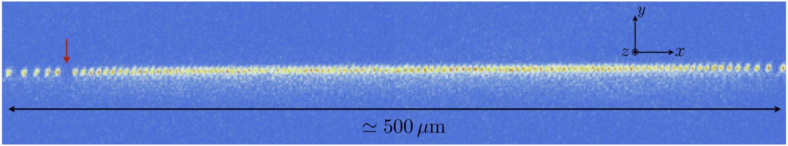
Experimental Progress on Quantum Computing with Atomic Qubits

Xiang Zhang



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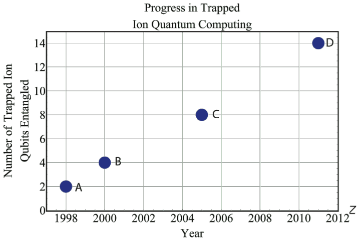
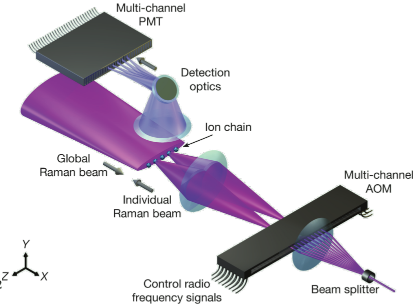
Outline

Trapped Ions: Promising Architecture[1]

Scalable and universal trapped-ions quantum computer

- Long coherence time: up to seconds or even hours
- Perfect quantum operation: fidelities of gate and measurement $> 99\%$
- Local scalibility: shuttling or addressing > 10 ions in one trap
- Quantum networks: remotely entangled ion chains through photons





[1] S. Debnath, et. al., Nature, 536, 63–66 (2016)

Ion Trap

- Captures and confines ions in a vacuum system
- Precision measurement: most accurate atomic clock, gyroscope
- Ionization and control: mass spectrometer, vacuum pump/gauge
- Penning trap: an axial magnetic ring and two endcaps
- Paul trap: four RF electrodes and two DC needles

Perfect pure quantum system

- Isolated system with ultra-high vaccum ($< 10^{-11}$ torr)
- Atomic levels and well designed harmonic trapping potential
- Universal rich set of quantum operations

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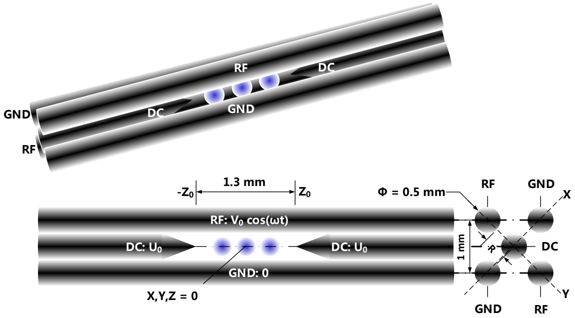
4-rod Trap

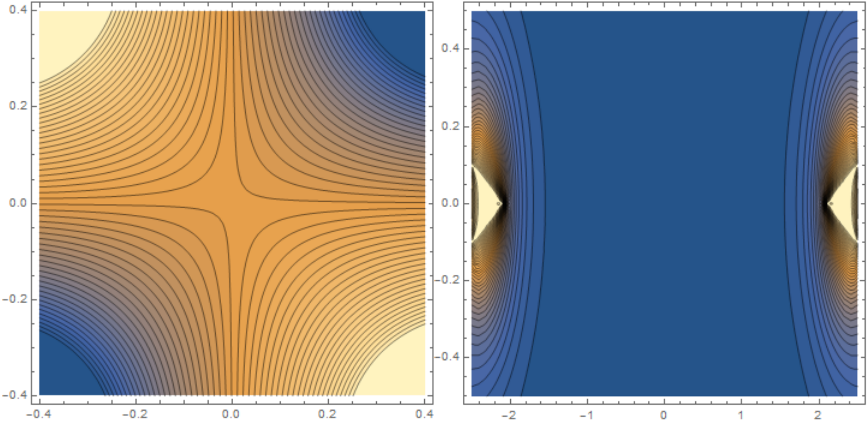
Trap design

- 4 rods: parabolic pseudopotential formed by rotating RF field
- 2 needles: static Coulomb potential
- 2 extra electrodes: compensate background electric field
- Ions arranged into a linear string



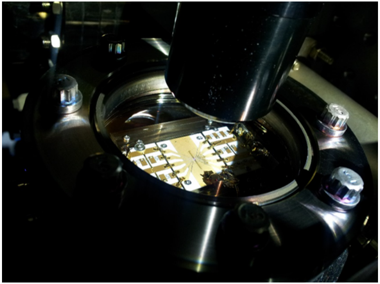
4-rod Trap

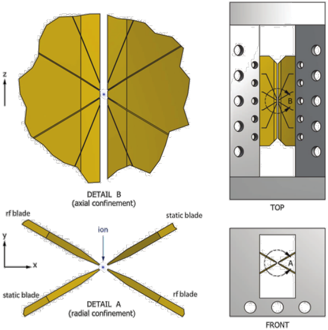
Calculating trap's X-Y and Z potential with BEM method



