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To cite this version:
Philippe Bouyer. Matter Waves: from quantum simulators to tests of general relativity. Mesoscopic Physics in Complex Media, Jul 2010, Cargèse, France. <hal-00502396>

HAL Id: hal-00502396
https://hal.archives-ouvertes.fr/hal-00502396
Submitted on 14 Jul 2010

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Matter waves: from quantum simulators to tests of general relativity

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Atom Interferometry consists in physical phenomenas where the wave nature of atoms (and in particular the external degrees of freedom) is concerned.

- Analogous to light waves phenomenas, but for de Broglie waves

\[ \lambda_{opt} \Rightarrow \lambda_{opt} = \frac{\hbar}{m v_{at}} \]

- More generally understood as interferences between quantum paths
ATOM INTERFEROMETRY

✓ ~1990 : first demonstrations

- Young fringes
- Interferometers with physical gratings
- Interferometers with light gratings
- Interferometers with light pulses

✓ Related to de Broglie waves

- Works with “any king” of molecules (even fullerene and eventually viruses)
Light is used to cool down atoms: exchange of energy between atoms and light

- Relies on photon absorption, no coherence, no interferences.
COOLING ATOMS TO µK TEMPERATURE

Vapeur d’atomes

Piégeage et refroidissement

300 K

~50 µK
Atoms cooled below 1 µK
Distribution of particles with velocities around mm/s
Distribution on matter waves with de Broglie wavelength $\approx 1 \, \mu$m

✓ It is possible to observe atomic diffractions, interferometry ...
Light is used to cool down atoms: exchange of energy between atoms and light

- Relies on photon absorption, non coherent, no interferences.

Light can be used to manipulate coherently the matter waves

- Coherent manipulation of atomic states
  - Rabi oscillation (coherent)
  - Photon momentum exchange

- Non-dissipative potentials made with light
  - No photon scattering (coherent)
  - Dispersive (dephasing) part of radiative force

\[ U = -d \cdot E = -\alpha(\omega)E^2 \]
Thanks to our ability to manipulate matter waves, we can create:

- Coherent beams of atoms, atom lasers.
- Atom interferometers
- Quantum simulators using matter and light
Atoms cooled below 1 µK
Distribution of particles with velocities around mm/s
Distribution on matter waves with de Broglie wavelength ≈ 1 µm

✓ It is possible to observe atomic diffractions, interferometry ...
High Temperature $T$:
thermal velocity $v$
density $d^{-3}$
"Billiard balls"

Low Temperature $T$:
De Broglie wavelength
$\lambda_{DB} = \frac{h}{mv} \propto T^{-1/2}$
"Wave packets"

$T = T_{\text{crit}}$:
Bose-Einstein Condensation
$\lambda_{DB} \approx d$
"Matter wave overlap"

$T = 0$:
Pure Bose condensate
"Giant matter wave"
COOLING ATOMS TO BOSE–EINSTEIN CONDENSATION
COOLING ATOMS TO BOSE–EINSTEIN CONDENSATION

Vapeur d’atomes

300 K temperature

~50 μK
BEC is a coherent matter wave

From the light bulb ... ... to the laser
An atom interferometer will use a series (at least two) coherent splitting processes to “create” multiple paths that will interfere.

Atom cloud (N atoms)

Interrogation time: T

coherent beam splitting

coherent beam mixing

Sensitivity: \( \frac{\Delta \phi}{\Delta \phi_{\text{min}}} \sim \sqrt{N} \times T^\alpha \)
ATOM INTERFEROMETER

✓ Absorption of photon from on laser and stimulated emission to the retroreflected beam

⁻ Rabi oscillation between 2 (or more) state
⁻ Different momenta since photons carry momentum
Coherence: all the paths interfere

- The free falling quantum state is forbidden

- Quantum levitation

A series of interferometer:

\[ \Delta \phi = -2kgt^2 + \delta \phi_0 \]

Final fringe separation

\[ \Delta T = \frac{\pi}{2kgT} \]

Measures g with $10^{-5}$ precision
First pulse is the 1st beam splitter
- Coherent superposition
- Different speed
- The two components split

Second pulse: mirror
- Redirect wavepackets

Last $\pi/2$ pulse when wavepackets recombine
- Output depends on phase difference

The phase depends on the center of mass position of the atomic WP: $\Phi(t_i) = kx(t_i) + \Phi_0$

