

Creating non-classical motional states of trapped ions

Level: Bachelor/ Master

ECTS: 10-15 / 45-60

Topic: To a good approximation, the trapping potential of an ion trap is harmonic. In the quantum mechanical description, the motional energy levels of the ion are thus discrete in equidistant steps with energies $E_n = \hbar\omega_z(n + 1/2)$, $n = 0, 1, 2, \dots$, where ω_z is the vibration frequency.

Light pulses that are red-detuned or blue-detuned compared to an electronic transition resonance allow us to step up and step down the ion on this ladder of motional energy levels. By repeatedly stepping down, it's possible to cool the ion to the motional ground state, $n = 0$.

Alternatively, by using a strategic sequence of step-up and step-down pulses, it's possible to prepare the ion in a highly non-classical state or even create a cat state.

You will work on designing the pulse sequences to prepare these non-classical states, as well as doing simulations to predict the outcome of the experiments.

Research activities:

- Simulate the outcome of state-preparation experiments
- Program execution of pulse sequences using ArtiQ
- Optimizing laser stabilization

Skills gained:

- Practical experience with quantum technology
- Understanding and application of various types of laser systems.
- Hands-on laboratory skills in optics and precision measurement

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Robust optically-induced qubit control and two-ion entanglement gate

Level: Master

ECTS: 45-60

Topic: Strongly driving a qubit with a phase-modulated optical field makes it adiabatically follow the drive, stabilizing the qubit against slow drifts of the relative phase between drive and qubit and reducing its sensitivity to the drive's exact amplitude. We have already established this double-dressing scheme experimentally for single $^{138}\text{Ba}^+$ qubits in our cryogenic Paul trap. The next step is to use the same phase-modulated drive to generate multi-qubit entanglement between co-trapped ions: by correctly engineering the modulation parameters, the motional sidebands of the double-dressed manifold mediate a Mølmer-Sørensen-type entangling Hamiltonian built on the double-dressed rather than the bare qubit basis. The project involves designing and simulating this entangling pulse sequence, characterizing the noise sources that limit its fidelity, and implementing and benchmarking the gate on two co-trapped ions in our setup. Full verification of the entangled state via state tomography requires distinguishing the individual ions' contributions, so the project will also explore whether effective individual qubit addressing is feasible in our setup, e.g., via a second ion species or by adiabatically adjusting the trap frequency to shift the ions' equilibrium spacing relative to the laser phase.

Research activities:

- Get familiar with trapped ions and the double-dressing scheme.
- Design, simulate, and implement a phase-modulated Mølmer-Sørensen-type entangling gate on two co-trapped ions.
- Characterize noise-limiting gate fidelity and evaluate individual addressing for state tomography.

Skills gained:

- Dressing, double-dressing, and phase-modulated entangling gate schemes.
- Trapped-ion experiments: two-qubit gate design, benchmarking, and tomography.
- Simulating noisy, driven two-qubit systems.

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Sideband cooling a single ion to its three-dimensional motional ground state

Level: Master

ECTS: 60

Topic: The motion of a trapped ion in a radio-frequency (RF) trap can be approximately understood as that of a particle in a three-dimensional harmonic oscillator potential. From quantum mechanics, we know that such confined motion is quantized, which becomes apparent close to the ground state. Utilizing a technique called sideband cooling, it is possible to cool an ion with high probability to this ground state. At this point, a single quantized excitation can be resolved and, when trapping multiple ground-state-cooled ion qubits, used as a mediator for information in a quantum computer. So far, in our group, we are able to sideband cool the axial mode of a single Ba^+ ion very efficiently. In your project, you will expand this to sideband-cooling of the two radial modes of motion by developing, implementing, and optimizing schemes for this and comparing experimental results with your theoretical expectation of residual excitation probabilities.

Research activities:

- Get familiar with the present Doppler and sideband cooling in our ion setup.
- Interpret sideband spectra.
- Calculate transition rates and residual phonon distribution.
- Optimize our sideband cooling in one dimension.
- Design a scheme for pulsed sideband cooling of all three modes.
- Implement and optimize your schema.
- RF-field amplitude noise control for lowering ion heating rates.

Skills gained:

- General understanding of ion trapping and laser cooling.
- Lab experience with lasers, AOMs, optical frequency combs, ns real-time experimental control, etc.
- Calculation of atom-light coupling rates in semi-classical theory.

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Isotope selective ionization of barium

Level: Bachelor

ECTS: 10 or 15

Topic: The first step in any ion trapping experiment or quantum computer is to ionize neutral atoms. By exploiting narrow atomic resonances, the process can be performed isotope-selectively. In our cryogenic barium ion trap, we currently ionize using a scheme with two different lasers: a precise 413 nm laser to isotopically selectively excite a neutral barium atom, and a second 532 nm laser to ionize this excited atom. Recent research has shown, however, that if we shift the ionizer wavelength slightly to 530.8 nm, there should be a 100-fold increase in ionization rate.

