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ANOTHER LOOK AT QUANTUM TELEPORTATION

L. VAIDMAN*, N. EREZ*,† and A. RETZKER*

*School of Physics and Astronomy,
Raymond and Beverly Sackler Faculty of Exact Sciences,
Tel-Aviv University, Tel-Aviv 69978, Israel

†Institute for Quantum Studies and Physics Department,
Texas A&M University, College Station, TX 77843-4242, USA

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A dialog with Asher Peres regarding the meaning of quantum teleportation is briefly reviewed. The Braunstein–Kimble method for teleportation of light is analyzed in the language of quantum wave functions. A pictorial example of continuous variable teleportation is presented using computer simulation.

Keywords: Teleportation; continuous variables; quantum optics; quantum information.

1. Introduction

I, Lev Vaidman, knew Asher Peres since the beginning of my interest in the foundations of quantum mechanics. Mostly, we were fighting to prove that the interpretations of quantum effects adopted by each of us were better. Asher was against the usage by Aharonov and myself of a quantum state evolving backwards in time[1–4] and contesting our interpretation of the physical meaning of "weak measurements".[5–7] He objected to the names I gave to my proposals like "cryptography with orthogonal states"[8–10] or "interaction-free measurements".[a] Our disagreements did not make our interactions less fruitful: we agreed about physical facts and discussion of the interpretation only sharpened our (at least my) understanding of various aspects of these effects.

Even the most basic disagreement, where Asher says, "Quantum mechanics needs no interpretation",[11] and I write that the many-worlds interpretation is by far the best way to view quantum mechanics,[12] is also essentially a disagreement only about names. Asher explains his view describing Kathy, an experimental physicists who, after making a quantum experiment becomes a superposition of a lady who ate a cake and a lady who ate a fruit. Asher says that even at this stage, in principle,

[a]Asher told me that the name should be "energy and momentum exchange-free measurements."

it is still possible to reverse the evolution and come back to the state which was before the quantum measurement. For me, this story is a gedanken test of the many-worlds interpretation. We completely agree on the facts: there is no such thing as the collapse of the quantum wave function. I interpret this story as splitting and reunion (with the help of super-technology) of two worlds, while Asher, to avoid paradoxes, considers this as an argument in favor of the approach according to which quantum mechanics should not be taken as a description of an objective reality.

The main part of this paper is devoted to the renewed analysis, performed together with two members of the quantum group of Tel-Aviv University, of the topic on which I and Asher, in a way, collaborated — the issue of teleportation. I was very pleased to hear from Asher that finally we came to an agreement. In the last e-mail I received from him two weeks before he left us, he recommended to the *Jerusalem Report* to interview me instead of him (due to his health condition) about teleportation. In his paper "What is actually teleported?",[13] Asher jokes about the suggestion of Charlie Bennett to cite the "weak measurements" of Aharonov and myself, but he mentions that in another work[14] there are seeds of the teleportation paper.[15]

Indeed, I had the tools to find the solution for the teleportation problem. When I saw the abstract of this seminal paper, I immediately new how to do it (in my way). But it took the genius of Asher and his collaborators to ask the question. Still, my way of teleportation was useful too. I proposed a method for two-way teleportation which is applicable also for continuous variables.[16] The importance of this work became clear only a few years later, when Braunstein and Kimble found a realistic way to implement the continuous variables teleportation experiment using squeezed light.[17] This experiment was successfully accomplished in 1998[18] and recently improved.[19]

Braunstein and Kimble[17] described their proposal in the language of Wigner functions, the common approach of the quantum optics community. Numerous analysis and further experiments since then mostly continued to use the Wigner function formalism. I believe that the language of quantum states has advantages in discussions of the foundations of quantum mechanics, so it is of interest to present the Braunstein–Kimble experiment in the language of quantum states. Section 3 is devoted to this purpose. In Sec. 4, the results of Sec. 3 are demonstrated on a particular example. But before this, I cannot resist the temptation to continue the interpretation dialogue with Asher.

