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Pulsed Evaporative Cooling of Ion Cloud in an Electron Beam Ion Trap

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Abstract

A technique for producing cold ensembles of trapped highly charged ions is described. The ions, trapped in an electron beam ion trap, can undergo a drastic contraction during the pulsed mode of evaporative cooling, if a truncated Boltzmann distribution is assumed. The underlying theory and the experimental results are presented.

1. Introduction

The recent realization of Bose–Einstein condensation (BEC) [1–3] for dilute atomic gas was based on the concept of evaporative cooling [4]. The successful implementation of this technique has lead to a phenomenal increase in the profile of physics using low temperature trapped atoms. We proposed that the same concept could be used to prepare cold ensembles of highly charged ions (HCIs) [5]. By sacrificing the hottest members of trapped HCIs prepared in an electron beam ion trap (EBIT) or a similar device, the remaining ions can be cooled. This approach is distinct from evaporative cooling more usually used for trapped HCIs [6]; the trap depth is actively lowered so as to enhance the cooling process. For charged particles, the evaporation process should show unique characteristics at low temperature. Because of the long-range nature of the Coulomb interaction, the collision rate increases monotonically as the temperature drops. Accordingly, the evaporation should be accelerated towards the end of the process.

Actually this accelerated evaporation was numerically predicted also by Marrs [7] during strong self-cooling of HCIs. In this paper, we refer to this active type of evaporative cooling as pulsed evaporative cooling (PEC), rather than self evaporative cooling; there may be mixed evaporation of both HCIs and lowly charged ions (LCIs) in a real EBIT.

Since the HCI dynamics in a real EBIT is not fully understood, the hopeful prediction about PEC is still a questionable issue. However, this paper points out one important fact; *the ion cloud in an EBIT can undergo a drastic contraction during the pulsed mode of evaporative cooling, if the truncated Boltzmann distribution is assumed.* In the next section, this is theoretically accounted for.

2. Theory

Our theory is an elementary one. The resulting transition of the ion cloud is between an unbound state and a bound state, which is as drastic as a first-order phase transition. Despite of its close resemblance, this drastic change is completely different from Wigner crystalization [8], which is already a familiar topic in ion-trap physics; our contraction can happen even for weak-coupling plasma (i.e. $\xi = 0$ in Eq. (5).).

In an EBIT, the ion cloud is confined radially by the long-range (space-charge) potential $V(r)$, produced around the electron beam. This is readily seen by inspecting the asymptotic behavior of $V(r \to \infty)$. From Gauss's law, we have

$$V(r \to \infty) \to 2V_0 \log(r) + const, \tag{1}$$

if the electronic and the ionic distributions are axially symmetric. V_0 is a constant voltage produced by the charge of the trapped ions and the electron beam (i.e. the total space-charge)

$$V_0 = \frac{Q_e - Q_i}{4\pi\varepsilon_0 L_0} = \frac{Q_e(1-\xi)}{4\pi\varepsilon_0 L_0}, \tag{2}$$

where Q_e and Q_i are the total charge of electrons and ions in the trap, respectively, ε_0 is the permittivity of free space, L_0 is the length of the drift tube and ξ is the neutralization factor, Q_i/Q_e. Inserting this asymptotic form into the Boltzmann distribution, we find that the radial distribution of the ion density should be

$$n(r \to \infty) \propto \exp\left(-\frac{ZqV(r \to \infty)}{kT}\right) \to r^{-2ZqV_0/kT}, \tag{3}$$

where k is the Boltzmann constant, Zq is the charge of a HCI concerned. (Note that the ion distribution does not depend on the magnetic field as long as the thermal equilibrium is assumed [9].) The relative probability density of ions at r is given by the proportionality

$$2\pi r n(r) \propto r^{1-2ZqV_0/kT}. \tag{4}$$

When $1 > 2ZqV_0/kT$ or $kT > 2ZqV_0$, this probability density diverges for $r \to \infty$. Hence, the ion cloud is unbound. On the other hand, if $kT < 2ZqV_0$, the ion cloud is confined in a finite region around the electron beam. So this is a transition, from an unbound state to a bound state at a definite temperature $kT = 2ZqV_0$. Actually the critical temperature separating the two states is

$$kT_c = ZqV_0 = \frac{ZqQ_e(1-\xi)}{4\pi\varepsilon_0 L_0}, \tag{5}$$

because the thermal average of the potential-energy diverges above kT_c.

If the ion cloud is heated up above kT_c, the resulting unbound state is a very ideal initial condition for realizing PEC. There are two main reasons for this. First, if a majority of HCIs is outside the electron beam at the beginning of PEC, they are less heated by the electron beam. Accordingly,

it is possible to lower the axial trap very slowly so as to keep the truncation parameter (i.e. the ratio of the trap-depth to the ion temperature) higher and, thereby, to enhance the efficiency of BEC-type evaporative cooling [4]. Second, the fraction of HCIs inside the electron beam should increase in the final phase of PEC, if the ion cloud is drastically contracted by the transition from the unbound state to the bound state. In this final phase, the evaporative cooling must be considerably accelerated and so the effect of the electron heating is comparatively small. Beside, the increased overlap between the ion cloud and the electron beam may compensate the loss of HCIs by evaporation. This means an increase of HCIs staying inside the electron beam, even after the substantial disposal of HCIs from the trap via evaporation. In the next section, we present some experimental indications of this increase.

