

Introduction to Quantinuum
Trapped-Ion Quantum Computing

Steve Sanders KEK Workshop 26 March, 2024

### Outline

- Introduction to Quantinuum as a Company
- Our Quantum Computing Architecture the Trapped Ion Quantum Charged Coupled Device (QCCD)
- Current H-Series Machine Performance and Features
- What can you do with the machine?
- The Future Scaling to Larger Systems

# Introduction to Quantinuum

- The Trapped Ion Quantum Charged Coupled Device (QCCD)
- Current H-Series Machine Performance and Features
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# Quantinuum at-a-glance

WHO WE ARE

### LARGEST PLAYER

in integrated quantum hardware and software

375+

scientists and engineers (of which > 200PhDs)



Global teams in largest quantum markets (USA, UK, Europe, Japan)

>155

Scientific publications from Quantinuum

WHAT WE OFFER

### H-SERIES

World class QCCD, ion trap hardware with industry-leading fidelity and scalability

### **FULL STACK**

InQuanto<sup>™</sup> Quantum chemistry software.

TKET<sup>™</sup> open-source developer tool kit.

LAMBEQ<sup>™</sup> open-source natural language processing



Collaborations and partnership with leading commercial and academic organization

**USER COMMUNITY** 

>80

Scientific publications using H-Series hardware

> 400

Global users of H-Series hardware

>1,500,000

Downloads of TKET™ open-source tool kit

**CUSTOMERS & PARTNERS** 

Premier financial institutions:
JPMC | HSBC

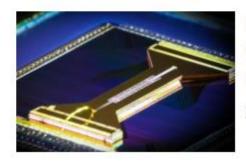
**Top industrials:**Honeywell | BMW |
Airbus | JSR

US Department of Energy Labs, RIKEN

Cloud service partner: Microsoft Azure Quantum

### **BEST IN CLASS HARDWARE**

### **BEST IN CLASS SOFTWARE**



H1 series quantum computers (H1-1 CO, H1-2 MN)

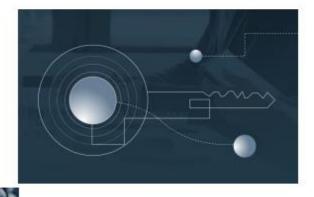
Linear ion trap – QCCD Architecture

20 fully-connected qubits

- Two-qubit gate fidelity: ≥ 99.8%
- Single-qubit gate fidelity: 99.99%
- State prep & measure fidelity: 99.6%

### Cybersecurity

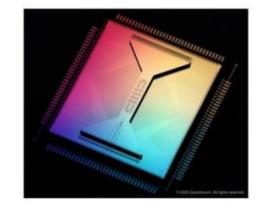
World's only quantumcomputing-hardened encryption keys



### H2 series quantum computer

Racetrack – QCCD Architecture Launched with 32 fully connected qubits

- Space to grow qubit number
- Improvements in ion loading
- Steps towards scaling optics & electronics



**TKET** 

Open-access architectureindependent quantum software stack and development platform



State of the art quantum computational chemistry platform







# Accelerating Quantum Computing with an Integrated Approach

### **Applied Algorithms**

Monte Carlo, PDEs, Optimization, QML, QNLP, Condensed Matter Physics, etc.



### Chemistry

Quantum Computational Chemistry:
Transforming the discovery of new materials
and novel processes



### Cybersecurity

Quantum Origin: Enterprise-grade quantum-computing-hardened cryptographic solution



### Third party platforms

Enables other partners to leverage the power of quantum via open-source access



# NEXUS

The integrated platform for *users* of quantum computers

### TKET

High-performance quantum software development kit | Open-source | > 1 M downloads

**Ecosystem back-ends** 

### **H – Series Quantum Computers**

Powered by **Honeywell** 



Quantinuum Products

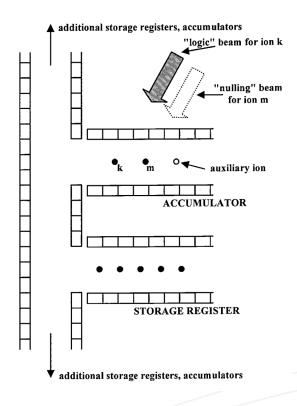
Partner / Ecosystem Products



Introduction to Quantinuum

- The Trapped Ion Quantum Charged Coupled Device (QCCD)
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# Quantum Charged Coupled Device (QCCD) Architecture



Wineland et al., J. Nat. Inst. Stand. Tech (1998)



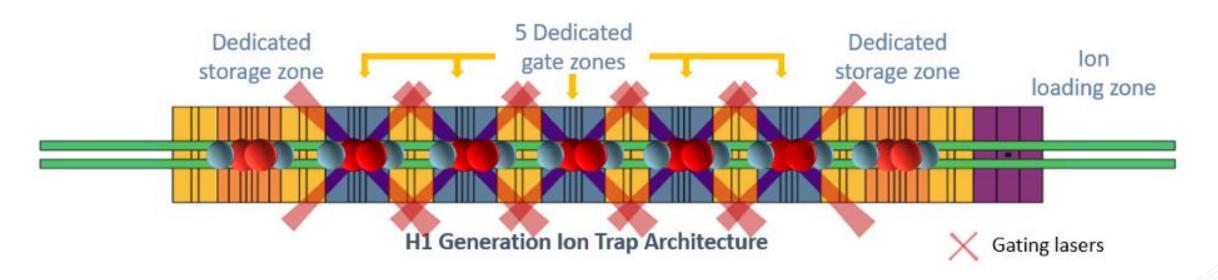
Image credit: NIST

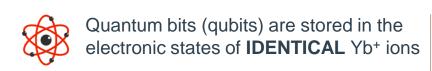
- 1 qubit = 1 ion
- Qubits are mobile
- Lasers perform gate operations
- Laser zones fixed
- Gate in pairs or singles
- Rearrange for arb connectivity
- Laser zones separated → low cross-talk





# Quantinuum QCCD Trapped-ion Architecture





Hyperfine qubit

171Yb+ - |1

QCCD architecture enables using gate zones

- · Minimal and frequent calibrations
- All-to-all connectivity
- High fidelity operations

Cooling ions provide mid-circuit cooling, maintaining circuit fidelity throughout circuit

<sup>138</sup>Ba+



Cooling ion



# **QCCD** Operation

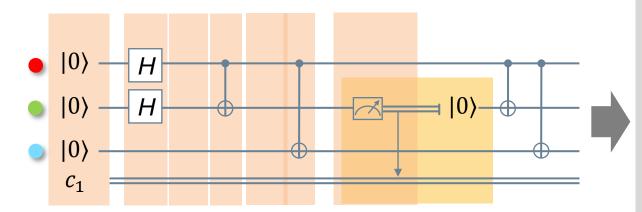
Qubits move to operation zones, eg gate zones

