Engineering local U(1) symmetries

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Could we use cold atoms to study high-energy physics?
Laser systems for potassium and sodium

Rack with electronics and experiment control

Optical table with vacuum system

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Laser systems for potassium and sodium

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Optical table with vacuum system

Atoms
Sodium
\[ \hat{H} = \int d^3x \sum_{\alpha} \hat{\psi}^\dagger_{s,\alpha}(x) \left[ -\frac{\nabla^2_x}{2m_s} + V_s(x) + E_{s,\alpha}(B) \right] \hat{\psi}_{s,\alpha}(x) + \frac{1}{2} \int d^3x \sum_{\alpha,\beta} g^s_{\alpha\beta} \hat{\psi}^\dagger_{s,\alpha}(x) \hat{\psi}^\dagger_{s,\beta}(x) \hat{\psi}_{s,\beta}(x) \hat{\psi}_{s,\alpha}(x) + \int d^3x \sum_{\alpha,\beta} g^{Mix}_{\alpha\beta} \hat{\psi}^\dagger_{N,\alpha}(x) \hat{\psi}^\dagger_{L,\beta}(x) \hat{\psi}_{L,\beta}(x) \hat{\psi}_{N,\alpha}(x) \]

All microscopic parameters known

\[ \mathcal{L}_{QED} = \bar{\psi} \left( i \gamma^\mu D_\mu - m \right) \psi - \frac{1}{4} F^{\mu\nu} F_{\mu\nu} \]

\[ \mathcal{L}_{QCD} = \sum_{f_i} \bar{\psi}^{f_i} \left( i \gamma^\mu D_{\mu i} - m_f \right) \psi^{f_i} - \frac{1}{2g^2} Tr \left( G^{\mu\nu} G_{\mu\nu} \right) \]

Particle

Gauge field


Simulation of Higgs decay from CMS
\[ \mathcal{L}_{QED} = \bar{\psi} \left( i \gamma^\mu D_\mu - m \right) \psi - \frac{1}{4} F_{\mu \nu} F^{\mu \nu} \]

\[ \mathcal{L}_{QCD} = \sum_{f_i} \bar{\psi}^{f_i} \left( i \gamma^\mu D_{\mu ij} - m_f \right) \psi^{f_i} - \frac{1}{2g^2} \text{Tr} \left( G^{\mu \nu} G_{\mu \nu} \right) \]

Particle

Gauge coupling

Gauge field

Simulation of Higgs decay from CMS
Conserved local charges = Conserved local gauge symmetry

\[ \text{div } E(r) = e\rho(r) \]

\[ E_c = \frac{m_e^2 c^3}{\hbar q_e} \approx 10^{18} \text{V/m} \]
Can we construct a quantum simulator?

\[ E_c = \frac{m_e^2 c^3}{\hbar q_e} \approx 10^{18} \text{V/m} \]
Philippful for describing equilibrium phenomena, no systematic techniques such as quantum Monte Carlo have been remarkably success high-thermalization after heavy-ion collisions and pair creation studied at mental for the understanding of many physical phenomena, including chain of trapped ions (dynamics of a minimal model of a lattice gauge theory, realizing the is approximated as a stroboscopic sequence of quantum gates quantum simulation scaling up these devices quantum gates to act on a few qubits, with a clear roadmap towards tum computers programmable quantum devices simulations of non-Abelian lattice gauge theories. 

Real-time dynamics of lattice gauge theories with a term intention is to extend this approach to real-time quantum time evolution of entanglement in the system, which illustrates how and the vacuum persistence amplitude. Moreover, we track the real-particle–antiparticle generation by monitoring the mass production an ion trap architecture interactions, which can be directly and efficiently implemented on quantum resources, we map the original problem to a spin model creation of electron–positron pairs. To make efficient use of our to quantum fluctuations, which manifests itself in the spontaneous Schwinger model realizing (1 of a digital quantum simulation of a lattice gauge theory, by implemented the associated local conservation laws (Gauss laws) need to be mechanically devices, with the difficulty that gauge invariance and schemes for simulating such theories on engineered quantum-effort, using Feynman's idea of a quantum simulator. Gauge theories are fundamental to our understanding of Real-time dynamics in gauge theories is a notorious challenge for classical real-time dynamics in gauge theories: such simulations are funda...
Sodium
$N_{at} \sim 300 \times 10^3$

