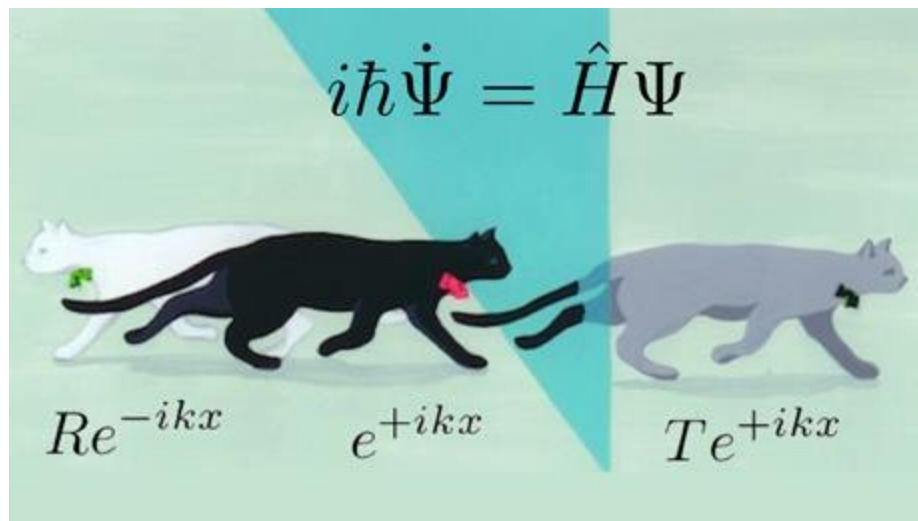


Exploring Quantum Physics

Instructors: Charles W. Clark and Victor Galitski

Quantum Gases

Part 2. Bose-Einstein condensation in experiment



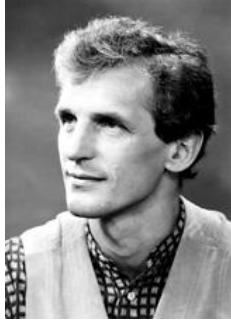
Bose-Einstein Condensation

BEC attained in laboratory 1995. Enabling technology: cooling and trapping of atoms

Wikimedia Public Domain



Eric A. Cornell
1961 -



Wolfgang Ketterle
1957 -

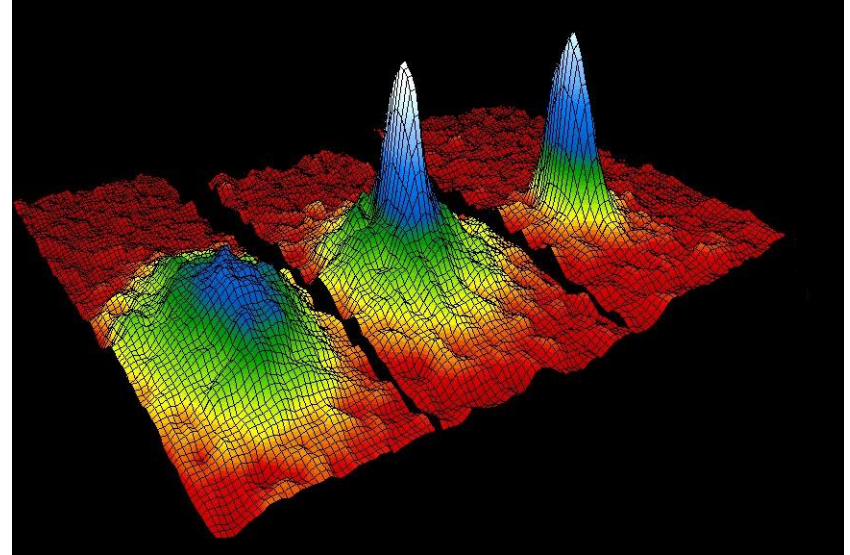


Carl E. Wieman
1951-

2001 Nobel Prize in Physics

"for the achievement of Bose-Einstein condensation in dilute gases of alkali atoms, and for early fundamental studies of the properties of the condensates".

