Pathfinding Quantum Simulations of Neutrinoless ββ Decay

IonQ-UW Collaboration

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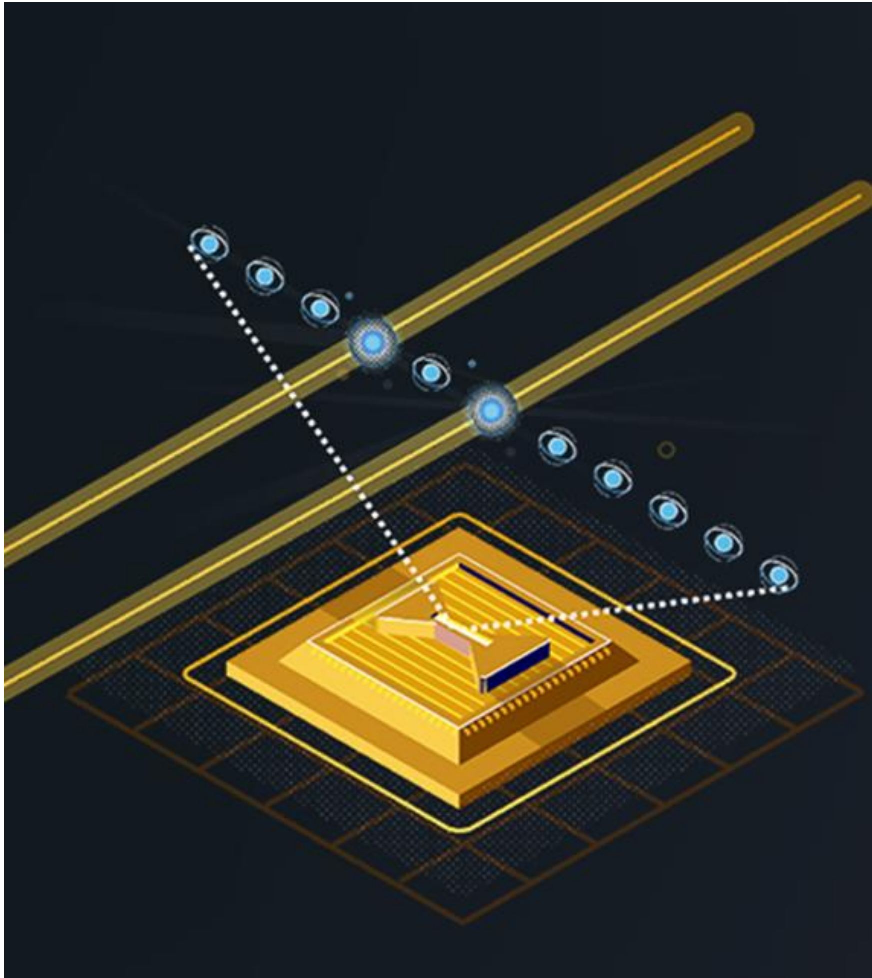
Why IonQ?

Empowered by Unique Technological Advantages

- Identical and naturally quantum
- Perfectly isolated from environmental influences
- Capable of running at room temperature
- Reconfigurable and highly-connected – modular and scalable
- Long qubit lifetime and long coherence time
- High fidelity and low SPAM errors



Neutrinoless Double-β Decay

The $0\nu\beta\beta$-decay is a potential exotic nuclear decay relevant for searches for new physics.

Future quantum simulations can be used to determine or constrain new physics – current work is a step along the path.

The current work involves lattice simulations of the decay of two baryons restricted to two spatial sites.

- Both strong and weak interactions are included.
- Majorana neutrino mass term explicitly violates lepton-number conservation.
- The coupling constants and masses are deliberately tuned to kinematically favor double-β decay but suppress single-β decay (in this volume).

We leveraged the power of co-designed simulations to maximally benefit from the **all-to-all connectivity** and native gate-set available on IonQ's trapped-ion quantum computers.

New techniques for mitigating statistical and device errors that are tailored to be maximally effective for the observables measured.

Circuits with **470 two-qubit gates** on IonQ Forte Enterprise and **2400 two qubit gates** on IonQ Forte were executed.

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Model and Qubit Mapping

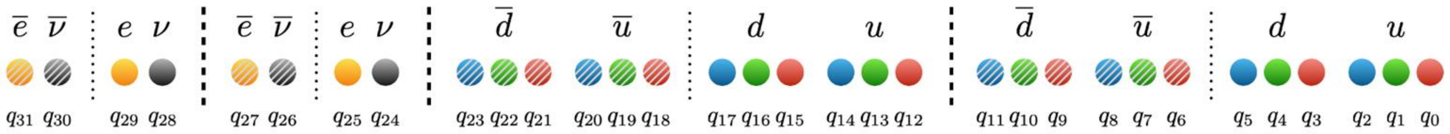
A model for the $0\nu\beta\beta$-decay of a nucleus is simulated in 1+1D lattice QCD with:

- up and down quarks (u, d).
- three colors (r, g, b) .
- electrons and neutrinos (e, ν).

L = 2 spatial lattice sites with PBC. This is the minimum size to host decay products.

Jordan-Wigner transformation is used to map the fermionic Hilbert space to 16L qubits → 32 qubits in total.

An additional 4 qubits are used as ancillae for error mitigation.



Lattice-to-qubit mapping

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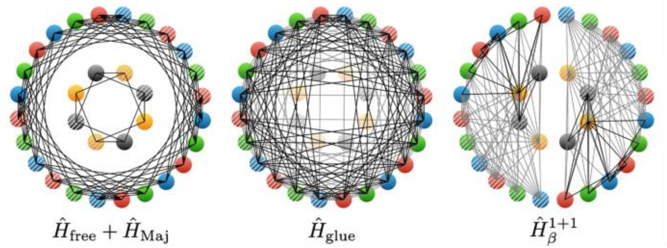
The Lattice Hamiltonian

$$\hat{H} = \hat{H}_{\text{free}} + \hat{H}_{\text{glue}} + \hat{H}_{\beta}^{1+1} + \hat{H}_{\text{Maj}}$$



$\hat{H}_{\text{free}}$ → **Free staggered fermions.**
Describes the kinetic energy (hopping) and masses of all quarks and leptons.

$$\hat{H}_{\text{free}} = \sum_{f} \sum_{n=0}^{2L-1} \left[m_f (-1)^n \phi_n^{(f)\dagger} \phi_n^{(f)} + \frac{1}{2} \left(\phi_n^{(f)\dagger} \phi_{n+1}^{(f)} + \text{h.c.} \right) \right]$$

$\hat{H}_{\text{glue}}$ → **QCD interactions.**
Color Coulomb interactions approximated to nearest-neighbor interactions to reduce gate count.

$$\hat{H}_{\text{glue}} = \frac{g^2}{2} \sum_{n=0}^{2L-1} \sum_{s=1}^{\lambda} \left(-s + \frac{s^2}{2L} \right) (1 - \frac{1}{2}\delta_{s,L}) \sum_{a=1}^{8} Q_n^{(a)} Q_{n+s}^{(a)}$$

$\hat{H}_{\beta}^{1+1}$ → **Weak interactions.**
Couples quarks to leptons.

$$\hat{H}_{\beta,\text{valence}}^{1+1} = \frac{G}{\sqrt{2}} \sum_{n \text{ even}} \left(\phi_n^{(u)\dagger} \phi_n^{(d)} \phi_n^{(e)\dagger} \phi_{n+1}^{(\nu)} + \text{h.c.} \right)$$

