

Concept

# Elements of QIP with Trapped $\text{Yb}^+$ -Ions

Experiment

## Team Hamburg

Theory

W. Neuhauser

Chr. Balzer

A. Braun

M. Ettlér

Chr. Wunderlich

Th. Hannemann

N. Timoney

M. Loewen

F. Mintert

Chr. Paape

I. Weisgerber

Concept

# Elements of QIP with Trapped $\text{Yb}^+$ -Ions

Experiment

## Team Siegen

Theory

Chr. Wunderlich

V. Elman

A. Braun

Chr. Schneider

M. Johanning

D. Brüser

C. Weiss

Th. Collath

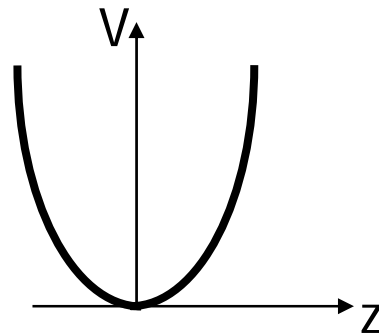
A. Khromova

N. Timoney

# Ion Spin "Molecule"

## State dependent force

Concept



Experiment

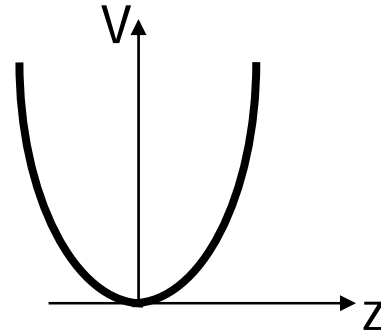


Theory



# Ion Spin "Molecule" State dependent force

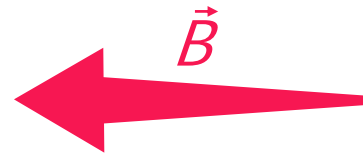
Concept



Experiment



Theory

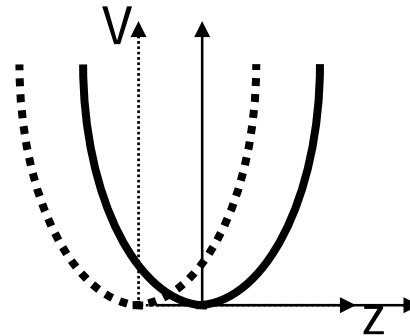




# Ion Spin "Molecule"

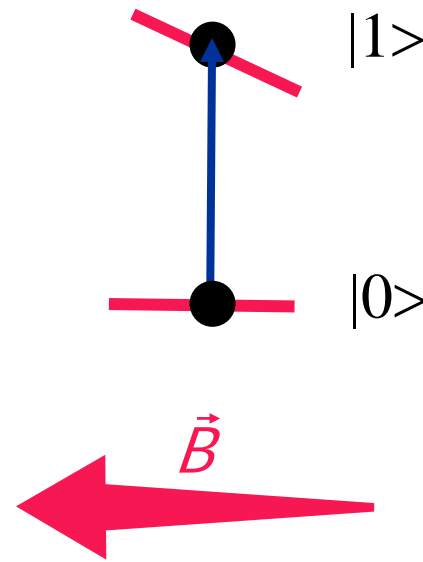
## State dependent force

Concept



Experiment

Theory



# Ion Spin "Molecule"

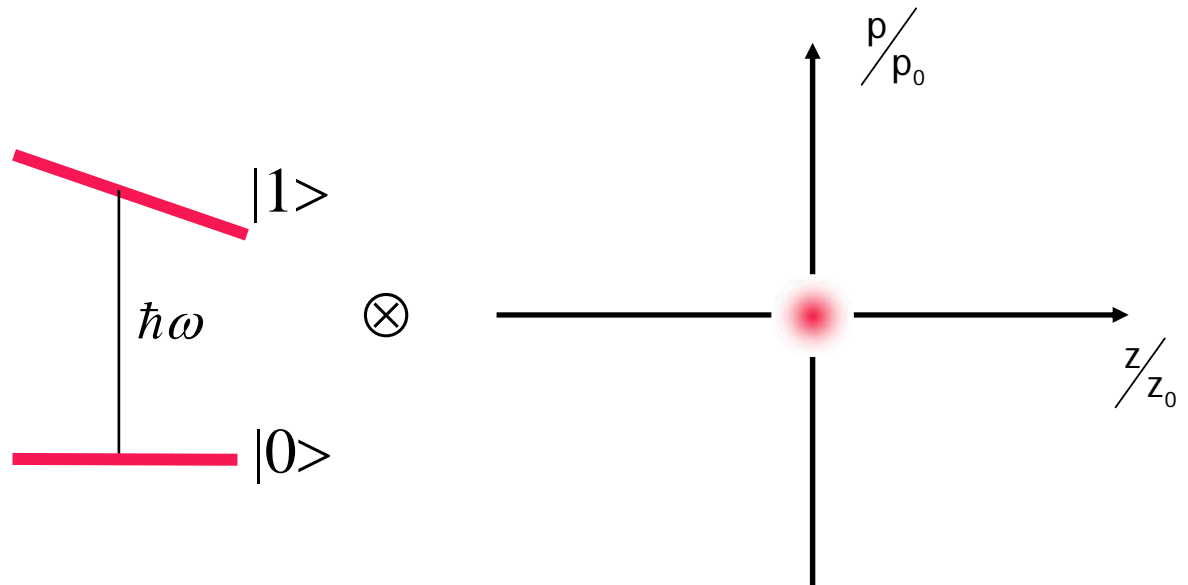
## Coupling internal/motional dynamics

Concept

- Application of field gradient:

Experiment

Theory



# Ion Spin "Molecule"

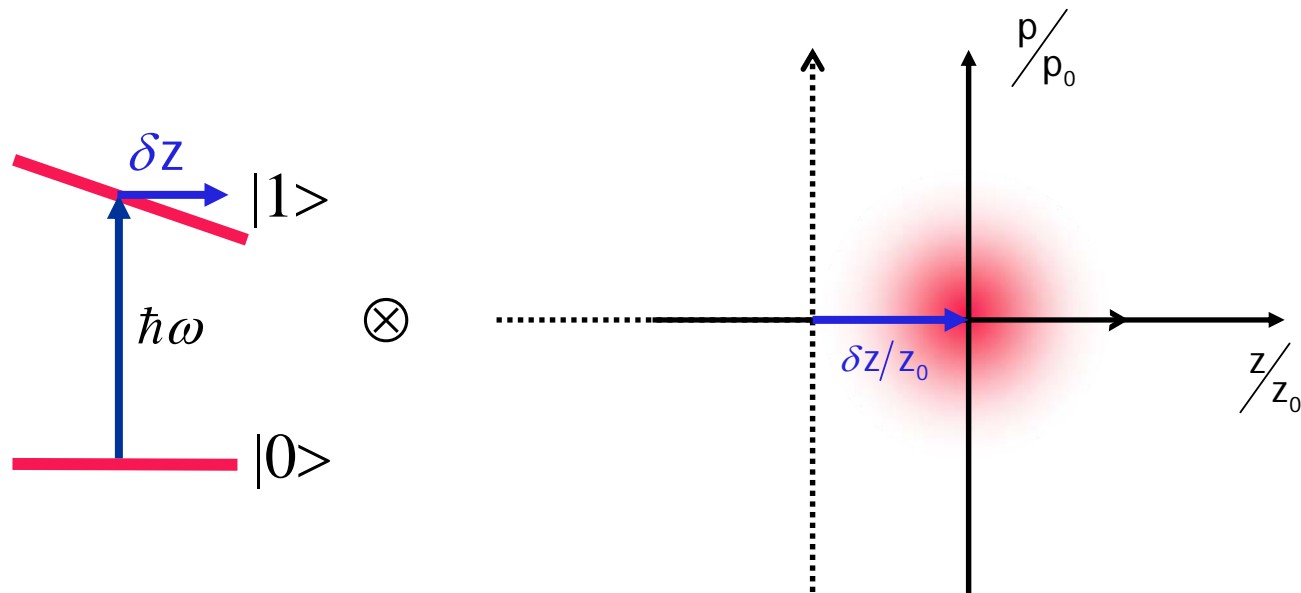
## Coupling internal/motional dynamics

Concept

- Application of field gradient:

Experiment

Theory



Coupling parameter:  $\kappa \equiv \frac{\delta z}{z_0} \propto \frac{\partial_z \omega}{\nu^{3/2}}$

# Ion Spin "Molecule"

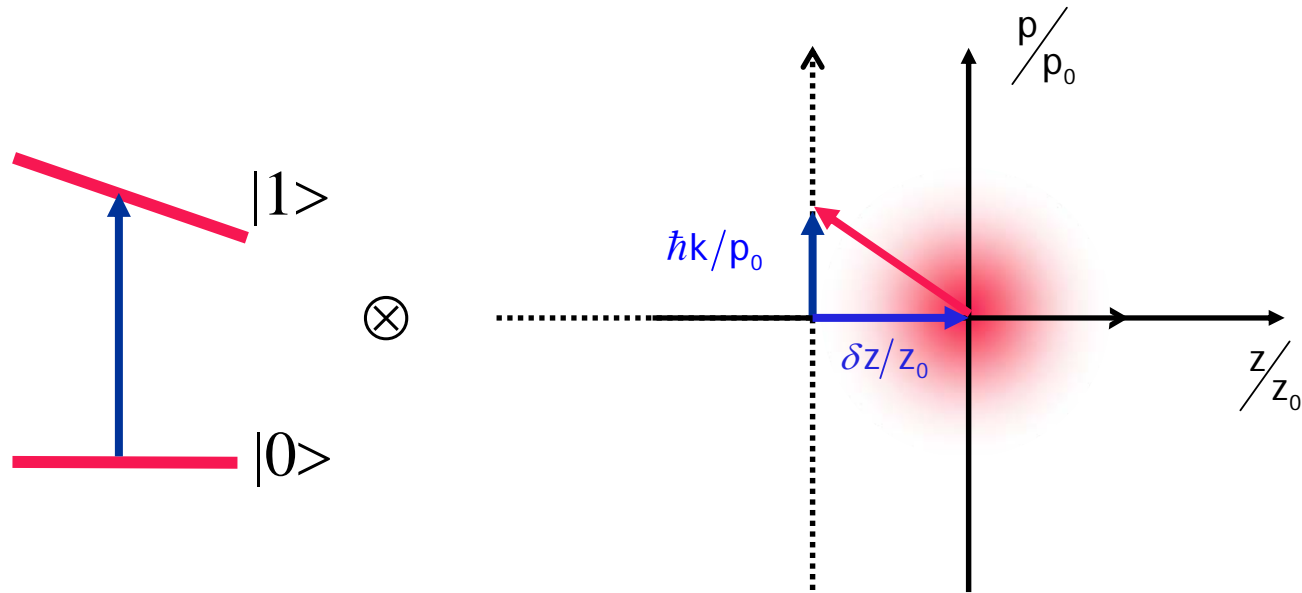
## Coupling internal/motional dynamics

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- Application of field gradient:

Experiment

Theory



Coupling parameter:  $\kappa \equiv \frac{\delta z}{z_0} \propto \frac{\partial_z \omega}{v^{3/2}}$

