

Matter Waves: from quantum simulators to tests of general relativity

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MATTER WAVES : FROM QUANTUM SIMULATORS TO TESTS OF GENERAL RELATIVITY

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Analogous to light waves phenomenas, but for de broglie waves



More generally understood as interferences between quantum paths



 $\lambda_r P_{ATHS} : |\mathcal{F}|^2 = |\mathcal{A}_z + \mathcal{A}_\pi|^2$ $= |d_z|^2 + |d_n|^2 +$ 2 Re to Ant.

BOUYER – Matter Waves – 13 July 2010



FRAf









- \checkmark ~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 fulerene and enventually viruses)







- Light is used to cool down atoms : exchange of energy between atoms and light
 - Relies on photon absorption, no coherence, no interferences.







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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

$$U = -\mathbf{d} \cdot \mathbf{E} = -\alpha(\omega)E^2$$







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✓ Thanks to our ability to manipulate matter waves, we can create :

Coherent beams of atoms, atom lasers.





Quantum simulators using matter and light











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 ...













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COOLING ATOMS TO BOSE-EINSTEIN CONDENSATION



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BEC is a coherent matter wave



From the light bulb ...



... to the laser







Peer pressure in the laser lab







 An atom interferometer will use a series (at least two) coherent splitting processes to "create" multiple paths that will interfere.























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✓ A series of interferometer :

$$\Delta \phi = -2kgT^2 + \delta \phi_0$$

✓ Final fringe separation





Measures g with 10⁻⁵ precision



«CLASSICAL» INTERFEROMETERS : INERTIAL SENSORS





 $\checkmark First pulse is the 1st beam splitter$

- Coherent superposition
- Different speed
 - The two components split

✓second pulse : mirror

redirect wavepackets

✓Last π/2 pulse when wavepackets recombine
✓ output depends on phase difference

 $\Delta \phi = \phi_1 - 2\phi_2 + \phi_3$









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• Interference fringes : $N_{at} \sim cos(2\pi aT^2/\lambda + \Phi)$







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Monitoring of local gravity using T = 400 ms fringes

√In laboratories, atom gravimeters beat the best comemrcial gravimeters Seismic wave detections Gravity monitoring ✓Watt ballance : quantum definition of the kilogram



Offset

Bias fluctuations : ± 10-8 g

Very robust experiment





560000

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FRAf

Density difference between water and oil : 0.8. 100 m3 of oil @ 100 m depth = 1 ng anomaly

Simulated navigation solutions.

5 m/hr system drift demonstrated.





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 Lis their average separation.

For the Earth-Sun system, we can find: $h_+ = -\frac{1}{R}\frac{G^2}{c^4}\frac{4m_1m_2}{r} = -\frac{1}{R}1.7 \times 10^{-10}$ meters.

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





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, ω is frequency of wave



 $\approx \text{Al sensitivity} : 10^{-15} \text{ m/s}^2$ $\approx 10 \text{ km separation} : h = 10^{-19}$







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- ✓ Compare the free fall of 2 different atomic species.
- ✓ Atom interferometry : use a precise ruler to get the position in time
- ✓ η =∆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.
 Drop capsule













 Compact experiment operating in the 0-g airbus of Novespace (CNES)





























- Correlation with low perf classical accelerometer allows to reconstruct the fringes
- ≈ 30 µg of resolution, 1000 times smaller than the noise.

STERN, G., et al., EUROPEAN PHYSICAL JOURNAL D, 2009. 53(3): p. 353-357.







BEC is a coherent matter wave



From the light bulb ...



... to the laser







Peer pressure in the laser lab







BEC is a coherent matter wave





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



$$i\hbar\frac{\partial\psi}{\partial t} = -\frac{\hbar^2}{2m}\nabla^2\psi + V\psi + gN\left|\psi\right|^2\psi$$

Propagation follows a non-linear shrödinger equation (Gross-Pitaevski)









Superfluidity



C. Raman et al., PRL. 83, 2502-2505 (1999).

Mott transition



M. Greiner et al.,

Nature 415, 39-44, 2002



Degenerate mixtures (bosons,fermions).

Controllable configurations and interactions BEC-BCS crossover







«Quantum simulators» : building a controllable quantum system to simulate other quantum systems.

Quantum system



toy-model of the magnified lattice structure of a "solid"



Controllable quantum system =

Quantum Simulator



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



Diffusive transport caused by scattering on lattice defects (Drude model)



In a perfectly ordered metal



Diffusive transport caused by scattering on lattice defects (Drude model) Thermal excitation increases diffusion = reduced conductivity



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Crossed dipole trap with 1 small beam





J.-F. Clément, et al., Phys. Rev. A 79, 061406(R) (2009).





G. Stern et al., arXiv:1003.4761

















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



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OPTICAL DISORDER FOR ATOMS : SPECKLE PATTERN





Depth of the optical wells

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Indirect (CCD) and direct (using HF spectroscopy) measurements Statistical properties verified $\sigma_I \sim < I >$ Potential depth σ_V calculated from σ_I

$$\sigma_V = \frac{2}{3} \frac{\Gamma^2}{2\delta} \frac{\sigma_I}{I_S}$$

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













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2D density scales as 1/r

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Since $k_{\rm B}T/\hbar\omega\approx 6\,$ and $k\sigma_y\approx 5\,$,we expect classical dynamics

3 regimes present during the expansion :

Below percolation threshold (E ≈ 0.5 V) : trapping







E/V=0.1



E/V=1

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

A. Weinrib PRB 1982



Since $k_{\rm B}T/\hbar\omega\approx 6\,$ and $k\sigma_y\approx 5\,$,we expect classical dynamics

3 regimes present during the expansion :

Below diffusion threshold (E \approx 2 V) : sub-diffusion





Since $k_{\rm B}T/\hbar\omega\approx 6\,$ and $k\sigma_y\approx 5\,$,we expect classical dynamics

3 regimes present during the expansion :

Diffusion









M. Robert-de-saint-Vincent, et al. arXiv:1004.0312, to appear in PRL







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





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Crossed dipole trap with 1 small beam



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MATTER WAVES AND ATOM INTERFEROMETRY



TEST FUNDAMENTAL LAWS SUCH AS GENERAL RELATIVITY, DETECT RESSOURCES



«BUILD» COHERENT MATTER WAVE BEAMS, ATOM LASERS ...



SIMULATE «QUANTUM MATERIALS» WITH ATOMS AND LIGHT





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