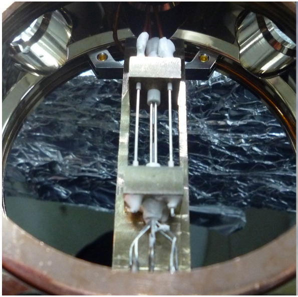
New Traps

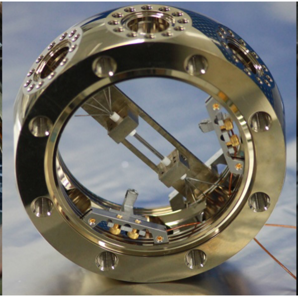
New trap designs

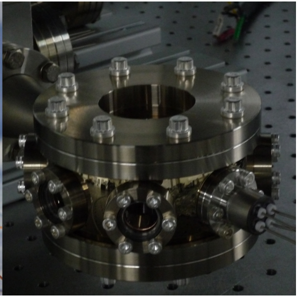


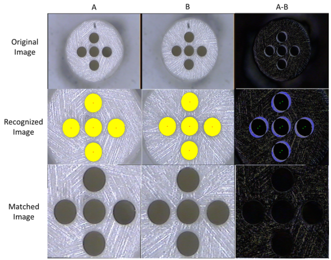


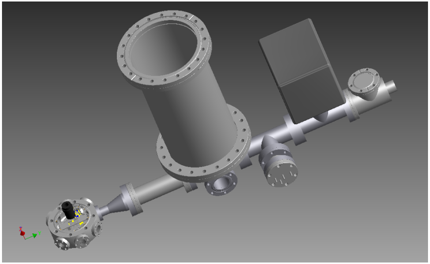
System Construction



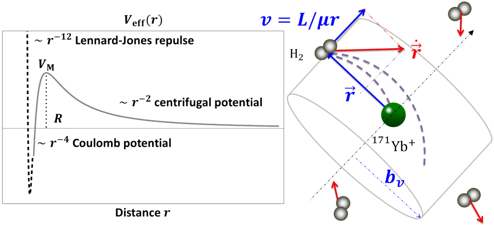




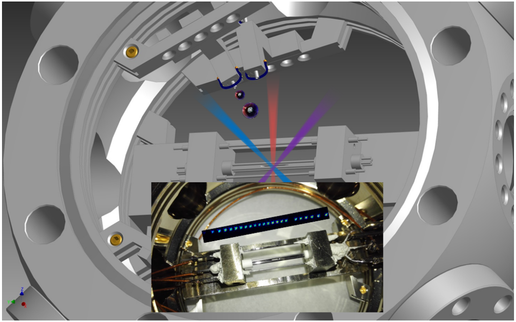


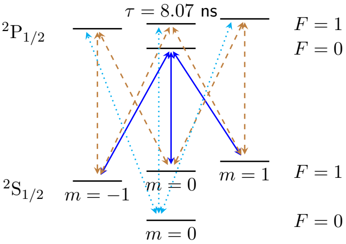


Collision Estimation and UHV Preparation

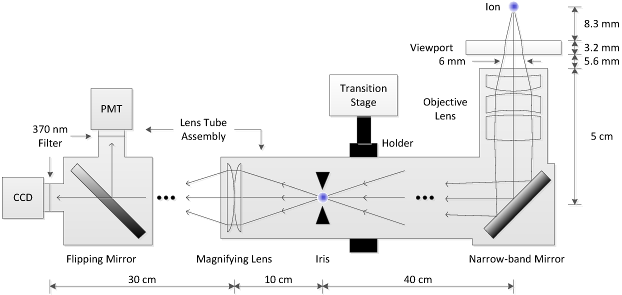


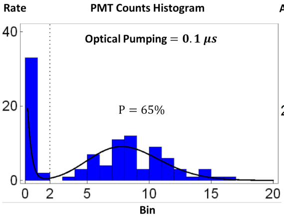
Ionization and Doppler Cooling

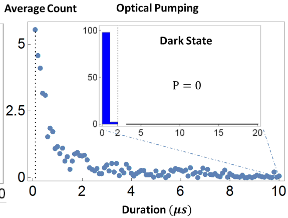




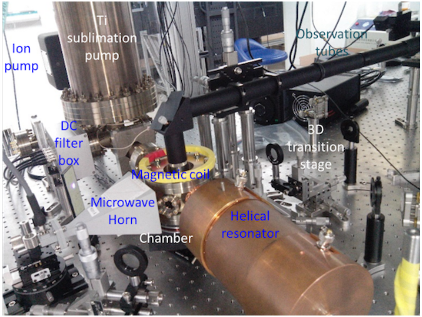
State Detection and Initialization

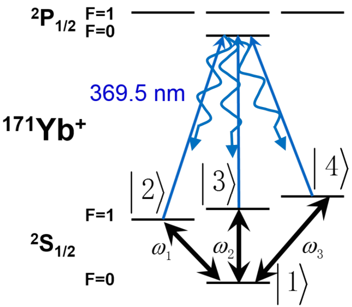


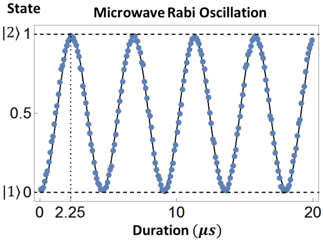


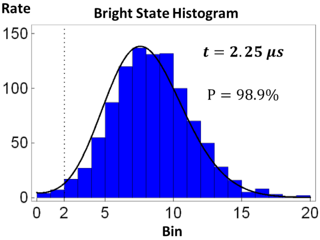


Microwave Manipulation

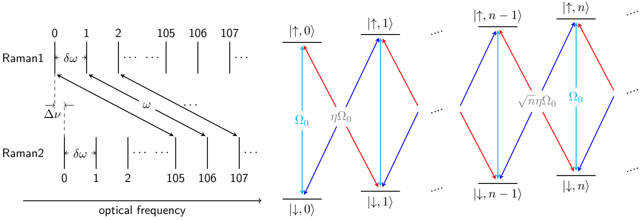


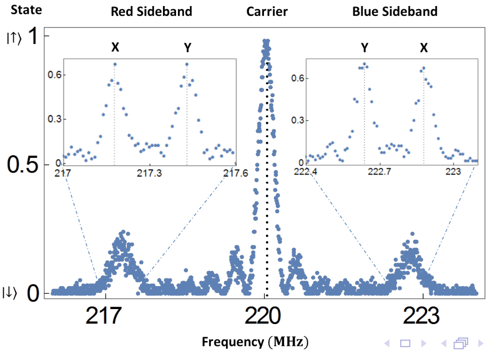




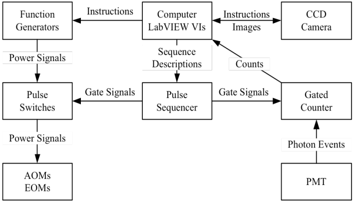


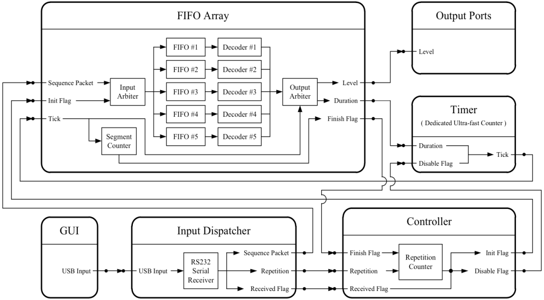
Pulse Laser Raman Transition



