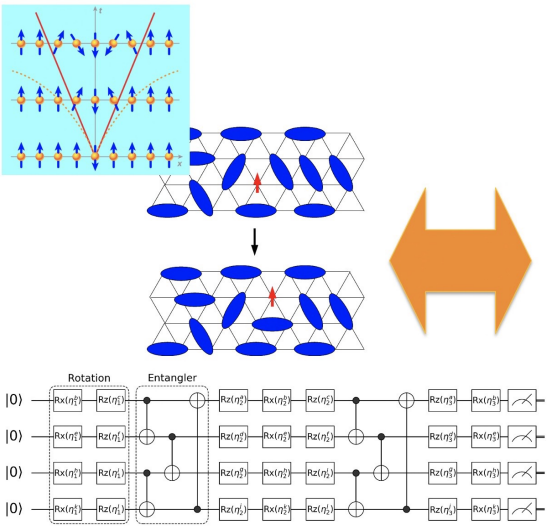
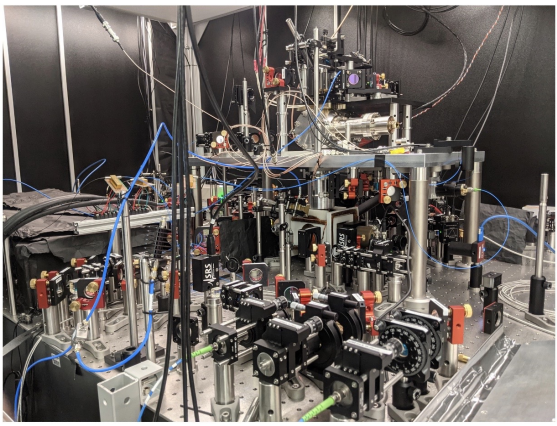
Quantum information processing and simulation with Rydberg atom arrays

Hannes Bernien





Overview:

I Single atoms as quantum building blocks

II Rydberg interactions + QIP

III Simulation + New Frontiers

I 1. typical atoms

1 H																	2 He*
3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne*
11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar*
19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr*
37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe*
55 Cs	56 Ba	57 La	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
87 Fr	88 Ra	89 Ac															

58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu
90 Th	91 Pa	92 U											

- blue: laser cooled atoms
- often exp. use atoms with one extra e⁻

e.g. Li, Na, K, Rb, Cs,

"easy level structure"

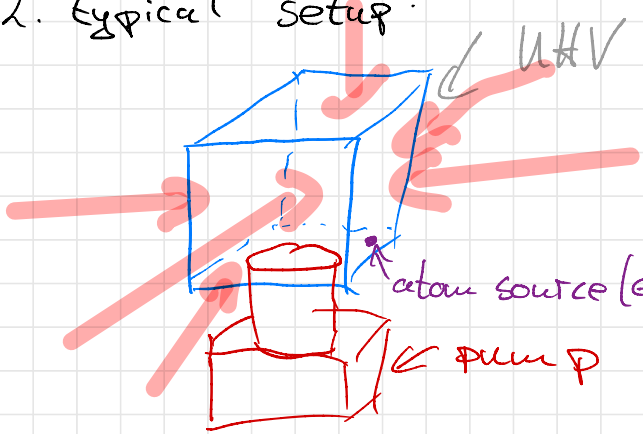
⇒ Rb "Silicon of atoms"

- also 2e⁻ atoms: Yb, Sr

⇒ more complex level structure

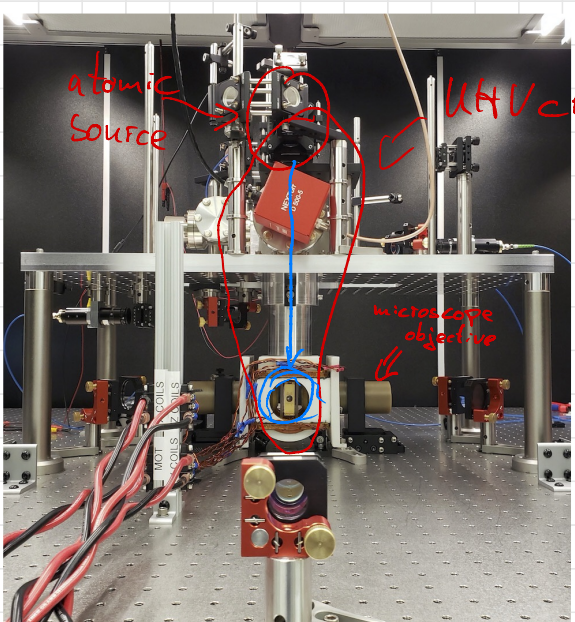
⇒ opportunities: - optical clocks
- nuclear spin

2. typical setup:



① load atoms from RT vapor (or atomic oven)

② laser light - cooling, trapping, state prep...