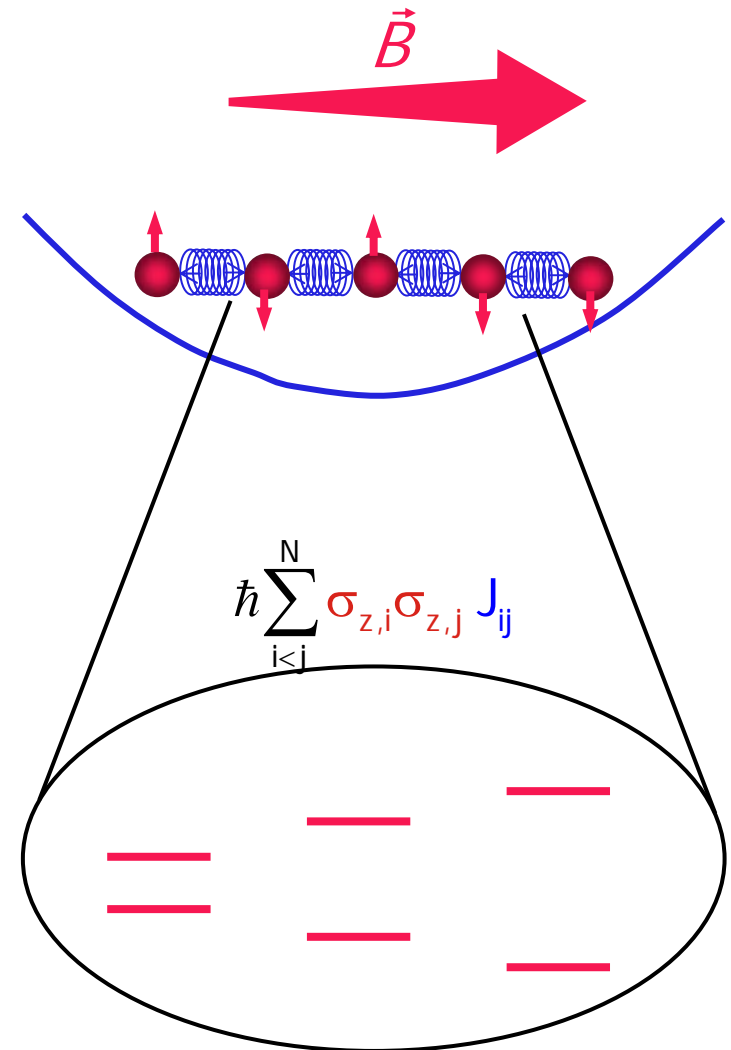
# Ion Spin "Molecule"

Concept

Experiment

Theory

- Qubit resonances shifted individually: addressing in frequency space
- Spin-Spin coupling between individual qubits



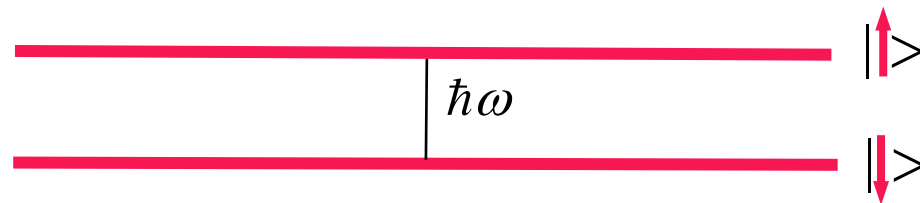
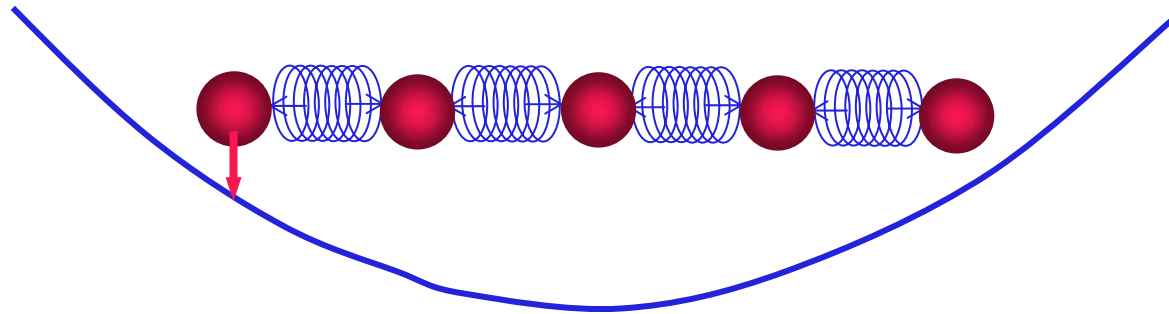
# Ion Spin "Molecule"

## Spin-Spin-Coupling

Concept

Experiment

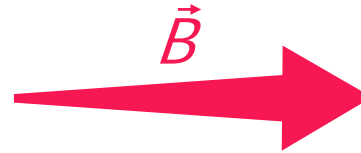
Theory



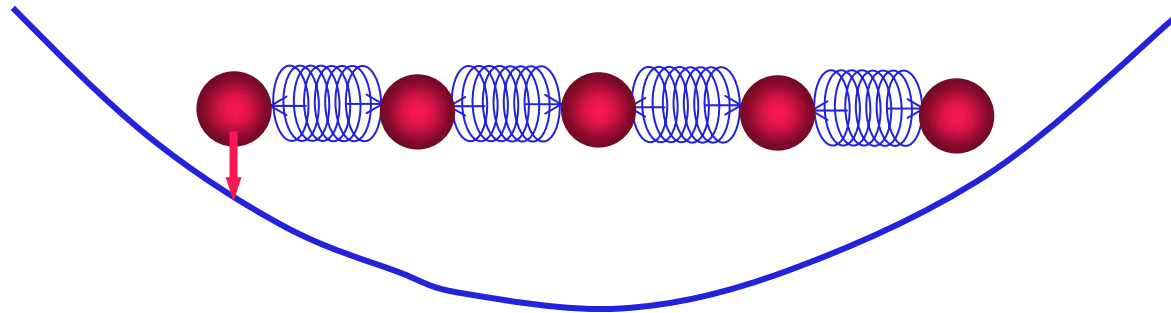
# Ion Spin "Molecule"

## Spin-Spin-Coupling

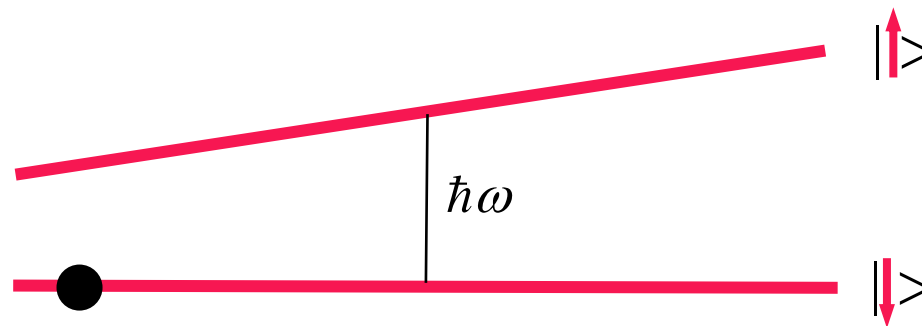
Concept



Experiment



Theory





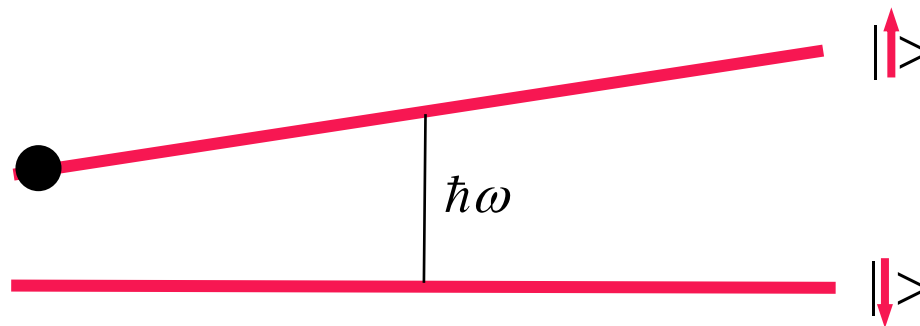
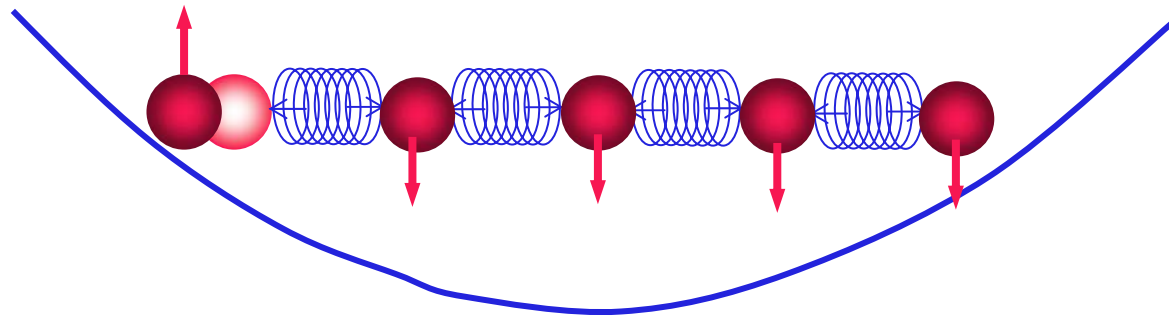
# Ion Spin "Molecule"

## Spin-Spin-Coupling

Concept

Experiment

Theory





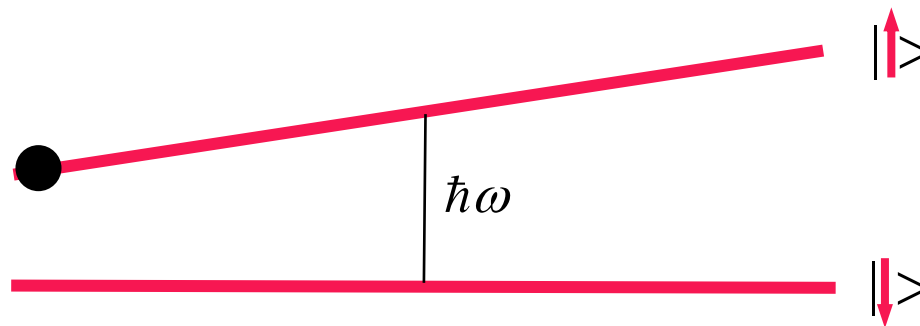
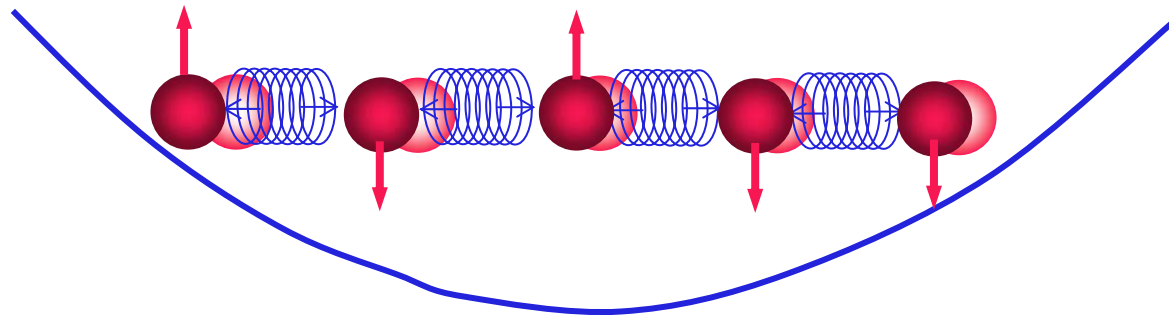
# Ion Spin "Molecule"

