Optica Applicata, Vol. XXXVI, No. 4, 2006

A way to the engineering of the quantum states of trapped ions – report of work in progress

EWA STACHOWSKA*, GUSTAW SZAWIOŁA, ADAM BUCZEK, WOJCIECH KOCZOROWSKI, BOGUSŁAW FURMANN, ANDRZEJ KRZYKOWSKI, DANUTA STEFAŃSKA, ADRIAN WALASZYK, ANDRZEJ JAROSZ, JERZY DEMBCZYŃSKI

Chair of Quantum Engineering and Metrology, Poznań University of Technology, Nieszawska 13B, 60-965 Poznań, Poland

*Corresponding author: E. Stachowska, Ewa.Stachowska@put.poznan.pl

We studied the influence of geometry on the interaction of ions in a Paul trap with microwave radiation and the spatial velocity distribution from the Doppler shift. Non-linear resonances in a Paul trap for Pr^+ ions were observed.

Keywords: Paul trap, nonlinear resonances, double optical-rf resonance technique.

1. Introduction

Much work has been devoted to the dynamical, temporal invariance, collision and space-charge effects for ions confined in a radio-frequency trap (see references in [1–3]), but still some effects have not been described and explained sufficiently. Especially our knowledge about the sensitive quantum effects is rather restricted.

Engineering of the quantum states of trapped ions has recently been intensively experimentally studied both regarding the cognitive as well as the applied aspects. These problems concern the following fields: extremely precise time and frequency measurements, fundamental physical laws determining storage, processing, transfer and readout of the information on the quantum level, leading to an implementation of a quantum processor.

In the present paper, we report experimental results obtained in the Chair of Quantum Engineering and Metrology at the Poznań University of Technology and the National Laboratory of Atomic, Molecular Physics and Optics in Toruń (KL FAMO). The results presented are intended to contribute to the techniques of full control of the quantum states of single cold ions confined in electromagnetic traps.

2. Optical–microwave resonance

The double optical–radio frequency (rf) resonance method is an advanced spectroscopic tool. In the case of a Paul trap, this method provides for a very precise experimental determination of hyperfine structure constants and higher nuclear moments of the confined ions. Using this method optical signals according to magnetic dipole transitions between hyperfine sublevels of the ground state $^9S_4$ of the ion $^{151}Eu^+$ have been observed in our laboratory in Poznań (see Fig. 1). The results obtained for have been performed on the optical transition at 420.5 nm with an upper level $4f^7(^8S_{7/2})6p_{1/2}$. Earlier similar measurements have been done at Mainz

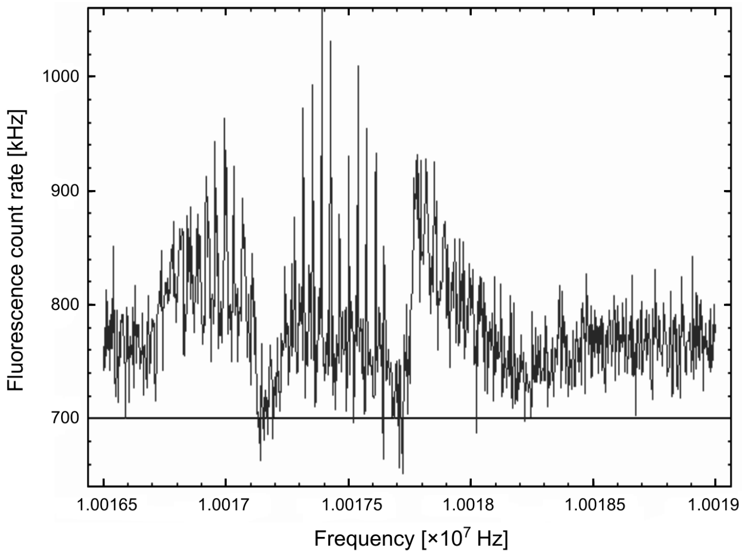

Fig. 1. The recorded signal of the double optical–microwave resonance of the magnetic dipole transitions in $^{151}Eu^+$ to the first metastable level $^9S_4$.

University, however based on a different optical transition than that used by us [4]. The radius of our trap was half the Mainz one, which reduced the size of the ion cloud, and could also influence the microwave propagation inside the trap. We could show that this geometrical change did not influence the results.

3. Observation of the spatial distribution of the Doppler shift

Doppler effect is one of the dominating effects in the shape of a spectral line recorded in a rf Paul trap. Usually the Doppler effect is caused by chaotic, thermal motion. In the case of an ion trap this effect is caused by the motion of the ions under the influence of the trapping electric fields [3].

