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Electron teleportation with quantum dot arrays

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Abstract. An electron teleportation protocol, inspired by the scenario by Bennett *et al.*, is proposed in a mesoscopic set-up. A superconducting circuit allows to both inject and measure entangled singlet electron pairs in an array of three normal quantum dots. The selection of the teleportation process is achieved in the steady state with the help of two superconducting dots and appropriate gating. Teleportation of the electron spin is detected by measuring the spin-polarized current through the normal dot array. This current is perfectly correlated to the pair current flowing inside the superconducting circuit. The classical channel required by Bennett's protocol, which signals the completion of a teleportation cycle, is identified with the detection of an electron pair charge in the superconducting circuit.

PACS. 74.50.+r Tunneling phenomena; point contacts, weak links, Josephson effects – 73.23.Hk Coulomb blockade; single-electron tunneling – 03.65.Ud Entanglement and quantum nonlocality (*e.g.* EPR paradox, Bell's inequalities, GHZ states, etc.)

Teleportation (TP) recently entered the realm of quantum physics when Bennett *et al.* [1] proposed a protocol to reconstruct the unknown state of a given particle at a different location. The sender, Alice, and the receiver, Bob, share an entangled pair [2] – , and Alice performs a joint measurement on the "source" particle and her part of the pair. The result of the measurement is communicated through a classical channel to Bob, allowing him to reconstruct the initial state on his part of the pair. This protocol has since been experimentally demonstrated with polarized photons [3], as well as proposed in atomic physics [4] and solid state optics [5]. TP is likely to become an essential element of future information processing schemes [6]. It is certainly relevant to test these manifestations of nonlocality [7] with massive particles in nanostructured devices, with the advantage that these can be integrated in (quantum) electronic circuitry. Similar analogies between photon propagation and phase-coherent electron transport in nanostructures were illustrated by the fermion version of the Hanbury-Brown and Twiss experiment [8].

The general principle of the present mesoscopic scheme for TP – an array of quantum dots with superconductors – is inspired of reference [1], but follows more closely its optical implementation [3]. Alice's measuring device for entangled (singlet) electron pairs is an *s*-wave superconductor, as is the generator of the entangled electron pairs [9–12]. Similarly to the the optics experiment only one of the four Bell states is measured (Fig. 1a).

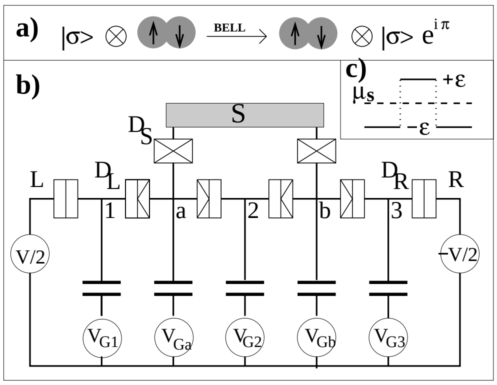

Fig. 1. a) The Bell state projection which operates on dots $1, 2, 3$: $|\sigma>$ is the spin to be teleported, the singlet is depicted in gray. b) The TP cell contains: i) NN junctions between reservoirs $\mathbf{L}, \mathbf{R}$ and dots **1** and **3**; ii) N-S junctions between $(\mathbf{1}, \mathbf{a})$, $(\mathbf{a}, \mathbf{2})$, $(\mathbf{2}, \mathbf{b})$ and $(\mathbf{b}, \mathbf{3})$, and S-S junctions between **a** (**b**) and the bulk superconductor $\mathcal{S}$. Detectors $D_{L,R,S}$ signal the passage of an electron/Cooper pair in the normal/superconducting circuit. c) Energy level configuration of dots **1**, **2** and **3** (μ_S is the superconductor chemical potential).

However photons do not interact together in vacuum. On the contrary, electrons in nanostructures experience strong Coulomb interactions, which can be used to ensure that electrons be injected one by one from/to a quantum dot through tunnel barriers [13]. Indeed, further control can be obtained in a multidot array, by means of intradot

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and interdot Coulomb correlations: here, the correct TP sequence (injection, pair creation, measurement, classical channel and detection) can be precisely selected, while operating in the steady state, by an appropriate initial choice of gate voltages.

