dr Tomasz Kawalec

Opracowanie utworu pod tytułem:

„Współczesne doświadczenia z zimnymi atomami" ***w ramach kursu zaawansowanego, organizowanego dniach 31.08 – 25.09.09 będącego kontynuacją szkoleń z zakresu eksploatacji i zarządzania dużą infrastrukturą badawczą organizowanego przez Narodowe Laboratorium Technologii Kwantowych***

INNOWACYJNA GOSPODARKA
NARODOWA STRATEGIA SPÓJNOŚCI

UNIA EUROPEJSKA
EUROPEJSKI FUNDUSZ ROZWOJU REGIONALNEGO

Projekt współfinansowany ze środków Europejskiego Funduszu Rozwoju Regionalnego w ramach Programu Operacjnego Innowacyjna Gospodarka

Introduction

some criteria:

• cold and ultracold gases + some examples with atomic beams

• spectacular experiments that show the quantum nature of atoms

• experiments in the fields that are currently or in close future being developed in Poland

• just my subjective choice ☺

General table of contents

Narodowe Laboratorium Technologii Kwantowych

Współczesne doświadczenia z zimnymi atomami
część I – fale materii

Tomasz Kawalec
Instytut Fizyki UJ
Zakład Optyki Atomowej

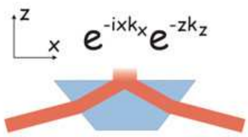
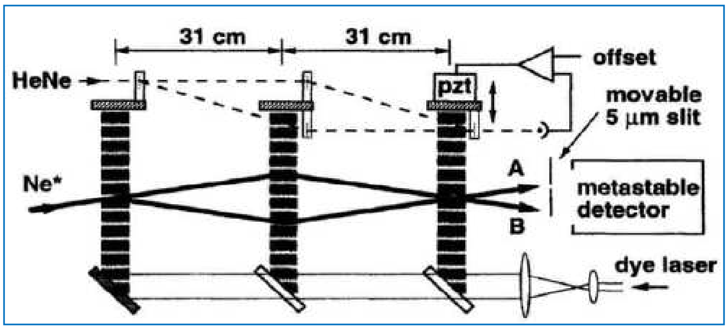
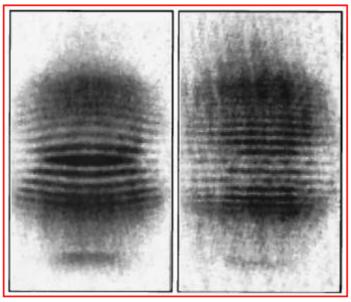


Table of contents





Atom optics

Atom optics – coherent manipulation of atomic motion requires that they are treated as waves, so many techniques to control atom waves comes from light optics.

Atom interferometry comes from the development of coherent manipulation of the translational motion of atoms and molecules and started in 90'.

Atom interferometer components (in analogy to an optical interferometer):
1. **state selection** to localize the initial state generally in momentum space: slits, atom cooling and trapping
2. **coherent splitting**, by e.g. diffraction to produce at least two localized maxima of the wave function with a well-defined relative phase: e.g. nanostructures, light gratings

$$\theta_n \approx \delta p_n / p_{beam} = n\lambda_{dB}/d$$

but transverse coherence length has to be ≈ a few „d"
momentum uncertainty in units of photon momentum (590 nm):

optical molasses or MOT: 20
collimated beam (transverse): 1
Bose-Einstein condensate: 0.1

3. free propagation so that **interactions** can be applied to one arm; great sensitivity:

$$\Delta\phi = 1 \text{ mrad} \Rightarrow U/E = 10^{-14} \text{ (energy resolution)}$$

4. **coherent recombination** so that phase information is converted back into state populations,
5. **detection** of a specific population, so the relative phase of the wave-function components can be determined from interference fringes.

Atomic interferometry

350-3.6 SR

XR 3,761,721

TX 3031 Y

United Stat

Altshuler et al.

[11] **3,761,721**

[45] **Sept. 25, 1973**

[54] **MATTER WAVE INTERFEROMETRIC APPARATUS**

[75] Inventors: **Saul Altshuler,** Manhattan Beach; **Lee M. Frantz,** Redondo Beach, both of Calif.

[73] Assignee: **TRW Inc.,** Redondo Beach, Calif.

[22] Filed: **July 6, 1972**

[21] Appl. No.: **269,492**

[52] **U.S. Cl.** .... **250/41.3,** 250/49.5 R, 350/3.5

[51] **Int. Cl.** **H01s 1/00**

[58] **Field of Search** .... 250/49.5 R, 41.9 ME, 250/41.3; 350/3.5

[56] **References Cited**

UNITED STATES PATENTS

3,686,501	8/1972	Taylor et al.	250/49.5 ED
3,532,879	10/1970	Braunstein	250/41.9

OTHER PUBLICATIONS

"The Formation of the Diffraction Image with Electrons in the Gabor Diffraction Microscope", Haine et al., J. Optical Soc. 1952

Primary Examiner—James W. Lawrence
Assistant Examiner—B. C. Anderson
Attorney—Daniel T. Anderson et al.

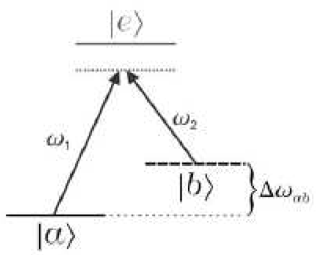
[57] **ABSTRACT**

An apparatus is disclosed which makes use of interferometry of the matter waves accompanying particles such as neutral atoms, charged ions or electrons. The apparatus includes a particle source and a beam splitter for splitting the original beam of particles into two beams having accompanying matter waves which are coherent with each other. The two beams are recombined by a pair of beam reflectors, and the resulting interference fringes may be measured by a suitable particle detector. Such an apparatus may be used for measuring variation of the gravitational field or the rate of rotation of the apparatus. In both cases the apparatus is capable of ultra precise measurement of acceleration, of the mass of an object or the rate of rotation. Alternatively, by utilizing charged particles it is possible to measure a magnetic field to obtain a magnetometer of great sensitivity. The apparatus may finally be used to carry out holography by matter waves.

calculated accuracy of gravitational field gradient measurement:

$$\delta g/g = 5 \times 10^{-7}$$

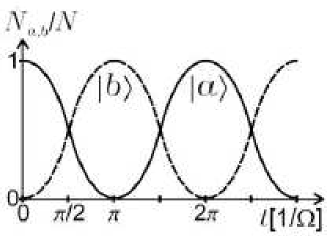
Atomic interferometry

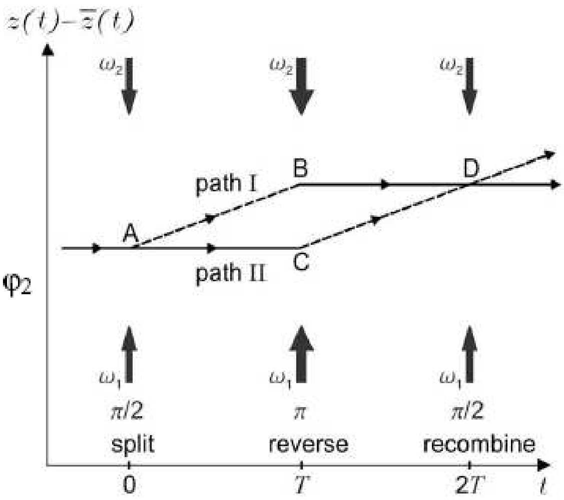


$$\Delta\phi_{tot} = \Delta\phi_{path} + \Delta\phi_{light}$$

$$\Delta\phi_{tot} = \Delta\phi_{light} = \phi_{C_1} - \phi_{C_2}$$
$$= k_{eff}\,(-gT^2) - \varphi_0 + 2\varphi_1 - \varphi_2$$

$$N_a/(N_a+N_b) \;\propto\; (1+cos[\Delta\phi_{tot}])$$



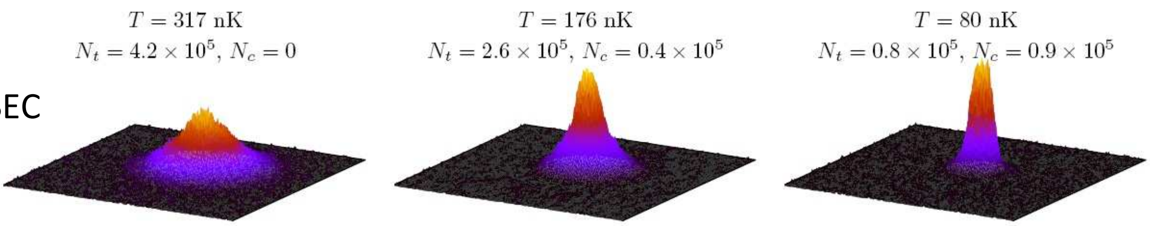


Phys. Lett. A 318, 184 (2003)

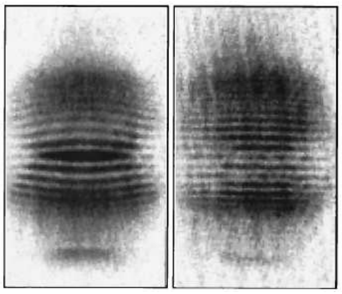
- trapped BEC ⇒ high spatial resolution, but phase diffusion, atomic density gradient (interaction induced decoherence)
- nondegenerate sample ⇒ lower spatial resolution
- fermions ⇒ collisions suppressed, but quantum pressure PRL **92**, 230402 (2004)
- Feschbach resonance ⇒ s-wave scattering length → 0 PRL **100**, 080405 (2008)

Atom laser – milestones

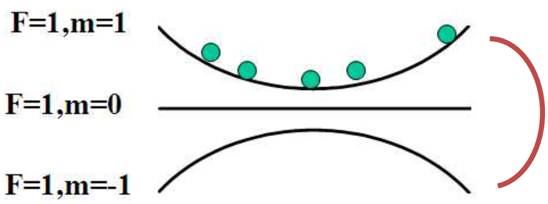
• achievment of BEC



• interference of condensates, showing first and second order coherence, long range correlations, temporal coherence, single particle coherence, many particle coherence



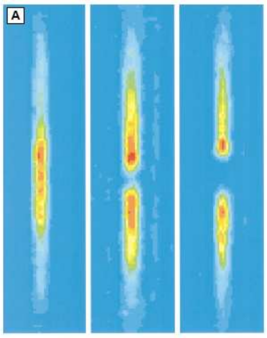
• a method of coherent outcoupling of atoms from BEC



Interference in BEC

many particle coherence

sodium condensates

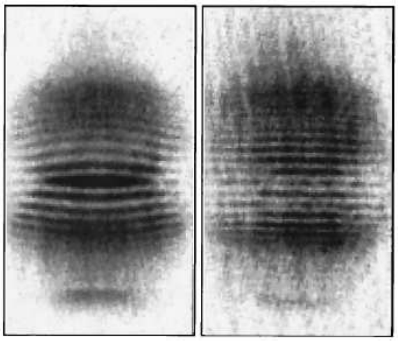


phase-contrast imaging

blue-detuned light-sheet knife

20 μm   15 μm – fringes period (λ)

0.5 mm



1.1 mm
(compressed)

absorption imaging

t = 40 ms TOF

Ketterle, Science **275,** 637 (1997)

for relative motion of atoms

$$\lambda = \frac{ht}{md}$$

d = some tens of μm

required λ_{dB} for an atom = 30 μm
which is 0.5 nK of kinetic energy

0.5 nK << zero point energy <
< mean field energy
but…
anizotropic expansion!

- first order coherence
- long-range correlations
- analog of of interference between independent lasers

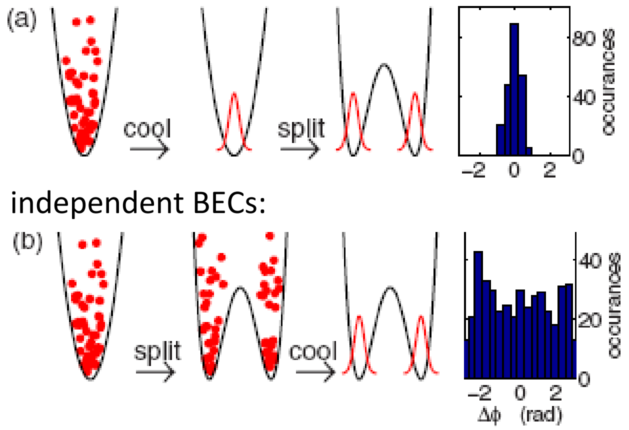
Interference in BEC

many particle coherence

atom chip experiment

coherent splitting of BEC:

independent BECs:



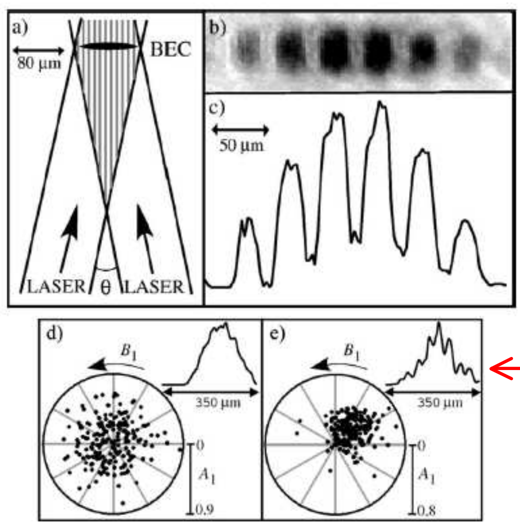
splitting by RF-field

phase difference, shot to shot

+ number-phase uncertainty considerations (why relative phase exists?)

