A single ion in an ultracold atomic gas

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Trapped Ions and Ultracold neutral Atoms

Good compatibility of traps!
Three stories

1) Putting atoms to work in an ion trap:
   cooling and micromotion compensation

2) An ion as a three-body reaction center

3) A „mysterious“ production of Rb\(^+\) and Rb\(_2^+\) ions
- Thermalization of ion within a few collisions, sympathetic cooling
- Loss of a few Rb atoms
- no further dynamics afterwards…. 
The role of excess micromotion

- coherent trap drive (5MHz) accelerates stopped ion again

- ion energy is set by excess micromotion $E_{\text{ion}} \sim \text{mK} \ k_B$

atoms $T \sim 1 \mu\text{K}$
confined by shallow dipole trap
$U_{\text{dip}} \sim 10 \mu\text{K}$
Observed elastic atom-ion collisions

Path to cold ion temperatures:

- Minimize micromotion
  \[ \varepsilon_{dc} = 0 \text{ V/m} \]
- Minimize atomic losses

Thermal cloud
\[ T \approx 100\text{nK} \]

Electric field offset
\[ \varepsilon_{dc} = 4 \text{ V/m} \]
Stray electric fields $\rightarrow$ excess micromotion

can be minimized by applying appropriate compensation voltages
initial conditions

Atom number
N \sim 80000

Temperature
180 \text{nK}

Density
n \sim 2.5 \times 10^{12} \text{cm}^{-3}

Interaction time
\tau = 2 \text{s}
initial conditions

Atom number
N ~ 80000

Temperature
180 nK

Density
n ~ 2.5 \times 10^{12} \text{ cm}^{-3}

Interaction time
\tau = 2 \text{ s}

Excess micromotion also changes temperature of atom cloud!
You can use cold atoms to compensate micromotion!

Sensitivity down to 0.1 V/m for stray electrical fields → micromotion energies \( \sim 10 \mu K \)

However, preliminary analysis indicates that some micromotion \( \sim 500 \mu K \) remains, probably due to rf phase difference on electrodes.

Also: Interesting collision dynamics
- non-thermal kinetic distribution
- heating/ cooling depends on m-ratio
Three stories

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The role of excess micromotion
Ion-induced atom loss

- Interaction time $\tau$ [s]
- Atom number $N_{at}$ [$\times 10^4$]
Atom number distributions

A. Härter et al. PRL 2012, in press
Collision dynamics

Interaction time [s]

Atom number $N_{at} \times 10^4$

number of outcomes
Collision dynamics

“catastrophic” event → interaction stops!

Interaction time [s]

Atom number $N_{at}$ [$\times 10^4$]

0 20 40

number of outcomes

0 20 40
Atom-atom-ion three-body recombination

We always observe $\text{Rb}^+$ in the end.

$\text{Rb}_2^+ + \text{Rb} + 0.7\text{eV}$
Measurement of the reaction energy

Result:
Ion has typical energy of a few 0.1 eV.
Data well described by three-body recombination dynamics

\[ K_3 \sim 3 \times 10^{-25} \text{ cm}^6 \text{ s}^{-1} \]

quadratic density dependence
→ atom-atom-ion three-body coefficient

A. Härtler et al. PRL 2012, in press
Three stories

1) Putting atoms to work in an ion trap: cooling and micromotion compensation

2) An ion as a three-body reaction center

3) A "mysterious" production of Rb\(^+\) and Rb\(_2\)\(^+\) ions
A „mysterious“ production of Rb\(^+\) / Rb\(_2\)^+ ions

\[ 4 \times 10^4 \ \text{^{87}Rb} \text{ atoms in an optical dipole trap at 1064 nm; } \]
\[ \sim 1 \mu K \text{ temperature; density } \sim 10^{13} \ \text{cm}^{-3}; \]

After a few seconds…
there is a Rb\(^+\) ion
(or even a Rb\(_2\)^+ ion)
Not a background effect, i.e. no charge transfer collisions of hot ions!

Ion production rate is quadratic in atomic density!
\[ \rightarrow 3\text{-body recombination process of Rb atoms!} \]

But that is not nearly enough energy to ionize Rb!!

\[ I_L = 4 \cdot 10^4 \text{ W/cm}^2 \]

![Graph showing ion production rate vs. atomic density](image)
You need 3 or 4 1064nm photons!

3 Rb $\rightarrow$ Rb$_2$ + Rb
Rb$_2$ + 3$\gamma$ $\rightarrow$ Rb$_2^+$ + e$^-$

Resonantly enhanced?
1064nm laser plays a crucial role!

Clear resonance structure!!

Laser frequency (GHz) – 281632 GHz
1064nm laser plays a crucial role!

High resolution! Narrow linewidths ~ 50 MHz!

Laser frequency (GHz) – 281632 GHz

- small Doppler broadening
- Rb$_2$ molecules slow after three-body recombination
- energy released in three body-recombination is not large (< 0.01 eV)
1064nm laser plays a crucial role!

Many lines!

Looks like hyperfine and rotational spectrum!

Can we understand the spectrum? Perhaps part of it!
From recent spectroscopy we know several spectra quite well!! (~200 MHz precision!)

Strauss et al., PRA (2010)
Takekoshi et al., PRA (2011)

collaboration with E. Tiemann

Possible resonance transition
\( a^3\Sigma_u, v = 26 \rightarrow a^3\Sigma_g, v' = 0 \)
Some calculated transitions

\[ ^3\Sigma_u, \; v = 26, \; + \text{parity} \rightarrow ^3\Sigma_g, \; v'= 0 \]

We might learn something about the three-body recombination!!

Preliminary calculations

Calculations from E. Tiemann, Hannover
What do we produce more of: Rb$^+$ and Rb$_2^+$?

This depends!

If we extract the ion quickly from the atom cloud ($\sim \mu s$), then we get mostly Rb$_2^+$ (55%) otherwise mostly Rb$^+$ ($\sim 97$%).

Possibly:

a) Ionization always produces Rb$_2^+$

b) Afterwards

$$\text{Rb}_2^+ + \text{Rb} + \gamma (?) \rightarrow \text{Rb}^+ + 2 \text{Rb} (?)$$
Three stories

1) Use atoms
   - cool ion
   - micromotion compensation

2) An ion as a three-body reaction center
   \[ \text{Rb}^+ + 2\text{Rb} \rightarrow \text{Rb}^+ + \text{energy} + (2\text{Rb}) \]

3) A “mysterious“ production of Rb ions
   \[ 3 \text{Rb} + 3\gamma \rightarrow \text{Rb}_2^+ + e^- + \text{Rb} \]
   \[ 3 \text{Rb} + 4\gamma \rightarrow \text{Rb}^+ + e^- + (2\text{Rb}) \]