Additional materials/Bose-Einstein condensation



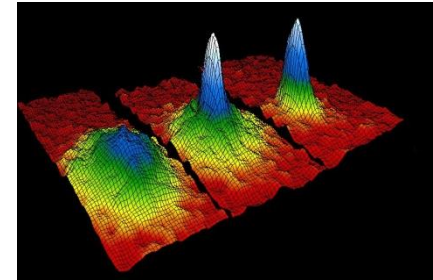
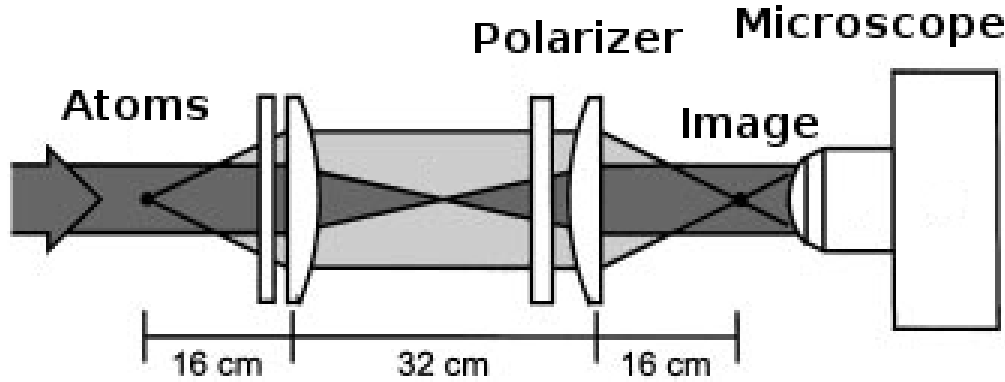
Density of ^{87}Rb gas released from an atom trap at three temperatures (left to right): 400 nK, 200 nK, 50 nK

Physics 2000

Bose-Einstein Condensation

Density images of quantum gases

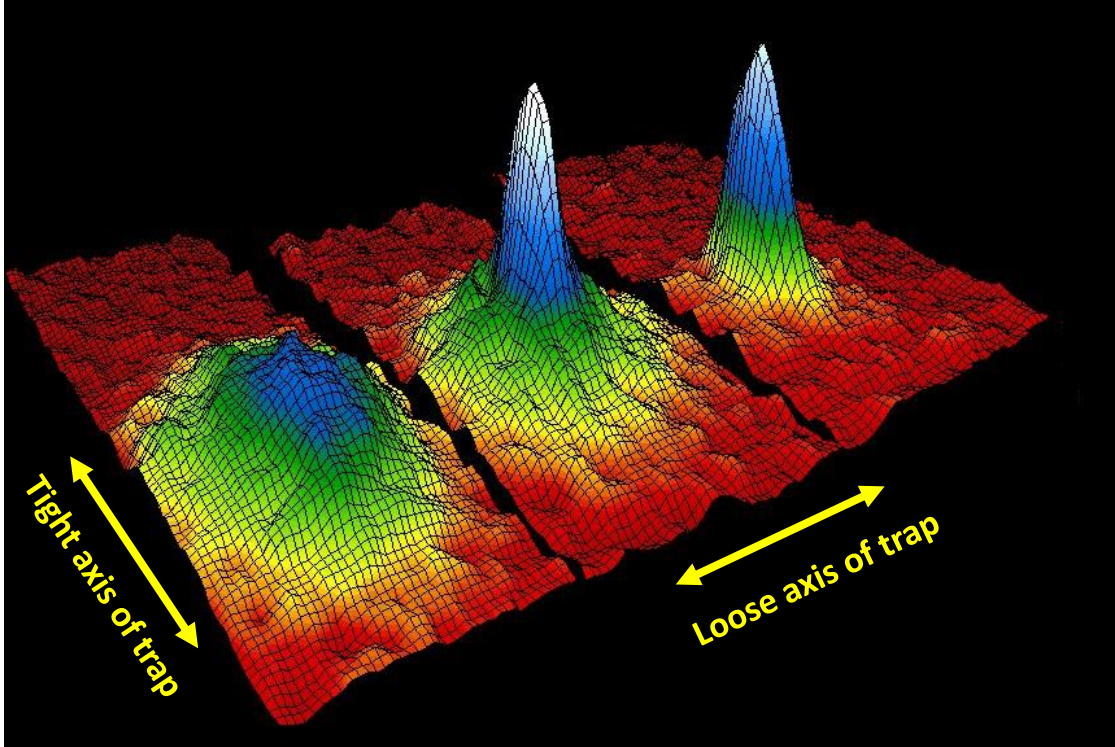
atomcool.rice.edu



These images are optical absorption measurements of the density profile of the gas after it has been released from the atom trap. The gas is illuminated from the left, the camera stands to its right. The vertical displacement of a pixel is proportional to the line integral of the gas density along the optical axis. Artificial colors are added to enhance visual contrast.

