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An ion in a ultracold sea of neutral atoms

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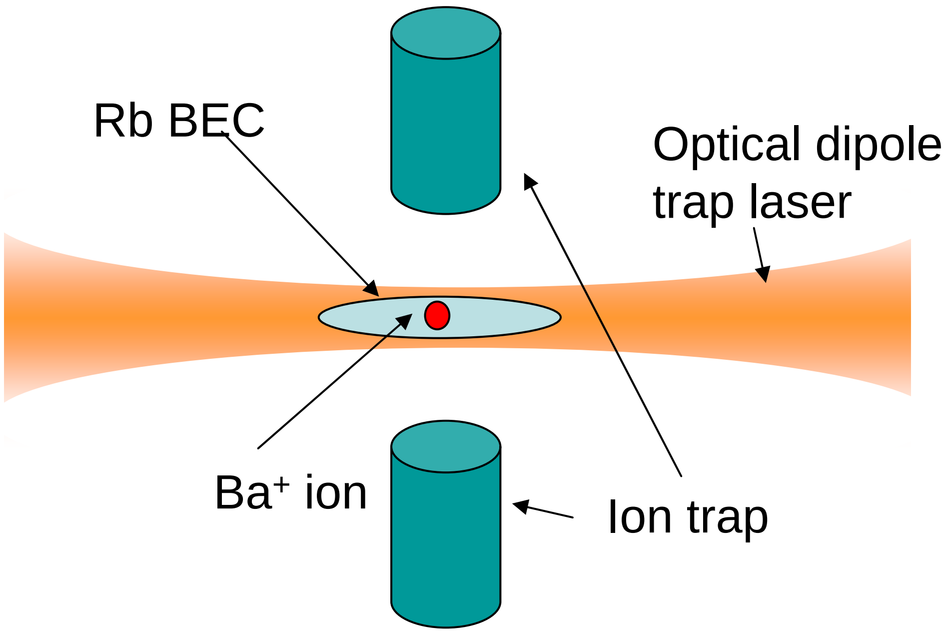
FWF Der Wissenschaftsfonds.

An ion in a sea of ultracold atoms



Ion and atom traps currently well separated research fields

First experiment: Cetina, Grier, Campbell, Chuang, and Vuletic, physics/0702025

Compatibility of traps

Ion trap:

- optical dipole trap for Rb is much weaker than ion trap
- ok with offset magnetic fields (important for Feshbach resonance)

λ = 493nm and 650nm

Rb trap:

- Electrical field of ion trap leads to small antibinding potential with trapping frequency of a few Hertz.

$$V = 1/2\ \alpha\ E^2$$

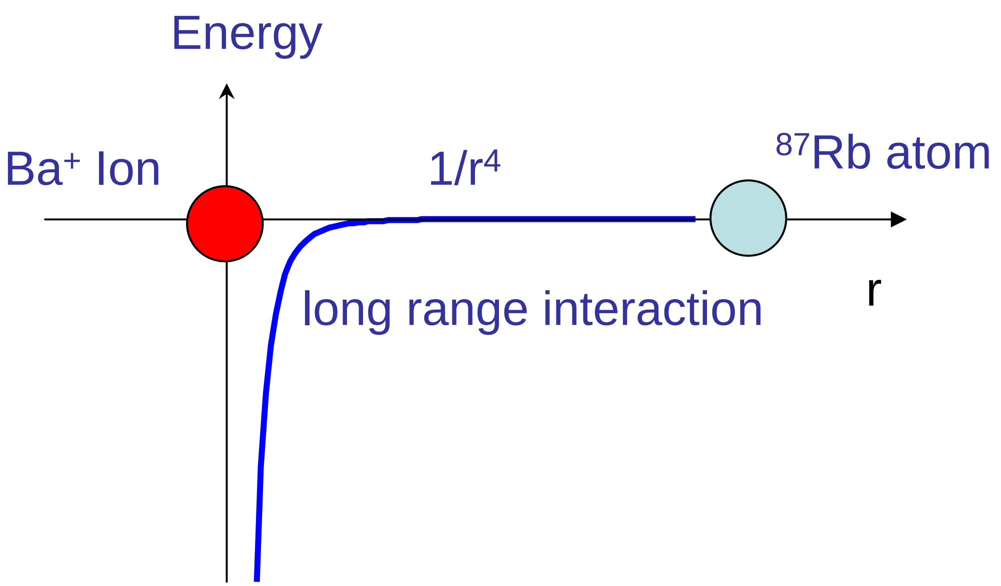
$$E(x,t) = A\ x \cos(\omega t)$$

λ = 780nm

The $1/r^4$ polarization potential

Potential = $-\frac{1}{2}\,\alpha\,E^2$

$E \propto 1/r^2$

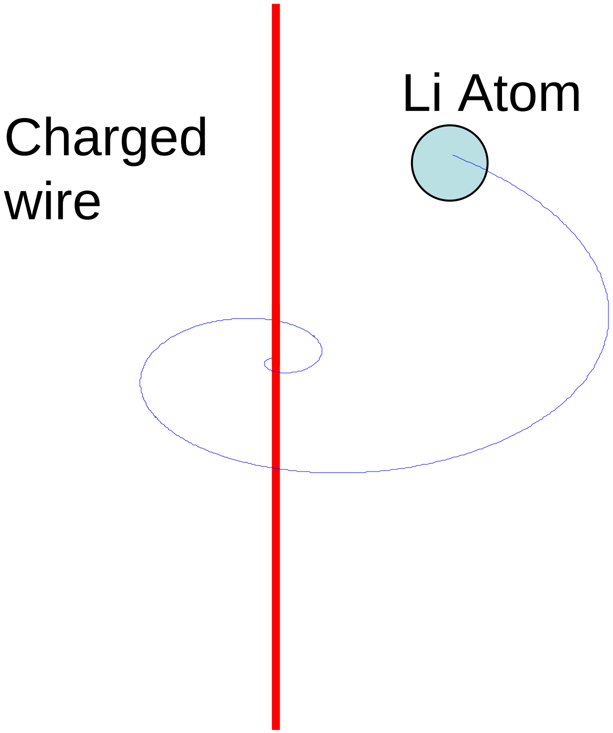


Compare with

v.d.Waals ~ $1/r^6$

- long range interaction
- large scattering length! (sympathetic cooling of ion)
- collision similar as between Alkali atoms

Related: Charged wire experiments



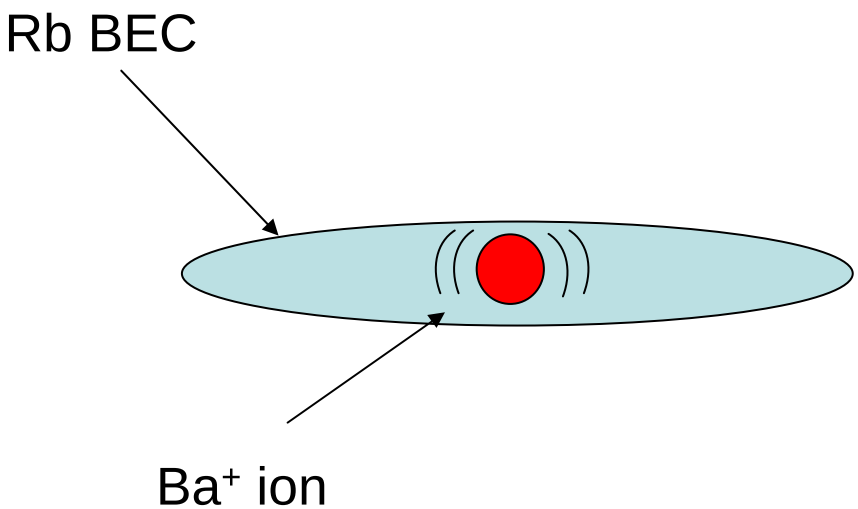
Potential = - ½ α E^2

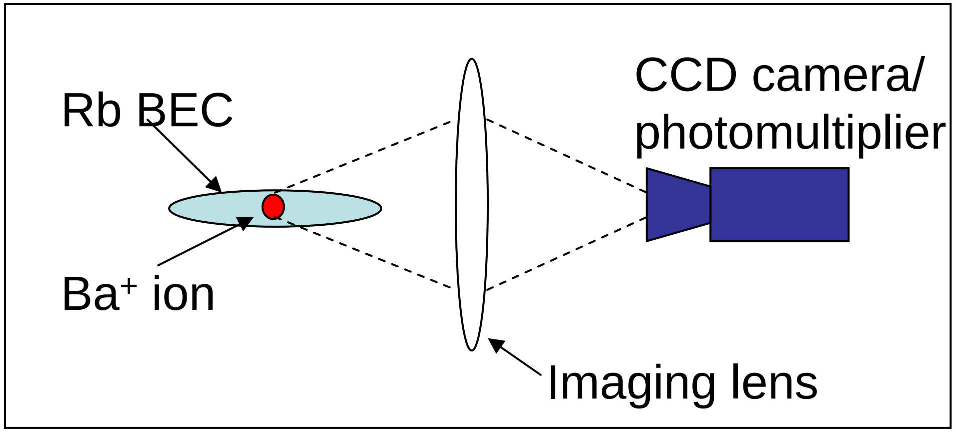
$$E \propto 1/r$$

$1/r^2$ polarization potential

Denschlag, Umshaus, Schmiedmayer, PRL **81**, 737 (1998)

Observables





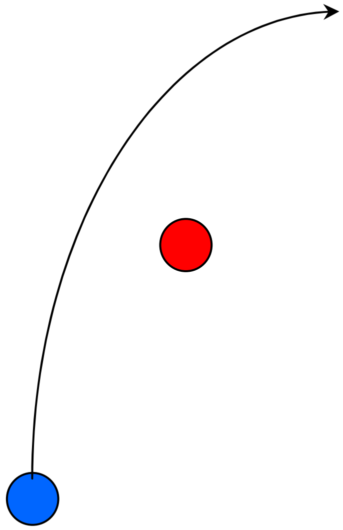
Ba-Ion „lighthouse"
- fluorescence
- temperature
- mass
  - (TOF, channeltron)
  - resonant heating
- spin state

Rb BEC
- atom number
- temperature
  (thermal component)

Planned experiments

- Cold atom- ion collisions
- Charged molecule production
- Novel mesoscopic bound state
- Entanglement / Quantum information processing
- Charge mobility

Cold atom- ion collisions



Elastic collisions

- Feshbach resonances?