### **Quantum Circuit**

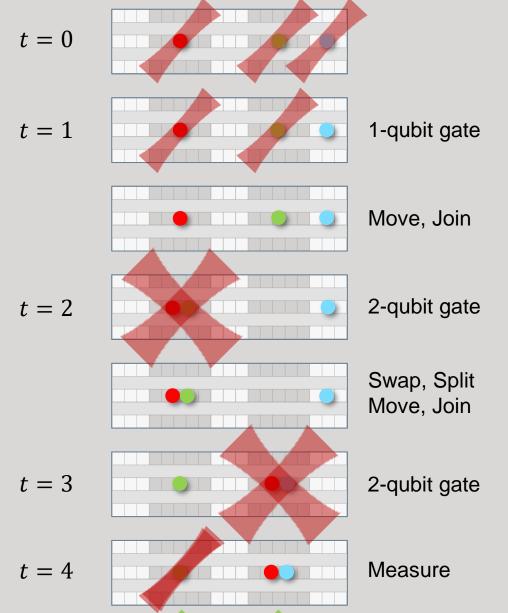
t = 0

1

2



Reinitialize the green qubit → now can use it again in circuit

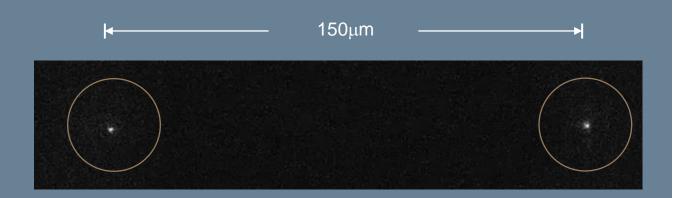


### **REAL-WORLD VIEW**

### **Split and Combine**

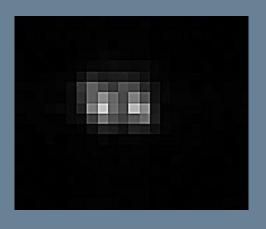
Ion is transported into the same zone

lons are combined into a single potential well and then re-separated



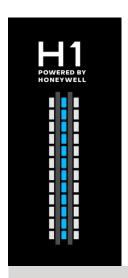
### Swap

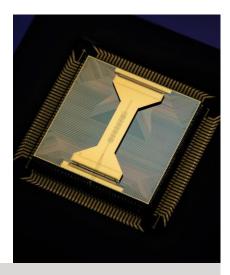
lons are carefully manipulated to reorder positions



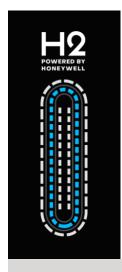
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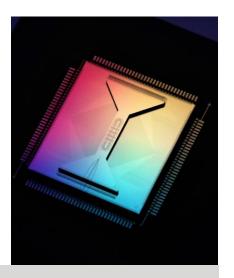
# H-Series Commercial Quantum Processing Units





- 20 fully-connected qubits
- 5 parallel gating zones
- TQ gate fidelity ≥ 99.8%
- SQ gate fidelity > 99.995%
- SPAM fidelity > 99.7%
- Measurement cross talk error < 0.01%</li>





- 32 fully-connected qubits
- 4 parallel gating zones
- TQ gate fidelity 99.8%
- SQ gate fidelity 99.997%
- SPAM fidelity > 99.8%
- Measurement cross talk error < 0.01%</li>

# **Key Features**

- Universal gate set + unique native arbitrary angle two qubit gate
- High fidelity emulator to aid in development and debugging
- Tightly coupled classical computing and advanced control features enable real-time, algorithmic decoding
- Communication API based on OpenQasm, compatible with QIR, Qiskit, TKET



### H2 Benchmarks<sup>1</sup>

### Component

- Single-qubit randomized benchmarking
- Two-qubit randomized benchmarking
- Two-qubit SU(4) randomized benchmarking
- Two-qubit parameterized gate randomized benchmarking
- Measurement crosstalk bright state depumping
- Reset crosstalk bright state depumping
- SPAM test
- Two-qubit cycle benchmarking

### System-level

- Mirror benchmarking
- Random circuit sampling
- GHZ state fidelity
- Quantum volume

### **Algorithmic**

- 1D transverse field Ising model simulation
- QAOA
- Repetition code
- HoloQUADS
- Logical circuits

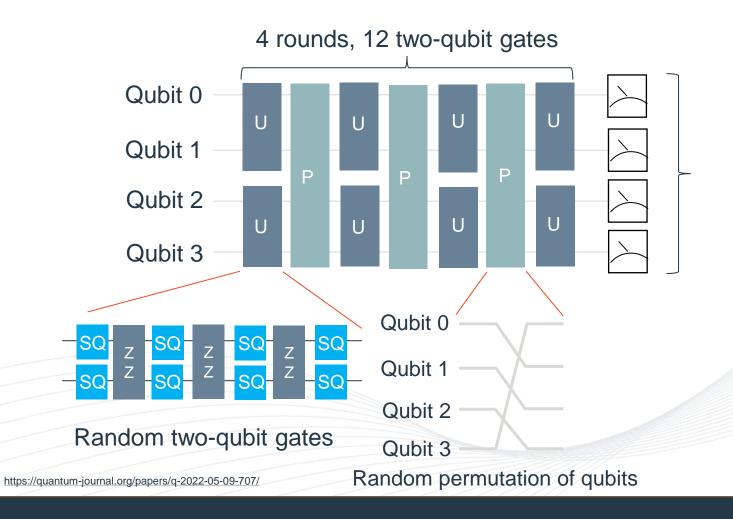
### **Transparency**

- Publish the data and processing scripts on Github<sup>2</sup>
  - 1- Phys. Rev. X **13**, 041052
  - 2- github.com/CQCL/quantinuum-hardware-h2-benchmark

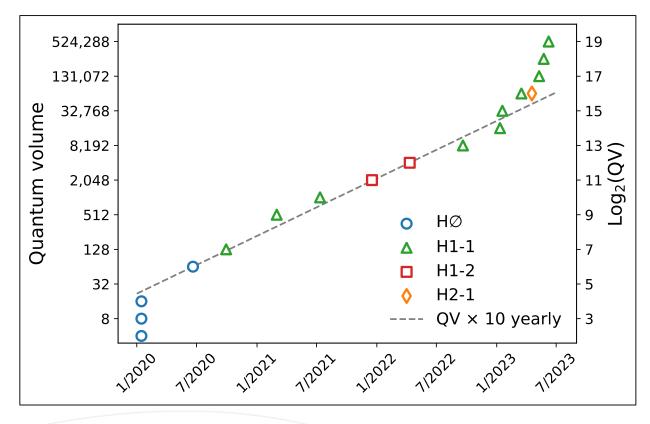


### Quantum Volume Benchmarks

Quantum volume is a measure of the largest circuit that can successfully be run with depth = qubit number.  $QV = 2^{min(depth, qubit number)}$ 