## Spin-Spin-Coupling

Concept

Experiment

Theory



# Ion Spin "Molecule"

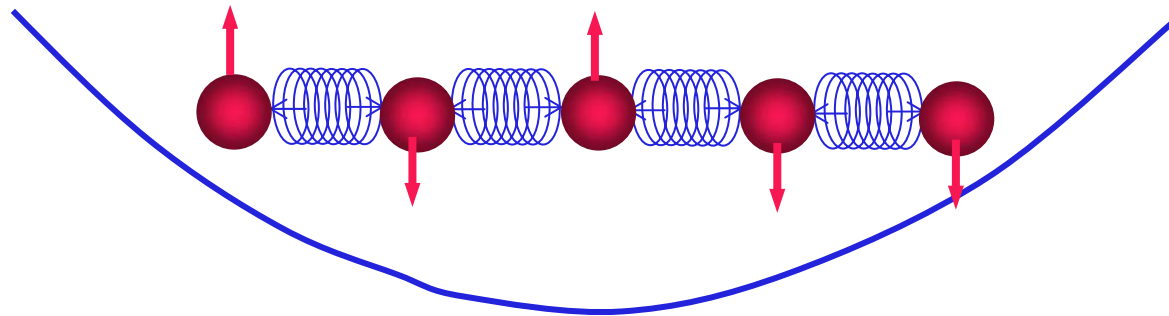
## Spin-Spin-Coupling

$$\tilde{H} = H_{\text{intern}} + H_{\text{extern}} - \hbar \sum_{i < j}^N \sigma_{z,i} \sigma_{z,j} \underbrace{\left[ \frac{1}{2} \sum_{n=1}^N v_n K_{ni} K_{nj} \right]}_{J_{ij}}$$

Concept

Experiment

Theory



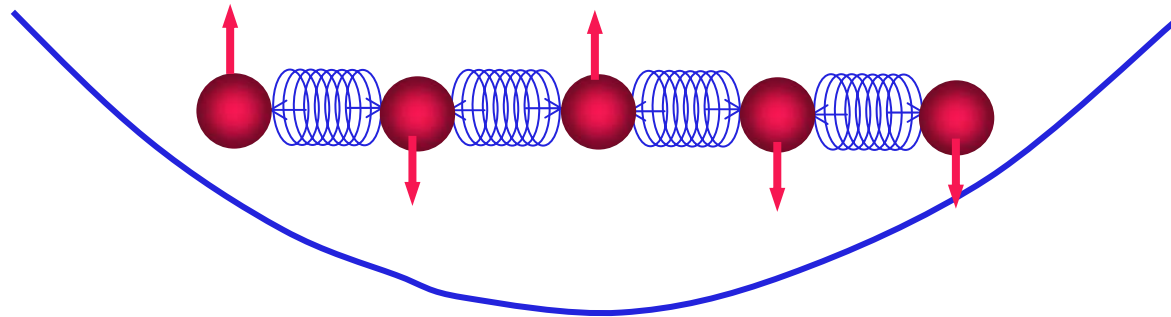
# Ion Spin “Molecule”

## Spin-Spin-Coupling

Concept

Conditional dynamics:  $\hbar \sum_{i < j}^N J_{ij} \sigma_{z,i} \sigma_{z,j}$  with  $J_{ij} \propto \left( \frac{\partial_z B}{v_1} \right)^2$

Experiment



Theory

Individual N-qubit “designer molecule”  
with adjustable coupling constants

CW in *Laser Physics at the Limit*, Springer, 2002, p. 261.  
available as quant-ph/0111158.

D. Mc Hugh, J. Twamley PRA **71**, 012315 (2005), quant-ph/0310015

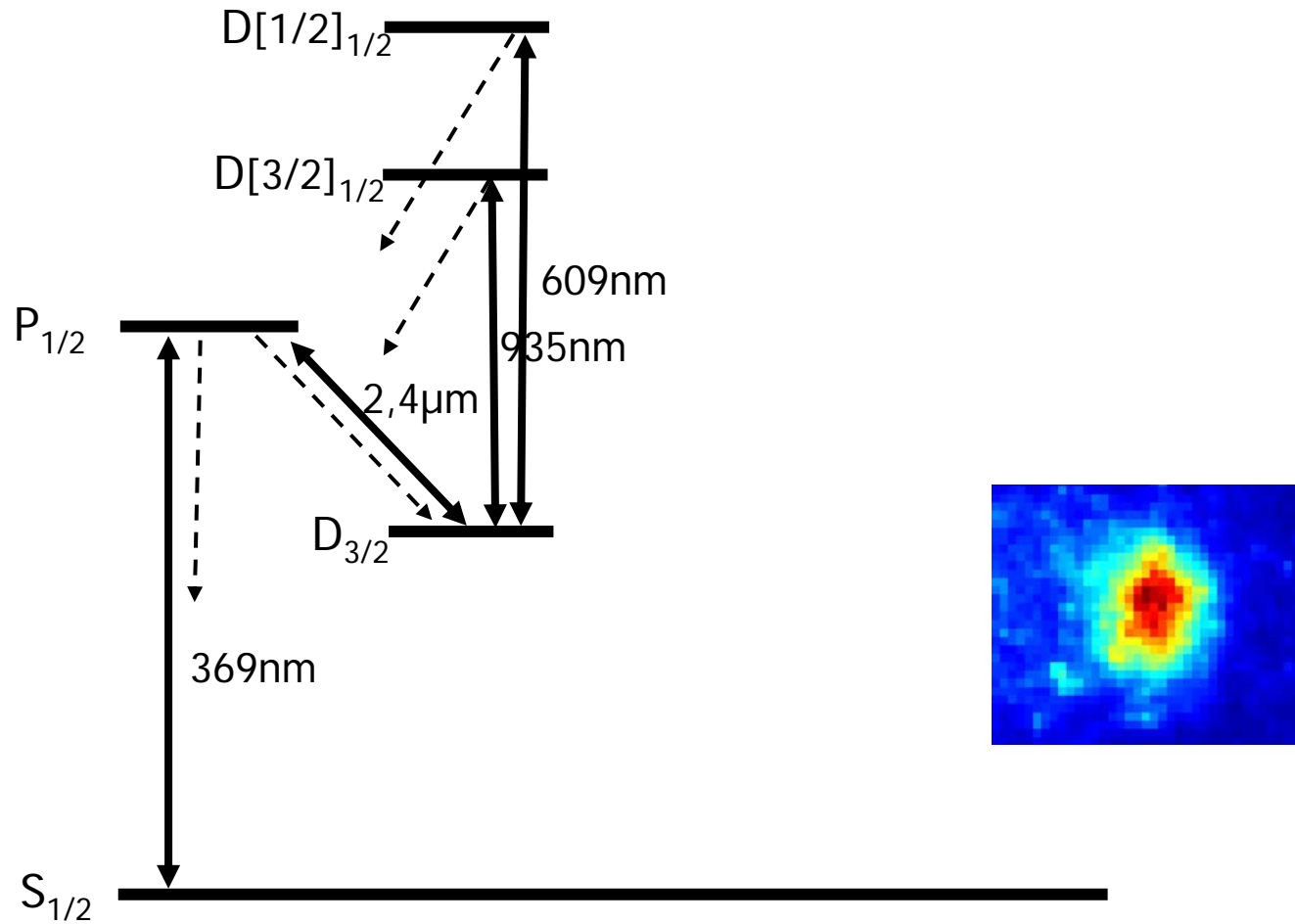
Spin coupled system using *optical* force instead:  
D. Porras and J. I. Cirac PRL **92**, 207901 (2004)

# Cooling and Detection of $\text{Yb}^+$

Concept

Experiment

Theory

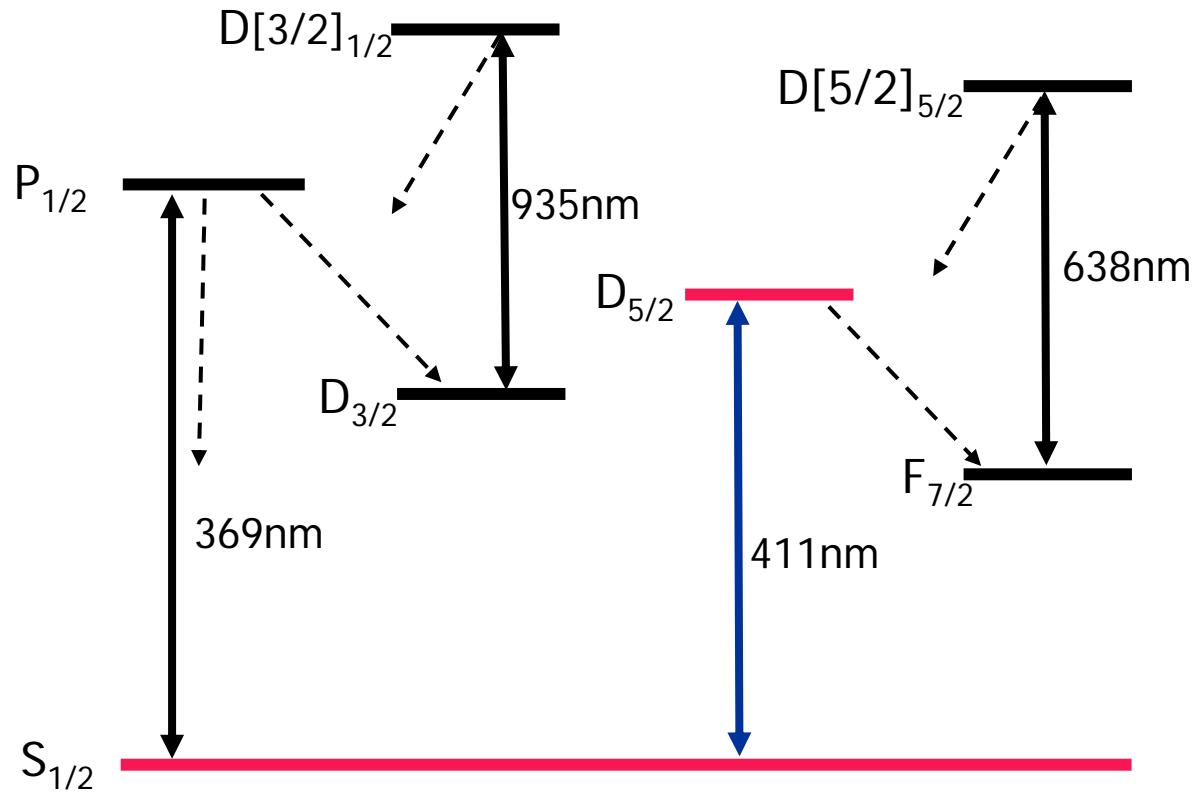


# Cooling and Detection of $\text{Yb}^+$

Concept

Experiment

Theory

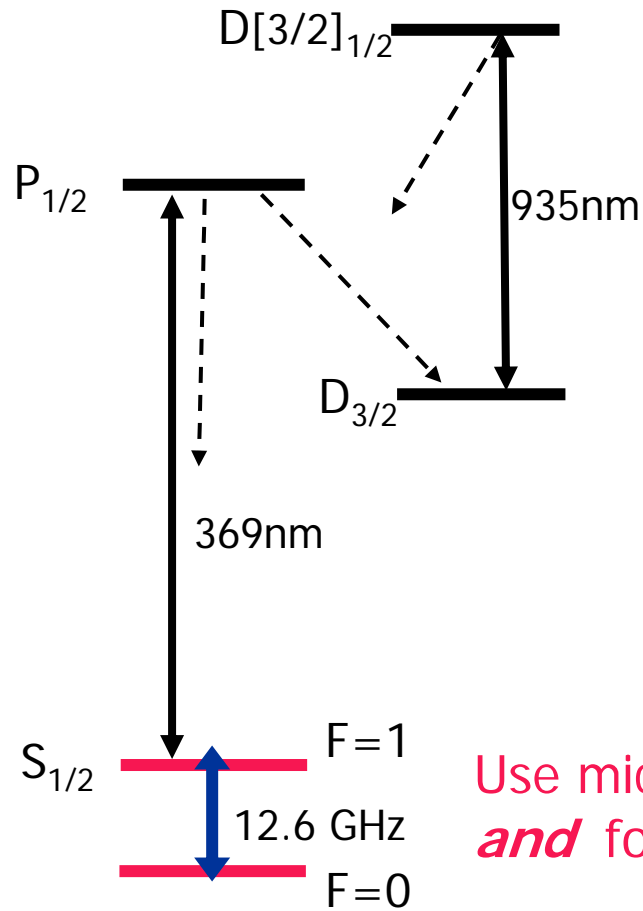


# Cooling, Detection, and Qubit

Concept

Experiment

Theory



Use microwave radiation for single-qubit gates *and* for conditional quantum dynamics.