Bose-Einstein Condensation

Asymmetry: signature of expansion of a quantum gas



When released from a trap, a classical gas cloud eventually becomes spherical, independent of the shape of the trap.

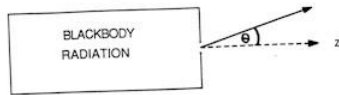
The expanding BEC cloud, on the other hand, eventually adopts the reverse-aspect-ratio of the original trapped cloud.

(uncertainty principle)

Bose-Einstein Condensation

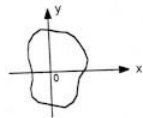
Asymmetry: analogy in optical measurements – importance of phase coherence

RADIATION FROM THERMAL SOURCES

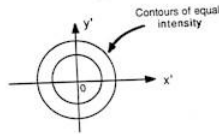


LAMBERT'S LAW

$$J(\theta) = J(0) \cos \theta$$



SHAPE OF EFFECTIVE SOURCE



FAR-FIELD PATTERN

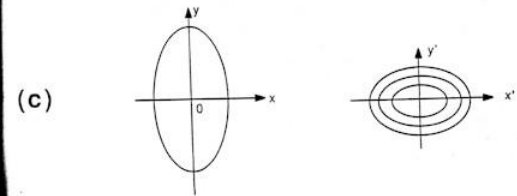
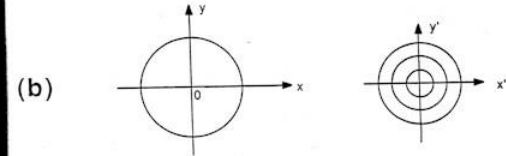
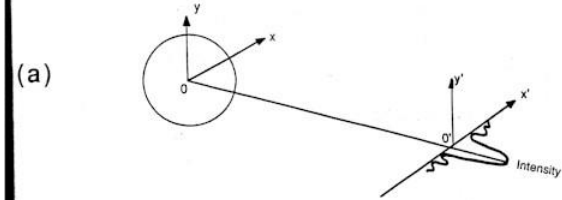
important characteristic
of thermal sources

FAR-FIELD INTENSITY PATTERN IS ROTATIONALLY
SYMMETRIC ABOUT THE NORMAL TO THE SOURCE PLANE,
IRRESPECTIVE OF SHAPE OF SOURCE

E. Wolf, *Modern Coherence Theory*

Short course at
given regularly
at Annual
Meeting of the
Optical Society
of America.

