Schrödinger-cat states with ultracold atoms in optical lattices

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Summary

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- Bose-Einstein condensation with ultracold atoms
- Schrödinger cats in double-well potentials

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- Teaching activity on Quantum Science at UNIPD

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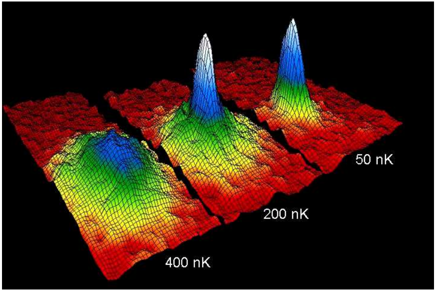
- Suggestions for teaching collaborations at UNIPD

P1. Bose-Einstein condensation with ultracold atoms (I)

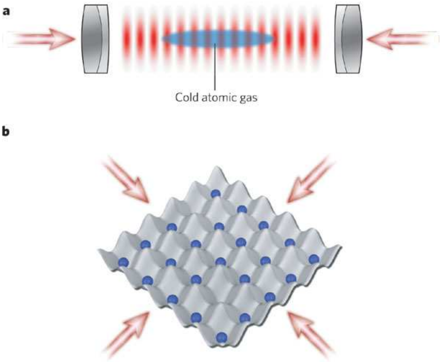
In 1995 Eric Cornell, Carl Wieman and Wolfgang Ketterle achieved Bose-Einstein condensation (BEC) cooling very dilute gases of ^{87}Rb and ^{23}Na atoms.



The BEC critical temperature is about $T_c \simeq 100$ nanoKelvin. The gas, made of dilute and ultracold neutral alkali-metal atoms, is in a meta-stable state which can survive for minutes.

P1. Bose-Einstein condensation with ultracold atoms (II)

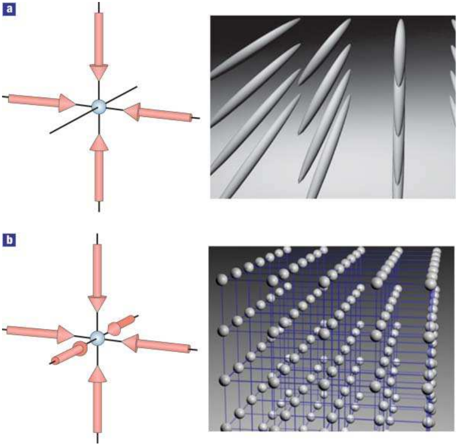
In 2002 the experimental group of Immanuel Block obtained with counter-propagating laser beams inside an optical cavity, stationary optical lattice which can trap ultracold atoms.



The resulting optical potential can trap neutral atoms in the minima of the optical lattice due to the electric dipole of atoms.

P1. Bose-Einstein condensation with ultracold atoms (III)

Now the study of neutral atoms trapped with light is a very hot topic of research.



Changing the intensity and shape of the optical lattice, it is now possible to trap atoms in very different configurations. One can have many atoms per site bit also one atom per site.

P1. Schrödinger cats in double-well potentials (I)

Dilute identical bosonic atoms can be described by a quantum field operator $\hat{\psi}(\mathbf{r}, t)$ which satisfies the Heisenberg equation of motion

$$i\hbar \frac{\partial}{\partial t} \hat{\psi}(\mathbf{r}, t) = \left[-\frac{\hbar^2}{2m} \nabla^2 + U(\mathbf{r}) + \frac{4\pi\hbar^2 a_s}{m} |\hat{\psi}(\mathbf{r}, t)|^2 \right] \hat{\psi}(\mathbf{r}, t) \, , \quad (1)$$

where $U(\mathbf{r})$ is the external potential and a_s is the s-wave scattering length of the inter-atomic potential.

We have theoretically studied static and dyanamical proprieties of ultracold bosonic atoms in the following external potential

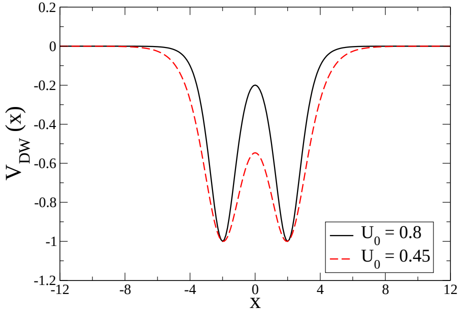
$$U(\mathbf{r}) = V_{DW}(x) + \frac{1}{2} m \omega_{\perp}^2 (y^2 + z^2) \, , \quad (2)$$

where $V_{DW}(x)$ is a double-well potential.