This project consists of first setting up and characterizing a very recently available commercial diode laser and tuning it to the desired 530.8 nm through temperature control. Secondly, isotope-selective loading of Ba^+ into our cryogenic ion trap will be demonstrated, and the loading rates will be compared to theoretical models that you will take part in developing.

Research activities:

- Set up a temperature-controlled diode laser system.
- Characterize the new laser wavelength, power, stability, and mode.
- Measure ionization rates using the new system.
- Construct a theoretical model and compare it to experiments.

Skills gained:

- Working with narrow-band lasers and fiber optics.
- Gain experience with various techniques to characterize laser spectra
- Control electronics for wavelength tuning.
- Experimental atomic spectroscopy and ion trapping.
- Modelling of light-matter interaction.

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Doppler cooling Barium ions using forbidden transitions

Level: Master

ECTS: 45-60

Topic: The usual Doppler cooling scheme in Barium ions uses the two dipole-allowed 494 nm $S_{1/2} \rightarrow P_{1/2}$ and 650 nm $D_{3/2} \rightarrow P_{1/2}$ transitions. Currently, we're using the electric quadrupole $S_{1/2} \rightarrow D_{5/2}$ (1762 nm) transition for sideband cooling and qubit preparation of a cooled ion. The scheme also needs a fourth $D_{5/2} \rightarrow P_{3/2}$ (614 nm) laser in order to bring the ion quickly back to the $S_{1/2}$ ground state.

With the arrival of a powerful fiber laser addressing the dipole-forbidden 2052 nm $S_{1/2} \rightarrow D_{3/2}$ transition, a new option for cooling emerges using just that and the 650 nm diode laser.

The number of required light sources is a critical factor in the development and commercialization of quantum computers. You will work on stabilizing the 2052 nm light sources via a frequency comb, describing the properties of a cooling cycle using fundamentally different transitions, and schemes for measuring the achieved ion temperature.

Research activities:

- Get familiar with laser Doppler cooling.
- Calculate the Doppler cooling limit using two transitions of very different linewidths.
- Establish and optimize the optical path for the 2052 nm.
- Devise temperature measurements in the sub mK regime.

Skills gained:

- Experience with the semi-classical theory for atom-light interactions.
- Experience with the basics of laser cooling theory.
- Experience with linear RF traps.
- Knowledge of AOMs and other optical components.

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High fidelity ion qubit state readout

Level: Master

ECTS: 45-60

Topic: The usual detection of ions in an ion trap is observing fluorescence light caused by the Doppler cooling cycle. We can detect whether a Ba^+ qubit ion is in the ground state ($S_{1/2}$) or the excited $D_{5/2}$ state by shining 494 nm light addressing the $P_{1/2} \rightarrow S_{1/2}$ transition and observing fluorescence light from the ion at the same wavelength.

By instead using the electric quadrupole $S_{1/2} \rightarrow D_{3/2}$ (2052 nm) transition and the dipole-allowed $D_{3/2} \rightarrow P_{1/2}$ transition (650 nm), 459 nm fluorescence can be observed with no scattered background radiation at the same wavelength. We're currently testing the scheme using the dipole-forbidden $S_{1/2} \rightarrow D_{5/2}$ (1762 nm) and a 614 nm laser addressing $D_{5/2} \rightarrow P_{3/2}$.

As the quadrupole transitions are very narrow ($\Gamma = 2\pi \cdot 1.99$ mHz for $S_{1/2} \rightarrow D_{3/2}$), powerful lasers are needed to create enough photons for background-free detection. With the arrival of powerful IR fiber lasers, this high-fidelity qubit readout scheme has become a viable option.

Research activities:

- Get familiar with laser Doppler cooling.
- Calculate the expected detection rate in the three-level system.
- Document resonance on the narrow quadrupolar transition.

Skills gained:

- Experiment with the semi-classical theory for atom-light interactions.
- Experience with camera calibration.
- Experience with linear RF traps.
- Insight into fiber laser technology.
- Knowledge about AOMs and other optical components.

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Mass-to-charge selection of ions in a cylindrical ion trap

Level: Bachelor

ECTS: 10 or 15

Topic: When a sample of molecules is sprayed through the electrospray ion source, there can be various impurities or isotopologues (same molecule, but containing different atomic isotopes), which are undesired.

Ideally, we wish to filter out any undesired ions or isotopologues from our sample. For this, we can employ the cylindrical ion trap (CIT) located in the middle of the electrospray. Ions with different mass-to-charge ratios become unstable at different voltage settings in the CIT; thus, we can move over different voltages to ensure that only the mass-to-charge ratio of the molecule we wish to investigate can be kept, effectively filtering everything else away.

At the moment, work is being done on storing ions within the CIT and attempting to investigate how fine a resolution it is possible to perform this mass-filtering with.

Research activities:

- Become familiar with the concept of electrospray ionization.
- Learn the working principles of ion traps.
- Design a method for selecting specific mass-to-charge ratios in an ion trap, while throwing others away.

Skills gained:

- Experience with electrospray ionization.
- Experience with radio frequency devices such as quadrupolar ion traps and octopole storage devices.
- Insight into mass spectrometry.
- Become comfortable/able to work in a laboratory environment.

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