Schmiedmayer, Nat. Phys. 2, 710 (2006)
Schmiedmayer, Nat. Phys. 1, 57 (2005)

30 BECs



density profiles

200 shots

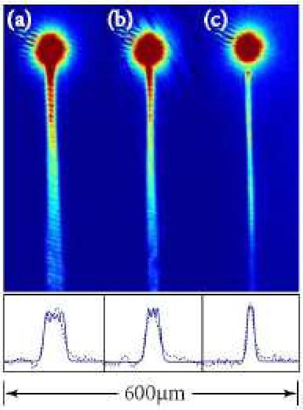
Dalibard, PRL **93**, 180403 (2004)

+ similar experiment on atom chip: Ketterle, PRA **72**, 021604 (2005)

Atom laser – properties

	atom "laser"	laser
output	coherent matter waves	coherent EM waves
resonator	trap	mirrors
active medium	thermal cloud of ultracold atoms	gain medium
excitation of the active medium	evaporative cooling	pumping
	stimulated emission of bosons into the same lasing mode	
threshold	critical temperature	pumping threshold
limit	Heisenberg uncertainty	diffraction limited

modes	single mode	many modes possible
modes	lowest mode	high cavity modes
interactions	yes	no
	atoms cannot be created	photons can be created
gravity	important	not important
	thermal equilibrium	non-equilibrium



PRA 77 063618 (2008)

beam quality:

- optics:

$$M^2 = \frac{w_{0R}\theta_{0R}}{w_0\theta_0}$$

- atom optics:

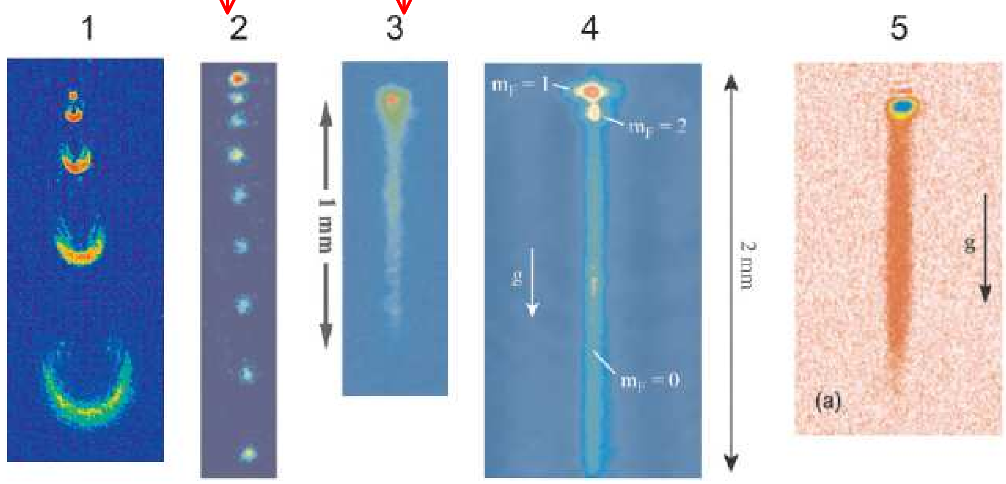
$$M^2 = \frac{2}{\hbar}\Delta x \Delta p_x$$

Atom laser – realizations

gravity-induced tunneling of many BECs in optical lattice
analog of mode locked pulsed laser

MT, optical Raman pulses, overlapping packets, additional momentum kicks from photons

magnetic trap (MT)
strong, short (5 μs)
RF field, same F,
different m_F

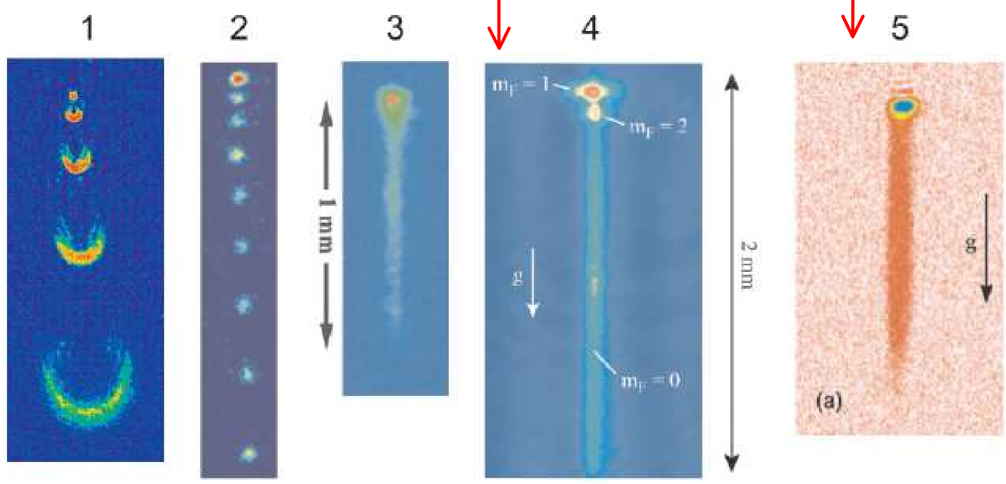


- 1. Ketterle, 1997, MIT
- 2. Kasevich, 1998, Yale
- 3. Phillips, 1998, NIST
- 4. Esslinger, 1999, ETH
- 5. Weitz, 2003, Tübingen

Atom laser – realizations

MT, weak RF field, 15 ms

optical dipole trap, optical potential lowering



- 1. Ketterle, 1997, MIT
- 2. Kasevich, 1998, Yale
- 3. Phillips, 1998, NIST
- 4. Esslinger, 1999, ETH
- 5. Weitz, 2003, Tübingen

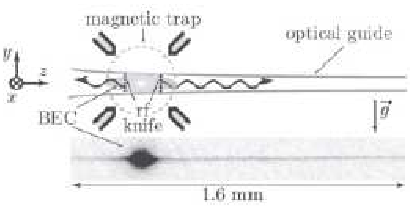
Atom laser – realizations

MT, RF knife, atoms released to an optical guide

optical Raman pulses

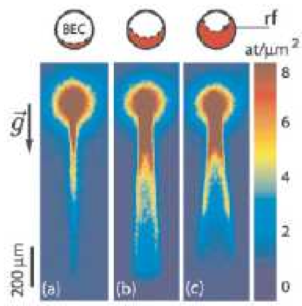
RF knife

6

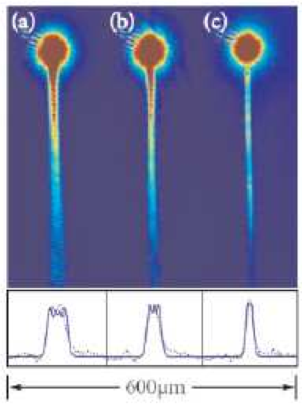


guided beam

7



8

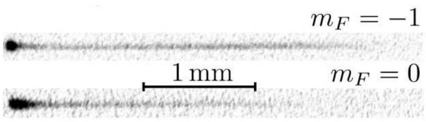


MT, RF knife, differen places
BEC mean field = diverging lens

- 6. Aspect, 2006, Orsay
- 7. Aspect, 2006, Orsay
- 8. Close, 2008, Canberra

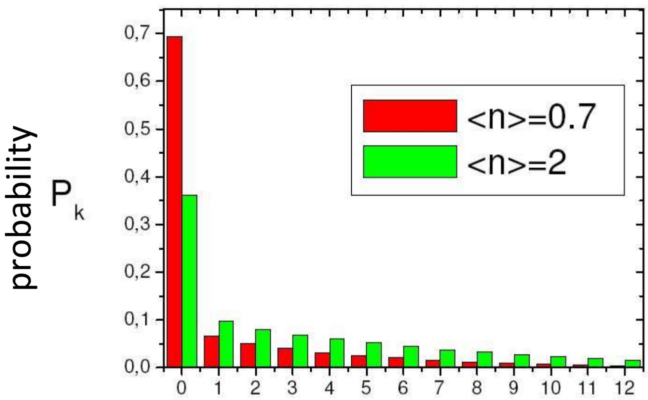
Atom laser – realizations

„universal" atom laser



guided beam

Zeeman sublevel on demand:
m_F = -1 or 0 or 1



transverse mode number

atomic waterfall

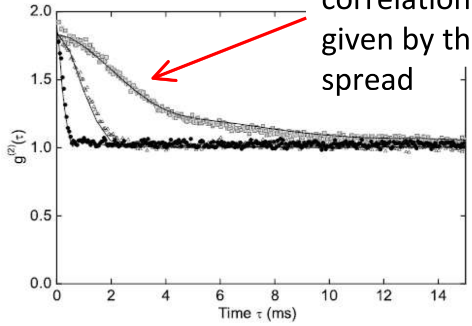
$m_F = 0 \Rightarrow$ physical constants measurements
$m_F \neq 0 \Rightarrow$ 0 magnetic field measurements

Atom laser – properties

a truly laserlike behavior – second order coherence

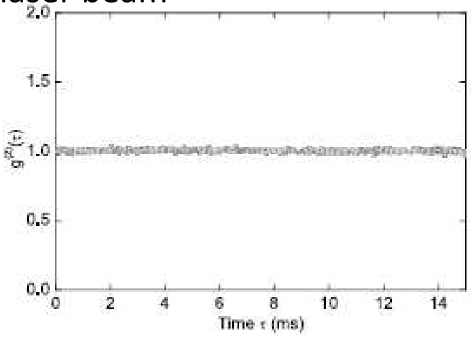
time-resolved counting of single atoms:

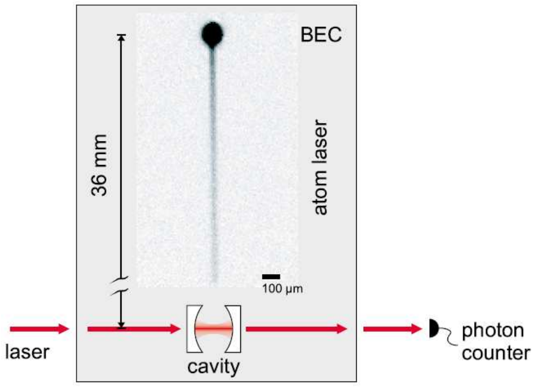
thermal beam



correlation time given by the energy spread

atom laser beam





Hanbury Brown–Twiss type experiment

the arrival time of an atom in the cavity is determined from the arrival times of all atoms the second order correlation is computed: $g^{(2)}(\tau)$

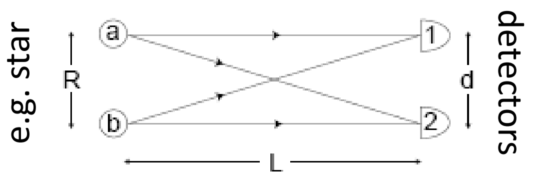
the effect used in high-energy physics

Glauber, PR 130, 2529 (1963)

Esslinger, PRL **95**, 090404 (2005)

Atom laser – properties

classical picture of HBT experiment:



$$A_1 = \frac{1}{L}\left(\alpha e^{ikr_{1a}+i\phi_a} + \beta e^{ikr_{1b}+i\phi_b}\right)$$ at detector 1

$$I_1 = \frac{1}{L^2}\left(|\alpha|^2 + |\beta|^2 + \alpha^*\beta e^{i(k(r_{1b}-r_{1a})+\phi_b-\phi_a)} + \right.$$
$$\left. + \alpha\beta^* e^{-i(k(r_{1b}-r_{1a})+\phi_b-\phi_a)}\right)$$

$$\langle I_1\rangle = \langle I_2\rangle = \frac{1}{L^2}\left(\langle|\alpha|^2\rangle + \langle|\beta|^2\rangle\right)$$

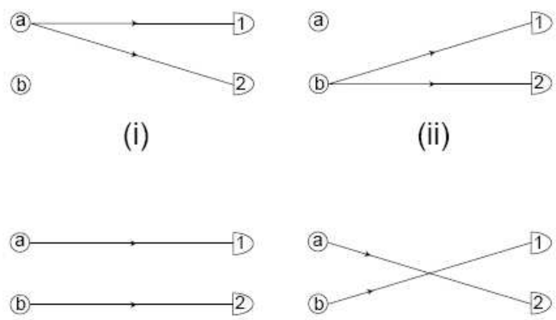
$$\langle I_1 I_2\rangle = \langle I_1\rangle\langle I_2\rangle + \frac{2}{L^4}|\alpha|^2|\beta|^2\cos\left(k(r_{1a} - r_{2a} - r_{1b} + r_{2b})\right)$$

$$g^{(2)}(\tau) = \frac{\langle I_1 I_2\rangle}{\langle I_1\rangle\langle I_2\rangle}$$

function of d

$\Rightarrow$ R/L (angular size)

quantum picture of HBT experiment:



symmetry of the wave function of the pair of bosonic particles

Acta. Phys. Pol. 29, 1839 (1998)

Atom laser – properties

atom lasers – advantages and disadvantages…

BEC:
- relative atom velocity 0.1 mm/s
- macroscopic coherence
- atoms interact ⇒ mean field interactions ⇒ chemical potential
- mean field energy > ground-state energy of the trap

mean field energy dominates in free expansion
- but still the velocity spread < photon recoil velocity
- it is easy to use in interferometers based on photon recoil paths separation

atom laser:
- bright source of atoms, but limited total flux (small cross sectional area)
- coherence length on the order of BEC size
- phase fluctuations < 700 Hz (Hänsch, PRL **87**, 160404 2001)
- chemical potential changes during outcoupling