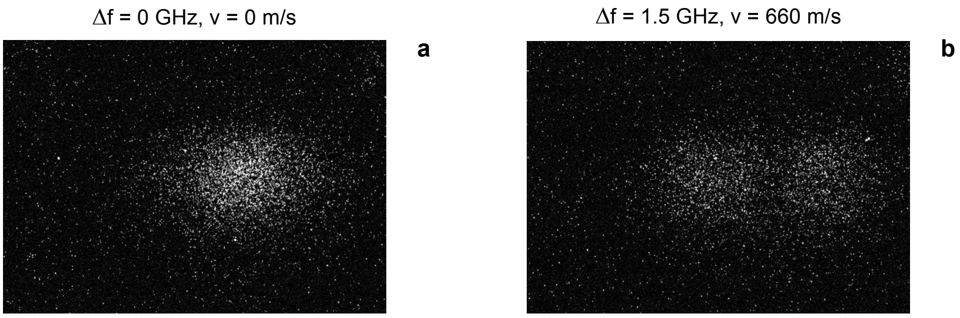

Fig. 2. Spatial Doppler shift of excited parts of the ion cloud. For each of the pictures the detuning frequency and the average velocity of the ions are given.

Searching for more efficient pumping of the metastable states of Pr^+ and optimizing the detection of the fluorescence light direct observations using a CCD camera have been done on the spatial velocity distribution of the ions along the direction of the exciting laser beam. This phenomenon has been recorded during the scan of the wavelength of the laser radiation which excites the ions. In Fig. 2, two pictures of excited parts of the ion cloud are presented at two selected values of the frequency of this laser.

4. Optical observation of the nonlinear resonances

Imperfections of the trapping potential cause unstable ion motion for some values of the trapping parameters a_z and q_z which are determined, for particular masses, by the frequency Ω of the trapping AC high voltage and respectively DC offset and AC amplitude of trapping voltages [2]. The implicit function of the a and q are the axial

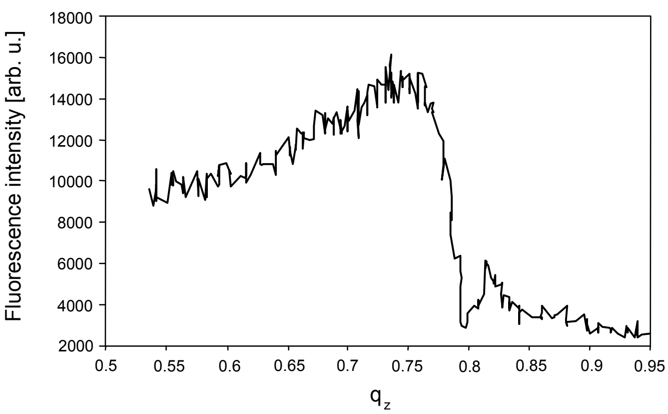

Fig. 3. Dependence of the laser induced fluorescence intensity in praseodymium on q_z at a_z = constant. For the value of q_z equal 0.77 an abrupt drop in intensity is observed, indicating a non-linear resonance.

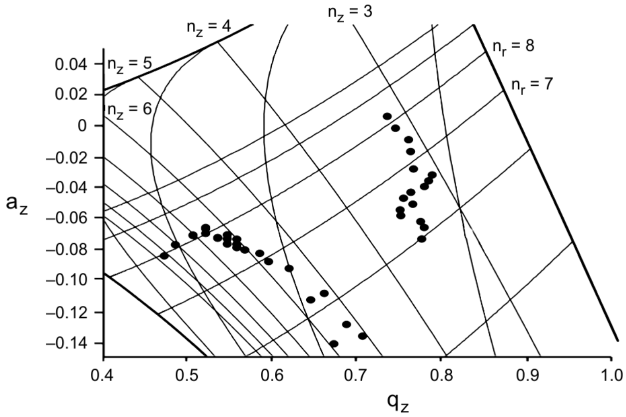

Fig. 4. Stability diagram with theoretical lines of nonlinear resonances and experimental points determined for the praseodymium ion.

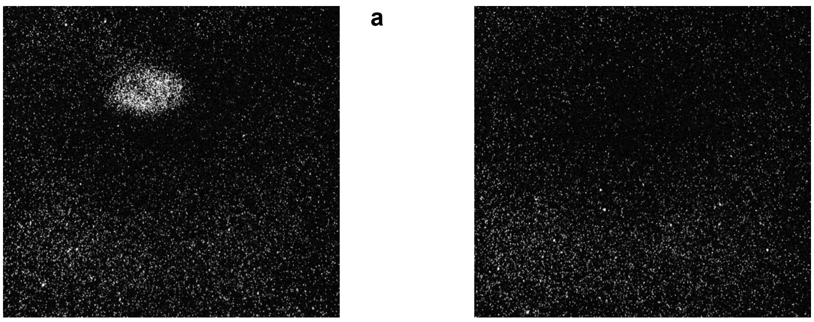

Fig. 5. Optical signal of the confined calcium ion cloud in a linear Paul trap.

and radial oscillation frequencies ω_r and ω_z of moving ions. The nonlinear resonances comply with a simple, but nevertheless fundamental, constraint: $n_r\omega_r + n_z\omega_z = k\Omega$ with k, n_r, n_z integers and relevant theoretical curves being depicted in Fig. 4. Calculating the ω_r and ω_z from the trapping parameters and taking into account the simple linear relation mentioned above the n_r, n_z modes as well as the order of nonlinear oscillations can be determined. The sum $|n_r| + |n_z| = N$ determines the $2N$ order of a perturbing multipole.

