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Simple and efficient photo-ionization loading of ions for precision ion-trapping experiments

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ABSTRACT We report a simple and efficient method to load a Paul trap with Ca^+ ions. A beam of neutral atomic calcium is ionized in a two-step photo-ionization process using uv-diode lasers near 423 nm and 390 nm. Photo-ionization of a calcium beam for loading a Paul trap has first been demonstrated by Kjærgaard et al. The advantages of our method are the use of cheap and easily handled diode-laser systems and the large cross section for field ionization when exciting high-lying Rydberg states. Finally, we discuss the advantages of photo-ionization for ion generation compared to loading by electron bombardment.

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1 Introduction

Among several proposals for a scalable quantum information processor, linear crystallized strings of ions in Paul traps are considered to be promising candidates [1]. Long-lived electronic states of individual ions represent the qubits, with the collective modes of motion of the ions in the crystal providing interactions between the qubits. It has been shown that single ions or strings of ions stored under ultra-high-vacuum conditions can maintain coherence for times greatly exceeding that required for two-bit quantum-gate operations. However, unexpected large heating rates of the collective vibrational modes, which are used for the quantum-gate operation, have affected the experimental efforts so far [2, 3]. Most probably, charged patches on the Paul-trap electrodes near the ion string are responsible. Detailed studies [2, 4] indicate that proper electrode surfaces lead to a lower heating rate.

We report on a highly efficient loading scheme for a Paul trap, using a two-step photo-ionization scheme on a weak thermal beam of neutral atomic calcium. The method avoids any charging of the nearby surroundings since no electron gun is used. Also, due to its extremely high efficiency, the atomic beam density can be greatly decreased, which allows one to severely reduce unwanted material sputtered onto the trap electrodes from the oven. Additionally, only the desired elements, even the desired isotopes, are ionized, which allows one to produce ion crystals of high purity [5].

2 Ionization scheme and experimental setup

The relevant levels for the ionization of atomic calcium are shown in Fig. 1. Our realized route is as follows: with the first laser field near 423 nm the dipole transition from the ground $4s\,^1S_0$ state to the $4p\,^1P_1$ excited state ($\Gamma_{\rm nat} = 34.7$ MHz) is driven. Due to the very small branching ratio ($\leq 10^{-4}$), the decay into the metastable $3d\,^1D_2$ state does not play a significant role. In the second step the atoms are excited with a laser field near 390 nm to a Rydberg state with principal quantum number $n \sim 30$. The Rydberg atoms are subsequently ionized due to the presence of strong electric fields. As the ions are captured only when the ionization occurs within the trapping volume, we hereby take advantage of the presence of the rf field to strongly enhance the ionization probability when comparing with direct photo-ionization into the continuum.

The resonant nature of the first excitation and the fact that the isotope shifts are considerably larger than the excitation line width ensure that we can ionize any calcium isotope selectively. Also, background atoms will not have a transition at exactly the same wavelength and thus can only be ionized through non-resonant multi-photon processes, which are extremely weak.

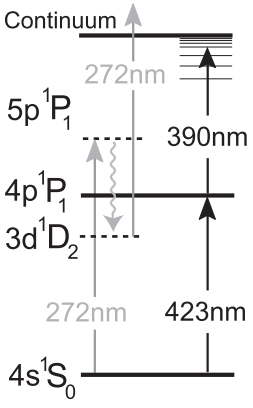

FIGURE 1 Level scheme of neutral calcium and relevant wavelengths for ionization. *Left-hand side, grey arrows*: method by Kjærgaard et al., *right-hand side*: actual work, two-step excitation by uv-diode laser sources only

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We take the two wavelengths required for the photo-ionization from the tables in [6], and find 422.791 nm (vac.) for the first step and 389.808 nm (vac.) for the photon energy from the $4p\,^1P_1$ level to the ionization limit. Until recently, dye lasers were the only tunable spectrally narrow sources with sufficient power in this region of the visible spectrum. We take advantage of the availability of reliable violet diode lasers to produce these two wavelengths both cheaply and with a significantly smaller amount of effort and maintenance.

Photo-ionization of calcium for loading a Paul trap has been demonstrated recently using laser light near 272 nm [5]: the excitation of the $4p\,^1P_1$ level, followed by the decay to the metastable $3d\,^1D_2$, is continued by the excitation far above the ionization limit (see Fig. 1). Our route avoids the use of an argon-ion-laser-pumped dye laser followed by frequency-doubling, and is thus much cheaper and less demanding in the laboratory.

For the frequency stabilization of both uv-diodes we decided to use the Littrow configuration. The diodes, the collimating lenses, and the mirror mounts holding the holographic grating (3600 lines/mm, piezo for fine adjustment) are mounted in a simple home-machined aluminum holder. We use a compact design such that the grating is ~ 10 mm from the front of the collimating lens.

