Analysis of a work of quantum art

Seth Lloyd
Department of Mechanical Engineering
Massachusetts Institute of Technology
MIT 3-160, Cambridge MA 02139 USA. slloyd@mit.edu

Abstract: This paper provides a quantum-mechanical analysis of an artwork, 'Wigner's friends,' by Diemut Strebe. The work consists of two telescopes, one on earth, one launched into space, and explores ideas of quantum correlations and quantum measurement. This paper examines the scientific basis of the work and analyzes the form of quantum correlation between the two telescope systems.

On November 23rd 2014, the Italian astronaut Samantha Cristoforetti launched a small telescope from the International Space Station. The twin of this telescope remained on earth, and will be attached to the James Webb telescope when it is launched in 2018. The two telescopes are part of an artwork by Diemut Strebe, entitled 'Wigner's friends.' The title of the work refers to Eugene Wigner's exploration of the quantum measurement problem in [1]. In the ordinary quantum time evolution governed by the Schrödinger equation, a measurement made on a quantum system that is initially in a superposition of two different states causes first the measurement apparatus to become correlated with the quantum system, and then the brain of the scientist who observes the measurement apparatus, and so on. The wave function of the system, measurement apparatus, and observer contains all possible outcomes of the measurement. Wigner noted that to obtain a quantum description in which only one outcome of the measurement is represented in the quantum wave function requires some additional effect, sometimes called 'wave function collapse,' in which the part of the wave function that is not actually measured or perceived to be the case goes away, leaving only the observed part. Wigner asked whether his friend – before she has told Wigner the result of her measurement – is actually in a quantum superposition. By contrast, if no additional dynamics beyond the Schrödinger equation is invoked, then the wave function of the system, measurement apparatus, and observer contains all possible outcomes of the measurement, a counter-intuitive situation that is sometimes called the 'many worlds' account of quantum measurement [2]. Strebe's work is a play on the idea of Wigner's friend and the many worlds theory. Although the work is a piece of art, not of science, she bases the work on several claims which do have scientific content. The purpose of this note is to discuss the scientific content of her claims.

Each telescope consists of an aluminum tube 40mm long, with a 9mm inner diameter and a 10mm outer diameter. The outer surface is anodized violet. Each telescope is connected to a commercial cellphone camera with plastic lenses and a 5 megapixel CCD array. Until it is launched on the James Webb telescope, the earthbound telescope will be powered and aimed at the sky. The telescope that was launched from the international space station is unpowered.

The first part of Strebe's work is called 'the universal show.' Following on the Jorge Luis Borges story, 'The Library of Babel,' Strebe notes that according to Wigner, in the absence of an observer to 'collapse' its wave function, the telescope in space contains simultaneously all possible artworks in quantum superposition in the pixels of its CCD array. The great majority of the images in the superposition will be random, but a small fraction of them will have patterns. (Borges's story imagines a library in which all possible books have been collected, the vast majority of them completely random.) Let's examine this claim in the light of various theories of quantum mechanics. The quantum state of the telescope's CCD array depends on the object in its field of view. For the moment, assume that the telescope is in the shadow of the earth, and pointing at interstellar space, so that the temperature of the telescope is the ambient $3K$ temperature of the cosmic microwave background radiation and the primary electromagnetic radiation entering the telescope is the same cosmic microwave background radiation. Note that because of dimensions of the telescope, this radiation enters the telescope through an attenuated, evanescent mode. (When the telescope is pointing at the sun, the conclusions will be similar, except that the light entering the telescope will now be in the visible range and its modes can be spatially resolved by the lens of the telescope and the CCD array.) This radiation causes the elements of the CCD array to undergo energy fluctuations corresponding to thermal radiation at 3 degrees Kelvin. Assigning numerical values to these fluctuations, and interpreting the numerical values as an intensity scale implies that the elements of the array are indeed registering all possible 5 megapixel images in quantum superposition.

It may be objected that the light entering the telescope is in a thermal state rather than a pure state, and so is technically a mixture rather than a quantum superposition. Note, however, that in the currently accepted quantum models of cosmology, the universe began in a pure state, underwent a period of rapid inflation, and then thermalized in the lead up to the big bang. If the time evolution of the quantum fields in the universe remains unitary throughout this evolution, then the universe remains today in a pure state: pieces of the universe such as the CCD array of the telescope can be in a mixed state, but only as the result of entanglement with the rest of the universe. That is, the thermal fluctuations in the CCD array are part of an entangled superposition with the remaining matter and energy in the universe. Accordingly, it seems not unreasonable to refer to the this fluctuating array as containing all possible images in quantum superposition, a quantum version of Borges' library of Babel.

