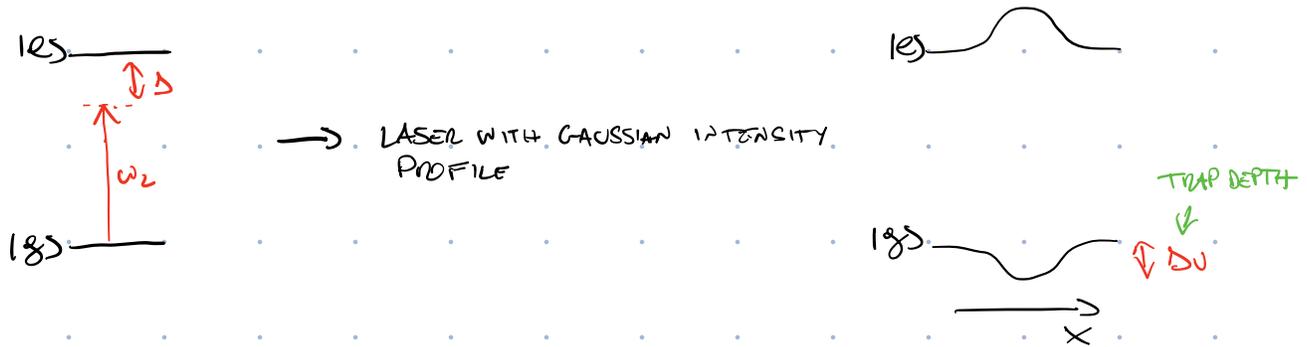# Neutral atoms in optical tweezers

Unlike ions that are trapped with electric fields, neutral atoms are trapped by virtue of light-matter interaction. This mechanism is based on the AC Stark shifts (as discussed in the course atoms,molecules and photons) induced by light which is far detuned from atomic transitions that confines atoms in the local intensity maxima (or minima, depending on the sign of the laser detuning)

$|e\rangle$ ⟍⟋ $\updownarrow \Delta$

ω_z

$|g\rangle$

⟶ LASER WITH GAUSSIAN INTENSITY PROFILE

$|e\rangle$ ⟍⌢⟋

TRAP DEPTH
↓
$\updownarrow \delta v$

$|g\rangle$ ⟍⌣⟋

⟶
X

Optical tweezers utilize this principle by focusing a laser to a micron-scale diameter, where individual atoms are trapped at the focus. The trap depth is typically expressed in units of temperature and in typically it is at most a few mK. This means that the atom's kinetic energy needs to be very small to be stably trapped. For this reason loading atoms in optical tweezers is done in steps. First, thermal atoms are cooled in a magneto-optical trap (MOT) that cools them from hundreds of K to tens of μK.