Inelastic collisions

- charge transfer?

  $Ba^+ + Rb \rightarrow Ba + Rb^+$

- $(BaRb)^+$ molecule formation?

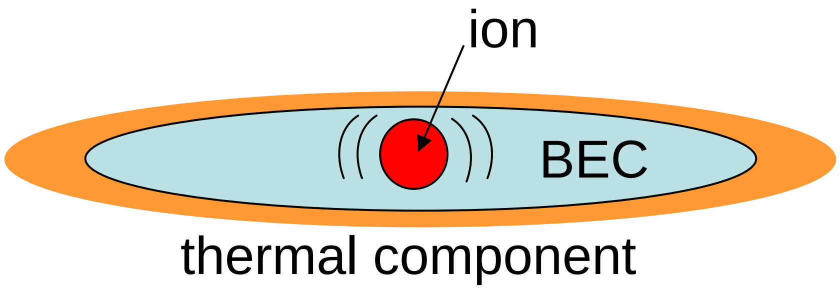
- Photoassociation?

- Spin flip

Elastic collisions

Method:

measure thermalization times / heating rates
(heat BEC by moving ion)



Expectation:

large interaction range
elastic cross section expected to be large
(scattering length ~ several 1000 a_0)

Application:

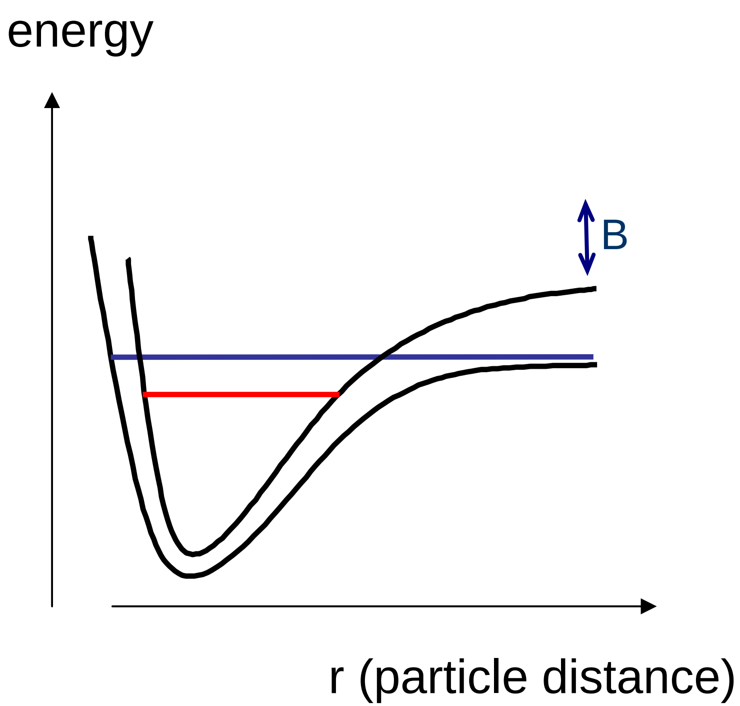
use for sympathetic cooling (useful for ion traps!)

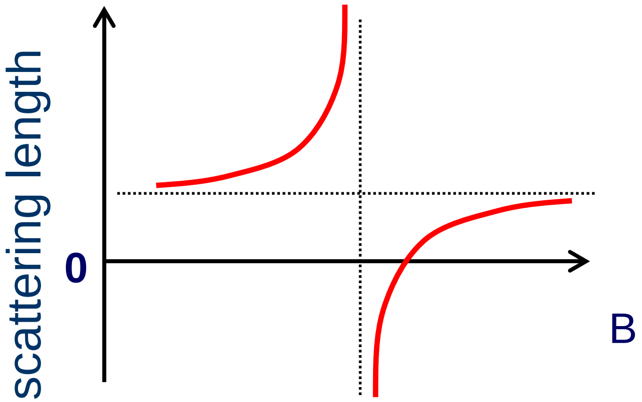
Feshbach resonances ?

Control interaction between atoms and ion

Rb (s = 1/2) + Ba$^+$ (s = 1/2) → triplet and singlet potential

Similar as for alkalies!

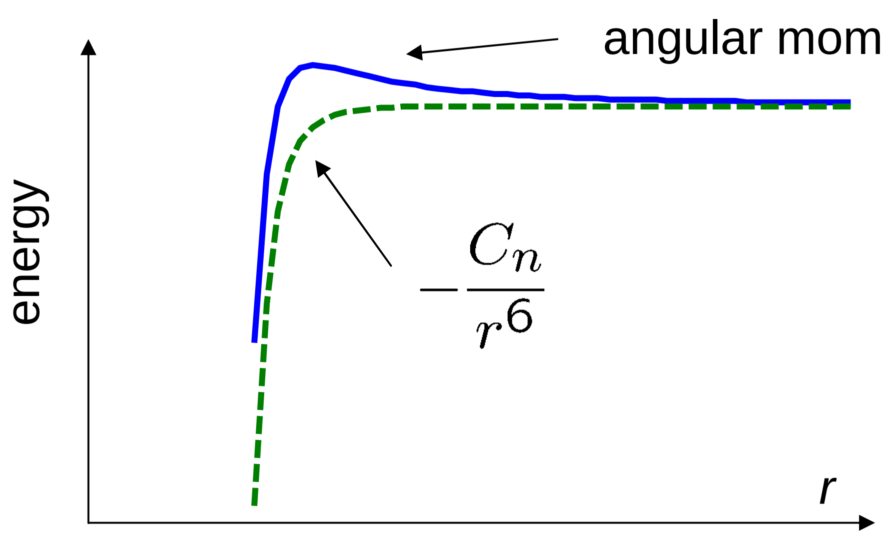




Cold enough for S-waves?

neutral atoms
short range vdWaals interaction
$V \sim 1/r^6$
s-wave for E_{kin} < mK

atom -ion
long range interaction
$V \sim 1/r^4$
s-wave for E_{kin} < nK



$$V = -\frac{C_n}{r^n} + \frac{l(l+1)\hbar^2}{2\ \mu\ r^2}$$

Inelastic collisions

e.g.

charge transfer
$Ba^+ + Rb \rightarrow Ba + Rb^+$

molecule formation
$BaRb^+$

Ba^+ spin flip

Detection method

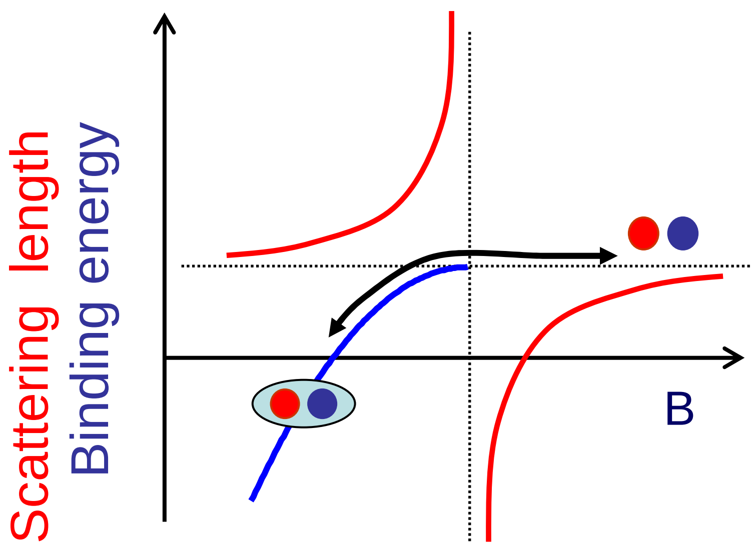
- observe sudden loss o [redacted] a^+ fluore [redacted] e
- meas [redacted] change of m [redacted]
- release [redacted] f [redacted] y using
- [redacted] ing

Controlled production of first ultracold charged molecules?

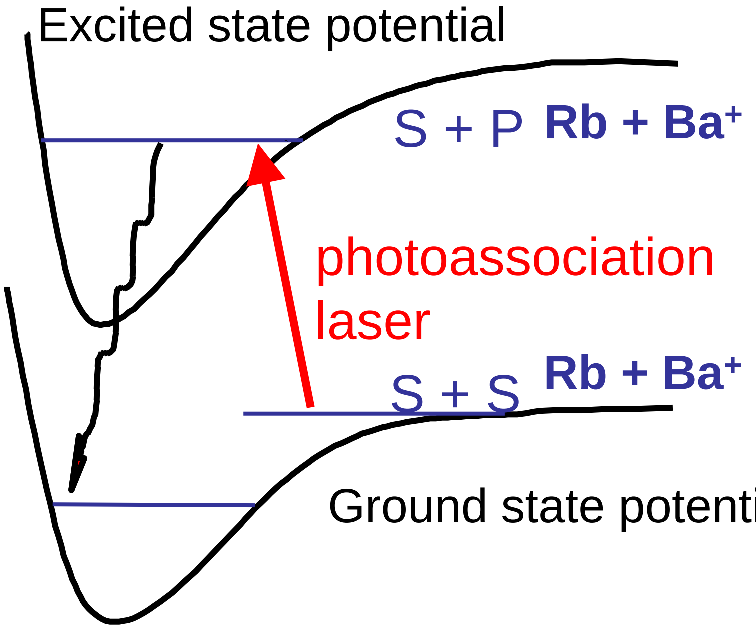
Controlled production of charged molecules

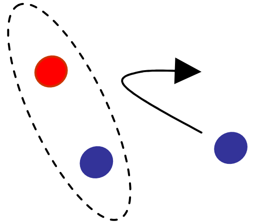
(BaRb)$^+$

Feshbach ramping



Photoassociation





Three-body recombination close to Feshbach resonance

Other chemical reactions

e.g.

