Undoing a weak quantum measurement of a solid-state qubit

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We propose an experiment which demonstrates the undoing of a weak continuous measurement of a solid-state qubit, so that any unknown initial state is fully restored. The undoing procedure has only a finite probability of success because of the non-unitary nature of quantum measurement, though it is accompanied by a clear experimental indication of whether or not the undoing has been successful. The probability of success decreases with increasing strength of the measurement, reaching zero for a traditional projective measurement. Measurement undoing (“quantum un-demolition”) may be interpreted as a kind of a quantum eraser, in which the information obtained from the first measurement is erased by the second measurement, which is an essential part of the undoing procedure. The experiment can be realized using quantum dot (charge) or superconducting (phase) qubits.

A careless scientist accidentally turns on a quantum detector, disturbing a precious, unknown, quantum state. Dismayed by this event, he desperately asks if there is a way to get the state back. Is it possible to undo a quantum measurement? According to the traditional theory of projective quantum measurement [1], the answer is no: wavefunction collapse is irreversible, the original state is gone forever and is impossible to resuscitate. However, as will be presently discussed, the situation is different for weak quantum measurements [2, 3, 4, 5]. It is possible to fully restore any unknown, pre-measured state, though with probability less than unity. Such undoing of the measurement disturbance [which we will also refer to as a quantum un-demolition (QUD) measurement] can be accomplished by making an additional weak measurement, which “erases” the information obtained from the first measurement (somewhat similar to the quantum eraser of Scully and Drühl [6]). The success of the undoing procedure is indicated by observing a certain result of the second measurement, in which case the unknown pre-measured state is fully restored. The probability of successfully undoing the quantum measurement decreases with increasing strength of the measurement, tending to zero for a projective measurement.

The possibility of physically undoing (or reversing) a quantum measurement has been previously discussed by Koashi and Ueda [7], who have proposed a quantum optics photon-counting implementation of the idea, using the Kerr effect. Reversible measurement has also been discussed by others [8, 9] (see also the closely related articles [10]), though mainly from a more formal perspective. In this Letter, we investigate the undoing of continuous weak measurements, particularly applied to solid state qubits. We first consider a quantum double dot qubit, measured by a quantum point contact, a system of extensive experimental investigation [11]. For this system, we discuss how to practically undo the measurement, and calculate the undoing probability, as well as the mean undoing time. The second system we consider is a superconducting “phase” qubit [12], measured by a nearby SQUID. Coherent non-unitary evolution due to measurement has recently been experimentally verified in this system [13]. We describe the undoing procedure for the phase qubit, and calculate the undoing probability, obtaining a result similar to the quantum dot system.

FIG. 1: (Color online). (a) Schematic of a double-quantum-dot (DQD) charge qubit continuously measured by a quantum point contact (QPC). (b) Illustration of the measurement undoing procedure for the charge qubit. The slanted lines indicate the detector output in the absence of noise, if the qubit is in state $|1\rangle$ or $|2\rangle$. The initial “accidental” measurement can be undone by waiting until the stochastic measurement result $r(t)$ crosses the origin.

Charge qubit.— A double-quantum-dot (DQD) qubit, measured continuously by a symmetric quantum point contact (QPC) [14] [Fig. 1(a)] has been extensively studied in earlier papers. The measurement is characterized by the average currents $I_1$ and $I_2$ corresponding to the qubit states $|1\rangle$ and $|2\rangle$, and by the shot noise spectral density $S_f$ [15]. We treat the additive detector shot noise...
as a Gaussian, white, stochastic process, and assume the detector is in the weakly responding regime, $|\Delta I| \ll I_0$, where $\Delta I = I_1 - I_2$ and $I_0 = (I_1 + I_2)/2$, with QPC voltage bias larger than all other energy scales, so that the measurement process can be described by the quantum Bayesian formalism [4].

