

Nondestructive measurement of electron spins in a quantum dot

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We propose and implement a nondestructive measurement that distinguishes between two-electron spin states in a quantum dot. In contrast to earlier experiments with quantum dots, the spins are left behind in the state corresponding to the measurement outcome. By measuring the spin states twice within a time shorter than the relaxation time T_1 , correlations between the outcomes of consecutive measurements are observed. They disappear as the wait time between measurements becomes comparable to T_1 . The correlation between the postmeasurement state and the measurement outcome is measured to be $\sim 90\%$ on average.

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I. INTRODUCTION

In standard quantum mechanics, repeated measurements of the same observable produce the same outcome.¹ Readout schemes with this property are called *nondestructive*. In reality, a measurement often destroys the measured physical object itself, in which case repeated measurements are not possible. This is the case, for instance, with conventional photon detectors where the photon does not exist any more after the measurement. Even if the physical object itself is not destroyed by the measurement, the state after the measurement may not correspond to the measurement outcome and a second measurement may give a different result from the first measurement. This we call a destructive measurement.

In quantum dots, nondestructive measurements of the charge state have been implemented.^{2,3} For spin states in quantum dots, however, all single-shot readout schemes used so far are destructive. Either the spin is always left in the ground state,⁴ or the number of electrons in the dot is changed as a result of the measurement.⁵ In both cases, repeated measurements will generally produce different outcomes. The question whether or not one is able to design a nondestructive single-shot measurement of the spin is still open. Beyond this fundamental point, nondestructive measurements are also of practical relevance in the context of quantum information processing. For instance, nondestructive measurements can be used to quickly (re)initialize selected qubits.⁶

Here, we present and implement a nondestructive, single-shot measurement scheme that distinguishes two-electron singlet from triplet states in a single quantum dot. In order to demonstrate experimentally the nondestructive nature of the measurement, we take advantage of the remarkably long spin relaxation time T_1 ,^{4,5,7} and of the single-shot nature of the measurement, to repeat the measurement twice within T_1 . We then demonstrate experimentally that the spin state after the readout corresponds to the measurement outcome.

II. NONDESTRUCTIVE SPIN MEASUREMENT SCHEME

Our measurement scheme is based on spin-to-charge conversion taking advantage of a difference in the rate with

which electrons tunnel between a quantum dot and a reservoir, depending on the spin state, as in Ref. 5. In the case of the singlet, both electrons are in the ground state orbital whereas for the triplet state, one electron is in the first excited orbital. The excited orbital has a stronger overlap with the reservoir than the lowest orbital, causing the tunnel rate to and from the triplet state Γ_T to be much larger than the tunnel rate to and from the singlet state Γ_S .⁵

To implement the nondestructive measurement, we pulse the potential of the dot at zero magnetic field so the electrochemical potential for both the singlet and the triplet state lies above the Fermi energy for a short time τ (see Fig. 1), satisfying the relation $1/\Gamma_T \ll \tau \ll 1/\Gamma_S$. In the experiment, $1/\Gamma_T \approx 5 \mu\text{s}$, $\tau = 20 \mu\text{s}$, and $1/\Gamma_{S,out} = 100 \mu\text{s}$ (for the singlet, we observe that the time to tunnel in is different from the time to tunnel out:⁸ $1/\Gamma_{S,in} \approx 1000 \mu\text{s}$). If the dot is in the singlet state, most of the time no electron tunnels out during the entire pulse sequence since τ is small in comparison with $1/\Gamma_S$, even though tunneling would be energetically allowed. In the case of the triplet state, an electron will tunnel off the dot after the pulse is applied, in a time $1/\Gamma_T$ much smaller than τ . In this case, an electron tunnels back in after the pulse and it will tunnel into the triplet state with high probability since $\Gamma_T \gg \Gamma_S$.