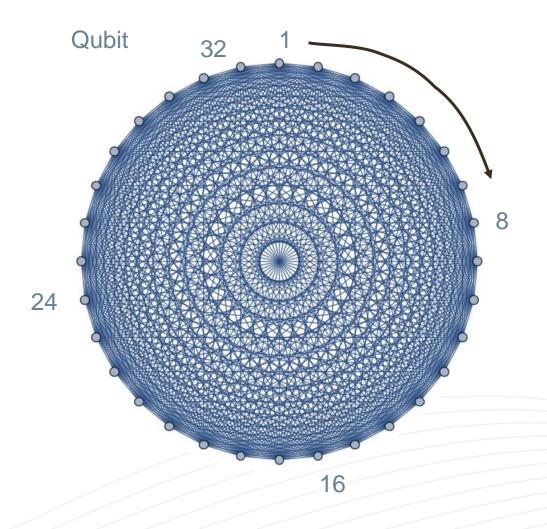
# H-Series: The Most Benchmarked. The Highest Performing.





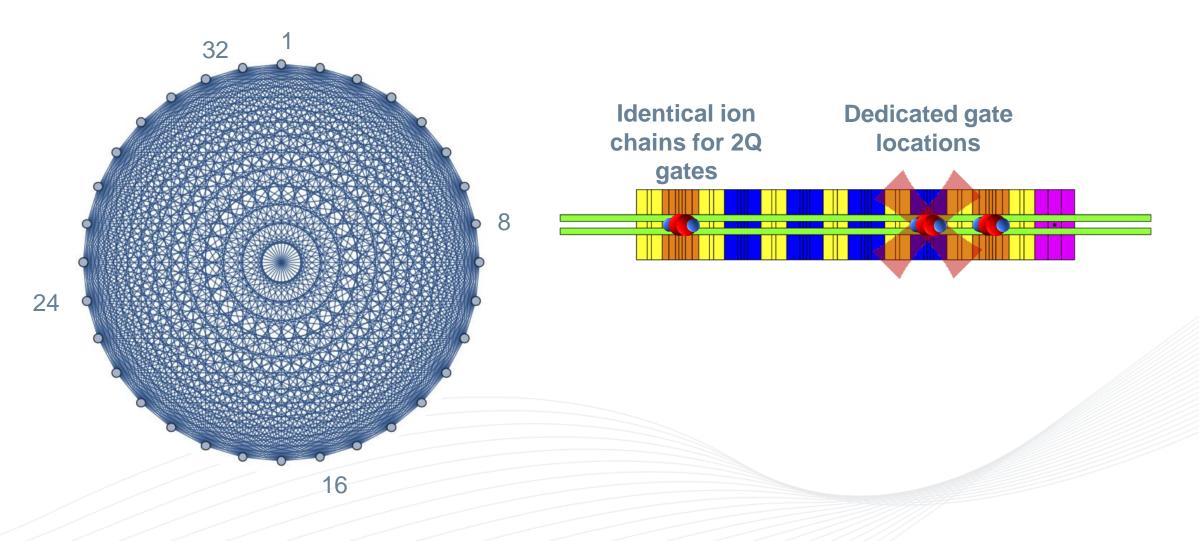
Quantum Volume ~ 1,000x higher than next best published result

# 32 qubits → 496 Qubit Pairings

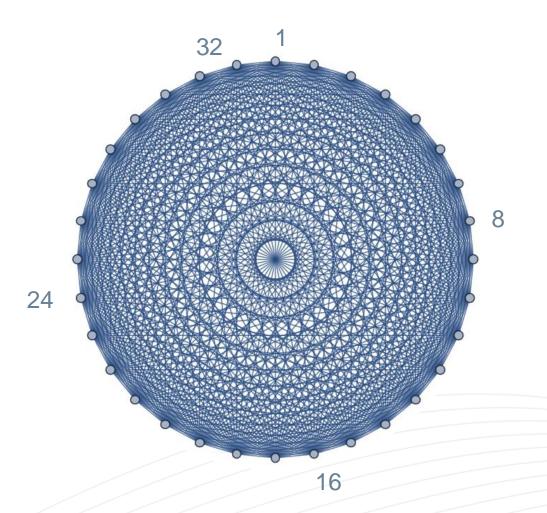


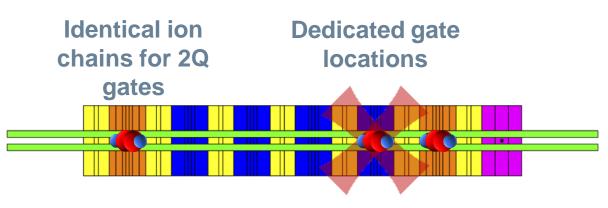


# 496 Qubit Pairings, All at High Fidelity



# 496 Qubit Pairings, All at High Fidelity



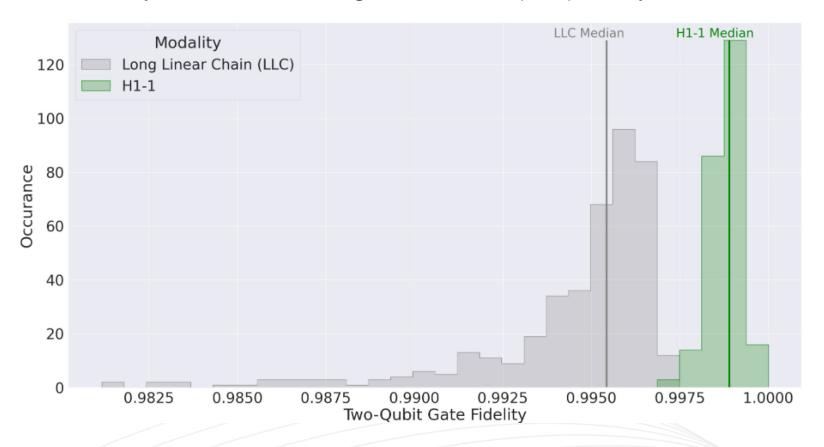


496 calibrations of qubit interactions replaced with 4 calibrations of gate zones