In this way we have investigated the **macroscopic quantum tunneling** of neutral atoms from one well to the other well.

P1. Schrödinger cats in double-well potentials (II)

Macroscopic quantum tunneling with neutral atoms is the analog of the **Josephson effect of superconductivity** (Josephson junction).



The system is well discribed by the two-site Bose-Hubbard Hamiltonian

$$\hat{H} = -\frac{J}{2}\left(\hat{a}_L^+ \hat{a}_R + \hat{a}_R^+ \hat{a}_L\right) + \frac{U}{2}\left(\hat{N}_L(\hat{N}_L - 1) + \hat{N}_R(\hat{N}_R - 1)\right) \quad (3)$$

where $\hat{a}_j$ and $\hat{a}_j^+$ are respectively the annihilation and creation operators of bosons in the site j ($j = L, R$), and $N_j = \hat{a}_j^+ \hat{a}_j$ is the number operator of site j. Here J is the hopping (tunneling) energy and U is the on-site energy.

P1. Schrödinger cats in double-well potentials (III)

The ground-state of the two-site Bose-Hubbard Hamiltonian with N bosonic atoms

$$|GS\rangle = \sum_{i=0}^{N} c_i \; |i\rangle_L \otimes |N-i\rangle_R \tag{4}$$

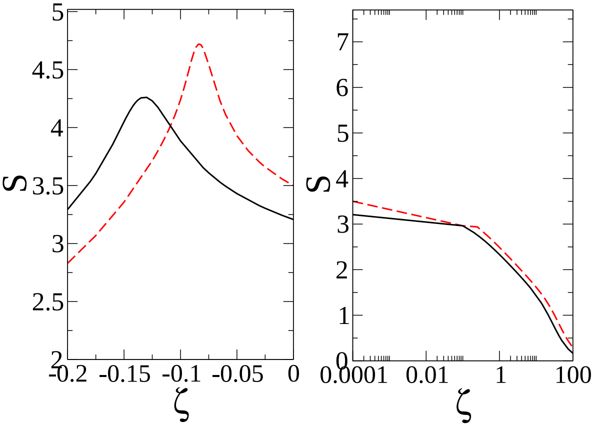
is strongly quantum entangled and characterized by the complex coefficients c_j which depend on the ratio U/J.[1] In simple cases

$$|GS\rangle = \begin{cases} |\frac{N}{2}\rangle_L \otimes |\frac{N}{2}\rangle_R & \text{if } U/J \gg 1 \\ \frac{1}{\sqrt{2}} \left(|N\rangle_L \otimes |0\rangle_R + |0\rangle_L \otimes |N\rangle_R \right) & \text{if } U/J \ll -1. \end{cases} \tag{5}$$

Thus, for $U/J \ll -1$ one gets a Schrödinger-cat state (NOON state). With ultracold atoms it is quite easy to experimentally obtain $U < 0$ by using the Feshbach-resonance technique. This is instead very difficult with superconducting Josephson junctions.

[1] G. Mazzarella, LS, A. Parola, F. Toigo, Phys. Rev. A **83**, 053607 (2011); L. Dell'Anna, G. Mazzarella, V. Penna, LS, Phys. Rev. A **87**, 053620 (2013); P. Rosson, G. Mazzarella, G. Szirmai, LS, Phys. Rev. A **92**, 063604 (2015).

P1. Schrödinger cats in double-well potentials (IV)



Entanglement entropy S of the ground-state $|GS\rangle$ of the two-site Bose-Hubbard Hamiltonian as a function of the parameter $\zeta = U/J$. Left panel: attractive bosons ($U < 0$). Right panel: repulsive bosons ($U > 0$). **Solid line**: $N = 20$. Dashed line: $N = 30$.

P2. Collaboration with INO-CNR on QT (I)

I am associate researcher at Istituto Nazionale di Ottica (INO) of CNR: Unit of Sesto Fiorentino at LENS.

QuantERA Call 2017

Proposal in which I am involved: Quantum mixtures for emerging quantum phenomena and technologies (QuMix)
"The goal of this project is to realize two complementary novel platforms based on superfluid atomic mixtures for simulating a broad variety of phenomena in quantum matter, ranging from condensed matter to the physics of neutron stars."
[INO-CNR, University of Birmingham, Ludwig-Maximilians Universitat, Universitat de Barcelona, University of the Basque Country, University of Lisbon. Coordinator: Chiara D'Errico (INO-CNR)].

Very recently we have passed the first selection stage.