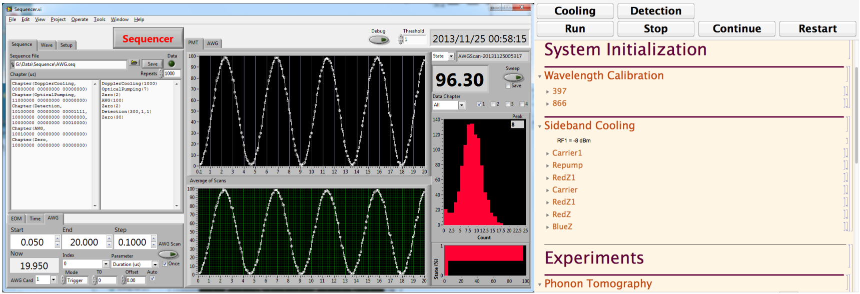


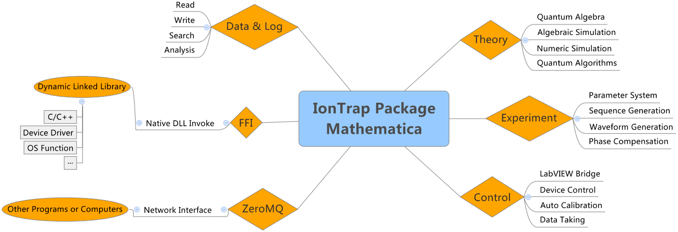
Control System: Hardware





Control System: Software





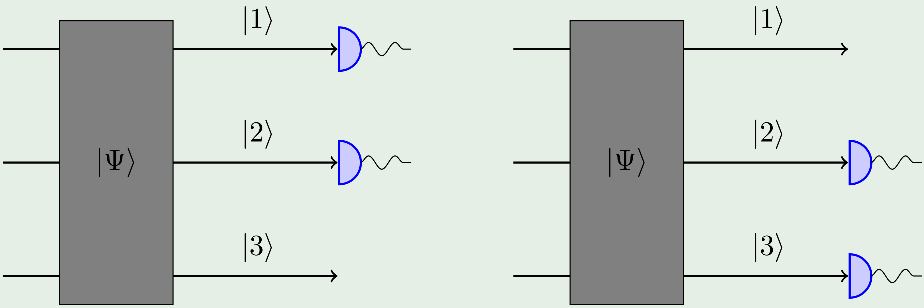
Outline

Non-Contextuality

Definition

Observables' probability distribution are **independent of measurement**.

Example



Pentagram Inequality

Hidden Variable Theory

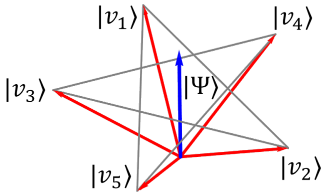
Let A_i be observables taking values ± 1, $\langle\cdot\rangle$ denotes average value. Then

$$\langle A_1 A_2\rangle + \langle A_2 A_3\rangle + \langle A_3 A_4\rangle + \langle A_4 A_5\rangle + \langle A_5 A_1\rangle \geq -3.$$

Quantum Mechanics

Let $A_i = I - 2\left|v_i\right\rangle\left\langle v_i\right|$ be observables on state $|\Psi\rangle$. Then $v(A_i) = \pm 1$, and

$$\langle A_1 A_2\rangle + \langle A_2 A_3\rangle + \langle A_3 A_4\rangle + \langle A_4 A_5\rangle + \langle A_5 A_1\rangle = 5 - 4\sqrt{5} \approx -3.944.$$



Experimental Demonstration

$d = 3$ system is the most fundamental system shows contextuality.