$Rb_2 + Ba^+ \longrightarrow (Rb_2Ba)^+$

$Rb_2^+ + Ba$

$BaRb^+ + Rb$

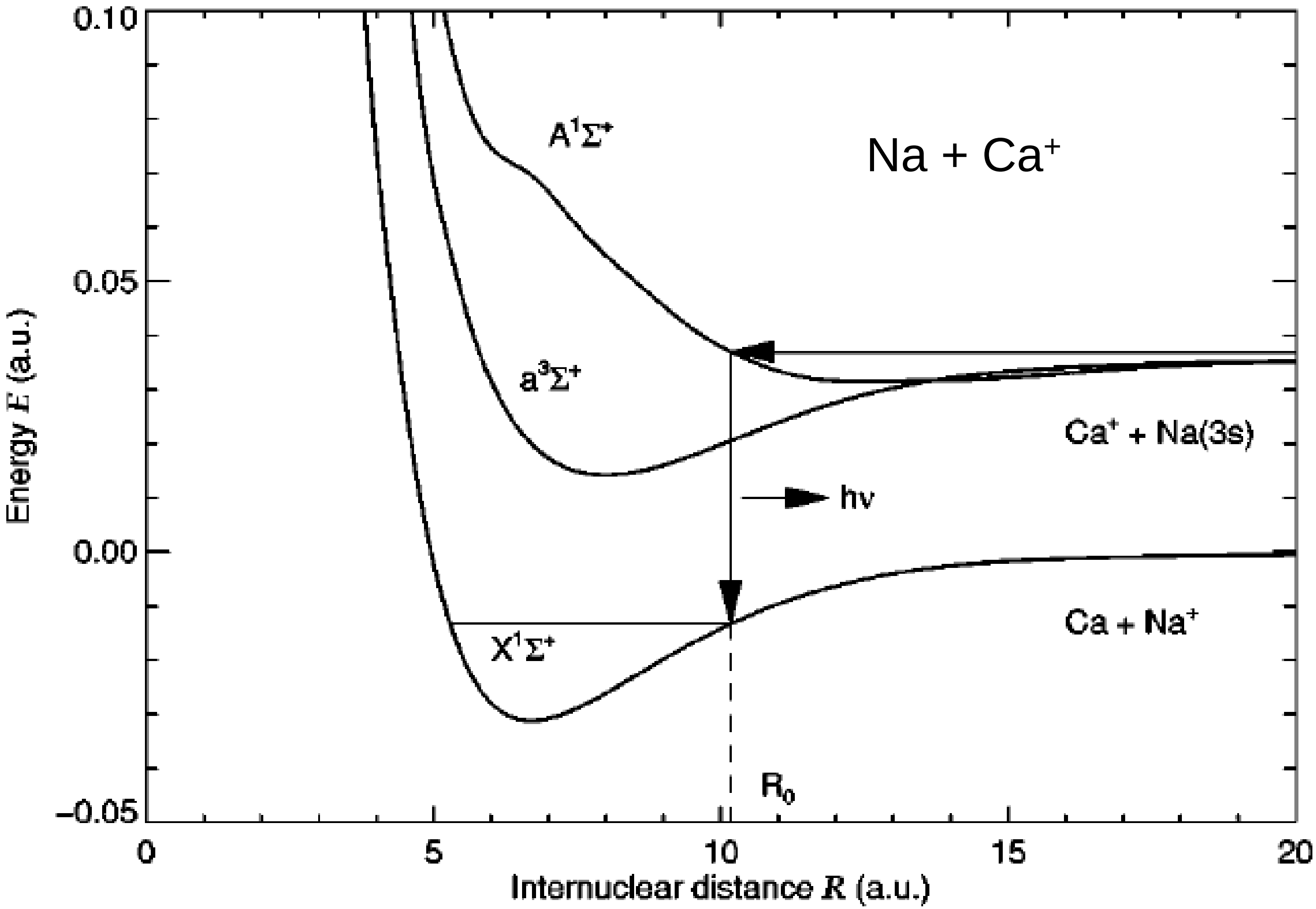
Produced from Rb BEC
via Feshbach resonance
+ optical lattice
Thalhammer et al., PRL 2006

analyze with time of flight
„mass spectrometer“

or $(BaRb)^+ + Rb\ (Rb_2) \longrightarrow$?

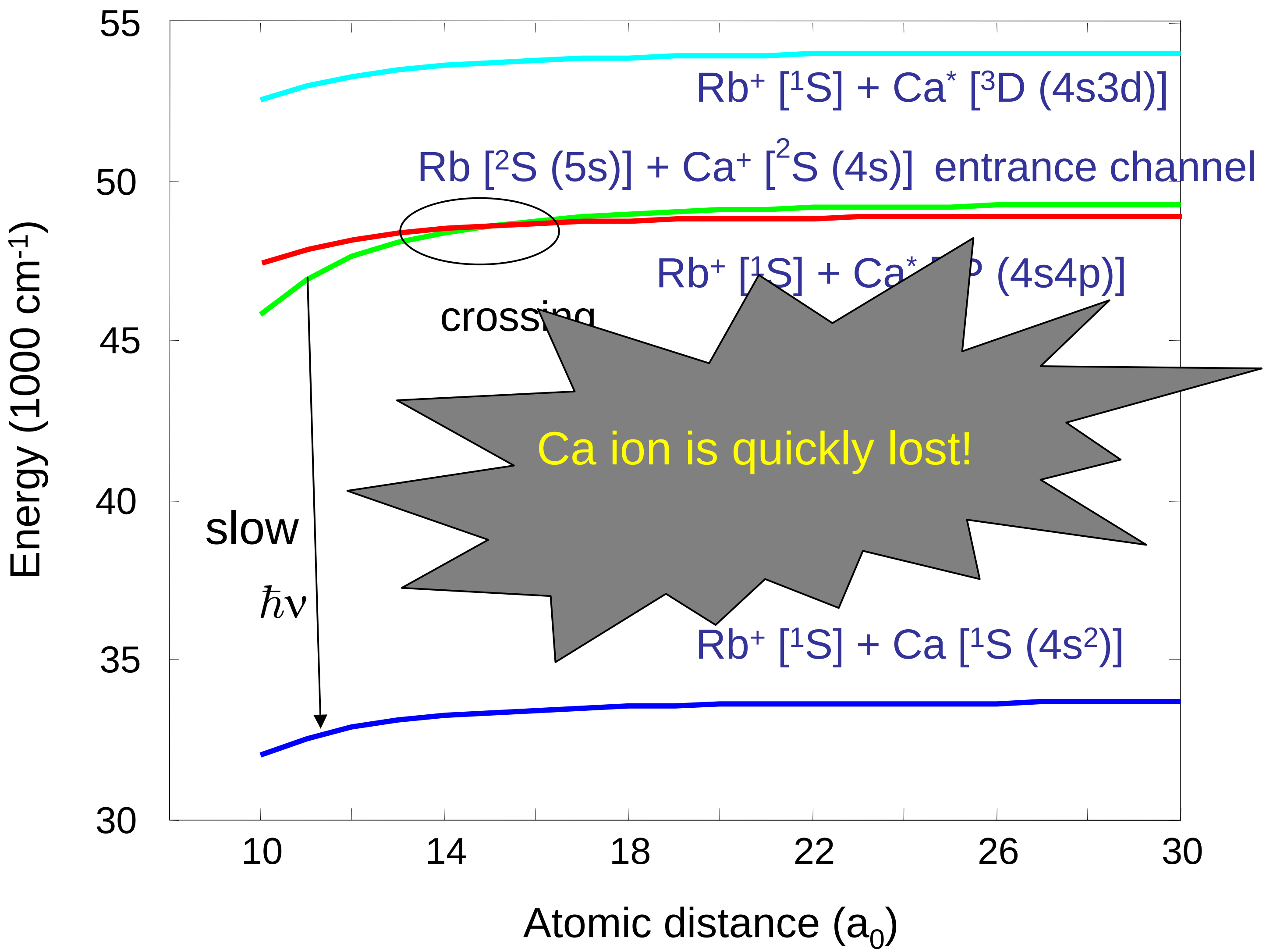
(Radiative) charge transfer

Makarov, Cote, Michels, Smith, PRA **67**, 042705 (2003)