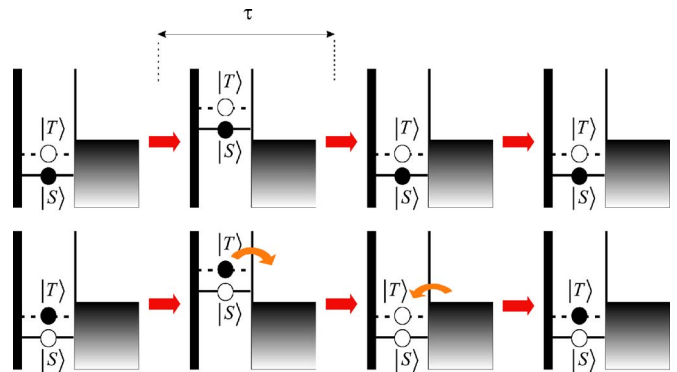


FIG. 1. (Color online) Schematic of the quantum dot throughout the nondestructive measurement scheme, for a singlet (top) or triplet (bottom) initial state. Curved arrows indicate tunnel process. The interesting feature is that the spin state is the same before and after the measurement.

The proposed readout scheme is thus nondestructive in the sense that the state after the measurement coincides with the measurement result. For a singlet initial state, the dot remains in the singlet all along; for a triplet initial state, the dot is reinitialized to the triplet state after the measurement.

We point out that the proposed scheme is conceptually similar to the measurement procedure used for trapped ions.⁹ In both systems, we can distinguish the two relevant states depending on whether or not a transition is made through a third state (a reservoir for the electron spin and a short-lived internal level for the ion).

III. EXPERIMENTAL TECHNIQUES

We test this measurement concept with a quantum dot [white dotted circle in Fig. 2(a)] and a quantum point contact (QPC) defined in a two-dimensional electron gas with an electron density of $1.3 \times 10^{15} \text{ m}^{-2}$, 90 nm below the surface of a GaAs/Al_xGa_{1-x}As heterostructure, by applying negative voltages to gates *L*, *M*, *T*, and *Q*. Fast voltage pulses on gate *P* are used to rapidly change the electrochemical potential of the dot. All measurements are performed at zero magnetic field. We tune the dot to the few-electron regime,^{10,11} and completely pinch off the tunnel barrier between gates *L* and *T*, so that the dot is only coupled to the reservoir on the right.¹² The conductance of the QPC is tuned to about e^2/h , making it very sensitive to the number of electrons on the dot.² A voltage bias of 0.7 mV induces a current through the QPC, I_{QPC} , of about 30 nA. Tunneling of an electron on or off the dot gives steps in I_{QPC} of 300 pA,^{13,14} and we observe them in the experiment with a measurement bandwidth of 60 kHz.

IV. SINGLE MEASUREMENT

First we demonstrate that the nondestructive measurement correctly reads out the spin states. The experiment consists in reconstructing a relaxation curve from the triplet to the singlet and comparing the results with those obtained using the known destructive readout scheme.⁵ The protocol is illustrated in Fig. 2(b). The starting point is a dot with one electron in the ground state (initialization). In the second stage of the pulse, the singlet and triplet electrochemical potentials are below the Fermi energy and a second electron tunnels into the dot. Since $\Gamma_T \gg \Gamma_S$, most likely a triplet state will be formed, on a time scale of $1/\Gamma_T$. The measurement pulse is applied after a waiting time that we vary. Due to the direct capacitive coupling of gate *P* to the QPC channel, ΔI_{QPC} follows the pulse shape [see Fig. 2(c)]. The precise amplitude of the QPC pulse response directly reflects the charge state of the dot throughout the readout pulse. If the two electrons remain in the dot, the QPC pulse response goes below a predefined threshold, and we conclude that the dot was in the singlet state [outcome '*S*', see Fig. 2(c) left]. Otherwise, if one electron tunnels out in a time shorter than the pulse response time, the QPC pulse response stays above the threshold and we declare that the dot was in the triplet state [outcome '*T*', see Fig. 2(c) right].¹⁵

