on the right are picked up. Under this condition, the photon on the right is expected to (self-) interfere as usual.

The second, more interesting mode of functioning refers to the case in which the path (polarization) chosen by the left-hand partner is known. If in this case a similar measurement is made on the right, the same result will be found. This knowledge can be put to use, for example, when a delay cable is inserted on the right. Then one (the empty) path can be blocked on the right without a single photon being missed. In this case, there will of course no longer be any interference. Similarly, if the predictive accuracy is not infinite but finite only, still the degree of interference cannot remain the same as before on the right (since otherwise "too much" would be known about the photon on the right [1, 13]). Quantitatively, Wootters and Zurek's [13] formula predicts that, for example, for an accuracy of path prediction of 94 per cent, a reduction in the degree of modulation (difference between the two channels divided by their mean) by 53 per cent should occur.

3. A Drawback and Its Partial Solution

As already briefly mentioned, Aspect's [8] experiment cannot be inserted directly as a building block into the experiment of Figure 1. The reason is simple. This experiment, like almost all EPR experiments with photons performed so far, employs correlated photons that are "unpolarized". More specifically, these photons are in the analogue of a singlet state in accordance with Bohm's [14] original proposal for a first feasible EPR experiment. That is, these photons are not in a state of definite polarization, but rather only in a superposition of such states. This fact is important for the understanding of their correlated behavior [15]. In the present experiment, however, we saw that "pre-polarized" (or at least predominantly polarized) light is required to enter the polarization splitter on the right if an interference pattern is to develop there as essential. Therefore, only correlated photons that are polarized from the beginning (or at least have a marked preference as to polarization) can be used in principle. (See, however, [29].)

This obviously is a major drawback. The only theoretical frame within which EPR correlations are canonically expected is the Bohm paradigm [14]. Unexpectedly, there exists a recent experiment, not formally based on the Bohm paradigm, in which EPR correlations were found in coexistence with a non-flat distribution as a function of angle. This is exactly the combination which is needed in the present context.

Specifically, the photon pairs studied by Alley and Shih [16] exhibited a maximal coincidence rate at a matching relative orientation (which was 90 degrees), irrespective of absolute orientation, only when the number of coincident counts (N_c) was first divided by the absolute number of counts in one channel (N_1). That is, there was an EPR correlation present. However, it was valid under a condition of marked dependence of N_1 on the angle of measurement chosen.

The quantitative dependence of N_1 on angle (θ_1) was unfortunately not given in the paper. Nevertheless there is indirect evidence that the dependence is indeed "marked". For example, at one particular angle ($\theta_1 = 30$ degrees), no significant value of N_c/N_1 was obtainable. This seems to be where the minimum lies. Similarly, the inference that there was a single maximum is in accordance with the data.

The Alley-Shih experiment appears to possess just the right properties needed for the EPR subexperiment in Figure 1. On the one hand, the non-flatness of N_1 (θ_1) guarantees that a certain degree of interference develops on the right. On the other, the correlation is still maximal, relatively speaking (namely, at $N_c/N_1 =$ 3.2 per cent), even at angles deviating $+45$ or -45 degrees from the angle of maximum absolute yield [16]. Therefore, path prediction is still optimal at these two deviating angles. Taken in combination, these two features suffice to guarantee that the experiment of Fig. 1 may work "in principle".

There are two remaining problems. 1) Since the particular shape of N_1 present is not known, there is the possibility in principle that the predictive accuracy is distributed among the two subpopulations, the larger and the smaller one, in just the right fashion that the net effect on the overall interference is zero. This possibility (that the rarer photons have a much higher predictive accuracy) is, however, apparently not supported by the data. 2) The predictive accuracy of path choice, among the coincident events, achievable so far appears to lie markedly below the 94 per cent of the Aspect experiment.

4. Discussion of the Alley-Shih Experiment

The Alley-Shih [16] experiment, described phenomenologically above, belongs to a „new type" of EPR experiments. For the first time, photon generated by parametric down conversion [17] were used in an EPR experiment. Here, a laser beam gives rise to two simultaneously generated new photons of the sum energy and sum momentum of the originating photons, in a nonlinear crystal. The two photons, which may be equal in frequency (so in the experiment of Alley and Shih), come with a fixed (equal) direction of polarization [16].