Previous Work

- $d \geq 4$. Nature **460**, 494 (2009).
- $d = 3$. Nature **474**, 490 (2011), PRL **109**,150401 (2012).

Recently Experimental Demonstration

- $d = 3$. PRL **110**, 070401 (2013)[a].
- state-independent Kochen-Specker inequality
- with a single trapped ion (indivisible system, no entanglement)
- close detection efficiency loophole

[a] X. Zhang, et al., Phys. Rev. Lett. 110:070401 (2013)

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State-independent Inequality[2]

Hidden Variable Theory

Let A_i $(i = 1, \cdots, 13)$ be observables taking values ± 1. Then

$$\langle \chi_{13} \rangle \quad := \quad \sum_{i \in V} \mu_i \langle A_i \rangle - \sum_{(i,j) \in E} \mu_{ij} \langle A_i A_j \rangle - \sum_{(i,j,k) \in C} \mu_{ijk} \langle A_i A_j A_k \rangle \leq 25.$$

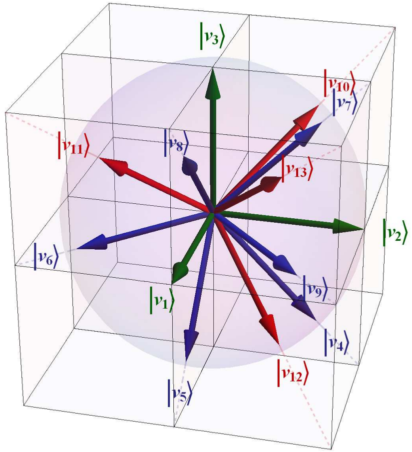
Quantum Mechanics

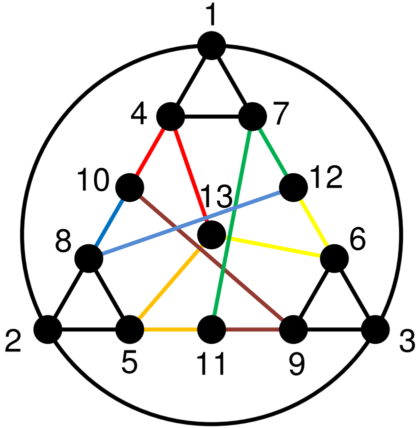
Let $|v_i\rangle$ be basis vectors, $A_i = I - 2|v_i\rangle\langle v_i|$ be observables. Then for any initial state $|\Psi\rangle$,

$$\langle \chi_{13} \rangle = \frac{83}{3} \approx 27.67.$$

[2] A. Cabello, et al., Phys. Rev. Lett. 109:250402 (2012)

Observables and Compatibility Relations





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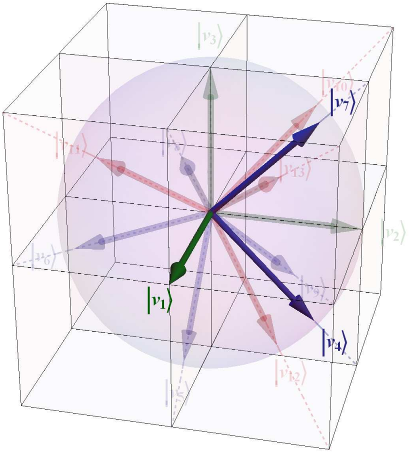
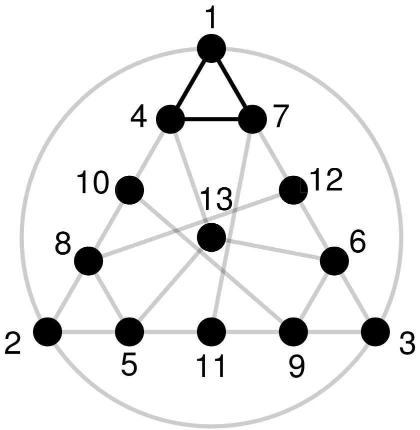
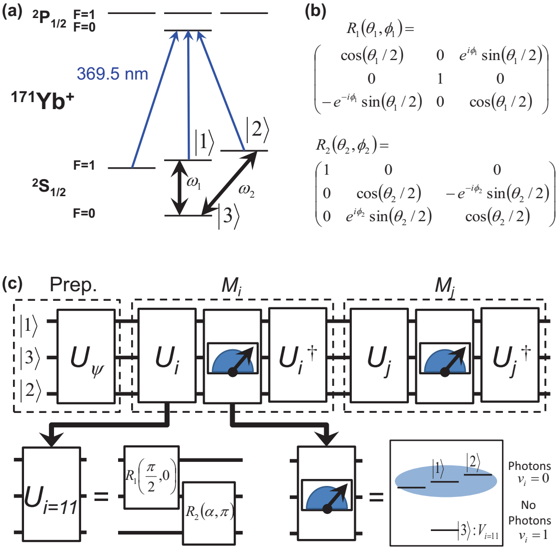
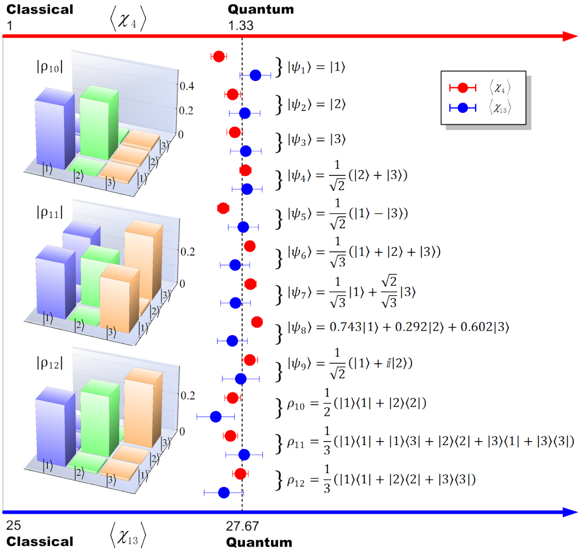




