7 Other research

7.1 Status of nonlocal quantum communication test

J. G. Cramer

The question we have been investigating is whether the intrinsic nonlocality of standard quantum mechanics is the private domain of Nature, as is generally assumed by the physics community, or whether in special circumstances the nonlocal connection between subsystems can be used to send signals from one observer to another. The basic nonlocal communication (NLC) scheme, as described in the references, is to use the connection implicit in momentum-entangled photon pairs to create a signal as the presence or absence of an interference pattern at the receiving end, depending on whether or not which-way information was extracted at the sending end of the experiment. This work has been reported in CENPA Reports in the past seven years[1,2,3,4,5,6,7].

In the quantum formalism there is an implicit complementarity relation between entanglement and coherence[8] that poses a problem for such communication, since the potential nonlocal signal depends on the presence of both two-photon entanglement and coherence of the waves to produce interference. We have argued[9] that creating a condition between the photon pair in which entanglement and interference were both present only at the 70% level (e.g., $\frac{1}{\sqrt{2}}$), as permitted by the complementarity relation, should permit survival of a nonlocal signal.

Two-particle interferometry is an interesting and intricate quantum problem. Its mathematical treatment is described in some detail in a little-known 1990 paper by Horne, Shimony, and Zeilinger[10], and we have applied this formalism to the current problem. In the past year we have made significant progress in understanding the issues associated with two-particle interference and in resolving the quantum paradox implicit in our proposed NLC experiment. Much of this progress was stimulated by a one-week visit in October 2013 to Prof. Anton Zeilinger's Institute for Quantum Optics and Quantum Information (IQOQI)in Vienna, Austria.

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[1] CENPA Annual Report, University of Washington (2007) p. 52.
[2] CENPA Annual Report, University of Washington (2008) p. 42.
[3] CENPA Annual Report, University of Washington (2009) p. 41.
[4] CENPA Annual Report, University of Washington (2010) p. 93.
[5] CENPA Annual Report, University of Washington (2011) p. 94.
[6] CENPA Annual Report, University of Washington (2012) p. 89.
[7] CENPA Annual Report, University of Washington (2013) p. 89.
[8] A. F. Abouraddy, M. B. Nasr, B. E. A. Saleh, A. V. Sergienko, and M. C. Teich, Phys. Rev. A **63**, 063803 (2001).
[9] J. G. Cramer, Chapter 18 in *Frontiers of Propulsion Science (Progress in Astronautics and Aeronautics)*, Eds. M. Millis and E. Davis, AIAA (2009).
[10] M. A. Horne, A. Shimony, and A. Zeilinger, *Sixty-Two Years of Uncertainty*, 113-119, Plenum Press, NY (1990).

Zeilinger's group had developed a Sagnac-mode entangled two-photon source[1] that is capable of producing over 10^6 polarization-entangled pairs per second, and in which the entanglement and coherence can be easily set to a desired ratio by the rotation of a half-wave plate. In 2008 they had used this source to perform an experimental test[2] of the complementarity between one- and two-photon interference[3]. This configuration is the equivalent of the momentum-entanglement NLC test that we have been investigating in this work, but it offers the advantage that since there are no D-mirrors, the incident beam can be a single mode throughout its path and the mathematical analysis is more straightforward. The IQOQI one- and two-photon interference test is shown in Fig. 7.1-1.

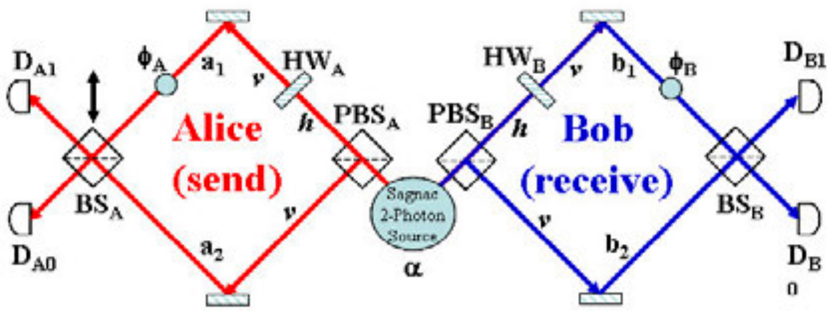

Figure 7.1-1. IQOQI Experiment; polarization-entangled photon pairs are converted to path-entangled pairs by the polarizing beam-splitters and half-wave plates, so that photons on all paths are in the same state v of linear polarization and can interfere. The α parameter of the source determines the degree of two-photon polarization entanglement provided by the source.