Let us first assume that there is no qubit Hamiltonian evolution (this can also be effectively done using “kicked” QND measurements \footnote{5}). As was shown in \footnote{4}, the QPC is an ideal quantum detector (which does not decohere the measured qubit), so that the evolution of the qubit density matrix $\rho$ due to continuous measurement preserves the quantity $\rho_{12}/\sqrt{\rho_{11}\rho_{22}}$, while the diagonal matrix elements are normalized at all times and evolve according to the classical Bayes rule:

$$\rho_{11}(t) = \frac{\rho_{11}(0)}{\rho_{22}(0)} \exp[-(\bar{I}(t) - I_1)^2t/S_I],$$

$$\rho_{22}(t) = \frac{\rho_{22}(0)}{\rho_{11}(0)} \exp[-(\bar{I}(t) - I_2)^2t/S_I],$$

where $\bar{I}(t) = \int_0^t I(t') dt'/t$ and we define the measurement result as $r(t) = \bar{I}(t) - I_0$, $\Delta I/S_I$. For times much longer than the “measurement time” $T_m = 2S_I/(\Delta I)^2$ (the time scale required to obtain a signal-to-noise ratio of 1), the average current $\bar{I}$ tends to either $I_1$ or $I_2$ because the probability density $P(\bar{I})$ of a particular $\bar{I}$ is

$$P(\bar{I}) = \sum_{i=1,2} \rho_{ii}(0) \sqrt{t/\pi S_I} \exp[-(\bar{I} - I_i)^2t/S_I].$$

Therefore $r(t)$ tends to $\pm \infty$, continuously collapsing the state to either $|1\rangle$ (for $r \to \infty$) or $|2\rangle$ (for $r \to -\infty$). Critical to what follows, notice that if $r(t) = 0$ at some moment $t$, then the qubit state becomes exactly the same as it was initially, $\rho(t) = \rho(0)$. This curious fact corresponds to an equal likelihood of the states $|1\rangle$ and $|2\rangle$, and therefore provides no information about the qubit.

**Measurement undoing for the charge qubit.**—Let the outcome of the “accidental” first measurement be $r_0$. The previous “no information” observation suggests the following strategy: continue measuring, with the hope that after some time $t$ the stochastic result of the second measurement $r_u(t)$ becomes equal to $-r_0$, so the total result $r(t) = r_0 + r_u(t)$ is zero, and therefore the initial qubit state is fully restored. If this happens, the measuring device is immediately switched off and the undoing procedure is successful [Fig. 1(b)]. However $r(t)$ may never cross the origin, and then the undoing attempt fails.

The success probability $P_s$ for this procedure may be calculated by noticing that the nondiagonal matrix elements of $\rho$ do not enter the probability of the detector output \footnote{4} (this is true only in the case of zero or QND-eliminated qubit Hamiltonian), and therefore the calculation is identical for a classical bit with probabilities $P_{1,2} = \rho_{11,22}(0)$ of being in state “1” or “2”. These probabilities should be updated (using the classical Bayes formula) with the information obtained from result $r_0$:

$$\tilde{P}_1 = P_1 e^{r_0}/[P_1 e^{r_0} + P_2 e^{-r_0}], \quad \tilde{P}_2 = 1 - \tilde{P}_1.$$

Assume for definiteness $r_0 > 0$. We will now calculate the probability that the random variable $r(t)$ crosses the origin at least once, known in stochastic physics as a first passage process. It follows from \footnote{2} that both cases may be described by two different random walks with the initial condition $r = r_0$ at $t = 0$, described by the Green function solution of the two Fokker-Planck equations

$$\partial_t G_i(r, t) = -v_i \partial_r G_i + D \partial^2_r G_i + \delta(r - r_0) \delta(t),$$

supplemented with an absorbing boundary condition at the origin, where $D = 1/(2T_m)$ is the diffusion coefficient, and $v_i = (-1)^i + 1/T_m$ are the two different drift velocities, depending on the bit state. Equations \footnote{3} may be solved with standard methods \footnote{17} and from the solution, the first passage time distribution $P_{\text{fpt}}(r_0)$ is found from the probability current flux at the origin,

$$P_{\text{fpt}}(r_0) = \frac{r_0}{\sqrt{4\piDt}} \exp\left[-(r_0 + v_0t)^2/(4Dt)\right].$$