# Photoionization

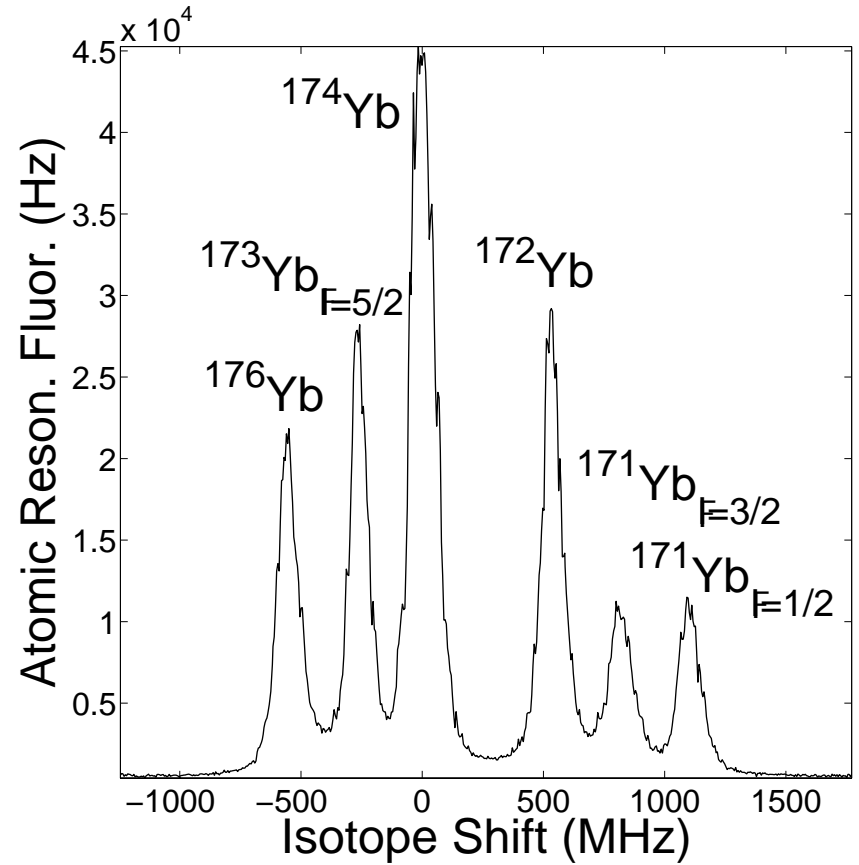
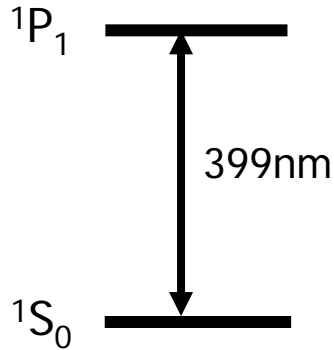
## Dopplerfree resonance fluorescence spectrum of Yb

Concept



Experiment

Theory



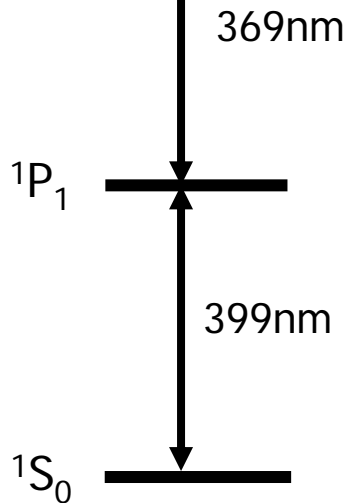
# Photoionization

## Loading of trap: photoionisation vs. $e^-$ collision

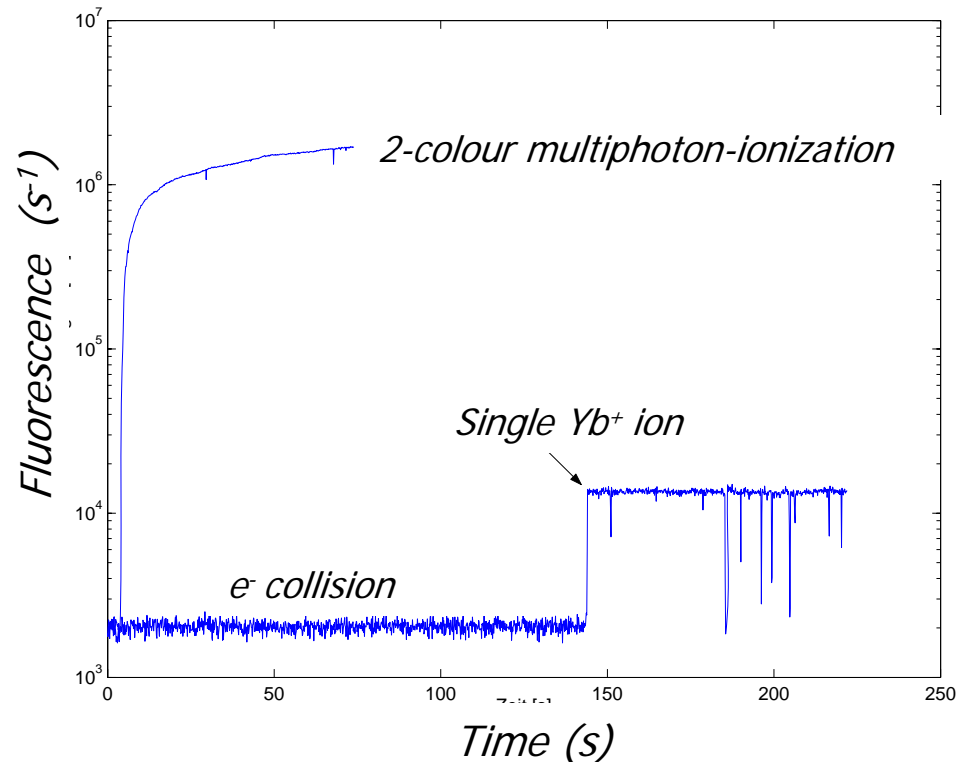
Concept



Experiment



Theory



- Trap structure remains free from  $e^-$  charge build-up.
- Trap remains free from deposition of atoms.
- Isotope selective.

# Photoionization

## Nearly deterministic loading by photoionization

Concept



Experiment

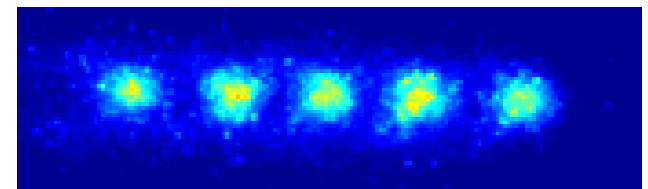
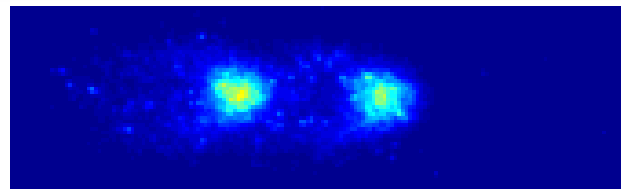
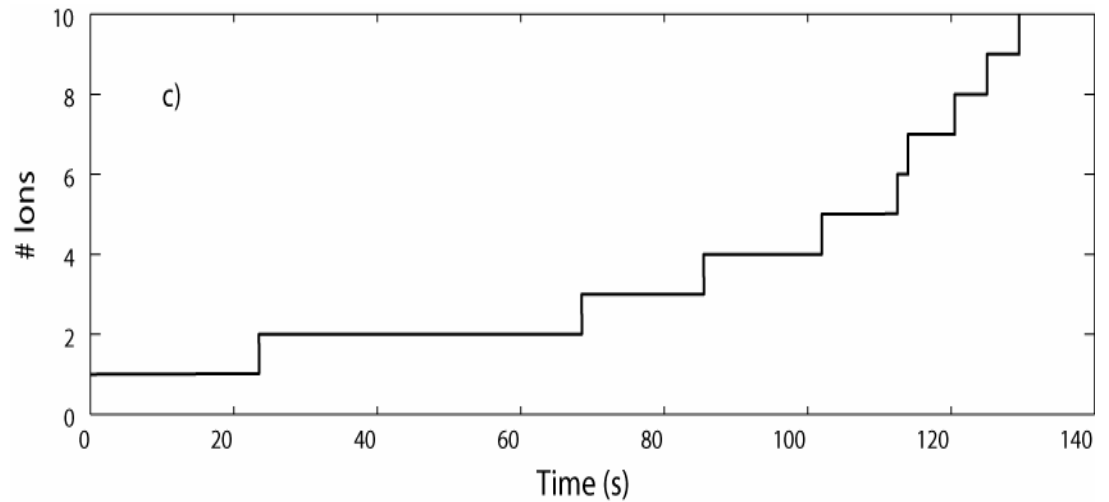
369nm

