Benchmarking the readout of a superconducting qubit for repeated measurements

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Readout of superconducting qubits faces a trade-off between measurement speed and unwanted back-action on the qubit caused by the readout drive, such as T_1 degradation and leakage out of the computational subspace. The readout is typically benchmarked by integrating the readout signal and choosing a binary threshold to extract the "readout fidelity". We show that such a characterization may significantly overlook readout-induced leakage errors. We introduce a method to quantitatively assess this error by repeatedly executing a composite operation —a readout preceded by a randomized qubit-flip. We apply this technique to characterize the dispersive readout of an intrinsically Purcell-protected qubit. We report a binary readout fidelity of 99.63% and quantum non-demolition (QND) fidelity exceeding 99.00% which takes into account a leakage error rate of $0.12 \pm 0.03\%$, under a repetition rate of $(380\text{ns})^{-1}$ for the composite operation.

Fast and accurate single-shot qubit readout is crucial for a multitude of quantum computing experiments including, measurement-based state preparation [1], entanglement generation [2–4] and quantum error correction (QEC) [5–10]. Recent advancements in superconducting qubit readout coupled with near-quantum-limited measurement efficiency have made it possible to demonstrate quantum error correction with both surface code [8, 9] and bosonic codes [5–7]. In these experiments, efficient entropy removal from the quantum system is achieved by repeated application of high fidelity readout and reset of the physical ancilla qubits. A quantum non-demolition (QND) measurement [11] perfectly correlates the post-readout state of the qubit with the readout outcome, alleviating the need for unconditional reset [12] of the ancilla. A purely dispersive interaction between a qubit and its readout resonator would yield a QND readout scheme. In reality, this interaction is approximately realized in superconducting circuits [13] when an artificial atom is linearly coupled to the readout resonator. The linear hybridization of the qubit and the readout resonator leads to Purcell decay of the qubit. This prevents arbitrary increase of the qubit-resonator dispersive interaction χ_{qr} and the external coupling rate of the resonator κ_r, which sets a maximum speed of the readout for a given power. Moreover, at higher readout power, the dispersive approximation breaks down [14], causing readout-induced leakage [15, 16] into the non-computational states of the physical qubit. These limitations prohibit the simultaneous pursuit of the readout speed, fidelity and QND-ness.

In QEC, entangling operations and ancilla readouts are repeated, as illustrated in Fig.1. The readout-induced leakage errors can leave the ancilla in undesirable highly-excited states for multiple cycles, and can also spread into neighbouring qubits [17]. Thus, even a small leakage probability poses a greater threat compared to discrimination error or Pauli error. Often, the "readout fidelity" [1, 18–23] extracted from the *binary-thresholded* outcomes is used as the only metric to experimentally optimize the readout parameters. While such a metric is sufficient to quantify the Pauli error (occurring during the readout process) and the discrimination error, it fails to faithfully identify readout-induced leakage, especially if the latter occurs with a low probability compared to other readout errors. The standard measure of QND-ness as the correlation of two successive binary readout outcomes [21–23] also overlooks leakage when the readout outcomes of the leakage states predominantly fall on one side of the threshold. Therefore, such methods do not reflect the true character of the repeated readout operations. Is there a complete way to benchmark the readout operation with binary outcome?

In this Letter, we demonstrate a novel readout benchmarking technique, "pseudo-syndrome detection", where we mimic a syndrome detection cycle in QEC by repeating a composite operation—a readout preceded by a random qubit flip. This method offers a faithful characterization of the readout under repeated implementations and provides an accurate estimation of the readout QND-ness. We perform the dispersive readout on a Purcell-protected transmon. We optimize the readout pulses

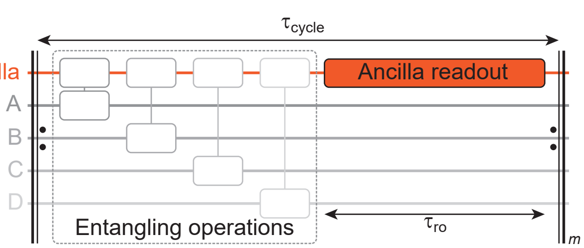

Figure 1. A syndrome detection cycle in QEC. Each cycle consists of an ancilla readout preceded by entangling operations with data qubits, mapping the syndrome onto the ancilla. We characterize the readout performance by mimicing this experiment on a single ancilla, with the "syndrome" artificially generated by randomly applying identity and bit-flip operations.