$\hat{H}_{\text{Maj}}$ → **Neutrino Majorana mass term.**
Explicit lepton-number symmetry breaking term.

$$\hat{H}_{\text{Maj}} = \frac{1}{2} m_M \sum \left(\phi_n^{(\nu)} \phi_{n+1}^{(\nu)} + \text{h.c.} \right)$$

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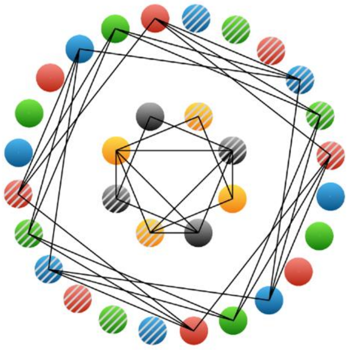
Initial State Preparation

Initial state: $|\psi_{\text{init}}\rangle = |\psi_{\text{vac}}^{(\text{lep})}\rangle\,|\Delta^-\Delta^-\rangle$

- Lepton sector vacuum: $|\psi_{\text{vac}}^{(\text{lep})}\rangle$
- Two-baryon state: $|\Delta^-\Delta^-\rangle = |\psi_{\text{vac}}^{(u)}\rangle|0\rangle^{\otimes 6}$

→ $|0\rangle^{\otimes 6}$ fully occupied register of *d*-quarks.

→ $|\psi_{\text{vac}}^{(u)}\rangle$ **SC-ADAPT-VQE** is used to prepare the non-trivial *u*-quark vacuum with a symmetry-preserving, shallow ansatz.



State preparation

Hamiltonian parameters are tuned so β-decay is disfavored while allowing the **lepton number violating** decay

$$|\Delta^-\Delta^-\rangle \rightarrow |\Delta^0\Delta^0\rangle + 2e^-$$

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Quantum Dynamics Simulation

The $0\nu\beta\beta$-decay process is modeled by the real time evolution of

$$|\psi(t)\rangle = e^{-i\hat{H}t}|\psi_{\text{init}}\rangle$$

Approximations

- Time-evolution is implemented with n_T = 2 first-order Trotter steps.
- Truncated range of the chromoelectric interaction. Reduces two-qubit gate count scaling from $O(N^2)$ to $O(N)$.
- The weak interaction only includes valence quarks and leptons.
- Remove Pauli terms with coefficients smaller than $t/16\ n_T$ → small angle rotation gates are discarded.

Observables of interest

Dynamical behaviour

Lepton number $\hat{\mathcal{L}} = \frac{1}{2}\sum_{n=0}^{3}\left(\hat{Z}_{24+2n} + \hat{Z}_{25+2n}\right)$

Lepton electric charge $\hat{Q}_e = -\frac{1}{2}\sum_{n=0}^{3}\hat{Z}_{25+2n}$

Physical symmetries (conserved quantities)

Color charges

$$\hat{r} = \frac{1}{2}\sum_{n=0}^{3}\sum_{f=0}^{1}\hat{Z}_{6n+3f}$$

$$\hat{g} = \frac{1}{2}\sum_{n=0}^{3}\sum_{f=0}^{1}\hat{Z}_{6n+1+3f}$$

$$\hat{b} = \frac{1}{2}\sum_{n=0}^{3}\sum_{f=0}^{1}\hat{Z}_{6n+2+3f}$$

Total electric charge

$$\hat{Q}_{\text{tot}} = \frac{1}{2}\sum_{n=0}^{3}\sum_{f=0}^{1}\sum_{c=0}^{2}q_f\hat{Z}_{6n+3f+c} + \hat{Q}_e$$

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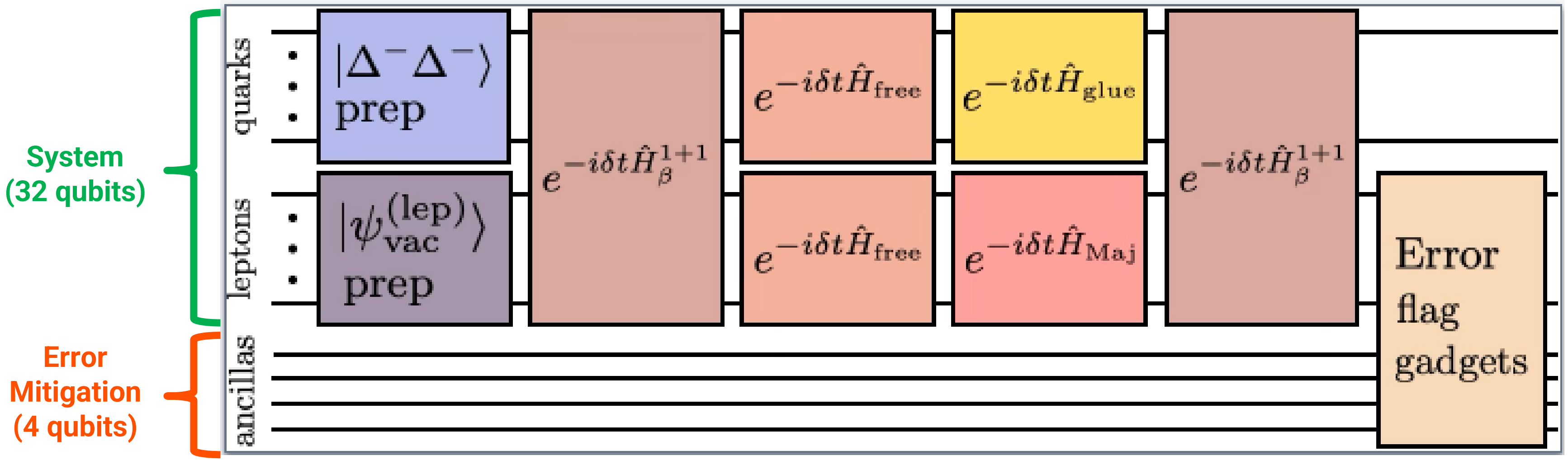
The Circuit

- The $0\nu\beta\beta$-decay process is modeled by the real time evolution of $|\psi(t)\rangle = e^{-i\hat{H}t}|\psi_{\text{init}}\rangle$
- A total of 32 qubits are used as the system qubits and 4 qubits are used as ancillae for error mitigation.



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Quantum Hardware: IonQ Forte and IonQ Forte Enterprise

Trapped-ion QPU technology of 36 $^{171}Yb^{+}$ ions.

Quantum information is encoded in two hyperfine levels of the ground state.

Gates:

- Arbitrary single-qubit rotations.
- Native two-qubit $R_{ZZ}(\theta)$ entangling gates.

Median DRB fidelities of entangling gates at time of execution:

- 99.3% (Forte)
- 99.5% (Forte Enterprise)

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Co-design: Advanced Error Mitigation

Noise Tailoring

Pauli Twirling
Coherent two-qubit over- and under-rotations.

XY4 Dynamical Decoupling
Phase and idling errors.

Measurement Twirling
Spontaneous emissions and readout bias.

Debiasing with Non-linear Filtering (DNL)

Multiple "variants" of the circuit are run (e.g., with different qubit embedding).

96 twirled variants with 150 shots each.