$\bar{\omega}/2\pi \sim 250\text{Hz}$

$B_0 \sim 2\text{G}$
Bosonic $^7$Li

$N_{at} \sim 60 \times 10^3$

$\bar{\omega}/2\pi \sim 500\text{Hz}$

$B_0 \sim 2\text{G}$
The gauge field is given by

$$\hat{H}/\hbar = \chi L_z^2$$

where \(L_z\) is the angular momentum operator in the \(z\)-direction. The states \(|\uparrow\rangle = |1,0\rangle\) and \(|\downarrow\rangle = |1,1\rangle\) are eigenstates of \(L_z\), with eigenvalues 0 and 1, respectively. The number of atoms \(N_{at}\) is estimated to be \(300 \times 10^3\).
\[ \hat{H}/\hbar = \chi \hat{L}_z^2 \]

\[
| \uparrow \rangle = |1,0\rangle
\]

\[
| \downarrow \rangle = |1,1\rangle
\]

\[ N_{at} \sim 300 \times 10^3 \]

\[ N_{at} \sim 50 \times 10^3 \]

Mil et al. Science **367**, 1128 (2020)
**Gauge field**

\[ \hat{H}/\hbar = \chi L_z^2 \]

\[ E \]

**Gauge coupling**

\[ \lambda \left( \hat{b}_p^\dagger \hat{L} - \hat{b}_v + \hat{b}_v^\dagger \hat{L} + \hat{b}_p \right) \]

**Matter field**

\[ \frac{\Delta}{2} \left( \hat{b}_p^\dagger \hat{b}_p - \hat{b}_v^\dagger \hat{b}_v \right) \]

\[ \left| \uparrow \right\rangle = \left| 1,0 \right\rangle \]

\[ \left| \downarrow \right\rangle = \left| 1,1 \right\rangle \]

Mil et al. Science **367**, 1128 (2020)
1.) Initialization

2.) Manipulation and evolution

3.) Read-out

Mil et al. Science 367, 1128 (2020)
1.) Initialization

\[ |p \rangle \]

\[ \hat{L} \]

\[ |v \rangle \]

2.) Manipulation and evolution

\[ X(\tau) \]

3.) Read-out

\[ \frac{N_p}{N} \]

\[ \frac{L_z}{L} \]

\[ |\uparrow\rangle \]

\[ |\downarrow\rangle \]

\[ \text{pulse length } \tau [\mu s] \]
1.) Initialization

2.) Manipulation and evolution

3.) Read-out

$p \rangle$

$\hat{L} \rangle$

$\nu \rangle$

$X(\tau)$

$L_z/L = -0.188$
1.) Initialization

\[ |p\rangle \]

2.) Manipulation and evolution

\[ \hat{L} \]

\[ \frac{L_z}{L} = -0.188 \]

\[ e^{i\hat{H}t_{evo}/\hbar} \]

3.) Read-out

\[ |v\rangle \]

\[ |\rangle \]

\[ |\rangle \]

|\rangle |v\rangle

\[ t_{evo} \]
The text on the page reads: 

\[ L_z/L = -0.188 \]
\[ \hat{H}/\hbar = \chi \hat{L}_z^2 + \frac{\Delta}{2} \left( \hat{b}_p^\dagger \hat{b}_p - \hat{b}_v^\dagger \hat{b}_v \right) + \lambda \left( \hat{b}_v^\dagger \hat{L}_- \hat{b}_v + \hat{b}_v^\dagger \hat{L}_+ \hat{b}_p \right) \]

\[ L_z/L = -0.188 \]
\[ \hat{H}/\hbar = \chi \hat{L}_z^2 + \frac{\Delta}{2} \left( \hat{b}_p^\dagger \hat{b}_p - \hat{b}_v^\dagger \hat{b}_v \right) + \lambda \left( \hat{b}_v^\dagger \hat{L} \hat{b}_v + \hat{b}_v^\dagger \hat{L} \hat{b}_p \right) \]

\[ L_z/L = -0.188 \]

\[ L_z/L = -0.418 \]
\[ L_z/L = -0.188 \]

\[ L_z/L = -0.418 \]

\[ | \downarrow \rangle \]

\[ | \pm \rangle \]

\[ | \downarrow \rangle \text{ } L_z/L \text{ } | \downarrow \rangle \]