1P<sub>1</sub>

Theory

399nm

1S<sub>0</sub>





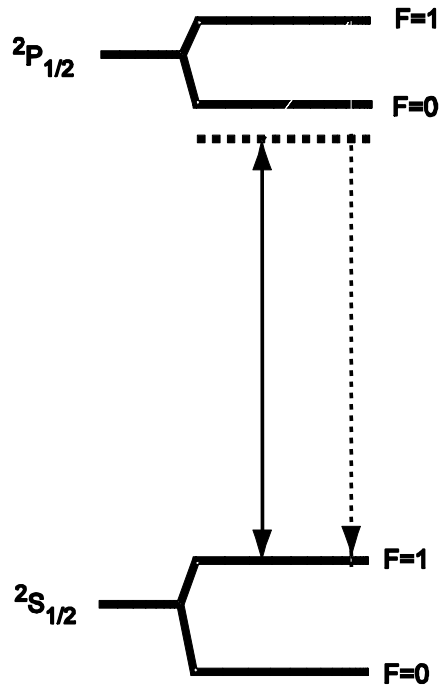
# Optimal State Preparation

## $^{171}\text{Yb}^+$ : Cooling, Detection

Concept

Experiment

Theory





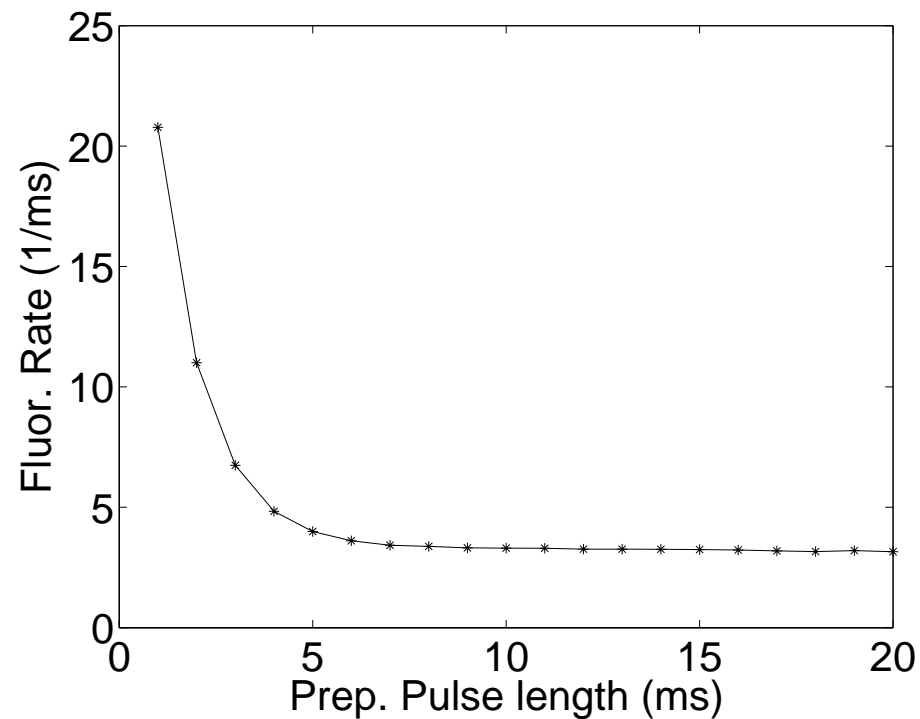
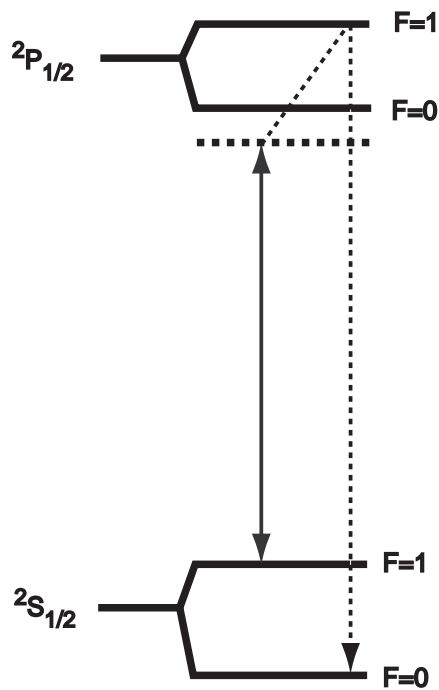
# Optimal State Preparation

## $^{171}\text{Yb}^+$ : Preparation in $S_{1/2} F=0$

Concept

Experiment

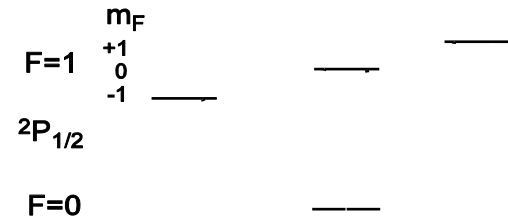
Theory



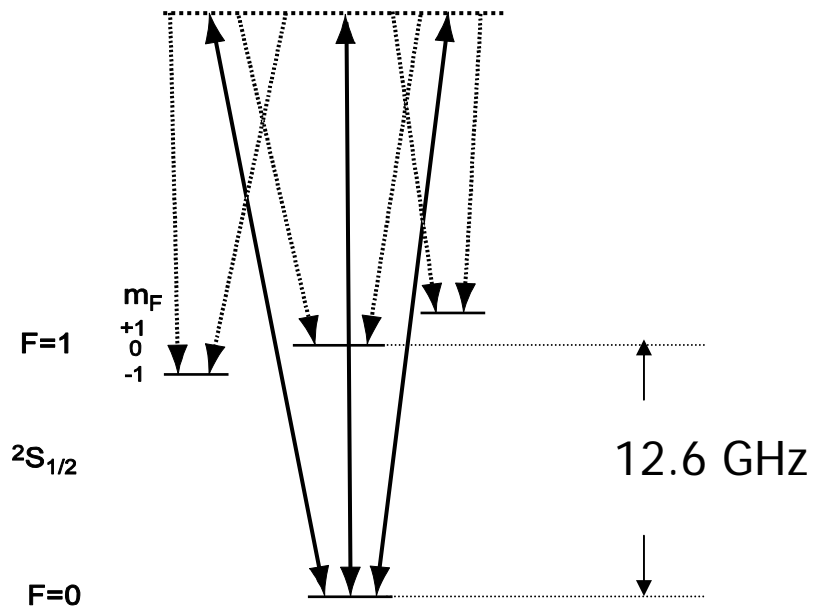
# Optimal State Preparation

## $^{171}\text{Yb}^+$ : Preparation in $S_{1/2} F=0$

Concept



Experiment



Theory

Is there a set of parameters allowing for efficient detection *and* state preparation?



# Optimal State Preparation

## $^{171}\text{Yb}^+$ : Preparation in $S_{1/2}$ $F=0$

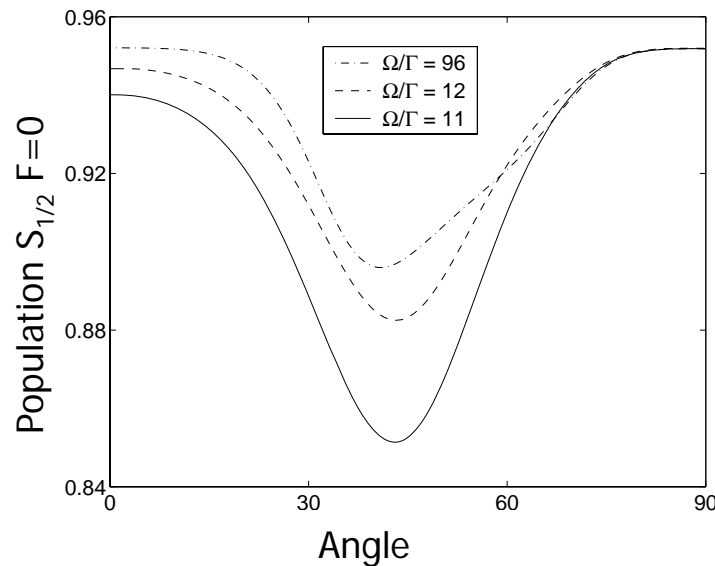
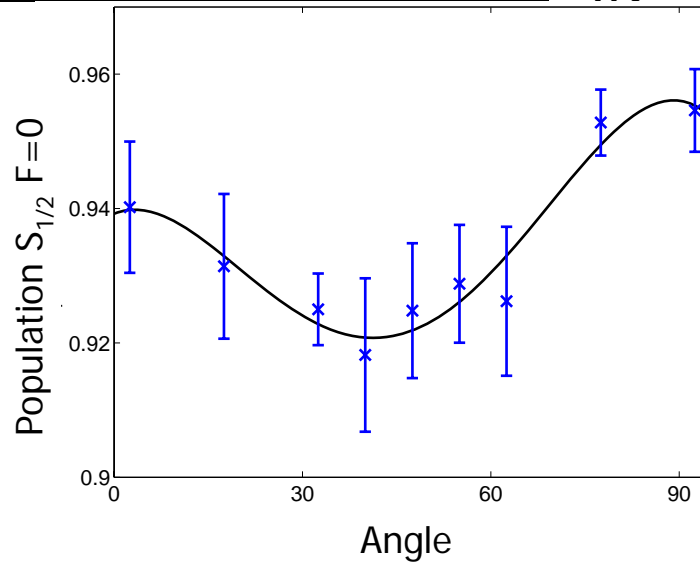
Concept

Experiment

Theory

Experiment

Theory

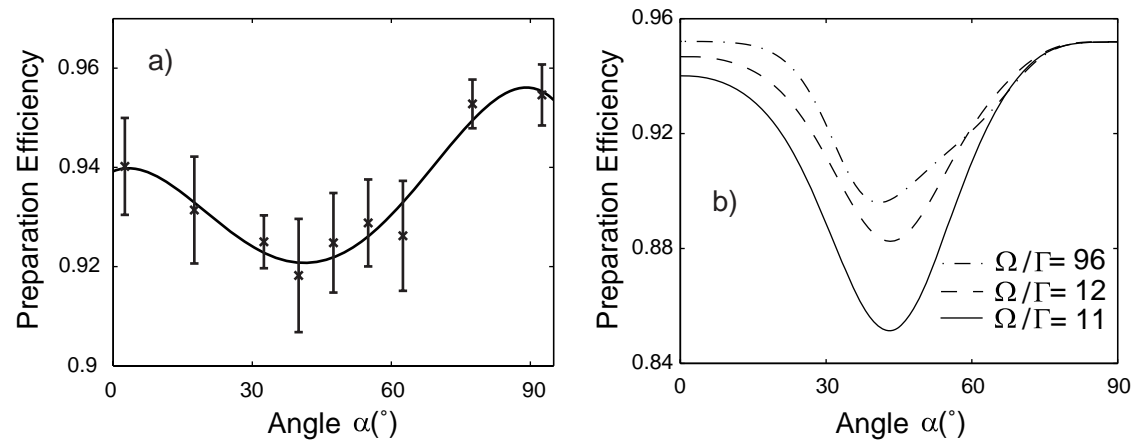


# Optimal State Preparation

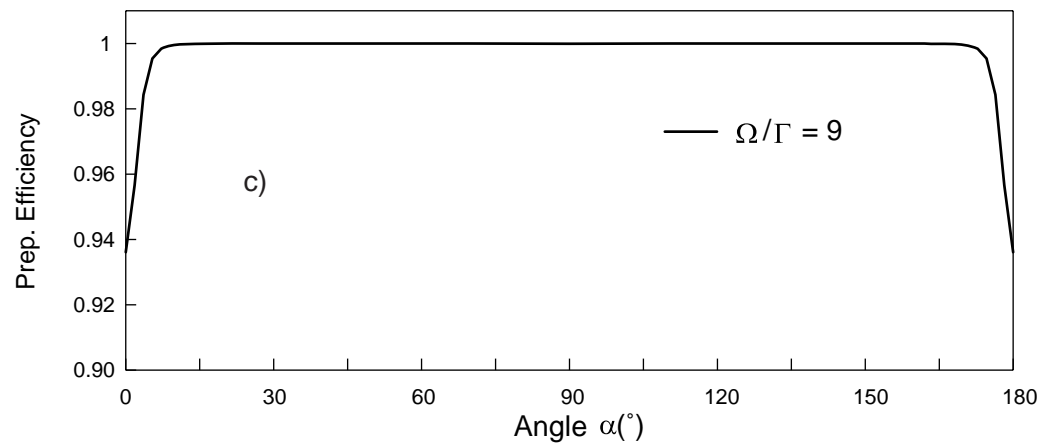
## $^{171}\text{Yb}^+$ : Preparation in $S_{1/2}$ $F=0$

