Increasing interaction of Quantum Optics and Solid-State physics

Quantum optical concepts + condensed-matter systems:
- SQUIDS, Cooper-pair boxes, quantum dots: "artificial atoms"
- Rabi oscillations, controlled coupling, ...
  e.g. cond-mat/0402216: cavity QED
  with superconducting stripline resonator + Cooper pair box

Condensed-matter concepts + cold atomic systems:
- Bloch oscillations, Mott insulator, ...
- Kondo effect, Bose glass
- general quantum simulation

Cold atomic systems + condensed-matter systems:
- Atom chips

Atom chips: BEC meets the nanoworld

1. BEC on a chip
2. Coherent atom manipulation
3. Controlling atom-surface interactions
An atomic Bose-Einstein condensate is...

- a matter wave...
- a superfluid...
- an atom laser...
- ...a many-body quantum system

The route to BEC

$\rho \lambda_{\text{eff}}^2 = 1$

1995 JILA Rb
MIT Na
1995/97 Rice Li

1997 first follow-ups

MIT BEC apparatus

... it has become much easier
Magnetic Chip Traps ("Atom Chips")

\[ \nabla B = \frac{\mu I}{2\pi r^2} \]

\( r = 10 \, \mu \text{m} : 15 \, \text{T/cm} \)
\( r = 1 \, \text{mm} : 15 \, \text{G/cm} \)


Solving the Loading Problem

Example: Magnetic Conveyor chip
First magnetic chip trap (1998)

\( l = 1.5 \text{ mm} \)
\( w = 300 \mu \text{m} \)


Fast evaporation due to strong compression

- Strong compression is essential for efficient evaporative cooling
- On-chip conductors offer unparalleled compression factors
- E.g., in our BEC experiment: 220 Hz \( \rightarrow \) 6.2 kHz (transverse freq.)

Chip BEC

- Atom chips: Easy & fast way to create BECs.
- Exceptionally strong confinement – 1 MHz trapping freq. is possible.
- The method is rapidly spreading in the community:
  2001: First 2 chip BECs (our group & independent, simultaneous work in C. Zimmermann’s group, Tübingen)
  2003: ≥8 chip BECs worldwide, >10 more coming
- With atom chips, BEC is ready for applications – can even be portable.

2. Coherent atom manipulation
**Atomic Conveyor Belt**

**wire layout**

- $I_{a1}$
- $I_{a2}$
- $M_{c1}$
- $M_{c2}$

**potential**

- $B_0 = 30 \, e_x + 16 \, e_y$
- $I_0 = 1.5 \, A$
- $I_{M1} = 0.8 \, A \, \cos \phi$
- $I_{M2} = 0.8 \, A \, \sin \phi$

**absorption images**

- $q$ [mm]
- $\phi = 0$
- $\phi = \pi$
- $\phi = 3 \pi/2$

**Transporting a BEC**

A $\sim 500$ nK object, $\sim 100 \mu$m from a room temperature surface!


**Atomic Conveyor: Theme and Variations**

- conveyor belt (sinusoidal modulation)
- optimized conveyor belt (faster transport with less heating)
- “linear collider”
- integrated cold atom source
- ...with switchable output
- adiabatic splitting and merging

see also: splitting and merging in waveguides
Anderson / Cornell groups (Boulder)
Schmiedmayer group (Heidelberg)

**Atom chips: from first experiments...**

- Complex conductor pattern on chip
- On-chip creation of Bose-Einstein condensates
- Manipulation of atomic ensembles in complex potentials

- wire current $I$ ($\sim 1 \, A$)
- + external bias field $B_0$ ($\sim 10-100 \, G$)
- $\Rightarrow$ trapping freq. $\sim 100 \, \text{kHz}$
... towards an integrated quantum laboratory

Atoms in complex potentials
Josephson effect
BEC in ring traps
1D quantum gases

Interferometry and precision measurement
On-chip atomic clocks
Inertial sensors
Measurement of surface forces

Microcavities on chip
Cavity QED
Single atom detection

Quantum information processing with neutral atoms in microtraps

Why QIP with neutral atoms?

