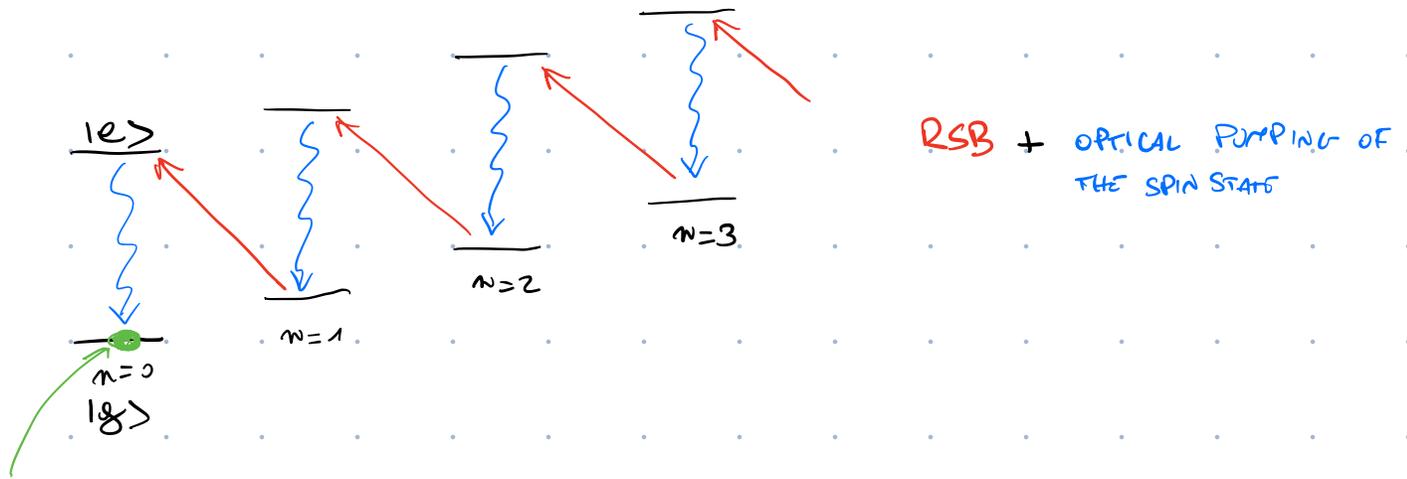


## Sideband cooling

In the presence of motion and, especially with large LD parameters, it is important to be able to cool the system down to the ground state of motion to achieve the highest fidelity and control of the qubit population transfer. In previous courses you talked about Doppler cooling, which however does not reach the motional ground state.

$$T_D = \frac{\hbar \Gamma}{2k_B} \quad \text{DOPPLER LIMIT TEMPERATURE}$$

To reach the ground-state of motion a typical sequence that achieves it is sideband cooling

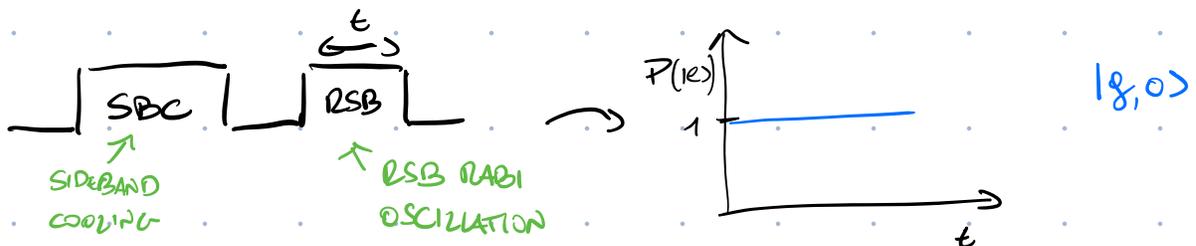


POPULATION ACCUMULATES IN  $|g, n=0\rangle$  WHICH IS THE ONLY DARK STATE OF THE SYSTEM.

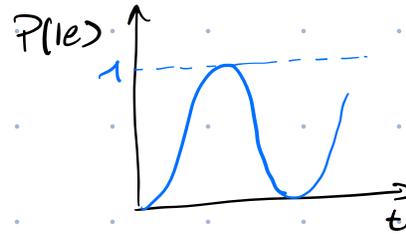
Notice that for sideband cooling to work we need to be able to resolve individual sidebands and drive only the red one.

In this case the state  $|g, n=0\rangle$  does not couple to any other state so it is the only dark state of the system. In this way you can imagine sideband cooling as optical pumping.