INNOWACYJNA GOSPODARKA
NARODOWA STRATEGIA SPÓJNOŚCI

UNIA EUROPEJSKA
EUROPEJSKI FUNDUSZ
ROZWOJU REGIONALNEGO

Outlook

atom optics – a flexible and precise tool for atom interferometers

• accelerating and decelerating atoms and molecules in "light crystals" and higher-order beam splitters will enable coherence to be maintained between wave function components with relative velocities of m/s! => far greater precision with much greater separation of the arms and much greater enclosed area

bigger and better interferometers will be applied to fundamental problems in gravity and quantum mechanics, e.g.:

• gravitational potential in experiments analogous to the scalar Aharonov-Bohm effect,

• in orbit around the Earth: fundamental gravitational measurements

• better measurements of G, gravitational fields, gravitational gradients, and in gyroscopes - navigation, geodesy, fine structure value

increased fluxes and longer interaction times, but! reduction of the atom densities necessary to suppress atom-atom interactions

atomic and molecular physics – measurements with higher precision

measurements of fundamental atom-surface interactions:

• the van der Waals and Casimir potentials

• study of the temporal and spatial behavior of EM fields close to the surface => w new probes of surface structure

Outlook

applications in quantum information science:

• how to characterize, control, and use entanglement and correlations in atomic ensembles: preparation of the ensembles in complex quantum states with high fidelity, and their characterization - with decoherence greatly reduced or with error-correction methods

search for fundamental short-range interactions:

• finding limits on non-Newtonian gravitational potentials at the micrometer length scale

study of many-atom systems and of atoms in lattices that model condensed matter:

• e.g. atomic interference as an indication of tunneling

study of phase transitions in mesoscopic ensembles:

• they are too large to permit full quantum calculations, but too small for the thermodynamic description, detailed look at the thermodynamic border

nanolitography – surface manipulation

Summary

atom lasers are at their early stage of development, however many interesting properties have been measured, like:

- long spatial correlations in BECs,
- first and second order coherence,
- temporal coherence

atom interferometers have been used and are a promising tool in precise measurements of physical constants, acceleration, gravitational field

Współczesne eksperymenty z zimnymi atomami
część II – atomy przy powierzchniach

Tomasz Kawalec
Instytut Fizyki UJ
Zakład Optyki Atomowej

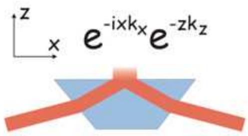
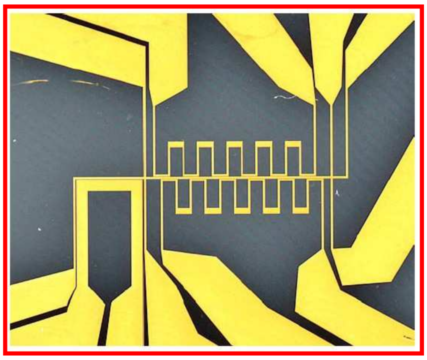
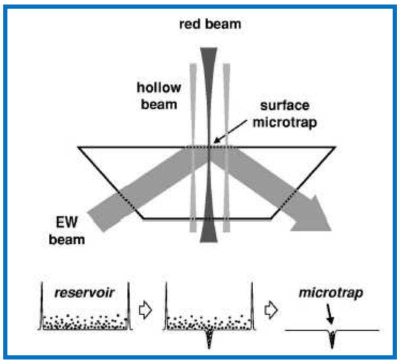


Table of contents

- why surfaces? why (ultra)cold atoms?
- atom-wall interaction
- magnetic devices – atom chips, permanent magnets, main achievments
- optical devices – surface mirrors and traps, main achievments
- outlook – surface devices: dead-end or promising tool?
- cold atoms as a tool in a basic surface science – Casimir-Polder force and quantum reflection





Atom-surface interactions

God made solids, but surfaces were the work of the Devil

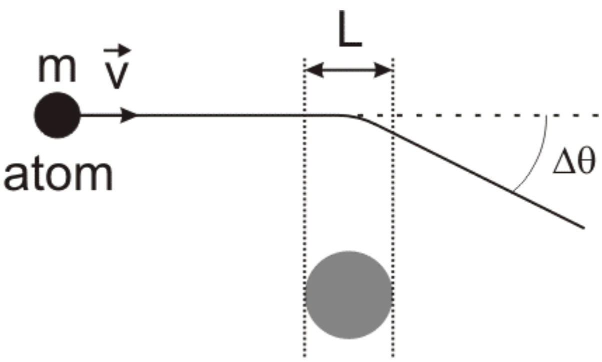
Wolfgang Pauli

why surfaces?

• possibility of testing basic science theories
• nanotechnology applications
• overlap between AMO physics, condensed matter and quantum optics
• may act as a support for wide range of experiments

why cold atoms?

• low velocity
• low velocity spread
• coherent matter waves



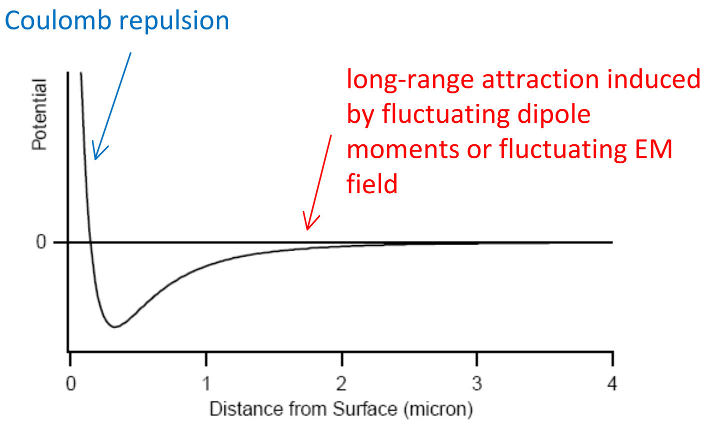
$$\Delta\theta \approx \frac{FL}{mv^2}$$

Atom-surface interactions

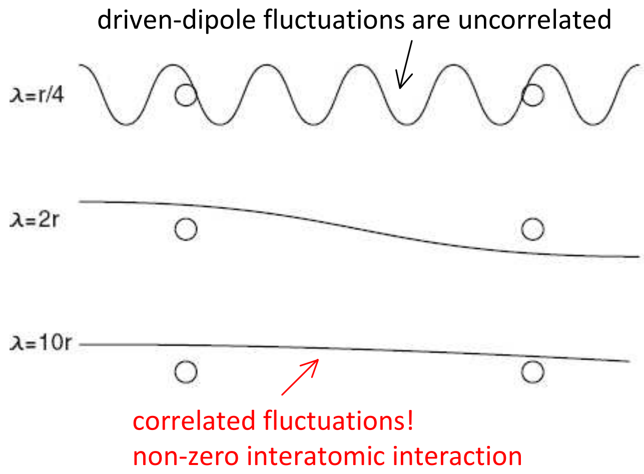
1881: van der Waals predicts existence of the attractive force between atoms and between an atom and a conducting surface

1932: Lennard-Jones describes the interction in a quantitative way (r^{-3})

1948: Casimir and Polder calculate the interaction energy including retardation effects and QED (r^{-4})



relevant wavelengths in atom-atom and atom-wall interaction



Atom-surface interactions

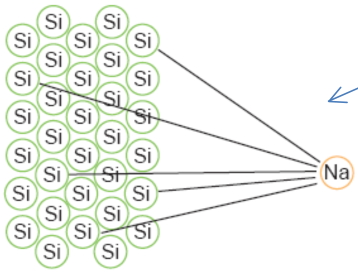
$V_{atom\text{-}atom}(r) = -C_6/R^{-6}$ — a) $r < c/\omega_0$ (atomic dipole moment fluctuations, self reaction)

$V_{\mathrm{atom-atom}}(r) = \hbar\ c\alpha_1\alpha_2/r^7$ — b) $r \gg c/\omega_0$ (EM zero point fluctuations)

$V_{\mathrm{atom-atom}}(r) = \ \alpha_1\alpha_2 k_B T/r^6$ — c) $r \gg c/\omega_0$ and $r \gg \lambda_T$ (thermal photons background)

ω_0 – dominating transition frequency

atom-wall interaction calculation:



wall as a boundary for vacuum field

integration to get atom-wall interaction;
surface structure neglected, but typical distance (at least 100 nm) >> a_0

atom-wall interaction:

a) $-1/r^3$
b) $-1/r^4$
c) $-1/r^3$

e.g.:
Hinds, Phys. Rev. A **41**, 1587 (1990)

Magnetic trapping and guiding

motivation: traps and guides for atoms in the micrometer scale

- high resolution and precision of surface structures → high resolution of trapping potentials
- high potential gradients → high energy separations between energy levels

- quantum engineering
- decoherence
- low-dimentional mesoscopic systems
- BEC beyond mean-field theory
- guides for matter waves
- quantum information technology

Magnetic trapping and guiding

microtraps for neutral atoms

neutral atom manipulation via interactions with external fields:

- magnetic
- electric
- optical

$V_{mag} = -\mu\cdot\mathbf{B} = -g_F\mu_B m_F B$

+ adiabatic approximation

U_B [μK] ~ 67B [Gs] @ $\mu = \mu_B$

$V_{el}(r) = -1/2\ \alpha E^2(r)$

U_{el} [μK] ~ $98E^2$ [V/μm]

atoms in magnetic field:

magnetic moment antiparallel to the B field direction → $V_{mag} > 0$
→ weak- field seeking state

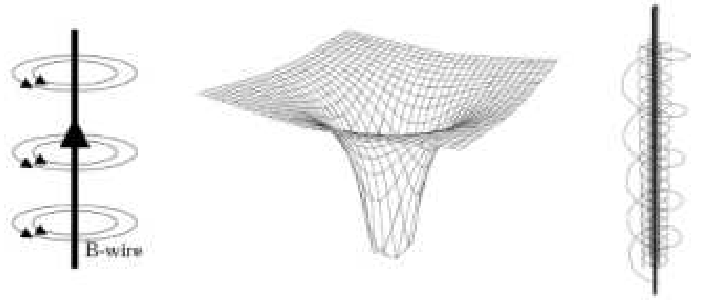
but: Majorana spin flips

magnetic moment parallel to the B field direction → $V_{mag} < 0$
→ strong-field seeking state

but: no local maxima of B in free space

Magnetic trapping and guiding

atoms in magnetic field:



Kepler guide

$V_{mag} \sim -I_w \, 1/r \, \mathbf{e}_\phi \cdot \mu$

(strong-field seeker)

proposed in 1933:

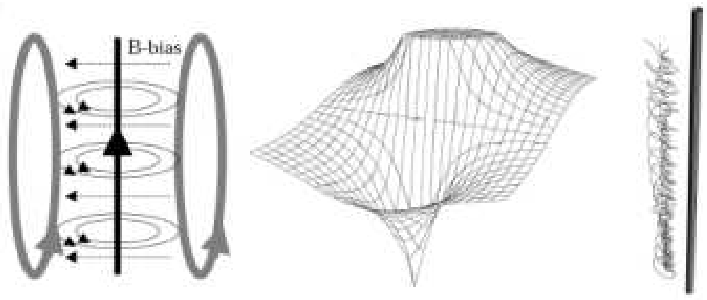
Side guide

$r_0 \sim I_w/B_b$ $dB/dr \sim B_b^2/I_w \sim B_b/r_0$

$\omega \sim B_b$

(weak-field seeker)

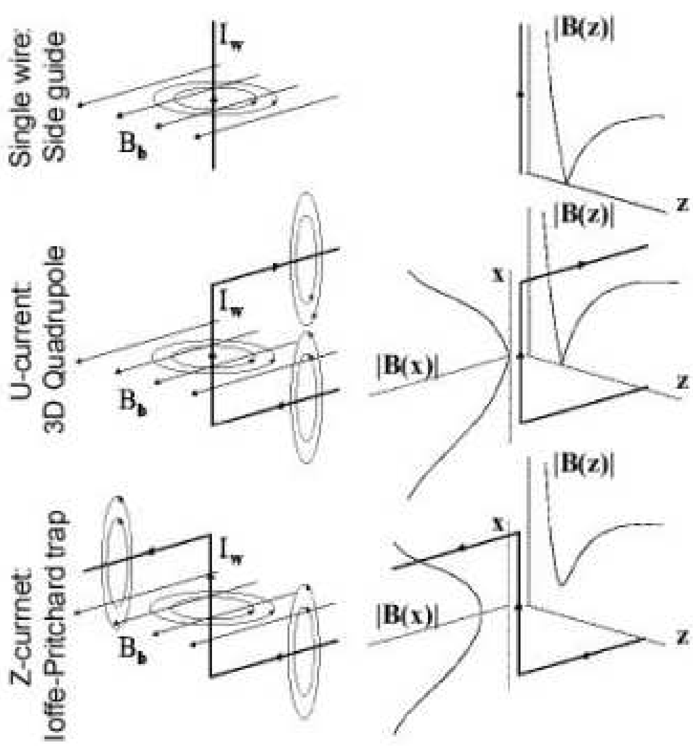
r_0 – distance between wire and the B field minimum