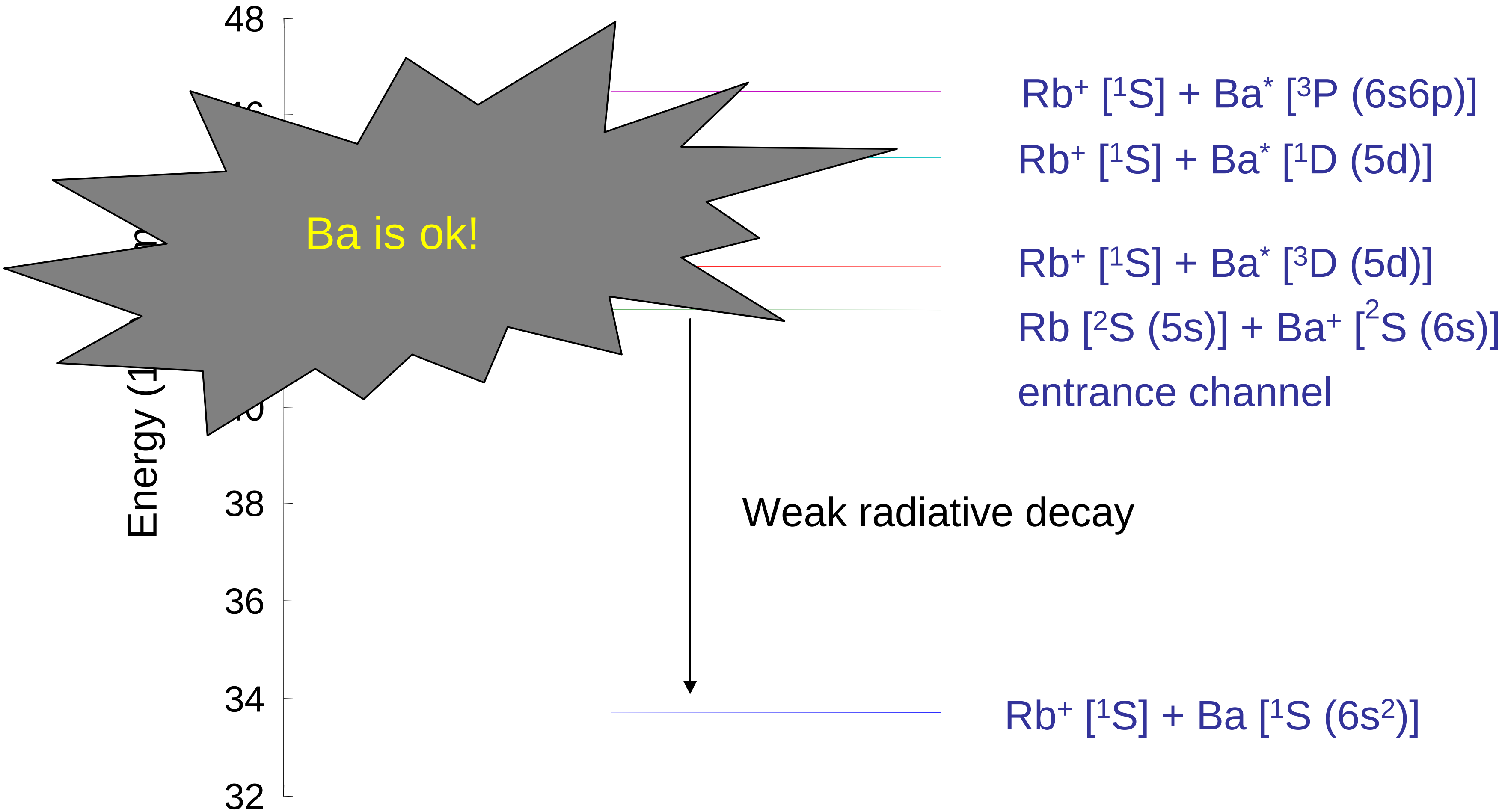
Probably similar to Ba^+ + Rb

Choice of species is important



R. Cote, private comm.

Asymptotic energy levels for Ba / Rb



Rb + Ba ground state: $0 cm^{-1}$

R. Cote, private comm.

Lifetime given by radiative decay

Makarov, Cote, Michels, Smith, PRA **67**, 042705 (2003)

$$\tau_{rt} = 1/(R_{rt}\ n)$$

n = Rb density

$$R_{rt} \propto \alpha^3 \omega^3 D$$

polarizability

laser frequency

dipole moment

$$R_{rt} \approx 2 \times 10^{-15} cm^3/s$$

$\Rightarrow$ $\tau_{rt} = 5s$ for $n = 10^{14} cm^{-3}$

(non-radiative charge transfer and charge transfer after laser excitation should also be negligible, Makarov et al.)

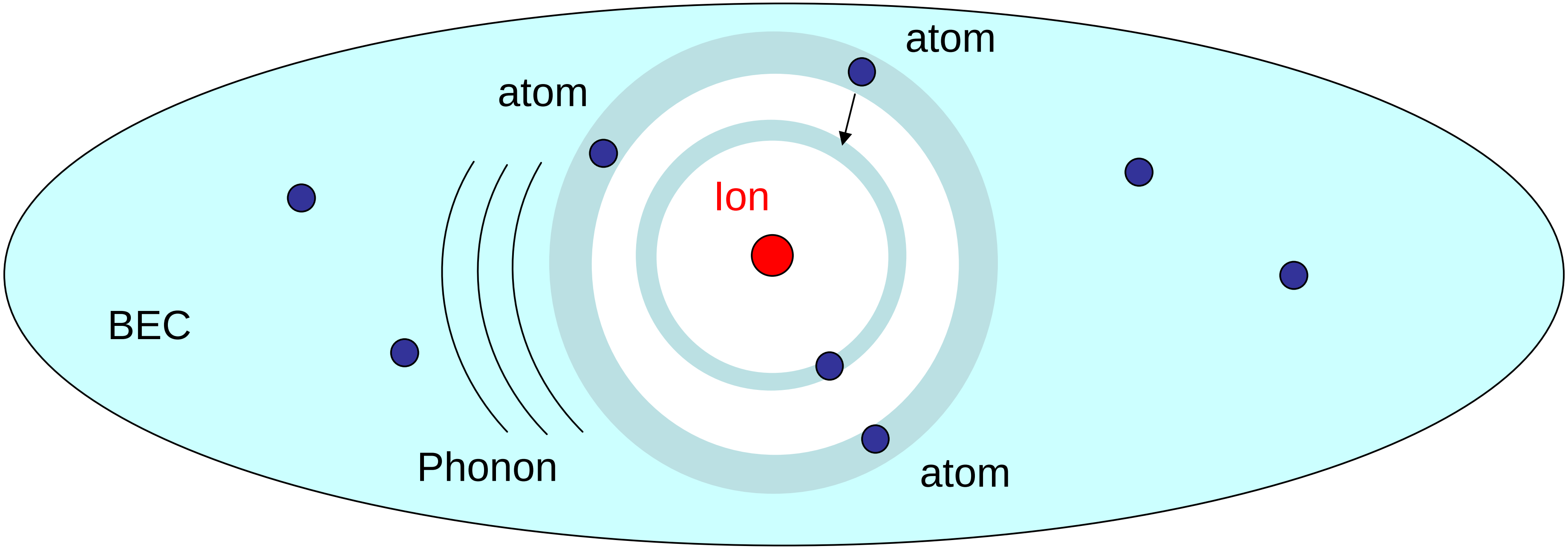
Distinguish charge transfer from chemical reaction

Planned experiments

- Cold atom- ion collisions
- Charged molecule production
- Novel mesoscopic bound state
- Entanglement / Quantum information processing
- Charge mobility

Novel mesoscopic molecular state

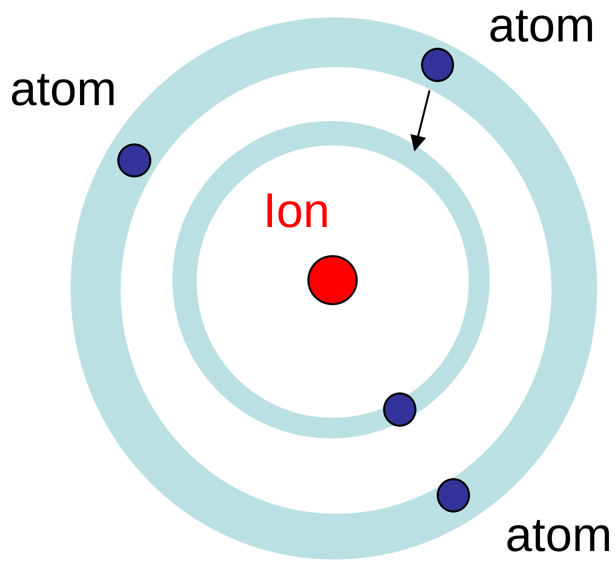
Cote, Kharchenko, Lukin, Phys. Rev. Lett. 89, 093001 (2002)



- shells of quantized bound states with 100-1000s of atoms
- binding energy ~ 1μK k_B, size of shell ~1μm
- formation within ms at density of 10^{14} cm^{-3}
- long lifetime (~10-100 ms)
- losses due to strong inelastic many body collisions between Rb atoms?

Novel mesoscopic molecular state

Cote, Kharchenko, Lukin, Phys. Rev. Lett. 89, 093001 (2002)



Detection:

- turn off dipole trap → BEC disappears
- ion bound atoms can be detected via absorption imaging

Measure mass:

- Release mesoscopic molecule from ion trap, detect with channeltron, after mass dependent time of flight