99.8% 2Q gate Fidelity is currently typical on H2 system

### 2-Qubit Gate Performance

H1-1 fidelity is 0.9988 and Long Linear Chain (LLC) fidelity is 0.9954



### **H1-1 Fidelity**

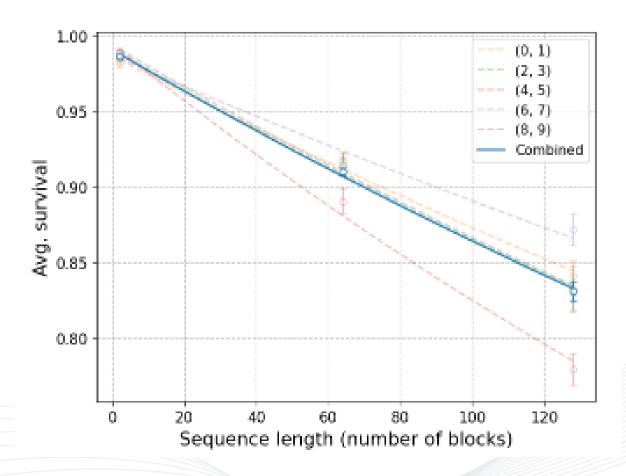
- Median 0.9989 ± 0.0004
- IQR: 0.0006

### **LLC Fidelity**

- Median 0.9954 ± 0.007
- IQR: 0.0023

H1-1 data across all 5 gate zones, ~2 months of operation

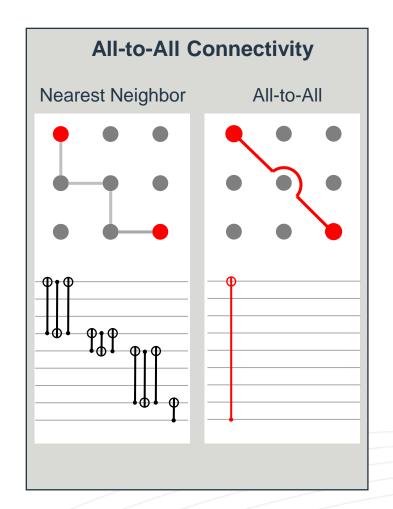
# Fidelity first in commercial systems

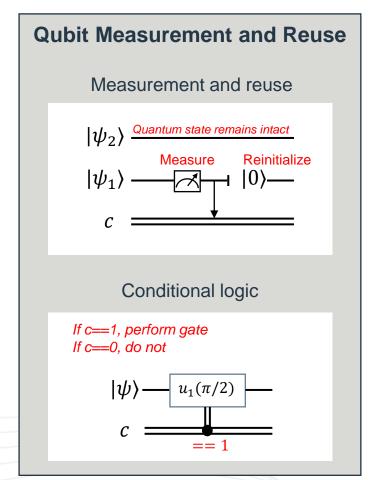


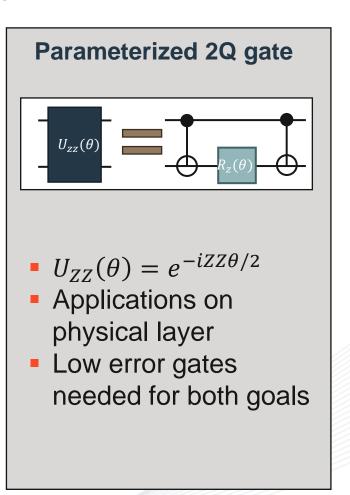
Average err < 0.1%, avg 2Q fidelity > 99.9%



# Differentiating Functionality







Advanced features + high fidelity → shorter time to solution

### **Native Gate Set**

Native single-qubit gates: 
$$U_{1q}(\theta,\varphi) = e^{-i\left(\cos\varphi\hat{X} + \sin\varphi\hat{Y}\right)\theta/2} = \begin{pmatrix} \cos\frac{\theta}{2} & -ie^{-i\varphi}\sin\frac{\theta}{2} \\ -ie^{i\varphi}\sin\frac{\theta}{2} & \cos\frac{\theta}{2} \end{pmatrix}$$

$$R_z(\lambda) = e^{-i\hat{z}\lambda/2} = \begin{pmatrix} e^{-i\lambda/2} & 0\\ 0 & e^{i\lambda/2} \end{pmatrix}$$

Fully entangling two-qubit gate:  $ZZ() = e^{-i\frac{\pi}{4}\hat{Z}\otimes\hat{Z}} = e^{-\frac{i\pi}{4}}\begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & i & 0 & 0 \\ 0 & 0 & i & 0 \end{pmatrix}$ 

Arbitrary angle two-qubit gate: 
$$RZZ(\theta) = e^{-i\frac{\theta}{2}\hat{Z}\otimes\hat{Z}} = e^{-\frac{i\theta}{2}}\begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & e^{i\theta} & 0 & 0 \\ 0 & 0 & e^{i\theta} & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

$$RZZ\left(\frac{\pi}{2}\right) = ZZ()$$

 $\hat{X}$ ,  $\hat{Y}$ , and  $\hat{Z}$  are the standard Pauli operators and the two-qubit matrix is written in the  $|0,0\rangle, |0,1\rangle, |1,0\rangle, |1,1\rangle$  basis.

It is important to note that the arbitrary rotation around the z-axis,  $R_z(\lambda)$ , is performed virtually within the software. All other gates are constructed from this set.

# QCCD Architecture: Scalable AND High Performance

Perfectly identical qubits.

Not engineered, no manufacturing variability.

Any-to-any connectivity with minimal calibrations.

Number of calibrations required << number of qubit pairs

Mid-circuit cooling: consistent performance for long circuits.

Included in QCCD architecture "by design",

Low cross-talk mid-circuit measurement.

Required for error correction.

Included in every generation of H-series



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### H-Series User Publications

Towards Quantum Gravity in the Lab on Quantum Processors

Illya Shapoval<sup>1</sup>, Vincent Paul Su<sup>2</sup>, Wibe de Jong<sup>1</sup>, Miro Urbanek<sup>1</sup>, and Brian Swingle<sup>3</sup>

<sup>1</sup>Lawrence Berkeley National Laboratory, 1 Cyclotron Rd, CA 94720, USA
<sup>2</sup>Center for Theoretical Physics and Department of Physics, University of California, Berkeley, CA 94720, U.S.A.
<sup>3</sup>Brandeis University, Waltham, MA 02453, USA

### RESEARCH

# Periodic Plane-Wave Electronic Structure Calculations on Quantum Computers

Duo Song $^{\dagger\dagger}$ , Nicholas P Bauman $^1$ , Guen Prawiroatmodjo $^2$ , Bo Peng $^1$ , Cassandra Granade $^2$ , Kevin M Rosso $^1$ , Guang Hao Low $^2$ , Martin Roetteler $^2$ , Karol Kowalski $^1$ 