Measurement Scheme



The Experimental Violation



$$\langle \chi_{13} \rangle = 27.38 \pm 0.21$$

Summary

Quantum Contextuality is rooted in the fundamental structure of QM.

Observed Experimental Violation

- $d = 3$. PRL **110**, 070401 (2013).
- state-independent Kochen-Specker inequality
- with a single trapped ion (indivisible system, no entanglement)
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Outlook

- Application: "true" random number generator[a]
- Loophole-free: simultaneously measurement

[a] U. Mark, X. Zhang, et al., Scientific Reports, 3:1627 (2013)

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Outline

Majorana Particle[3]

- Majorana particle is its own antiparticle
- Whether *neutrinos* are Dirac or Majorana particles still remains open

Majorana equation

$$\imath\hbar\gamma^{\mu}\partial_{\mu}\psi = mc\psi_c$$

γ^{μ} are Dirac matrices, ψ_c is the charge conjugate of the spinor ψ.

- Relativistic wave equation for fermions derived from first principles
- Preserves helicity and has no stationary solutions
- Relativistic quantum effects such as *Zitterbewegung*
- Time reversal and charge conjugation symmetries

[3] J. Casanova, et al., Phys. Rev. X, 1:021018 (2011)

"Unphysical" Mapping

Majorana equation for $(1+1)$ dimensions

$$\imath\hbar\partial_t\psi = c\hat{\sigma}_x\hat{p}_x\psi - \imath mc^2\hat{\sigma}_y\psi^*$$

with "unphysical" operation mapping to enlarged space

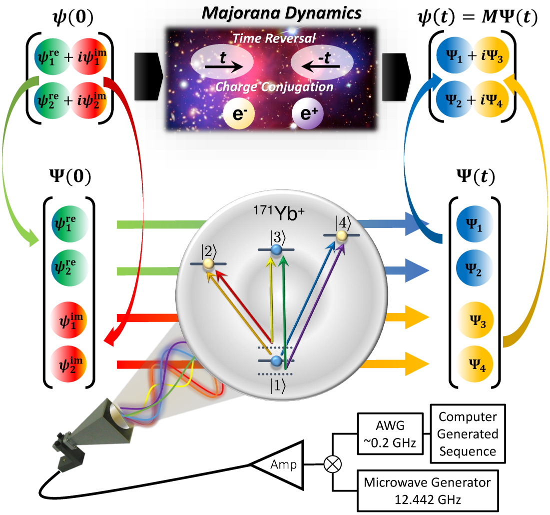
$$\psi = \begin{pmatrix}\psi_1\\ \psi_2\end{pmatrix} \in \mathbb{C}_\mathbf{2} \to \Psi = \begin{pmatrix}\psi_1^r\\ \psi_2^r\\ \psi_1^i\\ \psi_2^i\end{pmatrix} \in \mathbb{R}_\mathbf{4}$$

$$\psi = M\Psi = \begin{pmatrix}1 & 0 & i & 0\\ 0 & 1 & 0 & i\end{pmatrix}\Psi$$

becomes a $(3+1)$-dimensional Dirac equation

$$\imath\hbar\partial_t\Psi = [\hat{p}_x c(\mathbf{1}\otimes\sigma_x) - mc^2(\sigma_x\otimes\sigma_y)]\Psi$$

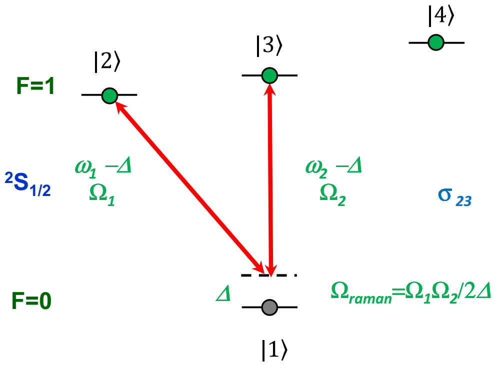
Embedding Quantum Simulator[4]



[4] X. Zhang, et al., Nature Communications, 6:7917 (2015)

Microwave Raman Transition

$$H_{\text{Majorana}} = \hat{p}_x c(\mathbf{1} \otimes \sigma_x) - mc^2(\sigma_x \otimes \sigma_y) \rightarrow \underbrace{pc(\sigma_{12}^x + \sigma_{34}^x)}_{H_1} + \underbrace{mc^2(\sigma_{23}^y - \sigma_{14}^y)}_{H_2}$$



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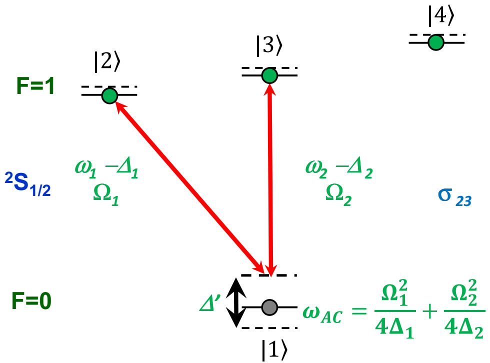

