Collisional cooling of trapped ions with cold atoms: results and insights

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Consider a single trapped ion in a Paul trap, immersed in a bath of cold atoms of uniform density. Whether the trapped ion will cool, heat or maintain its energy will depend on the mass ratios of the atom to ion, $r = m_a/m_i$ [1]. Specifically, the condition for ion cooling by elastic collisions with atoms is $r < 1$, ion heating is $r > 1$ and no net change in ion energy is expected when $r \approx 1$. This defines a critical mass ratio r_c, below which the trapped ion collisionally cools, while above this the ion will heat in collision with colder atoms. As a result, all previous experiments exclusively cooled ions with a buffer gas of lighter mass. Theoretical studies over the decades have reinforced the notion of critical mass ratios for trapped ion cooling.

In hybrid traps [2,3], where both atoms and ions are trapped, the cooled atoms form a localized density distribution at the center of the ion trap. It was then shown for the first time that trapped Rb^+ ions cool very effectively with equal mass localized Rb atoms [4]. This cooling is understood within the earlier framework [1] as a result of localized ion-atom collisions at the centre of the ion trap, where the deleterious effects of heating collisions is suppressed due to the near zero values of the oscillating electric field. So while ion cooling rates would be mass ratio dependent, the trapped ion will cool for virtually any mass of atom, irrespective of the value of r. Experimentally, we observed cooling and measured cooling rates of two different combinations of ion-atom pairs, K^+ and Rb ($r \approx 2.18$) and Rb^+ with Cs ($r \approx 1.57$) [5]. Analysis shows that the steady state ion temperature depends on the spatial density distribution of the cold atom cloud and only in the limit of very small size, the atom temperature.

The very efficient cooling in our earlier Rb^+-Rb experiment was attributed to resonant charge exchange (RCE), where during collision the electron hops from the atom to the ion [4]. RCE is only active for the homonuclear ion-atom system as it is symmetric under electron exchange. The RCE mechanism for ion cooling is demonstrated by measuring the cooling rate between Cs^+ and Cs MOT atoms, where RCE is active and Cs^+ and Rb MOT atoms, where the charge exchange channel is suppressed [6]. We determine energy lost by the ion in an average RCE collision to be between 39 and 154 times more than the average elastic collision.

In summary, new cooling mechanisms have been proposed and experimentally demonstrated for dynamically trapped ions. Spatial localization of the cooling reservoir upturns long held cooling viability criteria. The role of symmetry for ion cooling, in ion-atom collisions via RCE is shown to be dramatically efficient with respect to elastic collisions. In either case, all combinations of ion-atom mass ratios are collisionally coolable with localized atomic distributions.

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