Measurement induced quantum walks on an IBM Quantum Computer

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We study a quantum walk of a single particle that is subject to stroboscopic projective measurements on a graph with two sites. This two-level system is the minimal model of a measurement induced quantum walk. The mean first detected transition and return time are computed on an IBM quantum computer as a function of the hopping matrix element between the sites and the on-site potential. The experimentally monitored quantum walk reveals the theoretically predicted behavior, such as the quantization of the first detected return time and the strong increase of the mean first detected transition time near degenerate points, with high accuracy.

I. INTRODUCTION

Quantum walks are a central concept for quantum information processing [1, 2] as they are indispensable for quantum algorithm development and for modeling of physical processes. Furthermore, they provide a universal model of quantum computation [3] and can be considered as a quantum version of the classical random walk [4]. Measurement induced quantum walks [5] present a special class of quantum walks for which the unitary time evolution is supplemented by a (projective) measurement, resulting in a non-unitary evolution. To study this effect on a quantum computer, we consider a closed quantum system that is subject to repeated identical projective (stroboscopic) measurements and that evolves unitarily between two successive measurements. The combined evolution of the system is non-unitary and can be understood as a monitored evolution (ME) which has some surprising properties. Assuming stroboscopic measurements, where a projection is applied repeatedly after a fixed time interval \( \tau \), we count the number of measurements to observe a certain quantum state for the first time. This number depends on the size of the underlying Hilbert space, the time interval \( \tau \), the detected state as well as the initial state, in which the quantum system was prepared. We must distinguish two different cases: the first detected return (FDR), where the initial state and the measured state are identical and the first detected transition (FDT), where the initial state and the measured state are different. The FDR has been intensively studied and revealed some remarkable properties [6–14]: The mean FDR time \( \tau \langle n \rangle \) is quantized, where \( \langle n \rangle \) is equal to the number of energy levels [6, 7]. Degenerate energy levels count only once. This implies that \( \langle n \rangle \) jumps if we tune the system through a degeneracy. The quantization is related to the integer winding number of the Laplace transform of the return amplitude [6, 15] and exists also for random time steps \( \{ \tau_j \} \) when we average with respect to their distribution [16]. In the latter case, the mean FDR time is formally a Berry phase integral due to the time averaged measurements. The mean FDT time, on the other hand, is not quantized but has characteristic divergences near degenerate energy levels [17–19].

To the best of our knowledge, neither the quantization of the mean FDR time nor the divergences of the mean FDT time have been observed experimentally. However, due to the fast improvement of current quantum computers, including the possibility to implement mid-circuit measurements, which are, e.g., crucial for the realization of quantum error correction protocols [20], these computers provide an excellent platform for testing the theory of the ME with stroboscopic measurements directly. For this purpose, a tight-binding model on a finite graph is realized on an IBM quantum computer to study the mean FDR time and its fluctuations as well as the mean FDT time experimentally. In this work, we focus on the simplest case of a two-site graph with one particle which is already sufficient to observe the characteristic features of the ME, as described above. Such a system is implemented on the IBM quantum computer with one and with two qubits. For a small number of mid-circuit measurements, the error-mitigated results are found to be in very good agreement with the theoretically predicted exact results.

The paper is organized as follows: Sect. II is the theoretical part that describes the model and the ME. A detailed explanation of how the model is implemented on the quantum computer and a discussion of an appropriate error mitigation scheme is provided in Sect. III. In Sect. IV we present the experiments for the FDR/FDT time as well as their variance. We summarize our results in Sect. V and propose some ideas for future studies.

II. MODEL

The tight-binding model for a quantum particle on a finite chain of length \( l \) is described by the particle-number conserving Hamiltonian

\[
H = \sum_{j=1}^{l} (-\gamma_{j,j+1} |j\rangle \langle j+1| + |j+1\rangle \langle j|) + U_j |j\rangle \langle j|
\]
FIG. 1. Scheme of the tight-binding model with two sites. The quantum particle is prepared on the initial site 2 and periodically measured (indicated with the eye). $U$ and $\gamma$ denote the strength of potential and the hopping matrix element, respectively.

with proper boundary conditions. This tight-binding Hamiltonian is encoded by the qubit Hamiltonian

$$H_t = \sum_{j=1}^{l} (U_j \sigma_{z,j} - \gamma_{j,j+1}(\sigma_{x,j}\sigma_{x,j+1} + \sigma_{y,j}\sigma_{y,j+1})), \quad (1)$$

where $\sigma_x$, $\sigma_y$ and $\sigma_z$ are Pauli matrices. The states $|00\ldots0\rangle$, $|00\ldots1\rangle$, ... and $|10\ldots0\rangle$ encode the position of the particle at site 1, 2, ..., and $l$ along the chain. The first term of the Hamiltonian represents the on-site energy $U_i$ on each site $i$, and the second term represents the kinetic energy, parameterized by the hopping matrix element $\gamma$ between neighboring sites.