The device is depicted in Figure 1b: three normal (N) dots, **1**, **2** and **3**, and two superconducting (S) dots **a**, **b**, are placed in alternation: N-dots can only communicate *via* the S-dots. Dots **1** and **2** are coupled to dot **a** – Alice's measuring device – by tunnel junctions, while **2** and **3** are coupled to **b** – the source of entangled pairs. Furthermore, dots **a**, **b** are connected by tunnel junctions to a superconducting ($\mathcal{S}$) circuit where Cooper pairs only are transfered. Reservoir **L** emits in dot **1** the electron to be teleported, and reservoir **R** ("Bob") collects the teleported state from dot **3**.

First, focus on the isolated system of 5 dots. An entangled singlet pair of particles $|\Psi^S\rangle_{23} = 2^{-1/2}(|\uparrow\downarrow\rangle_{23} - |\downarrow\uparrow\rangle_{23})$ is produced by **b**. Coulomb blockade [13] prohibits double occupancy in each dot [9,10] (the same is true for Cooper pair occupancy in the superconducting dots). Bringing together the singlet $|\Psi^S\rangle_{23}$ with the state $|\sigma\rangle_1$ to be teleported, the resulting state with dots $\mathbf{1},\mathbf{2},\mathbf{3}$ occupied leaves the spin in **3** undetermined. This three-particle wave function is now decomposed among the 4 Bell states for electron spins in dots (**1**, **2**) [1]: $|\Psi\rangle_{123} = -(1/2)[|\Psi^S\rangle_{12}|\sigma\rangle_3 + \sum_\nu |\Psi^{T_\nu}\rangle_{12}|\tilde{\sigma}_\nu\rangle_3]$ where $|\tilde{\sigma}_\nu\rangle$ are unitary transforms of $|\sigma\rangle$ ($\nu = 0, \pm$) and $|\Psi^{T_{0+-}}\rangle_{12}$ the three triplet states. **a** acts as a detector for the singlet state of electrons in **1** and **2** (Fig. 1a): absorption of a Cooper pair only occurs if (**1**, **2**) contain a singlet. The remaining spin in dot **3** necessarily acquires the same state $|\sigma\rangle$ as the initial spin in dot **1**. The absorption of the singlet electron pair from (**1**, **2**) also *erases* the initial spin state from dot **1**. It becomes part of a Cooper pair which is absorbed by the superconductor a. This pair in a does not bear any memory of the initial spin state in 1, and the "non-cloning theorem" [14] is thus satisfied. As in [1], this transition is made irreversible: here it is followed by the (irreversible) injection of a "new" electron from L.

A microscopic Hamiltonian supports this TP protocol. N-dots are assumed to have a discrete spectrum, with level spacing comparable to the gaps $\Delta_{a,b,\mathcal{S}} \sim \Delta$ of the S-dots and S-circuit. The S-dots have a continuous quasiparticle spectrum, and $\Delta_{a,b} > E_{C_\mu} \equiv e^2/C_{\Sigma_\mu}$. Only two occupation numbers are kept for each dot. N-dots (S-dots) have "empty" states with an even number N_μ^0 of electrons, and have "filled" states with $N_\mu^0 + 1$ ($N_\mu^0 + 2$) electrons. The Hamiltonian which describes the TP cell reads $H = H_0 + H_t + H_C$ where H_0 describes the isolated elements (dots and reservoirs). The single electron hopping term H_t has amplitudes $t_{\alpha\beta}$ ($\alpha, \beta = \{\mathbf{L}, \mathbf{R}, \mathbf{S}, \mathbf{1}, \mathbf{2}, \mathbf{3}, \mathbf{a}, \mathbf{b}\}$). Only one level is relevant in each N-dot, and next nearest neighbor hoppings are neglected. The Coulomb contribution has the standard form: $H_C = (1/2)\sum_{\mu,\nu=1,2,3,a,b} U_{\mu\nu}\delta N_\mu \delta N_\nu$, where $\delta N_\mu = N_\mu - \bar{N}_\mu$ is the deviation from the effective number of electrons imposed by the gates (voltage $V_{G\mu}$). The coefficients $U_{\mu\nu}$ form the inverse capacitance matrix of this five dot system, and are computed [15] from the

