Studying strongly correlated many-body systems using cold Rydberg gases

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ac network analyzers, ca. 1925-1960
\[ \nabla \cdot \mathbf{E} = \frac{\rho}{\varepsilon_0} \]
\[ \nabla \cdot \mathbf{B} = 0 \]
\[ \nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t} \]
\[ \nabla \times \mathbf{B} = \mu_0 \mathbf{J} + \mu_0 \varepsilon_0 \frac{\partial \mathbf{E}}{\partial t} \]
network analyzer finds solutions through measurements on a scale model; effectively performs an **analogue computation** (later used for other calculations, e.g. elasticity, Schrodinger’s equation...)

\[
\nabla \cdot \mathbf{E} = \frac{\rho}{\varepsilon_0}
\]

\[
\nabla \cdot \mathbf{B} = 0
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\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}
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\[
\nabla \times \mathbf{B} = \mu_0 \mathbf{J} + \mu_0 \varepsilon_0 \frac{\partial \mathbf{E}}{\partial t}
\]
analogue computer →
digital computer

... but 30 years later...
Feynman’s problem

Simulating Physics with Computers

Richard P. Feynman

Department of Physics, California Institute of Technology, Pasadena, California 91107

Received May 7, 1981
Feynman’s problem

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classical world

quantum world

or

or

superposition

entanglement
A fully quantum calculation for 40 particles requires 1 TB of memory; the memory requirements for 80 particles exceed the amount of information stored in the history of mankind. **Consequence:** need
- quantum computer or
- quantum simulator = *analogue quantum computer*
Quantum simulators
Quantum simulators

\[ \hat{H} = \sum_i \hat{H}_i + \sum_{j,k} \hat{U}_{jk} + \sum_l \hat{V}_l + \ldots \]
Quantum simulators

\[ \hat{H} = \sum_i \hat{H}_i + \sum_{j,k} \hat{U}_{jk} + \sum_l \hat{V}_l + ... \]
An ideal quantum simulator

a collection of controllable quantum systems:
ultra-cold atoms (MOT, BEC,..)
An ideal quantum simulator to simulate an ordered system (crystal,…): cold atoms in optical lattices
An ideal quantum simulator to simulate an ordered system (crystal,...): cold atoms in optical lattices.

Interactions can come from on-site repulsion, Hamiltonian is then

\[ \mathcal{H} = -J \sum_{\langle i,j \rangle} \hat{a}_i^\dagger \hat{a}_j + \frac{1}{2} U \sum_i \hat{n}_i (\hat{n}_i - 1). \]
An ideal quantum simulator

Bose-Hubbard model: superfluid to Mott insulator transition
(Greiner et al., Nature 415, 39-44 (2002); Zenesini et al., PRL 102, 100403 (2009))

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An ideal quantum simulator

In order to study strongly correlated many-body systems, need strong interactions between nearest neighbours, next nearest neighbours… Ideally, these should be controllable to implement a range of Hamiltonians.
An ideal quantum simulator

Possible solution:
Excite atoms to Rydberg states
An ideal quantum simulator

**Lifetime:** $\sim n^3$

$n=100$  $1$ ms

**Polarizability** $\sim n^7$

Dipole moment: $\sim n^2$

$ea_0$

$n=100$  $10,000$ D ($\text{H}_2\text{O}$ $\sim 2$ D)

strong van-der-Waals or dipole-dipole interaction; orders of magnitude larger than contact interaction in ultra-cold gases (up to GHz at micrometer distances)!

Possible solution:

Excite atoms to Rydberg states

Rydberg atom
Towards a quantum simulator with cold Rydberg atoms

- excitation and detection of Rydberg excitations in a cold cloud
- revealing strong Rydberg-Rydberg interactions through counting statistics
- using full counting statistics as a tool for gaining insight into the system
- using cold Rydberg atoms to simulate a dissipative Ising system

Caveat:
Even then, Feynman acknowledged that desperation for research funding was driving a tendency by scientists to hype the applications of their work. Otherwise, a friend told him, "we won't get support for more research of this kind." Feynman's reaction was characteristically blunt. "I think that's kind of dishonest," he said.
Towards a quantum simulator with cold Rydberg atoms

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Excitation and detection scheme