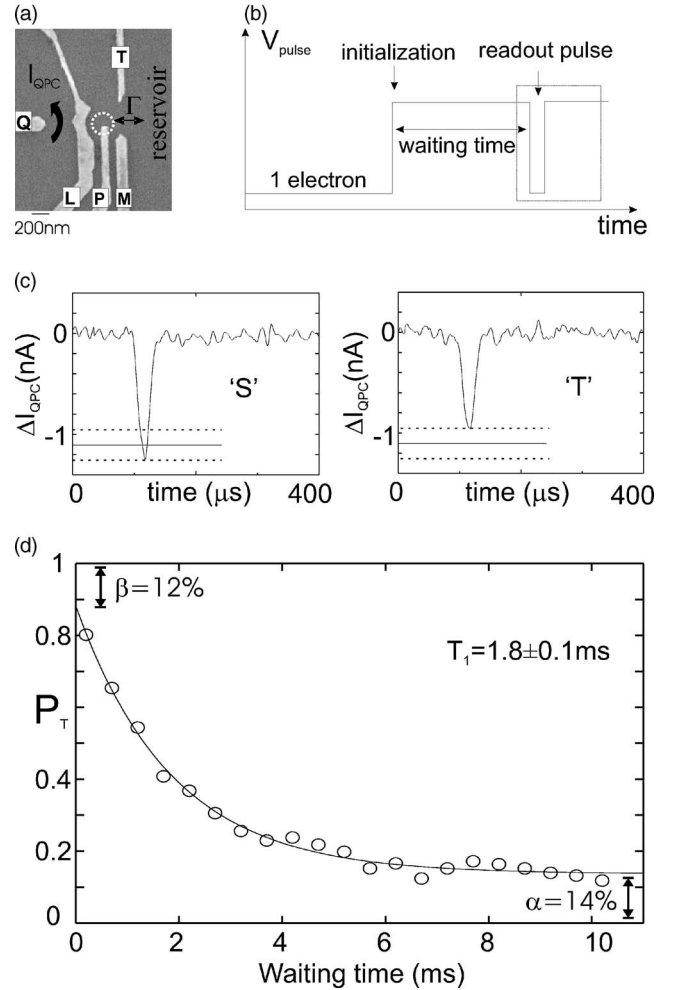


FIG. 2. (a) Scanning electron micrograph showing the sample design. (b) Voltage pulses applied to gate '*P*' for the relaxation measurement. (c) Typical QPC response in the 400 μs interval indicated by the rectangle in (b), for the case of singlet (left) and triplet (right). The reference of the time axis is taken 100 μs before the measurement pulse is applied. The solid horizontal line indicates the position of the threshold. The dotted lines indicate the expected value for the dip in ΔI_{QPC} for the case of '*S*' and '*T*'. (d) The probability for detecting a triplet state as a function of the waiting time. Each point is an average over 500 experiments. The solid line is an exponential fit to the data. The measurement errors α and β (see text) are indicated.

As expected, we observe an exponential decay of the triplet population as a function of the waiting time, giving a relaxation time T_1 equal to 1.8 ± 0.1 ms. The measurement errors are $\alpha = 0.14$ and $\beta = 0.12$, where α (β) is defined as the probability for the measurement to return triplet (singlet) if the actual state is singlet (triplet). We observe the same values (within error bars) when using the known destructive readout scheme in this same measurement run. In both cases, measurement errors are completely explained by the two different tunnel rates.⁵ The resulting measurement fidelity $1 - (\alpha + \beta)/2$ is 87%. It is worth noticing that in this readout scheme the measurement time $t_{meas} \approx \tau = 20 \mu\text{s}$ is much shorter than T_1 ($T_1/t_{meas} \approx 90$).