Of course, if one adopts an environmentally induced decoherence picture in which interactions between the elements of the CCD array and their environment effectively 'collapse' the wave function, then one could also reasonably claim the CCD array to have collapsed to one out all of these possible images. (Note that the CCD array of the telescope in space is unpowered, and so is not making an active measurement of the thermal fluctuations in its elements. Another difference between the situation where the telescope is pointing at the sun and at interstellar space is that the $3K$ radiation would be insufficiently strong to trigger a CCD signal even if the array were powered up, whereas the light from the sun is would trigger such a signal.) If one adopts either the many worlds interpretation or the perspective of Wigner, however, then the CCD array remains in a superposition of all possible images – Wigner has no friends in space.

Now consider the second claim of Strebe, that the telescope on the ground and the telescope in space exhibit quantum correlations that effectively connect the two telescopes, and that when the telescope on the ground detects a photon and creates a signal that can be observed by the viewers of the exhibit, the state of the telescope in space – conditioned on the state of the telescope on earth – undergoes a change as in Einstein's notion of 'spooky action at distance.' Clearly, this change, if it exists, must be very slight. Nonetheless, the Hanbury Brown Twiss effect [3-6] shows that a slight correlation between the photons entering the telescopes does indeed exist, and so detection of a photon by the ground based telescope does indeed change by a small amount the probability that a photon enters the space based telescope. This correlation is intrinsically quantum mechanical [4-6] and relies on the same coherent quantum effects that give rise to photon bunching and anti-bunching. Applying concepts of quantum information theory to Fano's elegant treatment of the Hanbury Brown Twiss effect in the low-photon number limit [4], we find that the quantum state of the two telescopes exhibits a non-zero amount of the form of quantum correlation [7] known as discord [8-9] (more technically, the density matrix for the two telescopes possesses off-diagonal terms when expressed in the Schmidt bases for the individual telescopes). Although discord is a weaker form of quantum correlation than entanglement, the existence of discord entering the two telescopes implies that any measurement made on one telescope must have an effect on the overall probabilities of joint measurements made on both. The telescopes do indeed possess a small measure of spooky action at a distance.

For the purpose of analysis, suppose that the two telescopes are momentarily focused on the same distant star. Light with wavelength λ entering the telescopes from the star is spatially coherent as long as the telescopes lie within the transverse coherence length of the source, $\ell_t \approx \lambda R/r$, where R is the distance to the source and r is the radius of the source [6]. For long wavelength light, the transverse coherence length of a distant star can easily extend for thousands of kilometers, so that the telescope in space and the telescope on the ground lie within the coherence length. The Hanbury Brown Twiss coherence length represents classical coherence of the waves entering the telescopes from the distant source. Quantum effects arise when one considers the particle-like nature of light, and the fact that that photons are indistinguishable particles with bosonic statistics [4-6]: for the two telescopes, the photons arriving from the star will be bunched – if a photon arrives at one telescope, a photon is more likely to arrive at the other telescope. Because of the small ratio of the aperatures of the telescopes to the area of the region of transverse coherence, the quantum mechanical bunching effect is also small. But small is not zero. Accordingly, Strebe's claim that the two telescopes exhibit quantum correlation seems not unreasonable.

If the two telescopes are momentarily focused on a single photon source such as a fluorescing atom, then the photons entering into the telescope exhibit anti-bunching [5]. Consider a single photon emitted by the source into a quantum superposition of two spatio-temperal modes entering the two telescopes at the same time (to within an accuracy $\Delta t \approx \lambda/c$). Conditioned on the presence of such a photon, the states of the CCD arrays within the two telescopes are entangled, and detection of a photon by the CCD array on the ground reduces the probability of a photon being absorbed by the CCD array in space to zero. This entanglement arises under the condition that a single such photon enters both telescopes simultaneously [5]. Without such a condition, the telescopes are in highly mixed, almost uncorrelated states and are almost certainly not entangled. Again, however, the very slight quantum correlation between the telescopes implies that their CCD arrays typically exhibit a small amount of quantum discord.