A filter is applied in post-processing, keeping only results that appear consistently across many variants, filtering out noise-induced outliers.

Post-Selection on Symmetries

Conserved quantities
The total electric and color charges (r, g, b).

Measurement violating these symmetries is discarded.

Flag-Gadgets and Leakage Detection

Mid-circuit symmetries verification via flag gadgets.

iSWAP and SWAP symmetry checks.

4 ancilla qubits are used to detect qubit leakage outside of the computational subspace.

~10% of shots survived all post-selection filters.

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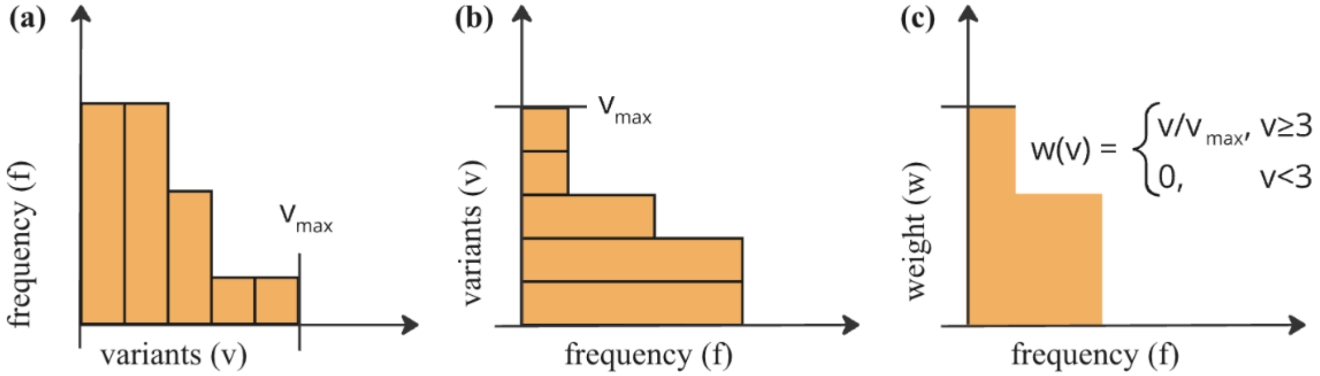
Co-design: Debiasing with Nonlinear Filtering (DNL)



- Multiple "variants" of the circuit are run (e.g., with different qubit embedding) – 96 twirled variants with 150 shots each.
- For each bitstring measured, a distribution of frequencies per variant is computed.
- This distribution is converted into the number of variants simultaneously "observing" the same bitstring at a given frequency.
- A filter is applied keeping only results that appear consistently across many variants, filtering out noise-induced outliers.

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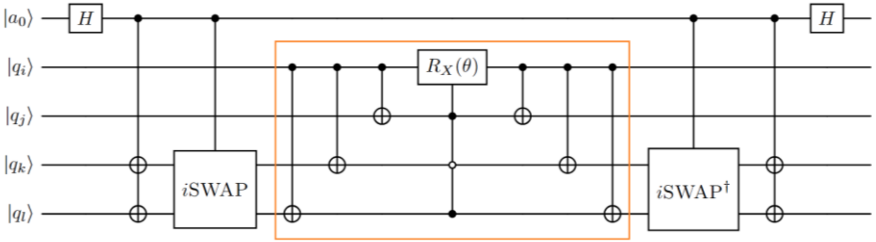
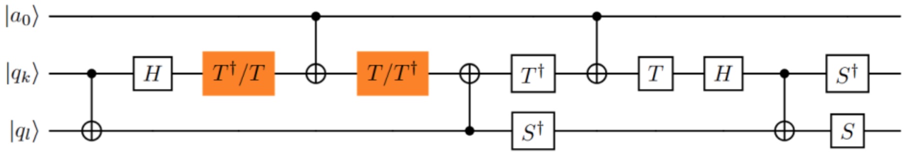
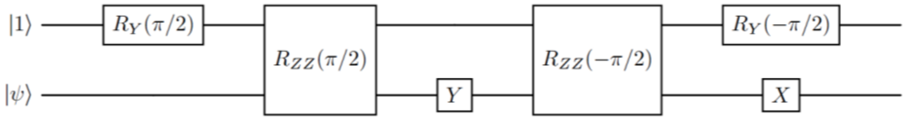
Co-design: Mid-circuit Symmetry Checks and Leakage detection





Optimized construction of controlled iSWAP checks with only 5 CNOTs leading to only a 6 CNOTs overhead per check

- Negated iSWAP checks are placed around the four-Fermi operator $\theta\sigma_i^-\sigma_j^+\sigma_k^-\sigma_l^+ + h.c.$ (orange box) on $k - l$ qubits.
- The controlled iSWAPs commute with the four-Fermi operator in absence of errors – detected in ancilla $a_0\rangle$



Leakage check for a target state ψ⟩

- Ancilla qubit is prepared in state $1\rangle$. This state is flipped if the target qubit is within the computational space

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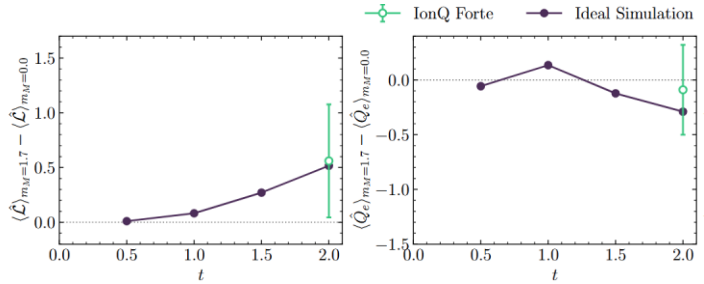
Estimating the limits of IonQ Forte

More complex version of the experiment with fewer approximations:

- Full weak interaction Hamiltonian.
- Small rotation angles not removed.

Resulting circuit with **2,356** two-qubit gates (~5x more).

Pre-compilation	Post-compilation	Post-compilation + symmetry checks
2,374	2,292	2,356



Only time point t = 2.0 was executed on **IonQ Forte**

Ideal Simulation			
$\langle\hat{\mathcal{L}}\rangle_{m_M=0}$	$\langle\hat{\mathcal{L}}\rangle_{m_M=1.7}$	$\langle\hat{Q}_e\rangle_{m_M=0}$	$\langle\hat{Q}_e\rangle_{m_M=1.7}$
0.0	0.57	-0.67	-0.76

QPU Results			
$\langle\hat{\mathcal{L}}\rangle_{m_M=0}$	$\langle\hat{\mathcal{L}}\rangle_{m_M=1.7}$	$\langle\hat{Q}_e\rangle_{m_M=0}$	$\langle\hat{Q}_e\rangle_{m_M=1.7}$
-0.02 ± 0.36	0.54 ± 0.37	-0.13 ± 0.29	-0.22 ± 0.29

Error mitigation: 24 twirled variants, each with 420 shots → 10,080 shots in total.