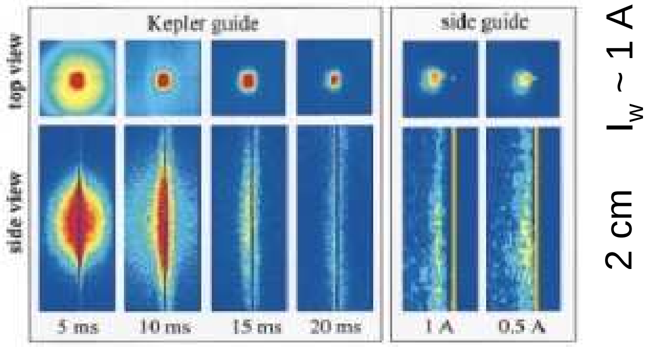


Schmiedmayer, Adv. At. Mol. Opt. Phys. **48**, 263 (2002) – this and next slides

Magnetic trapping and guiding

atom guiding





3D

$B_{min} = 0$
no matter what the direction of the bias field is

Ioffe-Pritchard trap
$B_{min} \neq 0$
for some directions of the bias field

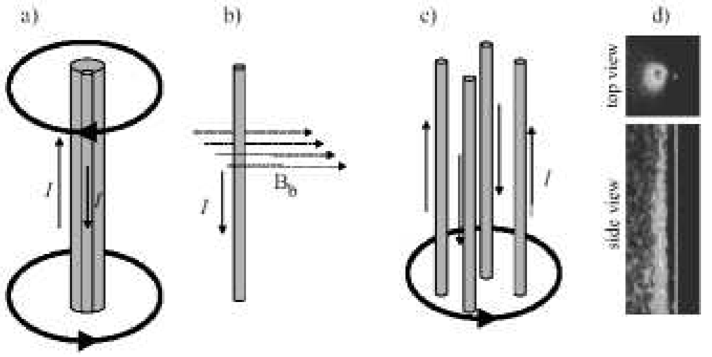
U and Z wires provide „endcaps"

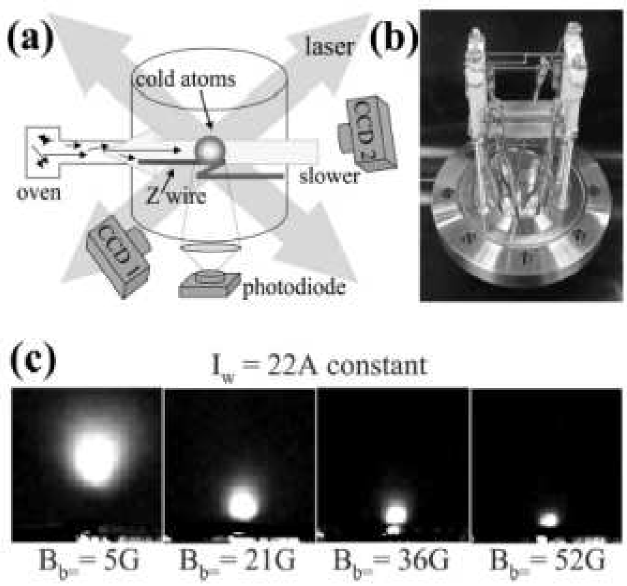
Magnetic trapping and guiding

- first experiments – beginning of 90' – focused on atom guiding along the wire and investigation of simple trap geometries

• typical currents: up to 20 A
• loading efficiency from MOT: up to 40%

weak field seeking traps





bent wire trap →

Magnetic trapping and guiding

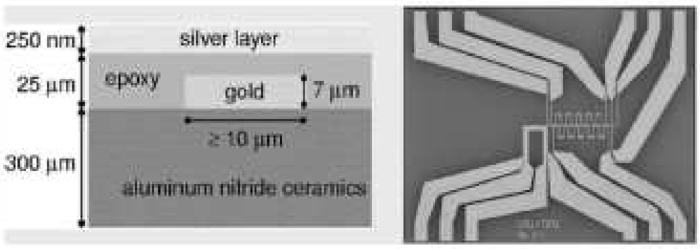
- experiments with free wires led to the construction of surface micro devices – atom chips

Advantages over free wires:

- ➢ greater stiffness
- ➢ greater current densities
- ➢ better heat removal
- ➢ stronger atom confinement (< 10 nm)

Problems:

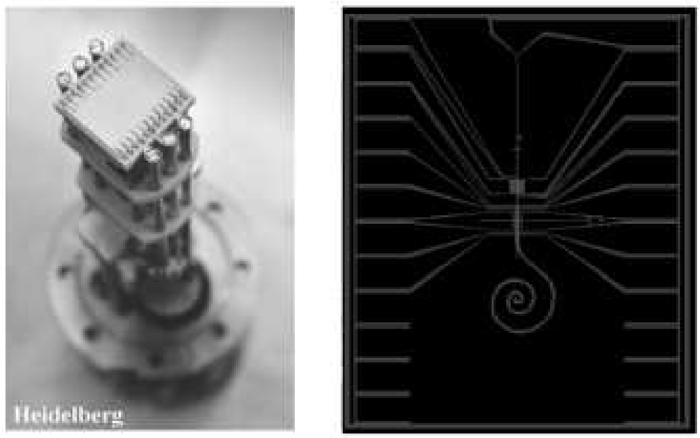
- ➢ non-linear current flows
- ➢ van der Waals type forces
- ➢ roughness at nano-scale



(electroplating)

close view at atom chips

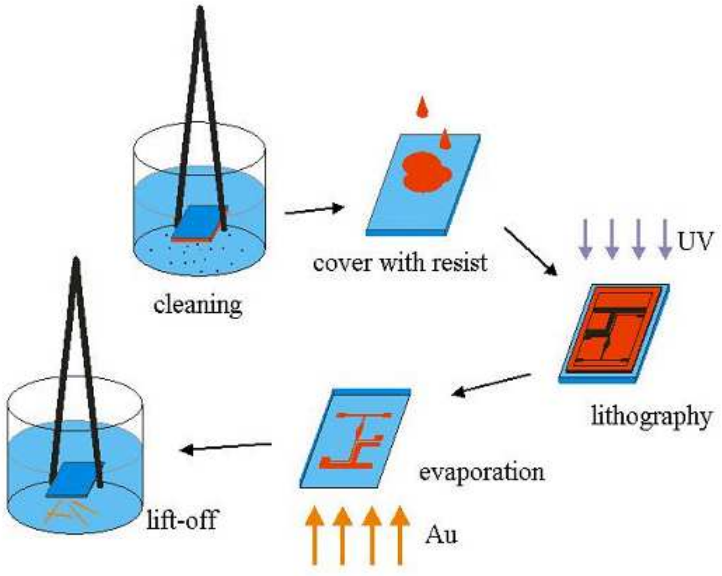
Hänsch, Phys. Rev. Lett. **86**, 608 (2001)

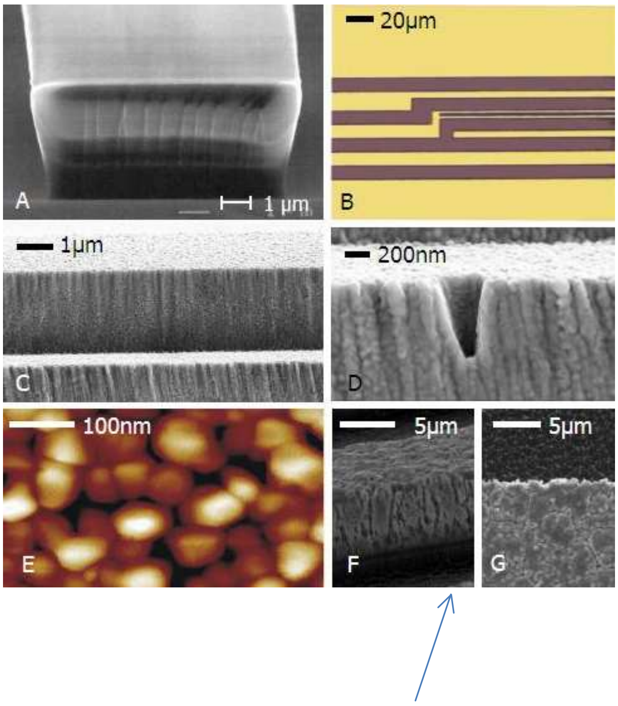


(nanofabrication)

Magnetic trapping and guiding

nanofabrication:





Aspect, Phys. Rev. A **70**, 043629 (2004)
galvanic method (electroplating)

Magnetic trapping and guiding

Exemplary values for F=2, mF=2 Rb atoms in single wire side guide with small Ioffe-Pritchard field (B_{IP}) along the wire to suppress spin flips and to get harmonic potential close to the bottom of the trap

Atom	Wire current [mA]	Bias fields		Potential			Ground state		
		B_b [G]	B_{ip} [G]	Depth [mK]	Distance [µm]	Gradient [kG/cm]	Frequency [kHz]	Size [nm]	Lifetime [ms]
Rb	1000	80	1	5.4	25	32	41	53	>1000
Rb	500	200	4	13	5	400	250	21	>1000
Rb	200	400	20	27	1	4000	1100	10	>1000
Rb	1000	2000	50	130	1	20000	3600	6	>1000

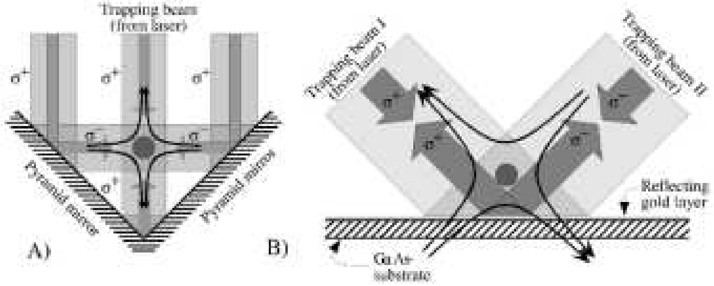
for comparison e.g.:
0.010 kG/cm in a MOT
2 kG/cm in a magnetic trap

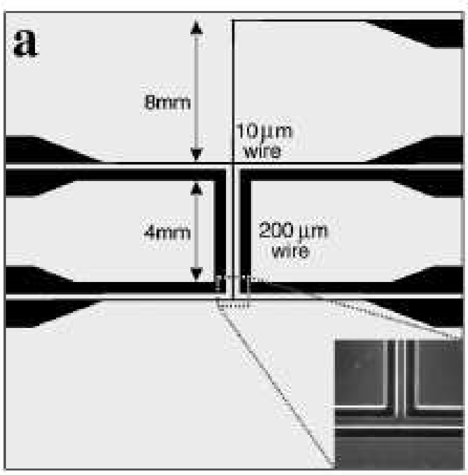
Magnetic trapping and guiding

Atom chip loading:

- cold atoms transport to the μtrap
- further cooling and trapping close to μtrap

mirror MOT
pyramid MOT

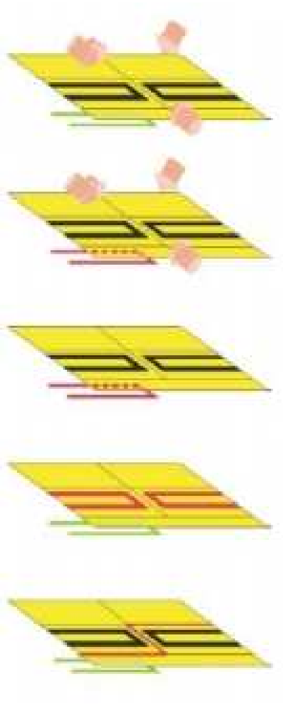




sketch of a μtrap

Magnetic trapping and guiding

gradual field swiching:



10^8 ^{7}Li atoms, a few mm over the surface

switching off MOT coils
switching on U field below the surface (up to 16 A)
switching on bias field (8 Gs)

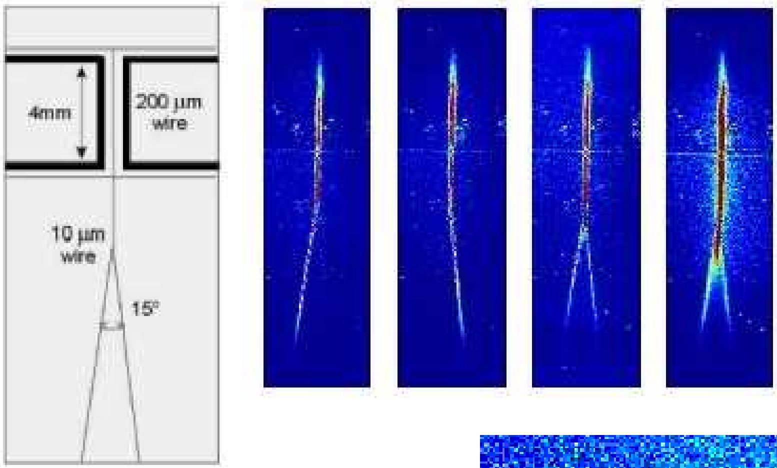
switching off laser beams
increasing bias field (19 Gs)

switching on U fields on the surface (2 A)
switching off U field below the surface
atoms are several hundreds μm above the surface

switching on Z fields
switching off U fields
increasing bias field (40 Gs)

lifetime: several tens of ms
height over surface: a few μm
transverse confinement: 100 nm
trap frequency: $\omega = 2\pi$ 200 kHz

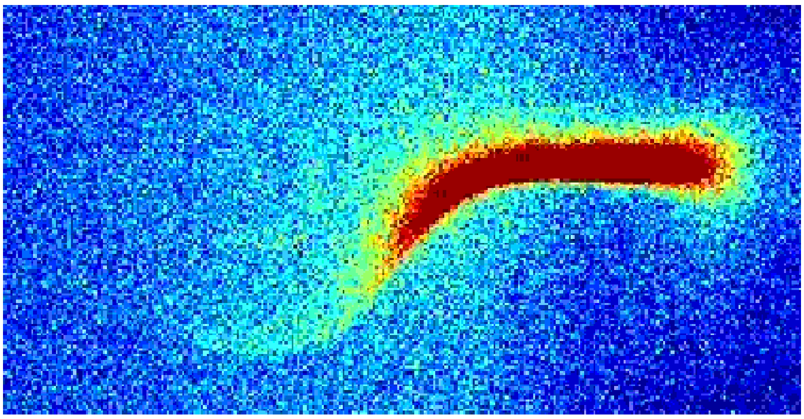
Magnetic trapping and guiding



Schmiedmayer, Phys. Rev. Lett. **85,** 5483 (2000)