To see the existence of discord in a mathematically explicit way, consider Fano's model of two atoms, both initially in the excited state, that transfer to their excitations to two other atoms, both initially unexcited. Following Fano, we call the emitting atoms a, b and the absorbing atoms c, d. Let D_{ac}, D_{ad} be the amplitudes that a emits a photon that is absorbed by c, d respectively; similarly, D_{bc}, D_{bd} are the amplitudes for photon transfer from b to c, d. Suppose that emitters a, b are initially in the excited state and the detectors c, d are initially in their ground state. The probability that c, d are both excited is $p_{cd} = |D_{ac}D_{bd} + D_{ad}D_{bc}|^2$. Note that this amplitude squared contains quartic cross terms such as $D_{ac}D_{bd}\bar{D}_{ad}\bar{D}_{bc}$ that contribute to the probability. As long as the two absorbers are within the HBT coherence length, these cross terms persist even when the emission is incoherent [4-6]. Comparing this coherent probability with the incoherent 'probability' $\tilde{p}_{cd} = |D_{ac}D_{bd}|^2 + |D_{ad}D_{bc}|^2$ that either a excites c and b excites d, or that a excites d and b excites c, we see that coherence – classical in the case of interference between the electromagnetic waves emitted by a, b, and quantum in the case of single photons – makes a difference in the probability of joint excitation of c and d. This coherence is the origin of the Hanbury Brown Twiss effect: averaged over all emitters in a distant star it leads to photon bunching – an enhancement of the joint absorption probability.

Applied to a single emitter, the same coherence leads to anti-bunching: a single photon emitted by the emitter can be absorbed by only one of the detectors. In the case of anti-bunching, a photon emitted by a single atom leads to a quantum superposition state $|\psi_{cd}\rangle = (1/\sqrt{2})(|1\rangle_c|0\rangle_d + e^{i\phi}|0\rangle_c|1\rangle_d)$, where the phase ϕ depends on the distances from the emitter to the absorbers. As noted above, such a state is entangled. In the actual telescopes, of course, the atoms will be in a highly mixed state that at any moment is probably not entangled. Nonetheless, the very slight admixture of a single entangled state typically leads to the creation of quantum discord [8-9]: for example, if the two atoms cd in the two different telescopes are in uncorrelated thermal state, with zero discord, and a single photon in state $|\psi_{cd}\rangle$ is mixed in with non-zero probability ϵ, then no matter how miniscule ϵ is, the resulting state possesses non-zero discord. When the joint state of the telescopes exhibits even a small amount of discord, then a measurement made on one telescope changes the quantum state of the two telescopes taken together. The exact characterization of the set of states such that admixture of an entangled state leads to quantum discord is an open question.

Summary: Quantum mechanics is well-known to be strange and counterintuitive. It should come as no surprise that weird quantum effects have inspired works of art. This note analyzed the quantum mechanics behind a recent quantum artwork consisting of two telescopes, one of which has been launched into space. The art evokes Wigner's account of the quantum measurement problem, the many worlds theory of quantum mechanics, and Einstein's notion of 'spooky action at a distance' (*spukhafte Fernwirkung*). No claim here is made for the artistic merit of 'Wigner's friends': judgement must remain with the viewers of the artwork. However, the science on which the artwork is based seems to fall within the bounds of artistic license.

Acknowledments: The author thanks H.J. Kimble for useful discussions and references on the Hanbury Brown Twiss effect (while in no way implying HJK's endorsement of any statements made here).

References:

[1] E.P. Wigner, *Symmetries and Reflections*, Indiana University Press, Bloomington, 1967.

[2] H. Everett, *Reviews of Modern Physics* **29** (3), 454-462 (1957).

[3] R. Hanbury Brown, R. Q. Twiss, *Nature* **178** (4541), 10461048 (1956).

[4] U. Fano, *American Journal of Phhysics* **29**, 539 (1961).

[5] H.J. Kimble, M. Dagenais, L. Mandel, *Physical Review Letters* **39** (11), 691 (1977).

[6] L. Mandel and E. Wolf, *Optical coherence and quantum optics,* Cambridge University Press, Cambridge 1995.

[7] M. A. Nielsen and I. L. Chuang, Quantum Computation and Quantum Information (Cambridge University Press, 2000).

[8] H. Ollivier and W.H. Zurek, *Phys. Rev. Lett.* **88**, 017901 (2001).

[9] L. Henderson and V. Vedral, *J. Phys. A: Math. Gen.* **34**, 6899-6905 (2001).