To experimentally diagnose that the ground state has been reached one can employ the following sequence:

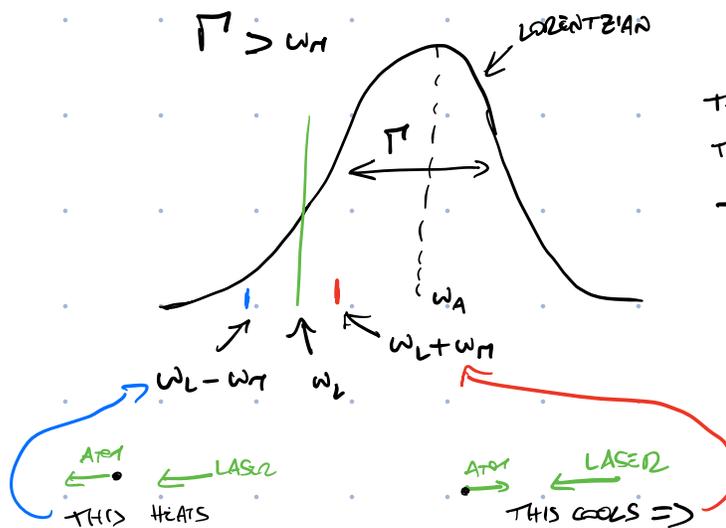


Or could do Rabi oscillation on the BSB transition, as we have seen before, which should produce perfect sinusoids (i.e. only one Rabi frequency)



$$\mathcal{R}_{BSB} = \eta \mathcal{R}_0$$

In the formalism of sidebands you can now understand why Doppler cooling does not reach the ground state of motion. As you have seen in previous courses, Doppler cooling works using dipole allowed transitions. The linewidth of these transitions are typically much larger than the motional frequencies. As you have also seen, to achieve the lowest Doppler temperature, the laser should be placed at the point of maximum slope of the linewidth (i.e. at half linewidth).

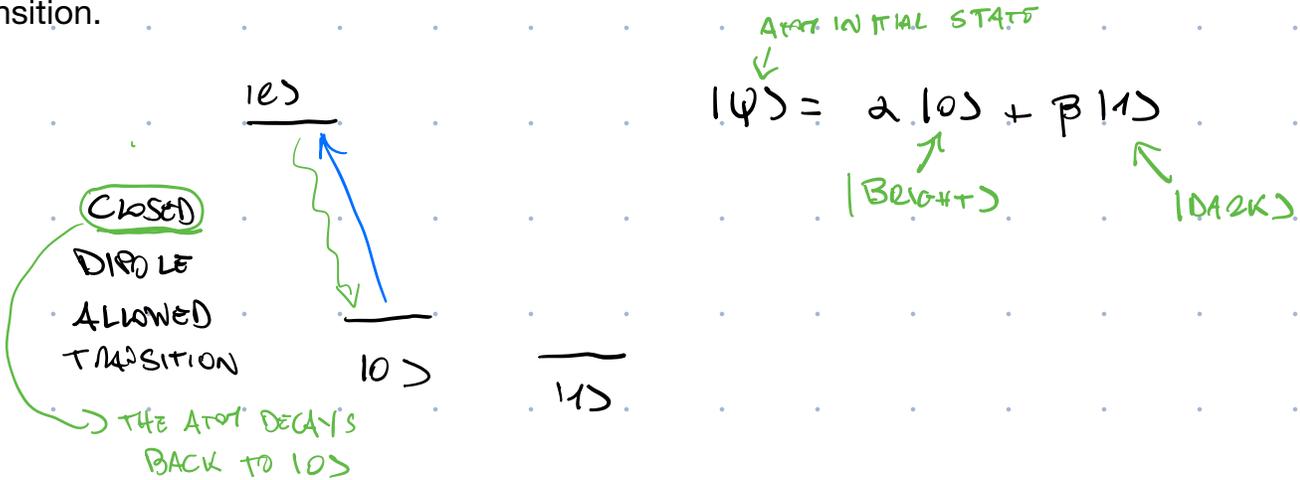


THINK IN THE REFERENCE FRAME OF THE ATOM.  
 → THE LASER FREQUENCY IS MODULATED AT  $\vec{k} \cdot \vec{v}$

Primarily there is an absorption on the carrier and red sideband, but there is also a bit of absorption in the blue sideband which depopulate the  $|g, 0\rangle$  state, and increases the motional occupation.