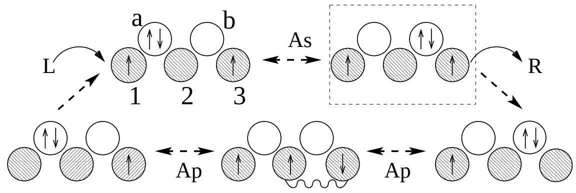

Fig. 2. TP sequence: upper dots (white) are S-dots **a** and **b**, lower dots (shaded) are N-dots **1**, **2**, **3**. Horizontal transitions only are resonant. Starting from the framed configuration (upper right), an electron in **3** escapes in **R**; next, a pair (from **b**) creates an entangled state $\mathbf{2},\mathbf{3}$ (wiggly line) with rate A_P, leaving all N-dots filled. A pair $\mathbf{1},\mathbf{2}$ then escapes in **a**. The electron in **3** acquires the spin state of dot **1**, as confirmed by the absorption of a singlet state in **a** and the subsequent injection of an electron from **L**.

individual capacitances C,C', C_s and C_g of the NN, NS, SS and gate junctions respectively (see Fig. 1a). The dots are coupled to the N/S reservoirs with energy line widths $\Gamma_{L,R} = 2\pi t^2_{L1(R2)} N_{L(R)}(0) \ll \Delta$, with density of states $N_{L,R}(0)$ (and similarly $\Gamma_{Sa} = \Gamma_{Sb}$). The chemical potential μ_S of the superconductor is located in the middle of the left/right reservoir potentials $\mu_S \pm eV/2$. Dot configurations are identified by the occupation numbers of dots $\mathbf{1}, \mathbf{a}, \mathbf{2}, \mathbf{b}, \mathbf{3}$: 0 or 1 (0, 1 or 2) for the N-dots (S-dots). Charging energy differences ΔE_i^f between the initial and final configurations of the five dot system enter the $O(H_t)^2$ calculation of the pair tunneling amplitude from b to 2, 3 (and similarly from **a** to(**1**, **2**)): $A_P^b \simeq 2\sum_{k,x} u_k^b v_k^b t_{2b} t_{3b}/(\mathrm{i}\eta - E_k^b - \Delta E_{00020}^{00x0\bar{x}})$, with η an infinitesimal, u_k, v_k the usual BCS parameters, $x = 0, 1 (\bar{x} = 1, 0)$. E_k is the quasiparticle energy involved in the creation of a quasiparticle. The amplitude $A_P^{a(b)}$ is at most comparable to $\Gamma_{Sa,b}$, and decreases with the distance between the two junctions involved in cross Andreev reflection [9,16]. The transition amplitude A_S between **a**(**b**) and the $\mathcal{S}$-circuit is calculated in a similar way [17]. Consider the system in the absence of connections with the N,S leads. Dot gate voltages are adjusted so that the 4 pair transitions $A_P^{a,b}$, $A_S^{a,b}$ are resonant. Discarding virtual processes with more than one quasiparticle in **a** or **b**, one obtains the effective pair Hamiltonian

$$H_{\mathit{eff}} = A_P^a \Psi_{12}^\dagger \Psi_a + A_P^b \Psi_{23}^\dagger \Psi_b + A_S(\Psi_a^\dagger + \Psi_b^\dagger)\Psi_{\mathcal{S}} + \text{h.c.} \quad (1)$$

where the $\Psi_{\alpha\beta}$ destroys a singlet pair in 2 N-dots and $\Psi_{a,b,\mathcal{S}}$ destroys a Cooper pair in the superconductors.