The probability that $r = 0$ is ever crossed is found by integrating \footnote{4} over all positive time to obtain $P_{c,1} = \exp(-v_1 r_0/D) = \exp(-2r_0)$ for the crossing probability if $i = 1$, and $P_{c,2} = 1$ if $i = 2$. This result is intuitive because starting at $r_0 > 0$, a negative drift velocity must cause an eventual crossing, while a positive drift velocity can only occasionally be beaten by the noise term. The mean first passage time may also be calculated from \footnote{4} to obtain $t_{c,i} = r_0/|v_i|$, averaging only over successful attempts. Analogous results for $r_0 < 0$ are straightforward.

Combining these results, the probability $P_s = \tilde{P}_1 P_{c,1} + \tilde{P}_2 P_{c,2}$ for a successful quantum undemolition measurement is

$$P_s = e^{-r_0}/[e^{r_0} \rho_{11}(0) + e^{-r_0} \rho_{22}(0)],$$

and the mean waiting time $T_{\text{undo}} = \tilde{P}_1 t_{c,1} + \tilde{P}_2 t_{c,2}$ until the measurement is undone is

$$T_{\text{undo}} = T_m |r_0|.$$
qubits, the QUD measurement restores the initial entangled state; the density matrix in 6 in this case can be obtained by tracing over all other quubits. (vi) After the initial measurement, the state evolution is given as a one-to-one map, whose inverse is known. However, the nonunitality of the inverse makes its realization impossible via Hamiltonian evolution; therefore a QUD measurement must be probabilistic. (vii) The undoing probability averaged over the result \( t_0, \rho_{av} = 1 - \text{erf}[\sqrt{t/(2T_m)}] \), depends on the “strength” \( t/T_m \) of the first measurement, but not on the initial state.

**Phase qubit.**— The second explicit example of erasing information and undoing a quantum measurement is for a superconducting “phase” qubit [12,13]. The system (similar to the “flux” qubit) is comprised of a superconducting loop interrupted by one Josephson junction [Fig. 2(a)], which is controlled by an external flux \( \phi_c \). Qubit states |1⟩ and |2⟩ [Fig. 2(b)] correspond to the two lowest states in a quantum well with potential energy \( V(\phi) \), where \( \phi \) is the superconducting phase difference across the junction (for consistency with the previous example, we do not use the more traditional notation \(|0⟩ \) and \(|1⟩ \)). The qubit is measured by lowering the barrier (which is controlled by \( \phi_c \)), so that the upper state |2⟩ tunnels into the continuum with rate \( \Gamma \), while state |1⟩ does not tunnel out. The tunneling event is sensed by a two-junction detector SQUID inductively coupled to the qubit [Fig. 2(a)].

For sufficiently long tunneling time \( t, \Gamma t \gg 1 \), the measurement corresponds to the usual collapse: the qubit state is either projected onto the lower state |1⟩ (if no tunneling is recorded) or destroyed (if tunneling happens). However, if the barrier is raised after a finite time \( t \sim \Gamma^{-1} \), the measurement is weak: the qubit state is still destroyed if tunneling happens, while in the case of no tunneling (a null-result measurement) the qubit density matrix evolves in the rotating frame as [13,14]

\[
\frac{\rho_{11}(t)}{\rho_{22}(t)} = \frac{\rho_{11}(0)}{\rho_{22}(0)} e^{-i\phi(t)}, \quad \frac{\rho_{12}(t)}{\sqrt{\rho_{11}(t)\rho_{22}(t)}} = \frac{\rho_{12}(0)}{\sqrt{\rho_{11}(0)\rho_{22}(0)}} e^{-i\phi(t)},
\]

