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Certifying Quantum Temporal Correlation via Randomized Measurements: Theory and Experiment

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We consider the certification of temporal quantum correlations using the pseudo-density operator (PDO), an extension of the density matrix to the time domain, where negative eigenvalues are key indicators of temporal correlations. Conventional methods for detecting these correlations rely on PDO tomography, which often involves excessive redundant information and requires exponential resources. In this work, we develop an efficient protocol for temporal correlation detection by virtually preparing the PDO within a single time slice and estimating its second-order moments using randomized measurements. Through sample complexity analysis, we demonstrate that our protocol requires only a constant number of measurement bases, making it particularly advantageous for systems utilizing ensemble average measurements, as it maintains constant runtime complexity regardless of the number of qubits. We experimentally validate our protocol on a nuclear magnetic resonance platform, a typical thermodynamic quantum system, where the experimental results closely align with theoretical predictions, confirming the effectiveness of our protocol.

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Introduction—Quantum correlations, both spatial and temporal, are distinguishing features of quantum mechanics. Over the past few decades, the utilization of quantum spatial correlations, particularly entanglement, has significantly shaped quantum information science [1]. Detecting and quantifying entanglement are also essential methods for benchmarking the capabilities of quantum devices [2–10]. Recently, the focus on certifying quantum correlations has been generalized to include temporal correlations [11–15]. Quantum temporal correlations, which emerge from sequential measurements on quantum systems, are crucial not only for deepening our understanding of the foundational aspects of quantum physics, but also for a wide range of sequential information processing tasks. For example, the Leggett-Garg inequalities, derived under the assumptions of macrorealism and noninvasive measurability, can be violated by quantum mechanical predictions [11,15–17]. Furthermore, temporal correlations have been employed to witness quantum dimensionality [18–20] and have proven to be central in the performance of time-keeping devices [21–23].

Among various methodologies for certifying temporal correlations, the pseudo-density operator (PDO) is a prominent tool due to its rich physical implications and concise mathematical form [24–35]. As illustrated in Fig. 1(a), the PDO is an extension of the density matrix to the time domain. Notably, it permits negative eigenvalues [24], which imply quantum temporal correlations, as density matrices constructed from a single time slice cannot exhibit such negativity. Additionally, compared to the violation of Leggett-Garg inequalities, negativity in the PDO functions as a subprotocol for inferring quantum causal structures [27,28] and can also be used to bound quantum channel capacity [36]. The conventional method for detecting negativity involves a process known as PDO tomography [24,28,29]. However, as the number of qubits increases, PDO tomography becomes impractical due to the exponential consumption of both quantum and classical resources. Moreover, tomography can lead to

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Neural Quantum Embedding via Deterministic Quantum Computation with One Qubit

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Quantum computing is expected to provide an exponential speedup in machine learning. However, optimizing the data loading process, commonly referred to as “quantum data embedding,” to maximize classification performance remains a critical challenge. In this Letter, we propose a neural quantum embedding (NQE) technique based on deterministic quantum computation with one qubit (DQC1). Unlike the traditional embedding approach, NQE trains a neural network to maximize the trace distance between quantum states corresponding to different categories of classical data. Furthermore, training is efficiently achieved using DQC1, which is specifically designed for ensemble quantum systems, such as nuclear magnetic resonance (NMR). We validate the NQE-DQC1 protocol by encoding handwritten images into NMR quantum processors, demonstrating a significant improvement in distinguishability compared to traditional methods. Additionally, after training the NQE, we implement a parametrized quantum circuit for classification tasks, achieving 98% classification accuracy, in contrast to the 54% accuracy obtained using traditional embedding. Moreover, we show that the NQE-DQC1 protocol is extendable, enabling the use of the NMR system for NQE training due to its high compatibility with DQC1, while subsequent machine learning tasks can be performed on other physical platforms, such as superconducting circuits. Our Letter opens new avenues for utilizing ensemble quantum systems for efficient classical data embedding into quantum registers.