Now we consider a particle moving on two sites and prepared initially on site 1 at time $t = 0$, which is measured stroboscopically on site 2 after the time $\tau$, $2\tau$ etc. (see Fig. 1). The two-site Hamiltonian $H_2$ acts on the computational basis states $|10\rangle$, $|01\rangle$ and $|11\rangle$ should not be populated. Since only two sites are occupied, we can simplify the two-qubit model described by the Hamiltonian in Eq. (1) to a single-qubit problem with the two basis states $|0\rangle = |01\rangle$ and $|1\rangle = |10\rangle$. In this basis the Hamiltonian matrix reads

$$\langle j| H_2 |j'\rangle = -\gamma \sigma_x + U \sigma_z = \begin{pmatrix} U & -\gamma \\ -\gamma & -U \end{pmatrix}, \quad (2)$$

whose eigenenergies are $E_{1,2} = \pm \sqrt{U^2 + \gamma^2}$.

The ME with $n$ stroboscopic measurements is defined by the evolution operator $|15, 19|

$$M_n = e^{-iH_2\tau}(Pe^{-iH_2\tau})^{n-1}, \quad P = 1 - |j\rangle\langle j| = |j'\rangle\langle j'| \quad (3)$$

with $j, j' \in \{0, 1\}$ and $j' \neq j$, which can also be written for $n \geq 2$ as

$$M_n = e^{-iH_2\tau}(j'\langle j'|e^{-iH_2\tau}|j'\rangle)^{n-2}(j'|e^{-iH_2\tau}). \quad (4)$$

Then, the FDR probability $|\phi_{r,n}|^2 = |\langle j|M_n|j\rangle|^2$ for $|j\rangle \rightarrow |j'\rangle$ reads

$$|\langle j'|e^{-iH_2\tau}|j\rangle|^2 \quad n = 1$$

$$|\langle j'|e^{-iH_2\tau}|j\rangle|^2|\langle j'|e^{-iH_2\tau}|j\rangle|^2 \quad n \geq 2 \quad (5)$$

and the FDT probability $|\phi_{r,n}|^2 = |\langle j|M_n|j\rangle|^2$ for $|j\rangle \rightarrow |j'\rangle$ reads

$$|\langle j'|e^{-iH_2\tau}|j\rangle|^2|\langle j'|e^{-iH_2\tau}|j\rangle|^2 \quad (6)$$

$$|\langle j'|e^{-iH_2\tau}|j\rangle|^2|\langle j'|e^{-iH_2\tau}|j\rangle|^2 \quad (7)$$

For the Hamiltonian $H_2$ with $U = 0$ we get $|\langle j'|e^{-iH_2\tau}|j\rangle|^2 = \cos^2(\gamma \tau)$ and $|\langle j'|e^{-iH_2\tau}|j\rangle|^2 = \sin^2(\gamma \tau)$. Similar but slightly more complex results are obtained for the parameter $c = \cos \left(\sqrt{U^2 + \gamma^2}\tau\right)$ in the general case with $U \neq 0$. Then, for $U = 0$ the distribution function $|\phi_{r,n}|^2$ depends on $c = \cos(\gamma \tau)$ and reads

$$|\phi_{r,n}|^2 = \begin{cases} c^2 & n = 1 \\ (1 - c^2)^2c^{2(n-2)} & n > 1 \end{cases} \quad (6)$$

for the FDR probability and for the FDT probability

$$|\phi_{r,n}|^2 = (1 - c^2)^2c^{2(n-1)}. \quad (7)$$

Thus, the sum of the FDR probabilities for all $n \geq 1$ gives 1 and the mean FDR time is $\tau(n)$. Subsequently, we will call $\langle n \rangle$ mean FDR time, assuming that it is implicitly multiplied by the time step $\tau$.