3. Experimental results and discussion

Our experimental setup is simple. The measurement started by creating and trapping HCIs in the Tokyo-EBIT [11]. Typically the trap was seeded with neutral coolant gas of Ar whilst Ba was a natural contaminant from the electron gun. In this initial stage, the axial trap was kept at the maximum available depth of –400 V. This was to heat up the HCIs as much as possible so that the ion cloud could be spread out and even turn into the predicted unbound state. For the same purpose, we took as long as a several seconds for this initial preparation; if more HCIs are trapped in an EBIT, the electronic space-charge can be further neutralized and so kT_c in Eq. (5) will be decreased, which makes it easier to prepare an unbound initial state of the HCI cloud.

After this initial preparation, we started the dump process: raising the axial potential from −400 V to +100 V in a linear fashion, as slowly as possible to keep the truncation parameter higher for realizing the efficient BEC-type evaporative cooling. The speed to raise the potential was typically several tens of Volts per second.

Throughout our PEC experiment, X-ray photons from trapped HCIs were detected with a Ge detector (LOAX-60495/30-P, EG&G ORTEC). For each detected photon, its energy and its arrival-time in a whole preparation-dump cycle was recorded [12]. The preparation-dump cycle was repeated many times, for about an hour, to build up sufficient statistics.

Figure 1 shows a typical result for Ba and Ar ions. In this two-dimensional histogram, the horizontal and the vertical axes indicate the X-ray energy and the arrival-time, respectively, and the number of observed X-ray counts is gray-scaled. In fact, the X-ray intensity should be a good measure of the number of ions inside the electron beam. Besides, characteristic X-ray photons, particularly produced through radiative recombination (RR), can be used for monitoring the species of HCIs in an EBIT.

Figure 1 shows some general features observed in our PEC experiment. After expelling all the ions from the trap at $t = 0$, the X-ray intensity was reduced to 0 and then it increased steadily as more ions were created. Within a few seconds, this rise terminated as the ion cloud seemed to find the equilibrium between heating and cooling and between creation and disposal of trapped HCIs. During

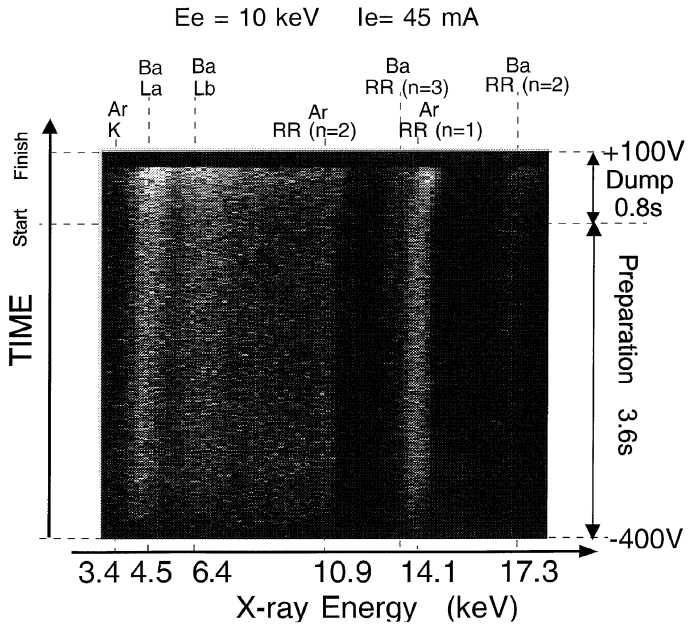

Fig. 1. Increase of X-ray intensity from Ba and Ar ions displayed with a gray-scaled two-dimensional histogram.

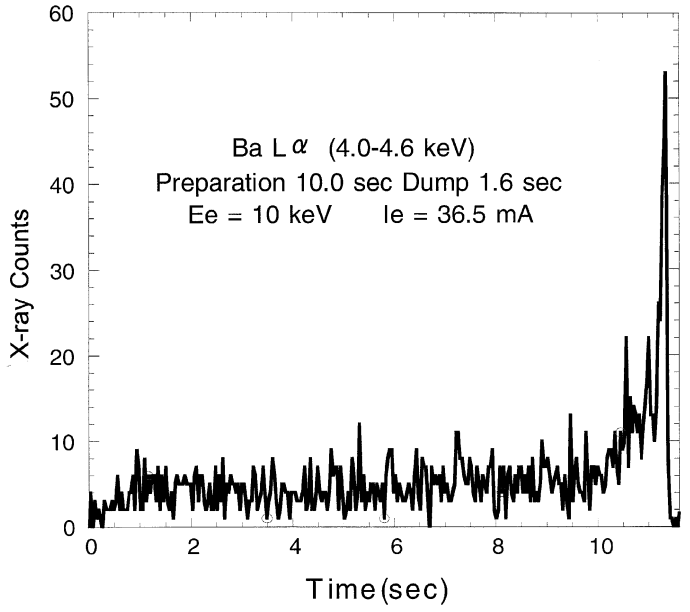

Fig. 2. Time profile of Ba L_α X-ray intensity with no injection of coolant Ar gas.

the dumping of the trap, the X-ray energies of the RR lines changed slightly; the electron-beam energy increased when the central drift tube voltage was increased. Towards the end of the dumping, there was an increase in the population of ions inside the electron beam, as evidenced by the increase in the observed X-ray intensity. This increase was then followed by a sudden decrease in X-ray intensity as the remaining ions left the trap.