We detected the nonlinear resonances by observing the variation in the laser induced fluorescence (LIF) of $^{141}Pr^+$ ions. The fluorescence light has been recorded with a photomultiplier. The evidence of these nonlinear resonances – a strong decrease of the intensity of the fluorescence light – is given in Fig. 3. Several points of experimentally observed nonlinear resonances are indicated in the stability diagram in Fig. 4.

5. Observation of a small number of ions in a linear Paul trap

Recently, our group has become involved in a research project within the framework FAMO in Toruń concerning confining calcium ions in a linear Paul trap [5]. We recorded the optical signal of a trapped calcium ion cloud with a CCD camera. The transitions used were: $^2S_{1/2} \rightarrow {}^2P_{1/2}$ for the pumping laser beam and $^2D_{3/2} \rightarrow {}^2P_{1/2}$ for a re-pumping laser beam. The re-pumping laser was required due to the relatively long lifetime of the level $^2D_{3/2}$ in the calcium ion, see, *e.g.*, [6].

Preliminary results are presented in Fig. 5, at different frequencies of the re-pumping laser. In Fig. 5**a** the re-pumping laser has been tuned to the transition frequency. In Fig. 5**b** the re-pumping laser has been detuned about 5 GHz from the center of the re-pumping transition.

6. Summary

Engineering of the quantum states of trapped ions requires advanced research tools, which allow precise measurement in both the frequency (time) and spatial domain. The work presented in this report is useful for the development of these aspects of quantum engineering.

Frequency measurements of double optical–microwave resonances (see Section 2) will be continued using ions of other elements (*e.g.*, praseodymium) which have not been investigated with this method. The observed Doppler effect (Section 3) allows spectroscopic investigation with spatial resolution: different parts of ion cloud can be observed according to the laser frequency detuning. The population of the ions investigated also depends on their properties. Nonlinear resonances as described in Section 4, allow selective elimination of ions according to the mass to charge ratio.

The investigations described in Sections 2–4 have been performed in a three -dimensional hyperbolic Paul trap. The relatively great amount of ions in that setup allows observations with a high fluorescence signal. On the other hand, reduction of the number of confined ions in the linear trap as in Section 5, although not always convenient for spectroscopic purposes, allows the observation of much smaller quantum effects such as: collective interactions and decoherence phenomena. This way of investigation leads to the analysis of important problems concerning the principles of quantum processing.

All the above mentioned experiments contribute to the development of quantum engineering methods and lead to a better understanding of the nature of quantum effects.

Acknowledgment – The research presented here has been supported by project PBZ KBN 043/P03/2001, the 6th European framework project – QUELE (FP6-003772) and project BW 63-025 of Poznań University of Technology (Poland), and was partially realized in the National Laboratory of Atomic, Molecular Physics and Optics KL FAMO, Toruń (Poland).

References

[1] MARCH R.E., HUGHES R.J., *Quadrupole Storage Mass Spectrometry*, Chemical Analysis Series, John Wiley and Sons, Vol. 102, New York 1989.

[2] MAJOR F.G., GHEORGHE V.N., WERTH G., *Charged Particle Traps*, Springer Series on Atomic, Optical and Plasma Physics Vol. 37, Springer 2005.

[3] SIEMERS I., BLATT R., SAUTER Th., NEUHAUSER W., *Dynamics of ion clouds in Paul traps*, Physical Review A **38**(10), 1988, pp. 5121–8.

[4] ENDERS K., BECKER O., BRAND L., DEMBCZYŃSKI J., MARX G., REVALDE G., RAO P. M., STACHOWSKA E., WERTH G., *Hyperfine-structure measurements in the ground state of radioactive $^{150}Eu^+$ ions*, Physical Review A **52**(6), 1995, pp. 4434–8.

[5] www.phys.uni.torun.pl/famo.

[6] LUCAS D.M., RAMOS A., HOME J.P., MCDONNELL M.J., NAKAYAMA S., STACEY J.-P., WEBSTER S.C., STACEY D.N., STEANE A.M., *Isotope-selective photoionization for calcium ion trapping*, Physical Review A **69**, 2004, p. 012711.

Received January 30, 2006
in revised form April 21, 2006