Realizing Richard Feynman’s Dream of a Quantum Simulator

IB, KITP Public Lecture 28 September, 2016
Overview

Motivation

Matter as a Wave

The Path to Ultracold Quantum Matter

Optical Crystal Formed by Laser Light

Applications

Outlook
Introduction

The Challenge of Many-Body Quantum Systems

- **Understand and Design Quantum Materials** - one of the biggest challenges in Quantum Physics in the 21st Century

- **Technological Relevance**
  
  **High-Tc Superconductivity** (Power Delivery)
  
  **Magnetism** (Storage, Spintronics...)
  
  **Novel Quantum Sensors** (Precision Detectors)
  
  **Quantum Technologies**
  (Quantum Computing, Metrology, Quantum Sensors,...)

Many cases: lack of basic understanding of underlying processes

**Difficulty to separate effects:** probe impurities, complex interplay, masking of effects...

Many cases: even simple models “not solvable”

Need to synthesize new material to analyze effect of parameter change
Introduction

Quantum Complexity

the ‘ultimate’ hard drive

Crystal of spins
Introduction

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the ‘ultimate’ hard drive

Crystal of spins
Introduction

Quantum Complexity

the ‘ultimate’ hard drive

Crystal of spins
\[ |\Psi\rangle = c_1 |\text{Config}_{1}\rangle + c_2 |\text{Config}_{2}\rangle + \cdots + c_{2^N} |\text{Config}_{2^N}\rangle \]

**2^N Configurations simultaneously!**
\[ \Psi = C_1 \ket{\text{Config}} + C_2 \ket{\text{Config}} + \cdots + C_{2^N} \ket{\text{Config}} \]

\(2^N\) Configurations simultaneously!
Roadrunner – Los Alamos

State of the art: < 40 spins \(2^{40} \times 2^{40}\) (what does it take to simulate 300 spins ?)

each doubling allows for one more spin 1/2 only

\(2^{300}\) estimated number of protons in the universe

1.1 Petaflops/s
2000 t
3.9 MW
The Challenge of Many-Body Quantum Systems

Control of single and few particles

Single Atoms and Ions

Photons

D. Wineland

S. Haroche
The Challenge of Many-Body Quantum Systems

Control of single and few particles

- Single Atoms and Ions
- Photons

Challenge: ... towards ultimate control of many-body quantum systems

R. P. Feynman’s Vision

A Quantum Simulator to study the dynamics of another quantum system.

Ion Traps (R. Blatt, Innsbruck)

Crystal of Atoms Bound by Light

Superconducting Devices (J. Martinis, UCSB, Google)
Simulating Physics with Computers

Richard P. Feynman

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

Received May 7, 1981

1. INTRODUCTION

On the program it says this is a keynote speech—and I don’t know what a keynote speech is. I do not intend in any way to suggest what should be in this meeting as a keynote of the subjects or anything like that. I have my own things to say and to talk about and there’s no implication that anybody needs to talk about the same thing or anything like it. So what I want to talk about is what Mike Dertouzos suggested that nobody would talk about. I want to talk about the problem of simulating physics with computers and I mean that in a specific way which I am going to explain. The reason for doing this is something that I learned about from Ed Fredkin, and my entire interest in the subject has been inspired by him. It has to do with learning something about the possibilities of computers, and also something about possibilities in physics. If we suppose that we know all the physical laws perfectly, of course we don’t have to pay any attention to computers. It’s interesting anyway to entertain oneself with the idea that we’ve got something to learn about physical laws; and if I take a relaxed...
The Challenge of Many-Body Quantum Systems

Control of single and few particles

Single Atoms and Ions

Photons

Challenge: ... towards ultimate control of many-body quantum systems

R. P. Feynman‘s Vision

A Quantum Simulator to study the dynamics of another quantum system.

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Crystal of Atoms Bound by Light

Superconducting Devices (J. Martinis, UCSB, Google)
Ultracold Quantum Gases
Gesellschaft der Wissenschaften.


Quantentheorie des einatomigen idealen Gases.

Zweite Abhandlung.

Von A. Einstein.
Centennial Nobel Prize in Physics! (2001)

Original lab book entry from W. Ketterle!
Centennial Nobel Prize in Physics! (2001)

Original lab book entry from W. Ketterle!