2. What is Actually Teleported?

In the framework of classical physics, teleportation, defined as, for example, "theoretical transportation of matter through space by converting it into energy and then reconverting it at the terminal point," the quotation from Asher's dictionary (Webster), is obviously a science fiction concept. Massive objects, "matter" cannot

"jump" from one place to another. The definition in the Oxford Dictionary:

> **teleportation**. *Psychics* and *Science Fiction*. The conveyance of persons (especially of oneself) or things by psychic power; also in futuristic description, apparently instantaneous transportation of persons, etc., across space by advanced technological means.

sounds equally impossible to implement. However, quantum theory makes it more plausible. According to quantum theory, all elementary particles of the same kind are identical. There is no difference between the electrons in my body and the electrons in a rock on the moon. Thus, what defines a particular person is not a collection of the elementary particles he is made of, but *the quantum state* of these particles. If I want to move to the moon, I need not move my electrons, protons, etc. to the moon. It is enough to reconstruct the quantum state of the same particles there. From my point of view, I *am* the quantum state, so creation of this quantum state on the moon is my teleportation to the moon. Compare this view with Asher's reply when he was asked by a newsman whether it was possible to teleport not only the body but also the soul: "only the soul."

In this approach, teleportation sounds as trivial as a FAX machine, but it is not. There are two reasons why it seems impossible. First, it is impossible to measure (to scan) the quantum state. Second, the amount of information needed to specify a quantum state even of a small object is so huge that it is not feasible to transmit it in a reasonable time. The dual channel of quantum teleportation does the trick: the quantum state is teleported without being scanned. The quantum channel consists of entangled pairs of elementary particles, as many as we need for the object to be teleported. Originally, at the remote location there is a mixture of different states in which probability for any state is the same. Then, local joint measurement performed on the system to be teleported together with the local part of the quantum channel specifies the particular decomposition of the mixture in the remote location with a relatively small number of states. Finally, the only information to be transmitted is the number of "actual" states in the mixture. In my view,[20] the local measurement creates numerous worlds with the teleported quantum state which is deformed in various ways. The final stage of teleportation is the correction of the deformation such that in all worlds the final state of the remote system is the initial state of the local system.

Clearly, Asher would not join me in considering myself as an (unknown) quantum state. For him, a quantum state is just the knowledge of the preparer[21]:

> A state vector is not a property of a physical system (nor of an ensemble of systems). . . . Rather, a state vector represents a procedure for preparing or testing one or more physical systems.

Then, the correction is really not that important: the preparer knows that I am teleported in a particular deformed way. The "deformed me" is, probably, not a living creature at all, so I tend not to accept Asher's approach. But, since we are both

sure that now and in any foreseeable future, a realistic teleportation experiment with people *is* a science fiction story, this disagreement is irrelevant.

3. Wave Function Description of the Braunstein–Kimble Scheme

In their seminal paper on the implementation of continuous teleportation with squeezed light,[19] Braunstein and Kimble used the Wigner representation. In this section, we explain their method using wave functions.

Figure 1 is a schematic representation of the experimental setup envisioned by Braunstein and Kimble. The (single mode) state of the beam incident on the "in port" is to be teleported to the "out port." To this end, a highly squeezed two-mode state is used (which leaves the source marked "EPR"). One half of the "EPR-pair" is combined via a 50–50 beam splitter with the "in" beam and the two resulting beams are measured using homodyne detectors D_x and D_p measuring x and p appropriately. The results of these measurements are then used to implement corrections on the other (remote) half of the EPR pair, which leave it in a state which closely approximates the input state.