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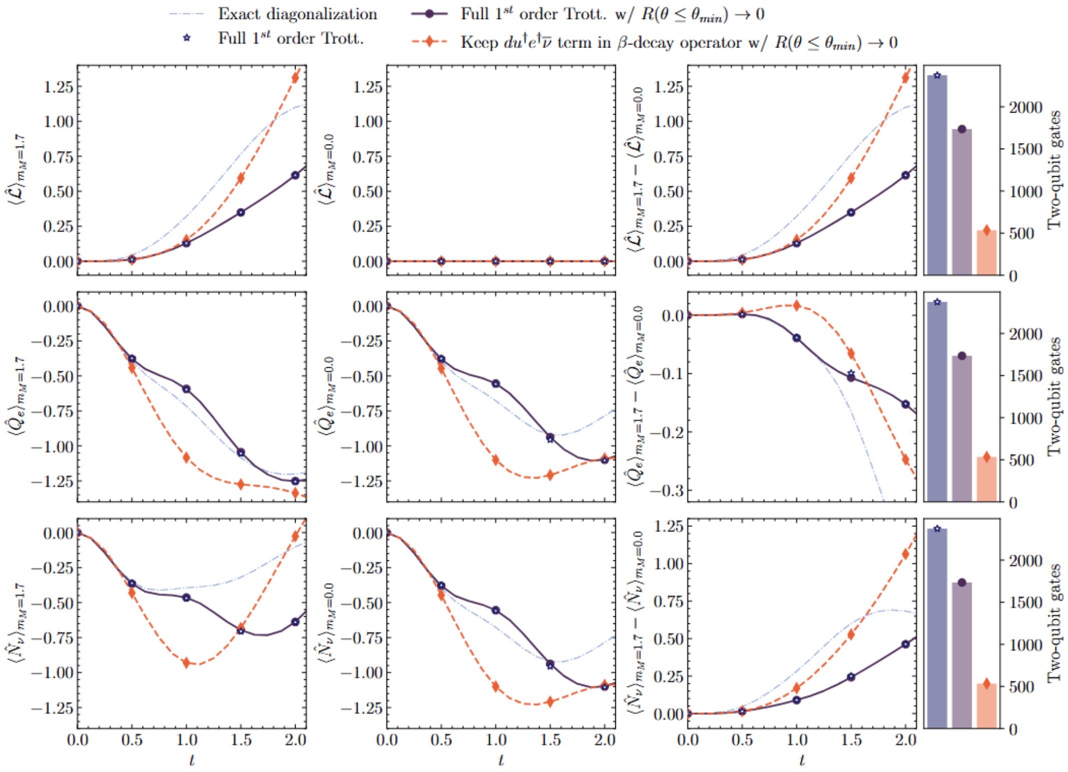
THE ββ-DECAY HAMILTONIAN



i) Exact diagonalization: the initial state preparation and time evolution are performed exactly.

ii) ii) Full 1st order Trotter: |Δ−Δ−⟩ is approximately prepared with SC-ADAPT-VQE, the range of the chromo-electric interaction is truncated to λ = 1 staggered sites and n_T = 2 steps of 1st order Trotterized time evolution are used.

iii) Full 1st order Trotter with $R(\theta \le \theta_{min}) \to 0$: The above approximations plus small rotation angles in the Trotterized time evolution circuits set to zero.

iv) Keep $du^\dagger e^\dagger \bar{\nu}$ term: The above approximations plus keeping only the term in H_β^{1+1} that acts on the valence quarks and valence leptons.

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Results (IonQ Forte Enterprise): Time evolution of $\langle\hat{\mathcal{L}}\rangle$ and $\langle\hat{Q}_e\rangle$

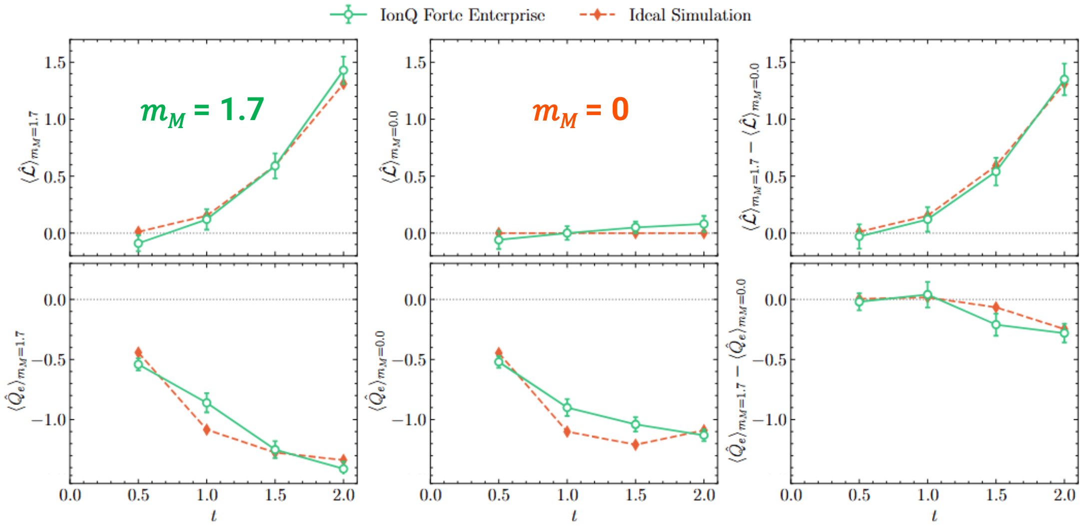
Pre-compilation	Post-compilation	Post-compilation + symmetry checks
534	454	470

Ideal Simulation

t	$\langle\hat{\mathcal{L}}\rangle_{m_M=0}$	$\langle\hat{\mathcal{L}}\rangle_{m_M=1.7}$	$\langle\hat{Q}_e\rangle_{m_M=0}$	$\langle\hat{Q}_e\rangle_{m_M=1.7}$
0.5	0.0	0.01	−0.45	−0.44
1.0	0.0	0.15	−1.10	−1.08
1.5	0.0	0.59	−1.20	−1.26
2.0	0.0	1.31	−1.09	−1.34

QPU Results

t	$\langle\hat{\mathcal{L}}\rangle_{m_M=0}$	$\langle\hat{\mathcal{L}}\rangle_{m_M=1.7}$	$\langle\hat{Q}_e\rangle_{m_M=0}$	$\langle\hat{Q}_e\rangle_{m_M=1.7}$
0.5	-0.06 ± 0.08	-0.09 ± 0.07	-0.52 ± 0.05	-0.54 ± 0.05
1.0	0.00 ± 0.06	0.12 ± 0.09	-0.90 ± 0.07	-0.86 ± 0.08
1.5	0.05 ± 0.05	0.59 ± 0.11	-1.04 ± 0.06	-1.25 ± 0.07
2.0	0.08 ± 0.07	1.43 ± 0.12	-1.13 ± 0.05	-1.41 ± 0.06



- Statistically significant (10σ) lepton number violation for m_M (Majorana mass) = 1.7 .
- Weak interaction truncated and small angles removed.

