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LEPTONS AS ELEMENTARY QUBITS: FEASIBILITY AND CHALLENGES [1]

Quantum computing traditionally encodes information in engineered quantum systems such as superconducting circuits, trapped ions, or quantum dots. In this theoretical study, we explore a paradigm shift by proposing the direct use of elementary particles, specifically charged leptons (electrons, muons, and tau particles), as natural qubits. We analyze the intrinsic quantum properties of leptons – particularly their spin-1/2 degree of freedom – for qubit encoding, discussing the potential for long coherence times and minimal fabrication complexity. The significant challenges of environmental decoherence, state measurement, and scalability are examined in detail, with a focus on the unique obstacle of particle decay for muons and taus. We propose potential mitigation strategies, including advanced trapping techniques and quantum error correction, and outline future research directions. While substantial experimental hurdles remain, lepton-based qubits represent a promising, fundamental approach to quantum information processing that warrants further investigation.

Keywords: quantum computing, qubits, leptons, decoherence, quantum error correction.

1. Introduction

The pursuit of a scalable, fault-tolerant quantum computer has led to a diverse ecosystem of qubit implementations. Dominant platforms include superconducting qubits [1], trapped ions [2], and semiconductor spin qubits [3], each with distinct advantages and limitations concerning coherence times, gate fidelities, and scalability. Common to all these architectures is that the qubit is encoded in emergent properties of composite systems, such as the charge or flux states of a Josephson junction or the electronic states of a trapped atom.

Our task is to investigate an alternative approach: leveraging the inherent quantum properties of fundamental particles themselves as qubits. Specifically, we focus on the charged leptons – the electron (e^-), muon (μ^-), and tau (τ^-). As spin-1/2 fermions, leptons are natural two-level quantum systems. Their quantum state can be described by a wavefunction $|\psi\rangle = \alpha|\uparrow\rangle + \beta|\downarrow\rangle$, representing a superposition of spin-up and spin-down states, making them ideal candidates for qubit encoding [4–6].

The potential advantages are compelling. Electrons in ultra-high vacuum and cryogenic environments can exhibit exceptionally long coherence times [7]. As fundamental particles, leptons are free from the material defects and fabrication inconsistencies that plague solid-state qubits. Furthermore, techniques for manipulating lepton spins, such as those used in electron paramagnetic resonance, are well-established [8].

However, this path is fraught with challenges. Leptons are highly susceptible to environmental decoherence from electromagnetic fields. The precise measurement of a single lepton's quantum state is nontrivial. Most critically, the muon and tau lepton are unstable, with lifetimes of approximately 2.2 μs and 290 fs, respectively, posing a fundamental constraint on their use [9]. Scalability to the many-qubit arrays necessary for useful quantum computation presents a further significant hurdle.

This work is structured as follows. In paragraph 2, we provide the necessary background on qubits and lepton physics. Paragraph 3 details the quantum

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properties of leptons suitable for qubit encoding. The profound challenges of this approach are analyzed in paragraph 4, while potential advantages are outlined in paragraph 5. Finally, we discuss future research directions and present our conclusions in paragraph 6. In paragraph 7 we present the case of muon decay quantum error correction for intrinsic qubit loss.

2. Background

2.1. Qubit fundamentals

A quantum bit, or qubit, is the fundamental unit of quantum information. Unlike a classical bit, which is strictly 0 or 1, a qubit can exist in a coherent superposition of its basis states, $|0\rangle$ and $|1\rangle$. The general state is $|\psi\rangle = \alpha|0\rangle + \beta|1\rangle$, where α and β are complex probability amplitudes satisfying $|\alpha|^2 + |\beta|^2 = 1$. A system of n qubits can represent 2^n states simultaneously, a property that when combined with quantum entanglement, enables the potential speedups of quantum algorithms [10, 11].