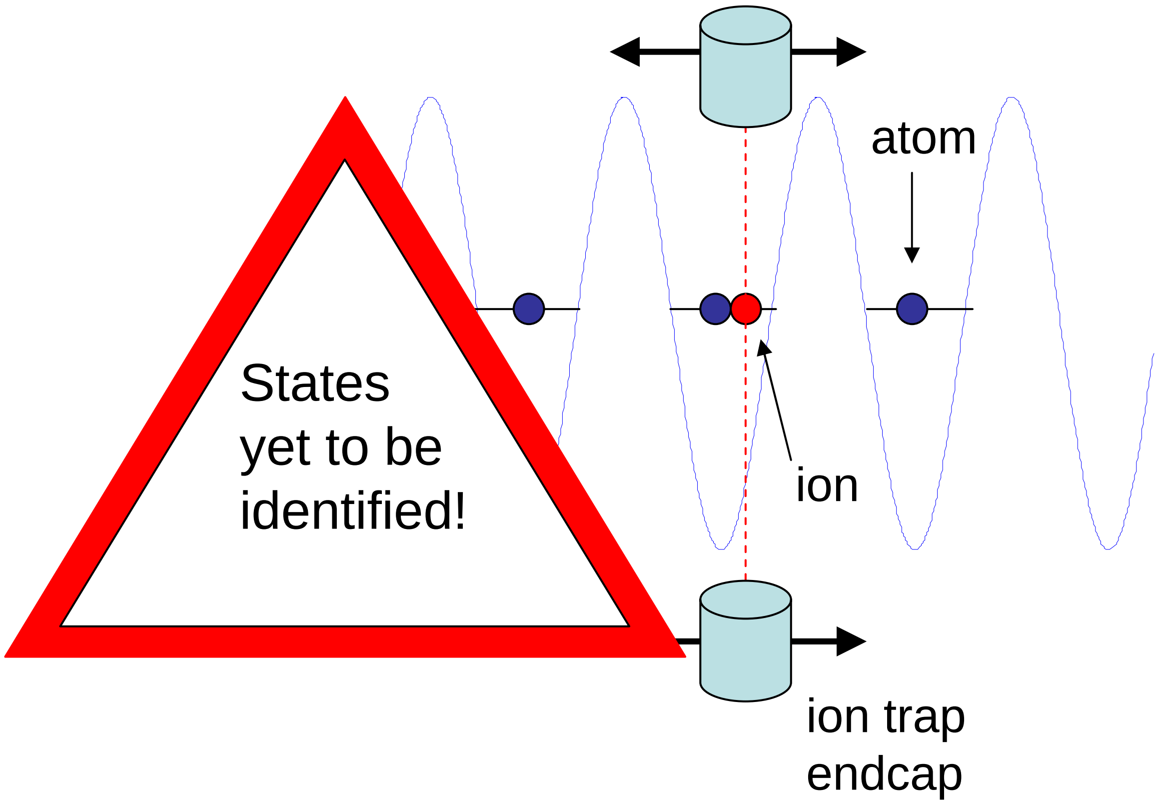
Spectroscopy:

- Excite transitions through resonant „shaking“ of trap at frequencies ~20kHz

Planned experiments

- Cold atom- ion collisions
- Charged molecule production
- Novel mesoscopic bound state
- **Entanglement / Quantum information processing**
- **Charge mobility**

Entanglement of atoms and the ion



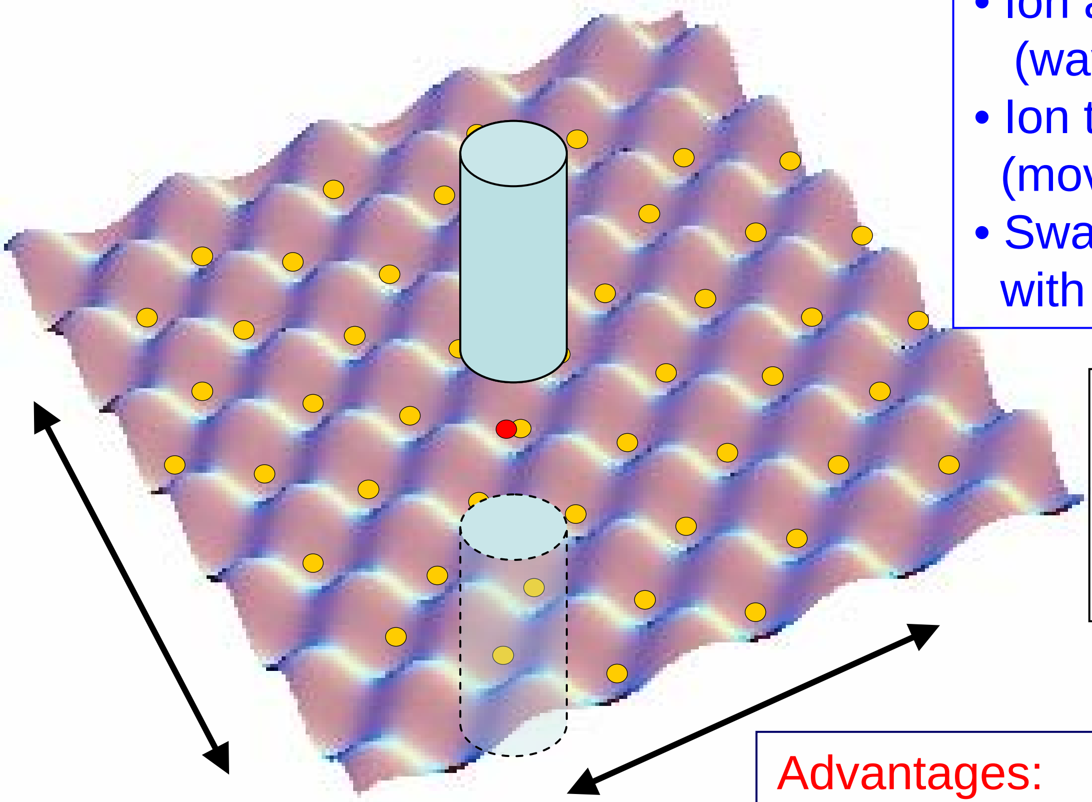
$\omega_{\text{Ion trap}} \sim 2\pi$ 500 kHz

$\omega_{\text{lattice}} \sim 2\pi$ 50 kHz

Via controlled collision! State dependent interaction.

See for example: Idziasek, Calarco, Zoller, to be published

Quantum information processing?



- Ion acts as read and write head (wavelength off resonant for Rb)
- Ion transports quantum information (move lattice or ion in linear trap)
- Swap and entanglement operations with atoms

Still unclear:
- Qubit states have to be identified (Rb hyperfine states, vibrational states)

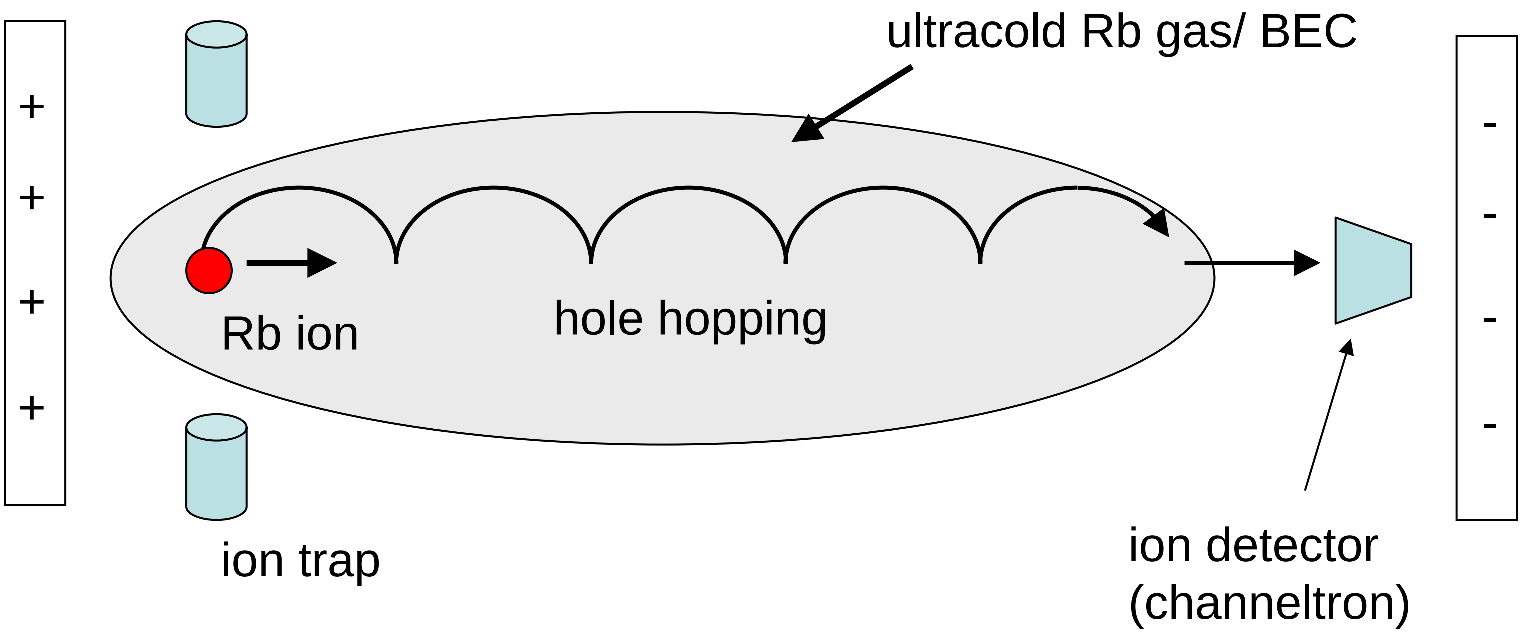
Advantages:
- Interesting for solution of addressing problem!
- Atoms in lattice store QI, long coherence times
- Strong atom ion interaction, faster gates…

Planned experiments

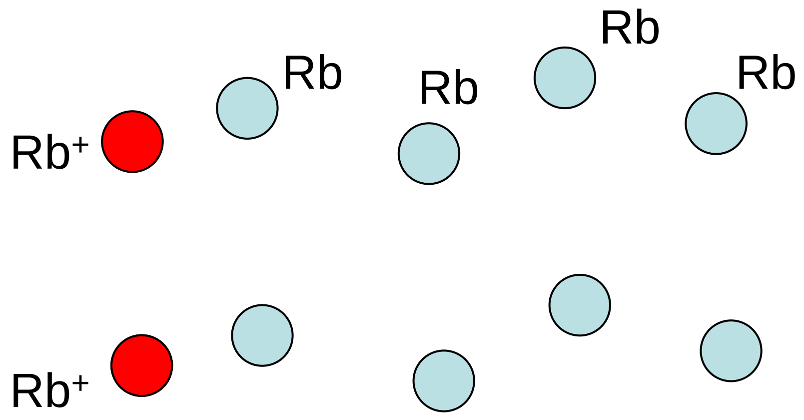
- Cold atom- ion collisions
- Charged molecule production
- Novel mesoscopic bound state
- Entanglement / Quantum information processing
- **Charge mobility**

