Direct frequency-comb Raman spectroscopy of pure rotational transitions in a single molecular ion

Level: Master
ECTS: 45-60
Topic: High-resolution spectroscopy and pure quantum state manipulation of molecular ions have many applications such as precision tests of fundamental theories, ultracold chemistry, or quantum computation. Purely rotational transitions are typically of ~ 1 THz for light diatomic molecules and hence in a range accessible only with weak THz-sources or through two-photon Raman transitions driven by two phase-locked lasers. Given the large number of molecular internal states one could want to address, this method is difficult to implement experimentally due to the many different laser frequencies needed. A more versatile technique would be to use a femtosecond frequency comb laser to drive such Raman transitions. This innovative approach is based on our recent achievements in The Ion Trap Group in driving the fine structure transition (split by 1.8 THz) of a single atomic ion with this technique.

Research activities:

- Set up the optical beam-path incl. AOMs, prism compressor, etc.
- Rethink and implement a new RF-chain used for active stabilization of the femtosecond laser cavity
- Theoretical calculations of the Raman coupling between the frequency comb and the molecular ion
- Quantum logic spectroscopy of pure rotational states using direct frequency comb Raman excitation
- Accuracy study and error budget

Skills gained:

- Experience with optics incl. optical fibers, lasers, and the most advanced optical frequency measuring tools
- Introduction to cutting-edge experiments on quantum state manipulation of atoms and molecules
- Experience with rf electronics
- Experimental interfacing (Python) and data analysis

The Ion Trap Group
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Space-resolved frequency-comb coherent manipulation of a chain of ions

Level: Master
ECTS: 45-60
Topic: Once trapped and laser-cooled, ions are localized to a very small volume in space due to so-called Coulomb crystallization. External perturbations from the environment can thus be controlled extremely well and this allows for increased coherence time to perform high precision measurements or qubits operations. This together with the fact that individual ions can be addressed selectively (thanks to the relatively large spacing between neighboring ions), make ion chains one of the most promising hardware to implement quantum computing or quantum simulation. Following our recent achievements in The Ion Trap Group in driving a so-called Raman transition in a single ion with a femtosecond laser, we propose to use the inherent space/time relation of such a laser to selectively manipulate individual ions in a chain.

Research activities:

- Set up the optical beam-path including AOMs, prism compressor, motorized translation stage, etc.
- Rethink and implement a new RF-chain used for active stabilization of the mode-locked laser cavity
- Space-resolved coherent manipulation of a chain of ions
- Study the chain coupling dynamics by locally exciting one ion

Skills gained:

- Experience with optics incl. optical fibers, lasers, and the most advanced optical frequency measuring tools
- Introduction to cutting-edge experiments on quantum state manipulation of atoms and molecules
- Experience with rf electronics
- Experimental interfacing (Python) and data analysis

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Rovibrational photon-recoil spectroscopy and rotational cooling of a single molecular ion using a quantum cascade laser

Level: Master
ECTS: 45-60
Topic: Precision spectroscopy of molecular ions provides information on their internal structure. This allows for many fundamental investigations ranging from tests of quantum electrodynamics (QED), improved constraints on the electron-to-proton-mass ratio, as well as on the electron dipole moment, to, via comparison with astrophysical data, detecting drifts over time in natural constants. Good spectroscopic data of a transition can also be used for rotational cooling, and thus to prepare the molecular ion in a well-defined internal state. This has many other interests in metrology, quantum computing, as well as in ultracold chemistry and astrochemistry. Based on our recent achievements in measuring an electronic transition in the Mg^+ atomic ion by so-called photon-recoil spectroscopy, we want to transpose the technique to two specific rovibrational transitions in the MgH^+ molecular ion.

Research activities:

- Numerical simulation of the population dynamics of MgH^+ during photon-recoil spectroscopy
- Photon-recoil spectroscopy of two specific rovibrational transitions using a quantum cascade laser (QCL)
- Accuracy study and error budget
- Laser cooling of a single molecular ion using a QCL

Skills gained:

- Experience with optics incl. optical fibers, lasers, and the most advanced optical frequency measuring tools
- Introduction to cutting-edge experiments on quantum state manipulation of atoms and molecules
- Experimental interfacing (Python) and data analysis

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A cryogenically cooled diode laser system for quantum state manipulation of Ba^+ ions

Level: Bachelor/Master
ECTS: 10 or 15 / 45-60
Topic: Today, diode lasers are one of the most frequently used types of lasers with applications ranging from barcode scanners in shops to the most delicate and precise atomic physics experiments at metrology institutes. Even though diode lasers operating at room temperature can emit light over a large spectrum ranging from near-infrared to UV, there still exist "spectral holes" where these lasers cannot be used. This is for example the case of the $D_{5/2} \leftrightarrow P_{3/2}$ transition at 614 nm in the Ba^+ ion. Being able to drive this transition with laser light is important for our research to directly cool individual Ba^+ ions to the quantum mechanical ground state in our cryogenic ion trap as well as for sympathetic ground state cooling of larger, complex molecular ions. The aim of this project is to cool a commercial diode, operating around 635 nm at room temperature, using liquid nitrogen, to reach the wavelength of 614 nm needed for the trapped Ba^+ experiment.

