Initializing Neutral-Atom Qubits

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Both atom families use the same approach: optical pumping into a single "dark" level, sometimes followed by a coherent transfer pulse. What differs is where the qubit is stored, which sets the pumping scheme. Usually every atom is first prepared in $|0\rangle$ (or $|1\rangle$), and individual atoms are then flipped to the other state with a gate rather than pumped there directly.

Alkali atoms (Rb, Cs)

The qubit. In ^{87}Rb the qubit is the "clock" pair $|0\rangle = |F=1, m_F=0\rangle$ and $|1\rangle = |F=2, m_F=0\rangle$, separated by 6.835 GHz. Cs uses F=3 and F=4, $m_F=0$, separated by 9.193 GHz. States with $m_F = 0$ have no first-order Zeeman shift, so the qubit is insensitive to magnetic-field noise.

1. **Set a quantization axis.** A bias magnetic field of about 0.3–1 mT splits the Zeeman sublevels so m_F is well defined.
2. **Pump into the dark state.** π-polarized light ($\Delta m_F = 0$) is tuned to $F=2 \rightarrow F'=2$. Rb usually uses the D1 line at 795 nm, because its excited levels are widely spaced and few nearby levels are excited by mistake. A repumper on $F=1 \rightarrow F'=2$ returns atoms that fall into F=1. The $|F=2, m_F=0\rangle \rightarrow |F'=2, m_{F'}=0\rangle$ transition has a Clebsch–Gordan coefficient of exactly zero, so that state never absorbs a photon. Every other sublevel keeps scattering photons until it lands in $|2,0\rangle$, where it stays. All atoms gather in $|1\rangle$ in about 10–50 μs.
   - To pump into $|0\rangle = |1,0\rangle$ instead, use π light on $F=1 \rightarrow F'=1$ ($|1,0\rangle \rightarrow |1',0\rangle$ is likewise forbidden) with a repumper on F=2.
   - Alternative route: pump with σ^+ light into the stretched state $|F=2, m_F=+2\rangle$, then move to the clock states with microwave or Raman π pulses.
3. **Clean up (optional).** Pumping fidelity is typically about 99–99.5%, limited by polarization impurity, field misalignment, and the tweezer's own light shifts. Two ways to improve it:
   - Apply a microwave π pulse $|2,0\rangle \rightarrow |1,0\rangle$, then remove any atoms still in F=2 with a resonant push-out beam. Wrongly pumped atoms are lost rather than counted as errors, and the loss can be detected and post-selected.
   - Repeat the pump-and-check cycle.
4. **Set the other state where needed.** A global microwave π pulse (fidelity about 99.9%) flips the whole array. Light-shift addressing plus a microwave pulse, or focused Raman beams, puts selected atoms in $|1\rangle$ and leaves the rest in $|0\rangle$.

Alkaline-earth and alkaline-earth-like atoms (Sr, Yb)

These atoms have two valence electrons. Their ground state $^1S_0$ has total electronic angular momentum J = 0, so it is not split the way an alkali ground state is. Three qubit types are in use.

1. Nuclear-spin qubit (^{171}Yb, I = 1/2; ^{87}Sr, I = 9/2)

The qubit is two nuclear-spin sublevels of $^1S_0$, for example $|0\rangle = |m_I = +½\rangle$ and $|1\rangle = |m_I = −½\rangle$ in ^{171}Yb. They are split only by the small nuclear Zeeman effect, a few kHz in typical millitesla fields. Because J = 0, the qubit barely responds to magnetic noise or trap light and has very long coherence.

- **Initialization:** σ-polarized light on the narrow intercombination line $^1S_0 \rightarrow {}^3P_1$ (556 nm for Yb, 689 nm for Sr) drives one sublevel but not the other. The undriven sublevel is dark, so atoms pile up in it. For ^{87}Sr the pumping targets a stretched state such as $m_F = 9/2$ among the ten nuclear sublevels, and two chosen sublevels form the qubit.
- **Rotations:** RF fields at the kHz nuclear splitting, or optical Raman transitions through $^3P_1$ (Ma et al. 2022 and Jenkins et al. 2022 for Yb; Barnes et al. 2022 for ^{87}Sr).

2. Metastable ("omg") qubit, used for erasure conversion

The atom is pumped in the ground state as above, then a clock-laser π pulse (578 nm for Yb, 698 nm for Sr) transfers it to the long-lived $^3P_0$ state. ^{171}Yb carries its nuclear-spin qubit into $^3P_0$ (Ma et al. 2023).

- Rydberg excitation from $^3P_0$ needs only one UV photon (302 nm for Yb, 317 nm for Sr).
- Most errors return the atom to $^1S_0$, where it can be detected without disturbing the stored qubits.

Lis et al. and Norcia et al. (both 2023) also use the split between ground and metastable states for mid-circuit measurement.

3. Optical-clock qubit (^{88}Sr, I = 0)

With no nuclear spin, the ground state has only one level, so every cooled atom is already in $|g\rangle = {}^1S_0$. The state $|e\rangle = {}^3P_0$ is reached in one of two ways:

- A coherent π pulse on the narrow 698 nm clock line.
- Incoherent pumping: drive $^1S_0 \rightarrow {}^3P_1$ (689 nm), then $^3P_1 \rightarrow {}^3S_1$ (688 nm). $^3S_1$ decays into the ^3P states, and lasers at 679 nm and 707 nm empty $^3P_1$ and $^3P_2$, so atoms end up in $^3P_0$ (Madjarov et al. 2020).

Main differences

	Alkali (Rb, Cs)	Alkaline-earth (Sr, Yb)
Qubit splitting	GHz hyperfine	kHz nuclear Zeeman, or an optical transition (hundreds of THz)
Pumping light	Broad D lines (795/780 nm, 894/852 nm)	Narrow intercombination line (556/689 nm), plus clock line (578/698 nm)
Dark-state mechanism	Forbidden $m_F=0 \rightarrow m_{F'}=0$ (π light)	Stretched or one-sided nuclear sublevel (σ light)

	Alkali (Rb, Cs)	Alkaline-earth (Sr, Yb)
Field sensitivity of qubit	Second order (clock states)	Very low (nuclear spin, J = 0)
Extra step	Microwave transfer and push-out cleanup	Clock π pulse to $^3P_0$ for omg and erasure qubits

Relevance to neutral-atom arrays

- **Tweezer light shifts.** In alkalis the tweezer shifts the two hyperfine states slightly differently, which detunes the pumping and later the qubit. Atoms in deeper traps see a larger shift, so uneven trap depths across an SLM array lower the fidelity at some sites. Many groups lower the trap depth during pumping.
- **Magic wavelengths.** For Sr and Yb the tweezer wavelength can be chosen "magic" for the clock transition (for example 813 nm for Sr), so neither state is shifted. That choice constrains which SLM and laser wavelengths can be used.

References

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