The TP sequence is now illustrated (Fig. 2) in a steady state operation of the whole circuit ("TP cell"), by applying a constant bias between reservoirs **L** and **R**. Circuit parameters and gate voltages are chosen such that the TP cell is symmetric in changing **1** (**a**) into **3** (**b**), thus $A_P^a = A_P^b$ (no phase difference exists in the S part of the cell). The whole TP sequence is depicted in Figure 2. It repeats itself cycle after cycle, each one achieving teleportation of an electron injected in **1** from **L**, and detection in **R** of the teleported electron in **3**. Start with dots **1**, **3** and **b** occupied (upper right in Fig. 2). The teleportation process is triggered by the escape of the electron in **3** in reservoir **R**. Doing so, the energy level in **b** is lowered, thus interrupting the previously resonant Cooper pair transfer. Now (lower right) the pair in **b** resonates with $(\mathbf{2},\mathbf{3})$, building with **1** the aforementioned state $|\Psi\rangle_{123}$. Measurement of the singlet state in $(\mathbf{1},\mathbf{2})$ by **a** (Alice) is achieved when a new electron is injected into **1**, raising the energy level in **a** in the process. The remaining electron in **3** thus acquires the state of the previous one in **1**, while the new electron waits in **1** to be teleported in the next sequence.

Note that: i) Incoherent processes are brought by the reservoirs and the applied bias. The latter bias also determines the direction of TP (right or left) in an otherwise symmetric TP cell. This allows pair production from **b** and pair measurement in **a** to be both irreversible. ii) Successive TP cycles are linked together in such a way that a detection event triggers pair production for the next cycle, and an injection event triggers pair measurement for the previous cycle. iii) The classical channel corresponds to the detection of an extra Cooper pair in the superconducting circuit $(\mathbf{a}+\mathcal{S}+\mathbf{b})$. In Figure 1, this detection is depicted by the presence of a detector D_S, positioned between **a** and $\mathcal{S}$. The detection is classical insofar as the change in Coulomb energy is irreversible due to the reservoirs (it is triggered by the transfer of an electron from **L** to **1**) and it is computed from straightforward classical electrostatics. It conveys the information about the "charge" in quantum dot **1**, while the (quantum) spin part is reconstructed by the measurement, by means of the entangled pair, in full agreement with the TP principle [1]. v) As in optics [3,18,19], measurement of the sole singlet state reduces to 1/4 the efficiency of TP, but not the fidelity, equal to 1 in the ideal sequence depicted above.

The sequence reads: ...10021] → [10020 ↔ 10101 ↔ 02001] → [12001 ↔ 10001 ↔ 10021]... Close inspection of the energy balance ΔE_i^f of all the electronic transitions in the TP cell reveals that it is possible to force this sequence with the help of constant gate voltages only [15]. As an example, we assume that $C = C' = C_s = 100C_g$. First, the resonance condition for pair transitions implies $\Delta E_{10020}^{10101} = \Delta E_{10101}^{02001} = \Delta E_{12001}^{10001} = \Delta E_{10001}^{10021} = 0$. One finds that it fixes $\bar{N}_{a,b} = 0.97$, and $\bar{N}_1 + \bar{N}_2 = 0.67$. Second, injection and detection are ensured (with $\mu_{L,R} = \pm eV/2$) by $\Delta E_{02001}^{12001} < eV/2$, $\Delta E_{10021}^{10020} < eV/2$, therefore $V > (\bar{N}_1 - 0.9)e/C$. Third, the transfer of an electron from **3** to **R** is allowed from state 10021 but, among other unwanted transitions, not from 10101 or 02001: this can be achieved in a certain range of V because $\Delta E_{10101}^{10100} - \Delta E_{10021}^{10020} = 2U_{b3} - U_{23} = 11e^2/30C > 0$ and $\Delta E_{02001}^{02000} - \Delta E_{10021}^{10020} = U_{13} + 2U_{b3} - 2U_{a3} = 13e^2/30C > 0$.