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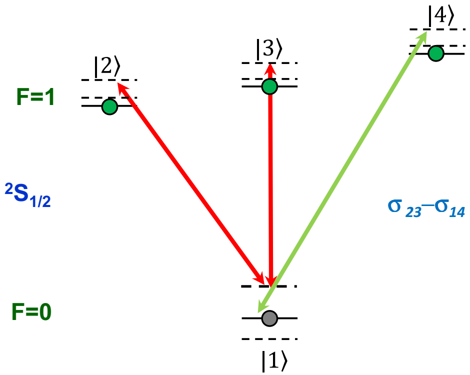

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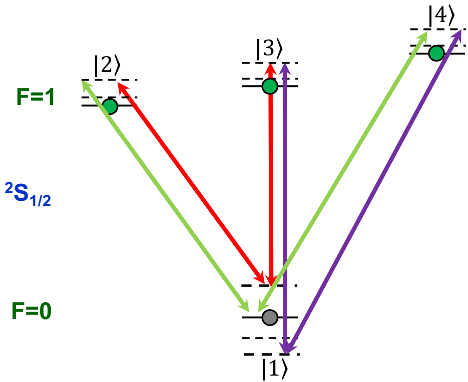
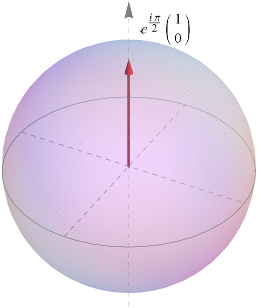


Global Phase Effect

For parallel initial states with different global phase

$$|\psi_\theta(t=0)\rangle := e^{\imath\theta}\begin{pmatrix}1\\0\end{pmatrix}\otimes|p\rangle$$

the fidelity defined as $F(t) = |\langle\psi_\theta(t)\,|\,\psi_0(t)\rangle|^2$ is not conserved.



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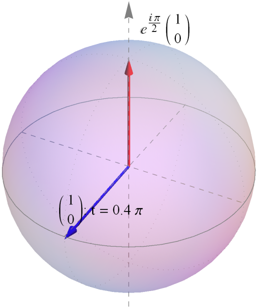

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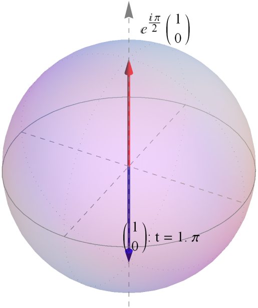

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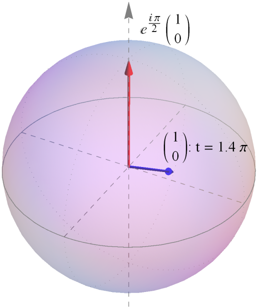

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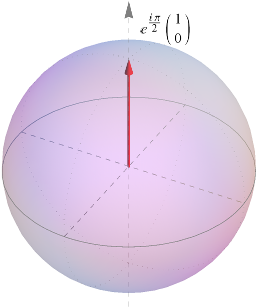
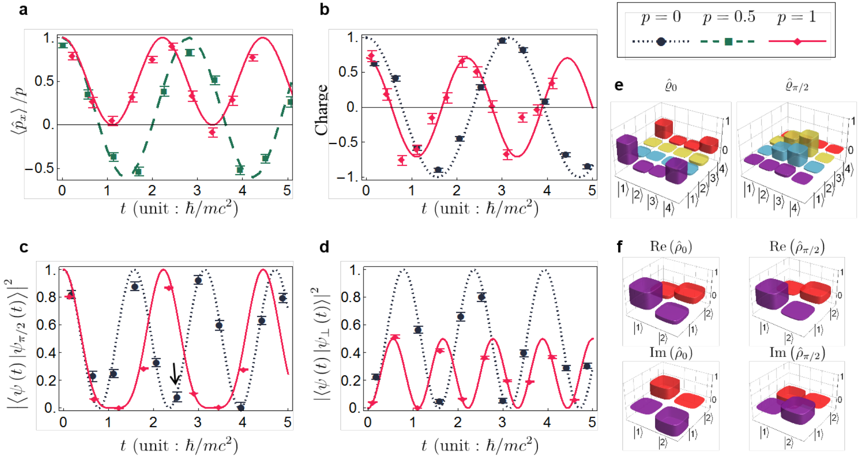


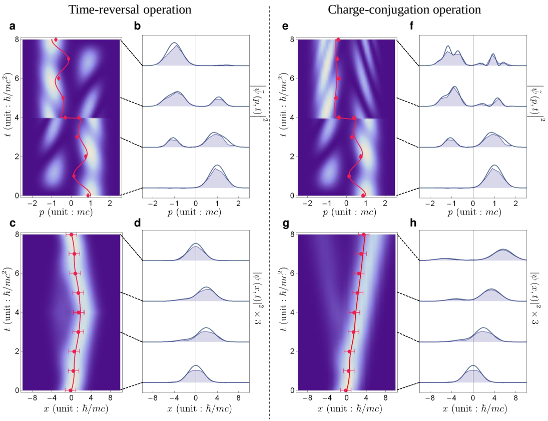
Non-unitary Dynamics



Symmetry Operations

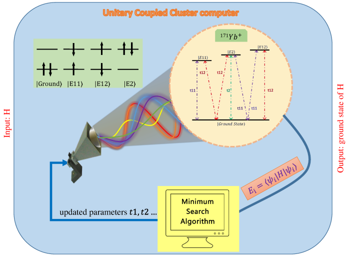
Apply symmetry operations at midpoint, with initial wave packet