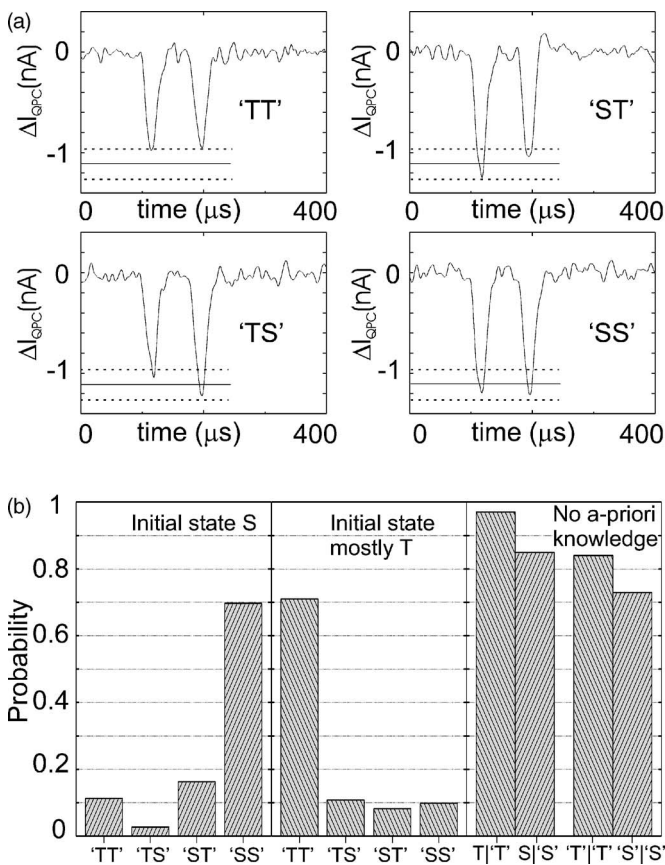


FIG. 3. (a) Typical QPC response for two consecutive measurements in the cases of 'SS', 'TT', 'ST', and 'TS'. The threshold is the same for the two nondestructive measurement pulses. The pulse width is 20 μs and the delay between the two measurement pulses is 60 μs . The dotted lines indicate the expected value for ΔI_{QPC} for the cases of 'S' and 'T'. (b) The recorded probabilities for each of these four events over 3000 runs, with the singlet (first graph) and mostly the triplet (second graph) as the initial state. In the third graph, the conditional probabilities $P(T|T')$ and $P(S|S')$ that the state after the first measurement corresponds to the outcome of the first measurement and the conditional probabilities $P(T'|T')$ and $P(S'|S')$ that the second measurement gives the same outcome as the first one are presented. They are extracted from the two previous graphs and the known α and β with no *a priori* knowledge of the initial state.

V. REPEATED MEASUREMENTS

We next test whether the measurement is nondestructive by studying the correlations between the outcomes of two successive measurements. We program a second readout pulse 60 μs after the end of the first pulse and record the probability for each of the four combined outcomes, 'SS', 'TT', 'ST', 'TS' (Fig. 3). In order to accurately characterize the measurement, we first do this with singlet initial states (prepared by waiting 20 ms for complete relaxation), and then again with mostly triplet initial states (prepared by letting the second electron tunnel in 200 μs before the first measurement¹⁶). A clear correlation between consecutive measurement outcomes is observed [Fig. 3(b)], for both singlet and triplet initial states.

