Towards Quantum Information Processing with Atomic Ions in a Penning Trap

S R de Echaniz†, R. Hendricks, K. Koo, A. de Lange, E S Phillips, H F Powell, J.Sudbery, R.C.Thompson and D.M.Segal,

Blackett Laboratory, Imperial College London, London SW72AZ
Email contact: d.segal@imperial.ac.uk
†Presently at: ICFO - Institut de Ciències Fotòniques, Jordi Girona 29, Nexus II, E-08034 Barcelona, SPAIN

We report on progress in experiments aimed at assessing individually addressable laser cooled ions held in a Penning trap as a candidate system for Quantum Information Processing (QIP). The Penning trap employs static electric and magnetic fields as opposed to the oscillating electric field employed in the more familiar radio frequency Paul or linear traps. As a result, the decoherence rate may prove to be significantly lower in this system. The motion of an ion in a Penning trap consists of a harmonic oscillation in the electrostatic potential well along the axis of the trap and an epicyclic superposition of two circular motions in the radial plane: the modified cyclotron motion and a slower **E**×**B** drift around the center of the trap, the magnetron motion. As a result of the rather complicated motion of ions in a Penning trap, laser cooling is less straightforward than it is in a radio frequency trap. The magnetron motion is particularly difficult to minimize so that single ions are not as well localized as they are in a radio frequency trap.

Our experiments are either carried out using either $^{24}Mg^+$ ions or $^{40}Ca^+$ ions. We report a study of the axialization and laser cooling of single $^{24}Mg^+$ ions and small clouds of $^{24}Mg^+$ ions in a Penning trap. A weak radio frequency (rf) signal applied to a segmented ring electrode couples the magnetron motion to the cyclotron motion, which results in improved laser cooling of the magnetron motion. This allows us to approach the trapping conditions of a Paul trap, but without any micromotion. Using an ICCD camera we show that the motion of a single ion can be confined to dimensions of the order of 20 μm or less (20 μm is an upper bound set by the resolution of our imaging apparatus but is already a significant improvement over the situation without axialisation). We have measured increased magnetron cooling rates for clouds of a few ions, using an rf-photon correlation technique.

In another experimental setup we are studying $^{40}Ca^+$ ions. The level structure of this ion is more complicated than that of $^{24}Mg^+$ and this means that more laser frequencies are required. However, the extra energy levels make $^{40}Ca^+$ more suitable for QIP. We have laser cooled a small cloud of $^{40}Ca^+$ ions stored in a Penning trap. The large Zeeman splittings that result from the presence of the imposed magnetic field necessitate the use of two cooling lasers tuned to the $^2S_{1/2}$ – $^2P_{1/2}$ transition near 397 nm (whereas a single blue laser frequency is required for this ion in an rf trap). The 397 nm radiation is provided by a pair of blue diode lasers operated in extended cavities. Ions can escape from the cooling cycle by falling into a $^2D_{3/2}$ state. There is also a small probability that ions can be pumped into a $^2D_{5/2}$ state. The presence of the large Zeeman splittings complicates the provision of repumper radiation to empty the D-states. We describe two repumping schemes. The first scheme employs 5 infrared extended cavity diode lasers (ECDLs). A second scheme employs three infra-red ECDLs, two of which have their injection current modulated to produce sidebands. An upper bound to the temperature of 0.5K is inferred from the linewidth of the 397 nm transition. We are currently working on axialisation of $^{40}Ca^+$. The expected improvements in localization and laser cooling should allow us to work routinely with single $^{40}Ca^+$ ions. We are also developing an ultra-stable Ti:Sapphire laser which will allow us to probe the decoherence rate in our system by driving Rabi oscillations on the S-D quadrupole (qubit) transition.