$c^2 = 1$ plays a special role because then the transition $|j\rangle \rightarrow |j'\rangle$ is completely suppressed:

$$\langle n \rangle = \sum_{n \geq 1} n|\phi_{r,n}|^2 = \begin{cases} 2 & c^2 < 1 \\ 1 & c^2 = 1 \end{cases} \quad (8)$$

The corresponding results of the FDT probabilities are

$$\sum_{n \geq 1} |\phi_{r,n}|^2 = \begin{cases} 0 & c^2 = 1 \\ 1 & c^2 < 1 \end{cases} \quad (9)$$

$$\langle n \rangle = \sum_{n \geq 1} n|\phi_{r,n}|^2 = \begin{cases} 0 & c^2 = 1 \\ 1/(1 - c^2) & c^2 < 1 \end{cases} \quad (10)$$

These FDR/FDT results are obtained for an infinite number of measurements. Since an experiment allows only a finite number of measurements, the corresponding mean FDR/FDT results for $N$ measurements are given in the Supplemental Material. An important difference for a finite number of measurements is that $\langle n \rangle$ in Eq. (10) vanishes rather than diverges for $c^2 \sim 1$.

III. IMPLEMENTATION ON A QUANTUM COMPUTER

A. Single-Qubit Implementation

General operators, such as the unitary evolution operator $\exp(-iH\tau)$, must be constructed on a quantum computer as a product of elementary gate operators. The difficulty is that these gate operators do not commute.
However, if the Hamiltonian $H$ consists of a sum of simple qubit operators we can employ time slicing or Trotterization \cite{21}. In terms of $\exp(-iH_2\tau)$ this means that we divide the time $\tau$ into $k$ time slices $\Delta t$ with $\Delta t = \tau/k$, which provides the approximation 

\[ e^{-iH_2\tau} \approx (e^{i\gamma_3 \sigma_z \Delta t} e^{-iU \sigma_z \Delta t})^k. \]

(11)

In the limit $k \to \infty$ the approximation becomes exact. Therefore, for a good approximation the Trotter number $k$ must be large. In the single-qubit case of $H_2$ we have

\[ e^{-i\gamma_3 \sigma_z \Delta t} = \begin{pmatrix} \cos (\gamma_3 \Delta t) & -i \sin (\gamma_3 \Delta t) \\ -i \sin (\gamma_3 \Delta t) & \cos (\gamma_3 \Delta t) \end{pmatrix} \]

(12)

and

\[ e^{-iU \sigma_z \Delta t} = \begin{pmatrix} e^{-iU \Delta t} & 0 \\ 0 & e^{iU \Delta t} \end{pmatrix} = R_x(2\gamma_3 \Delta t), \]

(13)

such that the single-qubit unitary operator can be written as

\[ e^{-iH_2\tau} \approx \{ R_z(2U \Delta t) \cdot R_x(2\gamma_3 \Delta t) \}^k. \]

(15)

The unitary evolution is followed by a projective measurement in the computational basis, defined by the projectors $P_0 = |0\rangle \langle 0|$ and $P_1 = |1\rangle \langle 1|$. To implement the unitary operator in Eq. (15), followed by projective measurements, we run the following quantum circuit (circuit (1)) on the quantum device

where $k$ denotes the number of Trotter steps and $N$ the number of measurements. The gates $R_z$ and $R_x$ implement the rotations $R_z(2U \Delta t)$ and $R_x(2\gamma_3 \Delta t)$ in Eq. (15), respectively, and the initial state $|j\rangle$ is either $|0\rangle$ or $|1\rangle$.

B. Two-Qubit Implementation

In analogy to the single-qubit case we approximate the unitary time evolution for two qubits with the Hamiltonian

\[ H_2^2 = -\gamma (\sigma_x \otimes \sigma_x + \sigma_y \otimes \sigma_y) + U \sigma_0 \otimes \sigma_z \]

(16)

as

\[ e^{-iH_2^2\tau} \approx (e^{i\gamma \sigma_z \Delta t} e^{i\gamma \sigma_z \Delta t} e^{-iU \sigma_0 \sigma_z \Delta t})^k. \]

(17)

The single factors are written in the basis of $|00\rangle, ..., |11\rangle$ as

\[ e^{i\gamma \sigma_z \Delta t} \approx R_{xx}(2\gamma \Delta t) \]

(18)
This three-qubit repetition code is able to mitigate bit-flip errors by performing a majority vote after each measurement sequence \[22, 23\]. This technique in particular is successful if read-out errors dominate the two-qubit gate errors which is the case if the distribution function \(|\phi_n|^2\) has most of its weight at low number of measurement \(n\) and therefore the result depends only on the first few measurements.