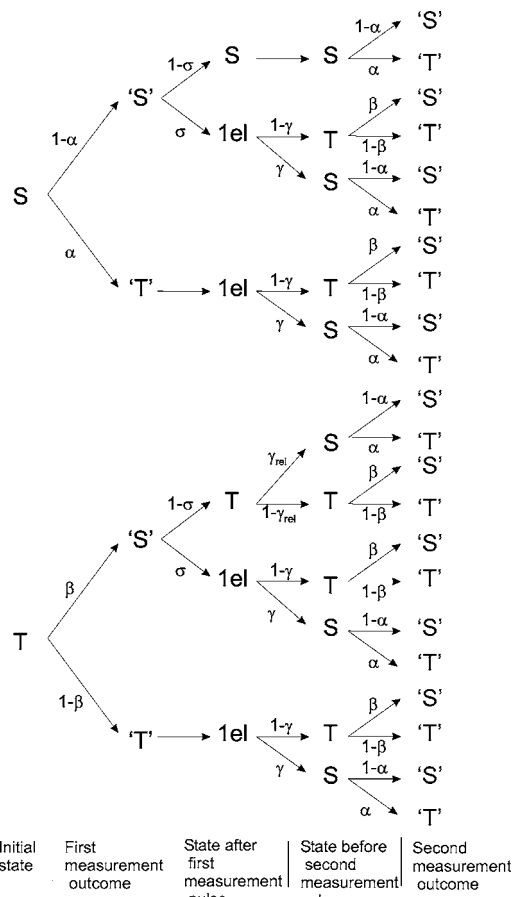


FIG. 4. Different events and their probabilities throughout the process of the two consecutive measurements for singlet S or triplet T as an initial state. State 1 corresponds to the dot configuration where only one electron is in the dot. α and β are defined as the probability for the measurement to return respectively triplet and singlet if the actual state is singlet and triplet. They are obtained directly from the relaxation curve, giving $\alpha=14\%$ and $\beta=12\%$. γ_{rel} is the known probability that the triplet state relaxes to singlet between the two measurement pulses separated by 60 μs . $\gamma_{rel}=3\%$ from the knowledge of T_1 . σ is the probability for an electron to tunnel out even though the QPC signal did go below the threshold and a 'S' outcome has been declared (we assume that σ is equal for singlet and triplet initial states). Finally, γ is the probability that, after reinitializing to a two-electron state and subsequent relaxation for 60 μs , a singlet state is present in the dot. In the experiment, $\sigma=5\%$ and $\gamma=3\%$, determined from the above probability tree, the known values of α , β , γ_{rel} , and the correlation data.

When we average over S or T initial states (i.e., when we have no *a priori* knowledge of the spin state), we find, from the correlation data and the known values of α and β , an 85% (73%) conditional probability for outcome 'T' ('S') in the second measurement given that the first measurement outcome was 'T' ('S').

The degree to which the scheme is nondestructive is quantified via the probability for obtaining an S or T post-measurement state (60 μs after the end of the first pulse) conditional on the measurement outcome. From the correlation data and the known values of α and β , we extract a 97% (84%) conditional probability $P(T|T')$ [$P(S|S')$], again as-

suming no *a priori* knowledge of the initial state. For a triplet outcome, one electron tunneled out during the measurement pulse, and another electron tunneled back in after the pulse. A triplet state is formed with near certainty in this reinitialization process (since $\Gamma_T/\Gamma_{S,in} \approx 200$), but the triplet state can relax to the singlet during the $60 \mu\text{s}$ wait time between the two measurements. This occurs with a probability γ of 3%, which explains the observed conditional probability $P(T|T')$. The conditional probability $P(S|S')$ can be found as $1 - P(T,S')/P(S')$. $P(S')$ is simply $[(1-\alpha)+\beta]/2$ (averaged over S and T initial states). There are two main contributions to $P(T,S')$. First, for $\beta=12\%$ of the triplet initial states, both electrons remain on the dot. In this case, a singlet outcome is declared but the postmeasurement state is almost always a triplet. Second, for singlet initial states, a singlet outcome is obtained with probability $1-\alpha=86\%$. For $\sigma=5\%$ of those cases, one electron nevertheless tunneled out and the postmeasurement state is a triplet. The full statistical description of the repeated measurement process is presented in Fig. 4.

An attractive feature of nondestructive measurements is that it allows one to study the time evolution between two successive measurements. As a proof of principle, we let the spin evolve under relaxation for a controlled time in between two measurements. The singlet state is not affected by relaxation, so we initialize the dot (mostly, as before) in the triplet state. In Fig. 5(a), the probabilities for the four possible outcomes are recorded as a function of the waiting time. We notice that $'TT'$ and $'TS'$, respectively, decay and increase exponentially, with a time constant 1.5 ± 0.3 ms, within the error bars of the relaxation time obtained from Fig. 2(d).