T ~ 700 K

Magneto optical trap

~ 10 μK

Yb SAMPLE
OVEN

CAPILLARIES TO COLLIMATE THE ATOM FLUX

3D COOLING

MOT CLOUD WITH 10^7 ATOMS

In a second step, an array of optical tweezers (1D, 2D and sometimes even 3D) is overlapped with the cold atom cloud. Multiple atoms are then loaded in each tweezer
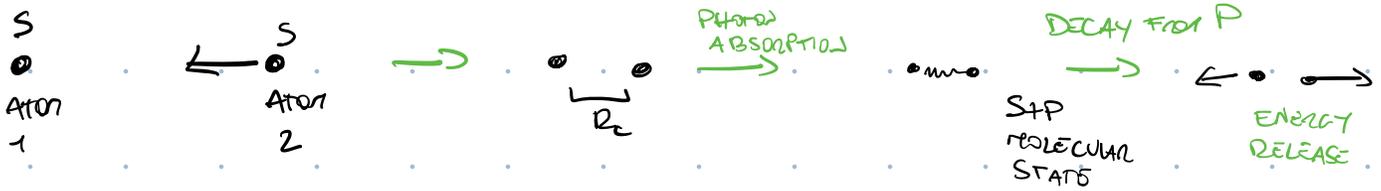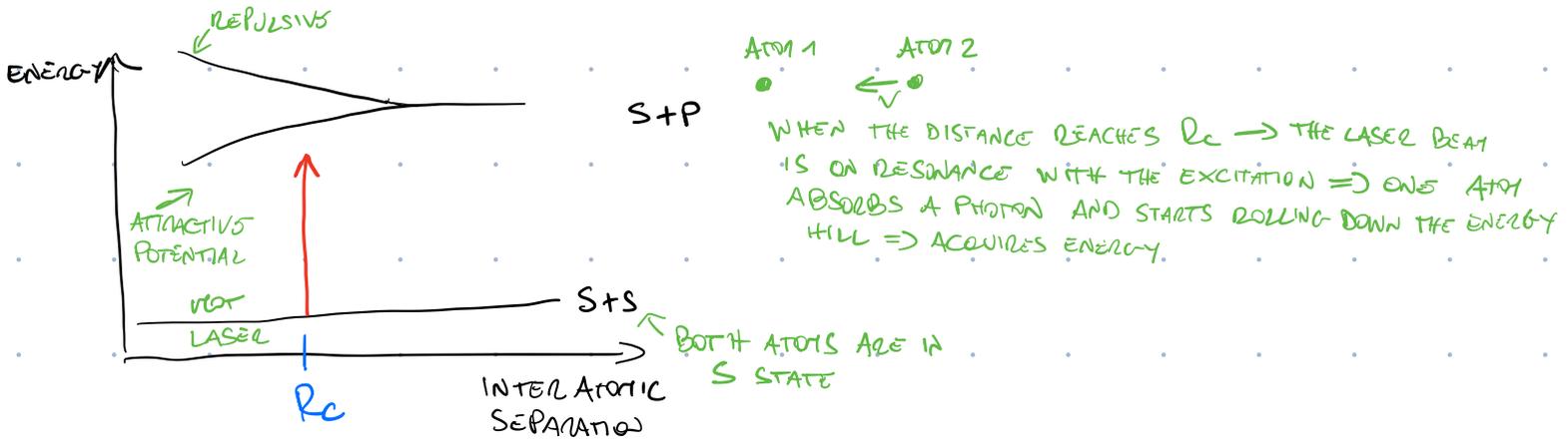
TWEEZERS

MOT
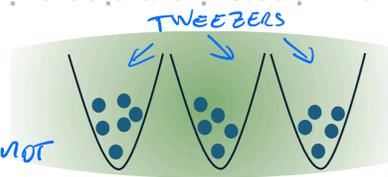
Tightly focused tweezers operate in a 'collisional blockade' regime, in which they load atoms from the MOT but pairs of loaded atoms are

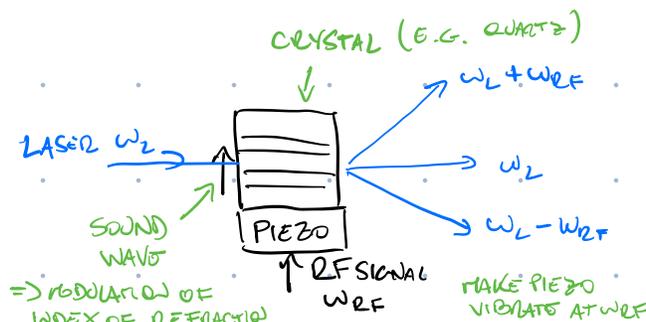ejected due to light-assisted collisions (LACs) induced by the MOT lasers

← DETUNED FROM RESONANCE

The LAC process is defined by the excitation of atom pairs from an S +S to S +P electronic state at a

resonant internuclear distance R_C (Condon radius) *← THERE IS A DIPOLE DIPOLE INTERACTION*

ENERGY

REPULSIVE

ATTRACTIVE POTENTIAL

S+P

ATOM 1   ATOM 2

WHEN THE DISTANCE REACHES R_C → THE LASER BEAM IS ON RESONANCE WITH THE EXCITATION ⇒ ONE ATOM ABSORBS A PHOTON AND STARTS ROLLING DOWN THE ENERGY HILL ⇒ ACQUIRES ENERGY