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Error Mitigation Effects

DNL = Debiasing with Non-linear filtering **PS** = Post-selection **FG** = Post-selections on flag gadgets

t	Error Mitigation	$\langle\hat{\mathcal{L}}\rangle_{m_M=0}$	$\langle\hat{\mathcal{L}}\rangle_{m_M=1.7}$	$\langle\hat{Q}_e\rangle_{m_M=0}$	$\langle\hat{Q}_e\rangle_{m_M=1.7}$
0.5	No EM	-0.04 ± 0.02	-0.05 ± 0.02	-0.12 ± 0.01	-0.10 ± 0.01
	DNL	-0.16 ± 0.02	-0.14 ± 0.02	-0.26 ± 0.02	-0.26 ± 0.02
	DNL + PS	-0.06 ± 0.08	-0.10 ± 0.07	-0.54 ± 0.04	-0.52 ± 0.05
	DNL + PS + FG	-0.06 ± 0.08	-0.09 ± 0.07	-0.52 ± 0.05	-0.54 ± 0.05
1.0	No EM	-0.04 ± 0.02	-0.01 ± 0.02	-0.17 ± 0.02	-0.16 ± 0.01
	DNL	-0.12 ± 0.03	-0.01 ± 0.02	-0.37 ± 0.02	-0.36 ± 0.02
	DNL + PS	0.04 ± 0.07	0.11 ± 0.08	-0.89 ± 0.06	-0.87 ± 0.06
	DNL + PS + FG	0.00 ± 0.06	0.12 ± 0.09	-0.90 ± 0.07	-0.86 ± 0.08
1.5	No EM	-0.02 ± 0.02	0.07 ± 0.01	-0.20 ± 0.02	-0.19 ± 0.01
	DNL	-0.10 ± 0.03	0.19 ± 0.02	-0.4 ± 0.02	-0.43 ± 0.02
	DNL + PS	0.09 ± 0.06	0.68 ± 0.11	-1.05 ± 0.06	-1.24 ± 0.06
	DNL + PS + FG	0.05 ± 0.05	0.59 ± 0.11	-1.04 ± 0.06	-1.25 ± 0.07
2.0	No EM	-0.02 ± 0.01	0.28 ± 0.01	-0.31 ± 0.01	-0.30 ± 0.01
	DNL	-0.03 ± 0.02	0.37 ± 0.02	-0.45 ± 0.01	-0.41 ± 0.01
	DNL + PS	0.13 ± 0.07	1.41 ± 0.09	-1.10 ± 0.05	-1.38 ± 0.05
	DNL + PS + FG	0.08 ± 0.07	1.43 ± 0.12	-1.13 ± 0.05	-1.41 ± 0.06

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Summary and Outlook

- Performed a suite of path-finding quantum simulations of 0νββ-decay in 1+1D QCD induced by a lepton-number violating Majorana neutrino mass.
- Circuit design and error mitigation were co-designed to maximize the performance from IonQ’s Forte-generation QPUs.
- Executing benchmarking circuits with up to 2,356 two-qubit gates informed further improved approximations, circuit design and choices of error mitigation.
- Improved circuits with 470 two-qubit gates combined with error mitigation enabled observation of lepton number violation in 0νββ-decay induced by the valence weak operator on the QPU.
- This work marks the first time that real-time quantum simulations of this process have been performed on quantum hardware and establishes a path toward more realistic simulations to begin making contact with experiments.
- Expected improvements in both fidelity and qubit count in IonQ quantum hardware over the next few years would enable the extension to larger system sizes in 2+1D and 3+1D lattices.

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Backup

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IonQ Forte Enterprise Results - Post-processing

Total Workload: T = {0.5, 1.0, 1.5, 2.0} X {mass, no mass} – 64 variants for each circuit, 150 shots for each variant. 8 circuits, 512 variants, 76,800 shots total.

Flag gadgets
Ancilla measurement check for qubit leakage on the 4 shared ancilla qubits at the end of each circuit, post-selecting on shots without leakage

Total charge conservation
Post-selection on shots that conserve total charge

Lepton register
Zero out quark measurement register to post-select on lepton register for non-linear filtering

Non-linear filtering
Non-linear power law filter to emphasize high-probability variant occurrences within aggregated shots

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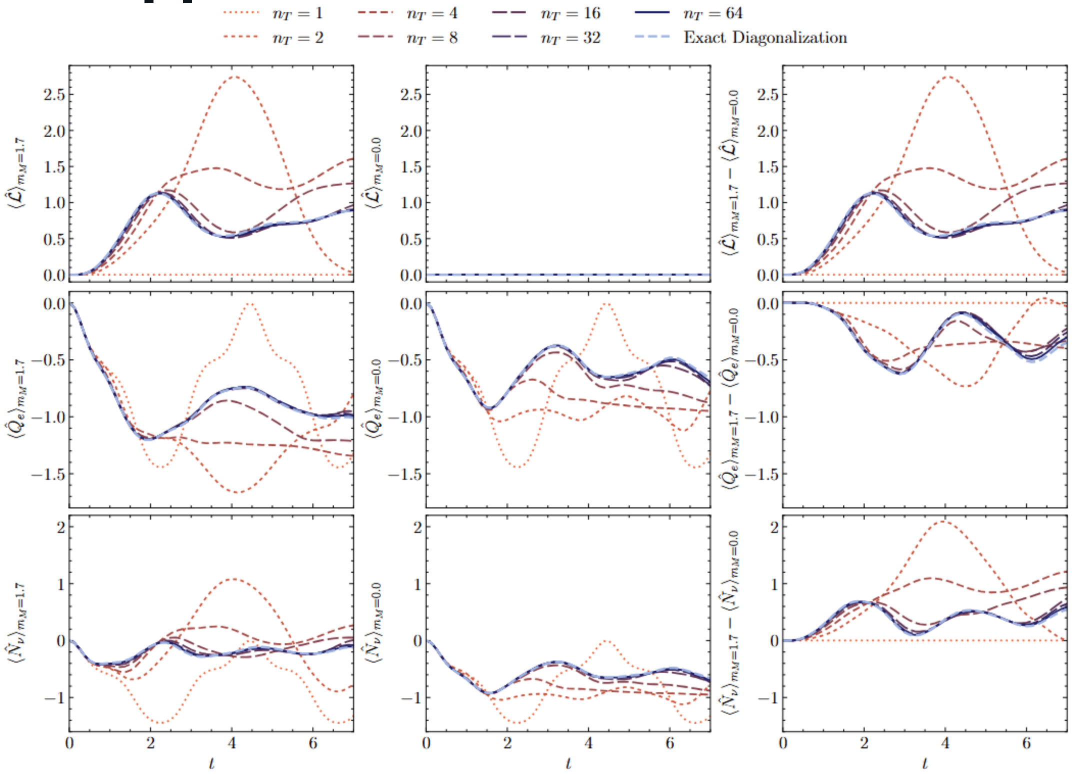
THE ββ-DECAY HAMILTONIAN



The lepton number, L, the electric charge in the lepton sector, Qe, and the neutrino number, Nv , computed throughout the time evolution starting from |ψinit⟩ = |ψ(lep)vac ⟩|Δ−Δ−⟩ as a function of the number of Trotter steps. These quantities are computed for L = 2 and for two Majorana masses, mM = {0.0, 1.7}. No approximations are made in the exact diagonalization results. An exact state-vector simulator is used to compute the time-evolution with nT Trotter steps, which have Trotter errors, as well as (small) errors coming from the SC-ADAPT-VQE preparation of |Δ−Δ−⟩. The quantum simulations that we performed on IonQ's Forte-generation quantum processors employed nT = 2 and were limited to t ≤ 2.

A. Chernyshev, R. C. Farrell, M. Illa, M. J. Savage, A. Maksymov, F. Tripier, M. A. Lopez-Ruiz, A. Arrasmith, Y. de Sereville, A. Brodutch, et al., "Pathfinding quantum simulations of neutrinoless double-*beta* decay," arXiv preprint arXiv:2506.05757, 2025.