## Qubit detection

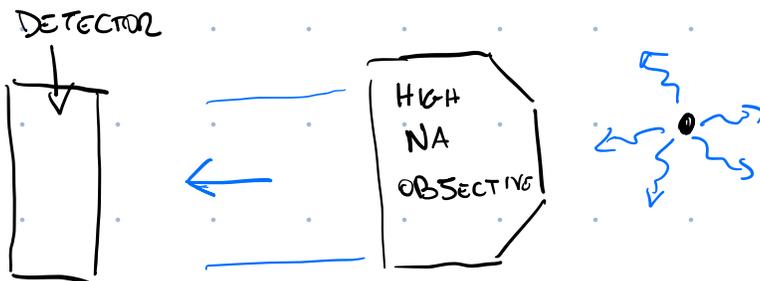
One other DiVincenzo's criteria we did not talk about is qubit readout. In atomic systems the preferred readout method is state-dependent fluorescence. With this technique, a detection laser beam resonantly couples one of the two qubit states to an excited state via a dipole allowed transition.



The transition that is used for detection is a closed dipole allowed transition. Closed means that an atom in the bright state gets excited and decays back to the same bright state. The fact that it is dipole allowed, means that the excited state is short-lived and the atom can fluoresce at a rate of  $10^7 - 10^8$  PHOTONS / SECOND  $\leftarrow$  IF ON RESONANCE (IF DETUNED THE RATE IS MUCH SMALLER).

Fluorescence light is emitted usually in a dipole emission pattern and then collected using high numerical aperture objectives that typically cover at most 10-20% of the  $4\pi$  solid angle. The collected fluorescence is then imaged on cameras or photomultiplier tubes.

The overall detection efficiency is usually below 10%



Detection times are in the range of few  $\mu\text{s}$  to tens of ms. These times are typically dictated by the overall collection efficiency and whether detection is resonant or not. Resonant fluorescence has the highest rates, but has the drawback of heating the atoms (due to recoil). If the trap is shallow (like it is for neutral atoms) this can result in atom losses. That is why, typical experiments work red-detuned from the transition which provides a bit of cooling while scattering photons. This comes at the expenses of a smaller scattering rate

TRAPPED IONS DET. TIMES 10 - FEW 100s  $\mu\text{s}$

NEUTRAL ATOMS " " FEW  $\mu\text{s}$  TO 100s OF  $\mu\text{s}$

ONLY FEW EXPERIMENTS CAN ACHIEVE THAT AND IT IS STRONGLY DEPENDENT ON THE SPECIFIC SYSTEM

Assuming that the detection of photons happens at a constant rate and independently of the time of previous detection events, the photon count distribution follows Poisson statistics. The Poisson

distribution is defined as

$$P(n|\lambda) = \frac{\lambda^n e^{-\lambda}}{n!}$$

AVERAGE NUMBER OF PHOTONS DETECTED IN DETECTION TIME  $t_D$

Ideally, for an atom initialized in the dark state, the average number of photons is  $\lambda_D = 0$

Despite this, stray light shining on the detector, electrical noise and cosmic rays contribute to an

average background photon counts  $\lambda_D = R_D t_D \approx 0.1 - \text{FEW PHOTONS (IN TYPICAL EXPERIMENTS)}$

BACKGROUND PHOTON COUNT RATE

For an atom in the bright state, the average number of photons detected within the detection time  $t_D$

$$\lambda_B = (R_B + R_D) t_D$$

$R_B, R_D$  already take into account the global detection efficiency of the setup, which depends both

on the properties of the lens system (ie. numerical aperture, lens coating etc...) and on the quantum efficiency of the detector

For a single atom in  $|\psi\rangle = \alpha |BRIGHT\rangle + \beta |DARK\rangle$  the probability of detecting  $n$  photons within a detection interval  $t_D$  is a superposition of two Poisson distribution

$$P(n) = \underbrace{P_D}_{|\beta|^2} P(n|\lambda_D) + \underbrace{P_B}_{|\alpha|^2} P(n|\lambda_B)$$