MOT LASER

S+S

← BOTH ATOMS ARE IN S STATE

R_C

INTER ATOMIC SEPARATION

S

ATOM 1

S

ATOM 2

PHOTON ABSORPTION

R_C

DECAY FROM P

S+P MOLECULAR STATE

ENERGY RELEASE

This mechanism ensures that tweezers are loaded with at most single atoms, but the loading is

probabilistic: each trap is loaded with a single atom with probability 50 – 60%. There are optimized

mechanisms that yield higher filling probabilities but we will not consider them in this course

To prepare deterministic atom arrays, we utilize a real-time feedback procedure, in which the

randomly loaded atoms are identified and then rearranged into pre-programmed geometries. Atom

rearrangement requires moving atoms in tweezers which can be smoothly steered to minimize

heating. Acousto-optic deflectors (AODs) are incredibly effective tools for this application, since they

deflect a laser beam by a tunable angle which is controlled by the frequency of a running acoustic

wave in the AOD crystal.

CRYSTAL (E.G. QUARTZ)

LASER ω_L

$\omega_L + \omega_{RF}$

ω_L

$\omega_L - \omega_{RF}$

SOUND WAVE

⇒ MODULATION OF INDEX OF REFRACTION

PIEZO

RF SIGNAL ω_{RF}

MAKE PIEZO VIBRATE AT ω_{RF}

Dynamic tuning of the acoustic frequency translates into smooth motion of an optical tweezer.

Moreover, a multi-frequency acoustic wave creates an array of laser deflections, which after focusing

through a microscope objective forms an array of optical tweezers with tunable position and

amplitude.
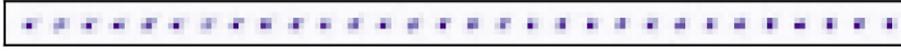
An alternative way of creating a tweezer array is to use a spatial light modulator (SLM) that imprints a

phase hologram on the wavefront of a single laser field, such that after propagating to the fo- cus of a

microscope objective, the laser forms a flexible, programmable array of tweezers in 2D.

EACH PIXEL OF AN SLM IS A SMALL LIQUID CRYSTAL

FROM HARRY LEVINE PHOTHESIS
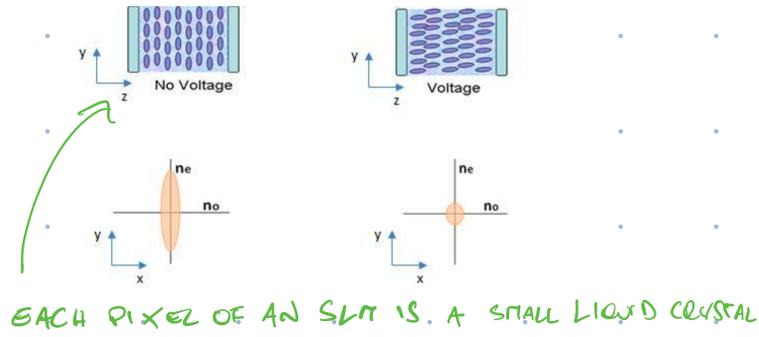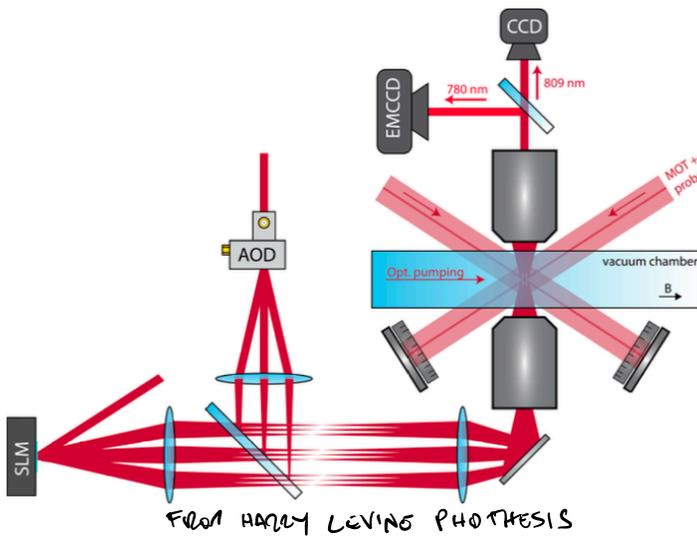
The orientation of the liquid crystal molecule can be changed according to the applied electric field

which is controlled by the voltage difference between the pixel electrodes. Different voltage applied

on the pixel electrodes will lead to different phase delay of the light field.

