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*Trapped Ions in a Bath of Ultracold Atoms*
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# Summary

This thesis describes an experimental setup for preparing an ultracold cloud of $^6$Li atoms, overlapped with trapped, laser-cooled Yb$^+$ ions. The apparatus was designed to explore the so-called quantum regime of interacting atoms and ions. This regime has not been reached in any experiment up until now, because the electric fields used for trapping the ions can cause heating. In particular, the ions undergo rapid driven motion (micromotion) when kept in a Paul trap, from which energy can be transferred to the atom-ion mixture when a collision occurs. Calculations show that this effect may be mitigated by using a heavy ion and a light atom. In our experiment, we use the ion-atom combination with the largest mass ratio that allows for straightforward laser cooling, Yb$^+$/$^6$Li, giving a mass ratio of 24-29 (depending on the ionic isotope). During my research, the quantum regime was not reached yet in our setup, but I could demonstrate that only a few improvements should be made to achieve this goal. Besides this, I studied the spin of a single ion held in a cold cloud of spin-polarized atoms and found that the spin of the ion aligns with that of the atoms after only a few collisions. We compared these measurements to molecular structure and scattering calculations performed by Dr. Michał Tomza. Surprisingly, even though the measurements were performed well outside the quantum regime, the results do give an indication of what could happen when the quantum regime were reached. In particular, the results suggest the existence of broad magneto-molecular (Feshbach) resonances in the ultracold regime. These resonances play a pivotal role in ultracold neutral atomic systems for tuning the interactions between atoms, but have never been seen between atoms and ions. The observation of Feshbach resonances between atoms and ions will have a huge impact on atomic quantum physics as it will open up completely new possibilities in studying quantum many-body physics as well as in quantum technology.

Specifically, this work answers three scientific questions.

- We calculated that our system can reach the quantum (or *s*-wave) regime of atom-ion collisions, taking into account realistic parameters and levels of micromotion that should be within reach. We have demonstrated experimentally that the requirements for the atoms can be achieved by creating an ultracold atomic cloud within the ion trap. For the ions, minor improvements on the ion

trap are needed to compensate so-called excess micromotion. The implementation of improved micromotion detection and temperature determination schemes will be crucial for proofing thermalization below the $s$-wave temperature. The 329 nm $^2S_{1/2} \rightarrow {}^2P_{3/2}$ transition that was investigated in this work could serve for Raman thermometry to achieve this.

- We found that the ionic spin rapidly exchanges with the atomic spin. Apparent spin-nonconserving relaxation rates may be due to impurity atoms in the wrong spin state. Thus, the measured rates can only be seen as an upper limit. So far, our combination of species shows the highest ratio of spin exchange to spin-relaxation rates of all systems. Further insight on the spin-relaxation and spin-coherence within an atomic bath could be obtained by employing the recently realized optically trapped atomic cloud, that allows for better control.

- By employing *ab initio* quantum scattering calculations, we find that the large spin-exchange rates result from a large difference between triplet and singlet scattering length, surprisingly even for collision energies far above the $s$-wave limit. As an encouraging result, this points towards the existence of broad Feshbach resonances close to the $s$-wave limits at experimentally feasible magnetic fields.