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Introduction—Quantum machine learning (QML) presents a compelling frontier for data science, pushing the field beyond the capabilities of classical information processing systems. While QML is inherently suited for learning from quantum data [1–4], the majority of data analysis tasks in modern society targets classical data. Thus, developing an effective approach for applying QML to classical data is of critical importance for a wide range of real-world problems. Addressing this challenge entails the intricate task of devising optimal feature mappings of classical data to quantum states, known as “quantum data embedding,” tailored to the specific datasets being used. Practical QML also faces the ongoing challenge of building universal and fault-tolerant quantum hardware. Various approaches have been proposed to leverage non-fault-tolerant quantum computers in QML [5–13]. However, the potential contribution of subuniversal quantum computers to this field remains unexplored. Developing useful applications of these less powerful yet more feasible quantum devices for QML represents a significant milestone toward practical quantum advantage.

To address these challenges, we propose a method for optimizing quantum data embedding using deterministic quantum computation with one qubit (DQC1) [14]. In particular, we focus on enhancing quantum data embedding for binary classification, a fundamental task in data analysis [15,16]. For an effective classifier, it is essential that the training data points from different classes exhibit large distances, while points within the same class remain closely clustered in the feature space [17–19]. To achieve this under

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Stable and High-Precision 3D Positioning via Tunable Composite-Dimensional Hong-Ou-Mandel Interference

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We propose a stable and high-precision three-dimensional (3D) quantum positioning scheme based on Hong-Ou-Mandel (HOM) interference. While previous studies have explored HOM interference in quantum metrology, they were mostly limited to one-dimensional scenarios, whereas real-world applications require full 3D spatial resolution. Our approach not only generalizes HOM positioning to 3D—achieving ultimate sensitivity as defined by the quantum Cramér-Rao bound under ideal conditions—but also stabilizes estimation accuracy through simple polarization tuning, ensuring that the Fisher information remains independent of the estimated parameters. Theoretical analysis and simulations demonstrate that our method achieves ultraprecise and reliable 3D positioning, even with a limited number of detected photons.

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Introduction—Photons, as fundamental carriers of quantum information, possess a variety of degrees of freedom—including frequency, polarization, and momentum—that have enabled groundbreaking advancements in quantum communication [1–3], computing [4,5], and metrology [6–10]. By utilizing quantum superposition and interference, quantum metrology can surpass classical limits, achieving ultimate precision as dictated by the quantum Cramér-Rao Bound (QCRB) [11,12].

Quantum positioning, an emerging frontier in quantum metrology, has witnessed significant progress in distance measurement via photon time-of-flight [13–15] and radial speed estimation using the Doppler effect [16–18]. However, real-world target positioning requires precise information in all three spatial dimensions. Conventional methods relying on time-delay measurements provide quantum enhancement only along the radial axis, limiting their applicability to full 3D localization. Fortunately, the rich degrees of freedom of photons offer new pathways to improve lateral positioning precision, enabling the extension of quantum parameter estimation to higher-dimensional scenarios.

Early quantum positioning and parameter estimation strategies typically relied on orthogonal squeezing [19–23] or N00N-state interferometry [24–28] to enhance resolution. However, these approaches demand extremely high phase stability in noisy environments, restricting their practicality [29,30]. In contrast, HOM interference [31], a fundamental quantum interference phenomenon, is highly sensitive to group delay while being robust against phase fluctuations [30–32] and certain types of dispersion [33–35]. This makes HOM interference particularly advantageous for precision measurement in realistic, noisy settings. A wealth of studies has demonstrated that HOM interference excels in ultraprecise time delay measurements [36–40], and recent research further confirms its ability to achieve quantum-limited sensitivity in transverse displacement estimation [41–43]. Interestingly, although the potential of the HOM effect for precision metrology has been recognized for decades [29], a rigorous analysis of the ultimate precision limits of HOM-based measurements has only been pursued in recent years [30,41]. Moreover, the existing literature has largely overlooked how the estimation accuracy of HOM-based schemes is affected by the target parameters. Ensuring that measurement precision remains independent of these parameters is essential for the stability and practical implementation of quantum metrology.