The tweezers generated with an SLM are static and cannot be dynamically moved (i.e the update rate

of the liquid crystal is at most in the kHz range so very slow). To rearrange atoms in 2D, one uses a

combination of SLM to provide an array of fixed traps and a second set of moving optical tweezers

that are steered by a pair of crossed acousto-optical deflectors
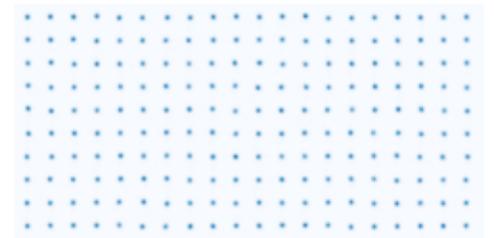
Rydberg interaction

We have now seen how we trap atoms in tweezers and how we can re-arrange them in any configuration we want. To finish with the discussion we need to now talk about how we make two atoms interact to perform two qubit operations. Unlike ions, neutral atoms cannot interact through the Coulomb force, and, as we discussed before, the use of detuned laser light (like in the case of cooling) causes LACs. This means that we also cannot have two atoms sitting in the same potential well. How do we make them interact? Through Rydberg interactions

Rydberg states are highly-excited atomic states, with principal quantum number $n \gg 1$

The properties of atomic states scale dramatically with principal quantum number.

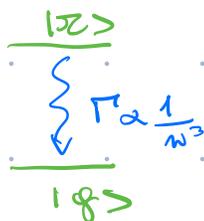- 🔴 VAN DER WAALS INTERACTION $V(R) = C_6 / R^6$ ← INTERACTION OF TWO Ry ATOMS

$$C_6 \propto n^{11}$$

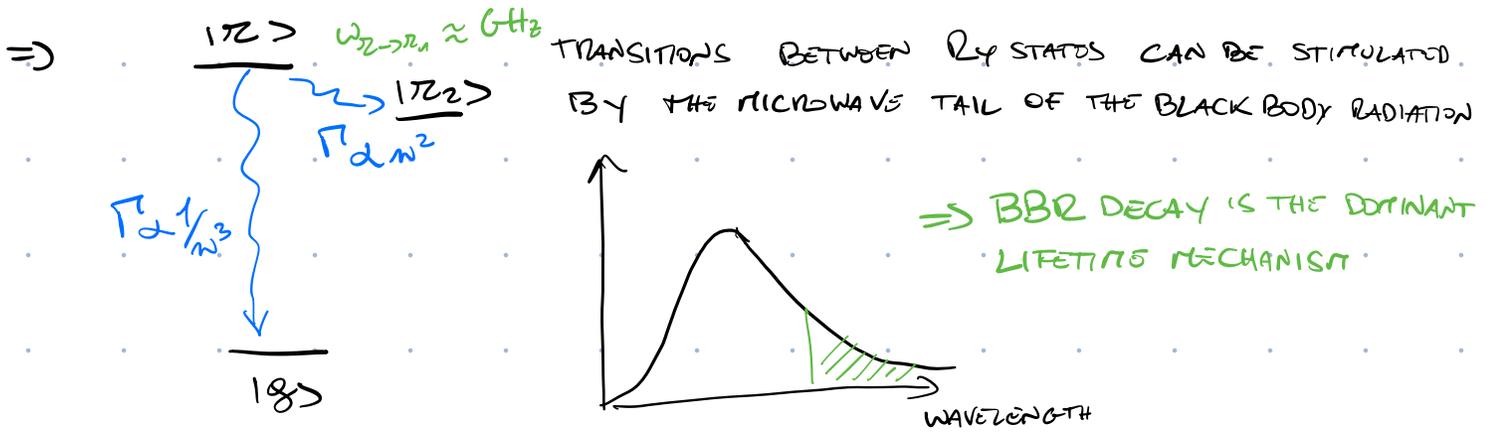↳ TYPICALLY $50 < n < 100$ AND $R \approx 1-5 \, \mu m$ ⇒ $V(R) \simeq 1 MHz - 1GHz$

↗ THIS SETS THE SPEED OF THE GATES! THE RABI FREQ. IS PROPORTIONAL TO THIS.