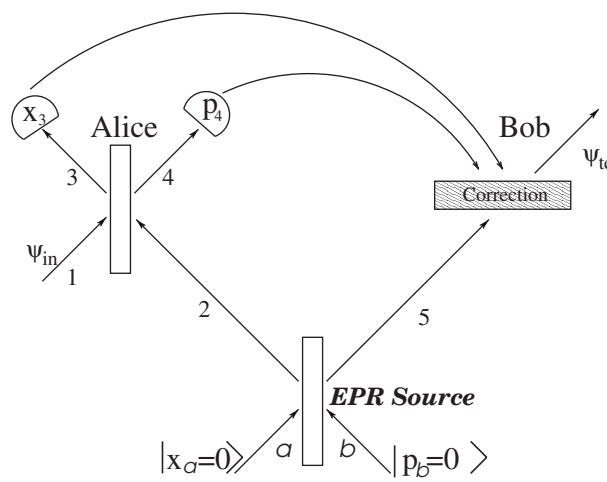

Fig. 1. The Braunstein–Kimble teleportation scheme.

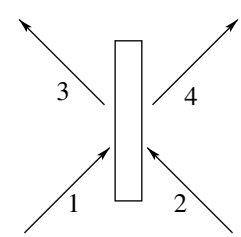

Fig. 2. Beam splitter.

For simplicity, we will consider the (asymmetric) 50–50 beam splitters (see Fig. 2) which act on single photons in the following way:

$$|1\rangle \mapsto \frac{|3\rangle + |4\rangle}{\sqrt{2}}, \quad |2\rangle \mapsto \frac{|4\rangle - |3\rangle}{\sqrt{2}}. \tag{1}$$

If the incident beams in ports 1 and 2 are described by the quadrature-wave function $\Psi(x_1, x_2)$, then the beamsplitter described by (1) leads to the transformation[22]:

$$\Omega(x_1, x_2) \mapsto \Omega\left(\frac{x_4 + x_3}{\sqrt{2}}, \frac{x_4 - x_3}{\sqrt{2}}\right). \tag{2}$$

We start with the initial state $\psi(x_1)$ for the quadrature-wave function of the input beam, $\phi(x_2, x_5)$ for that of the (approximate) EPR-pair (the quantum channel) and initial "ready" states of two measuring devices:

$$|\Psi\rangle = \int \psi(x_1)|x_1\rangle dx_1 \int \phi(x_2, x_5)|x_2\rangle|x_5\rangle dx_2 dx_5 \ |ready\rangle_{MD1}|ready\rangle_{MD2}. \tag{3}$$

Using Eq. (2), we have for the total state after the action of the beam splitter:

$$\int \psi\left(\frac{x_4 + x_3}{\sqrt{2}}\right) \phi\left(\frac{x_4 - x_3}{\sqrt{2}}, x_5\right) |x_3\rangle|x_4\rangle|x_5\rangle dx_3 dx_4 dx_5 |ready\rangle_{MD1}|ready\rangle_{MD2}. \tag{4}$$

At this stage, x_3 and p_4 are measured and the appropriate correction is applied to the state of the variable x_5. The wave function in the x representation is shifted by $\sqrt{2}x_3$, and the wave function in the p representation is shifted by $\sqrt{2}p_4$. At this stage of our analysis, we will not introduce the "collapse" of the quantum measurement, but continue to include the measuring device in the description of the total state. The shift in x leads to the following transformation:

$$\int \psi\left(\frac{x_4 + x_3}{\sqrt{2}}\right) \phi\left(\frac{x_4 - x_3}{\sqrt{2}}, x_5 - \frac{2x_3}{\sqrt{2}}\right) |x_3\rangle|x_3\rangle_{MD1}|x_4\rangle|x_5\rangle dx_3 dx_4 dx_5 |ready\rangle_{MD2}. \tag{5}$$

To see the effect of the shift in p, we apply a Fourier transform in x_4 and then multiply the function of x_5 by $e^{i\sqrt{2}x_5 p_4}$:

$$\int \frac{e^{-i(x_4 - \sqrt{2}x_5)p_4}}{\sqrt{2\pi}} \psi\left(\frac{x_4 + x_3}{\sqrt{2}}\right) \phi\left(\frac{x_4 - x_3}{\sqrt{2}}, x_5 - \frac{2x_3}{\sqrt{2}}\right) \times |x_3\rangle|x_3\rangle_{MD1}|p_4\rangle|p_4\rangle_{MD2}|x_5\rangle dx_3 dx_4 dx_5 dp_4. \tag{6}$$