2.2. Lepton Properties

Leptons are elementary, spin-1/2 particles that do not participate in the strong interaction. The three charged leptons are the electron, muon, and tau, each with an associated neutrino. Their key properties are summarized in Table. The electron is stable, while the heavier muon and tau decay via the weak interaction, primarily into lighter leptons and neutrinos. This intrinsic instability is a critical differentiator for their potential use as qubits.

3. Leptons as Qubits

3.1. Spin Qubit Encoding

The most straightforward encoding for a lepton qubit is the spin degree of freedom. The basis states are defined as:

$$|0\rangle \equiv |\uparrow\rangle, \quad |1\rangle \equiv |\downarrow\rangle,$$

where $|\uparrow\rangle$ and $|\downarrow\rangle$ represent the spin angular momentum projections along a quantizing axis (e.g., $+\hbar/2$ and $-\hbar/2$). The qubit state is then manipulated using external fields. For instance, the Hamiltonian for a lepton in a static magnetic field B_0 along the z-axis and a transverse oscillating field $B_1(t)$ is:

$$H = -\frac{\hbar}{2}\gamma B_0 \sigma_z - \frac{\hbar}{2}\gamma B_1(\cos(\omega t)\sigma_x + \sin(\omega t)\sigma_y),$$

where γ is the gyromagnetic ratio and σ_i are the Pauli matrices. Resonant microwave or RF pulses ($\omega = \gamma B_0$) can perform arbitrary single-qubit rotations, analogous to control in NMR quantum computing [12].

3.2. Other degrees of freedom

While spin is the most natural choice, other quantum numbers, such as lepton flavor, could in principle be used to encode a *qudit* (a d-level quantum system). However, flavor-changing interactions are suppressed in the Standard Model, making coherent control of flavor states extremely challenging. For the foreseeable future, spin remains the most practical encoding.

4. Challenges

4.1. Decoherence and Environmental Noise

Lepton qubits are highly susceptible to decoherence. Sources include:

Electromagnetic Noise: Fluctuating external EM fields couple directly to the lepton's charge and magnetic moment, causing dephasing and relaxation.

Thermal Effects: Blackbody radiation and collisions with residual gas molecules can disrupt the quantum state, necessitating ultra-high vacuum and cryogenic temperatures.

Radiative Decay: For muons and taus, particle decay is an irreversible source of qubit loss, acting on a fixed timescale. This is a unique form of "intrinsic decoherence" that must be overcome via quantum error correction (QEC) [13, 14].

Mitigation strategies involve a combination of Penning or Paul traps for isolation [15], active magnetic shielding, and operation at millikelvin temperatures.

Properties of charged leptons

Lepton	Mass (MeV/c^2)	Lifetime (s)	Primary Decay Mode
Electron (e^-)	0.511	Stable	–
Muon (μ^-)	105.7	2.2×10^{-6}	$e^-\bar{\nu}\nu_\mu$
Tau (τ^-)	1777	2.9×10^{-13}	$\mu^-\bar{\nu}_\mu\nu_\tau$ (and others)

4.2. Measurement and state readout

Projective measurement of a single lepton's spin state is a non-trivial task. Potential methods include:

Stern-Gerlach Type Separation: Using inhomogeneous magnetic fields to spatially separate spin states, though this is challenging for single particles.

Quantum Non-Demolition (QND) Measurements: Coupling the lepton's spin to an ancillary quantum system (e.g., a trapped ion or a cavity photon) whose state can be measured without disturbing the lepton spin [16, 17].

Precision Spectroscopy: Measuring the energy shift induced by the spin state in a magnetic field.

4.3. Scalability and Control

Building a quantum processor requires the precise control of many interacting qubits. A scalable lepton-based architecture would need:

Dense Trapping Arrays: Creating large, ordered arrays of trapped leptons, potentially using optical lattices for electrons or sophisticated RF traps for muons.

High-Fidelity Gates: Implementing two-qubit gates via controlled electromagnetic interactions, such as the spin-spin coupling mediated by magnetic dipole-dipole interactions or via shared photonic channels in a cavity QED setup.