However, the results referred to above were *not* obtained on these two photons, directly. Rather, the authors first recombined the two photons in a beamsplitter, after one had been rotated in its direction of polarization by 90 degrees with the aid of a $\lambda/2$ waveplate. (In an alternative experiment, first two circularly polarized photons – apparently of opposing orientations – were generated using a $\lambda/4$ waveplate in each branch, with qualitatively similar results [16].)

Recently, a similar proposal was made theoretically ([18], Figure 6). Two-mode interference was shown to generate a rotation-symmetric state of correlated photons, with the consequence of a violation of Bell's inequality being possible just as described by Alley and Shih [16].

However, what distinguishes the latter experiment is precisely its non-ideal nature. The rotation-symmetry was obviously perturbed. The most straightforward possibility is that a remnant non rotation-symmetric component is superimposed on a rotation-symmetric one. However, in this case the trick used by Alley and Shih (dividing N_c by N_1) would be counterproductive. Therefore the question arises of whether or not a new quantum effect may be involved in the experiment.

At first sight there is support from a theoretical proposal to employ photons, generated in a parametric amplifier, directly in an EPR experiment [19, 20]. However, this simple proposal disregarded the fact that the Hamiltonian of such systems is non rotation-symmetric in general. This prompted the more recent two-mode proposal [18] already mentioned. Furthermore there also is experimental evidence against the proposal. In an experiment performed under non-sparse flux conditions, rotation of the polarization of the analyzed signals by 45 degrees substantially reduced the number correlation (squeezing of the difference in intensity fluctuations) [21]. The reduction appeared complete compared to an experiment of a different type used for a control. The question of whether or not a rest effect (masked by noise) may have survived was not addressed. It is, however, precisely the existence of such a rest effect which is raised as a possibility by the Alley-Shih experiment.

Hong et al. [22] recently independently reproduced part of the Alley-Shih experiment. (The $\lambda/2$ waveplate and the analyzers were absent.) The two photons were found to behave identically in the beamsplitter (fourth-order interference), only when their travelling times were equal to less than 0.1 picosecond. This suggests that Alley and Shih's photons were not perfectly correlated number-wise.

There indeed exists a well-known uncertainty principle between number correlation and phase correlation [23]. This principle would be the ultimate reason why rotation symmetry has to be strived for to obtain EPR correlations (as done in references [16, 18]). No room seems to be left for "residual effects" like those needed in the present context. For the same reason there is little likelihood that, by formally extending Bell's [15] analysis to the more complicated case of two photons whose distribution is not independent of the direction of the analyzer (think of a Wigner cycle [24] – consisting of two equal polarization cubes facing back-to-back – added in front on either side, with one arm of the cycle leaking part of the polarized photons contained so that what comes out no longer has a circular distribution), it will be possible to uncover the desired effect.

Therefore, it is apparently necessary to look elsewhere for theoretical support. Selleri [25] showed that, following a measurement (or preparation) made in a Bohm [14] type experiment, the two particles, while no longer being in a singlet state (and hence no longer capable of perfect correlation when subjected to a new equal direction of measurement), nevertheless also are not in a general *un*correlated (neither singlet nor triplet) 2-particle state, but rather are in a "superposition" of a singlet and a triplet state [25]. Such a state has yet to be characterized in its quantitative implications. Its existence would certainly be compatible with Alley and Shih's unexpected success in finding a violation of Bell's inequality under highly non-ideal conditions.

5. Discussion

A new quantum experiment ("distant choice") was proposed. In it, the nonlocal features of an EPR experiment are combined with the high sensitivity (towards changes made in its preparation) of a delayed-choice experiment. Is basic theory compatible with this proposal?

At first sight there is a theorem which is not. Eberhard [26] and Ghirardi and Weber [27] showed that EPR correlations are necessarily confined to individual events and can never affect the distribution of events in which these individual events are embedded. Taken at face value, this theorem seems to say that while Bell's locality [15] can be violated, a more general postulate (call it closedness) cannot. Any unilaterally detectable EPR effect, violating closedness, appears to be ruled out. A positive outcome of the above experiment would be at variance with this generalized version of Eberhard's theorem.