In the limiting case, an ideal EPR pair,

$$\phi(x_2, x_5) = \delta(x_2 - x_5), \tag{7}$$

and the state (6), after the integration on x_4, has the form:

$$\int \frac{e^{ix_3 p_4}}{\sqrt{2\pi}} |x_3\rangle|p_4\rangle|x_3\rangle_{MD1}|p_4\rangle_{MD2} dx_3 dp_4 \int \psi(x_5)|x_5\rangle dx_5. \tag{8}$$

Thus, we have the desired teleportation of the wave function from mode 1 to mode 5. Of course, no information about the teleported state remains in the measuring devices.

In the process, we assumed ideal homodyne detectors and an ideal EPR source. The major difficulty is the creation of the EPR source. An approximate EPR state is obtained by shining beams of squeezed light on a beamsplitter (Fig. 1). The light in input mode a should be highly squeezed in the x quadrature and the light on the input mode b should be highly squeezed in p. The input beams are well approximated by Gaussians:

$$\frac{1}{\pi^{\frac{1}{4}}\sqrt{\sigma_a}}e^{-\frac{x_a^2}{2\sigma_a^2}}, \quad \frac{1}{\pi^{\frac{1}{4}}\sqrt{\sigma_b}}e^{-\frac{x_b^2}{2\sigma_b^2}}, \tag{9}$$

where σ_a is very small and σ_b is very large. We will require:

$$\sigma_a \ll 1/|p_1|, \quad \sigma_b \gg |x_1|, \tag{10}$$

for all probable values of x_1, p_1. For input beams (9), instead of the ideal EPR state we will get

$$\phi(x_2, x_5) = \frac{1}{\sqrt{\pi\sigma_a\sigma_b}}e^{-\left(\frac{x_2-x_5}{2\sigma_a}\right)^2}e^{-\left(\frac{x_2+x_5}{2\sigma_b}\right)^2}. \tag{11}$$

In order to get a feel for the distortion during the teleportation, we will consider two separate cases: one in which only the squeezed light in port a is not ideal and one in which only the squeezed light in b is not ideal. In the first case

$$\phi(x_2, x_5) = \frac{1}{\pi^{1/4}\sqrt{\sigma_a}}e^{-\left(\frac{x_2-x_5}{2\sigma_a}\right)^2}. \tag{12}$$

Then, the final state of the teleportation procedure (up to normalization) obtains the form:

$$\int e^{ix_3p_4}e^{-\left(\frac{x_5-v}{2\sigma_a}\right)^2}e^{-i\sqrt{2}p_4(v-x_5)}\psi(v)|x_3\rangle|p_4\rangle|x_5\rangle|x_3\rangle_{MD1}|p_4\rangle_{MD2}dx_3dp_4dx_5dv. \tag{13}$$

Now, there is a partial entanglement between the system with the teleported state and the measuring devices. Let us look at a particular outcome of the measurement in mode 4, p_4. This eliminates the entanglement. Then, the final teleported state (up to normalization) is

$$\psi_{\text{tel}}(x_5) = \int e^{-i\sqrt{2}p_4(v-x_5)}e^{-\left(\frac{x_5-v}{2\sigma_a}\right)^2}\psi(v)dv. \tag{14}$$

This is just a convolution of the input function with a (real) Gaussian multiplied by an (imaginary) exponent. If the Gaussian is narrow and we can neglect the distortion due to the exponent, the convolution yields approximately the input wave function, i.e. we obtain teleportation with good fidelity.