Integration with Control Hardware: The need for precise microwave pulses, laser control, and readout apparatus presents a significant engineering challenge.

4.4. Quantum error correction for intrinsic qubit loss: the case of muon decay

The most formidable challenge in employing muons as qubits is their intrinsic instability. With a mean lifetime of approximately $\tau_\mu \approx 2.2$ μs, the dominant error channel is not a bit-flip or phase-flip, but a complete and irreversible **qubit loss** event. This decay process, $\mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu$, constitutes a "leakage" error, where the qubit leaves the computational subspace entirely. Traditional QEC codes, designed for Pauli errors (XZ), are not sufficient to handle this. Therefore, a tailored approach combining leakage reduction units (LRUs) and codes designed for erasure errors is required.

4.4.1. Modeling muon decay as an erasure error

A key insight is that if the time of decay can be detected, the error can be treated as an erasure [18]. An erasure error is one whose location and time are known to the syndrome measurement apparatus. Remarkably, erasure errors are significantly easier to correct than Pauli errors of unknown location. For the surface code, the threshold for erasure errors can be as high as $\sim$50%, compared to $\sim$1% for Pauli errors [19].

The decay of a muon can be detected in several ways:

Direct Detection of Decay Products: The positron (e^+) from μ^+ decay (or electron from μ^- decay) carries a characteristic energy spectrum and can be registered by surrounding particle detectors (e.g., scintillators or silicon trackers). This provides a definitive, macroscopic signal that a specific muon qubit has been lost.

Ancilla-Based Detection: The muon's quantum state could be entangled with a stable ancilla qubit (e.g., an electron in a nearby trap or a solid-state spin). A sudden disentanglement or a change in the ancilla's coherence properties could herald the muon's decay.

The primary requirement is that the detection time, t_d, must be much shorter than the QEC cycle time, T_{QEC}, to allow for timely correction.

4.4.2. A proposed architecture: the bosonic-cat code interface

Given the difficulty of directly integrating a muon into a dense 2D qubit array, a hybrid architecture is likely the most feasible. We propose a system where a single muon qubit is strongly coupled to a high-Q microwave cavity mode, encoding information in a bosonic code [20].

Encoding: The logical qubit is encoded in the photonic state of the cavity using a cat code, defined by superpositions of coherent states: $|0_L\rangle \propto |\alpha\rangle + |-\alpha\rangle$ and $|1_L\rangle \propto |\alpha\rangle - |-\alpha\rangle$. This encoding is inherently robust against photon loss, the dominant error for cavities.

Role of the Muon: The muon acts as a non-linear element to perform quantum gates on the logical cat qubit. Its spin state can be coupled to the cavity via a magnetic dipole interaction, enabling operations like state preparation, entanglement, and syndrome measurement for the bosonic code [21].

Error Correction Cycle:

The quantum information resides primarily in the long-lived cat state.

The muon briefly interacts with the cavity to perform a necessary gate or stabilization measurement.

The muon is then decoupled. Its decay is continuously monitored.

If a decay is detected: The event is flagged as an erasure. Since the information was stored in the cavity, the loss of the muon does not destroy the logical qubit. A fresh muon is then injected into the trap and re-cooled. The cavity state is used to re-initialize the new muon's spin, and the system continues.

If no decay is detected: The standard bosonic QEC cycle continues to protect against photon loss.

This architecture effectively converts the problem of a catastrophic muon loss into a manageable erasure error on the *control* element, while the information is safeguarded in a more stable photonic memory.

4.4.3. Constraints and resource overhead

The feasibility of this approach is subject to stringent timing constraints. The QEC cycle time T_{QEC} must satisfy:

$$T_{\mathrm{QEC}} \ll \tau_\mu \approx 2.2\mu\mathrm{s}$$

to have a high probability of detecting a decay within a cycle. This demands extremely fast cavity quantum electrodynamics (cQED) operations with the muon, likely requiring the strong-coupling regime where the coupling rate g exceeds the decay rates of both the cavity (κ) and the muon spin (γ).