However, the literal version of the theorem would be obeyed. The population of events is indeed always the same, on the right-hand side, whenever counters are placed directly behind the polarization splitter on the right. The point, however, is that the correlated events are not even registered on the right. Something completely different is measured there, an interference between two equiprobable events (choice of the upper and the lower half path). These events remain equiprobable when a measurement is made on the left. Their "distribution" is the same. However, they become known individually in principle. It is this individual knowledge, not available locally, which nevertheless – as future knowledge – already destroys the presently possible interference result.

A distant measurement may be used to prepare the state of a different experiment. This new use to which a delayed-choice experiment may be put appears to be new also from the point of view of theory.

The preceding discussion was predicated on the assumption that the experiment may work in principle. Let us make the opposite assumption. If the experiment does not work, which ingredient is the most likely one to fail?

The most uncertain element in the chain no doubt is the Selleri correlation. It is new and untested. (The Alley-Shih [16] experiment only provides circumstantial evidence so far, see Section 4.) Is there independent evidence in its support?

Selleri's [25] implicit suggestion that a sum-spin 1/2 state may exist for two spin-1/2 particles indeed follows also from a novel and still unfinished approach to quantum mechanics proposed recently [28]. A classical universe may be set up in a computer (in a molecular-dynamics simulation) such that a macroscopic observer arises internally as an "explicit" far-from-equilibrium structure in the given chaotic Hamiltonian function. The observer may be equipped with an equally explicit, far-from-equilibrium measuring device, as well as an object particle. A measurement situation thereby becomes analyzable for the first time in an explicit (if classical) model. Unexpectedly, an action-type perturbation appears to limit the accuracy of measurement achievable by the internal observer [28]. Moreover, objectively correlated objects become subject to correlated perturbations. Hereby an analogue to the EPR effect applies. (No violation of Bell's impossibility theorem [15] is implied since the quantum effects exist only for the observer.) Furthermore – and this is why the approach is mentioned here –, the first measurement made on one of the two particles perturbs neither this particle alone nor both, but rather the originating single particle right before it disintegrated (since the two are but a means to measure the latter's state). Thus, Selleri's surprising state of partial correlation is something to be expected, in the model world.

To conclude, the spectrum of nonlocal implications of quantum mechanics may go beyond the two traditional paradigms of EPR correlations on the one hand and delayed-choice effects on the other. Even simply combining the two already leads to new questions.

Acknowledgements

I thank John Archibald Wheeler for early encouragement. Conversations with Martin Hoffmann, Claus Kahlert, Jürgen Parisi, Joachim Peinke and Brigitte Röhricht were also helpful. Peter Mittelstaedt kindly drew my attention to the proceedings of the 1986 Tokyo conference. Robert Graham kindly pointed out reference [21].

