Towards Rydberg excitation of laser-cooled $^{40}Ca^{+}$ ions

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Application Note

Introduction

Rydberg excitation of cold atoms is an interesting and rapidly growing field. The extremely strong dipole interaction between Rydberg atoms leads to a blockade which hinders the atoms from being excited into Rydberg states simultaneously. This effect allows for fast entangling quantum logic gate operations of individually trapped atoms [1-3].

On the other hand the degree of experimental control that can be reached over single trapped ions in Paul traps is astonishingly high allowing for high fidelity single qubit operations and entangling operations [4-6].

Our experiment aims at exciting laser cooled trapped $^{40}Ca^{+}$ ions to Rydberg states, thus combining the advantages of Rydberg physics and trapped ion quantum information processing. In addition the high polarizability of the Rydberg Ion in the time varying electric field of the Paul trap gives rise to new phenomena such as state dependent trapping potentials allowing for precise control over the motional modes of an ion crystal [7,8]. In our experiment the fast and reliable detection of individual ions in a large one dimensional or planar ion crystal is necessary.

Experimental Setup and Ion Detection

Our setup consists of an ultra-high vacuum vessel containing the ion trap. The Paul trap consists of four cylindrical electrodes and two endcaps. Trap frequencies are typically $\omega r=2\varpi\times500kHz$ and $\omega z=2\varpi\times120kHz$. Lasers are used for Doppler cooling, fluorescence detection, optical pumping and coherent manipulation of the $4S_{1/2}$ to $3D_{5/2}$ transition. A lens with high numeric aperture of NA=0.27 collects the laser induced fluorescence near 397nm onto the chip of the EMCCD camera. The excellent quantum efficiency of the EMCCD from Andor Technology (DU897-ECS-BBB) helps to detect enough photons in less than 1ms. For a rapid repetition of experiments, the exposure time with maximum EM gain can be about or even below 1ms for single ion detection and increases to about 3-5ms for bigger crystals. Here, the magnification of the optical system of 17 allows to clearly resolve individual ions in a large crystal with the resolution of about 1µm/pixel. The sensor with 512x512 pixels allows for detecting coulomb crystals with hundreds of ions in a field of view of about 500µm squared. The control of the camera is integrated into the computer control of the experiment. Our self-build software automatically determines the number of ions and their individual positions in the coulomb crystal.
Quantum bits may be encoded on the $4S_{1/2} == |o\rangle$ to $3D_{5/2} == |1\rangle$ transition, as the ions in the metastable level $|1\rangle$ do not emit fluorescence and appear as dark gaps in the ion crystal.

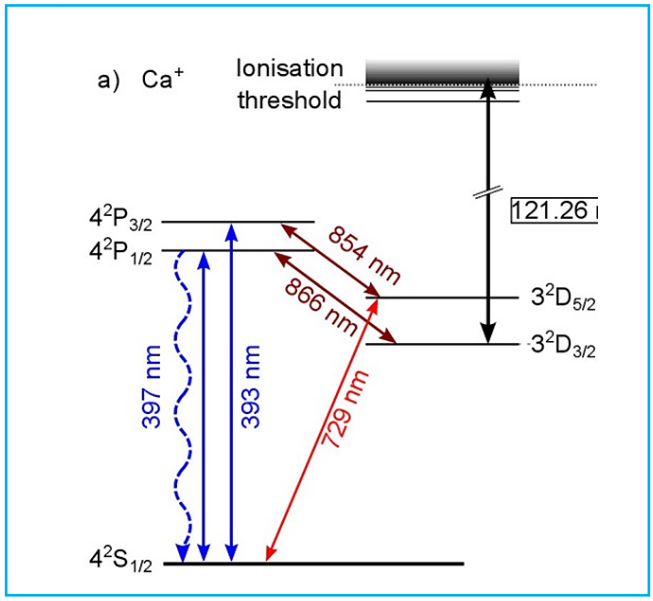

Fig. 1) Relevant energy levels of $^{40}Ca^{+}$. Lasers with 397nm and 866nm are used for Doppler cooling and fluorescence detection, light at 854nm and 393nm is used for optical pumping. The starting point for Rydberg excitation or ionization is the $3D_{5/2}$ level.