Deborah Jin (1968-2016)
What is Matter?
Matter Waves

Louis-Victor de Broglie (1892-1987)

Erwin Schrödinger (1887-1961)

\[ \lambda = \frac{h}{p} = \frac{h}{mv} \]

\[ i\hbar \frac{\partial \Psi}{\partial t} = H\Psi \]
What characterizes a wave?

Wave is a periodic oscillation in space and time!

**Frequency (Oscillations per s)**

\[ \nu = \frac{1}{T} \]

**Propagation velocity:**

\[ c = \lambda \cdot \nu \]
1+1=2? or not?

Matter + Matter = Twice as much matter
Superposition Principle for Waves

Waves can enhance each other!

contructive interference when two waves are added in phase

Waves can eliminate each other!

destructive interference when two waves are added $\lambda/2$ out of phase
Go To Interference Program...
Matter Waves

When can we perceive this wave character?

Propagation along straight lines

\[ \lambda \ll \text{Size of Object} \]

Waves are diffracted!

\[ \lambda \approx \text{Size of Object} \]

Licht \( \lambda = 500 \text{nm} \)

Schallwelle \( \lambda = 1 \text{m} \)
<table>
<thead>
<tr>
<th>Objekt</th>
<th>m (kg)</th>
<th>v (m/s)</th>
<th>λ (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elektron</td>
<td>9,1*10^{-31}</td>
<td>2*10^{6}</td>
<td>4*10^{-7} (0,00000004)</td>
</tr>
<tr>
<td>Neutron</td>
<td>1,7*10^{-27}</td>
<td>4*10^{3}</td>
<td>9*10^{-8} (0,00000009)</td>
</tr>
<tr>
<td>(^{87}\text{Rb Atom})</td>
<td>1,5*10^{-25}</td>
<td>270</td>
<td>2*10^{-8} (0,00000002)</td>
</tr>
<tr>
<td>(\text{C}_{60})</td>
<td>1,2*10^{-24}</td>
<td>210</td>
<td>3*10^{-9} (0,000000003)</td>
</tr>
<tr>
<td>Fussball</td>
<td>0,5</td>
<td>20</td>
<td>7*10^{-32} (0,0000000000000000000007)</td>
</tr>
</tbody>
</table>
What is interfering in the case of matter waves?

\[ E_{\text{det}} = E_1 + E_2 \]

\[ l \propto |E_1 + E_2|^2 \]

\[ \Psi_{\text{det}} = \Psi_1 + \Psi_2 \]

\[ n \propto |\Psi_1 + \Psi_2|^2 \]
Single Electron on Double Slit

Single Electron on Double Slit

Interference Phenomena with Matter Waves (2)

Beugung an einer Folie:

Beugung an einer Kante:

Abb. 3.18a,b. Vergleich (a) der Elektronenbeugung und (b) der Röntgenbeugung an einer dünnen Folie
Matter Waves

STM Images of Electron Surface Waves

Fe auf Cu (111)

Don Eigler
IBM Almaden Research Labs
http://www.almaden.ibm.com/vis/stm/
Interference of $C_{60}$ Matter Waves

C$_{60}$ Parameter

$\nu = 220$ m/s
$\lambda = 2.5$ pm

Gitter

Spaltbreite: 50 nm
Spaltabstand: 100 nm

Pressure $\sim 5 \times 10^{-7}$ mbar

M. Arndt et. al.
Nature 401, ff. 680, 1999
http://www.quantum.univie.ac.at/
Matter Waves From a classical gas to a Bose-Einstein Condensate

\[ T \gg T_c \]
Classical Gas

\[ T > T_c \]
\[ \lambda_{dB} = \frac{h}{mv} \propto T^{-1/2} \]

\[ T < T_c \]
\[ \lambda_{dB} \approx d \]

\[ T = 0 \]
Coherent Matter Wave

Predicted 1924...

A. Einstein  S. Bose
Laser emits one continuous wavetrain with a perfectly defined frequency!
Matter Waves

Thermal Light & Laser Light

BEC is for matter what the laser is for light!

Laser emits one continuous wavetrain with a perfectly defined frequency!
Matter Waves

Why is it hard to create a BEC?