For the two qubit quantum circuits we are using an error detection approach. Errors are detected by measuring both qubits and are present if the state \(|00\rangle\) and \(|11\rangle\) are measured. The data where errors were detected are disregarded.

**IV. FIRST DETECTED RETURN AND TRANSITION EXPERIMENTS**

We use IBM’s open-source Qiskit library for quantum computing. Qiskit provides tools for different tasks such as creating Trotter expansions, quantum circuits with mid-circuit measurements, performing simulations, and computations on real quantum devices \[24\]. Since only a finite number of mid-circuit measurement is possible on the real hardware we discuss the dependence of the result on the number of measurements \(N\) in the supplement.

We perform the experiments by initializing a particle on site 2, letting it freely evolve for some time before we measure if the particle is on site 1 (site 2) and repeat this process \(n\) times until we detect the particle on site 1 (site 2) as visualized in Fig. 1. Based on the stroboscopic measurement protocol, the statistics of the FDR time shows that the mean \(\langle n\rangle\) is quantized and equal to 2 in the two-site tight binding problem, except for the degenerate points, where the potential \(U\) is

\[
U_d = \sqrt{\frac{\pi^2 k^2}{\tau^2} - \gamma^2} \quad (k = 1, 2, \ldots).
\]

In that case we have \(\cos^2(\sqrt{U_d^2 + \gamma^2} \tau) = 1\) and get \(|\phi_{r,1}|^2 = 1\), according to Eq. (6), and \(\langle n\rangle = 1\). Therefore, the particle is measured at the first measurement with certainty.

We start with 5 one-qubit experiments (qubit 12 on IBMQ-Montreal) with 32000 runs for \(U = 0\), \(\tau = 0.4\) and varying \(\gamma\). We initialize the qubit in state \(|0\rangle\) and perform alternating an \(x\)-rotation and a measurement in the \(z\)-basis \(N = 40\) times according to circuit (1). The result is post-processed to obtain the FDT (FDR) probability \(|\phi_{r,n}|^2\) by evaluating the counts and \(n\) where the initial state and the measured state are for the first time different (the same), i.e., when the measured state is for the first time \(|0\rangle\) (\(|1\rangle\)), respectively. From these probabilities we can calculate the mean \(\langle n\rangle\), as defined in Eqs. (8), (10), as well as its second moments \(|n|^2\) for a finite number of measurements (cf. Supplemental Material). The mean FDR time \(\langle n\rangle\) is computed on the IBMQ Montreal with and without error mitigation, with results depicted in Fig. 2 (a). It clearly shows the quantization \(\langle n\rangle = 2\) as well as the degenerate points at \(\gamma = \pi k/\tau\) with \(\gamma = 0\), \(\gamma = \pi/\tau \approx 7.85\) and \(\gamma = 2\pi/\tau \approx 15.7\) (\(\tau = 0.4\), where \(\langle n\rangle = 1\) as expected. At these points the variance \(|n|^2 - \langle n\rangle^2\) shows the theoretically expected divergences in Fig. 2 (b). The experimental values are in very good quantitative agreement with the exact results for \(N = 40\) measurements and are improved by the repetition-code error-mitigation scheme introduced in Sect. III C, see circuit (3).

In Fig. 2 (c) the exact FDR probability is visualized as a function of the hopping matrix element \(\gamma\) and the number of measurements. This agrees very well with the experimental results of the corresponding FDR probability on IBMQ-Montreal without error mitigation in Fig. 2 (d).

According to the theory, the FDT time for the hopping to another site has different properties. Its mean FDT is not quantized and diverges already near the degeneracy \(U_d\). The results for the same parameter as for the FDR are presented in Fig. 3. In Fig. 3 (a) the mean FDT time is small and close to one and it grows near the degenerate points at \(\gamma = \pi k/\tau\), when the particle remains on the initial site. The exact results of the mean FDT time for \(N = 40\) measurements do not diverge at the degenerate points but are zero (cf. Supplemental Materials), in contrast to their divergence for \(N \to \infty\). The experiment shows a finite nonzero value. This is due to the fact that the qubit decays at a smaller \(n\), visible by comparing Fig. 3 (c) and Fig. 3 (d): the experimental FDT probability \(|\phi_{r,n}|^2\) is nonzero and not exactly zero as in Eq. (7).