where the phase \( \phi(t) \) accumulates because of the change of energy difference between states |1⟩ and |2⟩ when the barrier is lowered by changing \( \phi_c \). Notice that except for the effect of the extra phase \( \phi(t) \), the qubit evolution [7] is similar to the qubit evolution in the previous example; in particular, it also represents an ideal measurement which does not decohere the qubit, and has a clear Bayesian interpretation. Formally, the evolution [7] corresponds to the measurement result \( r = \Gamma t/2 \) in Eq. 4. The coherent non-unitary evolution [14] has been experimentally verified in Ref. [13] using tomography of the post-measurement state (in [13] the product \( \Gamma t \) was actually varied by changing the tunneling rate \( \Gamma \), while keeping the duration \( t \) constant).

**Measurement undoing for the phase qubit.**— A slight modification of the experiment [13] can be used to demonstrate measurement undoing. Suppose the tunneling event did not happen during the first weak measurement, so the evolution [7] has occurred. The undoing of this measurement consists of three steps: (i) Exchange the amplitudes of states |1⟩ and |2⟩ by the application of a π-pulse, (ii) perform another weak measurement, identical to the first measurement, (iii) apply a second π-pulse. If the tunneling event did not occur during the second measurement, then the information about the initial qubit state is erased (both basis states have equal likelihood for two null-result measurements). Correspondingly, according to Eq. 4 (which is applied for the second time with exchanged indices \( 1 \leftrightarrow 2 \)), any initial qubit state is fully restored (notice that the phase \( \phi \) is also canceled).

The success probability \( P_s \) for the undoing procedure is just the probability that the tunneling does not happen during the second measurement. If we start with the qubit state \( \rho(0) \), the state after the first measurement is given by Eq. 7. After the π-pulse, the occupation of the upper state is \( \rho_{22}^{'} = \rho_{11}(0)/[\rho_{11}(0) + \rho_{22}(0) e^{-i\Gamma t}] \), so the success probability \( P_s = 1 - \rho_{22}^{'}(1 - e^{-i\Gamma t}) \) can be expressed as

\[
P_s = e^{-i\Gamma t}/ [\rho_{11}(0) + e^{-i\Gamma t} \rho_{22}(0)],
\]

which formally coincides with Eq. 4 for \( r = \Gamma t/2 \). While measurement undoing is most important for an unknown state, in the demonstration experiment the initial state can be known, and tomography of the final state can be used to check that it is identical to the initial state.

**General theory of measurement undoing.**—Applying POVM formalism [2], we can describe a general quantum measurement with result \( r \) by a linear operator \( M_r \), so that for an initial state \( \rho \) the probability of result \( r \) is \( P_r(\rho) = \text{Tr}(E_r \rho) \), where \( E_r = M_r^\dagger M_r \), and the state after measurement is \( \tilde{\rho} = M_r \rho M_r^\dagger /\text{Tr}(E_r \rho) \). Here \( E_r \) is a positive Hermitian operator, obeying the completeness relation \( \sum_r E_r = 1 \). In order to undo this measurement, we should apply the inverse operation characterized by \( L_r = C M_r^{-1} \), where \( C \) is a complex number. Such an operation is physical (i.e., can be realized by a second measurement yielding a “lucky” result) only if all eigenvalues of \( L_r^\dagger L_r \) are not larger than 1 (otherwise completeness cannot be satisfied), which leads to the upper bound