The resource overhead involves the integration of single-muon generation/cooling sources, high-speed particle detectors, and a high-Q superconducting cavity. While experimentally ambitious, such a setup could be realized at existing muon beam facilities.

In conclusion, while muon decay presents a unique challenge, it is not necessarily a prohibitive one. By reframing it as a detectable erasure error and employing a hybrid architecture with bosonic codes, a path forward for a muon-based logical qubit can be envisioned. The development of such tailored QEC strategies is a critical theoretical and experimental direction for lepton-based quantum computing.

5. Potential Advantages

Despite the challenges, lepton qubits offer unique potential benefits:

High Natural Coherence: Electrons, when perfectly isolated, are fundamental particles with no internal structure to cause decoherence. Their coherence time is limited only by their environment, not by material imperfections. Theoretical models suggest the potential for coherence times exceeding those of leading solid-state qubits under ideal conditions.

Minimal Fabrication Complexity: There is no need to fabricate nanoscale Josephson junctions or quantum dots with atomic precision. The "qubit" is provided by nature, potentially leading to perfect qubit-to-qubit uniformity.

Compatibility with Established Techniques: The methods for controlling lepton spins (magnetic resonance) are mature and high-precision. This synergy with existing technologies could accelerate development.

6. Instead of Conclusions

The path toward realizing lepton-based quantum computing requires a concerted effort across theoretical and experimental physics. Key future directions include:

Advanced Trapping Experiments: Demonstrating long-lived quantum coherence for a single electron in a Penning trap, then progressing to multi-electron entanglement [22, 23].

Muon and Tau Feasibility Studies: Conducting proof-of-concept experiments at high-energy physics facilities (e.g., CERN, Fermilab) to trap and manipulate muon spins on quantum-relevant timescales.

Theory of Lepton-Specific QEC: Developing tailored quantum error correction codes that account for the qubit loss channel from muon and tau decay [24, 25].

Hybrid Quantum Systems: Exploring interfaces where a lepton qubit (e.g., an electron spin) is coupled to a photonic qubit, enabling long-distance entanglement and integration with quantum networks.

In conclusion, we have presented one way of exploring charged leptons as elementary qubits. While the challenges, particularly for the unstable muon and tau, are formidable, the potential payoffs in coherence and simplicity are significant. This approach connects the fields of high-energy physics and quantum information science, suggesting a novel and fundamental pathway toward harnessing quantum mechanics for computation. We believe this concept merits serious investigation as a complementary strategy within the broader quantum computing landscape.

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ЛЕПТОНИ ЯК ЕЛЕМЕНТАРНІ КУБІТИ: ДОЦІЛЬНІСТЬ ТА ПРОБЛЕМИ

Квантові обчислення традиційно кодують інформацію в спроектованих квантових системах, таких як надпровідні схеми, захоплені іони або квантові точки. У цьому теоретичному дослідженні ми аналізуємо зміну парадигми, пропонуючи безпосереднє використання елементарних частинок, зокрема заряджених лептонів (електронів, мюонів та тау-частинок), як природних кубітів. Ми аналізуємо внутрішні квантові властивості лептонів, зокрема ступінь вільності їхнього спіну 1/2, – для кодування кубітів, обговорюючи потенціал для тривалого часу когерентності та мінімальної складності виготовлення. Детально розглянуто проблеми декогеренції середовища, вимірювання станів та масштабованості з акцентом на унікальній перешкоді розпаду мюонів і тау-частинок. Ми пропонуємо потенційні стратегії пом'якшення труднощів включно з передовими методами утримування частинок та квантову корекцію помилок, а також окреслюємо напрямки майбутніх досліджень. Хоча суттєві експериментальні перешкоди залишаються, кубіти на основі лептонів – перспективний фундаментальний підхід до обробки квантової інформації, який вимагає подальшого дослідження.

Ключові слова: квантові обчислення, кубіти, лептони, декогеренція, квантова корекція помилок.