THE β-DECAY HAMILTONIAN

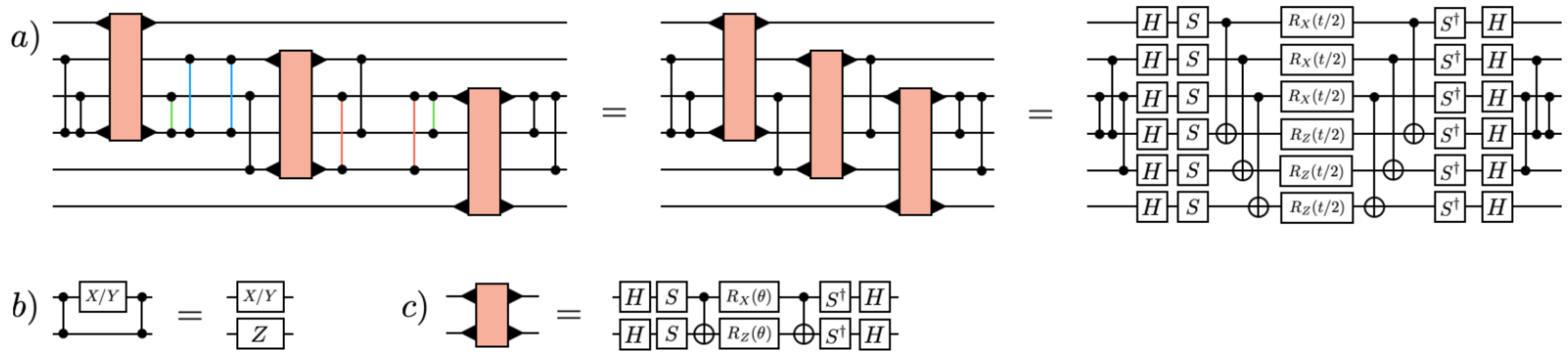


FIG. 2. A method for constructing shallow circuits on quantum computers with all-to-all connectivity. The barbells denote CZ gates, and the ▶-symbols on the orange blocks mark the qubits that are acted on. a) A quantum circuit that implements the time-evolution of the one-flavor quark kinetic term in Eq. (12). The red, blue and green CZ gates cancel against each other. b) A useful circuit identity. c) The definition of the light orange circuit block that implements $e^{-i\theta(\hat{\sigma}^+\hat{\sigma}^-+\hat{\sigma}^-\hat{\sigma}^+)}$.

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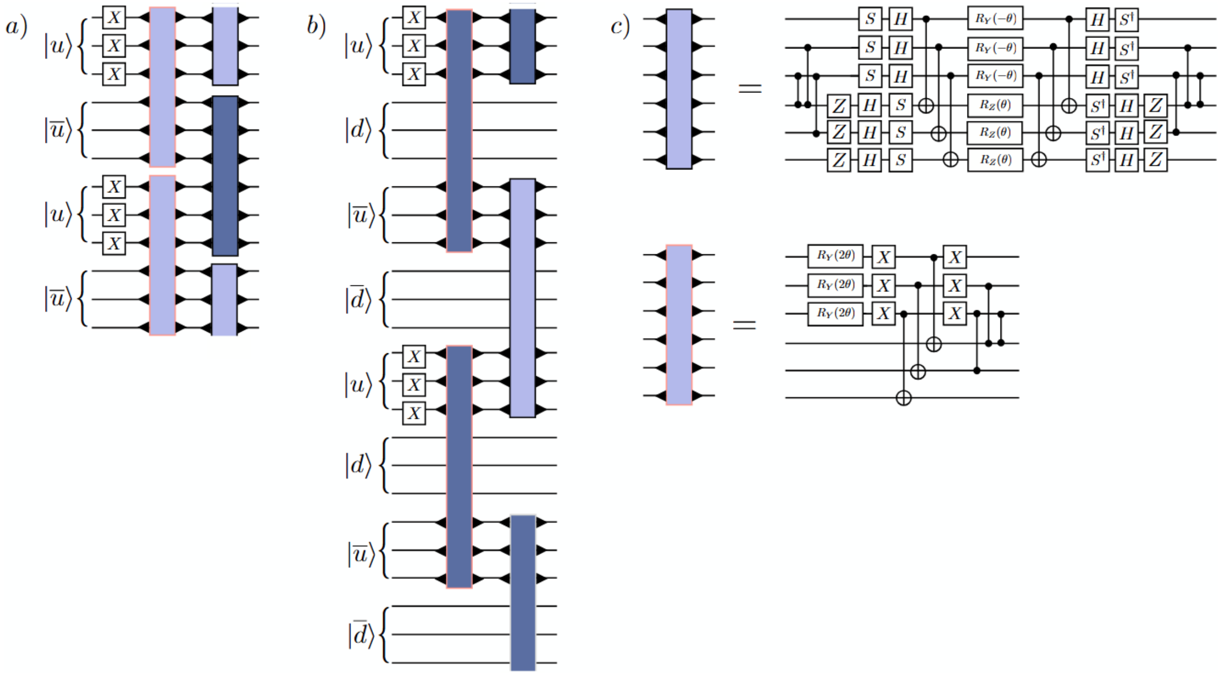

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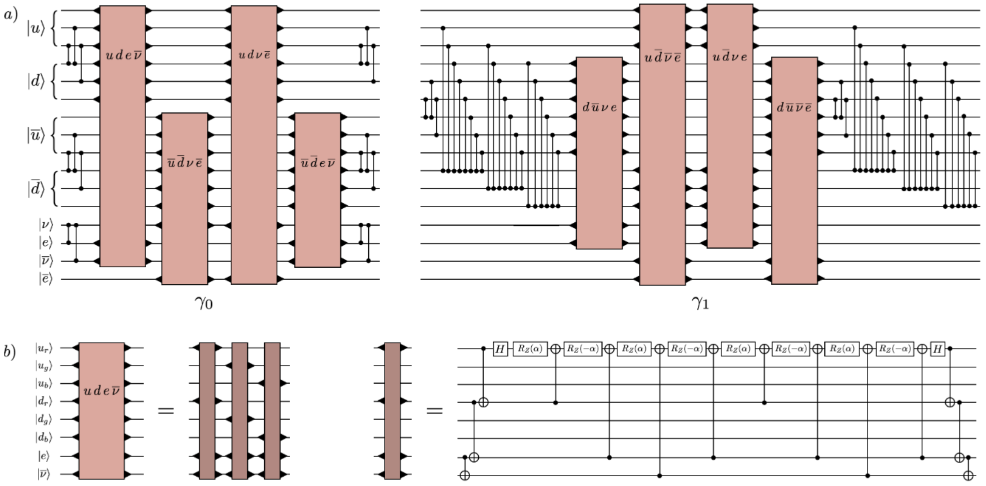