← beam splitter (not coherent!)

atom guide →



Magnetic trapping and guiding

atom chips – a toolbox for physicists:
• atom traps
• transport of atoms and atom guiding
• beam splitters
• interferometers

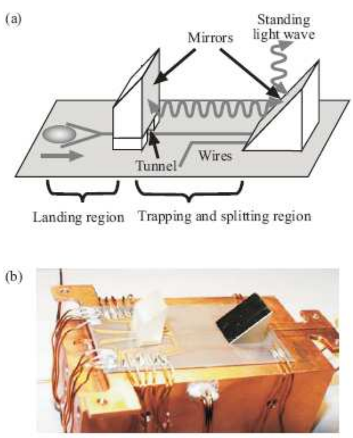
• BEC
first groups:

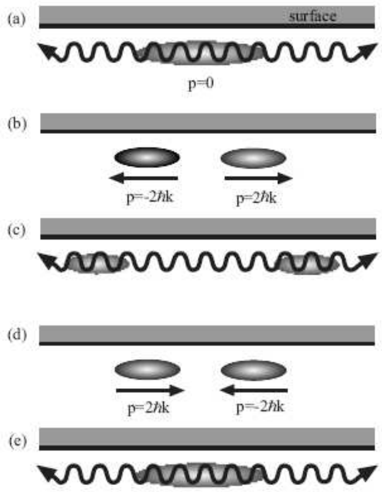
making BEC on a chip – somehow easier than in a free space because of very steep potentials leading to a high collision rate and short evaporative cooling time

on-chip condensation:
Zimmermann, Phys. Rev. Lett. **87**, 230401 (2001)
Hänsch, Reichel, Nature **413**, 498 (2001)
Reichel, J. Appl. Phys. B **74**, 469 (2002)

external condensation + transport to the chip:
Ketterle, Pritchard, Phys. Rev. Lett. **89**, 040401 (2002)

Magnetic trapping and guiding





splitting pulse

+ magnetic field gradient

reflecting pulse

recombining pulse

standing wave pulses

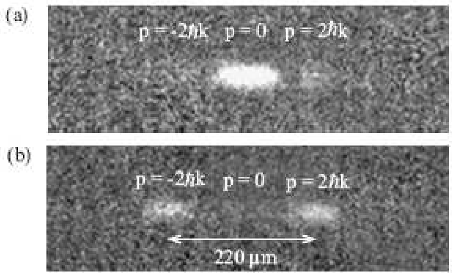


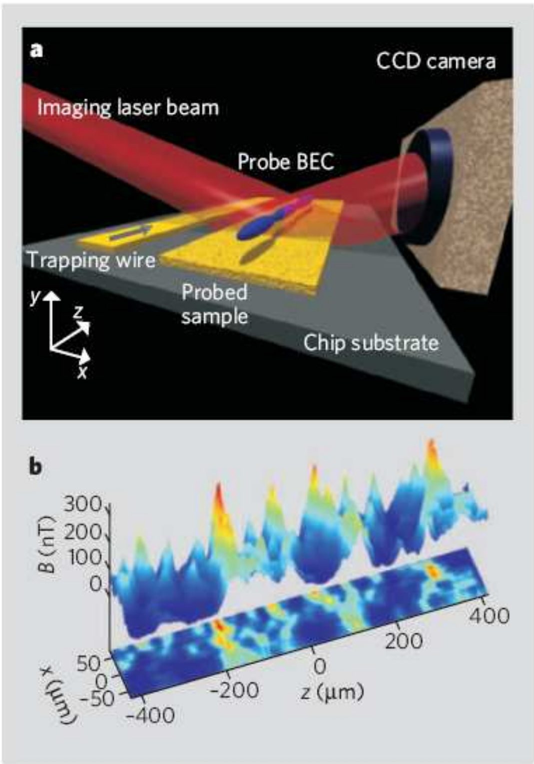
FIG. 3. Interference pattern of (a) phase shift = $2n\pi$ and (b) phase shift = $(2n+1)\pi$. The absorption images are taken 10 ms after the recombining pulse.

Michelson-type interferometer
splitting and recombination at the same place

Cornell, Phys. Rev. Lett. 94, 090405 (2005)

Magnetic trapping and guiding

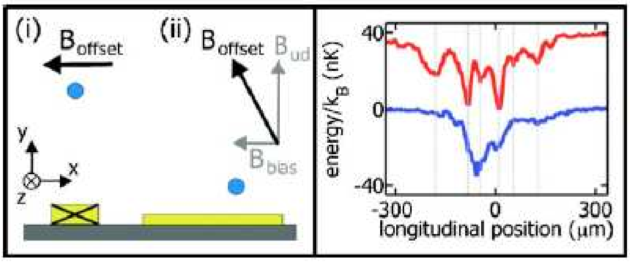
How to turn disadvantages to advantages?
magnetic field sensing!



spatial resolution: 3 µm
a few µm above the conductor surface
nT sensitivity

BEC aspect ratio: a few thousands (1 mm long)

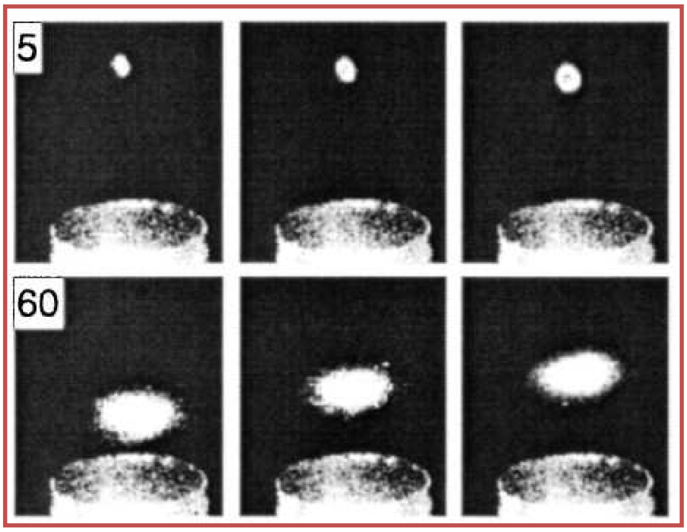
main wire test wire



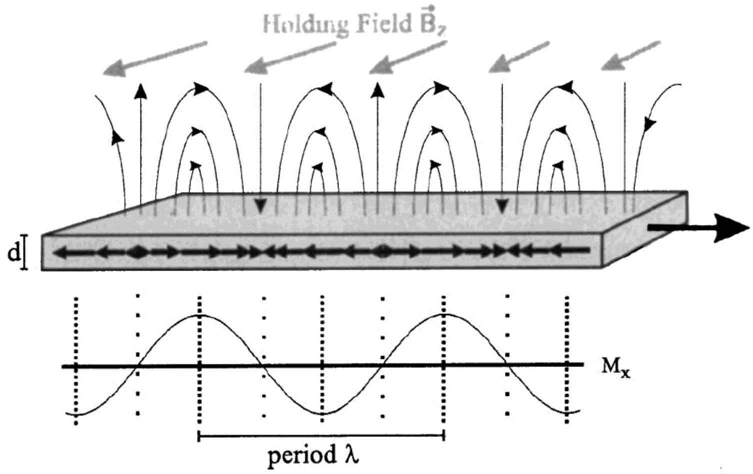
Schmiedmayer, Nature **435**, 440 (2005)
Schmiedmayer, Appl. Phys. Lett. **88**, 264103 (2006)

Magnetic trapping and guiding

flat or concave mirrors
no currents
domains ⇒ roughness
500 G on the tape surface



PRL **82**, 468 (1999)



$$\mathbf{M} = M_0 \cos(kx)\hat{\mathbf{x}}$$
$$B_0 e^{-kz}[-\cos(kx)\hat{\mathbf{x}} + \sin(kx)\hat{\mathbf{z}}]$$

PRA **63**, 053405 (2001)

Magnetic trapping and guiding

destructive factors in tom chips:

- trapped atom losses
- heating of atomic clouds
- decoherence

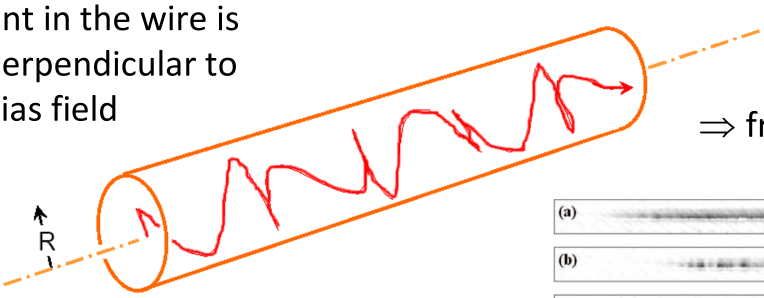
✓ escape through the potential barrier
✓ Majorana spin flips
✓ noise induced spin flips
✓ collisional losses
✓ tunneling towards the surface

- thermal and technical fluctuations
- interactions with light

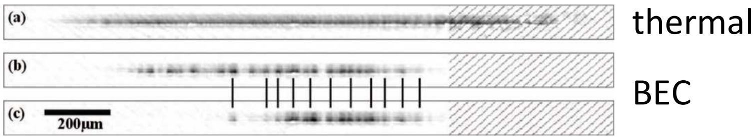
➢ coupling between atomic cloud and atom chip

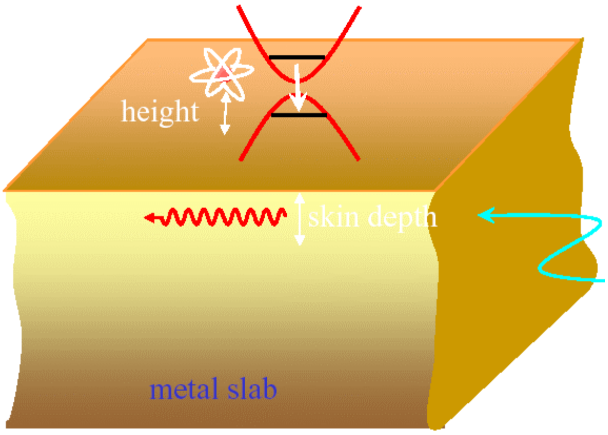
Magnetic trapping and guiding

current in the wire is not perpendicular to the bias field



⇒ fragmentation of the BEC along the wire





⇒ spin flips, heating, losses

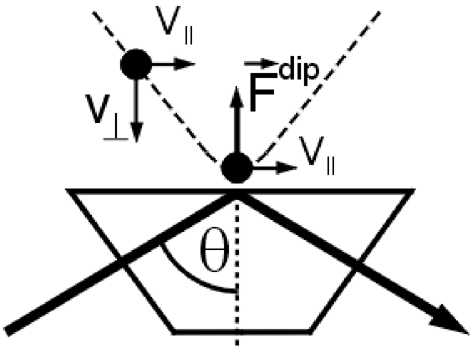
how to reduce spin flipping:
dielectric or thin conductor

Optical methods

evanescent wave mirror for atoms
first proposal: R.J. Cook i R.K. Hill, 1982
first experiments:
Letokhov, Phys. Rev. Lett. 60, 2137 (1988) – for beam of thermal atoms
Chu, Opt. Lett. 15, 607 (1990) – for atoms from MOT

$$I(\vec{r}) = I_0 \exp\left(-\frac{x^2}{w^2/\cos^2\theta}\right) \exp\left(-\frac{y^2}{w^2}\right) \exp\left(-\frac{2z}{d}\right)$$

evanescent wave

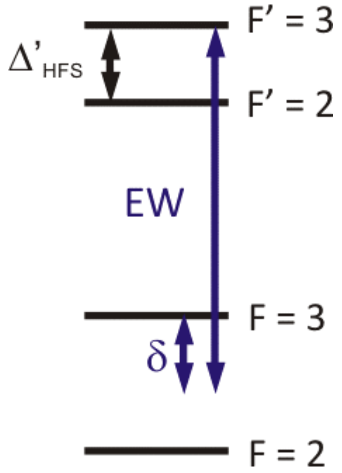


$$U^{dip}(\vec{r}) = \frac{3\pi c^2}{2\omega_0^3}\frac{\Gamma}{\delta} I(\vec{r})$$

(two-level atom and low saturation)

Optical methods

$$U(z) = U_{dip}(z) + U_g(z) + U_{vdW}(z) \;= U_0 e^{-\frac{2z}{d}} + mgz - \frac{q}{z^3}$$



for alkali atoms:

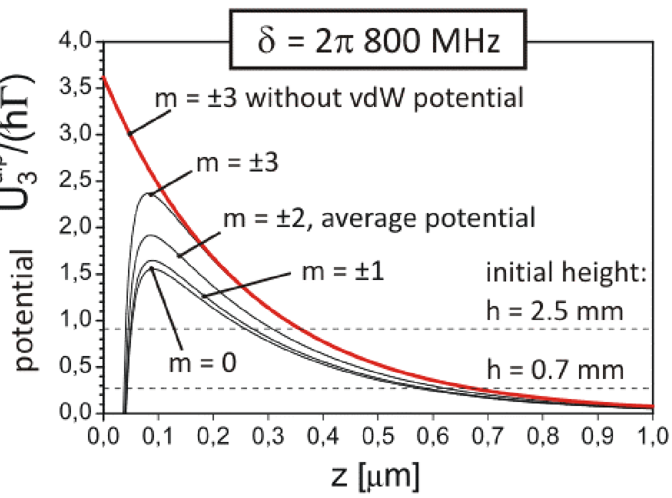
$$U_{Fm}^{dip}(z) = (2J'+1)\frac{3}{4}\frac{\Gamma \pi c^2}{\omega_0^3} I(z) \sum_{F'} \frac{|C_{Fm,F'm}|^2}{\delta_{FF'}}$$