For exciting ions to the Rydberg level, the $^{40}Ca^{+}$ ions are first pumped to the metastable $3D_{5/2}$ state from where they are to be excited to the 67P Rydberg state by single photon excitation with a VUV-laser at 122.04nm wavelength. The lifetime of the Rydberg state is about 100µs and thus too short for direct detection with the camera, therefore we employ a modified electron shelving scheme. Ions excited to Rydberg states will decay predominantly to the ground state $4S_{1/2}$ and thus will turn from non-fluorescing to fluorescing. The 397nm light is then detected with the iXon3 897 EMCCD camera. Based on a previously defined threshold value, the software can automatically determine in which state each ion is.

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Measurements

As a first experiment we produced doubly ionized ^{40}Ca by tuning the VUV-laser to an even shorter wavelength. In this case we detected the $^{40}Ca^{2+}$ by looking at position changes of the remaining $^{40}Ca^{+}$ ions. If the center ion of a three ion string is ionized, it appears as a dark void in the middle of the crystal, while the distance between the two outer ions is increased by 21% (8µm) due to increased Coulomb repulsion.

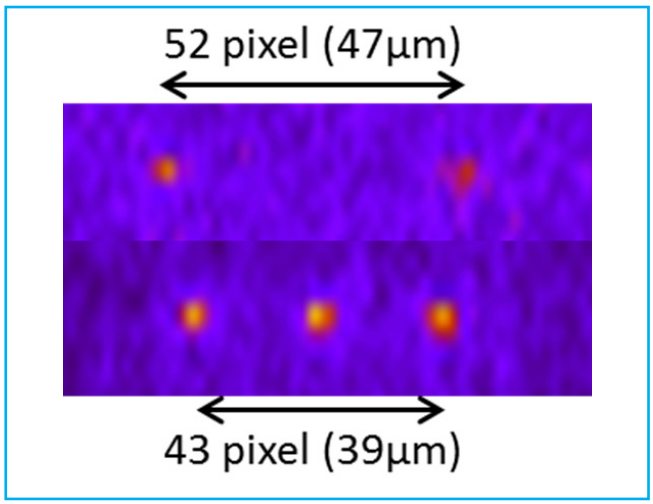

Fig. 2) Three ion crystal with and without $^{40}Ca^{2+}$ in center position. Due to the stronger coulomb repulsion the distance between ions is increased by 21% in the case of a doubly charged ion in center position.

The increased radial trapping potential of the $^{40}Ca^{2+}$ is similar to the predicted trapping potential of a $^{40}Ca^{+}$ ion in a high lying Rydberg state. This allows for measuring predicted effects on the vibrational mode structure of the ions with $^{40}Ca^{2+}$ instead of Rydberg ions [9]. Particularly interesting is the case of a long ion string with one or more $^{40}Ca^{2+}$ impurities. The collective modes of common vibrations in radial direction in the crystal is effectively separated into independently oscillating sub crystals, as can be seen in fig.3. The modes have been excited by applying an oscillating voltage with the eigenfrequency of the mode to the electrodes of the ion trap and the amplitude of the oscillation can be detected as a smear out of the fluorescence image.