We can be confident that this increase is indeed due to HCIs and not to neutral atoms; Fig. 1 shows an obvious increase of the Ar RR ($n = 1$) line, emitted by bare and/or H-like Ar ions inside the electron beam. Similar enhancement is also traceable for the Ba RR ($n = 2$) line in Fig. 1, which should be concerned with the charge states higher than Ne-like Ba^{+44}.

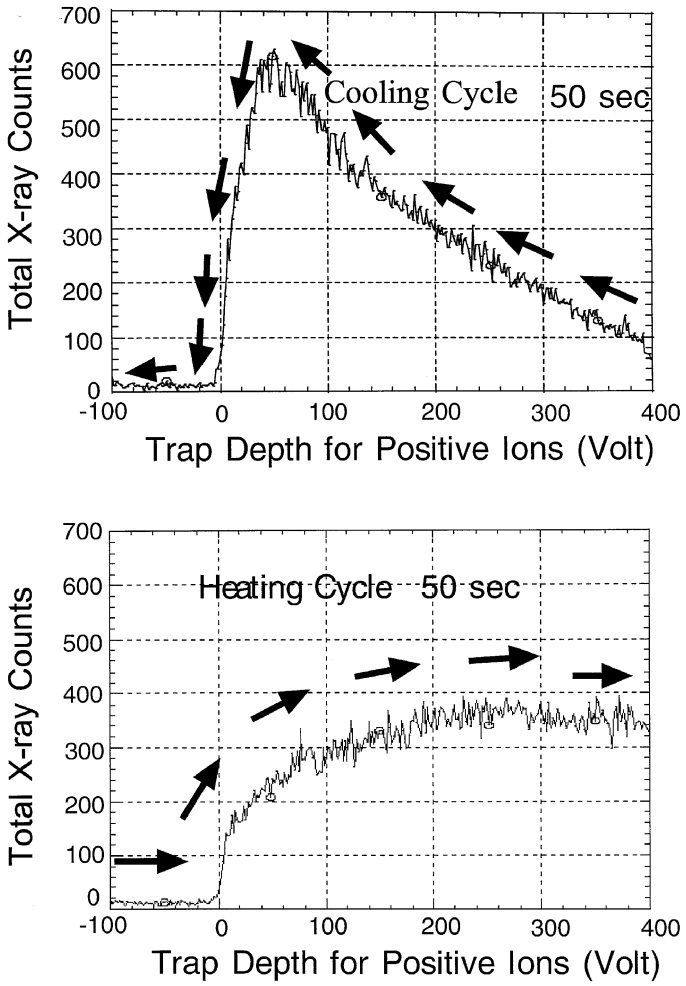

Fig. 3. Irreversibility of the X-ray intensity in respect to the change of the axial potential. The X-ray counts for Ba L_α and L_β lines are summed up. All the experimental conditions, except the rate to change the axial trap, are the same as Fig. 2.

Figure 2 shows that the increase of observed X-ray intensity became even stronger with the increased preparation-time and by stopping the injection of neutral Ar gas. Both of these parameter variations lead to a hotter initial ensemble of ions. Hence, these findings are consistent with our theory; the enhanced cooling causes a contraction of the ion cloud and, therby, results in a net increase of the number of ions inside the beam. In fact, a similar abrupt increase was also observed with the K_α line of Kr by injecting neutral Kr instead of Ar, which will be detailed elsewhere [13]. Provided the ions attain a sufficiently high temperature, the abrupt increase seems to be a universal phenomenon.

As shown in Fig. 3, we also confirmed that the increase of the ion-electron overlap is irreversible in respect to the change of the axial potential. As we gradually lowered the axial trap (in cooling cycle), there was a maximum in the X-ray intensity around the zero-depth of the trap. On the contrary, no peak was observed around 0 Volt when the trap was gradually deepened (in heating cycle). This observation is completely consistent with our picture of a contracting ion cloud; evaporative cooling should be more enhanced by lowering the axial trap than by deepening the trap.

As expected from the theory, we have thus obtained some experimental indications of the increased ion-electron overlap. However, we need clearly a lot more work before attributing this observation to the pulsed mode of evaporation. Actually the ion cloud is likely to be nonthermal, as shown by the recent direct imaging of HCIs in an EBIT [14]. So high-resolution visible spectroscopy is being prepared, using the Tokyo-EBIT, to monitor directly the Doppler temperature.

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