![FIG. 2: (a) Schematic of a phase qubit controlled by an external flux \( \phi_c \) and inductively coupled to the detector SQUID. (b) Energy profile \( V(\phi) \) with quantized levels representing the qubit states. The tunneling event is sensed by the SQUID.](image-url)
Therefore, the probability $P_r = \text{Tr}(L_r \rho)$ of the lucky result corresponding to $L_r$ is bounded by $(\min_r p_i)/P_r(\rho)$. Finally recalling that $\{p_i\}$ are probabilities of the result $r$ for eigenvectors of $E_r$, we find the upper bound for the probability of successful undoing (similar to the result of [7]):

$$P_s \leq (\min_r P_r)/P_r(\rho),$$

(9)

where $\rho$ is the initial state and $\min_r P_r$ is the probability of the result $r$ minimized over all possible initial states. Notice that averaging of $P_r$ over the result $r$ makes it independent of the initial state: $P_{av} = \sum_r (\min_r P_r)$.

Let us compare the general upper bound (9) for $P_s$ with the results (1) and (2) of the two previous examples. For the QPC measurement of the DQD qubit described by Eq. (1), the operator $E_r$ is diagonal in the measurement basis $|1\rangle$, $|2\rangle$ and has matrix elements

$$p_i = (\pi S_i/|t|)^{-1/2} \exp[-(I_1 - I_2)^2 S_i/I_3], i = 1, 2,$

related to the probability densities of the continuous variable $\bar{I}$. Then the upper bound (1) becomes $\min(p_1, p_2)/(p_1 p_{11} + p_2 p_{22})$, which coincides with Eq. (3) because $p_1/p_2 = e^{2\tau}$. We conclude that our undoing strategy is optimal, since the upper bound (1) is reached. For the example of phase qubit measurement, the operator $E_r$ corresponding to the null-result measurement (no tunneling) is also diagonal in the measurement basis $|1\rangle$, $|2\rangle$ and has matrix elements 1 and $e^{-\gamma \tau}$ respectively. Again, $P_s$ given by (1) reaches the upper bound (1), thus confirming the optimality of the analyzed undoing procedure.

**Explicit general procedure of measurement undoing.** We briefly discuss a procedure to undo (in principle) an arbitrary one-to-one measurement $M_r$ for any number $N$ of entangled charge qubits, using unitary rotations and measurement by a QPC with an extremely strong nonlinearity, so that tunneling (with rate $\gamma$) occurs in the QPC only when all qubits are in the state $|1\rangle$. For simplicity assume $M_r = \sqrt{E_r}$ (the generalization is trivial). In the basis of $2^N$ vectors $|i\rangle$ diagonalizing $E_r$, the desired undoing operator $L_r = \sqrt{\min_j p_j M_j^{-1}}$ (see above) is also diagonal: $L_{r,ii} = \sqrt{(\min_j p_j)/p_i}$. It can be realized in $2^N$ steps. The $i$th step consists of a unitary rotation of the vector $|i\rangle$ into the state $|1\ldots1\rangle$, measurement by the QPC for duration $\tau_i = -\gamma^{-1} \ln L_{r,ii}$, and the reverse unitary rotation. In each step the no-tunneling result corresponds to the measurement operator, which is almost unity, except for diagonal matrix element $e^{-\gamma \tau_i/2} = L_{r,ii}$ for the vector $|i\rangle$. The measurement undoing procedure is successful if no tunneling occurred in all steps. The corresponding success probability reaches the upper bound (1).

**Undoing continuous measurement of an evolving charge qubit.** In our first example we have assumed for simplicity that the qubit is not undergoing Hamiltonian evolution during the measurement process to be undone. We briefly note that a QUD measurement is also possible when Hamiltonian evolution is included. In this case the qubit evolution is described by the Bayesian equations [4], which can be used to find the operator $M_r$ from the measurement record $I(t)$ (the non-normalized version of the Bayesian equations is more appropriate for this purpose). Then the desired undoing operator $L_r$ can be realized in three steps, corresponding to the singular value decomposition of $L_r$: unitary rotation, continuous measurement by QPC (with internal qubit dynamics turned off), and one more unitary rotation. (The details of this calculation and the explicit undoing procedure will be presented elsewhere.)

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