Concept

Experiment



Theory

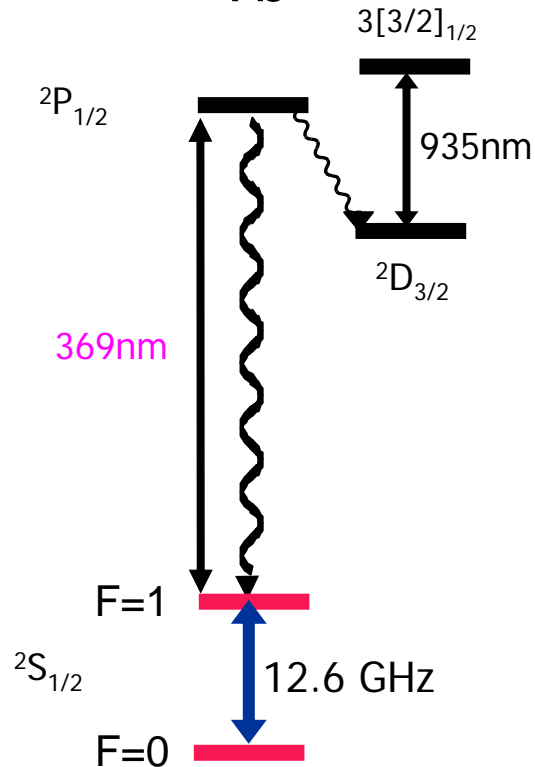


# Coherent Dynamics

## Rabi oscillations

Concept

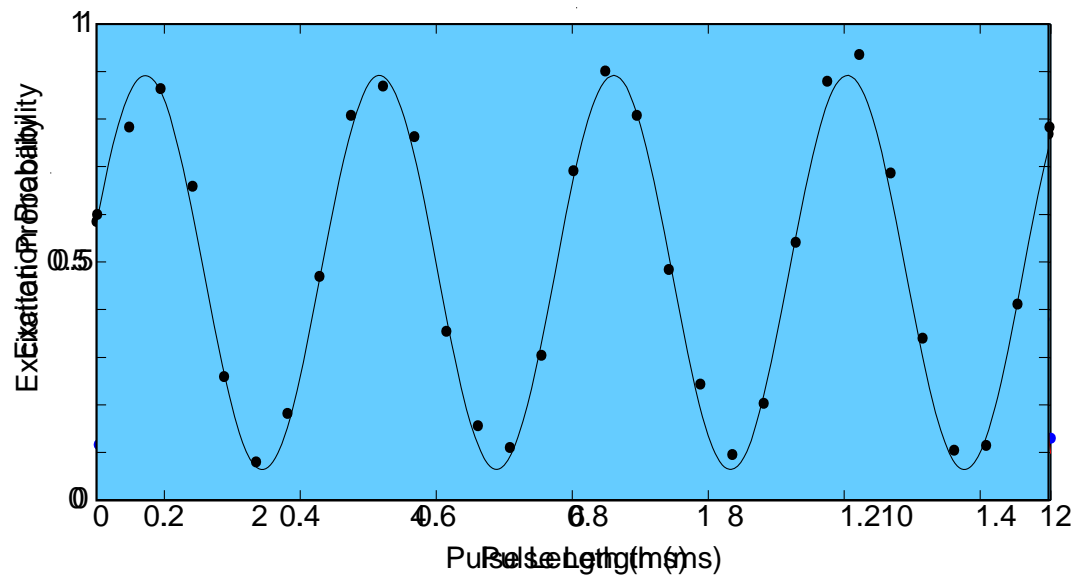
Yb<sup>+</sup>



Experiment

Theory

Individual Yb<sup>+</sup>-Ion



Rabi oscillations

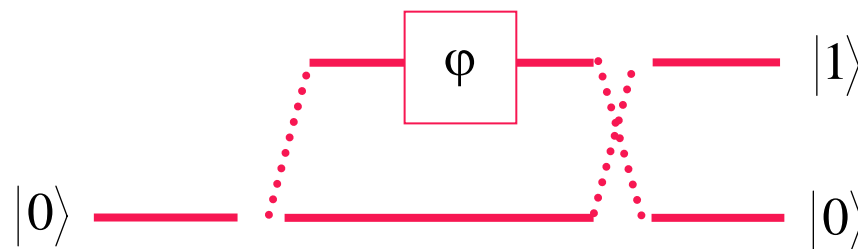
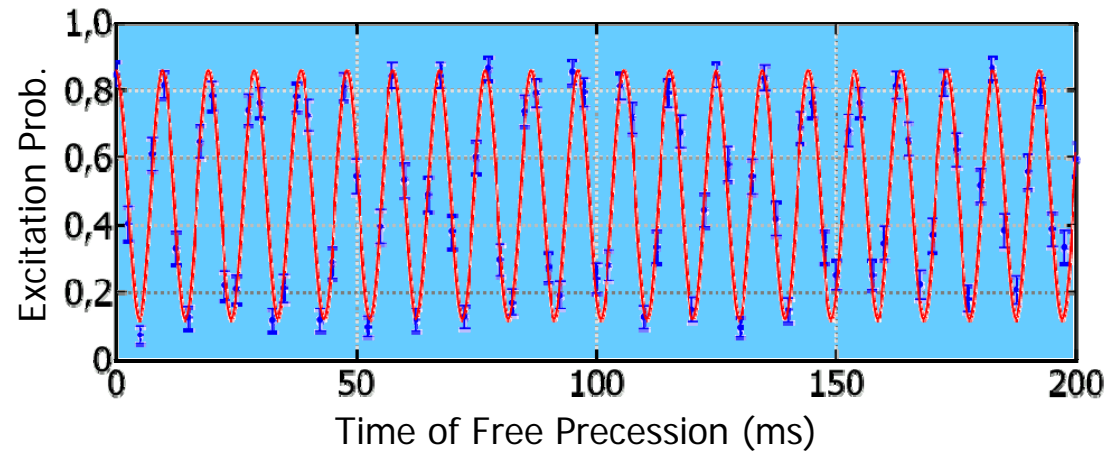
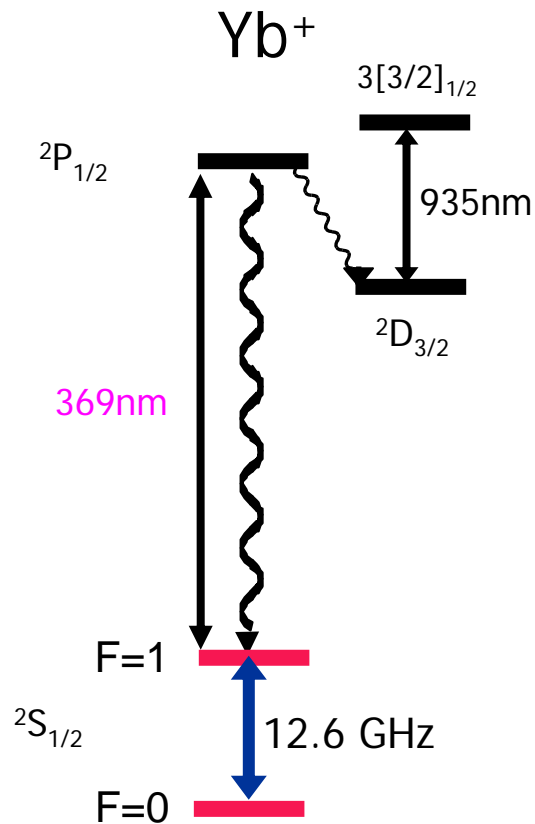
# Coherent Dynamics

## Ramsey Interference

Concept

Experiment

Theory



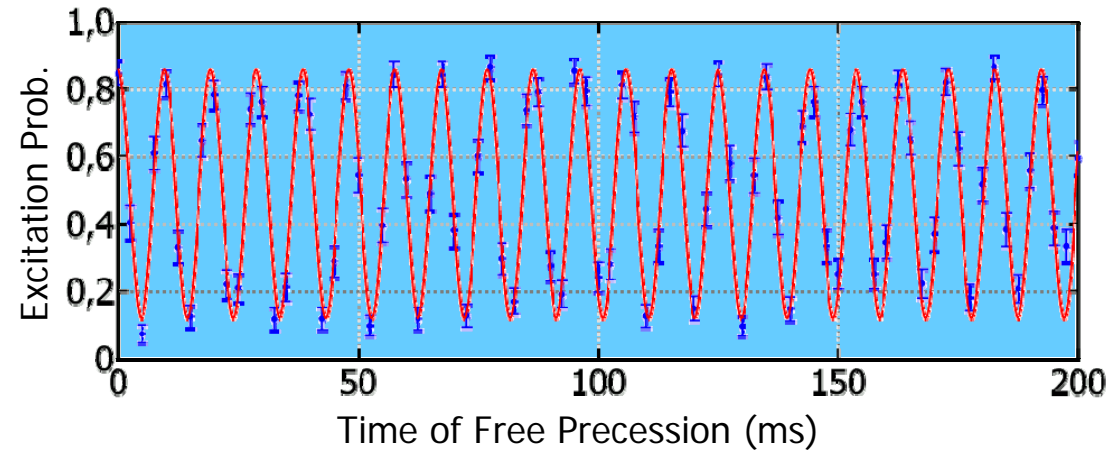
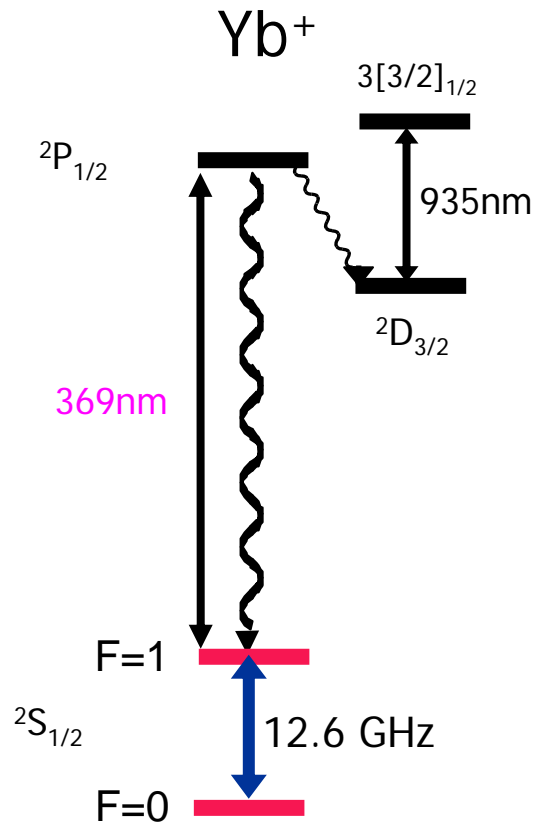
# Coherent Dynamics