To investigate further the mean FDR and FDT time for varying \(\gamma\), we consider 5 two-qubit experiments on IBMQ-Montreal (qubit 12 and 13) with 32000 runs for \(U = 0\), \(\tau = 0.4\) and varying \(\gamma\). We initialize the qubit in the state \(|01\rangle\) and perform alternating a two-qubit \(xx\)-rotation and \(yy\)-rotation and perform a measurement in the \(z\)-basis of both qubits (for the error mitigation) \(N = 40\) times. The result is post-processed to obtain the FDT (FDR) probability \(|\phi_{r,n}|^2\) by evaluating the counts and \(n\), where the initial state and the measured state are different (FDT) or the same (FDR) for the first time. Besides the relevant states \(|00\rangle\) and \(|01\rangle\) for the ME, the system can also occupy \(|00\rangle\) or \(|11\rangle\). Those contributions are used in our error detection strategy.

We present results in Fig. 4, with and without error mitigating. Similar to the one-qubit case, the mean FDR quantization \(|\langle n\rangle| = 2\) is clearly visible in the error mitigated data of Fig. 4 (a), while the raw experimental...
First detected return (FDR) probability

\[ |\phi_{r,n}|^2 \]

Exact \hspace{1cm} Exp. without EM

First detected transition (FDT) probability

\[ |\phi_{n}|^2 \]

Exact \hspace{1cm} Exp. without EM

FIG. 2. Single-qubit experiment \((U = 0)\): Mean FDR time \(\langle n \rangle\) (a) and variance of \(n\) (b) of the two-site system for the return \(|1\rangle \rightarrow |1\rangle\) for \(\tau = 0.4\) and \(N = 40\) as a function of the hopping matrix element \(\gamma\) exact (blue solid line) and computed on the IBMQ Montreal with (green dots) and without error mitigation (EM) (red triangles). The green shaded area marks the standard deviation of the error mitigated result. The FDR probability of the ME \(|\phi_{r,n}|^2\) as a function of \(\gamma\) and number of measurements \(n\) is presented for the theory in (a) and for the experiment on the IBMQ Montreal without error mitigation in (b).

FIG. 3. Single-qubit experiment \((U = 0)\): Mean FDT time \(\langle n \rangle\) (a) and variance of \(n\) (b) for the same system and the same model parameters as in Fig. 2. The blue solid curve is the theoretical result, while the computation on the IBMQ Montreal is presented with error mitigation (green dots) and without (red triangles). The green shaded area marks the standard deviation of the error mitigated result. The FDT probability of the ME as a function of \(\gamma\) and number of measurements from theory is in (c) and for the experiment on the IBMQ Montreal without error mitigation is in (d).
data in Fig. 4 (a) and Fig. 4 (c) is more noisy, and the mean FDR time is slightly larger than 2. Nonetheless the effect of degenerate points are clearly visible also in the mean FDT time of Fig. 4 (b), where ⟨n⟩ decreases at the degenerate points as expected from the exact curve at N = 40. In Fig. 4 (d) the experimental FDT probability |φn|2 is close to zero at the degenerate points in contrast to the one-qubit case of Fig 3 (a).

Next, we compute the two-site system with an on-site potential U on the IBMQ Montreal. The mean FDR time ⟨n⟩ is displayed as a function of U in Fig. 5. We have performed 5 one-qubit experiments (qubit 12 on IBMQ-Montreal) with 32000 runs for γ = −1, τ = 3 and varying U, after initializing the qubit in state |1⟩ and perform alternating x- and z-rotations and a measurement in the z-basis for N = 40 on the circuit (1) with Δt = 0.1 and k = 30 Trotter steps. Again, the mean FDR time is ⟨n⟩ = 2, except for ⟨n⟩ = 1 at the degenerate points Ud of Eq. (20). In the present case this is Ud ≈ 0.31, Ud ≈ 1.84 and Ud ≈ 2.98. The raw experimental data is in qualitative and the error mitigated data is in very good quantitative agreement with the exact results and the quantization of ⟨n⟩. The corresponding divergences of the variance ⟨n2⟩ − ⟨n⟩2 are also experimentally confirmed for nonzero U in Fig. 5 (a) and (b).