TP fidelity is reduced by other transport processes, yet which are suppressed by our choice of resonant Cooper pair transfers. First, a direct electron transfer can result from two consecutive cotunneling transitions from dot **1** to dot **2**, and from dot **2** to **3**, while generating virtual quasiparticles [16,20]. Cotunneling is avoided by maximizing the energy differences for transitions from dot **1** to dot **2**, by tuning the parameter $\bar{N}_1 - \bar{N}_2$. Positive (negative) gate voltages applied to dots **1**, **3** (dot **2**) guarantee that cotunneling involves a positive energy 2ε (Fig. 1c), with $A_P \ll \varepsilon < \Delta$. The amplitude for cotunneling from dot **1** to **3** is reduced as it scales like $A_P^2/\varepsilon \ll A_P$. Cotunneling is quenched by maximizing ΔE_{12001}^{02101}, ΔE_{10021}^{00121}, $\Delta E_{10001}^{00101} = (\bar{N}_1 - 8/15)e^2/C \sim 2\varepsilon$. At $T = 0$, optimal operation is obtained with $\bar{N}_1 = \bar{N}_a \sim 1$, $\bar{N}_2 \sim -1/3$ and finite bias $0 < V < e/3C$. A second process is Josephson tunneling between **a** and **b**, independently of the pair current involved in the TP sequence: Cooper pairs can be transmitted by cotunneling through dot 2 only. However, this process [9,21] involves quasiparticle excitations in **a** or/and **b**, contrary to the TP process.

Assuming the TP cell to be weakly coupled to the reservoirs, transport across the dot array can be described by a master equation. The microscopic model shows that the transfer process preserves spin, so let us first take L, R polarized in the same direction. Defining states $|\uparrow,2,0,0,\uparrow\rangle = |a\rangle$, $|\uparrow,0,0,0,\uparrow\rangle = |c\rangle$, $|\uparrow,0,0,2,\uparrow\rangle = |b\rangle$, $|\uparrow,0,0,2,0\rangle = |1\rangle$, $|0,2,0,0,\uparrow\rangle = |3\rangle$, and $|S\rangle$, $|T\rangle$ the states $|10101\rangle$ with wave functions $|\Psi^S\rangle_{12}|\sigma\rangle_3$ and $(1/\sqrt{3})\sum_\nu |\Psi^{T_\nu}\rangle_{12}|\tilde{\sigma}_\nu\rangle_3$, the Bloch equations for the reduced density matrix, describing both the populations and the coherences $\sigma_{\mu\nu}$ $(\mu,\nu = a,b,c,1,2,3)$ can be written in the general form [22,23] at zero temperature:

$$\dot{\sigma}_{\mu\mu} = \mathrm{i}\sum_\nu \Omega_{\mu\nu}(\sigma_{\mu\nu} - \sigma_{\nu\mu}) - \sum_\lambda (\Gamma_{\mu\lambda}\sigma_{\mu\mu} - \Gamma_{\lambda\mu}\sigma_{\lambda\lambda}) \tag{2}$$

$$\dot{\sigma}_{\mu\nu} = \mathrm{i}\sum_\lambda (\sigma_{\mu\lambda}\Omega_{\nu\lambda} - \sigma_{\lambda\nu}\Omega_{\mu\lambda}) - \frac{\sigma_{\mu\nu}}{2}\sum_\lambda (\Gamma_{\mu\lambda} + \Gamma_{\nu\lambda}) \tag{3}$$

with $\Omega_{ac} = \Omega_{ca} = \Omega_{bc} = \Omega_{cb} = A_S$, the tunneling rate for Cooper pairs from **a** to S (S to **b**). $\Omega_{1S} = \Omega_{S1} = -A_P/2$, $\Omega_{1T} = \Omega_{T1} = -\sqrt{3}A_P/2$, $\Omega_{3S} = \Omega_{S3} = A_P$, $\Gamma_{b1} = \Gamma_R$, $\Gamma_{3a} = \Gamma_L$, all the other $\Omega_{\mu\nu}$'s and $\Gamma_{\mu\nu}$'s are zero. The steady state TP current $I_{tel} = e\Gamma_R\sigma_{bb}$ (from L to R) is obtained:

$$I_{tel} = e\frac{\Gamma_L\Gamma_R}{(\Gamma_L' + 4\Gamma_R)}\frac{A_P^2}{[A_P^2 + 2\Gamma_L^2\Gamma_R/(\Gamma_L' + 4\Gamma_R)]} \tag{4}$$

with $\Gamma_L' = \Gamma_L(3 + \Gamma_R^2/2A_S^2)$. The above analysis does not depend on the polarization of L as depicted in Figure 2, as the two spin channels are totally decoupled. If L instead feeds an arbitrary spin sequence to the TP cell, and R has no polarization, each incoming spin is faithfully reproduced in R for each cycle, as the Bloch equations are identical for each spin direction. Aside from corrections due to cotunneling, the only transport channel through the dot array is the TP process. TP involves a spin-conserving current between **L** and **R**, which is *perfectly correlated* to a pair current $I_P = 2I_{tel}$ in the $\mathcal{S}$ circuit. This signature of the coupled quantum and classical channels allows to distinguish TP from the parasite processes described previously: in cotunneling the pair current is absent; in the Josephson process *via* 2, the normal current is missing. Here, a teleportation diagnosis lies in the nonlocal transfer of the injected electron spin from L into R, and in the perfect locking of the average TP current which flows between L and R with the average pair current in the S-circuit. Yet if one measures average currents it does not constitute a rigorous proof. To be more precise, the fingerprint of TP is that *each time* an electron appears in R with the same spin that was injected from L, a pair Cooper pair passes from simultaneously from **a** to **b**. Quantum mechanics confirms explicitly this perfect correlation of electron and Cooper pair currents.

In similar situations, such as Bell inequality tests [7,24], a diagnosis which measures correlations between particles independently of the chosen (classical or quantum) description of the apparatus is necessary. In fact, in the optics experiment [3], a coincidence measurement is performed, which measures the simultaneous detection of the Bell pair and the polarization of the teleported photon, given a specific initial polarization. In nanocircuits, counting single electrons or single Cooper pairs in a transport experiment still represents a challenging task. Nevertheless, equal time correlators such as the cross correlator $\langle N_S(t)(\sigma_z)_R(t)\rangle$ between the Cooper pair number and the electron spin in R can readily be expressed in terms of noise or current-current correlators $\int \mathrm{d}\omega \mathrm{e}^{\mathrm{i}\omega}\langle I_P(t)I_{tel}(0)\rangle$ (using a polarized reservoir R to detect the spin), which are the standard quantities considered in the steady state [11]. An experimental test of the device would require to monitor the electron current at the point of injection and detection, and the Cooper pair current between a and S, and to resolve the time correlations [8] between these two currents. In Figure 1b, such detectors $D_{L,R,S}$ are sketched, and these could operate using capacitive effects.

Finally, limiting factors are considered. First, it is crucial to maintain spin coherence during the TP sequence (on a time scale $\sim \hbar/\Gamma_{R,L}$, which turns out to be "short" in practice). This coherence can be destroyed by spin-orbit coupling, or by exchange interactions with the other electrons within the dot. Such spin-flip processes can be minimized provided that the level spacing in the dots is larger than the temperature and the resonance width of the dots [10]: "empty" dot states of $\mathbf{1},\mathbf{2},\mathbf{3}$ should preferably have even filling N_μ. Second, the present scheme is clearly optimized if Cooper pair transfer from the N-dots pairs to each S-dots has an maximal amplitude A_P. This amplitude is strongly reduced by a geometrical factor in 2D and 3D [9,10,16]. On the other hand, the size of the S-dots is large enough so that $E_{C_{a(b)}} < \Delta$, thus precise lithography bringing N-dot pairs close together (however avoiding direct tunneling between N-dots) is required. The use of 1D wires could possibly relax this constraint, also extending (over microns) the spatial range of TP. [25].