Suppose Alice, who controls the left (send) interferometer, wishes to send a nonlocal signal to Bob, who controls the right (receive) interferometer. The source is preset for a particular value of α, which may be $\alpha = 0$ for a Bell state that entangles the uppe/lower and lower/upper paths of the two interferometers, or $\alpha = \pi/4$ for a non-entangled coherent product state, or $\alpha = \pi/8$, which combines entanglement and coherence at 70% each. Alice can control the relative phase on the two paths of her interferometer by varying phase control ϕ_A, and Bob can do the same with ϕ_B. Alice can either attempt to send a signal to Bob by varying ϕ_A or by removing combiner BS_A so that her detectors do a which-way measurement on the two paths. The indication that a nonlocal signal could be achieved would be that the behavior of Bob's interferometer, operated without coincidences with Alice's detectors, depends explicitly on ϕ_A or on the removal of BS_A. It was our hope that with $\alpha = \pi/8$, this might be the case.

To analyze this system, we have applied the methods of Horne, Shimony, and Zeilinger[10] to construct a Mathematica 9 notebook, which may be viewed online at the website: `http://faculty.washington.edu/jcramer/NLS/NLCT.html`. The analysis reproduces the results of the IQOQI experiment[2] and shows that the singles probabilities of detecting a photon in Bob's detectors are: $P(D_{B1}) = \frac{1}{2}[1 + \sin(2\alpha)\sin(\phi_B)]$ and $P(D_{B0}) = \frac{1}{2}[1 -$

[1] A. Fedrizzi, T. Herbst, T. Jennewein, A. Poppe, and A. Zeilinger, Optics Express **15**, 15377 (2007).

[2] A. Fedrizzi, R. Lapkiewicz, X-S. Ma, T. Paterek, T. Jennewein, and A. Zeilinger (2008, unpublished).

[3] G. Jaeger, M. A. Horne, and A. Shimony, Phys. Rev. A **48**, 1023-1027 (1993).

$\sin(2\alpha)\sin(\phi_B)]$. This is the case whether BS_A is in or out of the system, or even if the left-going beam is blocked with a beam stop.. In other words, there is no nonlocal signal in the configuration of Fig. 7.1-1, independent of the value chosen for α and of the beam splitter position. The problem is that while the probability of photon detection in Bob's detectors in coincidence with either of Alice's detectors shows a definite signal, when the two coincidence-dependent probabilities are added to obtain the coincidence-independent singles probabilities, the signal terms cancel and vanish. This is a manifestation of the intrinsic complementarity between one- and two-particle interference[3]. This result suggests that it is Alice's two separate detectors that cause a washout of the signal, and that perhaps directing the two paths to the *same* detector might improve the situation. Therefore, we have analyzed a modification of the IQOQI Experiment that uses a 45° wedge mirror to deflect the a_1 and a_2 paths to the same detector. This is shown in Fig. 7.1-2.

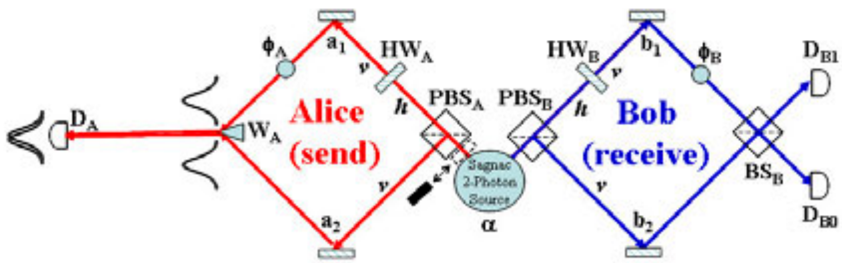

Figure 7.1-2. Modified IQOQI Experiment; paths a_1 and a_2 are directed to the same detector.

This configuration requires a more detailed analysis than the previous one because the wedge reflection places the two beams on slightly different trajectories and one Gaussian tail of each beam is truncated (and lost) at the wedge vertex, so that they are no longer a superposition of identical quantum modes. Therefore, the transport from wedge to detector must be done by integrating Huygens wavelets for the two beams over the effective aperture of the wedge. Fig. 7.1-3 shows the calculated interference pattern on the face of detector D_A for $\alpha = \pi/2$ and $\phi_A = \phi_B = 0$ as measured in coincidence with Bob's detectors D_{B1} and D_{B0}. The probability of singles photon detection for Bob's detectors D_{B1} and D_{B0} is obtained by integrating over these line shapes.

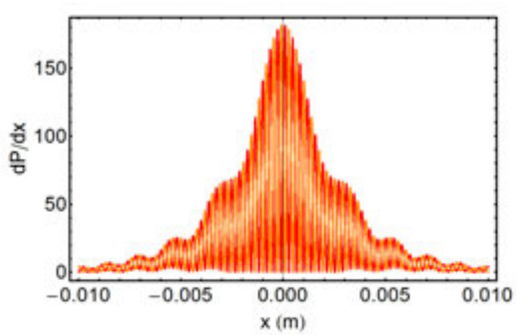

Figure 7.1-3. Profile of intensity patterns on the face of Alice's detector D_A for $\alpha = \pi/2$, $\phi_A = \phi_B = 0$ as measured in coincidence with Bob's detectors D_{B1} (red) and D_{B0} (orange).