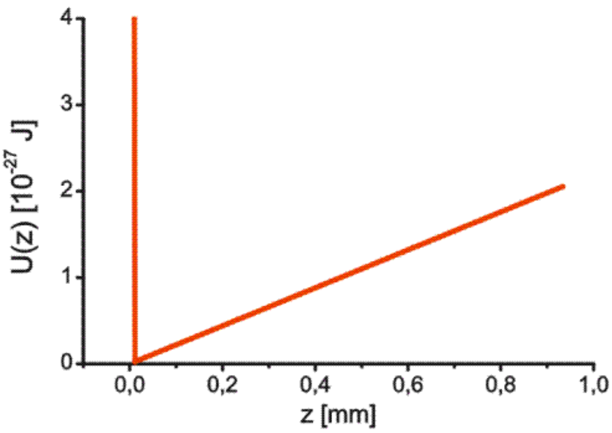
dipole potential depends on the quantum number m

Optical methods

$$U_{vdW} = -\frac{n^2-1}{n^2+1}\frac{1}{64\pi\epsilon_0}\frac{\frac{4}{3}e^2a_0^2\cdot 28.2}{z^3}$$

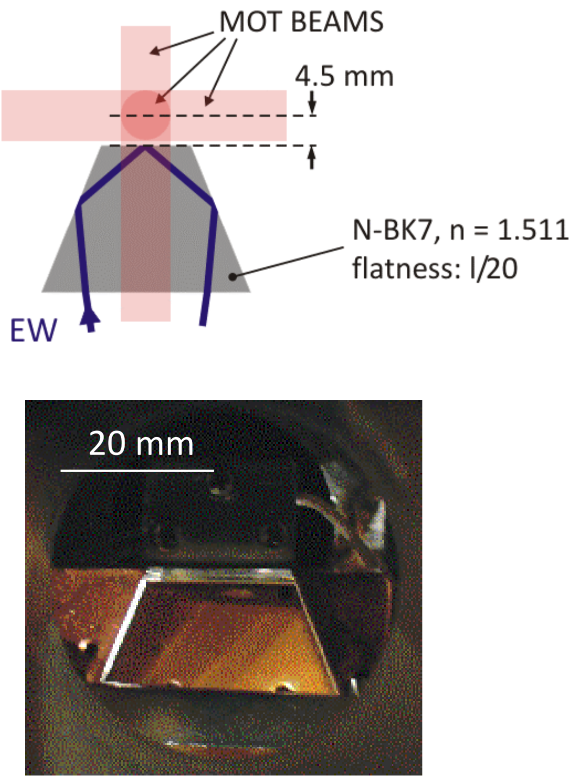
for J ≤ ½ (no quadrupole moments)



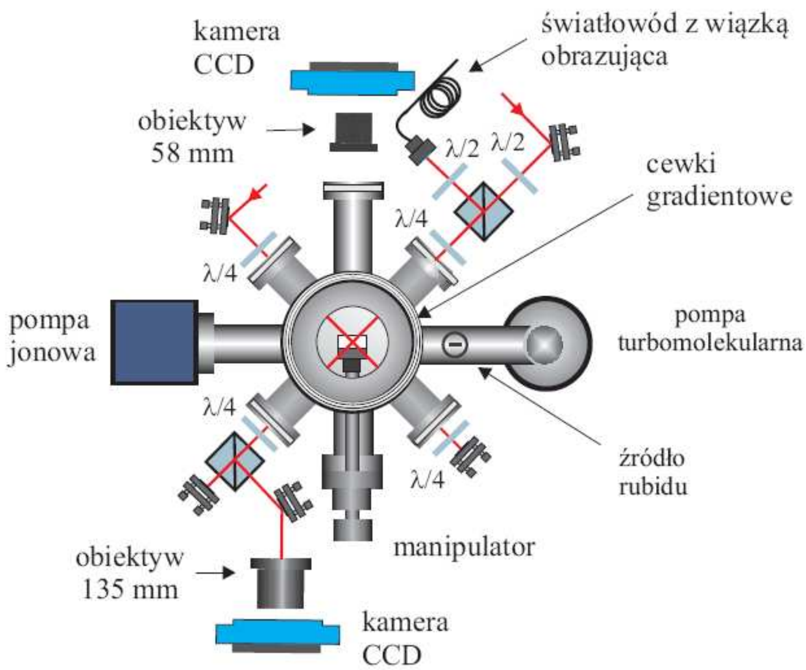


reflection from a „hard wall"

Optical methods

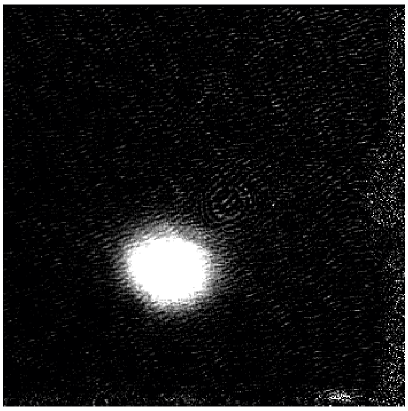


side view

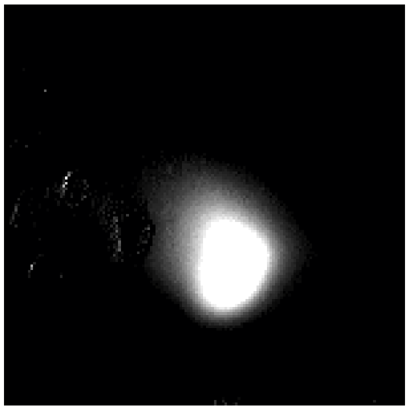


top view

Optical methods



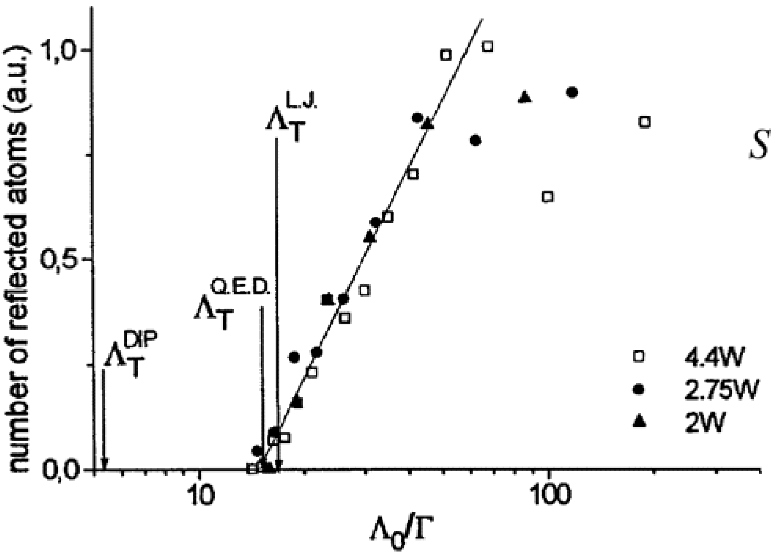
single reflection



double reflection

Optical methods

van der Waals force measurement



$$S = \pi \frac{w_x w_y}{2} \ln\left(\frac{\Lambda_0}{\Lambda_T}\right)$$

Aspect, PRL **77**, 1464 (1996)

Optical methods

decoherence – incoherent photon scattering

$$U^{dip}(\vec{r}) = \frac{3\pi c^2}{2\omega_0^3}\frac{\Gamma}{\delta}I(\vec{r}) \qquad \Gamma^{sp}(\vec{r}) = \frac{3\pi c^2}{2\hbar\omega_0^3}\left(\frac{\Gamma}{\delta}\right)^2 I(\vec{r})$$

$$p^{sp} = \int_{-\infty}^{\infty} \Gamma^{sp}(t)dt \qquad \frac{m}{2}\left(\frac{dz}{dt}\right)^2 + U^{dip}(z) = E_\perp$$

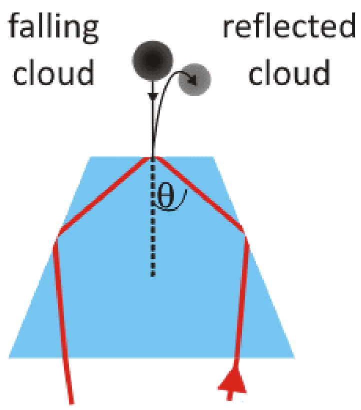
$$U_{dip}(z) = \frac{\hbar\delta}{2}\ln\left(1 + \frac{\frac{\Omega_1^2(z)}{2}}{\delta^2 + \frac{\Gamma^2}{4}}\right) \qquad \Gamma_{sp}(z) = \frac{\Gamma}{2}\frac{\frac{I(z)}{I_S}}{1 + \left(\frac{2\delta}{\Gamma}\right)^2 + \frac{I(z)}{I_S}}$$

two-level atom + saturation

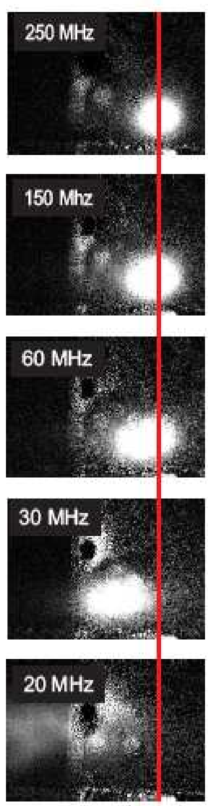
$$p^{sp} = \frac{md}{\hbar}\frac{\Gamma}{\delta}v_\perp$$

Optical methods

decoherence – incoherent photon scattering – radiation pressure



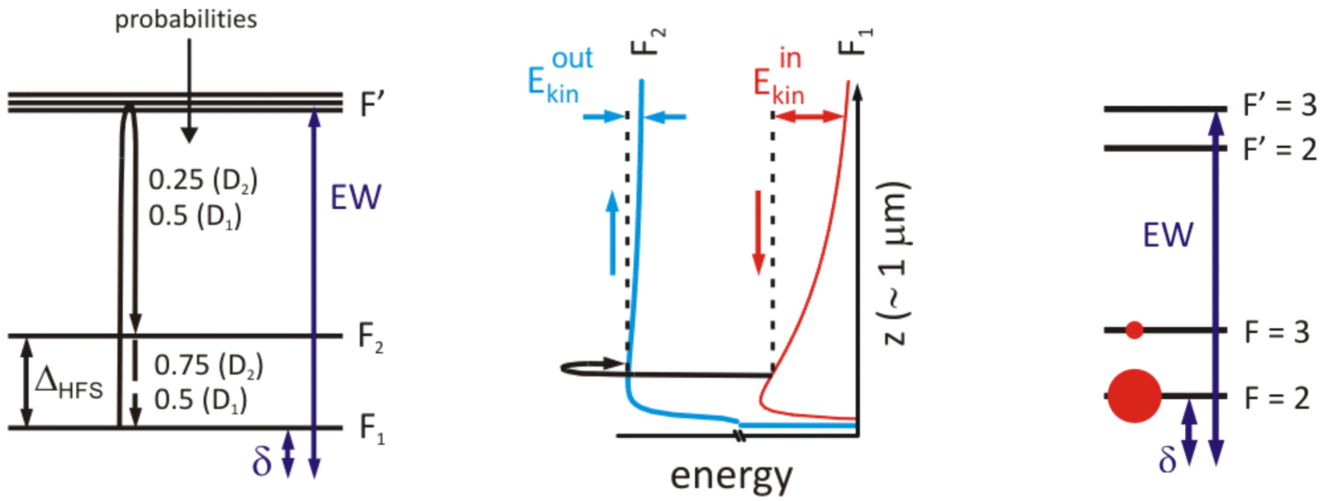
$$p^{sp} = \frac{md}{\hbar}\frac{\Gamma}{\delta}v_{\perp}$$



Optical methods

photon scattering may be usefull – Sisyphus cooling

proposed by:

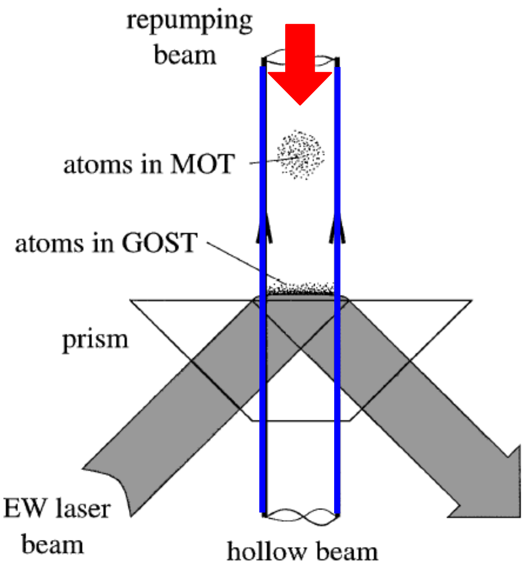


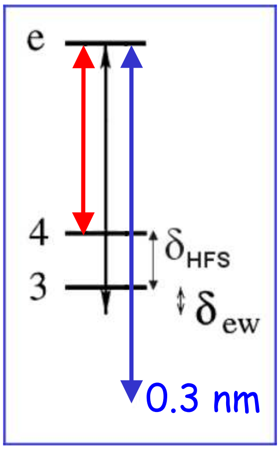
atoms climb up the high mountain but roll down the small hill...

cooling efficiency for single succesful inelastic reflection:

$$\frac{\Delta E_\perp}{E_\perp} = \frac{2}{3}\frac{\Delta_{HFS}}{\delta + \Delta_{HFS}} \approx 0.47$$