Finally, we remark that the nondestructive nature of the measurement relies on our ability to tune the dot in a regime where $1/\Gamma_T \ll \tau \ll 1/\Gamma_{S,out}$. If $\tau \gg 1/\Gamma_{S,out}$, $1/\Gamma_T$, the measurement is destructive, because one electron will tunnel off the dot during the readout pulse irrespective of the state of the dot. The information about the spin state is then lost after the readout and the postmeasurement state will always be a triplet. We can vary the duration of the pulse in order to make the transition from nondestructive to destructive readout. Here we initialize in the singlet state, since for triplet initial states the postmeasurement state does not change with τ . Figure 5(b) summarizes the results. The four different curves correspond to each combination of measurement outcomes as a function of the duration of the pulse. As expected, the $'TS'$ and $'TT'$ statistics are steady, while the $'SS'$ ($'ST'$) probabilities decay (increase) exponentially with a time constant $105 \pm 10 \mu\text{s}$, within the error bars of $1/\Gamma_{S,out}$.

VI. CONCLUSIONS AND PERSPECTIVES

We demonstrate our ability to implement a nondestructive measurement scheme for distinguishing two-electron singlet from triplet states in a single quantum dot. The spin system is

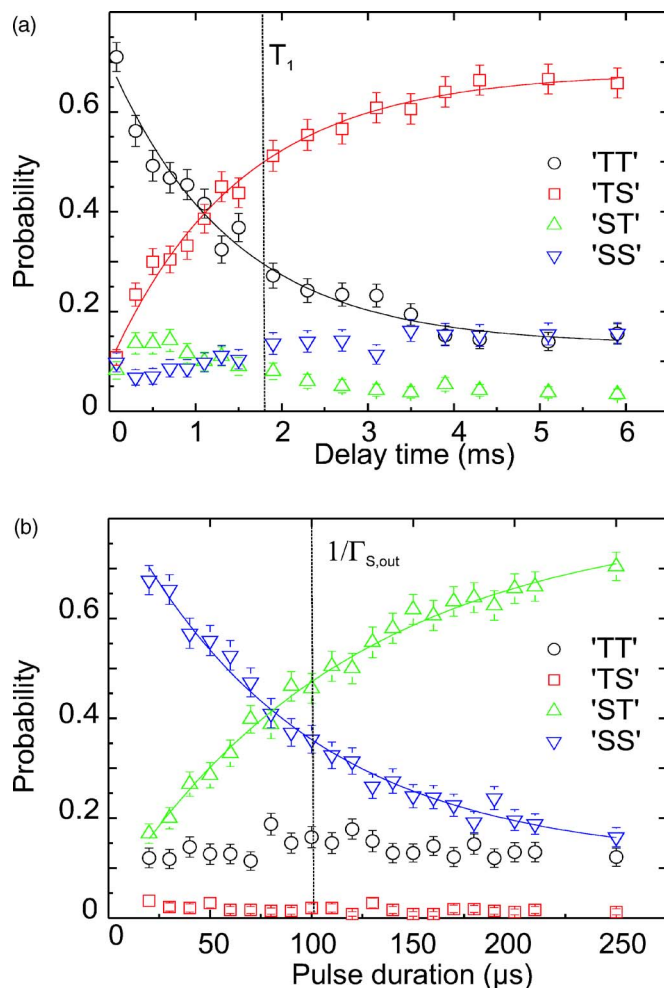


FIG. 5. (Color online) The probabilities for the two consecutive measurement outcomes as a function of (a) the measurement delay and (b) the measurement pulse duration. The solid lines represent exponential fits to the data.

not strictly preserved throughout the entire measurement process. In that respect, our scheme differs from a quantum nondemolition measurement.¹ Nevertheless, repeated measurements give the same results and the postmeasurement state corresponds to the measurement outcome. All the imperfections in the correlations observed in the experiments are explained by the ratio between the singlet and triplet tunnel rates, and the relaxation rate from triplet to singlet. Other spin-dependent tunnel processes, for instance as observed in double dots,^{17–20} can be used for nondestructive readout, possibly with even higher fidelity.

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