The distortion due to the exponent depends on the value of p_4. In order to estimate it, we can write an operator equation similar to those that appear in the

original continuous teleportation paper[16]:

$$p_4 = \frac{p_1}{\sqrt{2}} + \frac{p_a + p_b}{2}, \tag{15}$$

where p_1 is the "momentum" of the input mode and p_a and p_b are the "momenta" of the input modes of the EPR source. For our input state, we have

$$\langle p_a \rangle = 0, \quad \Delta p_a = \frac{1}{\sigma_a}, \quad p_b = 0. \tag{16}$$

Taking into account the first of the requirements (10), we see that for probable outcomes of the measurement of p_4, $|p_4| \lesssim \frac{1}{\sigma_a}$. Since we consider a narrow Gaussian such that $\psi(x)$ is nearly constant on an interval of length σ_a, the exponent does not lead to a significant distortion and we obtain

$$\psi_{\text{tel}}(x_5) \simeq \psi(x_5). \tag{17}$$

In the other case we had mentioned above, namely, that only the squeezing in mode b is not ideal, the "EPR" state is given by

$$\phi(x_2, x_5) = \delta(x_2 - x_5) \frac{e^{-\left(\frac{x_2+x_5}{2\sigma_b}\right)^2}}{\pi^{1/4}\sqrt{\sigma_b}}. \tag{18}$$

The final state after the teleportation procedure is now (up to normalization):

$$\int e^{ix_3 p_4} e^{-\left(\frac{x_5-\sqrt{2}x_3}{\sigma_b}\right)^2} \psi(x_5) |x_3\rangle |x_3\rangle_{MD1} |p_4\rangle |p_4\rangle_{MD2} |x_5\rangle dx_3 dp_4 dx_5. \tag{19}$$

Again, there is a partial entanglement between the system with the teleported state and the measuring devices. Let us look at a particular outcome of the measurement in mode 3, x_3. This eliminates the entanglement. Then, the final teleported state (up to normalization) is

$$\psi_{\text{tel}}(x_5) = \psi(x_5) e^{-\left(\frac{x_5-\sqrt{2}x_3}{\sigma_b}\right)^2}. \tag{20}$$

For the distortion to be small, we need the Gaussian to be approximately constant over the interval where $|\psi|$ is significant. Let us denote the length of this interval by l which, according to our second choice in (10), is much smaller than σ_b. The condition is then:

$$x_3 \ll \sigma_b^2 / l. \tag{21}$$

To estimate the range of the outcomes of measurement results of x_3, we can write [compare with (15)]:

$$x_3 = \frac{x_1}{\sqrt{2}} + \frac{x_a + x_b}{2}. \tag{22}$$

In this case, the input state of the EPR source is characterized by

$$x_a = 0, \quad \langle x_b \rangle = 0, \quad \Delta x_b = \sigma_b, \tag{23}$$

which, together with (10), ensures that condition for good fidelity teleportation (21) is satisfied.

We have seen two cases where simple estimation of teleportation distortion was possible: in one case the operation was essentially convolution with a narrow Gaussian, and in the other case the operation was essentially multiplication by a wide Gaussian. Note that we could consider the process of teleportation in the p representation and then we would have the same explanations, but with multiplication in the first case and convolution in the second.

We have shown that either of the choices

$$\sigma_a \ll 1/|p_1|, \sigma_b = \infty \quad \text{or} \quad \sigma_a = 0, \sigma_b \gg |x_1| \tag{24}$$

ensures that the distortion shall be small. In a real experiment, both input beams for the EPR source exhibit, of course, finite squeezing (9). Then, we can see from (6) that the final state of the teleportation procedure (up to normalization) is

$$\int e^{ix_3p_4} e^{-\left(\frac{x_5-v}{2\sigma_a}\right)^2} e^{-\left(\frac{x_5+v-\sqrt{2}x_3}{2\sigma_b}\right)^2} e^{-i\sqrt{2}(v-x_5)p_4} \psi(v)|x_3\rangle|x_3\rangle_{MD1} \times |p_4\rangle|p_4\rangle_{MD2}|x_5\rangle dx_3 dp_4 dx_5 dv. \tag{25}$$

Given particular outcomes of the measurements of p_4 and x_3, the final teleported state (25) (up to normalization) is

$$\psi_{\text{tel}}(x_5) = \int e^{-\left(\frac{x_5-v}{2\sigma_a}\right)^2} e^{-\left(\frac{x_5+v-\sqrt{2}x_3}{2\sigma_b}\right)^2} e^{-i\sqrt{2}(v-x_5)p_4} \psi(v) dv. \tag{26}$$

The analysis of this expression is more complicated, but condition (10) is sufficient to ensure that the function will be teleported with little distortion, as will be seen in the computer simulation presented in the following section.