Optical methods





T = 3 μK

450 reflections/s

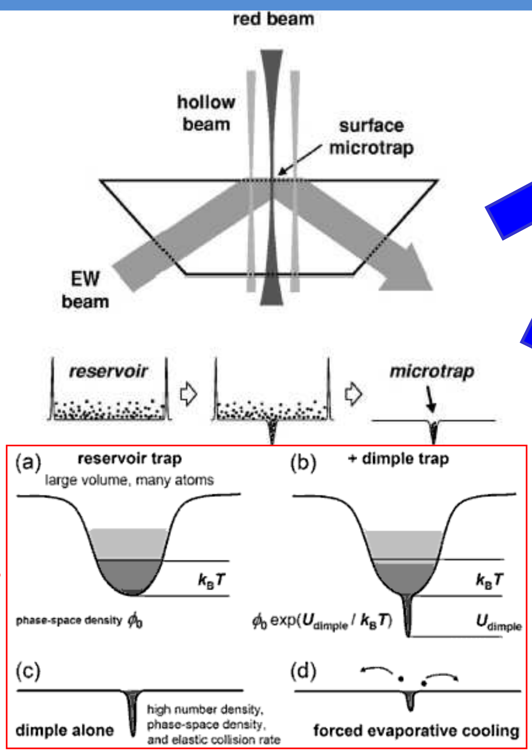
10000 reflections

cooling time ~ 2 s

N = 1.5·10^5 atoms

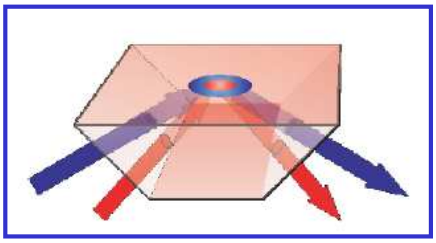
Gravito
Optical
Surface
Trap

Optical methods



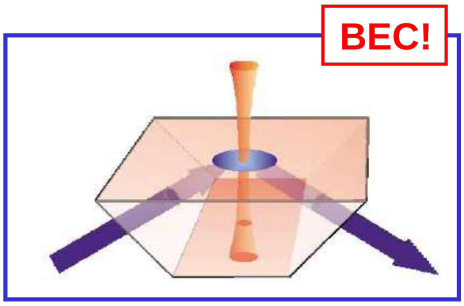
dimple trick!

Ultra-cold Fermi Gases, Course **CLXIV**, 2007



double evanescent wave trap

Grimm, PRL **90**, 173001 (2003)



2D BEC
2400 atoms

Grimm, PRL **92**, 173003 (2004)

- one of the ways of getting 2D degenerate gases
- 2D-BEC – investigation of vortices and solitons (different properties than in 3D)
- investigation of atom-surface interactions

Outlook

- further development of atom chips (including magnets) and multi-layer structures
- integration with other fields like micro-optics and photonics
- manipulation of single atoms – Bose-Einstein condensates or Fermi gases as reservoirs and coherent sources for atoms, atoms extracted on demand, quantum information
- atom optics – matter wave engineering
- investigation of quantum gases in periodic potentials, waveguide potentials with strong radial confinement, disordered potentials, 1D systems, continuous transformation from 3D to 1D with access to the dimensional crossover
- ultracold chemistry on a chip where reactions are controlled by incident matter waves
- a tool to search for fundamental short-range interactions: interferometric measurements of non-Newtonian gravitational potentials at the micrometer length scale

- on the other hand: many efforts to fight against atom-surface interactions and decoherence
- are „free space” devices like optical lattices better?

Outlook

Atom chips with vacuum system seem to be produced commercially.

ColdQuanta

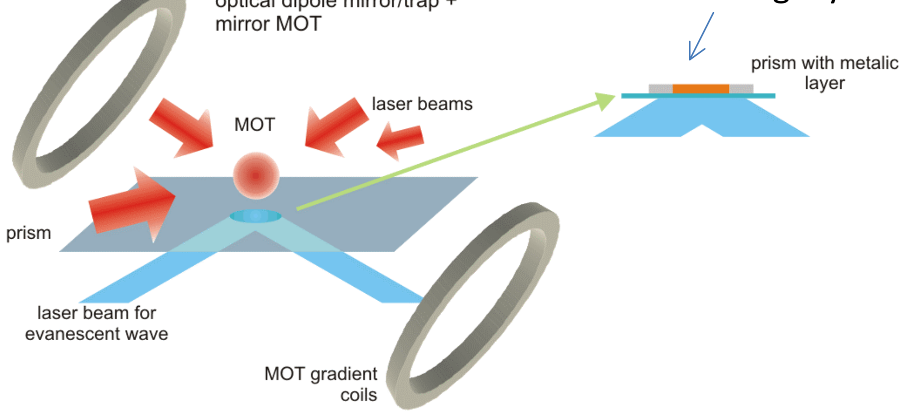
The company is proud of having: Dana Anderson, Theodor Hänsch and Jakob Reichel as members…

Outlook

possible ways of development (1):

surfce plasmon polaritons

Au and Ag layer – structured micropotentials



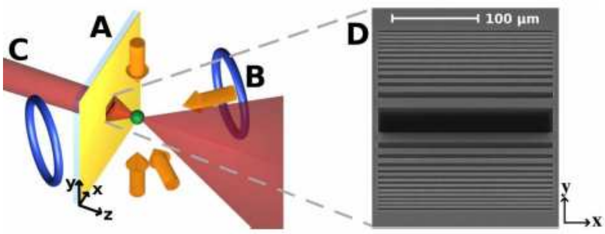
another way: standing wave surface plasmon polaritons

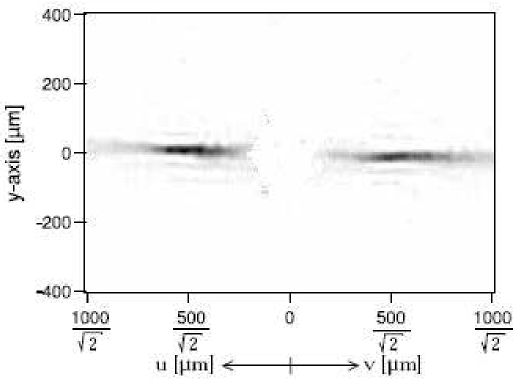
to be constructed in Cracow

Outlook

possible ways of development (2):

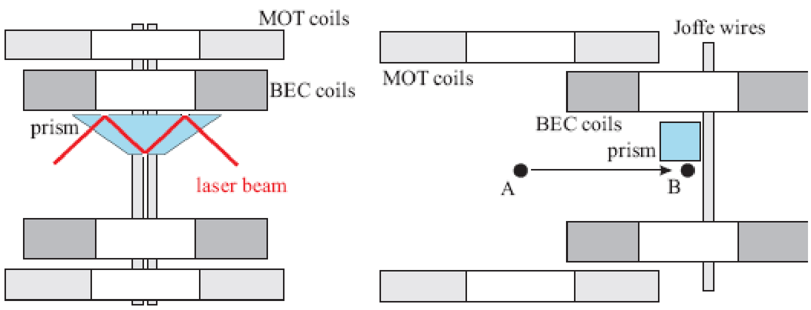
all-optical atom chip



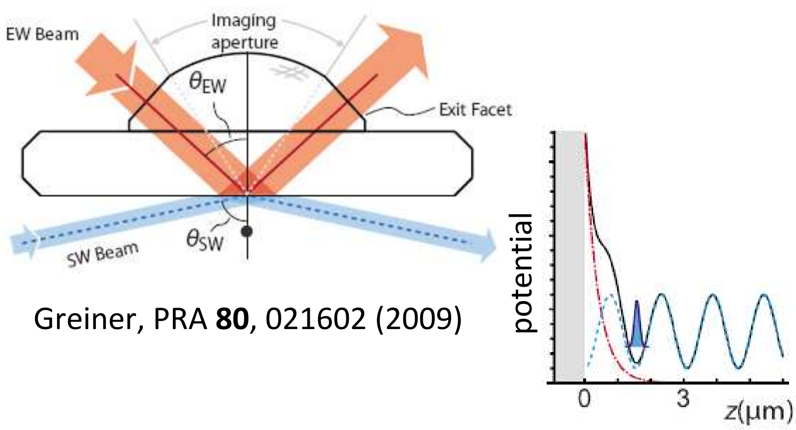


Opt. Express **14**, 12568, (2006)

hybrid traps:
magnetic and optical



Zimmermann, Appl. Phys. B **96**, 275 (2009)



Greiner, PRA **80**, 021602 (2009)

Casimir-Polder potential

Casimir-Polder force measurement: changes in BEC dipole oscillations

$$\gamma_x \equiv \frac{\omega_o - \omega_x}{\omega_o} \simeq \frac{1}{2m\omega_o^2} \langle \partial_x F_{CP} \rangle$$

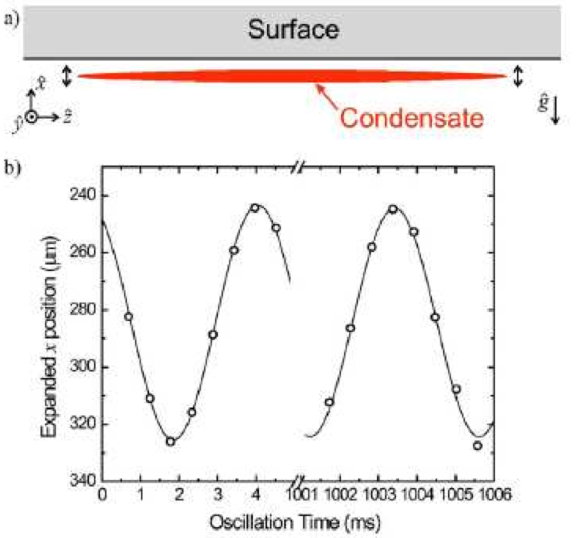


FIG. 1. (Color online) (a) Diagram, to scale, illustrating the aspect ratio of the condensate and typical oscillation position relative to the surface. The coordinate axis orientation and the direction of gravity are also indicated. (b) Typical data showing the radial dipole oscillation after expansion away from the surface.

Cornell, Phys. Rev. A **72**, 033610 (2005)

other experiments:

Aspect, Phys. Rev. Lett. **77**, 1464 (1996) – optical mirror

Shimizu, Phys. Rev. A **71**, 052901 (2005) – grazing angle reflection of Ne* (quantum reflection)

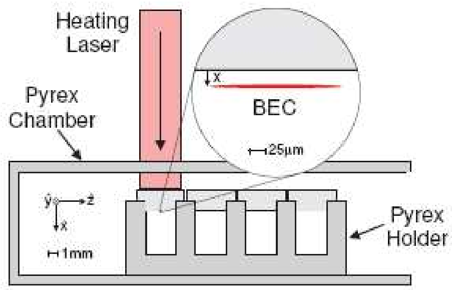
DeKieviet, Phys. Rev. Lett. **91**, 193202 (2003) – grazing angle reflection of ^{3}He (quantum reflection)

Vuletic, Phys. Rev. Lett. **92,** 050404 (2004) – BEC stability on atom chip

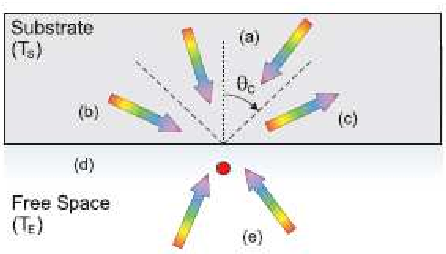
Ketterle, Phys. Rev. Lett. **93**, 223201 (2004) – BEC normal reflection (quantum reflection)

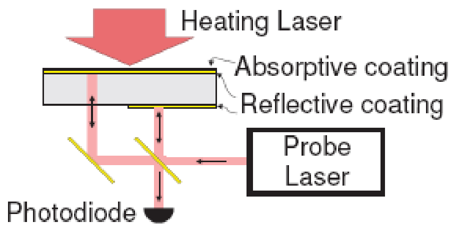
Casimir-Polder potential

Casimir-Polder force measurement:
temperature dependence



thermal fluctuations near the surface:



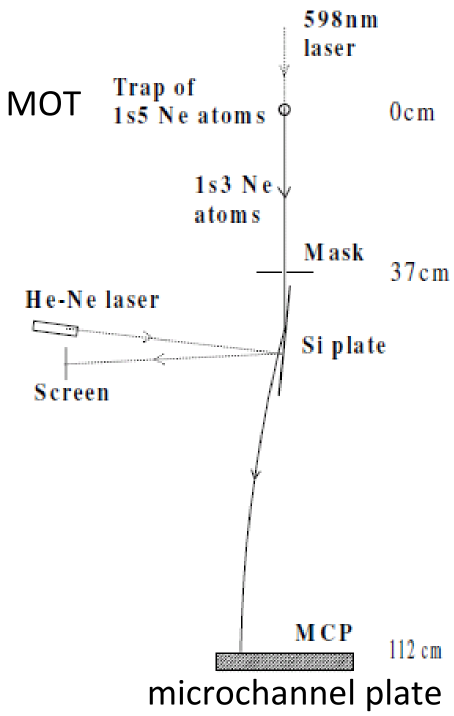


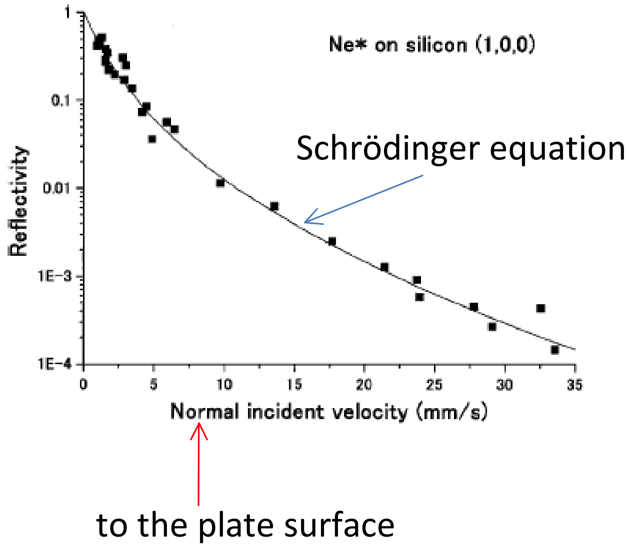
The strength of the C-P force increases by a factor of nearly 3 as the substrate temperature doubles (nonequilibrium conditions).