Research activities:

- Investigate the dependence of the laser diode's wavelength on temperature.
- Characterize the evolution and life time of the laser diode in extreme conditions (very low temperature).
- Characterize the frequency stability and linewidth of the diode laser and investigate the possibilities of frequency stabilization by external grating feedback and/or current modulation.
- Test of the laser system in laser cooling experiments of Ba^+ ions.

Skills gained:

- Experience with optics including optical fibers, diffraction gratings and polarization optics.
- Experience with diode lasers and characterization tools such as optical frequency measuring devices (wavemeter) and Fabry-Perot interferometers.
- Introduction to cutting-edge experiments on quantum state manipulation of atoms and molecules.
- Experience with electronics at cryogenic temperatures.
- Data analysis.

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Loading and laser cooling of Ba^+ ions into a cryogenically cooled linear Paul trap

Level: Bachelor/Master
ECTS: 10 or 15 / 45-60
Topic: With the aim of sympathetically cooling single complex molecular ions to the quantum ground state for performing photoabsorption investigations at the single photon level, we first need to trap and laser cool a single Ba^+ ion to the motional ground in our novel cryogenically cooled (T $\sim$ 6 K) linear Paul trap. The first step towards this intermediate goal will be to load isotopically pure ensembles of barium ions in the trap by resonance enhanced photoionization of neutral barium atoms. More specifically, to achieve a high isotopic purity, a diode laser with a wavelength of 791 nm will be used to drive the narrow $^1S_0 \leftrightarrow {}^3P_1$ transition in barium. Once produced, we can perform Doppler laser cooling on the Ba^+ ions by simultaneously driving the $^2S_{1/2} \leftrightarrow {}^2P_{1/2}$ and $^2D_{3/2} \leftrightarrow {}^2P_{1/2}$ transitions using lasers at 493 nm and 650 nm, respectively. Besides being an excellent coolant ion for sympathetic cooling of complex molecular ions, a single Ba^+ ion can be seen by eye!

Research activities:

- Setting up beam paths for laser cooling of Ba^+ and Ca^+.
- Testing the lasers necessary for loading and cooling of Ba^+.
- Isotope selective photoionization of barium.
- Laser cooling of Ba^+.
- Sympathetic cooling of complex molecular ions.

Skills gained:

- Experience with optics including optical fibers, polarization optics and acousto-optic modulators.
- Experience with external cavity diode lasers (ECDL), dye lasers, frequency doubling cavities and the most advanced frequency measuring tools.
- Experience with radio-frequency electronics.
- Experimental interfacing (Python) and data analysis.

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Frequency locking of a single-mode 1.5 μm fiber laser to a fiber cavity

Level: Bachelor
ECTS: 10 or 15
Topic: Frequency stabilization of single mode lasers have many applications ranging from primary and secondary frequency standards over high precision distance tools as exemplified by gravitational wave interferometers (e.g., LIGO) to telecommunication. As a reference for the only femtosecond frequency comb laser in Denmark, we want to enhance the performance of our current secondary frequency reference in the telecom band around 1.5 μm by improving the short time stability of a commercial fiber laser from NKT Photonic through frequency locking to a fiber cavity. In a longer perspective, the idea is in collaboration with NKT and Danish Fundamental Metrology institute (DFM) to develop a commercial all optical compact fiber laser system, which surpass the performance of current state-of-the-art single frequency fiber lasers.

Research activities:

- All optical fiber coupling of a fiber laser to a fiber optical resonator
- Realization of various feedback optical frequency locking schemes
- Optical frequency stability measurements
- Layouts for potential novel commercial single frequency fiber laser systems

Skills gained:

- Experience with optics in particular optical fibers and fiber lasers
- Experience with advanced optical frequency measuring tools
- Experience with feedback locking electronics
- Insight into optical designs of commercial laser products

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Pulsed laser cooling of ion Coulomb crystals in linear rf traps

Level: Bachelor/Master
ECTS: 10 or 15 / 45-60
Topic: While linear rf traps have been the preferential setup for research towards ion trap based general quantum computing, Penning traps have the past years been leading the impressive development in the field of quantum simulation in two-dimensional cold ion systems (ion Coulomb crystals). Since linear rf traps are considerable cheaper and more flexible than Penning traps, it would be interesting if cold planar ion crystals could be formed in rf traps as well. This possibility has so far been hampered by the so-called fast rf microtion of ions positioned away from the single rf-free axis of the linear rf trap, which lead to extremely large Doppler shifts and hence inefficient cooling by cw laser beams. In recent experiments we have, however, proven that it is indeed possible to reach very low laser cooling temperatures, if pulsed laser light synchronized with the rf trap fields is applied. While we have a good simple physical interpretation of this scheme, we still need to understand this novel cooling-scheme in more details. Hence, in this project we want to perform semi-classical simulations of the pulsed cooling process to gaining more insight before making new experiments.

Research activities:

- Get familiar with various laser-cooling schemes
- Establish and solve the optical Bloch equations for rf trapped ions under cw and pulsed excitations
- Calculate the corresponding mean laser cooling forces and momentum diffusion
- Devise optimal schemes for pulsed laser cooling of planar ion systems

Skills gained:

- Experience with the semi-classical theory for atom-light interactions
- Experience with basics of semi-classical laser cooling theory
- Experience with the functioning of linear rf traps
- Insight into Coulomb crystals and their properties
- Experience with computer simulations of complex dynamics

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