\*Corres eric.byl: <sup>1</sup>Funda Pacific Laborat USA Full list

Digitized-Counterdiabatic Quantum Algorithm for Protein Folding

Pranav Chandarana, 1,2 Narendra N. Hegade, 3,4, Iraitz Montalban, 5,5 Enrique Solano, 3,4,6,† and Xi Chen 1,2,\$

<sup>1</sup>Department of Physical Chemistry, University of the Basque Country UPV/EHU, Apartado 644, 48080 Bilbao, Spain <sup>2</sup>EHU Quantum Center, University of the Basque Country UPV/EHU, Barrio Sarriena, s/n, 48940 Leioa, Biscay, Spain <sup>3</sup>Kipu Quantum, Greifswalderstrasse 226, 10405 Berlin, Germany

<sup>4</sup>International Center of Quantum Artificial Intelligence for Science and Technology (QuArtist) and Physics Department, Shanghai University, 200444 Shanghai, China

<sup>5</sup>Department of Physics, University of the Basque Country UPV/EHÜ, Barrio Sarriena, s/n, 48940 Leioa, Biscay, Spain <sup>6</sup>IKERBASQUE, Basque Foundation for Science, Plaza Euskadi 5, 48009 Bilbao, Spain

We propose a hybrid classical-quantum digitized-counterdiabatic algorithm to tackle the protein folding problem on a tetrahedral lattice. Digitized-counterdiabatic quantum computing is a paradigm developed to compress quantum algorithms via the digitization of the counterdiabatic acceleration of a given adiabatic quantum computation. Finding the lowest energy configuration of the amino acid sequence is an NP-hard optimization problem that plays a prominent role in chemistry, biology, and drug design. We outperform state-of-the-art quantum algorithms using problem-inspired and hardware-efficient variational quantum circuits. We apply our method to proteins with up to 9 amino acids, using up to 17 qubits on quantum hardware. Specifically, we benchmark our quantum algorithm with Quantinuum's trapped ions, Google's and IBM's superconducting circuits, obtaining high success probabilities with low-depth circuits as required in the NISQ era.

### Portfolio Optimization via Quantum Zeno Dynamics on a Quantum Processor

Dylan Herman,\* Ruslan Shaydulin,\* Yue Sun,\* Shouvanik Chakrabarti, Shaohan Hu, Pierre Minssen, Arthur Rattew, Romina Yalovetzky, and Marco Pistoia Global Technology Applied Research, JPMorgan Chase, New York, NY 10017 USA

Portfolio optimization is an important problem in mathematical finance, and a promising target for quantum optimization algorithms. The use cases solved daily in financial institutions are subject to many constraints that arise from business objectives and regulatory requirements, which make these problems challenging to solve on quantum computers. We introduce a technique that uses quantum Zeno dynamics to solve optimization problems with multiple arbitrary constraints, including inequalities. We show that the dynamics of the quantum optimization can be efficiently restricted to the in-constraint subspace via repeated projective measurements, requiring only a small number of auxiliary qubits and no post-selection. Our technique has broad applicability, which we demonstrate by incorporating it into the quantum approximate optimization algorithm (QAOA) and variational quantum circuits for optimization. We analytically show that achieving a constant minimum success probability in QAOA requires a number of measurements that is independent of the problem size for a specific choice of mixer operator. We evaluate our method numerically on the problem of portfolio optimization with multiple realistic constraints, and observe better solution quality and higher in-constraint probability than the state-of-the-art technique of enforcing constraints by introducing a penalty into the objective. We demonstrate the proposed method on the Quantinuum H1-2 trapped-ion quantum processor, observing performance improvements from circuits with two-qubit gate depths of up to 148.

### Modeling singlet fission on a quantum computer

Daniel Claudino, <sup>1\*</sup> Bo Peng, <sup>2†</sup> Karol Kowalski<sup>2</sup> and Travis S. Humble<sup>3</sup>

<sup>1</sup> Computational Sciences and Engineering Division,
Oak Ridge National Laboratory, Oak Ridge, TN, 37831, USA

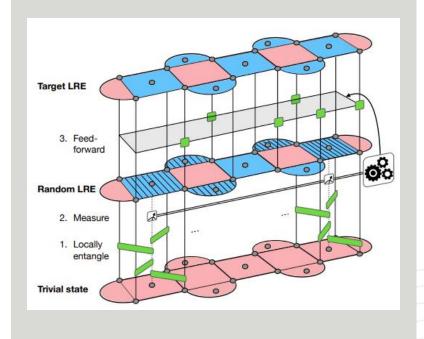
<sup>2</sup> Physical Sciences Division, Pacific Northwest National Laboratory, Richland, WA 99352, USA

<sup>3</sup> Quantum Science Center, Oak Ridge National Laboratory, Oak Ridge, TN, 37831, USA<sup>‡</sup>
(Dated: January 18, 2023)

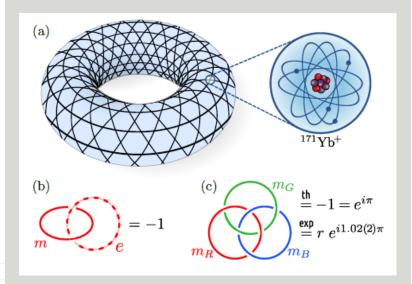
We present a use case of practical utility of quantum computing by employing a quantum computer in the investigation of the linear H<sub>4</sub> molecule as a simple model to comply with the requirements of singlet fission. We leverage a series of independent strategies to bring down the overall cost of the quantum computations, namely 1) tapering off qubits in order to reduce the size of the relevant Hilbert space; 2) measurement optimization via rotations to eigenbases shared by groups of qubit-wise commuting (QWC) Pauli strings; 3) parallel execution of multiple state preparation + measurement operations, implementing quantum circuits onto all 20 qubits available in the Quantinuum H1-1 quantum hardware. We report results that satisfy the energetic prerequisites of singlet fission and which are in excellent agreement with the exact transition energies (for the chosen one-particle basis), and much superior to classical methods deemed computationally tractable for singlet fission candidates.