RADIATION FROM SPATIALLY COHERENT SOURCES



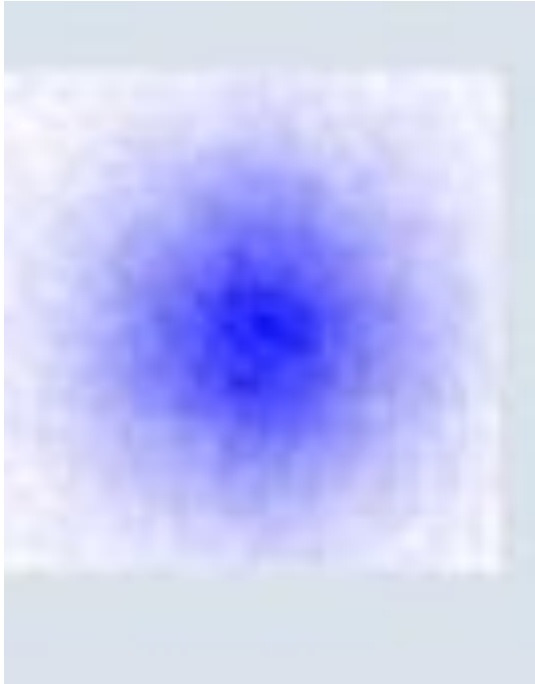
RECIPROCITY

SHAPE OF SOURCE

FAR-FIELD PATTERN

Bose-Einstein Condensation

Phase of a Bose-Einstein condensate –release of ^{87}Rb from an optical lattice



Density: 10^{-5} that of air

Pressure: 10^{-12} torr

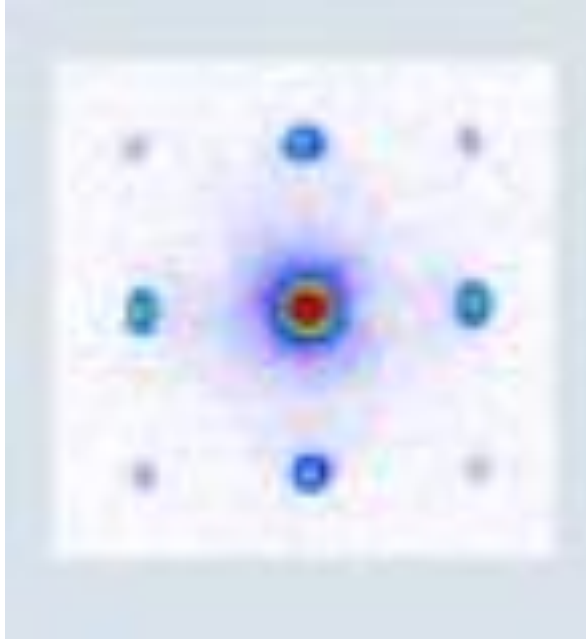
**Optical lattice of $\sim 150,000$
trapping sites**

**Non-BEC: Turn off lattice trap. Gas
expands according to naïve
expectations.**

Laboratory of T. W. Haensch

Bose-Einstein Condensation

Phase of a Bose-Einstein condensate –release of ^{87}Rb from an optical lattice



Density: 10^{-5} that of air

Pressure: 10^{-12} torr

**Optical lattice of $\sim 150,000$
trapping sites**

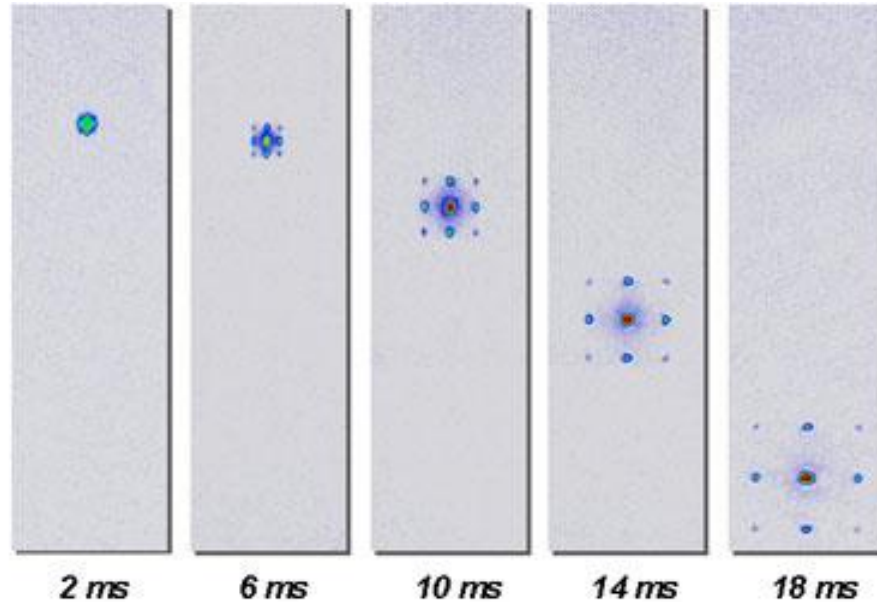
**BEC: Turn off lattice trap. Gas
expands as a cube!**

Laboratory of T. W. Haensch

Bose-Einstein Condensation

Phase of a Bose-Einstein condensate –release of ^{87}Rb from an optical lattice

Time sequence of expanding cloud



Laboratory of T. W. Haensch

Bose-Einstein Condensation

How do we describe the coherent matter wave associated with a BEC?