Conditions for BEC:

\[ n \cdot \lambda^3 \approx 1 \]

z.B. Water

For a typical density of water \( n_{H_2O} \) we obtain \( T_c = 1K \)

Problem: Water is a block of ICE @ 1K

Solution: Density has to be lowered by several orders of magnitude to prolong timescale for solid formation!
Matter Waves

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Even lower temperatures are needed!
de Broglie Wavelengths

**Thermal deBroglie wavelengths**

\[ \lambda = \frac{\hbar}{\sqrt{2\pi m k_B T}} \]

- **273 K (0°C, 32°F)**
  - Water freezes

- **77K (-197°C, -323°F)**
  - Air liquifies

- **4K (-269°C, -452 °F)**
  - He liquifies

These are temperatures we need to reach to create macroscopic matter waves!
Matter changes at low temperatures!

- **Matter can undergo a Phase Transition when lowering temperatures!**
  - Gas $\rightarrow$ Liquid
  - Liquid $\rightarrow$ Solid
  - Normal Conductor $\rightarrow$ Superconductor
  - Normal Liquid $\rightarrow$ Superfluid
  - Classical Gas $\rightarrow$ Quantum Gas (BEC)
*Superconductivity at Low Temperatures*

At very low temperatures some materials can lose all resistivity!

*They become superconductors!*
Meissner Effect
Meissner Effect
Radiation Pressure

A special way to cool!
Laser Cooling

Nobel in Physics 1997

Steve Chu  Claude Cohen-Tannoudji  Bill Phillips
Maximum Acceleration

\[ a_{\text{max}} = \frac{\hbar k \Gamma}{m} \times \frac{1}{2} \]

e.g. for \(^{87}\text{Rb}\)

Minimum Temperature

\[ T_{\text{min}} \approx 10\mu K \]
Laser Cooling at Work
Laser Cooling at Work
Matter Waves

The Path to Bose-Einstein Condensation

$n \cdot \lambda^3 \approx 1$
Energy of an atom in an external magnetic field \[ E = -\vec{\mu} \cdot \vec{B} \]

Force on an atom in an inhomogeneous magnetic field \[ \vec{F} = -\mu \cdot \nabla B \]
Traps

Magnetic Trap ‘Zoology’

Cloverleaf Trap

QUIC-Trap

Miniaturized Magnetic Traps
Evaporative Cooling

Tom Greytak

Daniel Kleppner
Go To Evap Applet...
Time-of-Flight Imaging
Time-of-Flight Imaging
Interference of Two Bose-Einstein Condensates

Trapped BEC‘s

BEC‘s after expansion time $t$

$$\lambda = \frac{h}{m\Delta v} = \frac{ht}{md}$$
Interference of Two Bose-Einstein Condensates

Trapped BEC’s

BEC’s after expansion time $t$

$$\lambda = \frac{h}{m \Delta v} = \frac{ht}{md}$$

M. R. Andrews et. al.
Science 275, ff. 637, 1997
we need a lot of optics!
Introduction

Optical Lattice Potential – Perfect Artificial Crystals

\[ \frac{\lambda}{2} = 425 \text{ nm} \]

Perfect model systems for a fundamental understanding of quantum many-body systems
Optical Lattices

courtesy: T. Hänsch
Optical Lattices
Seeing Single Atoms

- lattice beams 1064 nm
- mirror 1084 nm
- window 780 nm
- high-resolution objective NA = 0.68

single 2D degenerate gas
~ 1000 $^{87}\text{Rb}$ atoms (bosons)

resolution of the imaging system:
~700 nm
Snapshot of an Atomic Density Distribution

BEC
n=1 Mott Insulator
n=1 & n=2 Mott Insulator

Snapshot of an Atomic Density Distribution

BEC

n=1
Mott Insulator

n=1 & n=2
Mott Insulator

Temperature sensitivity down to 50 pK!!

Single Site Addressing

Ch. Weitenberg et al., Nature 471, 319-324 (2011)
Addressing Coherent Spin Flips - Positive Imaging

Subwavelength spatial resolution: 50 nm

Ch. Weitenberg et al., Nature 471, 319-324 (2011)
Single Atom Tunneling
Single Atom Tunneling
see exp: Y. Silberberg (photonic waveguides), D. Meschede & R. Blatt (quantum walks)...

Addressing Motional State Affected?
see exp: Y. Silberberg (photonic waveguides), D. Meschede & R. Blatt (quantum walks)...