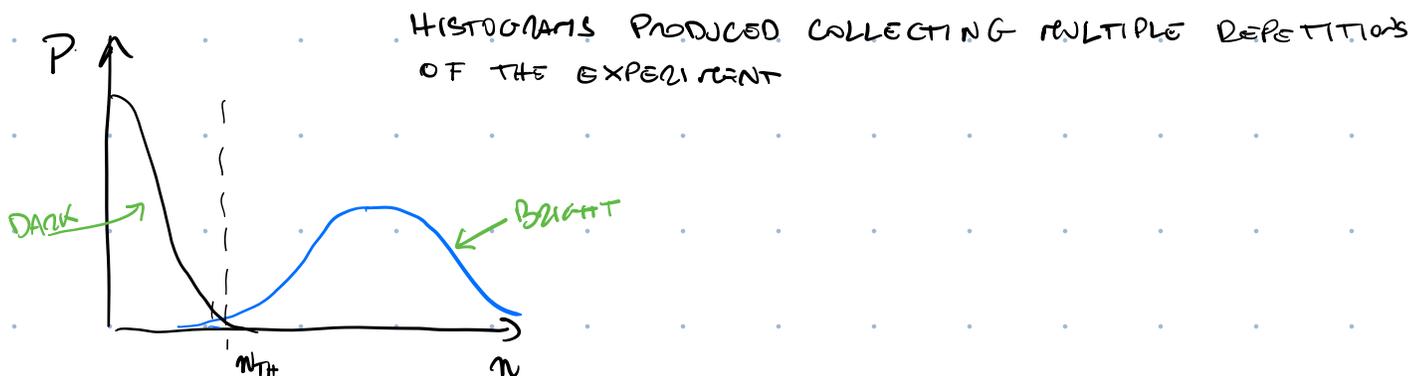
At the end of the detection, the number of photons detected by the detector is transmitted to the control electronics that manages the experiment where it is processed to discriminate the state of the atom.

**Thresholding** is the simplest method for discriminating a bright atom from a dark one. The state of the atom is determined by comparing the total number of photons  $n$  collected during a detection

$$\text{event to a threshold value } n_{TH} \quad \begin{cases} n \geq n_{TH} \rightarrow \text{BRIGHT} \\ n < n_{TH} \rightarrow \text{DARK} \end{cases}$$

Experiments are typically repeated multiple times (even more than 1000 times) to acquire statistics, so fraction of times that the atom produced fluorescence above (below) threshold gives the value for

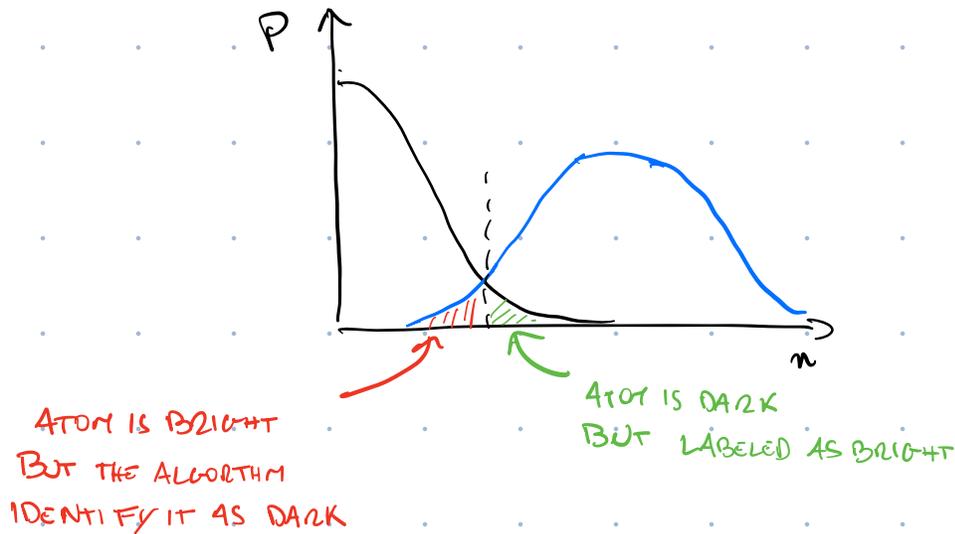
the probability of being bright (dark)  $P_B$  ( $P_D$ ).



For Poisson distributions, it can be shown that the optimal threshold lies at the intersection of the two distributions

$$n_{th} = \frac{\lambda_B}{\ln\left(1 + \frac{\lambda_B}{\lambda_D}\right)}$$

To understand why this is the case let's look at the discrimination error in the thresholding case



The error in this case is purely statistical. Since the atom can be in both states we want to move the threshold such that the two discrimination errors are the same. If you try to do the calculation you see that this happens when the two Poisson distributions intersect.

TYPICAL GOAL.: SEPARATE THE DISTRIBUTIONS. AS MUCH AS YOU CAN.. HOW?  
 FOR EXAMPLE INCREASING THE DETECTION TIME. HOWEVER THIS IS  
 NOT ALWAYS POSSIBLE DUE TO DEVIATIONS FROM THIS IDEAL SCENARIO  
 → ATOM LOSS, LEAKAGE FROM BRIGHT TO DARK ETC...