The Gross-Pitaevskii equation:

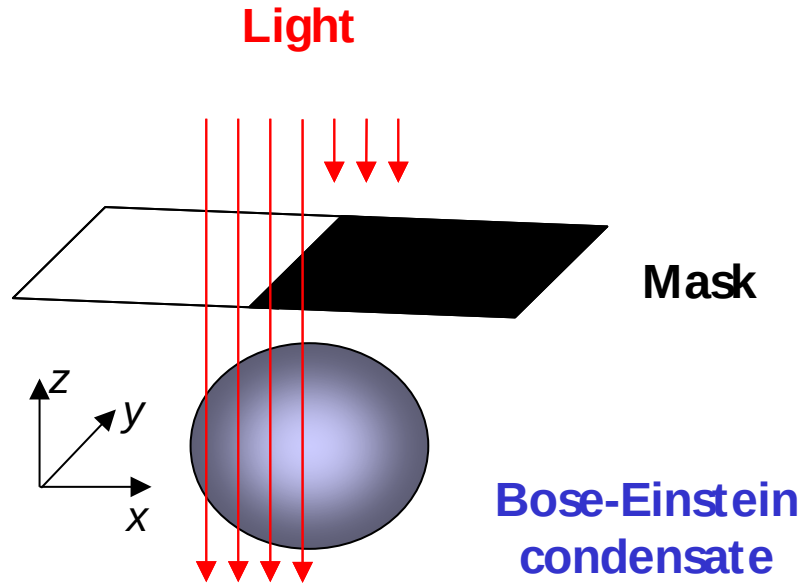
- N_0 atoms of mass M all occupy same orbital Ψ (Hartree approximation)
- Interaction between atoms replaced by Dirac delta pseudopotential (see lecture 11, part 1) characterized by a scattering length a
- Valid in low-density limit, which is that attained by most experimental BECS
- All parameters determined by experiment – none are adjustable

$$i\hbar \frac{\partial \Psi}{\partial t} = -\frac{\hbar^2}{2M} \nabla^2 \Psi + V_{\text{trap}}(\vec{r}, t) \Psi + \frac{4\pi\hbar^2 a N_0}{M} |\Psi|^2 \Psi$$

Exhibits nonlinear wave dynamics such as solitons, vortices, vortex rings

Bose-Einstein Condensation

Optical phase imprinting of a Bose-Einstein condensate



$$\Psi(\vec{r}, t) \rightarrow \Psi(\vec{r}, t) e^{i\phi(x_1, x_2)}$$

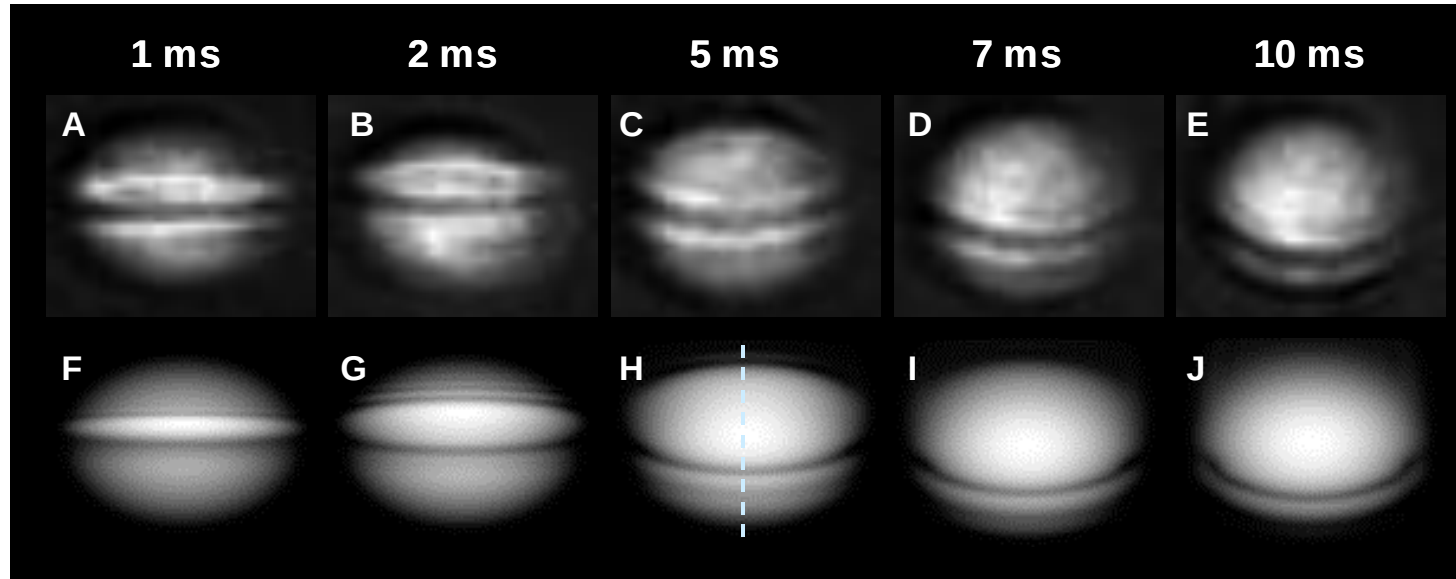
$$\phi(x_1, x_2) = -\frac{\hbar\Gamma^2}{8\Delta} \frac{I(x_1, x_2)}{I_0} \frac{t}{\hbar}$$