$\Delta \phi = \phi_1 - 2\phi_2 + \phi_3$
• Interference fringes: \( N_{at} \sim \cos\left(2\pi aT^2/\lambda + \Phi\right) \)

• Extract acceleration from interference signal

\[
\Delta a_{\min} = \frac{a}{\Delta \phi_{\text{acc}} = 1 \text{ rad}} = \frac{1}{2T^2 \sqrt{N}}
\]

\( \sim T = 100 \text{ ms} \): measures \( g \) with \( 10^{-9} \) precision and accuracy
In laboratories, atom gravimeters beat the best commercial gravimeters:
- Seismic wave detections
- Gravity monitoring
- Watt balance: quantum definition of the kilogram
Simulated navigation solutions.

5 m/hr system drift demonstrated.

Density difference between water and oil: 0.8. 100 m³ of oil @ 100 m depth = 1 ng anomaly
Gravitational waves are radiated by objects whose motion involves acceleration, provided that the motion is not perfectly spherically symmetric.

Interesting astrophysical objects (black hole binaries, white dwarf binaries) are sources of gravitational radiation in $0.01 - 10$ Hz frequency band.

Distance between objects modulates by $hL$, where $h$ is strain of wave and $L$ is their average separation.

For the Earth-Sun system, we can find:

$$h_+ = -\frac{1}{R} \frac{G^2}{c^4} \frac{4m_1m_2}{r} = -\frac{1}{R} 1.7 \times 10^{-10} \text{ meters}.$$ 

For $R \approx 1$ light-year, typical amplitudes will be $h \approx 10^{-26}$. 

BOUYER – Matter Waves – 13 July 2010
Differential accelerometer configuration for gravity wave detection.

Atoms provide inertially decoupled references (analogous to mirrors in LIGO)

Gravity wave phase shift through propagation of optical fields.

Gravity wave induced phase shift:

\[ \Delta \phi \sim h L \sin^2(\omega T/2) \]

\( h \) is strain, \( L \) is separation, \( T \) is pulse separation time, \( \omega \) is frequency of wave

\( \sim \) AI sensitivity : \( 10^{-15} \) m/s\(^2\)

\( \sim \) 10 km separation : \( h = 10^{-19} \)
✓ Compare the free fall of 2 different atomic species.
✓ Atom interferometry: use a precise ruler to get the position in time
✓ $\eta = \Delta a/a$ measured at the $10^{-7}$ level with 2 different isotopes and two different spins, can reach $10^{-15}$ on ground with specific apparatus.
GOING AIRBORNE

Compact experiment operating in the 0-g airbus of Novespace (CNES)
AND 0–GRAVITY
Vibrations correspond to 100 fringes shift.

No measurement possible?
Correlation with low perf classical accelerometer allows to reconstruct the fringes

30 µg of resolution, 1000 times smaller than the noise.

BEC is a coherent matter wave

From the light bulb ... ... to the laser
BEC is a coherent matter wave

BEC is a macroscopic quantum state where interaction play a important role

\[ i\hbar \frac{\partial \psi}{\partial t} = -\frac{\hbar^2}{2m} \nabla^2 \psi + V \psi + gN |\psi|^2 \psi \]

Propagation follows a non-linear Shrödinger equation (Gross–Pitaevski)
**Superfluidity**


**Mott transition**

M. Greiner et al., Nature 415, 39–44, 2002

**BEC–BCS crossover**


Degenerate mixtures (bosons, fermions).

Controllable configurations and interactions.
«Quantum simulators»: building a controllable quantum system to simulate other quantum systems.
One of the key topics in condensed matter physics is to study the response of electrons to an electromagnetic field.

Can we simulate transport and conduction of electrons with atoms. What is the role of disorder ...
In a perfectly ordered metal

Electronic conduction

Diffusive transport caused by scattering on lattice defects (Drude model)
In a perfectly ordered metal, electronic conduction occurs through the movement of free electrons in the presence of an electric field. Diffusive transport caused by scattering on lattice defects (Drude model) is a key mechanism for conductivity. Thermal excitation increases diffusion, leading to reduced conductivity.
Experimental implementation