Weak coupling to the environment
Coherence lifetimes \( \tau_{\text{coh}} \approx \text{seconds} \)
\( \tau_{\text{coh}} \approx 10^4 - 10^5 \) \( \tau_{\text{gate}} \) required for quantum error correction

Scalable manipulation techniques
- Atom chips provide tailored potentials
- Integration of many traps in parallel

Integration with solid-state systems possible

Proposal by A.S. Sørensen et al., PRL 92, 063601 (2004)

Coupling of Atoms to a superconductor on chip

Proposal by A. S. Sørensen et. al., PRL 92, 063601 (2004)

Atom chip QIP: Collisional phase gate proposal

Phase gate:
\[ \begin{array}{c|c}
|0\rangle|0\rangle & \rightarrow |0\rangle|0\rangle \\
|0\rangle|1\rangle & \rightarrow |0\rangle|1\rangle \\
|1\rangle|0\rangle & \rightarrow |1\rangle|0\rangle \\
|1\rangle|1\rangle & \rightarrow -|1\rangle|1\rangle \\
\end{array} \]

Ingredients:
1. Single qubit operations
2. Long coherence lifetime close to chip surface
3. Strongly confining, state-dependent potential
4. Single atom preparation and detection

Estimated gate time: \( \tau_{\text{gate}} \approx 0.4 \text{ ms} \)

T. Calarco et al., PRA 61, 022304 (2000).

Goal of our current experiments:
Full coherent control on the single-particle level

Internal states
First experiments with coherent superpositions on chip
- Qubit rotations and chip clocks

Measurement and control of small atom numbers

External states
Single atoms and BECs in a double well
Coherence of internal states

...is essential in QIPC with internal-state qubits, but also in atomic clocks.

...is more delicate to handle in traps than for untrapped atoms.

Good choice for magnetic trapping: $|1,-1\rangle$, $|2,1\rangle$ ($^{87}\text{Rb}$)

2 s coherence time has been demonstrated


Decoherence induced by the surface?

Surface decoherence and loss?

Loss and decoherence due to magnetic near-field noise

(Theory by C. Henkel et al., 1999-2003)

In our experiment at $d = 9 \mu m$:

- $\tau_{coh} = 2.8 s$
- $\tau_{gate} \approx 10^4 \tau_{gate}$
- Similar to experiments in macroscopic magnetic traps (Cornell group, Boulder)

Ramsey measurements: Ramsey spectroscopy

Surface decoherence and loss?

Casimir-Polder surface potential modifies the trap:

Ramsey contrast $CT_1(\%)$

Surface decoherence and loss?

Two-photon microwave-RF transition

States with equal magnetic moment:
- Experience same trapping potential
- Robust against decoherence

Rabi oscillation (qubit rotation):

0.0 0.2 0.4 0.6 0.8 1.0

Normalized atom number In [\%]

Pulse length [\mu s]

1 s

0.0 0.2 0.4 0.6 0.8 1.0

Normalized atom number In [\%]

Pulse length [\mu s]

1 s

15 W microwave power

~ 1 W RF power

1.2 MHz intermediate state detuning

$\Omega_{\text{RF}} = 0.2 - 1 \text{ kHz}$

Eff. two-photon Rabi frequency

Rabi oscillation (qubit rotation):

$20,000$ atoms in $F = 1, m_F = -1$

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Two-photon microwave-RF transition

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Eff. two-photon Rabi frequency
The way to atom-chip quantum gates

1. Single qubit rotations ✓
2. Long coherence times ✓
3. State selective potentials ?

|F=1,m_F=-1⟩ and |F=2,m_F=+1⟩

⇒ identical Zeeman effect in static B-fields
⇒ identical Stark shift in static E-fields
⇒ identical AC Stark shift (ℏA ≫ E_{mFS})

State selective microwave potentials

“AC Zeeman effect”

Coupling of levels with microwaves:

ℏΩ_m = μ_B B_{mww}

Energy shift (AC Zeeman):

U_{AC} = \frac{\hbar \Omega_m^2}{4 \Delta}

Microwave coupling leads to state-dependent energy shift!

Microwave near-fields on the atom chip

Atoms at d = 5μm are subjected to the near-field of the wire
⇒ state-dependent potentials varying on the micron-scale

wire carrying DC
⇒ microwave current

Towards atom-chip quantum gates

• Single qubit rotations ✓
• Long coherence times ✓
• State selective potentials ?