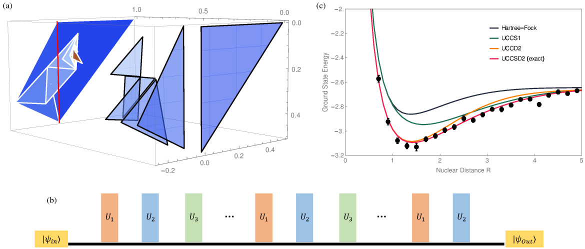
$$\psi(x, t=0) = (4\pi)^{-1/4} e^{-x^2/8} \frac{1}{\sqrt{2}} \begin{pmatrix} 1 \\ 1 \end{pmatrix} e^{\imath p_0 x/\hbar}$$



Technique Application: Quantum Chemistry[5]

Ground energy of HeH^+ calculated by Quantum Unitary Coupled Cluster





[5] Y. C. Shen, X. Zhang, et al., Phys. Rev. A. 95:020501 (2017)

Summary

Realization of non-unitary dynamics and symmetry operations in a trapped-ion quantum simulator.

Observed dynamics

- Global phase effect
- Orthogonality non-preservation
- Momentum *Zitterbewegung*
- Time reversal and charge conjugation

Outlook

- Test discrete symmetry
- Anti-unitary operations with real momentum operator

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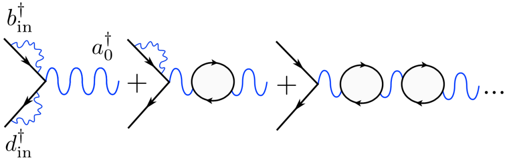
Simplified QFT Model[6]



(1+1) QFT model

- Scalar fermions and bosons
- Fermion and anti-fermions interacting through bosonic field modes

Key features

- Fermion self-interaction process
- Particle creation and annihilation
- Non-perturbative regimes beyond Feynman diagrams

[6] J. Casanova, et al., Phys. Rev. Lett., 107, 260501 (2011)

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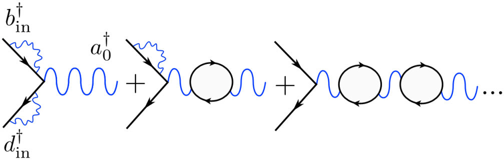

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Interaction Hamiltonian

$$H = g \int dx \psi^\dagger(0,x)\psi(0,x)A(0,x)$$
$$\doteq g(t)(e^{\imath\delta t} b_{in}^\dagger d_{in}^\dagger a_0 + e^{-\imath(2\omega_0+\delta)t} d_{in} b_{in} a_0)$$
$$+ g_1 e^{-\imath\omega_0 t}(b_{in}^\dagger b_{in} a_0 + d_{in} d_{in}^\dagger a_0) + \text{H.c.}$$

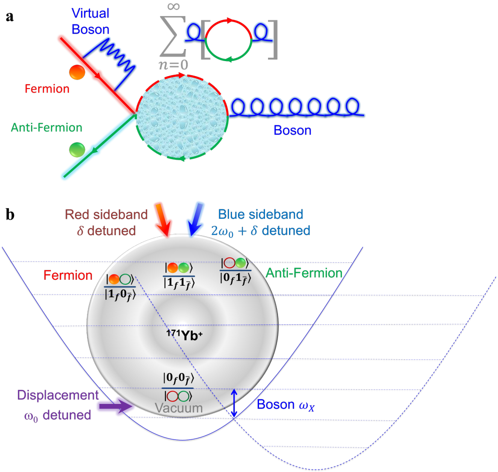
where $\delta = \omega_f + \omega_{\bar{f}} - \omega_0$ and interaction strength $g(t) = g_2 e^{-(t-T/2)^2/(2\sigma_t^2)}$.

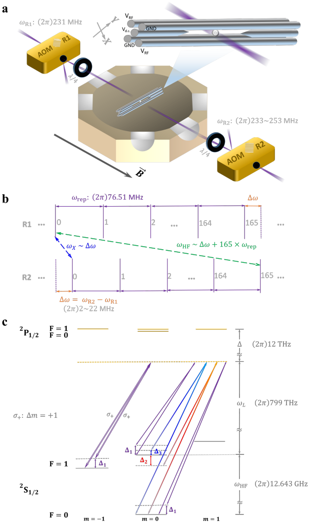
Jordan-Wigner mapping

$$b_{in}^\dagger = I \otimes \sigma^+, b_{in} = I \otimes \sigma^-, d_{in}^\dagger = \sigma^+ \otimes \sigma_z, d_{in} = \sigma^- \otimes \sigma_z$$
$$H_I = g_1(|0_f 0_{\bar{f}}\rangle \langle 0_f 0_{\bar{f}}| + 2 |1_f 0_{\bar{f}}\rangle \langle 1_f 0_{\bar{f}}| + |1_f 1_{\bar{f}}\rangle \langle 1_f 1_{\bar{f}}|)\hat{a}_0 e^{-i\omega_0 t}$$
$$- g(t)(|0_f 0_{\bar{f}}\rangle \langle 1_f 1_{\bar{f}}| \hat{a}_0^\dagger e^{-i\delta t} + |0_f 0_{\bar{f}}\rangle \langle 1_f 1_{\bar{f}}| \hat{a}_0 e^{-i(2\omega_0+\delta)t}) + \text{H.c.}$$