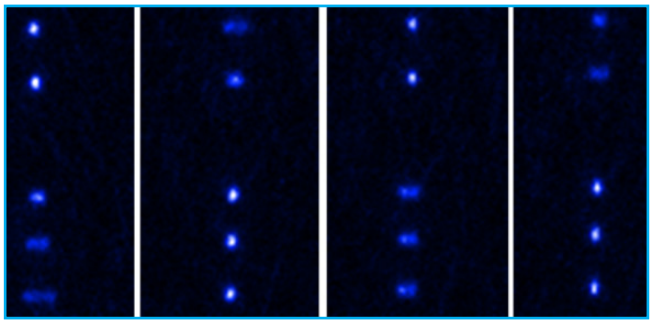

Fig. 3) Vibrational modes of a six ion crystal with one $^{40}Ca^{2+}$ impurity. The oscillation for each mode is restricted to one of the sub-crystals. The oscillation of the ions can be directly detected with the camera

For many of the envisioned experiments with Rydberg states it is necessary to excite specific ions in larger coulomb crystals. Since in our experiment it is not planned to focus the VUV-laser on single ions, we use a narrow, few µm wide focus of the laser beam at 729nm and excite only one single ion from the ground state to the $3D_{5/2}$ state which is the starting level for the Rydberg excitation. The addressing of a single ion in a planar Coulomb crystal is shown in fig.4.

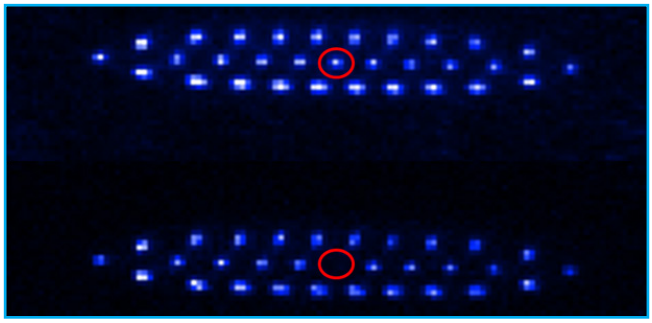

Fig. 4) Two dimensional coulomb crystal consisting of 31 ions. In the lower picture the middle ion is excited to the $3D_{5/2}$ state by a pulse of a tightly focussed beam at 729nm wavelength

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References

[1] M. Saffman, T.G. Walker, K. Molmer, "Quantum information with Rydberg atoms", Rev. Mod. Phys. 82 (2010)

[2] E. Urban, T. A. Johnson, T. Henage, L. Isenhower, D. D. Yavuz, T. G. Walker, M. Saffman, "Observation of Rydberg blockade between two atoms", Nature Physics 5, 110(2009)

[3] T. Wilk, A. Gaetan, C. Evellin, J. Wolters, Y. Miroshnychenko, P. Grangier, A. Browaeys, "Entanglement of two individual neutral atoms using Rydberg blockade", Phys. Rev. Lett. 104, 010502(2010)

[4] H. Häffner, C. F. Roos, R. Blatt, „Quantum computing with trapped ions", Physics Reports 469, 155(2008)

[5] T. Monz, P. Schindler, J. T. Barreiro, M. Chwalla, D. Nigg, W. A. Coish, M. Harlander, W. Hänsel, M. Hennrich, R. Blatt, „14-qubit entanglement: creation and coherence", Phys. Rev. Lett. 106, 130506(2011)

[6] J. P. Home, D. Hannecke, J. D. Jost, J. M. Amini, D. Leibfried, D. J. Wineland, "Complete Methods Set for Scalable Ion Trap Quantum Information Processing", Science 325, 1227(2009)

[7] F. Schmidt-Kaler, T. Feldker, D. Kolbe, J. Walz, M. Müller, P. Zoller, W. Li, I. Lesanovsy, „Rydberg excitation of trapped cold ions: a detailed case study", New J. Phys. 13 (2011), 075014

[8] W. Li, A. W. Glaetzle, R. Nath, I. Lesanovsky, „Parallel execution of quantum gates in a long linear ion chain via Rydberg mode shaping", Phys. Rev. A 87, 052304(2013)

[9] T. Feldker, L. Pelzer, M. Stappel, P. Bachor, R. Steinborn, D. Kolbe, J. Walz, F. Schmidt-Kaler, „Mode shaping in mixed ion crystals of $^{40}Ca^{2+}$ and $^{40}Ca^{+}$", accepted for publication in Applied Physics B

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