# Applications of Mid-Circuit Measurement

# Create Long-Range Entanglement in Constant Depth

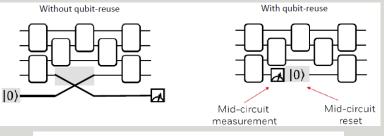


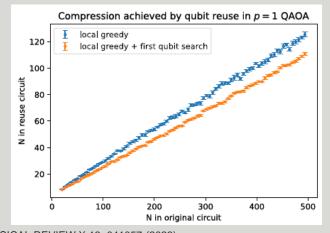
Create Topological States of Matter (non-abelian anyons)



Nature 626 (2024) 505-511

QAOA on Circuits having 4x more Qubits than your Machine (80 qubit MaxCut QAOA on H1 w/ 20 qubits)



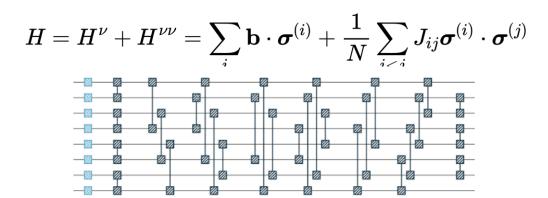


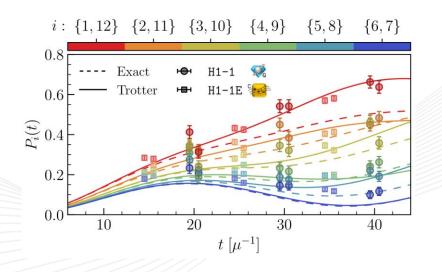
PHYSICAL REVIEW X 13, 041057 (2023)

arXiv:2302.03029

# Application: Neutrino Oscillations

- "Multi-Neutrino Entanglement and Correlations in Dense Neutrino Systems" by Marc Illa and Martin Savage at IQuS, University of Washington
  - Effective Hamiltonian for N neutrinos in a 2flavor space
  - All-to-all interactions
  - Trotter evolution circuits up to 12 qubits
- Emulator results and hardware results are consistent with the ideal Trotter evolution

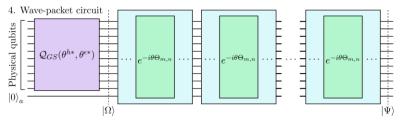




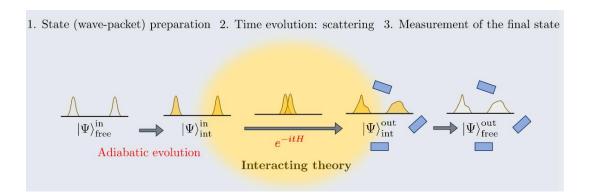
https://arxiv.org/abs/2210.08656

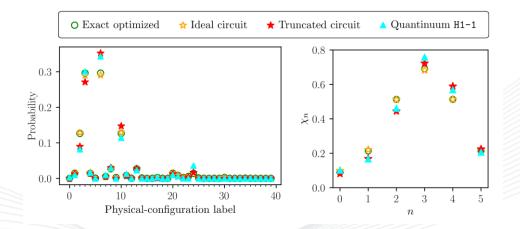
# Scattering States for Quantum Field Theory

- "Scattering wave packets of hadrons in gauge theories: Preparation on a quantum computer" by Zohreh Davoudi, Chung-Chun Hsieh, and Saurabh Kadam at UMD and IQuS
  - Use a shallow circuit ansatz to create wave packets for scattering experiments in gauge theories
  - Optimize circuits classically



- Prepare wave packets on H1-1 with high fidelity
- arxiv.org/pdf/2402.00840.pdf





### Toward Fault Tolerance and Quantum Error Correction

Deploy theoretically understood error correction codes (e.g. Surface code)



Explore Emerging paths (e.g. Non-Abelian Anyons, qLDPC, ...)

Both Paths require:

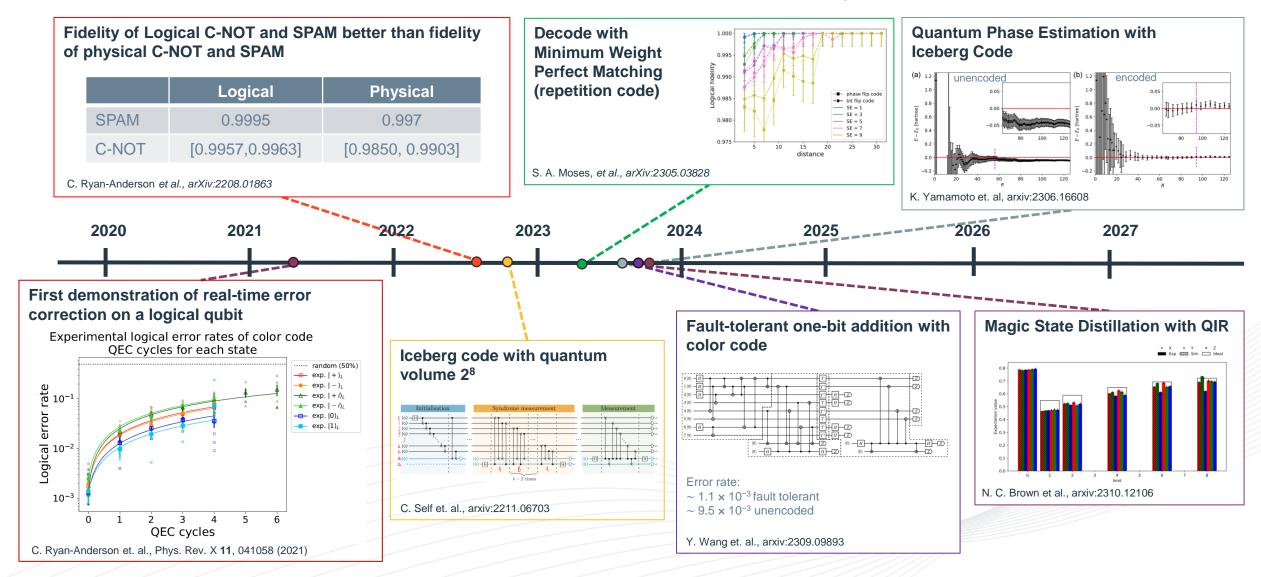
Low intrinsic physical errors

All-to-all connectivity

No fixed topology

Low cross-talk MCMR

# Fault-Tolerant Quantum Computing with QCCD



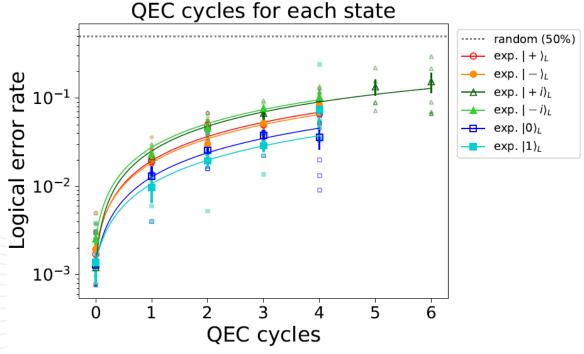
# Versatile QEC Testbed Enabled by High Quality Qubits