## Ramsey Interference

Concept

Experiment

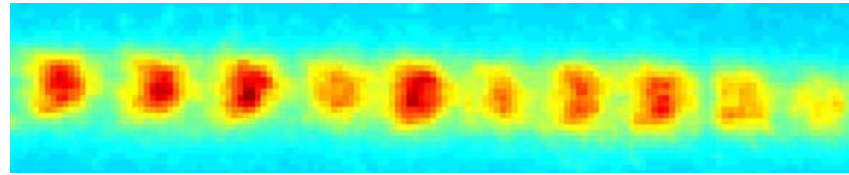
Theory



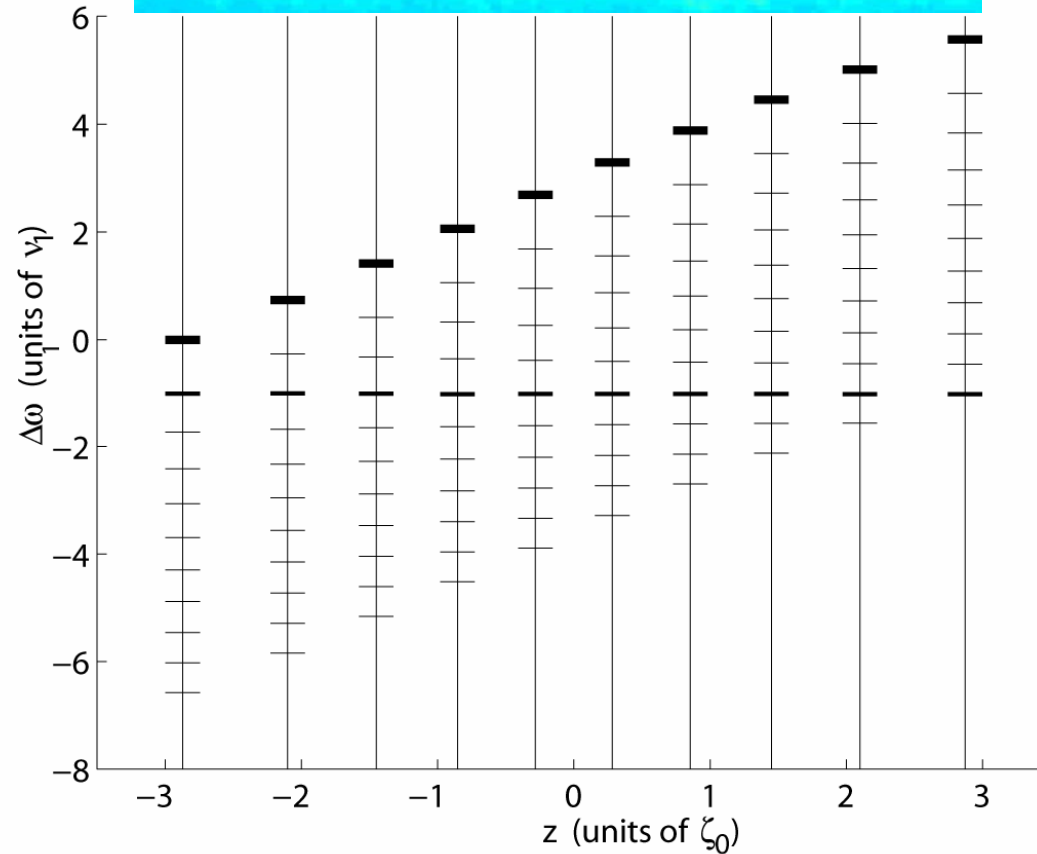
(Nearly) optimal quantum state estimation:  
Th. Hannemann et al. PRA **65**, 050303(R) (2002)

# Simultaneous Cooling of vibrational modes

Concept



Experiment



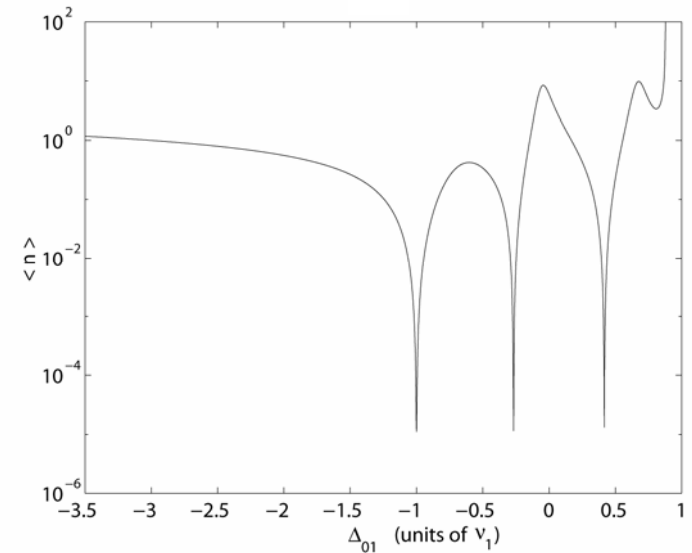
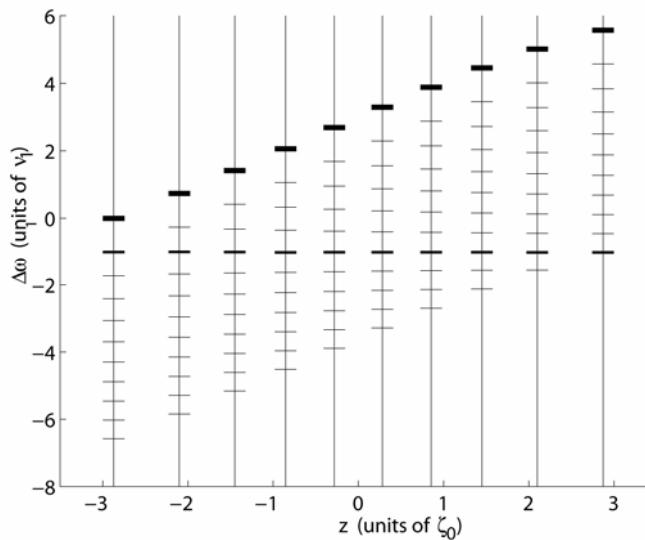
Theory

# Simultaneous Cooling of vibrational modes

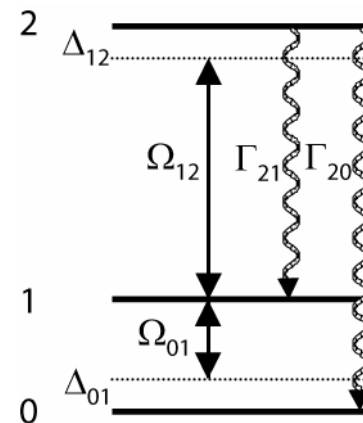
Concept

Experiment

Theory



CW, G. Morigi, D. Reiß,  
Phys. Rev. A **72**, 023421 (2005).

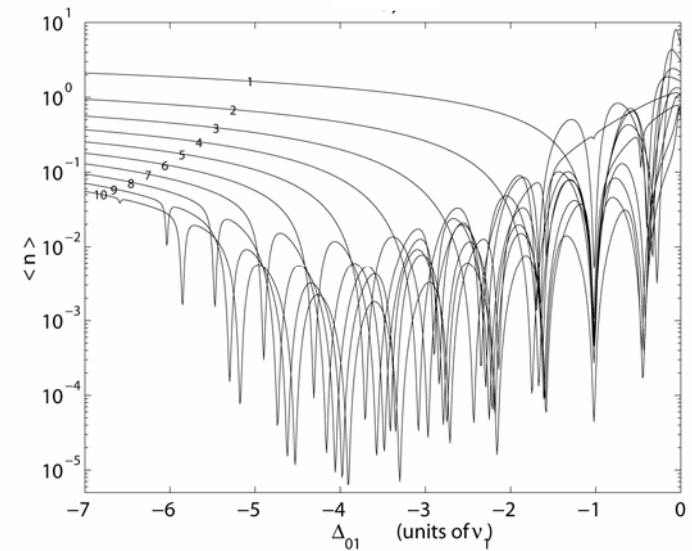
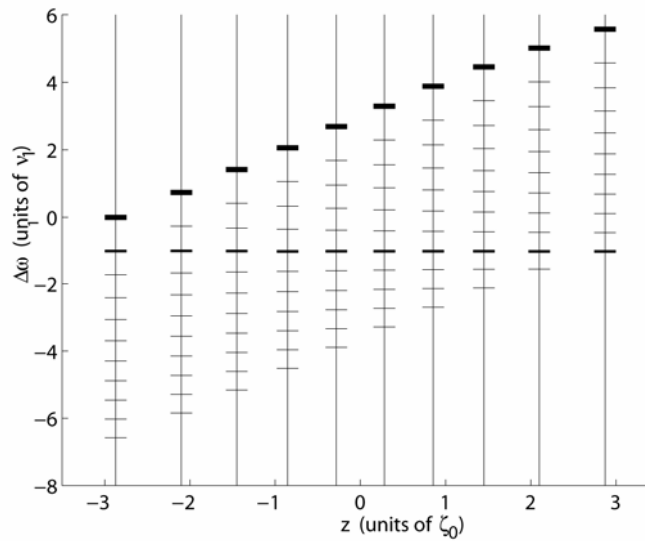


# Simultaneous Cooling of all vibrational modes

Concept

Experiment

Theory<sup>+</sup>



$$\Omega_{12} = 1 \times 2\pi\text{MHz}, \quad \Omega_{01} = 5 \times 2\pi\text{kHz}$$

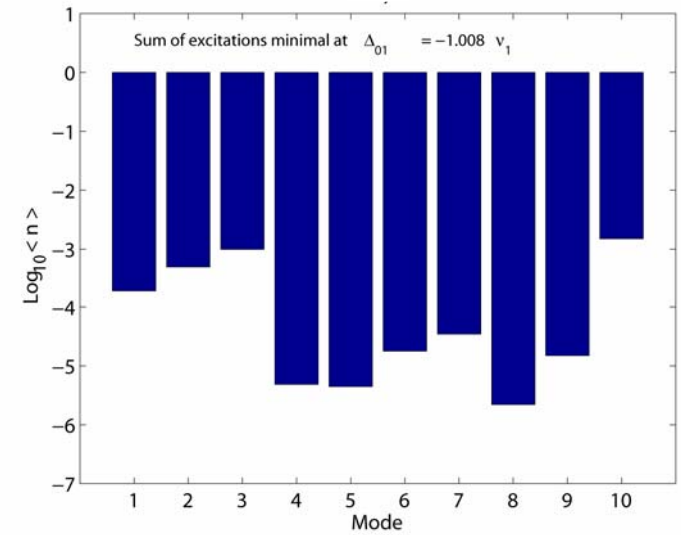
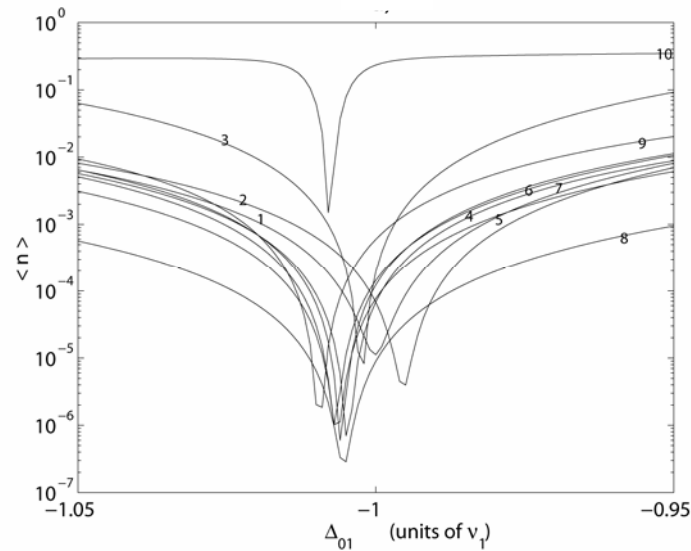
$$\Delta_{12} = -10 \times 2\pi\text{MHz}$$