Crossed dipole trap with 1 small beam

$\lambda=767\text{nm BLUE DETUNED}$
$P=150\text{mW}$
$f_z = 600\text{ Hz}$

$\omega_x = 1.1\text{ mm}$
$d = 22\text{ m}$

G. Stern et al., arXiv:1003.4761
2D trap optical setup

EM-CCD

Fluorescence imaging

Phase-plate

Science chamber
Expansion

$2D$ density scales as $1/r^2$

$$r^2(t) = r^2(0) + \frac{k_B T}{M} t^2$$
**Depth of the optical wells**

Indirect (CCD) and direct (using HF spectroscopy) measurements
Statistical properties verified $\sigma_l \sim \langle l \rangle$
Potential depth $\sigma_V$ calculated from $\sigma_l$

$$\sigma_V = \frac{2 \Gamma^2 \sigma_l}{3} \frac{\Gamma}{I_0}$$

Good agreement with HF measurements (calibration)
Disorder amplitude definition $\gamma : \gamma = \sigma_V / \mu$

**Spatial autocorrelation :** $C(\delta z) = \langle V(z) V(z+\delta z) \rangle$

$$\langle V(z) V(z+\delta z) \rangle = 1 + \left( \frac{\sin(\pi \delta z / \Delta z)}{\pi \delta z / \Delta z} \right)^2$$

$$\Delta z = \frac{\lambda}{2(N.A.)} = 0.8 \mu m$$
EXPERIMENTAL IMPLEMENTATION
**Diffusion**

**without disorder**

**with disorder**

2D density scales as $1/r$

\[ r^2(t) = r^2(0) + Dt \]

\[ r^2(t) = r^2(0) + \frac{k_B T}{M} t^2 \]
Since $k_B T / \hbar \omega \approx 6$ and $k \sigma_y \approx 5$, we expect classical dynamics. 3 regimes present during the expansion:

Below percolation threshold ($E \approx 0.5 \ V$): trapping

$L.N. \ Smith \ and \ C.J. \ Lobb, \ PRB \ 1979$

A. Weinrib PRB 1982
Since $k_B T / \hbar \omega \approx 6$ and $k \sigma_y \approx 5$, we expect classical dynamics.

3 regimes present during the expansion:

- Below diffusion threshold ($E \approx 2 \text{ V}$): sub-diffusion
Since $k_B T / \hbar \omega \approx 6$ and $k_\sigma \gamma y \approx 5$, we expect classical dynamics.

3 regimes present during the expansion:

**Diffusion**

$$D_\xi(E) = D_0^\xi (E/V)^{\gamma_\xi}$$

$\gamma_\xi = 2.8$

anisotropy of 3.7
Profiles contain ballistic wings + diffusive central part

Diffusion coefficients: $D_{x,y}(E)$

Profile = $\sum_E \left( e^{-\frac{r^2}{D(E)t}} \right)$

Pb: what is $D(E)$?

weak scattering: $D(E) \sim D_0 E^\alpha$

$D_0 \sim 0.13 \text{ mm}^2\text{s}^{-1} ; \alpha \sim 3$

M. Robert-de-saint-Vincent, et al.
If the length scales become small compared to the de Broglie wavelength and/or the phase coherence length, then quantum mechanics will rule the transport properties.

The probability for a particle to go from point A to point B is the sum of the amplitudes of all possible trajectories.

Interference terms can appear and the transport properties can be modified.
If mean free path smaller than de Broglie wavelength: constructive interference of trajectories returning to origin: localized states: insulator
Experimental implementation

Crossed dipole trap with 1 small beam

1D BEC EXPANDING IN AN OPTICAL GUIDE
Matter waves and atom interferometry

Test fundamental laws such as General Relativity, detect resources

«Build» coherent matter wave beams, atom lasers ...

Simulate «quantum materials» with atoms and light
Atom interferometry in microgravity
G. Stern, A. Bresson (ONERA), A. Landragin (LNE–SYRTE)
R. Geiger

Degenerate mixtures in optical structures
A. Landragin (LNE–SYRTE)
J–P. Brantut, M. Robert de Saint Vincent

Coherent Atom Sources and Atom Interferences
From fundamental properties of Atom laser to quantum atom sensor applications

Applications of atom interferometry
B. Battelier
A. Landragin (LNE–SYRTE)

Atom laser and quantum transport
V. Josse
J. Billy, A. Bernard, P. Cheinnet

BEC in optical high finesse resonators
A. Landragin (LNE–SYRTE)
S. Bernon, A. Bertoldi, T. Vanderbruggen