# Many codes already demonstrated on H-series

- Surface codes not yet published
- Color code [[7,1,3]] Ryan-Anderson et. al, Phys. Rev. X 11, 041058 (2021)
- [[5,1,3]] COde Ryan-Anderson et al. <arXiv:2208.01863>
- [[k+2,k,2]] codes Self et al. <arXiv:2211.06703>
- Bacon-Shor code not yet published
- [[16,2,5]], [[12,2,4]] code not yet published
- Non-Abelian Anyons Iqbal et al. <arXiv:2305.03766>
- [[8,3,2]] code Wang et al. arXiv:2309.09893 (2023)

# World's first demonstrations of real time decoding

Experimental logical error rates of color code

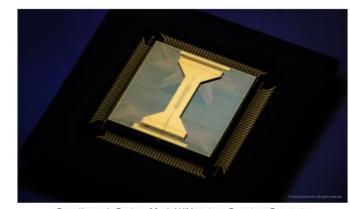




January 9, 2024

# H-SERIES

On-premise As a Service



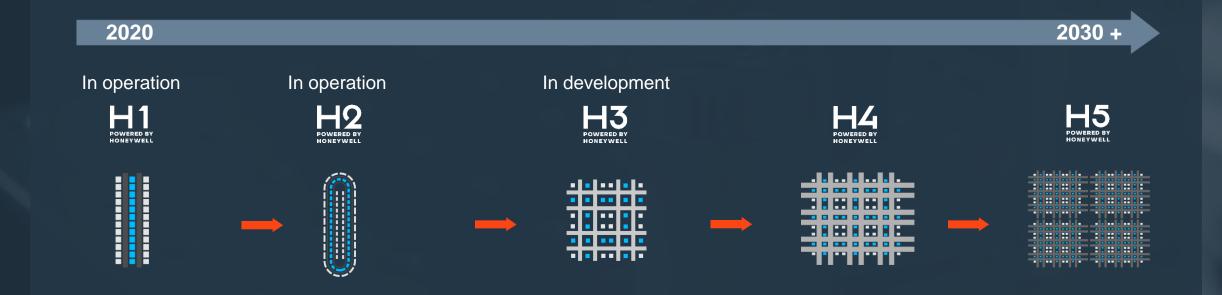
Quantinuum's System Model H1 Ion-trap Quantum Computer

The engagement provides RIKEN and its collaborators with on-premise access to Quantinuum's world-leading ion-trap quantum computer

Accelerates application development for quantum computers and supercomputers by project leaders RIKEN, SoftBank, University of Tokyo, and Osaka University

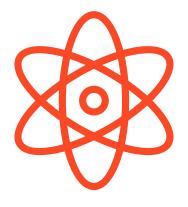
BROOMFIELD, CO, and LONDON, U.K., January 9, 2024 – Quantinuum, the world's largest integrated quantum computing company, and RIKEN, Japan's largest comprehensive research institution and home to a world-leading high-performance computing (HPC) center, have announced an agreement in which Quantinuum will provide access to Quantinuum's highest performing H1-Series ion-trap quantum computing technology to RIKEN. Under the agreement, Quantinuum will install the hardware at RIKEN's campus in Wako, Saitama.

# H-Series Product Roadmap



# Scaling Trapped-Ion Hardware – Our Strategy

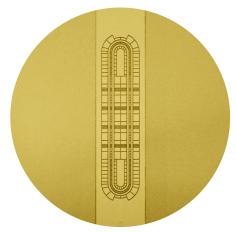
# High-fidelity qubits



### **Atomic Ions**

- Every ion identical
- lons easy to create
- Every ion high-fidelity
- Much more capability per qubit
- Need fewer qubits!

# High-performance, high-capacity traps



### **Ion Traps**

- More capable traps
- More qubits per trap area
- More qubits per trap electrode
- More qubits per trap power, etc.

### Modular, scalable subsystems



### **Light-Delivery to lons**

- Miniaturize the optics
- Integrate functionalities
- Move nearer to trap
- Move onto trap



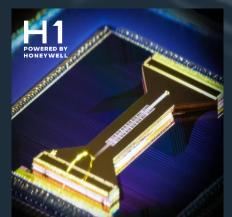
### **Control Electronics**

- Modular add cards
- Miniaturize ASIC
- Scalable software
- Hybrid computing for real-time error correction