Experimental Diagram

[7]

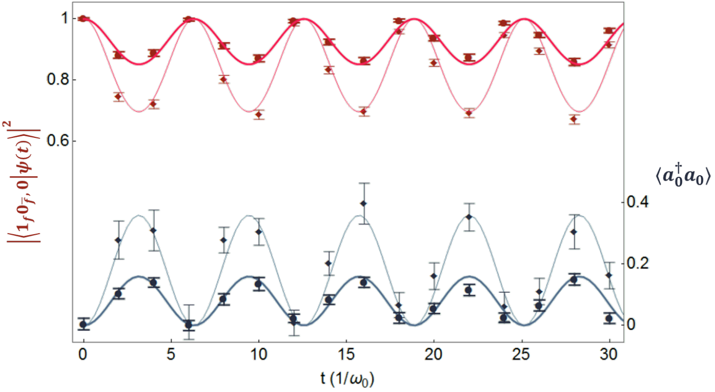




[7] X. Zhang, et al., Nature Communications, 9:135 (2018)

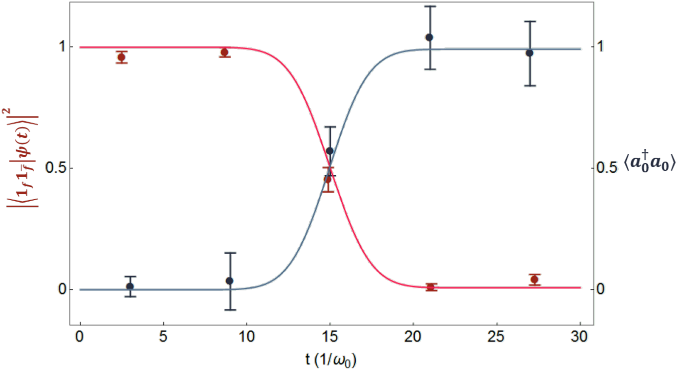
Fermion Self-interaction

- Experiment parameter: $g_1 = 0.15\omega_0, g_2 = 0, \sigma_t = 3/\omega_0$
- Initial state $\left|1_f 0_{\bar{f}}, 0\right\rangle$: one fermion state with no bosons
- Self-interaction dynamics: $\left|1_f 0_{\bar{f}}, n\right\rangle \leftrightarrow \left|1_f 0_{\bar{f}}, n \pm 1\right\rangle$



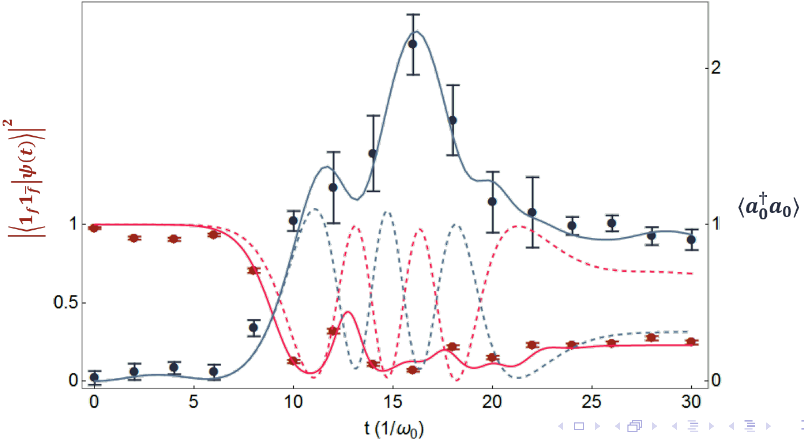
Creation and Annihilation

- Experiment parameter: $g_1 = 0.01\omega_0, g_2 = 0.21\omega_0, \sigma_t = 3/\omega_0$
- Initial state $\left|1_f 1_{\bar{f}}, 0\right\rangle$: fermion and antifermion state with no bosons
- Creation and annihilation dynamics: $\left|1_f 1_{\bar{f}}, 0\right\rangle \leftrightarrow \left|0_f 0_{\bar{f}}, 1\right\rangle$



Non-perturbative Regimes

- Experiment parameter: $g_1 = 0.1\omega_0, g_2 = \omega_0, \sigma_t = 4/\omega_0$
- Initial state $\left|1_f 1_{\bar{f}}, 0\right\rangle$: fermion and antifermion state with no bosons
- Strong interaction coupling $g_2 \geq \omega_0$
- Non-perturbative dynamics can't be calculated with Feynman diagram



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The first simulation of quantum field theory model with a trapped-ion quantum simulator.

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- Fermion self-interaction process
- Particle creation and annihilation
- Non-perturbative regimes beyond Feynman diagrams

Outlook

- Extension to many field modes with ion chains
- Open quantum system Markov process
- 10 ions and 5 phonons/ion with dimension of $2^{33} > 32\text{bit PC}$

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- Experimental violation of quantum contextuality
- Quantum simulation of symmetry operations and quantum field theory

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- Loophole-free quantum contextuality verification with Ca/Ba ions
- Anti-unitary operations with real momentum operator
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