We can evaluate the possibility of nonlocal communication in this configuration by plotting the difference in the non-coincident photon detection probabilities in Bob's detectors D_{B1} and D_{B0} as functions of α, ϕ_A, and ϕ_B for the two configurations. This is shown in Fig. 7.1-4. As can be seen from Fig. 7.1-4, there are essentially no differences in Bob's detection probabilities for the configuration of Fig. 7.1-1 and Fig. 7.1-2. The spikes are an artifact of the Mathematica 9 calculation and indicate points at which the numerical integration over the highly oscillatory beam profile on detector D_A had numerical problems. Our conclusion is that no nonlocal signal can be transmitted from Alice to Bob by varying Alice's configuration in any of the ways discussed here. We will continue to test the signaling issue the parameter space of the calculations, but the present conclusion is that Nature is well protected from the possibility of nonlocal signaling.

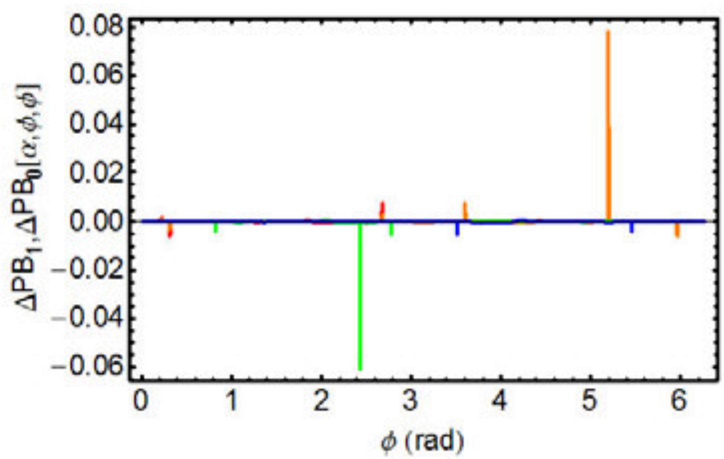

Figure 7.1-4. Configuration difference in non-coincident detection probabilities with $\alpha = \pi/4$ for D_{B1} (red) and D_{B0} (orange) and with $\alpha = \pi/8$ for D_{B1} (green) and D_{B0} (blue).

We would like to thank Anton Zeilinger, Radek Lapkiewicz, and Nick Herbert for very valuable recent contributions to this project.

7.2 Analysis of a wedge quantum interferometer

J. G. Cramer

The previous article (Sec. 7.1) describes the use of a 45° "wedge" mirror to combine interferometer beams at the face of a single detector. Dr. Nick Herbert pointed out to me that such a device had previously been examined as a quantum optics element in a paper by A. Y. Shiekh[1]. In that paper, the author argued that nonlocal communication could be achieved by splitting a laser beam with a 50:50 splitter, then sending one of the beams into a modified Mach-Zehnder interferometer in which the beams were recombined with a wedge mirror after one of the beams had been phase-shifted by 180°. He argued that the combined

[1]A. Y. Shiekh, Electr. Jour. of Theor. Phys. **19** 43 (2008); ArXiv 0710.1367v2 (2008).

beams must cancel to zero amplitude, as they do in the "dark" path of a conventional Mach-Zehnder interferometer. Thus, all photons at the initial splitter must avoid the suppressed path and must take the splitter's other beam path. Thus, it is asserted that by changing the interferometer phase between 0 and π, one should be able to modulate the intensity of the other beam and send a nonlocal signal.

This argument is based on a violation of unitarity in combining the beams and is clearly wrong, but it raises the interesting question of what actually *does* happen in such a situation, which is a simpler version of the modified IQOQI experiment described in the previous article. Fig. 7.2-1 shows a "wedge" interferometer based on this idea. Here the pentaprism reflectors are needed because simple 90° mirror reflections would place the "cut" edges of the half-Gaussian profiles on the outside of the recombined beams instead of rejoining them along the center line.