- 🔴 LIFETIME OF RYDBERG STATES $\propto n^3$ ⇒ LIFETIME IN THE ORDER OF $100s \, \mu s - 1 m s$

↑ THIS IS HOW LONG A Ry STATE TAKES TO DECAY TO THE GROUND STATES.

$$\frac{|r\rangle}{\underset{|g\rangle}{\overline{}}} \quad \Gamma \propto \frac{1}{n^3}$$

however, the dipole matrix element between neighboring Rydberg states also grows with n $(\propto n^2)$

$\Rightarrow$

$|r\rangle$ $\quad \omega_{r \to r_n} \approx GHz$ TRANSITIONS BETWEEN Ry STATES CAN BE STIMULATED

$\rightsquigarrow |r_2\rangle$ BY THE MICROWAVE TAIL OF THE BLACK BODY RADIATION

$\Gamma \propto n^2$

$\Gamma \propto 1/n^3$

$\Rightarrow$ BBR DECAY IS THE DOMINANT LIFETIME MECHANISM

$|g\rangle$

WAVELENGTH

● $\langle r| \vec{d} |g\rangle \propto n^{-3/2}$ $\quad \leftarrow$ THE WAVEFUNCTION OVERLAP IS SMALL!

$\Rightarrow$ HARD TO DRIVE THIS TRANSITION

● ATOM POLARIZABILITY $\propto n^7 \Rightarrow$ VERY SENSITIVE TO STRAY CHARGES

practical consideration: while higher Rydberg states have longer lifetimes and stronger interactions,

the laser excitation coupling is weaker, which can pose its own limitation, and the atom is more

sensitive to electric field noise.

EXAMPLE: ^{87}Rb $\quad |70\, S_{1/2}\; m_J = -1/2\rangle$ $\quad C_6 = 2\pi \times 874\; GHz/\mu m^6$

$\Rightarrow$ FOR $R = 3\mu m$ $\rightarrow V(R = 3\mu m) = 2\pi \times 1.2\; GHz$

RADIATIVE LIFETIME $440\; \mu s$ THAT IS REDUCED TO $147\mu s$ FROM BBR

$|r\rangle$

$\rightsquigarrow |r_1\rangle$

$|r_2\rangle$

$|g\rangle$
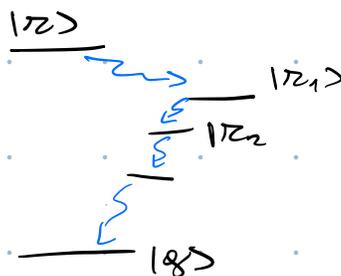
Excitation to Rydberg gates

Optical excitation from a qubit state in the low n levels to a target Rydberg state is a key ingredient in Rydberg experiments. There are different schemes each with its own advantages and disadvantages

🔴 The simplest is direct laser excitation with a single-photon transition. This is the most obvious operation but it can be hard to implement as it is often in the deep ultraviolet. Ultraviolet lasers pose serious experimental challenges, due to material degradation, unavail- ability of optical fibers and low-loss optics, and more.
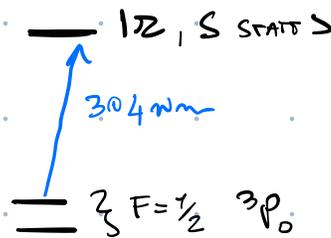
EXAMPLE : FOR ^{87}Rb THE TRANSITION IS AT 297 nm . THE QUBIT IS ENCODED IN THE $S_{1/2}$ GROUND STATE $\Rightarrow$ DUE TO SELECTION RULES THE SINGLE PHOTON TRANSITION IS $S \rightarrow P$. P STATES HAVE MORE HYPERFINE STRUCTURE , ANISOTROPY AND SENSITIVITY TO EXTERNAL FIELDS $\Rightarrow$ BAD COHERENT MANIPULATION

EXAMPLE 2: ^{171}Yb

$|z, S \text{ STATE}\rangle$

304 nm

$\{ F=1/2 \quad {}^3P_o$

$^1S_o \qquad \{ F=1/2$

2 POSSIBLE QUBITS ONE IN ^1S_o AND ONE IN ^3P_o .

^3P_o IS METASTABLE WITH A LIFETIME OF 11 y .