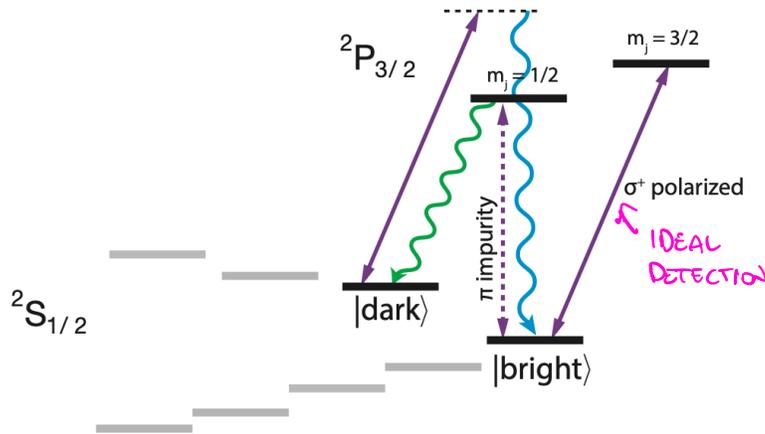
### Detection imperfections

One of the assumptions that we made is that once the state of the atom is collapsed into either the bright or the dark state, the atom continues to fluoresce at a constant rate. A change in the atom state within a detection event will modify the photon emission rate. If the time in which the ion switches state is not controlled and happens at random times, the photon counting statistics deviate from the Poissonian one. Lots of different causes

## OPTICAL QUBITS



## HYPERFINE QUBITS



- OFF RESONANT SCATTERING THAT PUMPS ATOM W/ |DARKS TO |BRIGHTS)
- POLARIZATION IMPERFECT THAT PUMPS |BRIGHTS TO |DARKS)
- IDEAL DETECTION

Let's consider only dark-to-bright leakage. Let's assume that an atom is initially prepared in the dark state, and that at time  $t = 0$  it begins a detection event of duration  $t_D$ . Assuming a dark-to-bright

repump rate  $\omega = 1/\tau$  the probability that the ion is found in the bright state after time  $t < t_D$

$$P_B = 1 - e^{-t/\tau}$$

So the probability that a decay happens between  $t$  and  $t+dt$  is

$$P(t) dt = \frac{1}{\tau} e^{-t/\tau} dt$$

If a repump event always occurs at a well-defined time  $t_D$  the number of counts  $n$  collected in within

a detection interval  $t_D$  is  $\lambda(t) = R_0 t_D + R_B (t_D - t)$

In reality, the repump time  $t$  is a continuous random variable. Therefore, what we need to calculate is

the density of means  $P(\lambda)$

ASSUME THAT  $|P(\lambda) d\lambda| = |P(t) dt|$  OK BECAUSE  $\lambda$  IS SINGLE VALUED FOR EVERY DECAY TIME  $t$

$$\Rightarrow P(\lambda) d\lambda = P(t(\lambda)) \frac{dt}{d\lambda} d\lambda = \frac{1}{\tau} e^{-t(\lambda)/\tau} \frac{dt}{d\lambda} d\lambda$$

FROM  $\lambda(t)$  ABOVE WE EXTRACT  $t$  AND PUT IT IN THE PREVIOUS EQUATION RESULTING

$$IN \quad P(\lambda) d\lambda = \frac{1}{R_B \tau} \exp\left(\frac{\lambda - t_0(R_D + R_B)}{R_B \tau}\right) d\lambda$$

IT FOLLOWS THAT, FOR AN ATOM PREPARED IN THE DARK STATE, THE PROBABILITY  $P_{\text{DARK}}(n, t_0)$  PROB. OF DETECTING  $n$  PHOTONS IN  $t_0$

IS THE SUM OF ALL THE POISSON DISTRIBUTIONS WITH MEAN VALUES BETWEEN  $\lambda_D = R_D t_0$  AND

$\lambda_B = (R_B + R_D) t_0$  WEIGHTED BY THE DENSITY OF THE MEANS  $P(\lambda)$

$$P_{\text{DARK}}(n, t_0) = \underbrace{P_0(t_0)}_{\substack{\uparrow \\ \text{PROB. THAT THE ATOM REMAINS} \\ \text{DARK FOR THE ENTIRE DETECTION EVENT}}} P(n | \lambda_D) + \int_{\lambda_D}^{\lambda_B} P(\lambda) P(n | \lambda) d\lambda$$

IDEAL CASE