Microwave atom chips:
Ph. Treutlein, P. Hommelhoff, T. Steinmetz, T. W. Hänsch & J.R., quant-phys/0311197

• Preparation and detection of single atoms ?


microwave current I_{mww} = ±10 mA
distance d = 5μm
detuning Δ = 100 MHz × 2π
⇒ potential barrier ΔU/h > 100 kHz
⇒ magnetic moments of |0⟩, |1⟩ change only by ∆μ < 10⁻³μ_B

|0⟩→|1⟩
Miniature atomic clock: Allan standard deviation

Short term stability comparable to commercial SRS PRS10 Rb clock.

Limited by:
- Magnetic field fluctuations in the lab (no shielding).
- Detection noise.
- Shot-to-shot variations in atom number.

Dominant contributions to noise

1) Detection noise: $\Delta N/N = 3\%$
   \[ \Rightarrow \Delta f = \frac{3\%}{\pi \sqrt{\tau}} \cdot \frac{\Delta N}{\sqrt{N}} = 12 \text{ mHz} \]

2) Collisional shift: $\Delta N/N = 3\%$ (at $n_0 = 1.5 \times 10^{12} \text{ cm}^{-3}$)
   \[ \Rightarrow \Delta f = 3 \cdot 10^{-15} \text{ cm}^{-1} (0.35 n_0) \cdot \frac{\Delta N}{\sqrt{N}} = 6.3 \text{ mHz} \]

3) Background magnetic field fluctuations: $\Delta B = \pm 6 \text{ mG}$
   \[ \Rightarrow \Delta f = \frac{\sqrt{2}}{3} \cdot 431 \text{ Hz G}^{-1} \cdot (\Delta B)^2 = 22 \text{ mHz} \]

Allan standard deviation:
\[ \sigma(\tau) = \sqrt{\frac{1}{\tau} \cdot \sum_{f} \frac{(\Delta f)^2}{f}} = 2 \times 10^{-11} \cdot (\tau [\text{s}])^{-1/2} \]

Straightforward improvements:
(\(\Delta B = \pm 1 \text{ mG}, n_0 = 2 \times 10^{10} \text{ cm}^{-3}, \Delta N/N = 0.3\%\), $\tau_{\text{cycle}} = 5 \text{ s}$) \[ \Rightarrow \sigma(\tau) = 3 \times 10^{-13} (\tau [\text{s}])^{-1/2} \]

Nondestructive Trapped Atom Detection

- Detect small $N_p$ with low noise.
- Keep atom(s) trapped, minimal heating.
  Ideally: keep in vibrational ground state!

Detect fluorescence?

- Lamb-Dicke factor: \( (\nu r/\nu)^2 \geq 10^{-2} \) (assuming trap freq. $\nu \leq 40 \text{ kHz}$)

- Limited collection & detection efficiency: Need 100s of photons.

Promising only in very strong 3D traps
Dispersive Trapped Atom Detection

- Phase shift from single atom is detectable
- However, a resonator is required to avoid spontaneous emission


Trapped atoms in an optical resonator (versatile system!)

Closely related to optical cavity QED situation (Rempe, Kimble groups) but with magnetically trapped atoms.

Problem: Macroscopic mirrors used in cavity QED are too large for us!

Dispersive atom detection with a resonator

Signal-to-noise ratio:

\[ \eta = \frac{\Delta \Phi_{\text{at}}}{\Delta \Phi_{\text{noise}}} = \frac{g^2 T}{\sqrt{\kappa \gamma}} \left( \frac{E}{\kappa \gamma} \right) \left( \frac{2}{2N_{\text{sp}}} \right) \]

Detectable signal: \[ \eta \geq 1 \]

No spont. emission: \[ N_{\text{sp}} < 1 \]

To obtain \( N_{\text{sp}} = 0.1 \) with \( \eta = 1 \) and detector efficiency \( \xi = 0.6 \), need

\[ \frac{g^2 T}{\sqrt{\kappa \gamma}} \left( \frac{\kappa \gamma}{\kappa \gamma + A} \right) = 6.3 \]

FP for cavity QED (CalTech) 14
Microsphere (ENS) 8

Resonator detectors: Different approaches

Whispering Gallery Mode (WGM)
in a silica microsphere
In collaboration with ENS Paris

Fiber resonator
Stable resonator (concave mirrors), Finesse > 2000

Also pursued in Heidelberg, Southampton (ACQP collaboration) ...
**Fiber-Fabry-Pérot Resonator**

- single-mode fiber
- multi-mode fiber
- coated fiber end faces

**Advantages:**
- compact
- easy coupling
- resonator axis <100µm from chip surface
- exceptionally small mode volume

**Coating the fibers: Transfer technique**

Spherical mirrors: Use sphere as intermediate substrate!