4. A Numerical Simulation

In this section, we show numerically the impact of each parameter in the teleportation. We use as our input wave function the silhouette of a woman Fig. (3). We would like to stress that the choice of a human figure is intended to aid in the visual assessment of the distortion and is not, of course, supposed to suggest that teleportation of humans is feasible.

The characteristics of the spatial wave function are

$$\langle x_1 \rangle = 50, \quad \Delta x_1 = 28, \quad l = 100, \tag{27}$$

where we have chosen units such that $\hbar = 1$. Then, the computer calculations show that the characteristics of the wave function in momentum space are

$$\langle p_1 \rangle = 0, \quad \Delta p_1 = 18. \tag{28}$$

First, we consider the case of infinite squeezing in port b and finite squeezing in port a. In Fig. 4(a), we show the results of the simulation for strong squeezing, $\sigma_a = 1/180$ $(= 1/10\Delta p_1)$ and a probable outcome of the measurement of the momentum in mode 4, $p_4 = 180$ $(= 1/\sigma_a)$. Figure 4(b) shows the results for the same strong squeezing, but a rare, large outcome of the measurement of the momentum,

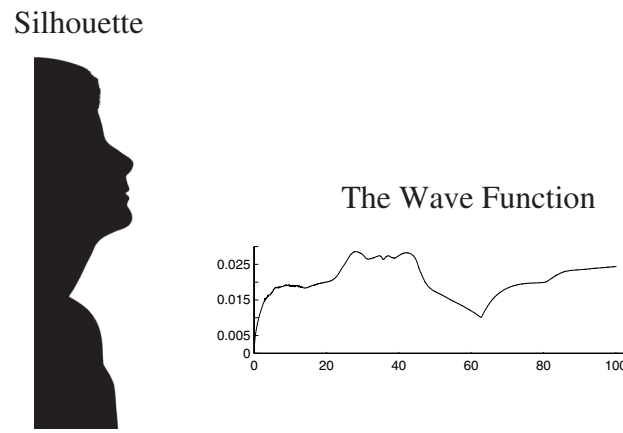

Fig. 3. The original wave function $\psi(x_1)$.

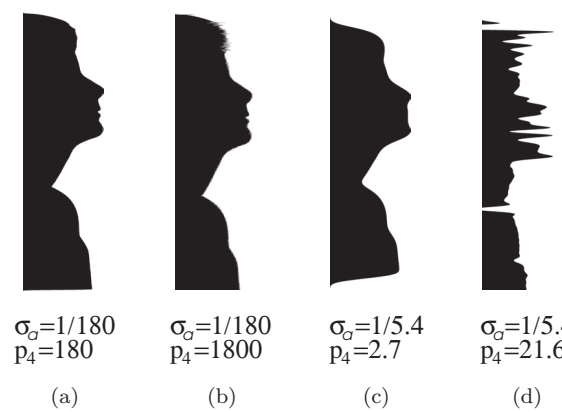

Fig. 4. Teleported silhouette with finite squeezing in a and ideal squeezing in b.

$p_4 = 1800$ $(= 10/\sigma_a)$. Figure 4(c) shows the results for weak squeezing, $\sigma_a = 1/5.4$ $(= 1/0.3\Delta p_1)$ and probable outcome of the measurement of the momentum $p_4 = 2.7$ $(= 0.5/\sigma_a)$. Finally, Fig. 4(d) shows the results for weak squeezing, $\sigma_a = 1/5.4$ $(= 1/0.3\Delta p_1)$ and rare, large outcome of the measurement of the momentum, $p_4 = 10.8$ $(= 2/\sigma_a)$.