Charge mobility in an ultracold gas

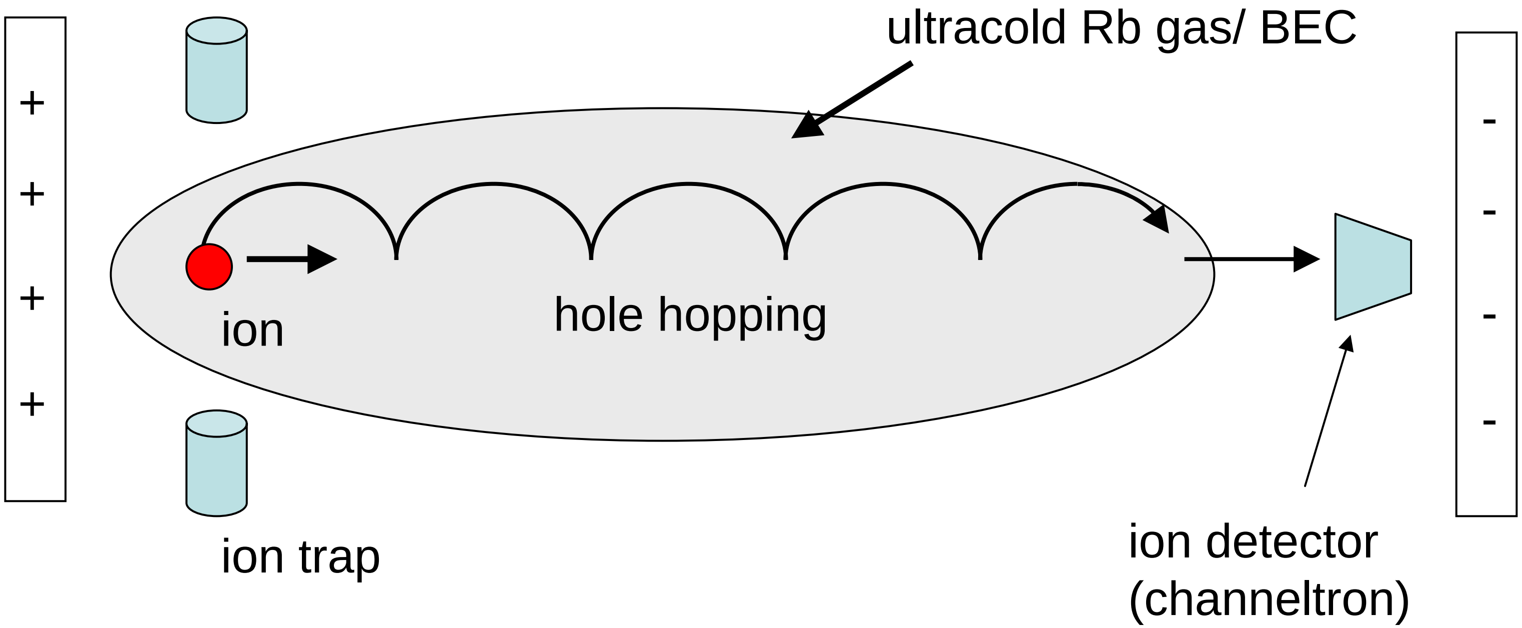
R. Cote, PRL 85, 5316 (2000)



2 ways of
transport



Charge mobility in an ultracold gas



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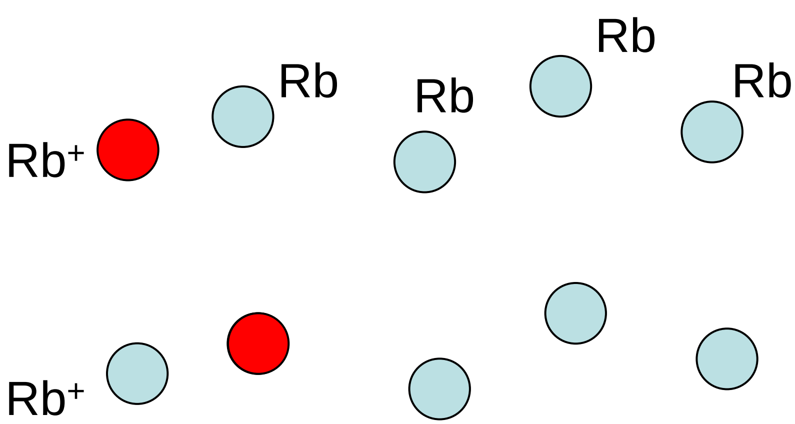
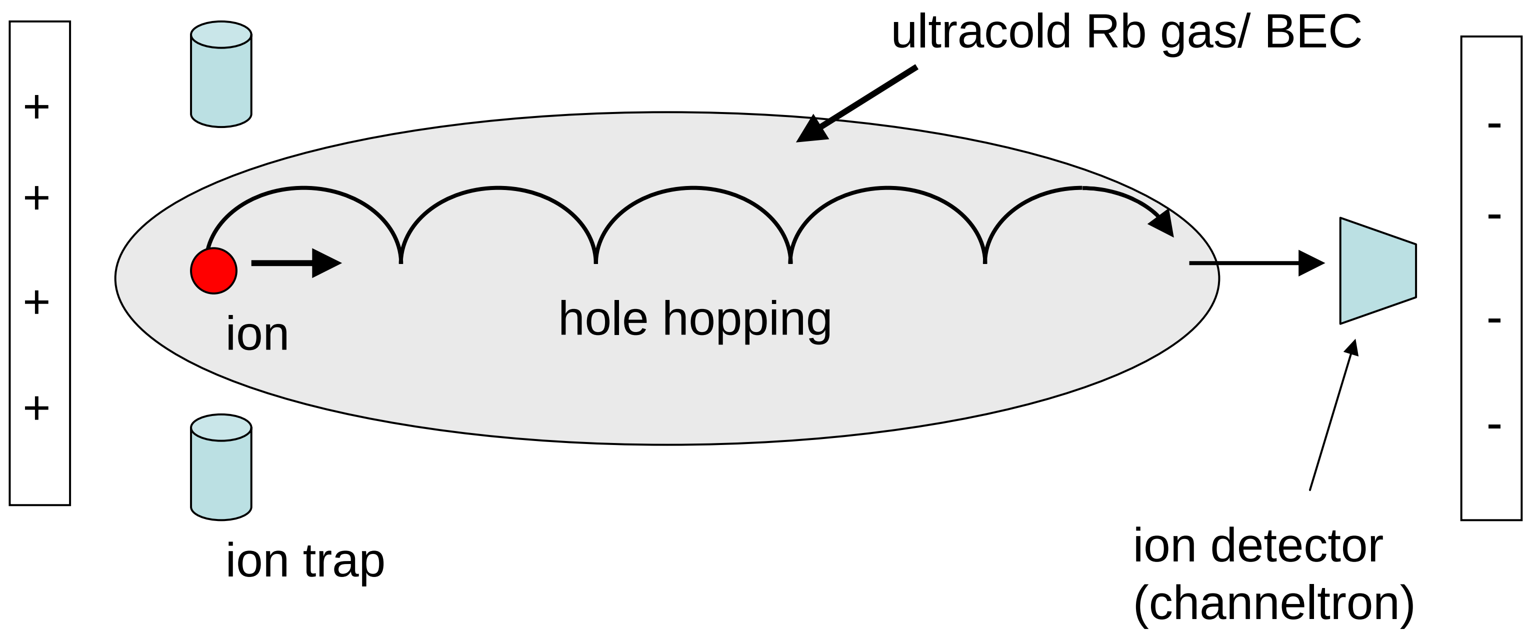
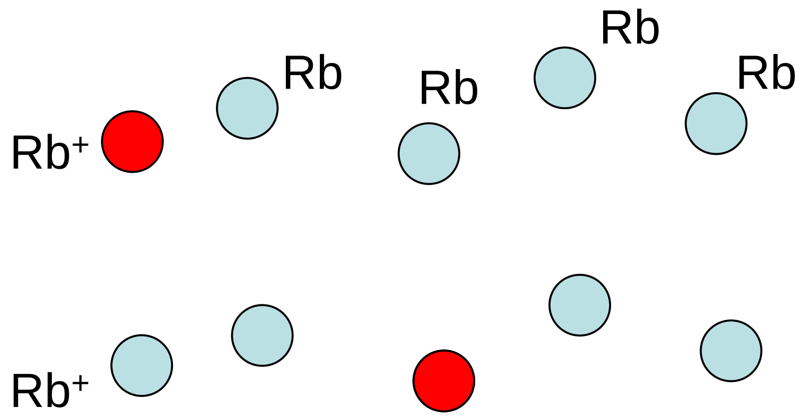