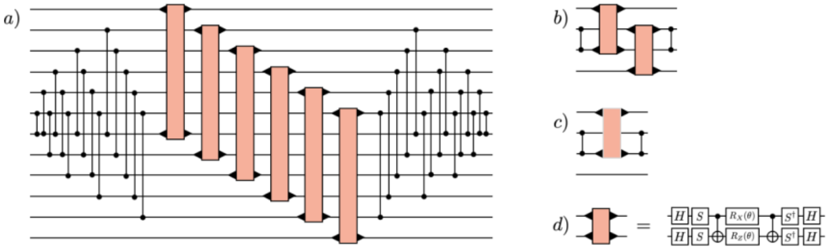

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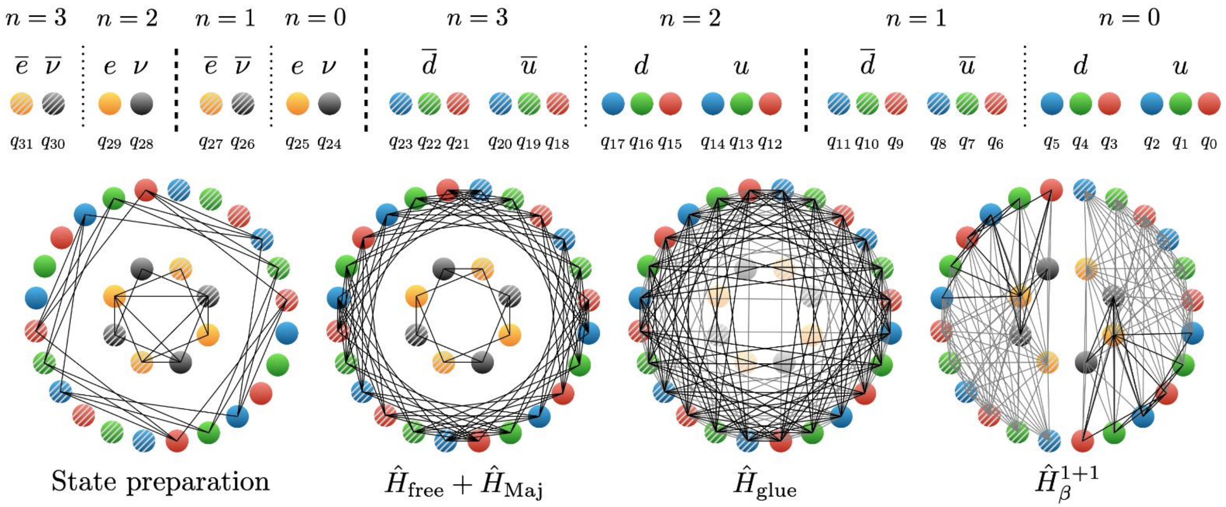
THE ββ-DECAY HAMILTONIAN

- We investigate a 2-site lattice model with quarks, electrons and neutrinos.
- The qubit mapping is done from right to left starting with the quarks.

Efficient qubit layout of L = 2 lattice for 0ϑββ-decay simulation



$$\hat{H} = \hat{H}_{\rm free} + \hat{H}_{\rm glue} + \hat{H}_{\beta,\rm valence}^{1+1} + \hat{H}_{\rm Maj}$$

$$\hat{H}_{\rm free} = \sum_{f}\sum_{n=0}^{2L-1}\left[m_f(-1)^n\phi_n^{(f)\dagger}\phi_n^{(f)} + \frac{1}{2}\left(\phi_n^{(f)\dagger}\phi_{n+1}^{(f)} + \text{h.c.}\right)\right]$$

$$\hat{H}_{\rm glue} = \frac{g^2}{2}\sum_{n=0}^{2L-1}\sum_{s=1}^{\lambda}\left(-s+\frac{s^2}{2L}\right)\left(1-\frac{1}{2}\delta_{s,L}\right)\sum_{a=1}^{8}Q_n^{(a)}Q_{n+s}^{(a)}$$

$$\hat{H}_{\beta,\rm valence}^{1+1} = \frac{G}{\sqrt{2}}\sum_{n\ \rm even}\left(\phi_n^{(u)\dagger}\phi_n^{(d)}\phi_n^{(e)\dagger}\phi_{n+1}^{(\nu)} + \text{h.c.}\right)$$

$$\hat{H}_{\rm Maj} = \frac{1}{2}m_M\sum\left(\phi_n^{(\nu)}\phi_{n+1}^{(\nu)} + \text{h.c.}\right)$$

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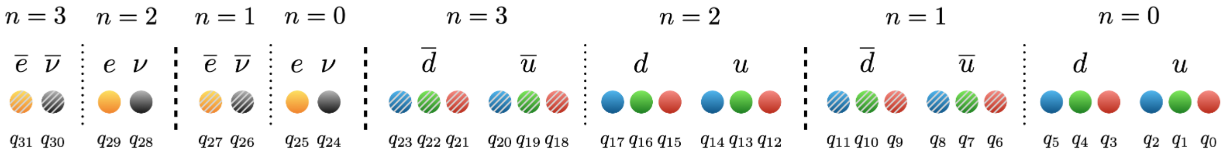
THE ββ-DECAY HAMILTONIAN

$$\hat{H} = \hat{H}_{\text{free}} + \hat{H}_{\text{glue}} + \hat{H}^{1+1}_{\beta,\text{valence}} + \hat{H}_{\text{Maj}}$$



Efficient qubit layout of L = 2 lattice for 0ϑββ-decay simulation

Conserved quantities during simulation:

Redness → $\hat{r} = \frac{1}{2}\sum_{n=0}^{3}\sum_{f=0}^{1}\hat{Z}_{6n+3f}$

Greenness → $\hat{g} = \frac{1}{2}\sum_{n=0}^{3}\sum_{f=0}^{1}\hat{Z}_{6n+1+3f}$

Blueness → $\hat{b} = \frac{1}{2}\sum_{n=0}^{3}\sum_{f=0}^{1}\hat{Z}_{6n+2+3f}$

Total Electric Charge → $\hat{Q}_{\text{tot}} = \frac{1}{2}\sum_{n=0}^{3}\sum_{f=0}^{1}\sum_{c=0}^{2} q_f \hat{Z}_{6n+3f+c} + \hat{Q}_e \quad \hat{Q}_e = -\frac{1}{2}\sum_{n=0}^{3}\hat{Z}_{25+2n}$

Lepton number → $\hat{\mathcal{L}} = \frac{1}{2}\sum_{n=0}^{3}\left(\hat{Z}_{24+2n} + \hat{Z}_{25+2n}\right)$

conserved only for zero Majorana mass m_M

Initial state for the system $|\psi_{\text{init}}\rangle = |\psi^{(\text{lep})}_{\text{vac}}\rangle\,|\Delta^-\Delta^-\rangle$

$$|\Delta^-\Delta^-\rangle = |\psi^{(u)}_{\text{vac}}\rangle|0\rangle^{\otimes 6}$$

0ϑββ-decay process

$$|\Delta^-\Delta^-\rangle \rightarrow |\Delta^0\Delta^0\rangle + 2e^-$$

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Neutrinoless Double-β Decay

The $0\nu\beta\beta$-decay is a potential exotic nuclear decay relevant for searches for new physics.

It can only happen if the exact **lepton number symmetry** of the Standard Model is **broken**.

Provides potential insight into two fundamental puzzles of the Standard Model:

- Nature of the neutrino mass, which requires Beyond the Standard Model physics to explain.
- Matter/anti-matter asymmetry created during the electroweak phase transition in the early universe.

Classical calculations of the decay rates of nuclei are quite challenging due to the strong correlation between nucleons.

Quantum computation may be better suited for this task.