The first excitation step is driven with a 30-mW Nichia diode (selected so that $\lambda = 422.3$ nm) [7]. With first-order optical feedback from the grating of $\sim 10\%$, we reduce the threshold by ~ 10 mA and achieve a tuning range ≥ 1.5 nm.[1] The second step is driven with a 5-mW Nichia diode (selected so that $\lambda = 391.0$ nm) in the similar Littrow configuration and the threshold is reduced by ~ 3 mA. We use a wavemeter to set both wavelengths within 5×10^{-6}. The laser for the first step operates on the resonant transition and the wavelength stabilization is more critical. For more accurate tuning of this laser we use a hollow-cathode calcium discharge lamp. A pick-off beam from the laser is sent into the lamp and the current modulation through the lamp is measured. We observe a Doppler-broadened lock-in signal and center the wavelength to within ≤ 100 MHz of this resonance. Both lasers are sufficiently passively stable that after a short period of adjustment they remain on wavelength for extended periods of time. The output beams are superimposed on a polarizing beam splitter and focused in between the trap electrodes with a waist size of $\sim 200\,\mu$m and a power of 1.5 mW (0.7 mW) for the laser near 423 nm (390 nm).

The experimental set-up of our ion-trapping apparatus has been described in detail before [8, 9], although an overview of the essentials is necessary. We produce a beam of atomic calcium by resistively heating a stainless steel oven, built from a tube of length 3 cm and inner diameter 1.8 mm. The oven heating current has been varied between 3 and 5 A, giving a measured oven temperature between $\sim 180\,^\circ$C and $350\,^\circ$C. The oven nozzle is directed to the center of our rf Paul trap, at a distance of 1.5 cm. The full opening angle of the calcium beam is ~ 15 degrees and we find a diameter of 6 mm at the position of the trap. The direction of the ionization laser beams is almost perpendicular to the atomic beam.

The pseudo-potential for trapping ions is generated by an electrode structure ($r_{\rm trap} = 0.7$ mm, $l_{\rm trap} = 6$ mm) operated at an alternating voltage of 23 MHz with $\sim 1000\,V_{\rm pp}$. When calcium is ionized within the confining field volume, the produced ions are trapped and laser-cooled by radiation near 397 nm on the transition $S_{1/2}$–$P_{1/2}$ of Ca^+. The resonance fluorescence of captured ions is detected with a PMT and an intensified CCD camera. Thus, we are able to count the ions (up to 30) and to distinguish whether crystals are pure Ca^+ ions. The oven and ion trap are housed in a stainless steel vacuum chamber, pumped by a titanium sublimation pump and an ion pump, with ultimate pressure below that measurable with our ion gauge, which is below 2×10^{-11} mbar.

3 Results

We have been able to load a variety of calcium crystals into our ion trap, ranging from thousands to single ions. The measured wavelengths were 422.792(2) nm and 390.6 nm (vac.). The first wavelength agrees well with the value reported in the literature; the second wavelength is clearly larger than that required to bridge the energy gap from the p state to the continuum (389.808 nm), so high-lying Rydberg states were excited. We studied the dependence of the ionization yield on the frequency of the first excitation step and found that the half-efficiency point was at -200 MHz and $+400$ MHz with respect to the maximum signal of the hollow cathode.[2] The loading works for any chosen rf amplitude equally well. At every capture run we have only

[1] We operate both diodes at 19 °C The measured wavelength shift of 0.1 nm/°C indicates that temperature tuning of the wavelength is inefficient.

[2] A residual Doppler shift caused by a slightly non-orthogonal laser direction with respect to the atomic beam may account for this effect.

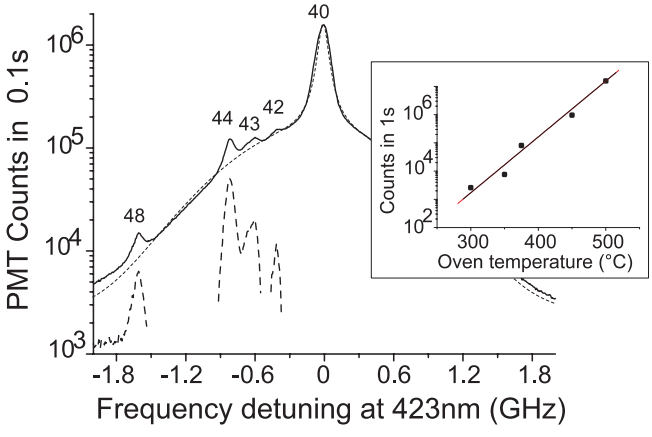

FIGURE 2 Excitation spectrum of neutral calcium on the $4^p\ ^1S_0$–$4^p\ ^1P_1$ resonance at 423 nm (1 mW). Data and fit (*dotted*) and residua (*dashed*). The observed isotopic shifts are 1.6, 0.8, 0.6, and 0.4 GHz. *Inset*: count rate on the ^{40}Ca resonance for different oven temperatures

ever seen pure crystals, never any non-fluorescing ions. This means that the ionization method is fully species- and isotope-selective. The crystal size is determined by the atomic beam flux density and the exposure time of the ionization laser beams: with 10 s and 350 °C oven temperature we load over a thousand ions, while at 200 °C the loading rate reduces to ~ 0.3 ions/s. This observation is consistent with the vapor pressures for these temperatures, which are 2×10^{-6} mbar and 10^{-11} mbar, respectively [10].

