Ultracold Fermions: an introduction

T. Giamarchi

http://dqmp.unige.ch/giamarchi/
Cold atoms

Immanuel Bloch, Jean Dalibard, and Wilhelm Zwerger
Rev. Mod. Phys. 80, 885 (2008)

T. Esslinger:

A. Georges, TG
Les houches lecture, arXiv:1308.2684

TG
Atom trapping and cooling

- Sub recoil cooling 1988
- Sisyphus 1988
- Doppler molasses 1985
- Dilution cryostats
- Liquid He 1908
- room

- $10^{-9} K$
- $10^{-6} K$
- $10^{-3} K$
- 1K
- $10^3 K$
- 1 cm/s
- 1 m/s
- 300 m/s
Groupe: I. Bloch (Munich U.)
Cooling and trapping

$T_{\text{universe}} = 2.725 \, \text{K}$

$T_{\text{at}} = 0.000\,001 \, \text{K}$

1997

Atomic clocks: 10 seconds error.....

.. since the beginning of the universe!
Even colder!

T_{at} = 0.000\,000\,001 \, K

2001: Cornell, Ketterle, Wieman
Group: T. Esslinger (ETH, Zurich)
Bose-Einstein condensation

Condensation de Bose Einstein

Special properties

Normal fluid:
“friction” on impurities

Flow without “friction”:
Superfluidity
New states of matter

4He
T = 2.17K ~ -271 C

Kapitsa
Allen
Misener

1938

Rb
1995

Cornell
Ketterle
Weiman

2001
So what?
Let us talk about materials (condensed matter physics)
20st century: age of silicon
Complete change of our society

20th century on the ENIAC*:

„Where a calculator on the ENIAC is equipped with 18000 vacuum tubes and weighs 30 tons, computers in the future may have only 1000 tubes and weigh only 1 ½ tons.“

Popular Mechanics, March 1949

1947 ENIAC
Electronic Numerical Integrator
And Computer
How to master materials?

- Understood: free electrons
- Real systems: Coulomb interaction
  \[ E \gg 10000 \text{ K} \]
- Properties of realistic systems?
- Free electron theory works quite well: Landau Fermi liquid
  \[ m \rightarrow m^* \]
Superconductivity

Onnes  Holst

1911
• Transistor


• Giant magnetoresistance

1956

2007
Materials of the future

(Y. Tokura, Japan)
Everything is described by the Dirac / Schrödinger equation

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The general theory of quantum mechanics is now almost complete (...). The underlying physical laws necessary for the mathematical theory of a large part of physics and the whole of chemistry are thus completely known, and the difficulty is only that the exact application of these laws leads to equations much too complicated to be soluble.''
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Quantum mechanics / Complexity

- More atoms in a 1 mm$^3$ system than stars in the universe

- Quantum degenerate (Pauli or Bose statistics) : $T_F \sim 12000$ K

- Quantum mechanics you can touch!

(D. Eigler et al.)
Need to understand interactions

$10^{23} = 100\,000\,000\,000\,000\,000\,000\,000\,000$

Swiss supercomputing center (Mano); machines with $7\,10^{15}$ operations per second

Quantum nature of the problem:
numerical instabilities with classical computers
How to study?

Very difficult!!

Example of High Tc superconductors (86)
CM: From reality to a simplified model

Usually still too complicated to solve!

Results: approximations on the model or reality?
Hubbard model (1963)

\[ H = -t \sum_{\langle i,j \rangle, \sigma} (c_{i,\sigma}^\dagger c_{j,\sigma} + h.c.) + U \sum_{i=1}^{N} n_{i\uparrow} n_{i\downarrow} \]
Methods

- Very difficult analytically

- Novel techniques: many body, field theory, topology concepts, ……… ????

- Very difficult numerically: fermions, error growing exponentially with the system size

- Novel (approximate or exact) numerical techniques (Monte-carlo, DMRG, DMFT, ….. ????)

And I’m not happy with the analyses that go with just the classical theory, because Nature isn’t classical, dammit, and if you want to make a simulation of Nature, you’d better do it quantum mechanical, and by golly it’s a wonderful problem because it does not look so easy.

