Quantum sensing and compensation of RF-fields using single ion

Level: Master
ECTS: 45-60
Topic:
Single trapped ions offer a unique avenue for quantum sensing of electric fields due to their strong Coulomb interaction.

Typically trapped ions are confined using a combination of oscillating (**RF**) and static (**DC**) electric fields. These fields are emitted from trapping electrodes, which need to be carefully co-aligned. Any misalignment will result in coupling between the ion and the RF-field, leading to a driven motion referred to as micromotion. This micromotion gives rise to a modulation of any light fields and imposes sidebands on the optical transitions of the ion.

This project aims to precisely measure the coupling strength to the RF-field using a technique know as sideband spectroscopy and then minimise the associated micromotion, via the adjustment of the DC-field. This will allow for the precise measurement any excess RF-fields at the quantum level.

Research activities:

- Measure single ion coupling to RF-field confining using sideband spectroscopy.
- Compensate static DC fields, using high precision electronics.
- Use single ion in compensated trap, as a high fidelity quantum RF-field sensor.
- Construct theoretical model and compare to experiment.

Skills gained:

- Working with narrow-band lasers and fiber optics.
- Controlling electronics for complex AMO experiments.
- Experimental atomic spectroscopy and ion trapping.
- Modelling of interaction between ions and electrical fields.

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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 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. In your project, you would expand this to sideband cool also the radial motion by developing, implementing and optimizing a scheme 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 schema for pulsed sideband cooling of all three modes.
- Implement and optimize your schema.
- Possibly characterize (and optimize) ion heating rates.

Skills gained:

- General understanding of ion trapping and laser cooling.
- Lab experience with lasers, AOMs, optical frequency combs, ns realtime experiment 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 using 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, however we intend to replace this fiddly 2-color ionization scheme with one using only a single laser. This project consists first of setting up a brand new 413 nm external cavity diode laser, locking it to a wavemeter reference, and characterizing it. Secondly, the laser will be used to perform isotope selective ionization in our ion trap, and the spectroscopy and loading rates compared to theoretical models that you will develop.

Research activities:

- Set up and characterize commercial CW laser system.
- Lock laser to high finesse wavemeter reference.
- Measure ionization rates using new system.
- Construct theoretical model and compare to experiment.

Skills gained:

- Working with narrow-band lasers and fiber optics.
- Control electronics for locking feedback.
- Experimental atomic spectroscopy and ion trapping.
- Modelling of light-matter interaction.

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Doppler cooling Barium ions using forbidden transitions

Level: Bachelor / Master
ECTS: 10 or 15 / 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 were 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 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 source via a frequency comb, describing the properties of a cooling cycle using fundamentally different transitions and schemes of measuring the achieved ion temperature.

Research activities:

- Get familiar with laser Doppler cooling
- Calculate the Doppler cooling limit using two transitions of very different linewidth
- 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 basics of laser cooling theory
- Experience with linear rf traps
- Knowledge about AOMs and other optical components

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High fidelity ion qubit state readout

Level: Bachelor / Master
ECTS: 10 or 15 / 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 ($P_{1/2}$) or the excited $D_{5/2}$-state by shining 494 nm light adressing the $P_{1/2} \rightarrow S_{1/2}$-transition and observing fluorescence light from the ion at the 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), 456 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 cryo cooled 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
- Documenting resonance on the narrow quadrupolar transition

Skills gained:

- Experience 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 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 of 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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