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Circuit Optimization and Error mitigation

- important to design the quantum circuits and error handling in tandem. On NISQ devices, this amounts to careful circuit optimization and error mitigation techniques.
- Combining the careful selec-tion of circuit-variant implementations with observable-specific post-selection rules allows for precise error detec-tion and higher shot efficiency. The approach chosen herecombines debiasing through symmetrization [105], post-selection on symmetry checks, and a novel parametrizednonlinear filtering method on the lepton qubit register.Post-selection is based on the usage of spare qubits forflag-based [106] mid-circuit symmetry checks and leakageerror detection to further reduce the errors.
- The all-to-all connectivity and native RZZ (θ) gatesavailable on IonQ's quantum computers is used to fur-ther optimize quantum circuits by merging blocks of two-qubit gates. This reduces the number of entangling-gatesby 15%.
- In addition to qubit remapping,we make use of a type of phase-flip twirling of two qubitgates in generating our variants as described in Ref. [105].For this project we also introduced a bit-flip symmetriza-tion of readout into this process.
- In post-processing, we combine the post-selected mea-surement statistics from different twirled variants, filter-ing out outlier bit strings. This filtering is accomplishedby checking if a given measured bit string appears in atleast some specified number of variants, referred to asthe filter threshold. The choice of the threshold is deter-mined by a combination of knowledge of the device noise,the number of twirled variants, and the number of shotstaken per variant. A higher threshold better mitigateshardware-noise induced biases, but requires more vari-ants and shots per variant.

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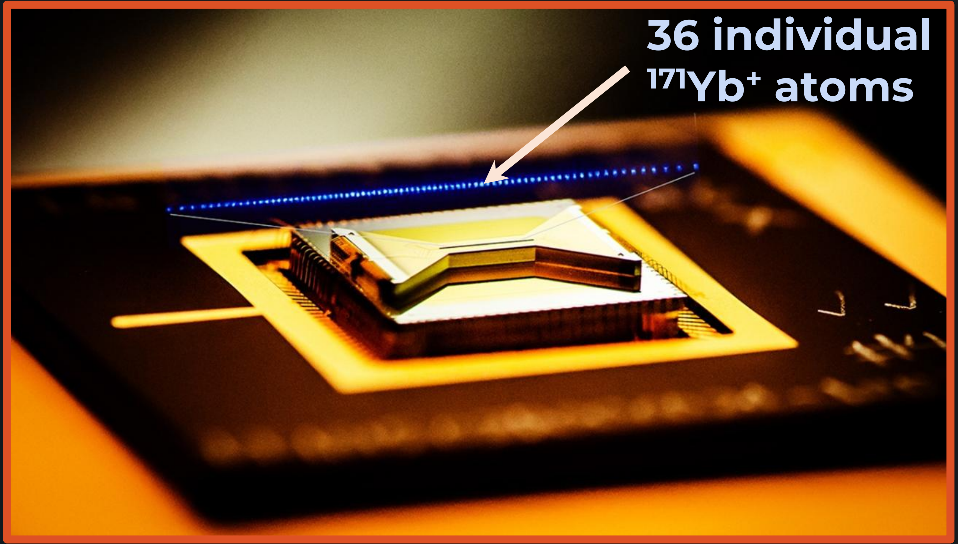
IONQ Qubit Technology



Based on Individual Atoms, with Fully Flexible Control

IonQ Quantum Differentiators - Our Qubits and Architecture

Perfect qubits
Since we use ions (atoms with one missing electron) which are naturally quantum objects, our qubits are perfectly identical. This lowers errors in the computation. Contrast this to superconducting qubits which are individually manufactured.

Best coherence time
Coherence time is about how long the unique quantum resources are available for use. IonQ's quantum coherence time is typically measured in seconds to minutes, longer than the competition.

Better gate fidelity
Better fidelity means better execution of code statements in your application, and this also lowers computing errors.

Low SPAM errors
Low state preparation and measurement (SPAM) errors improve overall application results.

Unique architecture
All-to-all connectivity between qubits with no limitations allows optimal implementation of any algorithm.

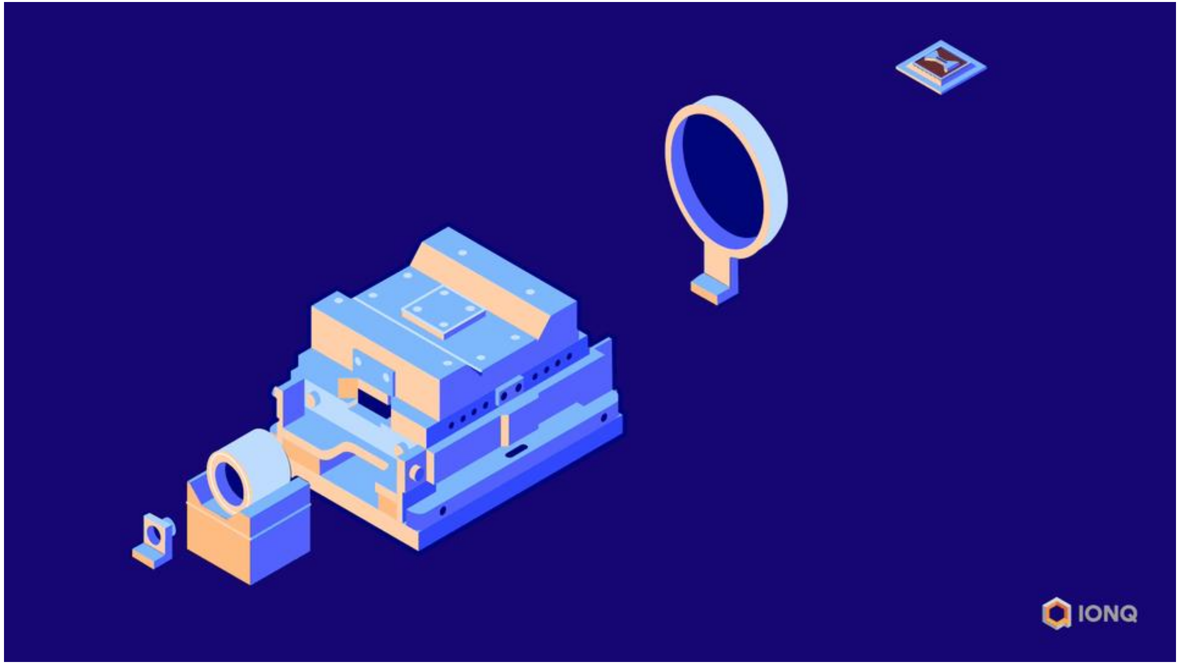
Wire free
Qubits are not hard-wired; literally no wires. They are connected through fully programmable laser beams. Contrast this to superconducting qubits which are hardwired together.

Many applications
We can implement many different types of gates (quantum operations) that can be adapted to any application.

Modular & scalable
Longer-term, IonQ's architecture will also scale more efficiently as we interconnect multiple quantum systems that behave as one whole system, in a modular architecture.

https://ionq.com/technology

Quantum Hardware: Ion Traps



Our Newest System - IonQ Forte

Forte is the latest evolution towards a software-configurable quantum computer with 36 qubits.

The new system features acousto-optic deflector (AOD) technology, which allows IonQ to dynamically direct laser beams that drive quantum operations towards individual ions. This offers better fidelity.

Qubit and gate configuration, can be tailored to user needs, creating a truly dynamic and flexible system

https://investors.ionq.com/news/news-details/2022/Introducing-IonQ-Forte-Improving-Quantum-Performance-with-a-Software-Configurable-Dynamic-Laser-System/default.aspx