In Fig. 5 (c) the exact FDR probability is shown as a function of the energy bias U and the number of measurements, and in Fig. 5 (d) the corresponding measured FDR probability on the IBMQ-Montreal is presented without error mitigation. Both results are almost identical, like in the U = 0 case for varying γ.

The mean FDT time in Fig. 6 (a) shows the complementary behavior. In the case where the FDT probability is large at small n close to U = 1 the raw experimental findings are in very good qualitative agreement with the exact values. For larger U the main contributions originates from larger n (see Fig. 6 (c), (d)), therefore, the measurement errors accumulate leading only to a qualitative agreement of the mean FDT time in Fig. 6 (a) and its variance in Fig. 6 (b). Here, eventually other error mitigation methods should be introduced since the applied scheme is not able to mitigate the errors for deeper quantum circuits (due to the error rate induced by the two-qubit gates in circuit (3)), which are needed to calculate the mean ⟨n⟩ in the FDT case for varying U.

We have demonstrated experimentally with a high accuracy that for the FDR problem of a particle in a two-site system, the mean return time ⟨n⟩ is quantized and equal to the dimension of the underlying Hilbert space.
FIG. 5. Single-qubit experiment ($U > 0$): Mean FDR time $\langle n \rangle$ (a) and variance of $n$ (b) of the two-site system for the return $|1\rangle \rightarrow |1\rangle$ for $\gamma = -1$, $\tau = 3$ ($\Delta t = 0.1$, $k = 30$) and $N = 40$ as a function of the on-site energy $U$ exact (blue solid line) and computed on the IBMQ Montreal with (green dots) and without error mitigation (EM) (red triangles). The shaded area shows the standard deviation of the error mitigated result (green). (c) FDR probability of the monitored evolution $|\phi_{r,n}|^2$ as a function of $U$ and number of measurements (exact). (d) FDR probability of the monitored evolution $|\phi_{r,n}|^2$ as a function of $U$ and number of measurements computed on the IBMQ Montreal without error mitigation.

FIG. 6. Single-qubit experiment ($U > 0$): Mean FDT time $\langle n \rangle$ (a) and variance of $n$ (b) for the same system and the same model parameters as in Fig. 5. The blue solid curve is the theoretical result, while the computation on the IBMQ Montreal is presented with error mitigation (green dots) and without (red triangles). The green shaded area marks the standard deviation of the error mitigated result. The FDT probability of the ME as a function of $U$ and number of measurements from theory is in (c) and for the experiment on the IBMQ Montreal without error mitigation is in (d).
with non-degenerate eigenvalues (in our case $\langle n \rangle = 2$). Moreover, at the degenerate points we found $\langle n \rangle = 1$. In our two-site (two-level) problems, this reflects the situation, in which the particle stays at the initial site. Because the experiment involves a large number of mid-circuit measurements, the readout-error mitigation is essential. We have successfully used an error mitigation scheme that is based on the repetition code with majority vote and error detection when the depth of the quantum circuits is relatively short.

V. CONCLUSION

For the first time, we experimentally investigated a monitored evolution of a tight-binding Hamiltonian on a quantum device and computed the mean FDR and mean FDT times for a one- and for a two-qubit system, where repeated measurements interrupt the unitary evolution by a projection after a time step $\tau$. To this end, we exploit the newly developed capabilities of mid-circuit measurements on IBM quantum devices. The predictions of the general theory for a finite but large number of measurements are accurately confirmed by the quantum computation. The FDR probability distribution of the monitored evolution is in a good quantitative agreement with the exact result. We experimentally verified the remarkable property of the FDR problem in a two-site system: the mean $\langle n \rangle$ is quantized and equal to the size of the system (in our case 2) for all $U$ and $\gamma$. $\langle n \rangle$ is reduced to 1 at the degenerate points, where the size of the system (i.e., the number of non-degenerate eigenvalues of $\exp(-iH_2\tau)$) is reduced to 1. In this case the quantum gates effectively act as an identity matrix, multiplied by a phase factor. The behavior is different for the FDT problem, since $\langle n \rangle$ diverges near the degenerate points. While the experimental data is very accurate for the FDR mean times, confirming the quantization, the jumps at the degenerate points and the strong fluctuations, the mean FDT times for a non-zero energy bias (finite $U$) is less accurate. In particular, the behavior near the degenerate points requires further experimental improvement on the hardware as well as on error mitigation scheme, since those results depend on the measurement of a deeper circuit. The latter might accumulate readout errors and two-qubits gate errors. The experimental data for a larger number of measurements will benefit from devices which are capable to perform and can process a larger amount of mid-circuit measurements.