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References

1. C.H. Bennett *et al.*, Phys. Rev. Lett. **70**, 1895 (1993)
2. A. Einstein, B. Podolsky, N. Rosen, Phys. Rev. Lett. **47**, 777 (1935)
3. D. Bouwmeester *et al.*, Nature **390**, 575 (1997)
4. S. Bose *et al.*, Phys. Rev. Lett. **83**, 5158 (1999)
5. J.A. Reina, N.F. Johnson, Phys. Rev. A **63**, 012303 (2000)
6. D. Bouwmeester, A. Ekert, A. Zeilinger, *The Physics of Quantum Information* (Springer-Verlag, Berlin, 2000)
7. A. Aspect, J. Dalibard, G. Roger, Phys. Rev. Lett. **49**, 1804 (1982); L. Mandel, Rev. Mod. Phys. **71**, S274 (1999); A. Zeilinger, Rev. Mod. Phys. **71**, S288 (1999)
8. M. Henny *et al.*, Science **284**, 296 (1999); W. Oliver, J. Kim, R. Liu, Y. Yamamoto, *ibid.* **299** (1999); T. Martin, R. Landauer, Phys. Rev. B **45**, 1742 (1992); M. Büttiker, *ibid.* **46**, 12485 (1992); Phys. Rev. Lett. **65**, 2901 (1990)
9. M.S. Choi, C. Bruder, D. Loss, Phys. Rev. B **62**, 13569 (2000)
10. P. Recher, E.V. Sukhorukov, D. Loss, Phys. Rev. B **63**, 165314 (2001)
11. G.B. Lesovik, T. Martin, G. Blatter, Eur. Phys. J. B **24**, 287 (2001); N. Chtchelkatchev, G. Blatter, G.B. Lesovik, T. Martin, Phys. Rev. B **66**, 161320 (2002)
12. G. Deutscher, D. Feinberg, Appl. Phys. Lett. **76**, 487 (2000)
13. M.H. Devoret, H. Grabert, In *Single Charge Tunneling*, edited by H. Grabert, M.H. Devoret (Plenum, New York, 1992); D. Estève, *ibid.*
14. W.K. Wooters, W.H. Zurek, Nature **299**, 802 (1982)
15. O. Sauret, D. Feinberg, T. Martin, in preparation
16. G. Falci, D. Feinberg, F.W.J. Hekking, Europhys. Lett. **54**, 255 (2001)
17. K.A. Matveev, M. Gisselfält, L.I. Glazman, M. Jonson, R.I. Shekhter, Phys. Rev. Lett. **70**, 2940 (1993)
18. J.W. Pan, S. Gasparoni, M. Aspelmeyer, T. Jennewein, A. Zeilinger, Nature **421**, 721 (2003)
19. D. Bouwmeester, J.-W. Pan, H. Weinfurter, A. Zeilinger, J. Mod. Opt. **47**, 279 (2000)
20. D.V. Averin, Yu.V. Nazarov, in *Single Charge Tunneling*, H. Grabert, M.H. Devoret (Plenum, New York, 1992)
21. L.I. Glazman, K.A. Matveev, Pis'ma Zh. Eksp. Teor. Fiz. **49**, 570 (1989) [JETP Lett. **49**, 659 (1989)]
22. U. Geigenmüller, G. Schön, Europhys. Lett. **10**, 765 (1989); D.V. Averin, A.N. Korotkov, K.K. Likharev, Phys. Rev. B **44**, 6199 (1991); C.W.J. Beenakker, *ibid.* **44**, 1646 (1991)
23. S.A. Gurvitz, Ya.S. Prager, Phys. Rev. B **53**, 15932 (1996)
24. J.S. Bell, Rev. Mod. Phys. **38**, 447 (1966); J.F. Clauser *et al.*, Phys. Rev. Lett. **23**, 880 (1969)
25. P. Recher, D. Loss, Phys. Rev. B **65**, 165327 (2002); V. Bouchiat, N. Chtchelkatchev, D. Feinberg, G. Lesovik, T. Martin, J. Torres, Nanotechnology **14**, 77 (2003)