Burger *et al.* 1999
Denschlag *et al.* 2000

Bose-Einstein Condensation

Evolution of soliton after phase imprinting

Experiment



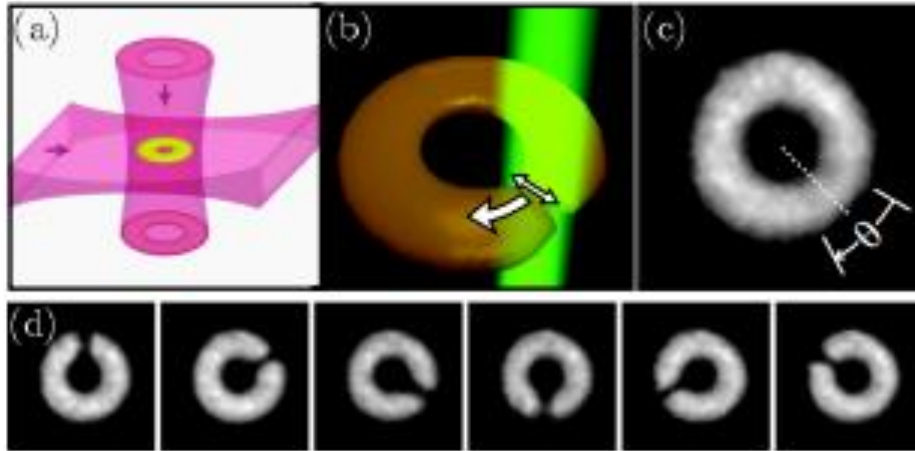
Theory

“Generating solitons by phase engineering of a Bose-Einstein condensate ,” J. Denschlag, et al. *Science* **287**, 97 (2000)

Bose-Einstein Condensation

Experimental determination of quantization of angular momentum: Stirring BEC in a ring-shaped trap

Schematic of optical trap



Procedure:

- Form ground-state BEC of $\sim 500,000$ ^{23}Na atoms in ring trap (radius ~ 20 microns)
- Stir with light “paddle”
- Release and measure density

Bose-Einstein Condensation

Experimental determination of quantization of angular momentum: Stirring BEC in a ring-shaped trap

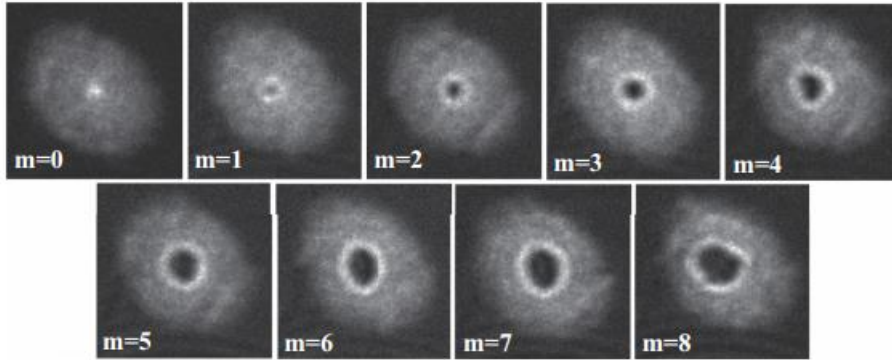


FIG. 4. Time-of-flight images of the condensate after ramp down and release from the trap and 10 ms TOF. Each image is labeled with the circulation m that was determined by analysis of hole size as shown in Fig. 2.