**Fiber resonator on the chip**

- detector position
- x10
- magn.
- transport

- waist: R = 1mm
- x10

**Spherical fiber Fabry-Pérot resonator: Properties**

Piezo tuning, (two-freq. calibration):

- FSR ~ 15THz
- resonator length ~ 10µm
- Mirror curvature R=1mm
  ⇒ Mode cross-section ~10µm
  ⇒ Coupling g/2π ~ 400 MHz
- FWHM ~ 13,5GHz
  ⇒ Finesse: ~1100

Transmission/reflection measurement:

- Each mirror:
  - transmission T ~ 5*10^-4
  - losses A ~ 3*10^-3
  ⇒ Faser-Fabry-Pérot-Resonator

\[
\frac{g}{\sqrt{T A}} = 0.8
\]

**Full coherent control on the single-particle level**

- Internal states
  - First experiments with coherent superpositions on chip
  - Qubit rotations and chip clocks

- Measurement and control of small atom numbers

- External states
  - Single atoms and BECs in a double well

**Internal states**
- Measurement and control of small atom numbers

**External states**
- Single atoms and BECs in a double well
BEC in Magnetic Double Well

- On-site interaction = $g\beta$
- Josephson oscillations in BECs, "self-trapping"
- Essence of Mott insulator transition
- Trapped-atom interferometer
- Collisional phase gate

\[ H = \gamma(a^\dagger_1 a_2 + a^\dagger_2 a_1) + g\beta/2(a^\dagger_1 a_1)^2 + (a^\dagger_2 a_2)^2 \]

Trapped-Atom Interferometer

- Single atom in trap ground state
- Atom in superposition state
- Atom in superposition state
- Single atom in the 1st excited state

Single-atom device (requires single-atom detector)

Split BEC on our current Chip: Large Well Separation

- Minimum spacing on current chip: ~60 µm
- $\nu_1 \sim 2.1$ kHz, $\nu_1 \sim 70$ Hz
- $\lambda = \hbar / m \nu \sim 1.6$ µm
- Can't resolve fringes – use new substrate, ~3 µm features

A Conductor Layout for a Magnetic Double Well

- Single well ($s=0$)
  - $B_{ox} = 3.95$ G
  - $B_{oy} = 3.95$ G
  - $I_{ox} = 2.93$ mA
  - $I_{oy} = 2.93$ mA

- Two wells ($|s|=1$)
  - $B_{oz} = 3.95$ G
  - $B_{oz} = 3.95$ G
  - $I_{ox} = 14.0$ mA
  - $I_{oy} = 1.25$ mA
Double-well chip
In collaboration with Ben Lev, Hideo Mabuchi (CalTech)

Surface-induced evaporation

Recently, BEC has been achieved with this cooling mechanism:

Interactions of ultracold atoms with a room-temperature surface
- Unexplored area of atom-surface physics
- Theoretical work by C. Henkel et al., 1999-2003
How close can the cold atoms be brought to the surface?

- **Metal surfaces**: Fluctuating, thermally excited currents in the surface cause trap loss.
- **Dielectric surfaces**: No such effect. Casimir-Polder potential can be observed.

**Vision: Coherent interaction with mesoscopic solid-state system**

BEC on chip could be used as:
- quantum actuator
- quantum probe

("quantum"=all degrees of freedom are controlled on the quantum level).

Couple atoms to mesoscopic solid-state systems:
- Spin detection
- Fundamentals of detection and decoherence:
  A coherent two-level system coupled to an engineered, mesoscopic, solid-state system

**The Microtrap Team**

Frequent guest:
- Benjamin Lev (Mabuchi group, CalTech)

**Former members:**
- Peter Hammelhoff (now Stanford)
- Wolfgang Hänsel (now Innsbruck)

Diploma students:
- Christian Sartena
- Chiara Chiffi
- Tim Rom
- Astrid Richter

**PhD and postdoc positions available!**