Ytterbium, allows single photon excitation to a Rydberg state of type S with a direct single photon excitation. A similar mechanism is also true for $^{88}S_x$

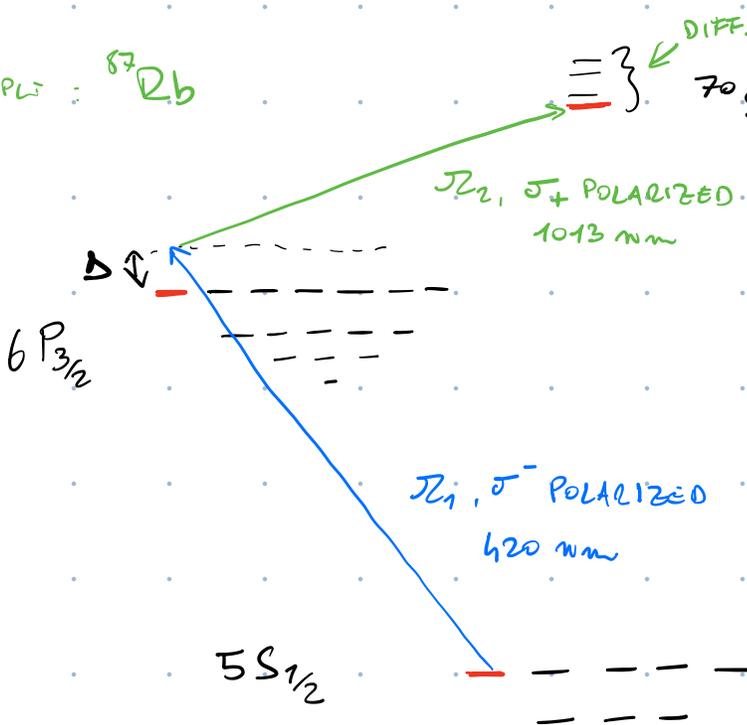🔴 Alternatively, two-photon laser excitation can be used to couple ground S states to Rydberg S states through an intermediate P state. This method is similar to the Raman mechanism we discussed earlier, with the difference that the atom absorbs two photons.

$|r, SS\rangle$ — (top level)

Ω_2

P — — — $\Uparrow \Delta$

Ω_1

— S
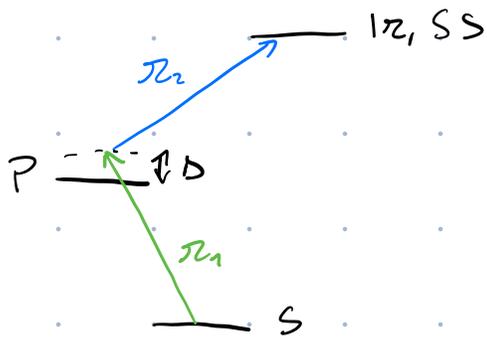
LIKE FOR RAMAN $\Delta \gg \Omega_1, \Omega_2, \Gamma_1$

$\uparrow$

P STATE DECAY

EXAMPLE: ^{87}Rb

$= \} \swarrow$ DIFF. m_I STATES $I = 3/2$

$70\,S_{1/2}$, $m_J = -1/2$

Ω_2, σ_+ POLARIZED

1013 nm

$\Delta \sim$ GHz $\nearrow$ MUST BE LARGE TO AVOID OFF-RESONANT SCATTERING FROM $P_{3/2}$

$6\,P_{3/2}$ $\quad \Delta\Uparrow$

$\Omega_{EFF} = \dfrac{\Omega_1 \Omega_2}{2\Delta}$

Ω_1, σ^- POLARIZED

420 nm

$5\,S_{1/2}$

Note that when labeling Rydberg states, the good quantum numbers are m_J and m_I, rather than F

and m_F ; this is because the hyperfine interaction is very weak in Rydberg states and therefore even

at small Gauss-scale magnetic fields, the level structure is in the Paschen-Back regime.