Motivated by these challenges, we propose a stable and high-precision 3D quantum positioning strategy that exploits the unique influence of various photonic degrees of freedom on HOM interference. Unlike previous schemes limited to one-dimensional radial or transverse

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Letter

Experimental virtual quantum broadcasting

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The quantum no-broadcasting theorem states that it is fundamentally impossible to perfectly replicate an arbitrary quantum state, even if correlations between the copies are allowed. While quantum broadcasting cannot occur through any physical process, it can be achieved via postprocessing of experimental data using a process called virtual quantum broadcasting (VQB). In this work, we report an experimental implementation of a quantum circuit based on the linear combination of unitaries, integrated with a postprocessing protocol, to realize VQB in a nuclear magnetic resonance system. VQB can be expressed as a linear combination of two channels: the universal cloner, which broadcasts the target quantum state, and the universal antisymmetrizer, which reduces broadcasting error. We implement both channels within the same circuit and demonstrate that the universal cloner is the closest physical map to VQB. In addition, we show how the universal antisymmetrizer can be utilized to mitigate imperfections in the cloner, enabling near-ideal fidelity. Our method is applicable to broadcasting quantum systems of any dimension.

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Introduction. Distributing quantum information to multiple recipients is of foundational importance to quantum technologies such as quantum network [1], distributed quantum computing [2,3], and sensing [4,5]. However, quantum mechanics limits the ability to distribute quantum information, as unknown pure quantum states cannot be perfectly copied [6]. Extending this principle to mixed states, the quantum no-broadcasting theorem states that no physical process, i.e., a completely positive trace-preserving (CPTP) map, can broadcast an unknown quantum mixed state to two separate parties while preserving its reduced density matrices [7]. Nevertheless, optimal physical protocols exist that can approximately broadcast quantum states [8–11].

Interestingly, quantum broadcasting can be achieved by relaxing the positivity requirement, a process referred to as virtual quantum broadcasting (VQB) [12]. VQB belongs to a broader class of quantum operations known as Hermitian-preserving and trace-preserving (HPTP) maps and is inspired by recent advancements in quantum spatiotemporal correlations [13–28]. While infinitely many such HPTP maps satisfy the broadcasting condition, three physical assumptions uniquely single out one [12]. HPTP maps are linear maps that transform Hermitian operators into Hermitian operators but do not necessarily preserve positivity [29,30]. For instance, they can map a density matrix to a nonpositive operator.

HPTP maps can, however, be simulated by sampling quantum operations combined with postprocessing measurement statistics from output states, aligning with a paradigm referred to as virtual operations. Virtual operations reproduce the measurement effects necessary for quantum information processing tasks without requiring physical implementation, operating at the level of expectation values rather than directly on quantum states or their dynamics, and relying on classical postprocessing of outputs [31–33]. It has found applications in quantum error mitigation [34–36], virtual quantum resource distillation [37–40], and reversing unknown quantum operations [41]. Given the fundamental significance of VQB, its explicit simulation and practical feasibility within existing quantum technologies remain open questions.

In this Letter, we employ concepts from the linear combination of unitaries [42–44] to design an explicit protocol for implementing VQB, which is subsequently realized on a nuclear magnetic resonance (NMR) quantum processor [45,46]. First, inspired by the fact that VQB can be expressed as a linear combination of two channels—the so-called universal cloner and antisymmetrizer [12]—we design and implement a single quantum circuit to probabilistically realize both channels, along with a postprocessing procedure to obtain VQB. Secondly, we experimentally verify that the universal cloner is the closest CPTP map to VQB by comparing the trace distances of the Choi states of the VQB map with those of a suitably chosen set of CPTP maps. Finally, we treat the

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RESEARCH ARTICLE
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Hardware-efficient quantum principal component analysis for medical image recognition

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ABSTRACT

Principal component analysis (PCA) is a widely used tool in machine learning algorithms, but it can be computationally expensive. In 2014, Lloyd, Mohseni & Rebentrost proposed a quantum PCA (qPCA) algorithm [*Nat. Phys.* 10, 631 (2014)] that has not yet been experimentally demonstrated due to challenges in preparing multiple quantum state copies and implementing quantum phase estimations. In this study, we presented a hardware-efficient approach for qPCA, utilizing an iterative approach that effectively resets the relevant qubits in a nuclear magnetic resonance (NMR) quantum processor. Additionally, we introduced a quantum scattering circuit that efficiently determines the eigenvalues and eigenvectors (principal components). As an important application of PCA, we focused on classifying thoracic CT images from COVID-19 patients and achieved high accuracy in image classification using the qPCA circuit implemented on the NMR system. Our experiment highlights the potential of near-term quantum devices to accelerate qPCA, opening up new avenues for practical applications of quantum machine learning algorithms.

Keywords quantum simulation, quantum principal component analysis, nuclear magnetic resonance