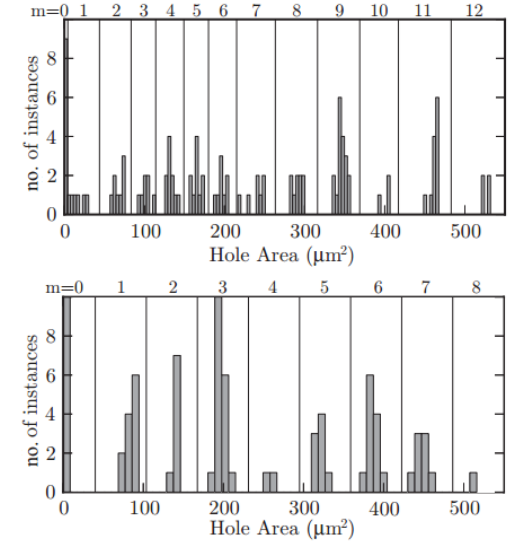


FIG. 2. Circulation of stirred condensates was determined experimentally from the distribution of hole sizes in the expanded cloud. These distributions are shown in the histograms above for the direct-release case (upper) and for the ramp-and-release cases (lower). The winding number m assigned for a given hole area is labeled for each bin.

“Probing the circulation of ring-shaped Bose-Einstein condensates,” N. Murray, et al. *Phys. Rev. A* **88**, 053615 (2013)

Bose-Einstein Condensation

Finding angular momentum of BEC after stirring in a ring-shaped trap

Experiment/theory comparison

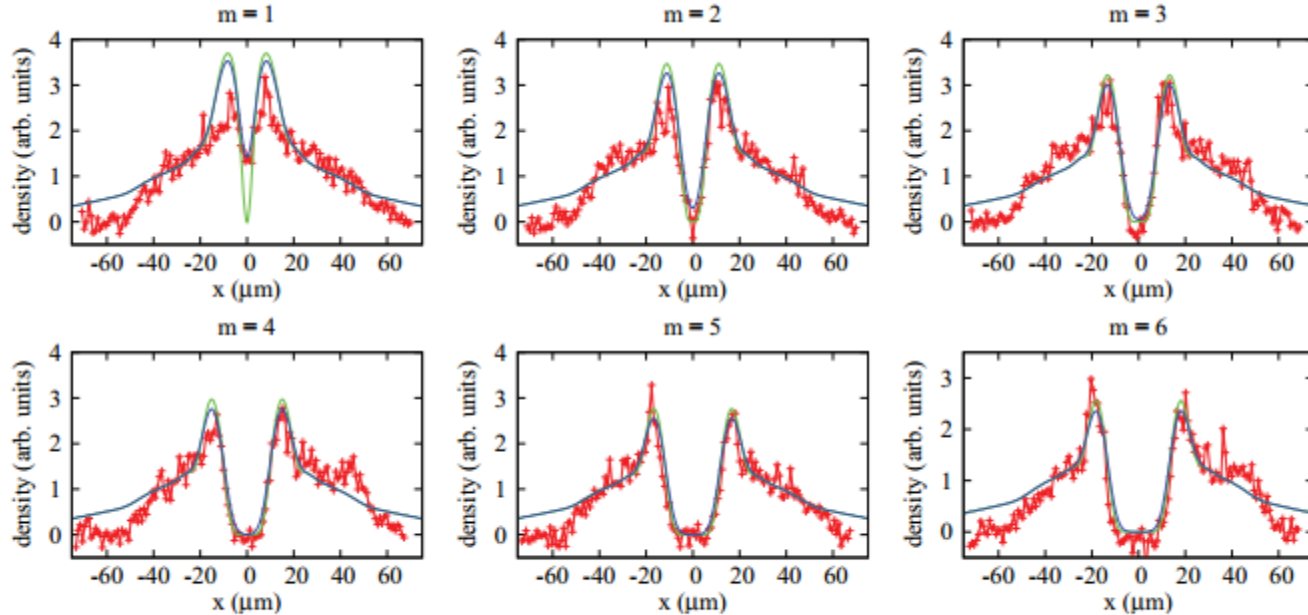


FIG. 7. (Color online) Comparison of the cut through of the condensate optical density data after ramp down and release and 10 ms TOF with GP simulations for initial circulations $m = 1, \dots, 6$.