We see in Fig. 4(a) that with strong squeezing and not too large a value of p_4, the wave function is teleported without significant distortion. Figure 4(b) shows that for strong squeezing, but an improbable, large value of p_4 leads to distortion of the regions which require large momenta. Figure 4(c) shows that weak squeezing causes the smoothing out of small details of the wave function and large p_4 and weak squeezing lead to complete distortion of the teleported wave function.

Let us analyze, for example, the smoothing out of small details of the wave function, which we have seen in Fig. 4(c). The teleported wave function is given by

the convolution (14) which, with the parameters $1/\sigma_a = 5.4$ $p_4 = 2.7$, reads

$$\psi_{\text{tel}}(x_5) = \int e^{-i3.8(v-x_5)} e^{-\left(\frac{x_5-v}{0.37}\right)^2} \psi(v) dv. \tag{29}$$

In Fig. 5, we draw the terms of the convolution (29). The graph shows only the real part. The imaginary part is an order of magnitude smaller than the real part. The multiplication of the Gaussian by the exponent has a small effect, since the width of the Gaussian is smaller than most details of the wave function $\psi(v)$. Thus, the result of the convolution is close to the original wave function, yet some details do disappear, like the mouth.

The second case is infinite squeezing in port a and finite squeezing in port b. In Fig. 6(a), we show the results of the simulation for strong squeezing, $\sigma_b = 280$ ($= 10\Delta x$) and a probable outcome of the measurement of position, $x_3 = 280$ ($= \sigma_b$). Figure 6(b) shows the results for the same good squeezing, but rare, large outcome of the measurement of position, $x_3 = 2800$ ($= 10\sigma_b$). Figure 6(c) shows the results for weak squeezing, $\sigma_b = 8.4$ ($= 0.3\Delta x$) and probable outcome of the measurement of position $x_3 = 4.2$ ($= 0.5\sigma_b$). Figure 6(d) shows the results for weak squeezing,

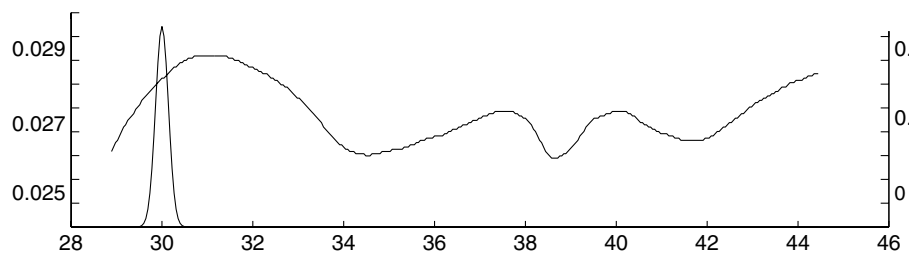

Fig. 5. The function $\psi(v)$ and (the real part of the) convolution kernel of Eq. (29) ($x_5 = 30$) corresponding to Fig. 4(c). On the left is the scale of the wave function and on the right, that of the kernel.

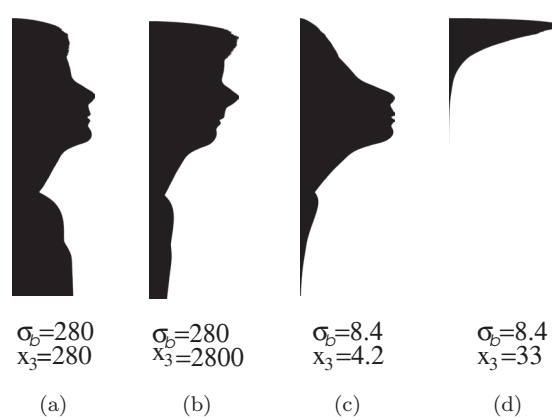

Fig. 6. Teleported silhouette with finite squeezing in b and ideal squeezing in a.