# Simultaneous Cooling of vibrational modes

Concept

Experiment

Theory



$$\Omega_{12} = 100 \times 2\pi\text{kHz}, \quad \Omega_{01} = 5 \times 2\pi\text{kHz}$$

$$\Delta_{12} = -10 \times 2\pi\text{MHz}$$

# Ion Spin Molecule

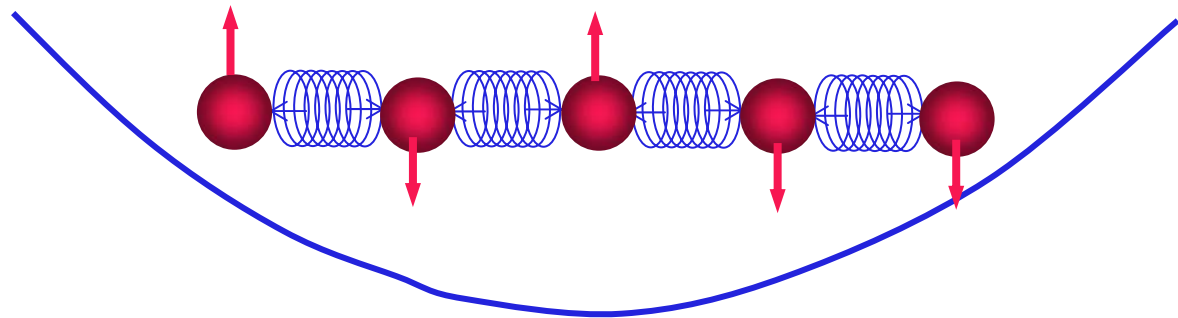
## Thermal Excitation

Concept

$$\tilde{H} = -\frac{\hbar}{2} \sum_{n=1}^N \omega_n \sigma_z^{(n)} + \hbar \sum_{n=1}^N \nu_n a_n^\dagger a_n - \frac{\hbar}{2} \sum_{\substack{k,l=1 \\ k < l}}^N J_{kl} \sigma_z^{(k)} \sigma_z^{(l)} + \tilde{W}$$

Experiment

Theory



# Ion Molecule

## Thermal effects: Summary

Concept	⇒ Resonance frequencies depend on occupation of modes: <b>Compensated by refocussing.</b>	} Scale favourably with $\nu_z$
Experiment	⇒ 3-Qubit coupling is induced: <b><math>\approx 10^{-6} J_{ij}</math>.</b>	
Theory	⇒ Thermally induced 2-Qubit coupling: <b>Max. rel. shift <math>\approx 10^{-3} J_{ij}</math>.</b>	
	⇒ 1-Qubit rotations: <b>Fidelity <math>\approx 1 - 10^{-5}</math></b>	

⇒ **Quantum logic with thermal ensemble feasible**

# Ion Spin Molecules

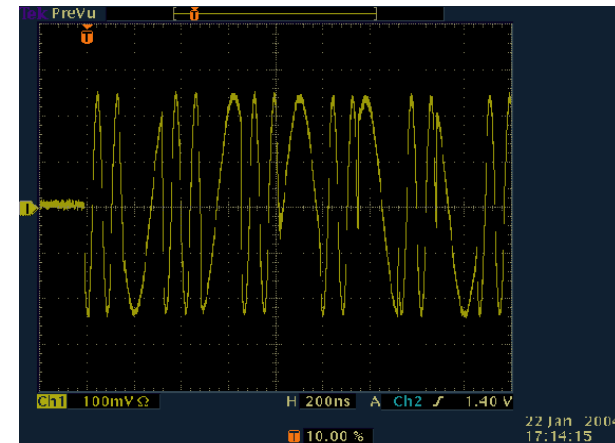
- Coherent manipulation using rf and microwave radiation of long-lived spin states.
- Use sophisticated NMR concepts and techniques.
- Spin-spin coupling adjustable.
- (Nearly) insensitive to thermal excitation  $\Rightarrow$  many ions in single trap:
  - Multi-qubit gates.
  - Quantum simulations.
  - Transport of quantum information.
  - Entanglement and decoherence.



# Hardware

## Phase coherent signal generator

- Coherent manipulation:  
reference needed for each qubit's evolution
- Conventionally requires one dedicated oscillator per qubit.
- Generator preserves relative phase for all qubits when switching between frequencies.  
**Phase coherent and phase continuous switching in ns.**
- Frequency range: 1 - 150 MHz,  
resolution better 0.1 Hz.
- Freely programmable via USB from PC.

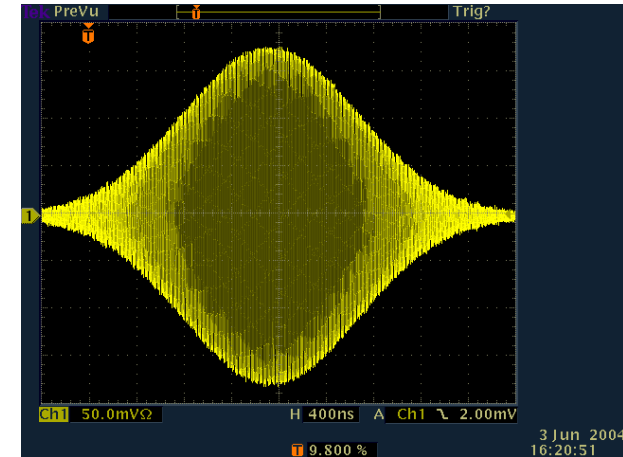




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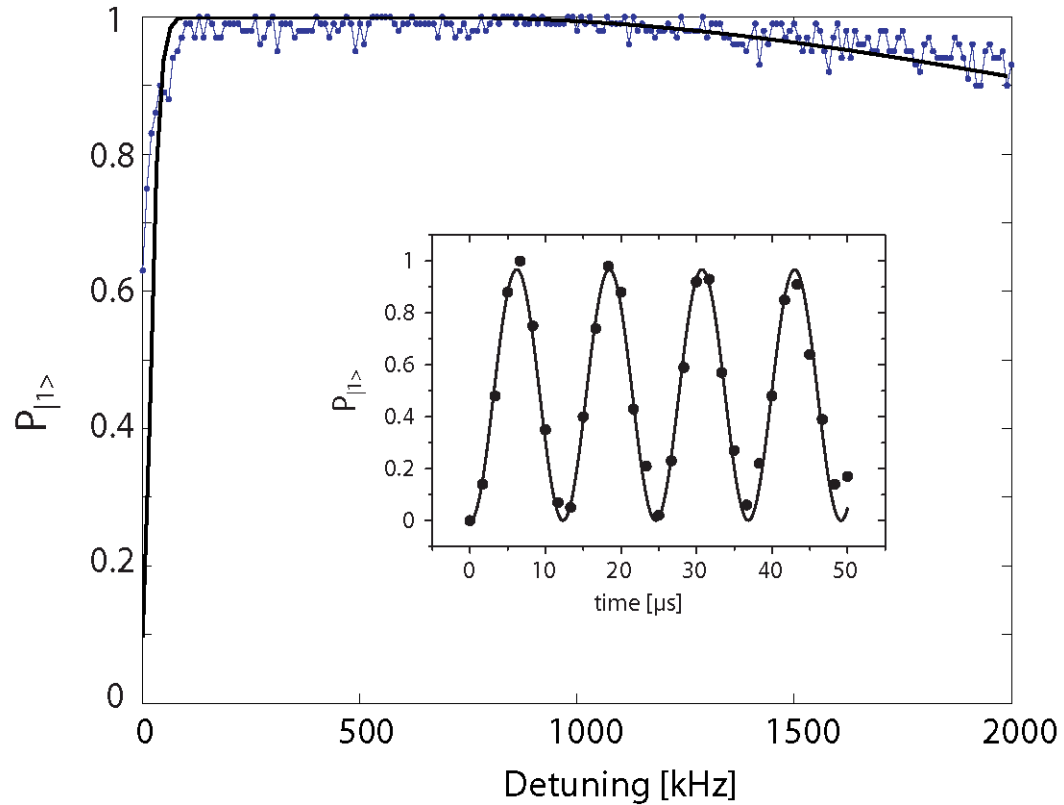


# Adiabatic transfer

Concept

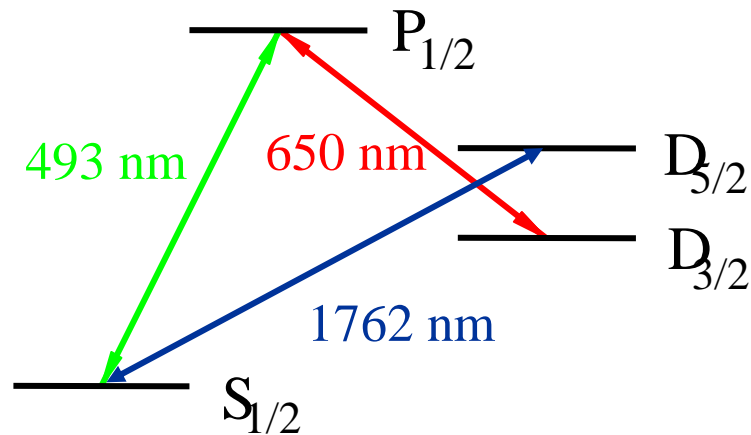
Experiment

Theory+



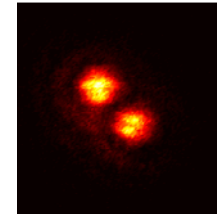
# QIP with trapped ions

Ba<sup>+</sup>

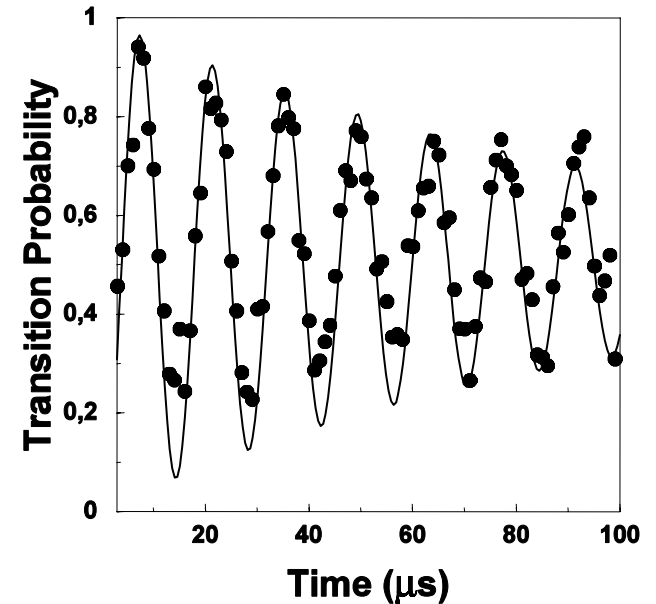


- Robust Raman cooling of all modes well below the Doppler limit.

D. Reiß et al., PRA **65**, 053401 (2002)



- Coherent excitation of optical E2-transition  
CW, Chr. Balzer, Adv.At.Mol.Opt.Phys. **49**, 295 (2003).





# Siegen

- PhD / Postdoc position available