Addressing Motional State Affected?
Addressing Higher Band Tunneling

Excellent agreement with simulation.

Interesting extension: Quantum walks of correlated atoms/spins...
Addressing Arbitrary Light Patterns

Digital Mirror Device (DMD)
Addressing Arbitrary Light Patterns

Digital Mirror Device (DMD)

Measured Light Pattern
Addressing

Arbitrary Light Patterns

Digital Mirror Device (DMD)

Almost Arbitrary Light Patterns Possible!

Single Spin Impurity Dynamics, Domain Walls, Quantum Wires, Novel Exotic Lattice Geometries, ...
‘Higgs’ Amplitude Mode in Flatland


D. Podolsky, A. Auerbach, D. Arovas, PRB 2011
Quantum Matter at Negative Absolute Temperature


Negative Temperatures That Are Hotter Than The Sun

Listen to the Story
Talk of the Nation

Quantum gas goes below absolute zero
Uncertain Principles

What Does “Negative Temperature” Mean, Anyway?

Posted by Chad Orzel on January 8, 2013

Below Absolute Zero: Negative Temperatures Explained

Absolute zero, or 0 degrees Kelvin, is the temperature where all motion stops. It’s the lowest limit on the temperature scale, but recent news articles have heralded a dip below that limit in a physics lab. Is absolute zero less absolute than we thought? Read on to find out.
The world best clocks:
• Navigation, Positioning
  GPS, GLONASS, deep space probes
• Geodesy
• Datation of millisecond pulsars
• VLBI
• Synchronisation of distant clocks
  IAT
• Fundamental physics tests
Ex: general relativity
Search for a drift of the fine structure constant $\alpha$:

$\alpha^{-1} \frac{d\alpha}{dt}$ at $10^{-16}$/ year
Clock = Oscillator + Counter
Sundial since 3500 v. Chr.

One period per day
Sundial since 3500 v. Chr.
One period per day

Pendulum clock since 1656
One period per second
Clocks

Sundial since 3500 v. Chr.
One period per day

Quartz oscillator since 1918
32.768 periods per second

Pendulum clock since 1656
One period per second
Clocks

Measurement of Time

Sundial since 3500 v. Chr.
One period per day

Quartz oscillator since 1918
32.768 periods per second

Pendulum clock since 1656
One period per second

Cesium atomic clock since 1955
9.192.631.770 oscillations per second
8 fountains in operation at SYRTE, PTB, NIST, USNO, Penn St, IEN, ON. 5 with accuracy at $1 \times 10^{-15}$. More than 10 under construction.
The best clock: atoms in optical lattices

\[ |g\rangle \quad \rightarrow \quad |e\rangle \]

\[ \omega_{\text{trap}} \]

\[ ^{87}\text{Sr} \quad ^{1}P_{1} \quad ^{3}P_{0} \quad ^{1}S_{0} \]

461 nm (\(\sim 5\) ns)

698 nm (\(\sim 150\) s)

Quality factor > \(10^{17}\)

Optical dipole moment
\(~10^{-4} - 10^{-5}\) Debye


from: Jun Ye (JILA, Boulder)
Sr clock - a new frontier for stability & accuracy

![Graph showing the fractional frequency uncertainty over time for different types of clocks: Cs Beam/Cs Fountain, Ion Clock, Sr Optical Lattice Clock, and Yb Optical Lattice Clock. The x-axis represents the year from 1960 to 2010, and the y-axis represents the fractional frequency uncertainty from $10^{-17}$ to $10^{-10}$. The graph illustrates improvements in accuracy over time.]
Sr clock - a new frontier for stability & accuracy

Sr: lowest uncertainty in all atomic clocks: $6.4 \times 10^{-18}$

Achieving this x 100 faster than ion clocks

Bloom et al., arXiv:1309.1137
The inaccuracy of such a clock corresponds to 1s over the entire lifetime of the universe!
Outlook

- Search for New Phases of Matter
- Extremely Strong Magnetic Field Physics
- Novel Quantum Magnets
- Controlled Quasiparticle Manipulations
- Non-Equilibrium Dynamics (Universality?)
- Thermalization in Isolated Quantum Systems
- Entanglement Measures in Dynamics
- Supersolids
- Cosmology - Black Hole Models?
- High Energy Physics/String Theory
- New clocks/Navigation

Quantitative testbeds for theory!