$\sigma_b = 8.4$ and rare, large outcome of the measurement of the momentum, $x_3 = 33$ $(= 4\sigma_b)$.

We see in Fig. 6(a) that with strong squeezing and not too large a value of x_3, the wave function is teleported without significant distortion. It is the product (20) of the original function with a wide Gaussian, which for the above parameters reads

$$\psi_{\text{tel}}(x_5) = \psi(x_5)e^{-\left(\frac{x_5+400}{280}\right)^2}. \tag{30}$$

Figure 7 shows the wave function and the Gaussian of the product (30). We can see that the Gaussian is nearly constant over the support of the wave function, thus causing little distortion.

Figure 6(b) shows that strong squeezing, but an improbable, large value of x_3 leads to distortion of the relative amplitude. Figure 6(c) shows that weak squeezing and small x_3 yield relatively faithful teleportation of a small part of the wave function and distortion (elimination) of other parts. Again, weak squeezing together with large x_3 leads to complete distortion of the teleported wave function.

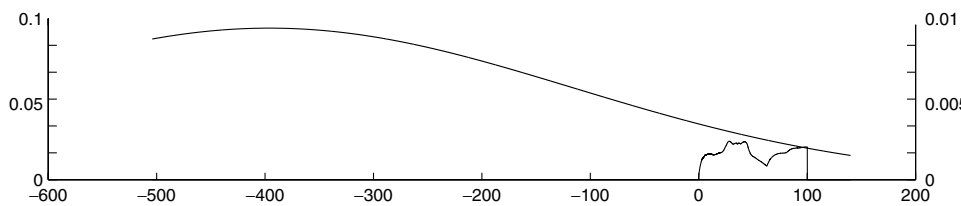

Fig. 7. The function $\psi(v)$ and the Gaussian which are the terms of the product (30) corresponding to Fig. 6(a). On the left is the scale of the wave function and on the right, that of the Gaussian.

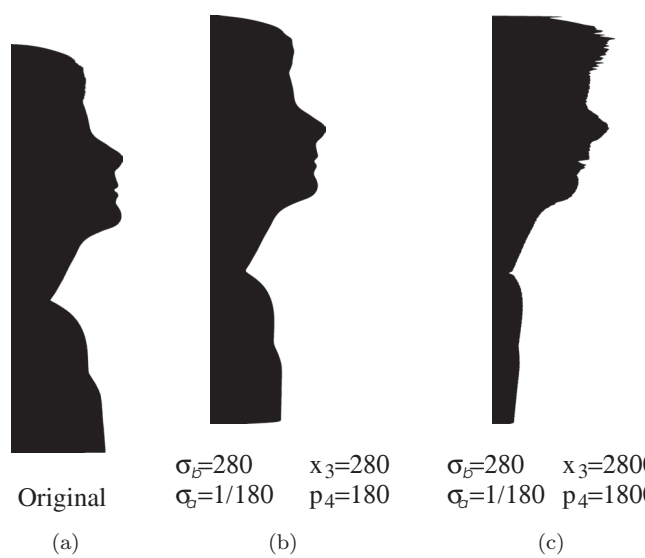

Fig. 8. Teleported silhouette with finite squeezing in a and b.

Finally, we compute the teleported wave function when both input states are not ideal. Figure 8(b) shows that strong squeezing $\sigma_b = 280\ (= 10\Delta x),\ \sigma_a = 1/180\ (= 1/10\Delta p)$ and probable outcomes $p_4 = 180\ (= 1/\sigma_a),\ x_3 = 280\ (= \sigma_b)$ together lead to a very good fidelity, while large improbable outcomes $p_4 = 1800\ (= 10/\sigma_a), x_3 = 2800\ (= 10\sigma_b)$ lead to significant distortion, see Fig. 8(c).

The discussion of the physical meaning of teleportation and the analysis of the continuous variables teleportation experiment which we performed here provides an intuitive picture of the process and helps to understand the effect of various parameters on the fidelity of teleportation. We hope it will be useful for designing better teleportation experiments.

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