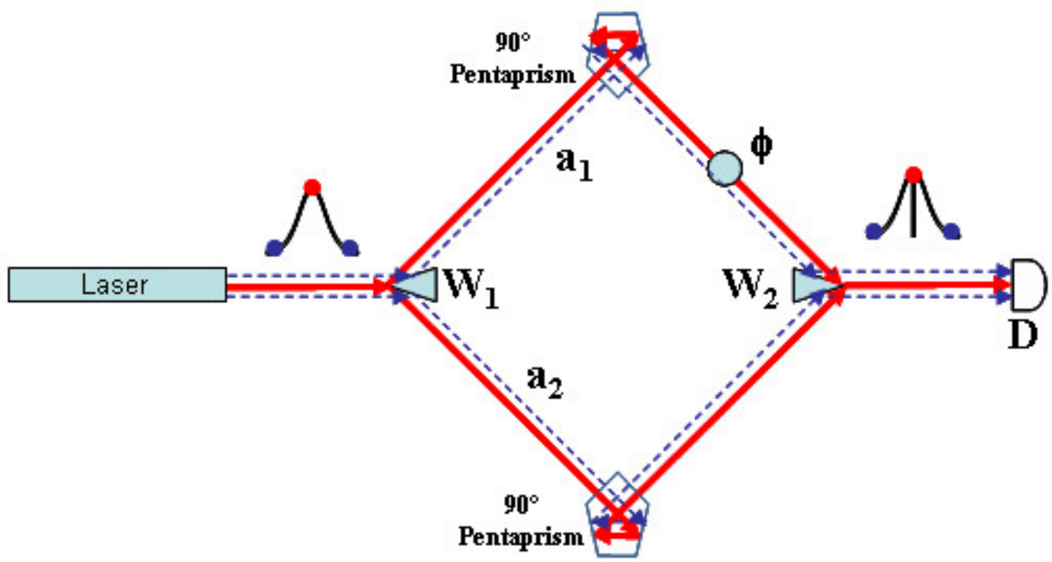

Figure 7.2-1. A Gaussian single-mode laser beam is split into two halves with a 45° wedge mirror, reflected 90° by pentaprisms, recombined with a second wedge mirror, and sent to a detector. The upper beam is shifted in phase by ϕ. Dashed lines and colored dots indicate paths and locations of the tails of the Gaussian lineshapes.

The question of interest is the shape of the interference pattern observed at the detector when the phase ϕ is varied between zero and π. The naive assertion that with $\phi = \pi$ the beams will cancel and vanish is not correct. Splitting a single-mode Gaussian beam into two half-Gaussians produces two multi-mode beams, and their interference pattern is rather complicated. However, it can be calculated by integrating the Huygens wavelets that comprise the two beams over the effective aperture of the second wedge as they are transported to the detector. This has been done in a Mathematica-9 notebook, which may be viewed online at the website: `http://faculty.washington.edu/jcramer/NLS/Wedge/D-Patterns_2.html` .

Fig. 7.2-2 shows the calculated interference patterns for phases of $\phi = 0$, $\phi = \pi$, and $\phi = \pi/2$. As can be seen, when the phase is $\phi = 0$, a Gaussian beam profile with some

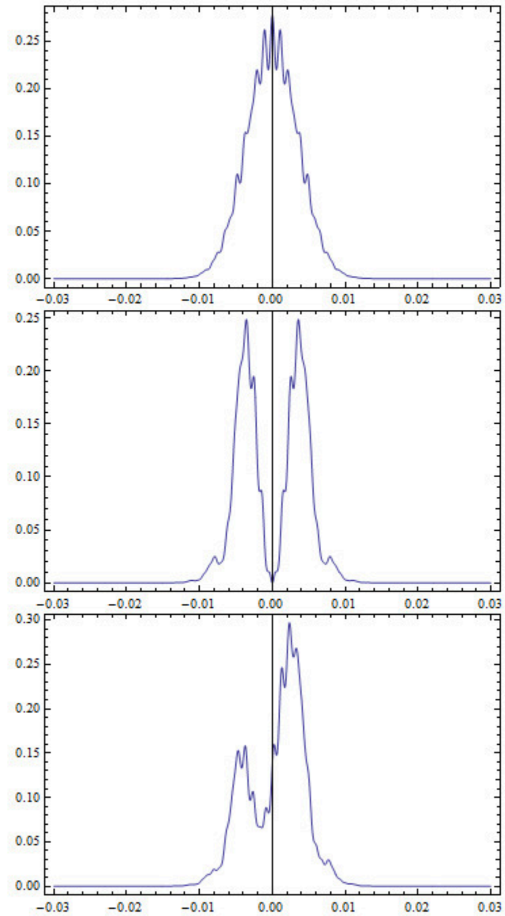

Figure 7.2-2. Calculated line-shape profiles at the detector with phases of $\phi = 0$ (red) , π (green), and $\pi/2$ (blue). All profiles have the same area.

structure from truncation is transported to the detector. When the phase is $\phi = \pi$, the beams indeed cancel along the center line, but constructively reinforce as narrower side peaks to the right and left of the center line. The intermediate case of $\phi = \pi/2$ give some intensity along the center line and produces asymmetric side peaks to the right and left of the center line. The integrals of these line shapes are essentially equal, indicating that no net beam intensity is lost in varying the phase and that, excepts for truncated Gaussian tails, the detector receives all the photons transmitted by the laser. Thus, the Shiekh scheme for nonlocal communication is fatally flawed.