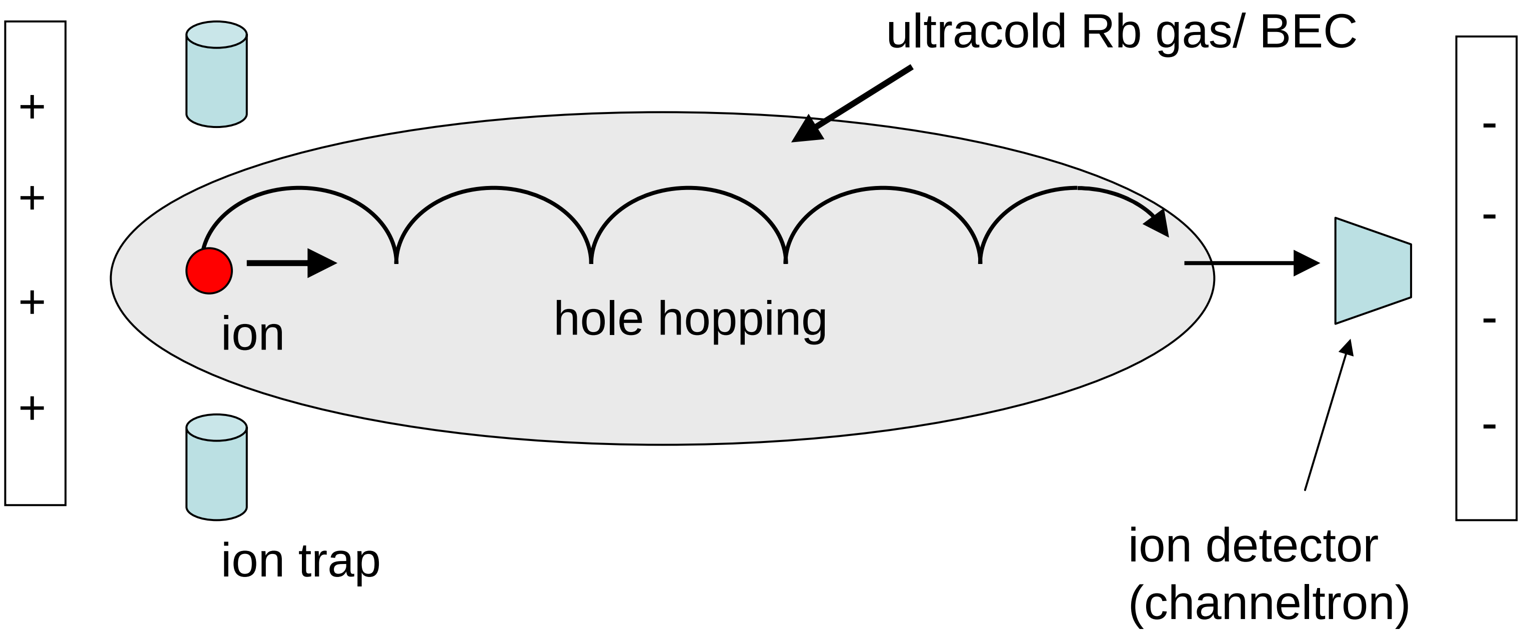
Charge mobility in an ultracold gas

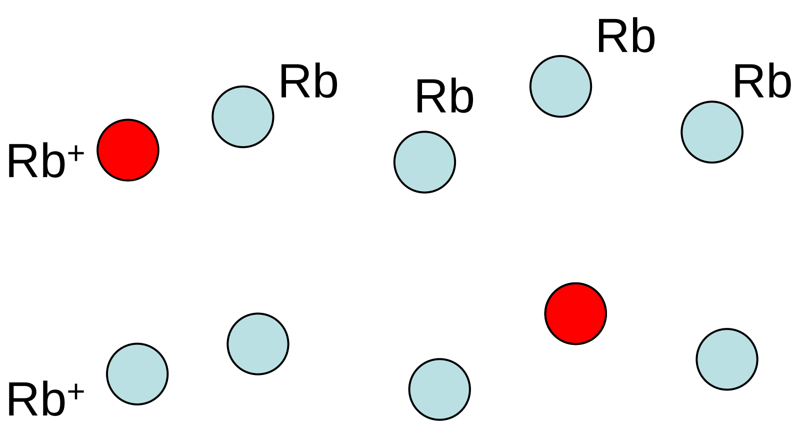


2 ways of
transport



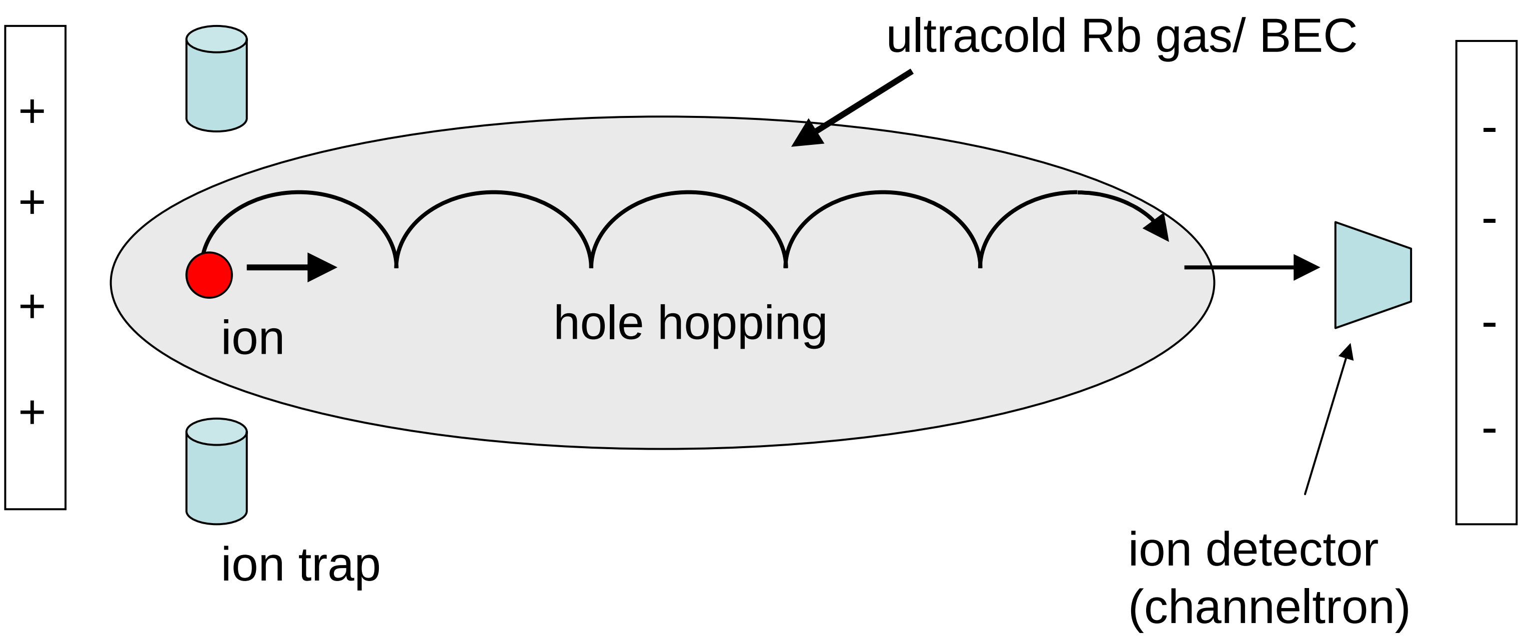
Charge mobility in an ultracold gas



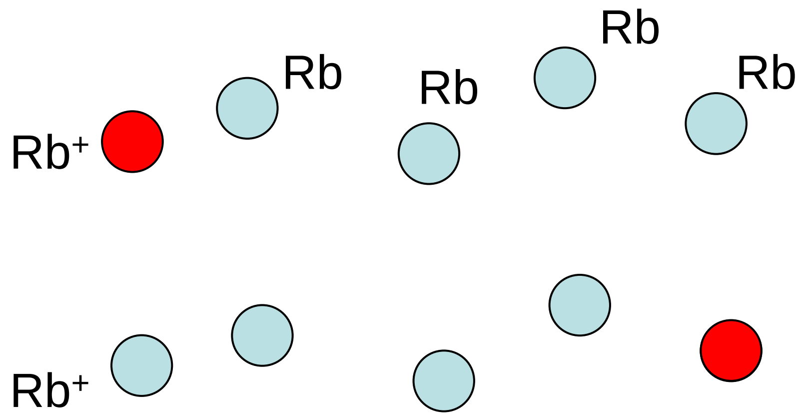


2 ways of transport

Charge mobility in an ultracold gas



2 ways of transport

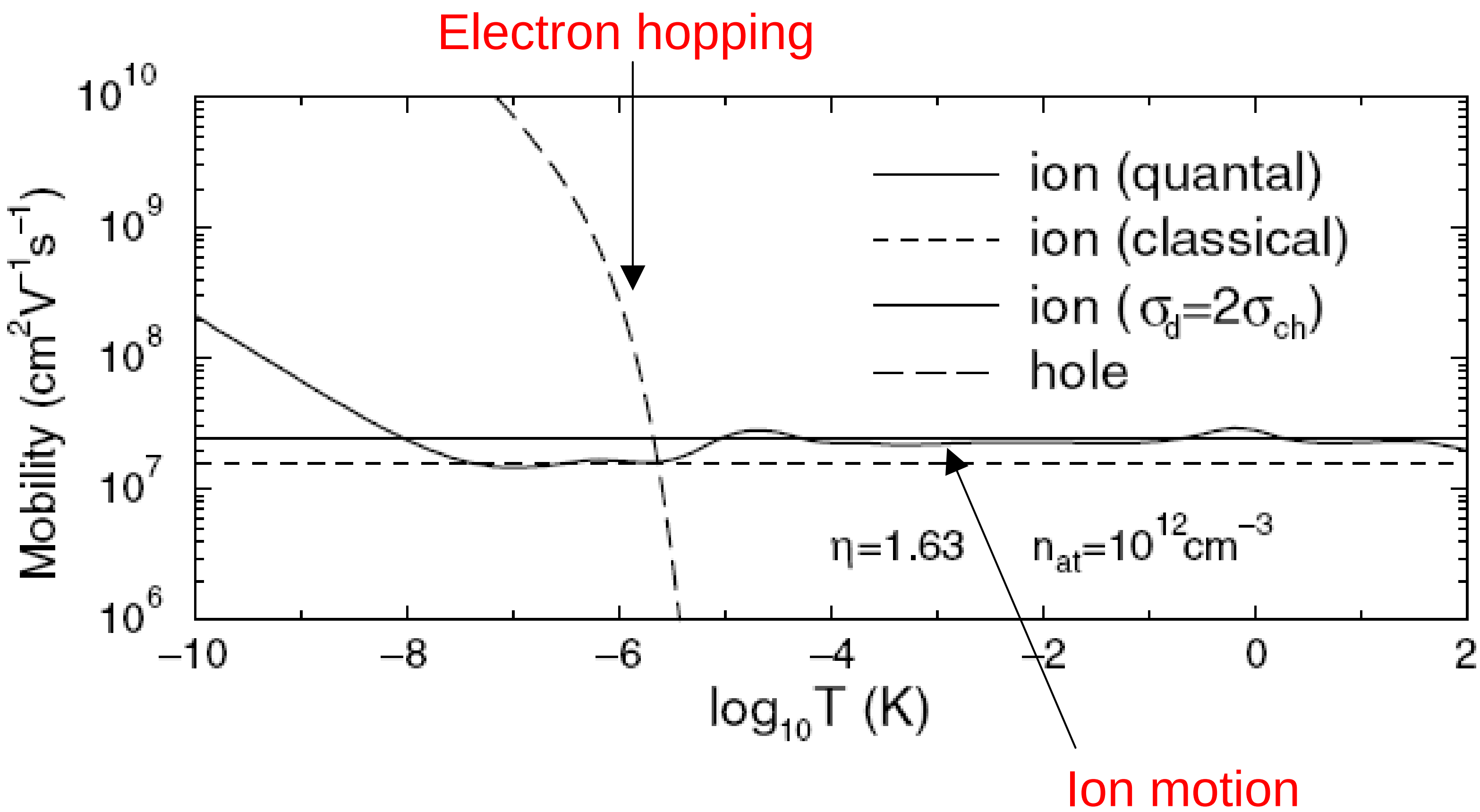


Motion of ions

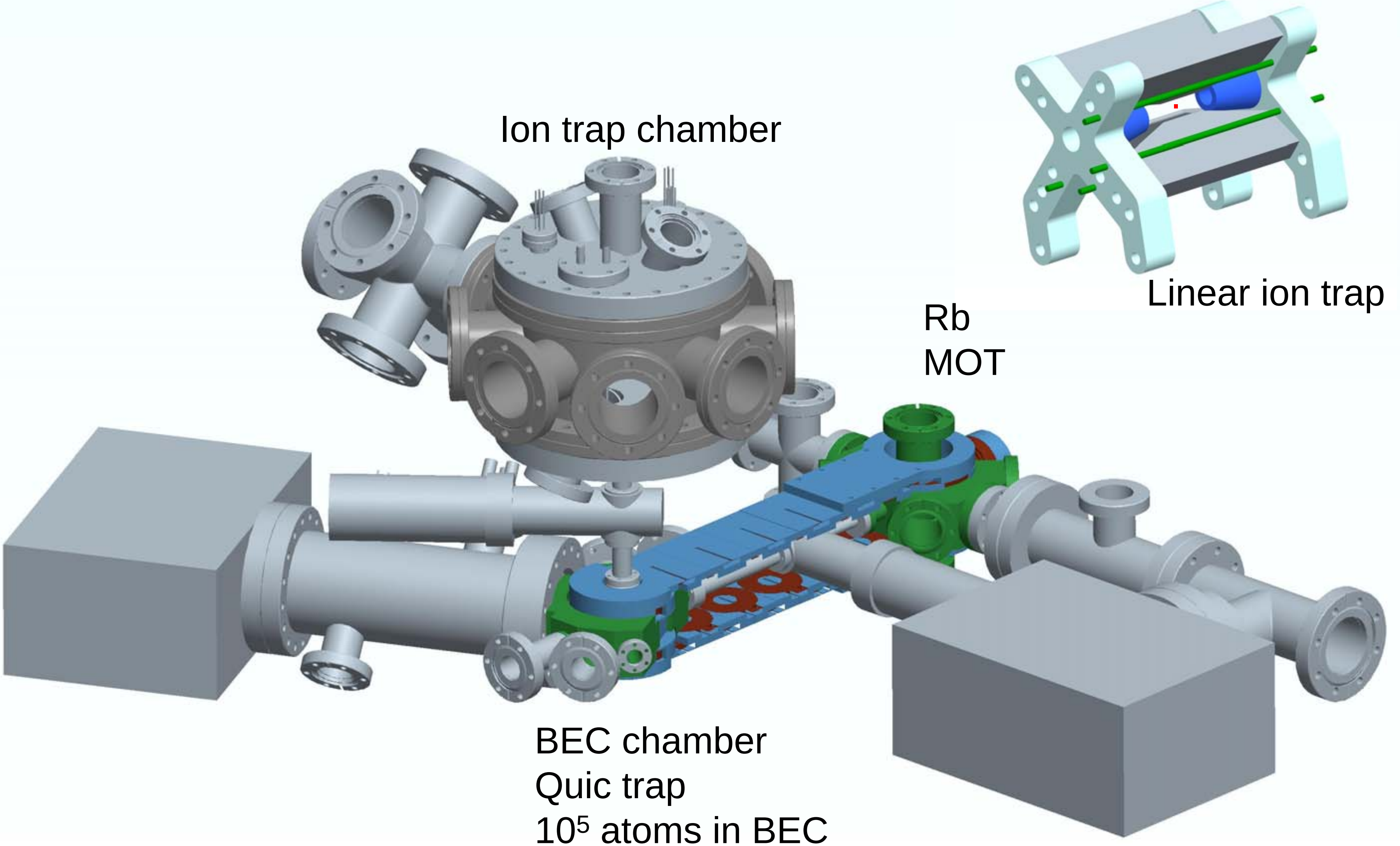
Electron hopping

Charge mobility in an ultracold gas

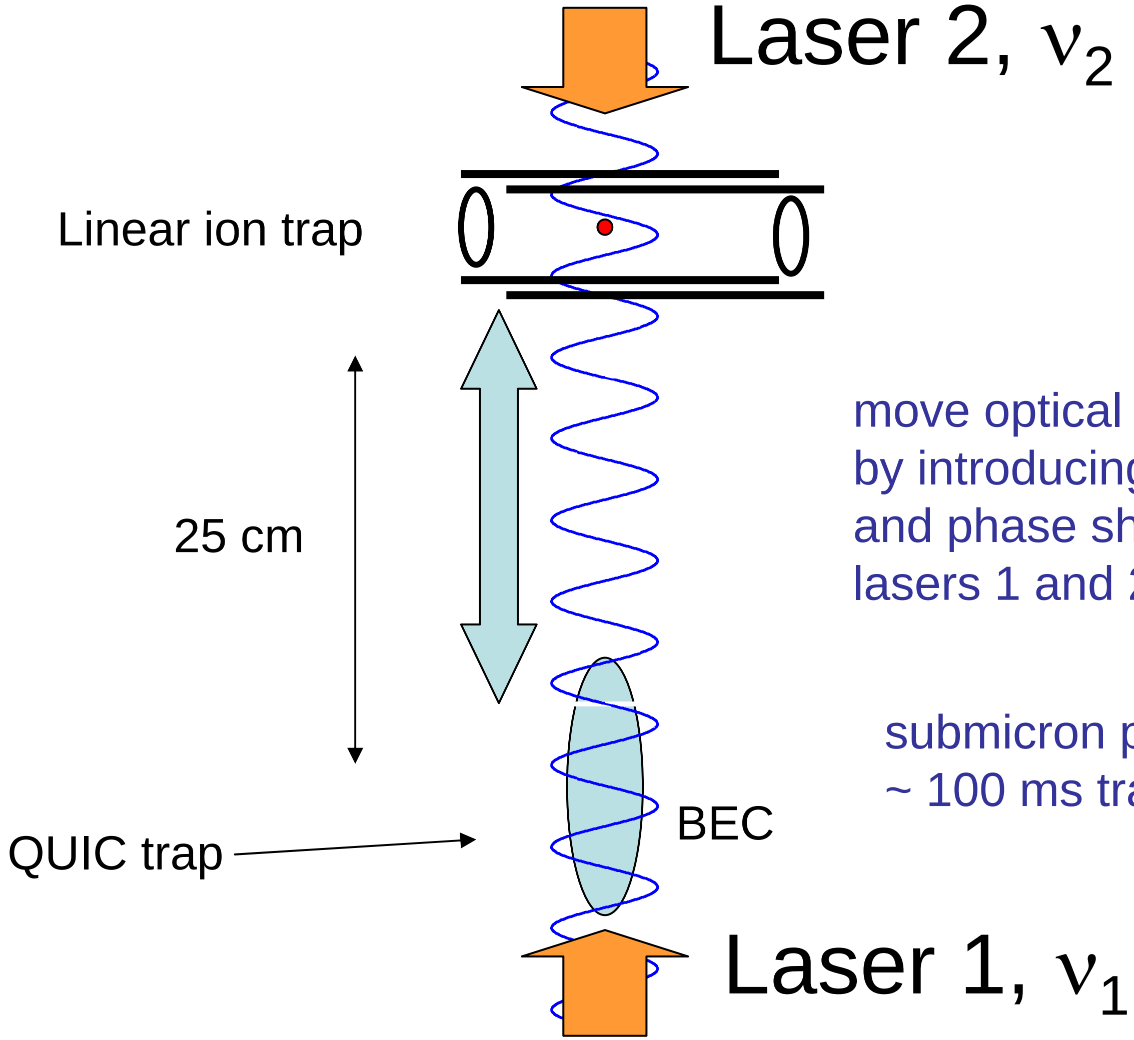
R. Cote, PRL 85, 5316 (2000)



Ion in a Sea: Set up



Vertical transport



λ = 1064nm,
width = 300 μm

move optical lattice by introducing frequency and phase shifts between lasers 1 and 2

submicron precision!
~ 100 ms transport time

see also St. Schmid et al., New J. Phys. 8 (2006) 159

Summary

Many new and exciting experiments:

- Cold atom- ion collisions
- Charged molecule production
- Novel mesoscopic bound state
- Entanglement / Quantum information processing
- Charge mobility

Status:

Apparatus and laser system are under construction