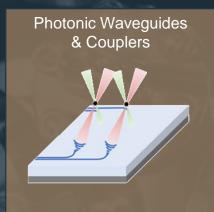
# Trap Scaling Roadmap

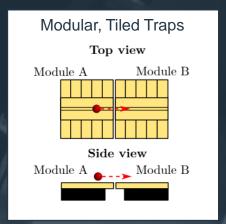








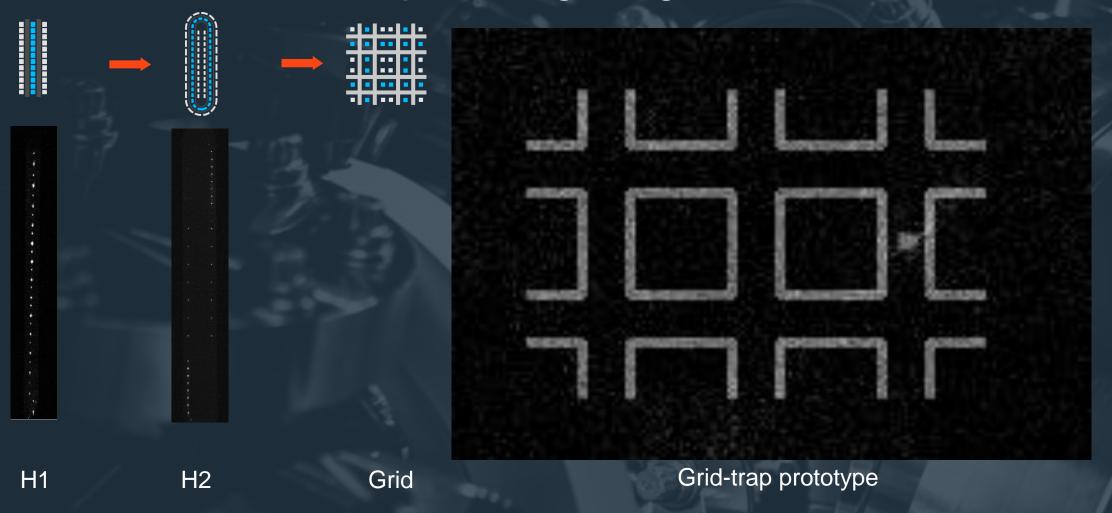




Akhtar et al, (Sussex/Universal Quantum) arxiv.org/pdf/2203.14062.pdf

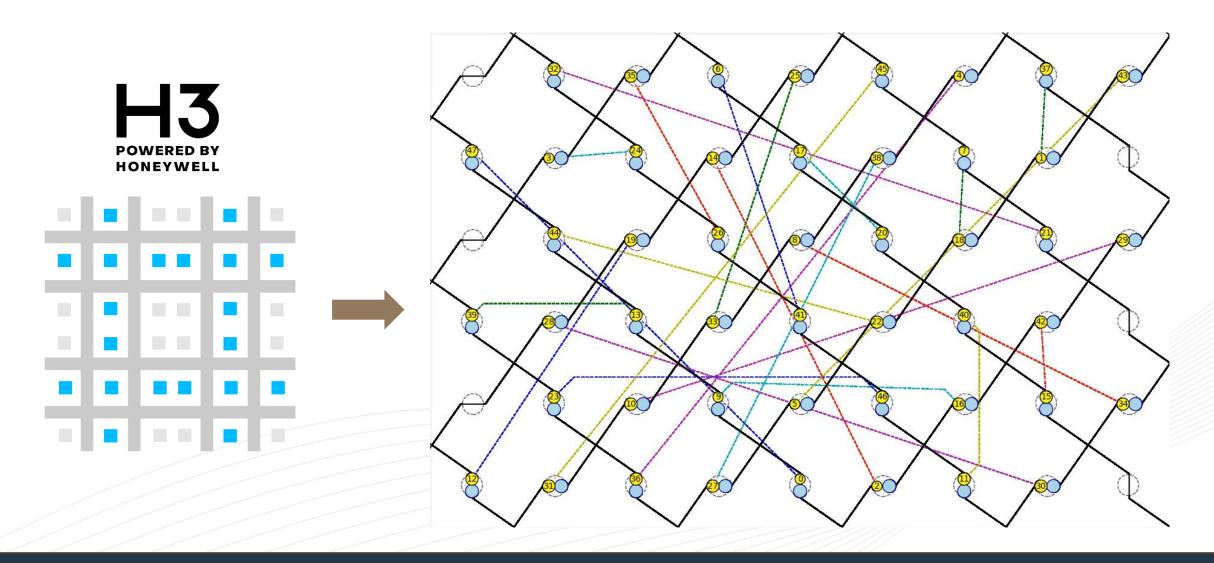


# Trap Scaling Progress

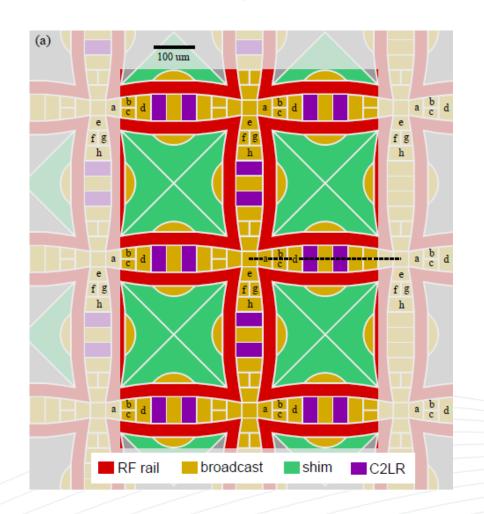




# Ion Sorting in Full 2D QCCD Array: Concept



# Ion Sorting in Full 2D Grid: Realized (with reduced electrode count)





# Future Applications – High Energy and Nuclear Physics?

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Discovery of <sup>39</sup>Na

PRL 129, 212502 (2022)

D. S. Ahn, <sup>1,*</sup> J. Amano, <sup>3</sup> H. Baba, <sup>1</sup> N. Fukuda, <sup>1</sup> H. Geissel, <sup>5</sup> N. Inabe, <sup>1</sup> S. Ishikawa, <sup>4</sup> N. Iwasa, <sup>4</sup> T. Komatsubara, <sup>1</sup> T. Kubo<sup>©</sup>, <sup>1,†</sup> K. Kusaka, <sup>1</sup> D. J. Morrissey, <sup>6</sup> T. Nakamura, <sup>2</sup> M. Ohtake, <sup>1</sup> H. Otsu, <sup>1</sup> T. Sakakibara, <sup>4</sup> H. Sato, <sup>1</sup> B. M. Sherrill, <sup>6</sup>

Y. Shimi

PRL 129, 212502 (2022)

T. Komatsubara, <sup>1</sup> T. Sakakibara, <sup>4</sup> H. Sato, <sup>1</sup> B. M. Sherrill, <sup>6</sup>

Y. Shimi

PRL 129, 212502 (2022)

Existence of Atomic Nuclei
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R. J. Cha Chajeck Manfred Santama Wuosma

# Measurement of the α-Particle Monopole Transition Form Factor Challenges Theory: A Low-Energy Puzzle for Nuclear Forces? PRL 130, 152502 (2023)

```
S. Kegel®, P. Achenbach®, S. Bacca®, N. Barnea®, J. Beričič, D. Bosnar®, L. Correa, M. O. Distler®, A. Esser, H. Fonvieille, I. Friščić®, M. Heilig, P. Herrmann, M. Hoek®, P. Klag, T. Kolar®, M. Leidemann®, H. Merkel®, M. Mihovilovič, J. Müller, U. Müller®, G. Orlandini®, J. Pochodzalla®, B. S. Schlimme®, M. Schoth, F. Schulz, C. Sfienti®, S. Širca®, A. Spreckels, Y. Stöttinger, M. Thiel®, A. Tvukin, L. Tvukin, L. Storekels, L. Correa, J. M. Tvukin, D. Distler®, L. Correa, M. O. Distler®, A. Esser, H. Fonvieille, I. Friščić®, M. Heilig, P. Herrmann, M. Hoek®, P. Klag, T. Kolar®, J. W. Leidemann®, R. M. Mihovilovič, J. M. Mihovilovič, J. M. Müller®, G. Orlandini®, R. J. Pochodzalla®, B. S. Schlimme®, M. Schoth, L. Schulz, L. C. Sfienti®, J. Sirca®, J. R. Spreckels, M. Stöttinger, M. Thiel®, A. Tvukin, L. Tvukin, L. Schulz, L.
```

### Prediction of the neutron drip line in oxygen isotopes using quantum computation arXiv:2306.06432v1

```
Chandan Sarma,<sup>1,*</sup> Olivia Di Matteo,<sup>2,†</sup> Abhishek Abhishek,<sup>2,‡</sup> and Praveen C. Srivastava<sup>1,§</sup>

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<sup>2</sup>Department of Electrical and Computer Engineering,

The University of British Columbia, Vancouver, British Columbia V6T 1Z4, Canada

(Dated: June 13, 2023)
```

# Thank you! QUANTINUUM