Our measurements show that photo-ionization is over five orders of magnitude more efficient than the electron-bombardment method which we used previously to produce ions: at an oven temperature of 350 °C and an electron-beam exposure time of a few minutes we used to trap a single ion or a few ions.

To investigate the atomic Ca beam in detail, we have set up a second vacuum vessel with an oven construction similar to that for loading the ion trap. The atoms are excited under a right angle to the beam direction, from the ground state to the $4p\,^1P_1$ level. We observe the emitted fluorescence with a photomultiplier while the laser at 423 nm is tuned over the resonance (see Fig. 1). The spectrum in Fig. 2 exhibits five Lorentzian resonances for the isotopes of calcium, and the relative signal strengths are in coarse agreement with the natural abundances, ^{40}Ca (96.9%), ^{42}Ca (0.647%), ^{43}Ca (0.135%), ^{44}Ca (2.086%) and ^{48}Ca (0.187%). We do not detect a resonance for ^{46}Ca (0.004%). The observation of clearly resolved resonances (FWHM 90 MHz) proves our ability of isotope-selective photo-ionization. Measured isotope shifts are indicated in Fig. 2. The isotope frequency shift of calcium isotopes has been studied in detail [11]. To obtain a large signal to noise ratio, the oven temperature was increased to ~ 500 °C, and thus the vapor pressure is higher by $\sim 10^7$ compared with conditions chosen for loading single ions into the Paul trap. Under these conditions, a ~ 2.8 MHz (FWHM) Gaussian background is observed, probably due to collisions, which give rise to a wider range of Doppler shifts. This background disappears at lower vapor pressures. We have observed that the sharp resonance for ^{40}Ca is shifted by ~ 100 MHz from the center of the hollow-cathode signal.[2] The inset of Fig. 2 shows the increase of the ^{40}Ca peak count rate as a function of the oven temperature, which reproduces nicely the scaling of Ca vapor pressure [10].

4 Conclusion

In conclusion, we have demonstrated a highly efficient, cheap and low-maintenance method of loading a Paul trap. This is of great interest as ion traps are being investigated by our group and many other groups worldwide as a good environment in which to perform quantum computation operations or for atomic frequency standards. Previously it has been found [2] that loading of ion traps by electron bombardment creates patch potentials, producing a heating of the motional states of ions. Our method of ion production avoids such problems. Indeed, we observe that the applied correction voltages necessary for centering the ion in the trap remain the same within $\sim 1\%$ over months. Moreover, sputtered material from ovens also needs to be avoided for the same reason. With the five orders of magnitude efficiency gain, the atomic beam flux can be greatly reduced and thus unwanted sputtering almost completely avoided.

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REFERENCES

1 D. Bouwmeester, A. Ekert, A. Zeilinger (Eds.): *The Physics of Quantum Information* (Springer, Berlin 2000)
2 Q.A. Turchette, D. Kielpinski, B.E. King, D. Leibfried, D.M. Meekhof, C.J. Myatt, M.A. Rove, C.A. Sackett, C.S. Wood, W.M. Itano, C. Monroe, D.J. Wineland: Phys. Rev. A **61**, 063 418 (2000)
3 D.J. Wineland, C. Monroe, W.M. Itano, D. Leibfried, B.E. King, D.M. Meekhof: J. Res. Natl. Inst. Stand. Technol. **103**, 259 (1998)
4 D. Leibfried: private communication
5 N. Kjærgaard, L. Hornekær, A.M. Thommesen, Z. Videsen, M. Drewsen: Appl. Phys. B **71**, 207 (2000)
6 A.A. Radzig, B.M. Smirnov: *Reference Data on Atoms, Molecules and Ions* (Springer-Verlag, Berlin 1985)
7 Toptica Photonics, Munich (http://www.toptica.com/)
8 H. Rohde, S.T. Gulde, C.F. Roos, P.A. Barton, D. Leibfried, J. Eschner, F. Schmidt-Kaler, R. Blatt: J. Opt. B **3**, 34 (2001)
9 Ch. Roos, Th. Zeiger, H. Rohde, H.C. Nägerl, J. Eschner, D. Leibfried, F. Schmidt-Kaler, R. Blatt: Phys. Rev. Lett. **83**, 4713 (1999)
10 J.F. O'Hanlon: *A User's Guide to Vacuum Technology* (Wiley, New York 1989)
11 A. Andl, K. Bekk, S. Göring, A. Hanser, G. Nowicki, H. Rebel, G. Schatz, R.C. Thompson: Phys. Rev. C **26**, 2194 (1982); P. Müller, B.A. Bushaw, W. Nörtershäuser, K. Wendt: Eur. Phys. J. **D 12**, 33 (2000)