b 在重复测量中添加超导标准的读数

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超导码头的读数面临着测量速度和由读取驱动器引起的量子的不良反作用之间的权衡，例如T_1降解和从计算子空间中泄漏。读数通常是通过集成读数信号并选择二进制阈值来提取“读数保真度”的基准标准的。我们表明，这种特性可能会大大忽视读出诱导的泄漏错误。我们引入了一种通过反复执行复合操作的方法来定量评估此错误的方法 - 读出之前是随机量子翼。我们应用此技术来表征本质上受purcell保护的量子的色散读数。我们报告二进制读数保真度为99．63%和量子非demolition（qnd）的保真度超过99．00%，考虑到0．12 ± 0 ± 0．03%的泄漏错误率，在（380ns）下（380ns）。

快速准确的单次量子量读数对于多种量子计算实验，基于测量的状态制备[1]，实体生成[2-4]和量子误差校正（QEC）[5-10]至关重要。超导量子读数的最新进展以及近量子限制的效率效率使得可以通过表面代码[8、9]和骨码[5-7]证明量子误差校正[5-7]成为可能。在这些实验中，通过重复应用高保真读数并重置物理附件量子位来实现从量子系统中的有效熵去除。量子非拆卸（QND）测量[11]将量子的后读数状态与读数结果完美相关，从而满足了对Ancilla的无条件重置[12]的需求。量子及其读出谐振器之间的纯粹分散相互作用将产生QND读数方案。实际上，当人工原子与读出谐振器线性耦合时，这种相互作用大约在超导电路[13]中实现。量子的线性杂交和读出谐振器导致量子的purcell衰变。这样可以防止Qubit谐振器分散互动χ_{qr}和谐振器κ_r的外部耦合率的任意增加，该均值设置了给定功率的最大读数速度。此外，在较高的读出功率下，分散式接近分解[14]，导致读数引起的泄漏[15，16]进入物理量子的非计算状态。这些限制禁止同时追求读数速度，忠诚度和QND。

如图1所示，在QEC中，重复纠缠操作和Ancilla读数。读出引起的泄漏错误可能会使Ancilla以多个周期的高度激发状态使Ancilla处于相邻的量子状态[17]。因此，与犯罪错误或保利错误相比，即使是较小的泄漏概率也会构成更大的威胁。通常，从二进制阈值结果中提取的“读数”[1，18-23]被用作实验性的唯一指标优化读取参数。尽管这样的度量足以量化Pauli错误（在读数过程中发生）和歧视错误，但它无法忠实地识别读数引起的泄漏，尤其是与其他读数错误相比，后者的概率较低。 QND度的标准度量作为两个连续的二进制读数的相关性，而当泄漏状态的读数结果主要落在阈值的一侧时，也可以忽略泄漏。因此，这种方法不能反映重复读取操作的真实特征。是否有一种完整的方法可以用二进制结果对读取操作进行基准测试?

在这封信中，我们演示了一种新颖的读数台式标记技术，即“伪综合征检测”，在该技术中，我们通过重复复合操作来模仿QEC中的综合征检测周期 - 读出读数之前是ran-dom Qubit Flip。此方法在重复实现下提供了忠实的读数字符，并提供了对读取QNDESS的准确估计。我们在受保护的transmon上执行分散读数。我们优化了读取脉冲

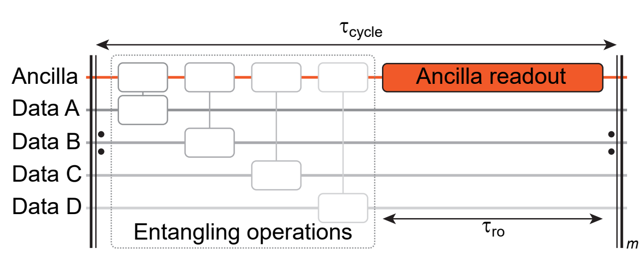

图1。QEC中的综合征检测周期。每个循环都由一个Ancilla读数组成，此前是将操作与数据量置的操作，将综合征映射到An-Cilla上。我们通过模仿单个Ancilla的该实验来表征读数性能，而“综合征”通过随机应用身份和位翼型操作来形成艺术中的“综合征”。