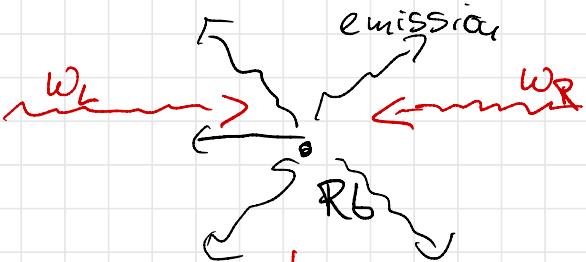


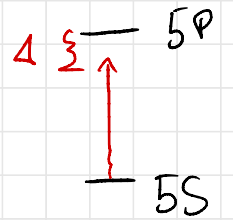
Tools:

- vacuum tech
- laser tech
- optics, electronics
- cameras
- CS

3. Laser cooling:

- atoms @ RT travel with $v \sim 300 \frac{m}{s}$
- $\Rightarrow$ need to cool





- moving atom sees laser freq. shifted by Doppler shift $\Delta\omega = \vec{k}\vec{v}$ $\left(|k| = \frac{2\pi}{\lambda}\right)$

$\Rightarrow$ atom absorbs photon from counter-propagating beam

① absorbtion

$$\vec{p}_{atom} = m\vec{v} - \hbar\vec{k}_{abs}$$

② emit photon

$$\vec{p}_{atom} = m\vec{v} - \hbar\vec{k}_{abs} + \hbar\vec{k}_{emit}$$

- atom emits in random direction

$$\langle \vec{k}_{emit} \rangle = 0$$

$\Rightarrow$ atom is slowed down

- need to slow down in x y z

$\Rightarrow$ typical 6 counter propagating

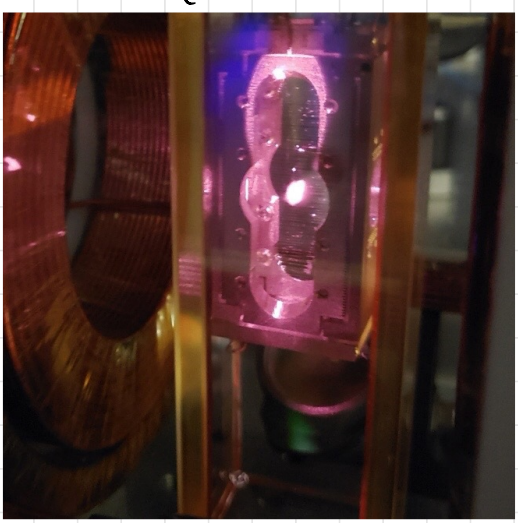
Laser beams

- combination with magnetic fields

Magneto-Optical-Trap

⇒ spatially dependent restoring force

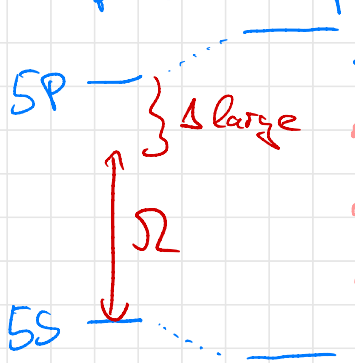
⇒ a cold ensemble (cloud) of spatially confined atoms



- $T \sim \mu K$, $v \sim \frac{cm}{s}$
- cloud $\sim 10^9$ atoms

4. trapping single atoms:

- optical dipole trap: detuned laser shifts energy levels



- AC stark shift
- light shifts
- dressed states

$$\frac{H}{\hbar} = \begin{pmatrix} 0 & \frac{\Omega}{2} \\ \frac{\Omega}{2} & \Delta \end{pmatrix}$$

$$\Omega = \frac{|E d|}{\hbar}$$

d ← transition dipole element

E ← E-field of laser

Question:

1) derive the energy shift of TLS with far off resonant light

2) a) lookup the dipole element for $5S_{\frac{1}{2}} \leftrightarrow 5P_{\frac{1}{2}}$ transition in Rb

b) assume you have 1 mW of laser light @ 810nm focused to $1\,\mu m^2$ calculate the energy shift

c) can this trap a 10 μK cold atom

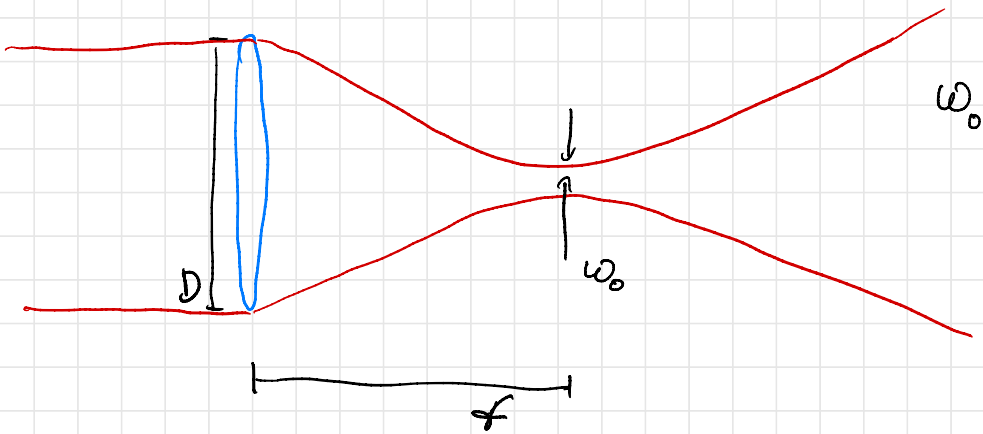
- $\omega_{Laser} < \omega_{atom}$ ("red detuned")
  ⇒ atom is attracted to high intensity

- $\omega_{laser} > \omega_{atom}$ ("blue detuned")

  $\Rightarrow$ atom is repelled

$\Rightarrow$ both can be used for trapping

5. trapping single atom



$\omega_0 \approx \frac{2f\lambda}{\pi D}$

$\Rightarrow$ to have tight trapping need $\frac{D}{f}$ large

$\Rightarrow$ use microscope objective

$\left(NA = \frac{D}{2f}\right)$

typ $NA \sim 0.65$; $\lambda \sim 810\,nm$ (Rb)

$\Rightarrow$ $\omega_0 \sim 500\,nm$

- how many atoms trapped?

  $\Rightarrow$ light assisted collisions $\Rightarrow$ 0 or 1 atom when tight focus