L4 Quantum information and computing (QIC) 2020-21

Lecture 15: Polarization selection rules and optical pumping

December 22, 2020

Aims of Lecture 15: To understand how we can use the polarization of light to select and control the qubit state.

Introduction:

In the last few lecture we have discussed how to create a trap for a single atom using focused laser beams, and how to load atoms into the trap using laser cooling. Now we turn our attention to how to control the state of the atom inside the trap using. In particular, we shall look at how we can use the polarization of light to select particular states and drive transitions between those states.

For alkali atoms, due to the electron spin, S, and the nuclear spin, I, the ground state is $(2S+1)(2I+1)$-fold degenerate. For Cs with $I = 7/2$, there 16 hyperfine states levels in the ground state. These are split into two groups by the hyperfine interaction. The lower hyperfine state with total angular momentum $F = 3$ contains $2F + 1 = 7$ states labelled $m_F = -3$ to $m_F = +3$. The upper hyperfine state with total angular momentum $F = 4$ contains $2F+1 = 9$ states labelled $m_F = -4$ to $m_F = +4$. After laser cooling the atom may be in any of these states and we need a way to select only one to initialise our qubit.

Magnetic quantum numbers:

Atomic states have an angular momentum that is the sum of electronic (labelled J) and nuclear (labelled I) angular momenta.[1] The projection of the angular momentum onto the magnetic field direction is labelled using the **magnetic quantum number**, m.[2] Note that for small magnetic fields (where the Zeeman shift is less than the fine or hyperfine structure) the Zeeman shift is linearly proportional to m, i.e. $\Delta E = gm\mu_B B$, where μ_B is the Bohr magneton and g, the gyromagnetic ratio, is a number that depends on the angular momentum quantum numbers of the state. Consequently, the m quantum number is defined with respect to the magnetic field direction.[3]

Polarization selection rules

The polarization of light allows us to drive transitions between states with different m.

Conservation of angular momentum requires that when a photon is absorbed, the angular momentum of the photon is transferred to the atom. For a conventional laser beam mode, we may assume the photons can drive transitions with $\Delta F = -1, 0, +1$. The projection of photon angular momentum along the quantization axis (parallel to an external magnetic field) is transferred to the magnetic quantum number, and we may have $\Delta m_F = -1, 0, +1$. The three case, $\Delta m_F = -1, 0, +1$, are known as σ_-, π and σ_+ transitions, respectively.

The simplest case is when the light propagate in the same direction as the magnetic field, i.e. along z. Consider a right-circularly polarized photon. This has angular momentum $-\hbar$ along z (see *Optics f2f*, p. 57) therefore it will drive a $\Delta m = -1$ (σ_-) transition. A left-circularly polarized photon, has angular momentum $+\hbar$ along the propagating direction and drives a $\Delta m = +1$ (σ_+) transition. However, if we reverse the magnetic field, the projection of the photon momentum onto the quantization axis changes sign and now left- and right-circularly polarized

[1] An atom like ^{88}Sr is special because the angular momentum of the ground state is zero. It has zero nuclear spin $I = 0$ and two-valence electrons which in ground state have zero orbital angular momentum, $L = 0$, and form a spin singlet, $S = 0$. Recall that states are labelled as $^{2S+1}L_J$. The ground state of Sr is $^1S_0$. However all of the excited states, apart from the singlet S series, still have angular momentum.

[2] There are magnetic quantum number associated with each of the different types of angular momentum, m_s for the electron spin, m_ℓ for the orbital angular momentum, m_j for the total electronic angular momentum, m_I for the number spin and m_F for the total atomic (electronic plus nuclear) angular momentum.

[3] Often we can take the magnetic field direction to be along the z axis and we call this the quantisation axis. However, there are cases where the magnetic field changes sign. For example, in the magneto-optical trap (MOT) used to accumulate laser cooled atom, the magnetic field changes sign at the origin. If $B > 0$ for $z > 0$ and $B < 0$ for $z < 0$, then the state we label as $m = +1$ for $z > 0$ becomes $m = -1$ for $z < 0$.

light drives $\Delta m = -1$ and $+1$ transition. Opposite to before.[4]

Linearly polarized light propagating along z drives a superposition of σ_+ and σ_- transitions. Linear light polarized along z (propagating perpendicular to z) drives $\Delta m = 0$, known π) transitions. These cases are summarised in Fig. 1

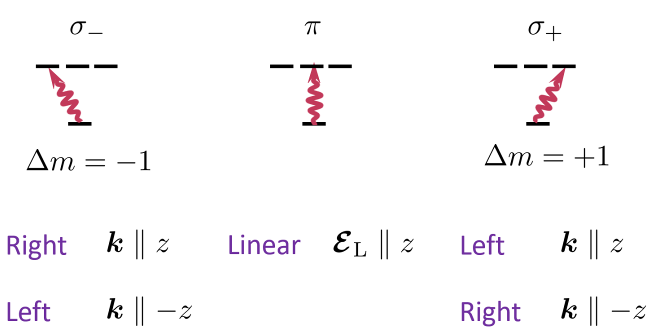

Figure 1: Polarization selection rules.