[1] A. Einstein, in: Institut International de Physique Solvay, Rapport et Discussions du 5ᵉ Conseil, p. 253, Paris 1928.
[2] C. F. von Weizsäcker, Z. Physik **70,** 114 (1931).
[3] J. A. Wheeler, "The 'past' and the 'delayed-choice' double-slit experiment", in: Mathematical Foundations of Quantum Theory, A. R. Marlow, Ed., Academic Press, New York 1978, p. 9.
[3a] P. Mittelstaedt, "Quantum logical analysis of delayed-choice experiments", Proc. 2nd Int. Symp. Foundations of Quantum Mechanics, Tokyo 1986, pp. 53–58.
[4] A. Einstein, B. Podolsky, and N. Rosen, Phys. Rev. **47,** 777 (1935).
[5] H. Primas, Chemistry, Quantum Mechanics and Reductionism, Springer-Verlag, Zürich 1981.
[6] J. A. Wheeler, Ann. N.Y. Acad. Sci. **48,** 219 (1946).
[7] C. A. Kocher and E. D. Commins, Phys. Rev. Lett. **18,** 575 (1967).
[8] A. Aspect, D. Grangier and G. Roger, Phys. Rev. Lett. **49,** 91 (1982).
[9] A. Fresnel and F. Arago (1817). Quoted in: F. Matossi, Optics (in German). Vol. 3 of Bergmann-Schafer, Lehrbuch der Experimentalphysik, de Gruyter, Berlin 1966, p. 381.
[10] H. Paul, Photons (in German), Vieweg, Braunschweig 1985.
[11] O. G. Jacubowicz, "A delayed random choice quantum mechanics experiment using light quanta", University of Maryland Ph.D. dissertation 1984; C. O. Alley, O. G. Jakubowicz and W. C. Wickes, "Results of the delayed-random-choice quantum mechanics experiment with light quanta", Proc. 2nd Int. Symp. Foundations of Quantum Mechanics in the Light of New Technology, Hitachi, Tokyo 1986, M. Namiki, Y. Ohnuki, Y. Murayama, and S. Nomura, Eds., Physical Society of Japan, Tokyo 1987, pp. 36–47.
[12] T. Hellmuth, "Interference experiments on the quantum mechanical measurement process: A delayed-choice version of the Young double-slit experiment" (in German), University of Munich Ph.D. dissertation 1985; T. Hellmuth, A. G. Zajonc, and H. Walter, "Realization of a 'delayed-choice', Mach-Zehnder interferometer", in: Symposium on the Foundations of Modern Physics, 50 Years of the Einstein-Podolsky-Rosen Gedankenexperiment, Finland 1985, P. Lahti and P. Mittelstaedt, Eds., World Scientific, Singapore 1985, pp. 417–422.
[13] W. K. Wootters and W. H. Zurek, Phys. Rev. **19 D,** 473 (1979).
[14] D. Bohm, Phys. Rev. **85,** 169 (1952).
[15] J. S. Bell, Physics **1,** 195 (1964).
[16] C. O. Alley and Y. H. Shih, "Proposal of a new type of EPR experiment using light quanta produced by a non-linear optical process", Proc. 2nd Int. Symp. Foundations of Quantum Mechanics, Tokyo 1986, M. Namiki et al., Eds., Physical Society of Japan, Tokyo 1987, pp. 47–52.
[17] J. M. Manley and H. E. Rowe, Proc. IRE **44,** 904 (1956).
[18] M. D. Reid and D. F. Walls, Phys. Rev. **34 A,** 1260 (1986).
[19] R. Graham, Phys. Rev. Lett. **52,** 117 (1984).
[20] M. D. Reid and D. F. Walls, Phys. Rev. Lett. **53,** 955 (1984).
[21] A. Heidmann, R. J. Horowitz, S. Reynaud, W. Giacobino and C. Fabre, Phys. Rev. Lett. **59,** 2555 (1987).
[22] C. K. Hong, Z. Y. Ou, and L. Mandel, Phys. Rev. Lett. **59,** 2044 (1987).
[23] M. Kitagawa and Y. Yamamoto, Phys. Rev. **34 A,** 3974 (1986).
[24] E. Wigner, Amer. J. Phys. **31,** 6 (1963).
[25] F. Selleri, The Debate about the Quantum Theory (in German), Vieweg, Braunschweig 1983, p. 92.
[26] P. Eberhard, Il Nuovo Cim. **46 B,** 392 (1978).
[27] G. C. Ghirardi and T. Weber, Il Nuovo Cim. **78 B,** 9 (1983).
[28] O. E. Rössler, "Endophysics", in: Real Brains, Artificial Minds, J. L. Casti and A. Karlqvist, Eds., Elsevier, North-Holland, New York 1987, pp. 25–45.
[29] *Added in proof*: There actually is a loop-hole. According to a result in reference [18] (see the discussion following Equation (56) there), Figure 1 above can be safely replaced by a simpler analogue in which the 2 parallel polarization splitters are replaced by 2 parallel ordinary 50%–50% beamsplitters (without the waveplate). There is a choice of appropriate 2- and 4-mode sources. Insertion of $\theta = \phi = 0$, into Equation (61) or (71) of reference [18], then formally guarantees the desired result.