- MOT containing around $10^5$ atoms, density $10^{10}$ cm$^{-3}$, temperature 150 µK
- two-photon excitation scheme (87-Rb) with Rabi frequencies up to 500 kHz
- detection by field ionization; detection efficiency around 40%
Towards a quantum simulator with cold Rydberg atoms

- **creation and detection** of Rydberg excitations in a cold cloud
- **revealing strong Rydberg-Rydberg interactions** through counting statistics
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Revealing strong interactions through counting statistics

Van-der-Waals interaction shifts additional excitations within the blockade volume out of resonance
-> dipole blockade
Revealing strong interactions through counting statistics

\[ Q = \frac{\langle N_e^2 \rangle - \langle N_e \rangle^2}{\langle N_e \rangle} - 1 \]

\[ Q = 0 : \text{Poissonian counting statistics} \]

\[ Q = -P_e \approx -0.1 \]

\[ Q = -P_{e}^{\text{coll}} \approx -1 \]

\[ Q \approx -1 : \text{strongly sub-Poissonian counting statistics indicating anti-correlation of excitations} \]
Revealing strong interactions through counting statistics

![Graphs showing time evolution of observables](image-url)
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Full counting statistics as a tool

Resonant excitation: \textit{exclusion} due to dipole blockade

Off-resonant excitation: \textit{inclusion} due to two-photon resonant pair excitation or single-photon excitation of a single atom at resonant distance from an already excited one ("facilitation")
**Full counting statistics as a tool**

**On resonance:** saturation due to dipole blockade for long times

**Off resonance:** slow growth due to pair / facilitated excitations

Rydberg state: 70S
Full counting statistics as a tool
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Simulating a dissipative Ising system

\[ H = \sum_j \left[ -\Delta |e\rangle\langle e|_j + \frac{\Omega}{2} (|e\rangle\langle g|_j + |g\rangle\langle e|_j) \right] + \frac{V}{N-1} \sum_{j<k} |e\rangle\langle e|_j \otimes |e\rangle\langle e|_k. \]

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Dynamical phases and intermittency of the dissipative quantum Ising model

Cenap Ates,1,2 Beatriz Olmos,1,2 Juan P. Garrahan,1 and Igor Lesanovsky1,2

Spatial correlations of one dimensional driven-dissipative systems of Rydberg atoms

Anzi Hu,1 Tony E. Lew,2 and Charles W. Clark1
Simulating a dissipative Ising system

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Dynamical phases and intermittency of the dissipative quantum Ising model

Anzi Hu, Tony E. Lee, and Charles W. Clark

Spatial correlations of one dimensional driven-dissipative systems of Rydberg atoms
Simulating a dissipative Ising system

- **on resonance**, the distribution becomes highly sub-Poissonian for large mean numbers.

- **off resonance**, the distribution is bimodal with varying weights of the two modes.
Simulating a dissipative Ising system

- mean number kept constant by adjusting Rabi frequency
- bimodality becomes more pronounced for longer excitation durations

\[ b = \frac{(\gamma^2 + 1)}{\left(\frac{\mu_4}{\mu_2^2}\right)} \]
Simulating a dissipative Ising system

- **on resonance** (grey) the counting statistics goes from Poissonian to highly sub-Poissonian (negative Q-factor)
- **off resonance** (blue) the variance is positive and peaks at half the maximum number
Simulating a dissipative Ising system

- the higher central moments reveal subtle details of the counting distribution, so they can be used to test model predictions with high accuracy
Simulating a dissipative Ising system

- the Binder cumulant shows a characteristic dependence on the mean number both on resonance and off resonance.
- possibly useful for identifying phase transitions (finite size scaling)?
Simulating a dissipative Ising system
Towards a quantum simulator with cold Rydberg atoms

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✓ revealing strong Rydberg-Rydberg interactions through counting statistics

✓ using full counting statistics as a tool for gaining insight into the system

✓ using cold Rydberg atoms to simulate a dissipative Ising system

➢ study dynamics

➢ finite size scaling

➢ move towards coherent regime

➢ ordered structures (optical lattice)
Towards a quantum simulator with cold Rydberg atoms

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- study dynamics
  - finite size scaling
  - move towards coherent regime
  - ordered structures (optical lattice)

C. Simonelli, Tesi di laurea, Pisa 2014