“Probing the circulation of ring-shaped Bose-Einstein condensates,” N. Murray, et al. *Phys. Rev. A* **88**, 053615 (2013)

Bose-Einstein Condensation

Hysteresis in a quantized superfluid 'atomtronic' circuit

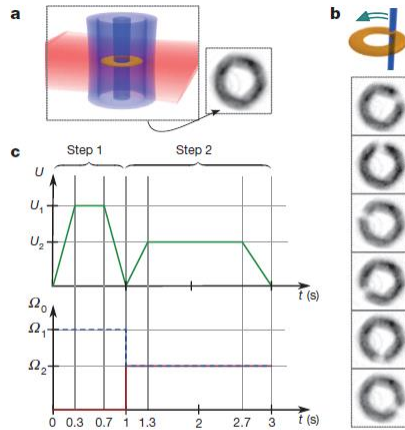


Figure 2 | Experimental set-up and procedure. a, Schematic and *in situ* images of our trap, which is formed by crossing a ring-shaped dipole trap for radial confinement and a sheet trap for vertical confinement. b, Schematic and *in situ* images of a ring rotated by a repulsive weak link. c, Two-step experimental sequence: the height, U , of the repulsive potential and the angular rotation rate, Ω , as a function of time. Step 1 sets the initial winding number using Ω_1 (either 0 or 1.1 Hz) and U_1 ($\sim 1.1\mu_0$); step 2 probes the hysteresis with Ω_2 and U_2 (see text).

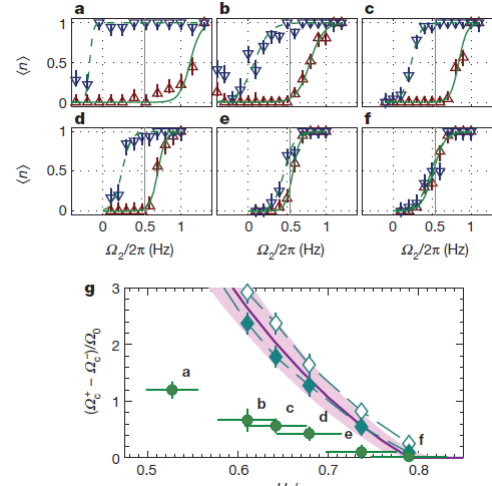


Figure 3 | Hysteresis data. a–f, Hysteresis loops with sigmoid fits. The red up-triangles and blue down-triangles show the winding number n averaged over ~ 20 shots when starting with $n = 0$ and, respectively, $n = 1$. All error bars show the 68% confidence interval. The fits determine $\Omega_c^\pm$ and $\Omega_0/2$ (vertical grey lines; Methods) and their uncertainties. g, Hysteresis loop size versus U_2 . The green circles show the experimental data. The magenta line and band are respectively the prediction and uncertainty of an effective one-dimensional hydrodynamic model²⁸. The open and filled cyan diamonds and their uncertainties are the results of our GPE simulation with $A = 0$ and, respectively, $A = 0.01$.



“Hysteresis in a quantized superfluid ‘atomtronic’ circuit,” S. Eckel, et al., *Nature* **506**, 200 (2014)

Bose-Einstein Condensation

Further reading on ultracold gases

“Many-Body Physics with Ultracold Gases,” Immanuel Bloch, Jean Dalibard, Wilhelm Zwerger, *Rev. Mod. Phys.* **80**, 885 (2008) arXiv:0704.3011

“Artificial graphene as a tunable Dirac material,” Marco Polini, Francisco Guinea, Maciej Lewenstein, Hari C. Manoharan, Vittorio Pellegrini, *Nature Nanotech.* **8**, 625 (2013) arXiv:1304.0750

“Theory of ultracold Fermi gases,” Stefano Giorgini, Lev P. Pitaevskii, Sandro Stringari, *Rev. Mod. Phys.* **80**, 1215 (2008) arXiv:0706.3360