Cornell, Phys. Rev. Lett. **98**, 063201 (2007)

Quantum reflection

- reflection of ultraslow metastable neon on the silicon and BK7 surface
- 1 mm/s – 3 cm/s
- reflectivity: 30% @ 1 mm/s





Shimizu, Phys. Rev. Lett. **86**, 987 (2001)

Summary

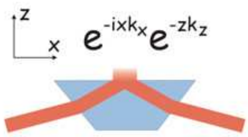
• surfaces may be a convenient platform for atom trapping and manipulation
• there are magnetic, optical, electrical and hybrid methods of confining atoms close to surfaces
• all the methods have their physical and technical limitations

milestones (surfaces as a tool):
• BEC in an atom chip
• 2D BEC in optical surface trap
• atom optics on atom chips, including interferometry

milestones (basic science):
• quantum reflection
• measurement of the Casimir-Polder force

Współczesne doświadczenia z zimnymi atomami
część III – some properties and applications of cold atoms

Tomasz Kawalec
Instytut Fizyki UJ
Zakład Optyki Atomowej

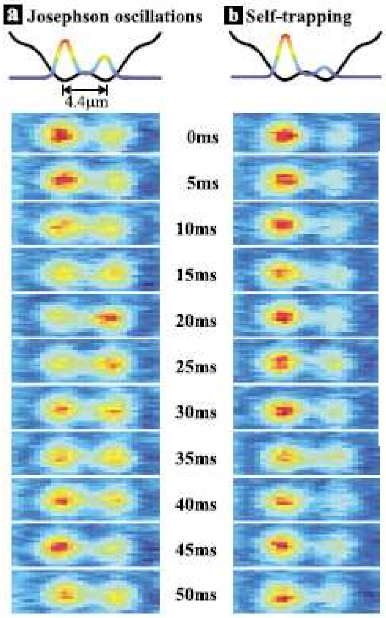


Some experiments

- **basic property of bosonic and fermionic gas**
- **Josephson junction**
- superfluidity, BCS-BEC crossover
- vortices, solitons
- **applications of cold atoms – atomic clock**

Josephson junction

bosonic Josephson junction



$z = (N_l - N_r)/(N_l + N_r)$ relative population

$\phi = \phi_r - \phi_l$ relative phase

$$\dot{z} = -\sqrt{1 - z^2}\sin\phi$$

dynamics

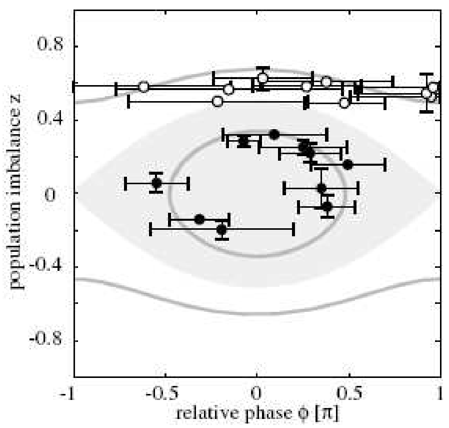
$$\dot{\phi} = \Lambda z + \frac{z}{\sqrt{1 - z^2}}\cos\phi$$

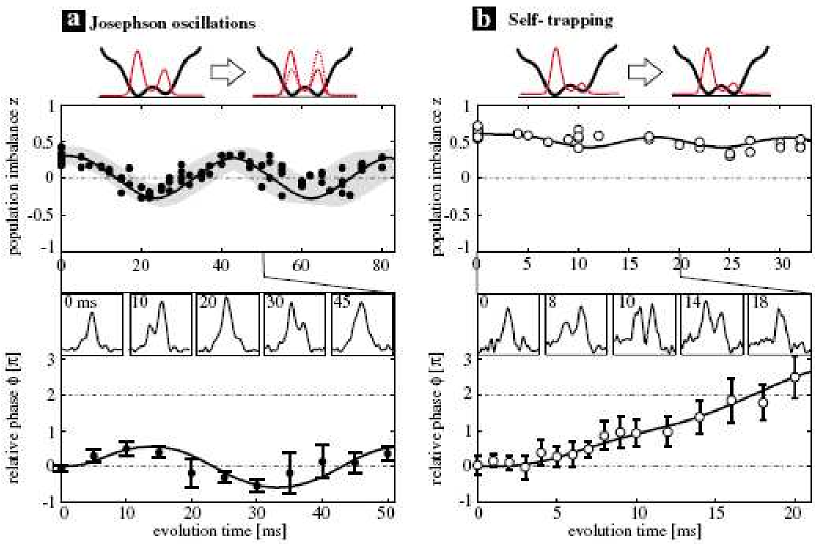
analogy: mechanical nonrigid pendulum:
tilt angle ϕ and angular momentum z and length sqrt(1-z^2)

Oberthaler, PRL **95**, 010402 (2005)

Josephson junction

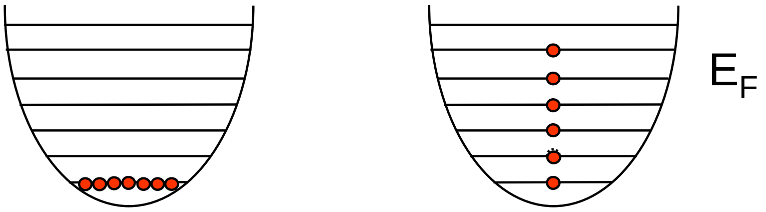
bosonic Josephson junction

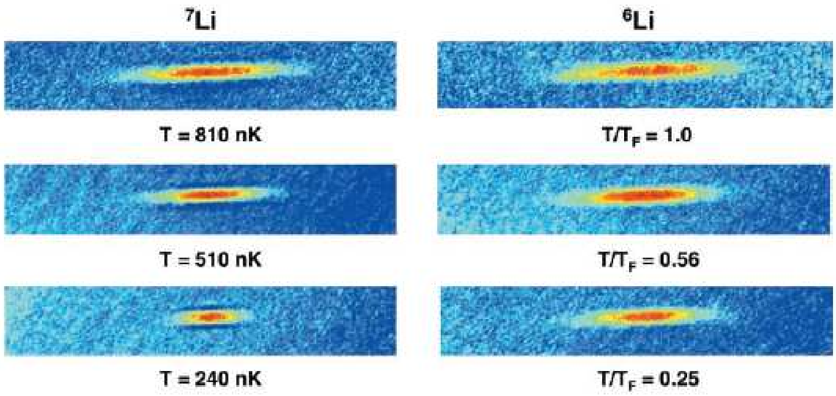


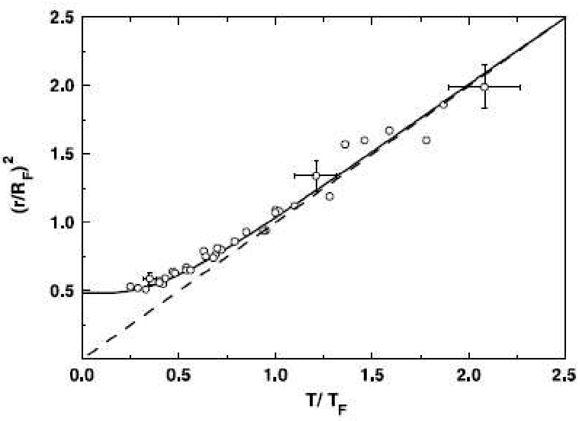


Quantum pressure

quantum pressure







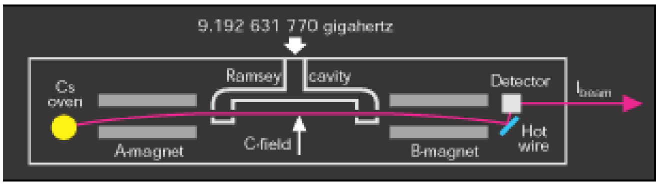
sympathetic cooling

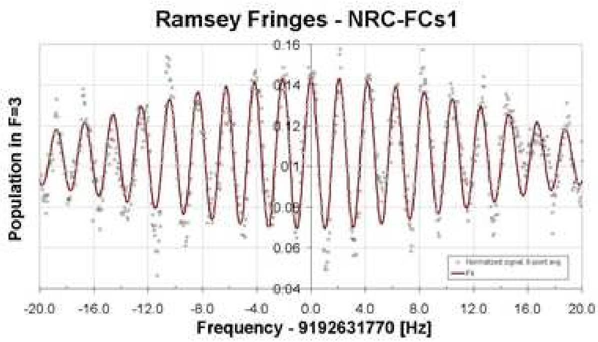
Hulet, *Science* **291**, 2570 (2001)

Atomic clock

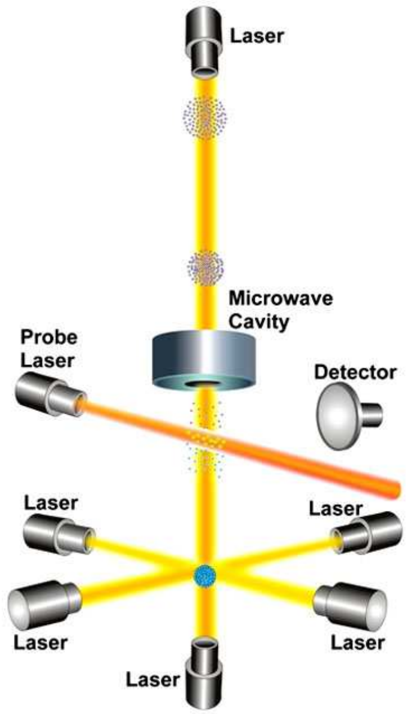
- Navigation: GPS, GLONASS, distant spacecrafts
- Geodesy
- Datation of millisecond pulsars
- Synchronisation of distant clocks
- Fundamental physics tests like Shapiro delay, drift of fundamental constants

http://www.aero.org/



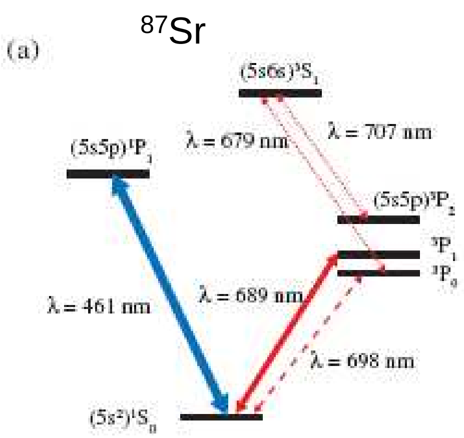


www.nrc-cnrc.gc.ca

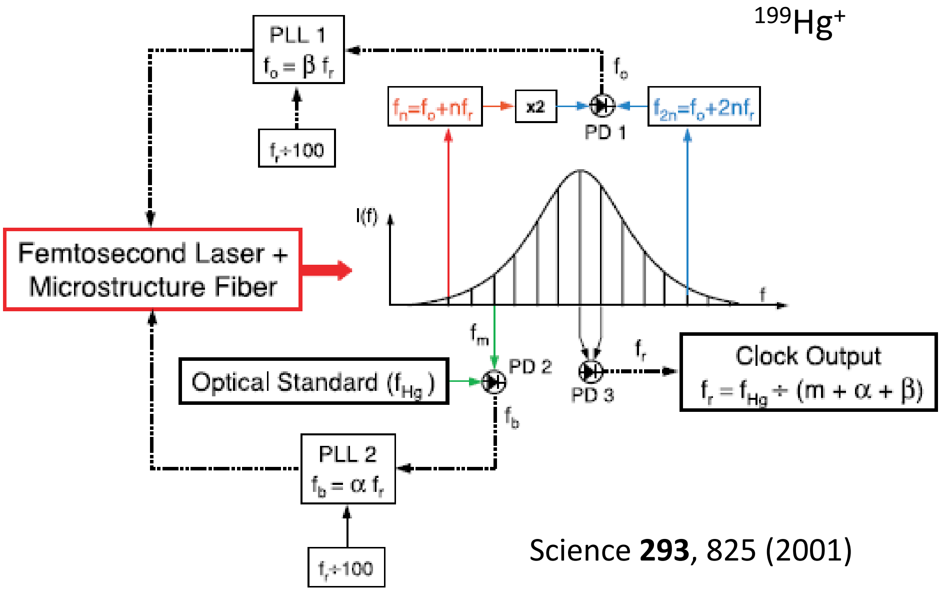


NIST webpage

Atomic clock



Metrologia **45**, 539 (2008)



Science **293**, 825 (2001)

Allan deviation:

$$\sigma_y(\tau) \approx \left\langle \frac{\Delta \nu_{rms}}{\nu_0} \right\rangle_\tau \approx \frac{\Delta \nu}{\pi \nu_0} \sqrt{\frac{T}{\tau N}}$$

$\Delta\nu$ – spectral width of the transition
N – number of atoms
T – time for measuring the line frequency
ν_0 – transition frequency
τ – averaging time