\[ 30 \text{ ms} \]
$B = B_0 = 2.118 \text{G}$

$\Delta(B_0)$

30 ms

$\Delta(B_0)$

$|p\rangle$

$|v\rangle$
$B = B_0 = 2.118\text{G}$

$B = B_0 - 50\text{mG}$

$B = B_0 - 100\text{mG}$

$B = B_0 - 110\text{mG}$

$B = B_0 - 150\text{mG}$

$\Delta(B_0)$

$30\text{ms}$

$|\uparrow\rangle \rightarrow |p\rangle$

$|\downarrow\rangle \rightarrow |v\rangle$

$magnetic field$
$B = B_0 = 2.118\, \text{G}$

$B = B_0 - 50\, \text{mG}$

$B = B_0 - 100\, \text{mG}$

$B = B_0 - 110\, \text{mG}$

$B = B_0 - 150\, \text{mG}$

$magnetic\ field$

$\begin{align*}
\Delta(B_0) \\
L_z/L \\
30\, \text{ms}
\end{align*}$

$\lambda$

$\chi$

$\Delta(B_0)$

building block

$L_z/L$
\[ \hat{H} = \sum_n \]
\[ \hat{H} = \sum_n [\hat{H}_n] \]
\[
\hat{H} = \sum_n [\hat{H}_n + \hbar \Omega (\hat{b}^\dagger_{n,p} \hat{b}_{n,v} + \text{h.c.})]
\]

Mil et al. Science 367, 1128 (2020)
\[ \hat{H} = \chi \hat{L}_z^2 + \frac{\Delta}{2} \left( \hat{b}_p^\dagger \hat{b}_p - \hat{b}_v^\dagger \hat{b}_v \right) + \lambda \left( \hat{b}_v^\dagger \hat{L}_- \hat{b}_v + \hat{b}_v^\dagger \hat{L}_+ \hat{b}_p \right) \]

Mil et al., Science **367**, 1128 (2020)

Zache et al., PRL **122**, 50403 (2019)
\[ \hat{H} = \chi \hat{L}_z^2 + \frac{\Delta}{2} \left( \hat{b}_p^\dagger \hat{b}_p - \hat{b}_v^\dagger \hat{b}_v \right) + \lambda \left( \hat{b}_v^\dagger \hat{L}_{-} \hat{b}_v + \hat{b}_v^\dagger \hat{L}_{+} \hat{b}_p \right) \]

\[ 23\text{Na} \quad \uparrow \]

\[ \chi \quad \lambda \]

\[ 7\text{Li} \quad \downarrow \]

Mil et al., Science 367, 1128 (2020)

Zache et al., PRL 122, 50403 (2019)

Non-abelian gauge fields?

(a) \[ \begin{array}{c|c|c|c} \Delta t & \Delta t & \cdots & \Delta t \\ \hline \end{array} \]

(b) \[ \begin{array}{c} \text{link} \\ \text{vertex} \\ \text{coherent control} \end{array} \]


Higher dimensions?

Could we use **cold atoms** to study **high-energy physics**?

Could we use **electric circuits** to engineer **local symmetries**?

H. Riechert  
L. Bretheau  
J. Halimeh  
E. Zohar  
V. Kasper  
P. Hauke
\[ H = \frac{\Delta}{2} \sum_x (-1)^x a_x^* a_x + \Omega \sum_{x \text{ odd}} (a_x^* b_x^* a_{x+1} + c.c.) + \Omega \sum_{x \text{ even}} (a_x^* b_x a_{x+1} + c.c.) \]
\[ H = \frac{\Delta}{2} \sum_{x} (-1)^{x} a_{x}^{*} a_{x} + \Omega \sum_{x \text{ odd}} (a_{x}^{*} b_{x}^{*} a_{x+1} + c. c.) + \Omega \sum_{x \text{ even}} (a_{x}^{*} b_{x} a_{x+1} + c. c.) \]
\[ H = \frac{\Delta}{2} \sum_x (-1)^x a_x^* a_x + \Omega \sum_{x \text{ odd}} (a_x^* b_x^* a_{x+1} + c.c.) + \Omega \sum_{x \text{ even}} (a_x^* b_x a_{x+1} + c.c.) \]
initial energy

\[ \text{driving} \]

\[ \text{gauge field} \]

\[ \text{matter field} \]

\[ a_1 \rightarrow b_1 \rightarrow a_2 \rightarrow b_2 \rightarrow a_3 \rightarrow b_3 \rightarrow a_4 \rightarrow b_4 \rightarrow a_5 \]

\[ V_1 \]

\[ V_{1'} \]

\[ V_2 \]

\[ \text{Static link} \]

\[ f_{rf} - f_{drv} / \text{kHz} \]

\[ f_{rf} / \text{kHz} \]

\[ f_{drv} / \text{kHz} \]

\[ \tilde{f}_{drv} \]

\[ \tilde{f}_{drv} \]

\[ \tilde{f}_{drv} \]

\[ \tilde{f}_{drv} \]

\[ \tilde{f}_{drv} \]
Building block with atomic mixtures realized

1D Lattice in classical electric circuits realized
Building block with atomic mixtures realized

Thank you for your attention