Our results reflect the large potential of the new capabilities provided by the IBM quantum computers in terms of mid-circuit measurements. Our ME, in connection with the topologically protected quantization of the mean FDR time, establishes a new, very flexible and scalable method for testing the performance of a quantum computer. The simple example of a single particle on two sites already indicates the direction in which an improvement in terms of long-time behavior and more complex systems is necessary. Future work should consider (i) larger systems with more particles and (ii) the application of measurement-induced quantum walks to quantum control and quantum algorithms, e.g., for quantum search or constrained quantum optimization [25, 26].

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From the distributions of the FDR and FDT probabilities (cf. the main text) we can calculate the sum of the probabilities and the moments of $n$ for a finite number of measurements $N$. For instance, the sum of the FDR probabilities reads

$$\sum_{n=1}^{N} |\phi_{r,n}|^2 = 1 - (1 - c^2) c^{2(N-1)} \quad (1)$$

and the sum of the FDT probabilities

$$\sum_{n=1}^{N} |\phi_{t,n}|^2 = 1 - c^{2(N-1)} \quad (2)$$

While the FDR sum is 1 for $c^2 \leq 1$, the FDT sum is 1 for $c^2 < 1$ but vanishes for $c^2 = 1$ in the limit $N \to \infty$. The latter reflects the fact that the two-level system always stays in the initial state if $c^2 = 1$, since the transition matrix element is $1 - c^2$. Moreover, for the mean FDR time $\langle n \rangle$ we obtain

$$\langle n \rangle = \sum_{n=1}^{N} n |\phi_{r,n}|^2 = 2 + c^{2(N-1)} [N(c^2 - 1) - 1], \quad (3)$$

which gives $\langle n \rangle \sim 2$ for $c^2 < 1$, $N \sim \infty$ and $\langle n \rangle = 1$ for $c^2 = 1$. The second moment reads

$$\langle n^2 \rangle = \frac{2 - c^{2(N-1)} \left[ (N^2 - N) c^4 + 2 (1 - N^2) c^2 + N^2 + N \right]}{1 - c^2}. \quad (4)$$

Finally, for the mean FDT time we obtain

$$\langle n \rangle = \sum_{n=1}^{N} n |\phi_{t,n}|^2 = \frac{1 + c^{2N} [N(c^2 - 1) - 1]}{1 - c^2}. \quad (5)$$

It should be noted that the last two expressions vanish for $c^2 \to 1$ at any finite $N$, while they diverge when we take $N \to \infty$ first and then $c^2 \to 1$. This means that the limits $c^2 \to 1$ and $N \to \infty$ do not commute. In Figures 1, 2 and 3 we plot the mean FDR time $\langle n \rangle$ and variance of $n$ as well as the mean FDT time for different number of measurements $N$ as a function of $U$ and $\gamma$. 


FIG. 1. Mean FDR time $\langle n \rangle$ of the two-site system for the return $|1\rangle \rightarrow |1\rangle$ (a) as a function of $\gamma$ ($\tau = 0.4, U = 0$) and (b) as a function of $U$ ($\tau = 3, \gamma = 1$) for different number of measurements $N$.

FIG. 2. Variance of the FDR time $\langle n^2 \rangle - \langle n \rangle^2$ of the two-site system for the return $|1\rangle \rightarrow |1\rangle$ (a) as a function of $\gamma$ ($\tau = 0.4, U = 0$) and (b) as a function of $U$ ($\tau = 3, \gamma = 1$) for different number of measurements $N$. 
FIG. 3. Mean FDT time $\langle n \rangle$ of the two-site system for the return $|1\rangle \rightarrow |0\rangle$ (a) as a function of $\gamma$ ($\tau = 0.4, U = 0$) and (b) as a function of $U$ ($\tau = 3, \gamma = 1$) for different number of measurements $N$. 

- **(a)**: Graph showing $\langle n \rangle$ as a function of $\gamma$ with $\tau = 0.4$ and $U = 0$ for different values of $N$.
- **(b)**: Graph showing $\langle n \rangle$ as a function of $U$ with $\tau = 3$ and $\gamma = 1$ for different values of $N$. 

Legend:
- Green line: $N = 10$
- Blue line: $N = 40$
- Red line: $N = 400$