Interactions between Rydberg atoms play a central role in many-body experiments and in quantum computing. These interactions take the form of an energy shift for pairs of atoms that are simultaneously excited to the Rydberg state. When this interaction shift V is larger than the strength of the excitation coupling Ω excitation to doubly excited states is suppressed.
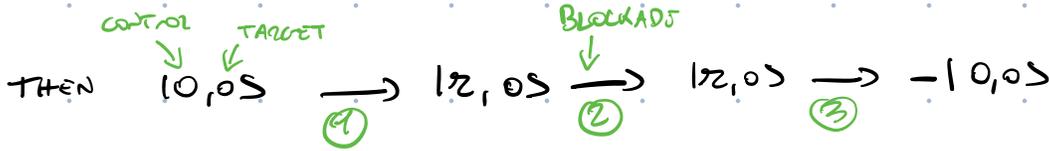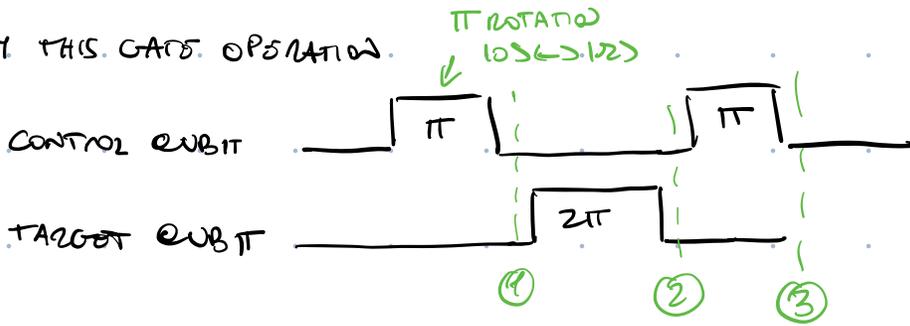
RYDBERG BLOCKADE

d LARGE — COMPARED TO VAN DER VAALS INTERACTION

d SMALL

$|rr\rangle$

$V \uparrow\downarrow$ $|rr\rangle$

SHIFT OF THE RESONANCE DUE TO THE INTERACTION

Ω

VAN DEER VAALS INTERACTION

$|grr\rangle, |r,g\rangle$

Ω

$|g,r\rangle, |r,g\rangle$

$|gg\rangle$

$|gg\rangle$
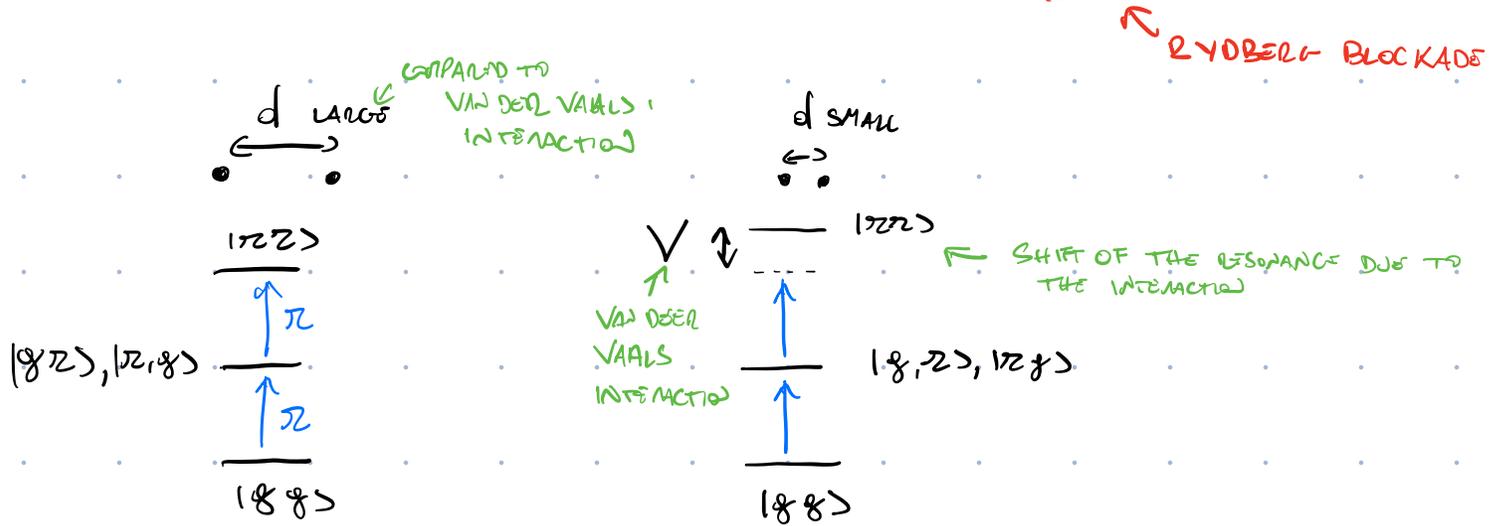
IF $V \gg \Omega$ $\Rightarrow$ IT IS NOT POSSIBLE TO EXCITE BOTH ATOMS TO THE RYDBERG STATES.