Quantum simulators

Experimental system that implements as closely as possible one of the canonical models

Read the answer on the experiment (no approximation)

Benchmark some of the theoretical methods
Cold atoms and condensed matter: a love story
Virtual solids

Tunnelling

Short range interaction

Proposal: D. Jaksch et al PRL81 3108 (98)
I have a feeling we're not in Kansas anymore.
Bosons: from insulator to superfluid

Perfect control on the model

Interactions
(Lattice, Feschbach resonance)

Statistics

Bosons

Dimensionality

Fermions
Two dimensional superfluids

LETTERS

Berezinskii–Kosterlitz trapped atomic gas

Zoran Hadzibabic\textsuperscript{1}, Peter Krüger\textsuperscript{1}, Marc C
Fig. 58. – Observation of vortices in a strongly interacting Fermi gas, below, at and above the Feshbach resonance. This establishes superfluidity and phase coherence in fermionic gases. After a vortex lattice was created at 812 G, the field was ramped in 100 ms to 792G (BEC-side), 833G (resonance) and 858G (BCS-side), where the cloud was held for 50 ms. After 2 ms of ballistic expansion, the magnetic field was ramped to 735G for imaging (see text for details). The field of view of each image is 880 μm x 880 μm. More recent version of Fig. 3 in [55].

Making, probing and understanding ultracold Fermi gases

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Massachusetts Institute of Technology, Cambridge, Massachusetts, 02139, USA

arXiv:0801.2500v1
Hubbard model

**LETTERS**

A Mott insulator of fermionic atoms in an optical lattice

Robert Jördens 1*, Niels Strohmaier 1*, Kenneth Günter 1,2, Henning Moritz 1 & Tilman Esslinger 1

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**Metallic and Insulating Phases of Repulsively Interacting Fermions in a 3D Optical Lattice**

U. Schneider, 1 L. Hackermüller, 1 S. Will, 1 Th. Best, 1 I. Bloch, 1,2 T. A. Costi, 3 R. W. Helmes, 4 D. Rasch, 4 A. Rosch 4

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**BREAKTHROUGH OF THE YEAR**

**THE RUNNERS-UP**

Quantum Simulators Pass First Key Test
Real time observation of the Hubbard model

Letter

*Nature* 462, 74-77 (5 November 2009) | doi:10.1038/nature08482; Received 20 July 2009; Accepted 3 September 2009

A quantum gas microscope for detecting single atoms in a Hubbard-regime optical lattice

Waseem S. Bakr¹, Jonathon I. Gillen¹, Amy Peng¹, Simon Fölling¹ & Markus Greiner¹

ARTICLE LINKS
- Figures and tables

SEE ALSO
- Editor’s Summary

ARTICLE TOOLS
A firmer grip on the Hubbard model
Many additional possibilities

- Exotic lattices
- Novel probes (double occupation etc.)
- Perfectly controlled disorder/ Isolated quantum systems
- Dynamical scales easily accessible
- Long range interactions (dipolar; Rydberg)
Some imperfections of the simulator (for the moment).....
I am your worst nightmare
Confining potential
Confining potential

\[ H = \int d^3 r \frac{1}{2} \omega_0^2 r^2 \rho(r) \]

- No homogeneous phase!
Main points to improve

• Inherent inhomogeneity

• Fermions: temperature between $T_F/20$ and $T_F/6$ (2000 K !)

• In some occasions: Probes
Beyond quantum simulators
Many possibilities

• Out of equilibrium physics (isolated systems)

• Artificial gauge fields (A); very large fields

• Novel matter (mixtures, bosons with “spin”, SU(N) etc.)

• Weird potentials (quasicrystals etc.)
Transport
Observation of quantized conductance in neutral matter

Sebastian Krinner¹, David Stadler¹, Dominik Husmann¹, Jean-Philippe Brantut¹ & Tilman Esslinger¹
Transport between superconductors

E. Scheer et al. PRL 78 3535 (1997)


Periodic one dimensional structure

Conclusions / Perspectives

• Remarkable CM-CA interplay
• Quantum simulators and beyond
• Remarkable new way to think/measure
• [Many important developments coming soon]
Louis, I think this is the beginning of a beautiful friendship.