P2. Collaboration with INO-CNR on QT (II)

The Proposal Quantum mixtures for emerging quantum phenomena and technologies (QuMix) is characterized by a synergetic experiment-theory approach, centred around to two complementary experimental setups:
– a ^{41}K - ^{87}Rb mixture with tunable interactions (INO-CNR)
– a coherently coupled spinor condensate of Rb (Birmingham)
The most ambitious goals of our project are the first experimental observation of:
(i) the Andreev-Bashkin (AB) effect – the mutual non-dissipative drag in a superfluid mixture – that will pave the way to simulation and comprehension of the inner dynamics of neutron stars;
(ii) an analog of quantum-chromodynamics (QCD) confinement and string breaking for opposite charged half-vortices in coherently coupled spinor condensates;
(iii) the analog of Hawking radiation – the radiation emitted by black holes – for spin waves in Bose-Einstein condensates (BECs).

P2. Teaching activity on quantum science at UNIPD

Presently I am teaching:
– **Structure of Matter**, MSc in Physics.
– aka, **Advanced Quantum Physics**, MSc in Mathematical Engineering.
– **Structure of Matter**, BSc in Optics and Optometrics.
– **Theoretical Physics**, BSc in Philosophy.

In the past I was teaching
– **Quantum Field Theory in Condensed Matter Physics**, PhD in Physics, a.y. 2015-2016.
– **Introduction to Quantum Information**, PhD in Physics, a.y. 2013-2014.
– **Macroscopic Quantum Phenomena and Quantum Information**, Galileian School of Advanced Studies, a.y. 2010-2011.
– **Macroscopic Quantum Phenomena**, PhD in Physics, a.y. 2008-2009, a.y. 2009-2010.

2011-2017 theses on BEC, BCS-BEC crossover, Superconductors, Quantum Entanglement: 23 BSc theses, 8 MSc theses, 2 PhD theses.

P3. Suggestions for research collaborations at UNIPD (I)

My theoretical research activity with ultracold atoms in optical lattices belongs to the pillar **Quantum Simulators** of the Quantum Manifesto.

In the last years I investigated ultracold atoms, superfluidity, and quantum entanglement in several papers, collaborating with F. Ancilotto, L. Dell'Anna, P.A. Marchetti, and P.L. Silvestrelli (Padova), B. Malomed (Tel Aviv), G. Szirmai (Budapest), V. Penna (Torino), A. Polls and B. Julia-Diaz (Barcelona), T. Macri (Natal), F. Cinti (Stellenbosch).

Very recent results:
– Non-Universal Equation of State of the Two-Dimensional Bose Gas
LS, Phys. Rev. Lett **118**, 130402 (2017).
– Vortices and antivortices in two-dimensional ultracold Fermi gases
G. Bighin and LS, Sci. Rep. **7**, 45702 (2017).
– Itinerant ferromagnetism of 2D repulsive fermions with Rabi coupling
LS and V. Penna, New J. Phys. **19**, 043018 (2017).

P3. Suggestions for research collaborations at UNIPD (II)

Now I am mainly working in the following topics:
– Quantum dynamics of the Bose-Hubbard model with dissipation
– Bosonic and fermionic mixtures with Rabi coupling
– Bosons with dipolar interactions
– Superfluids and superconductors in the BCS-BEC crossover

My suggestions for QT research at UNIPD:

- It can be very useful to have at Padova (UNIPD or CNR) an experimental group working on ultracold atoms.
- It can be very useful to create at UNPD an International Center on Quantum Sciences and Technologies, with the contribution of both experimentalists and theoreticians (from Physics, Chemistry, Mathematics, Engineering, ...).

P3. Suggestions for teaching collaborations at UNIPD

My suggestions for QT teaching at UNIPD:

- It can be very useful to have within the MSc in Chemistry a course on **Quantum Information**.
- It can be very useful to have within the PhD in Material Science a course on **Macroscopic Quantum Phenomena and Quantum Information**.
- It can be very useful to have within some MSc in Engineering a course on **Macroscopic Quantum Phenomena**.

Acknowledgements

Thank you for your attention!

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– UNIPD BIRD Project "Superfluid properties of Fermi gases in optical potentials" (2016-2017)
– UNIPD Project "Spin-orbit coupling in two-dimensional ultracold fermionic gases" (2015-2016)
– MIUR PRIN Project "Collective Quantum Phenomena: from Strongly-Correlated Systems to Quantum Simulators" (2013-2015)
– CARIPARO Project "Macroscopic Quantum Properties of Ultracold Atoms under Optical Confinement" (2012-2014)
– UNIPD Project "Quantum Information with Ultracold Atoms in Optical Lattices" (2012-2014)