$\Rightarrow$ THIS IS A RADIUS CALLED RYDBERG BLOCKADE RADIUS BELOW WHICH WE OBSERVE BLOCKADE.
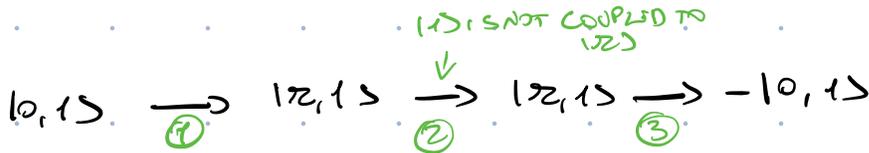
This asymmetric mechanism can be used to realize gates. In particular a simple one is the controlled-phase gate (C-Z)
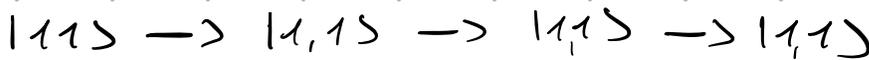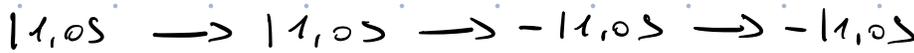
CONSIDER ___ $|r\rangle$ $|0\rangle$ IS COUPLED TO $|r\rangle$ WHILE $|1\rangle$ IS NOT

$|0\rangle$ ___

$|1\rangle$ ___

PERFORM THIS GATE OPERATION

π ROTATION
$|0\rangle \leftrightarrow |r2\rangle$

CONTROL QUBIT ___ | π | ___ | π | ___

TARGET QUBIT ___ | 2π | ___

① ② ③

CONTROL   TARGET

THEN $|0,0\rangle \xrightarrow{①} |r2,0\rangle \xrightarrow{②} |r2,0\rangle \xrightarrow{③} -|0,0\rangle$ CONTROL PICKS A -1 PHASE
BECAUSE IT DOES A 2π ROTATION

BLOCKADE

$|1\rangle$ IS NOT COUPLED TO $|2\rangle$

$|0,1\rangle \xrightarrow{①} |r2,1\rangle \xrightarrow{②} |r2,1\rangle \xrightarrow{③} -|0,1\rangle$

$|1,0\rangle \longrightarrow |1,0\rangle \longrightarrow -|1,0\rangle \longrightarrow -|1,0\rangle$

$|11\rangle \longrightarrow |1,1\rangle \longrightarrow |1,1\rangle \longrightarrow |1,1\rangle$

$\Rightarrow \begin{pmatrix} -1 & & & 0 \\ & -1 & & \\ & & -1 & \\ 0 & & & 1 \end{pmatrix} = -C\text{-}Z$

$C\text{-}Z$ CAN BE TURNED IN A CNOT WITH H GATES.

The Rydberg blockade effect is generally insensitive to the particular strength of the interaction, as long as $V \gg \Omega$