Optical Pumping:

We can exploit the polarization selection to 'pump' the atoms in a particular magnetic sublevels. This technique[5] is used to initialise the atoms in a particular qubit state $|0\rangle$ or $|1\rangle$.

If we apply resonant light to drive a transition from a ground $|\mathrm{g}\rangle$ with total atomic angular momentum F, to an excited state $|\mathrm{e}\rangle$ with total atomic angular momentum F', we can use polarization to redistribute the atomic population amongst the ground state magnetic sublevels. An example for Cs is shown in Fig. 2.

The selection rules for optical pumping are:

1. For excitation, we can select $\Delta m_F = -1, 0, +1$ transitions (σ^-, π and σ^+) by using right-circular (propagating along z), linear (polarized along z) and left-circular (propagating along z), respectively.

2. For decay, $\Delta m_F = -1, 0, +1$ and $\Delta F = -1, 0, +1$ are all allowed. Atoms may fall into the other F level in the ground state so we also need a **repump** laser.

3. The exception to rules 1. and 2. is that $m_F = 0 \rightarrow m'_F = 0$ is not allowed when $F = F'$. This can be used to pump atoms into the $m_F = 0$ state, see Fig. 3.

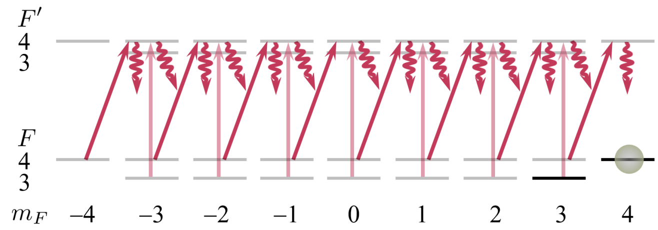

Figure 2: Example of optical pumping into the $6\mathrm{s}^2S_{1/2}(F = 4, m_F = 4)$ state in Cs which can be used as one of the qubit states. For light propagating in the magnetic field direction, left-circularly polarized light resonant with $6\mathrm{s}^2S_{1/2}(F = 4) \rightarrow 6\mathrm{p}^2P_{3/2}(F = 4)$ drives $\Delta m_F = +1$ transitions. A linearly polarized **repump** resonant with the $6\mathrm{s}^2S_{1/2}(F = 3) \rightarrow 6\mathrm{p}^2P_{3/2}(F = 4)$ transition prevents the population accumulating in the lower hyperfine state. An advantage of this scheme is that the final state $F = 4, m_F = 4$ is dark so the pumped atoms are not heated by further scattering.

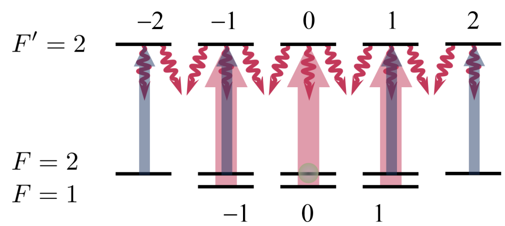

Figure 3: Example of optical pumping into the $5\mathrm{s}^2S_{1/2}(F = 2, m_F = 0)$ state in ^{87}Rb ($I = 3/2$). For light linearly polarized parallel to the magnetic field direction, we drive $\Delta m_F = 0$ transitions. However, for a laser tuned to $5\mathrm{s}^2S_{1/2}(F = 2) \rightarrow 5\mathrm{p}^2P_{3/2}(F' = 2)$ transition the $m_F = 0 \rightarrow m'_F = 0$ transition is not allowed. Consequently atoms accumulate in $6\mathrm{s}^2S_{1/2}(F = 2, m_F = 0)$. The microwave transition, $6\mathrm{s}^2S_{1/2}(F = 1, m_F = 0) \rightarrow 6\mathrm{s}^2S_{1/2}(F = 2, m_F = 0)$ is **magnetically insensitive**. This transition is used in atomic clocks, and is a good choice for quantum computing, see Lecture 16. The 'red' laser repumps out of the lower hyperfine level.

Summary:

What do you need to be able to do?

1. Explain why labeling a laser beam σ_-, π or σ_+ does not make sense.

2. Work out what configuration of laser beam polarizations and propagation directions are needed to drive particular transitions and hence optically pump atoms into a particular state.

3. Sketch optical pumping diagrams for different cases.

[4] Confusingly, some books and publications label the light as $\sigma^\pm$ but light cannot be $\sigma^\pm$, light only has a particular polarization and a propagation direction. What transitions particular light polarizations drive depends on the propagation direction relative to the direction of an external magnetic field (which defines the quantization axis).

[5] Optical pumping was pioneered by Alfred Kastler who won the Nobel Prize in 1966.