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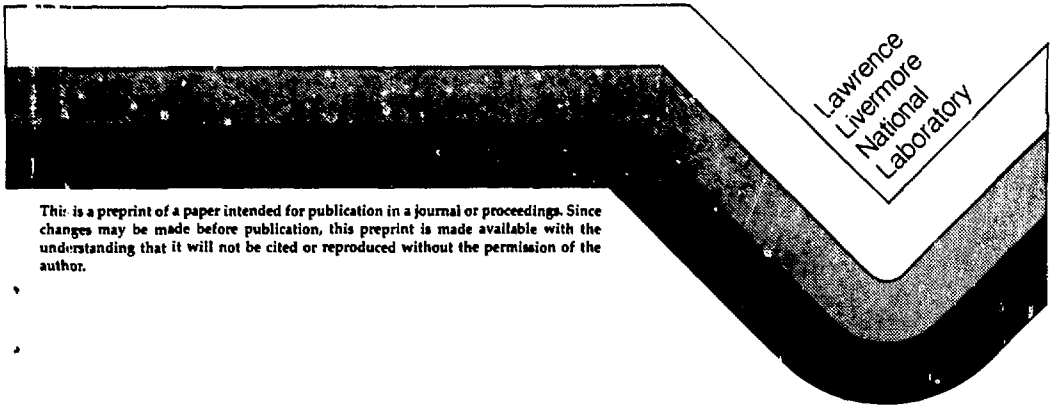

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EVAPORATIVE COOLING OF HIGHLY CHARGED IONS IN EBIT: AN EXPERIMENTAL REALIZATION **

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ABSTRACT

Both the total number and trapping lifetime of near-neon-like gold ions held in an electron beam ion trap have been greatly increased by a process of 'evaporative cooling'. A continuous flow of low-charge-state ions into the trap cools the high-charge-state ions in the trap. Preliminary experimental results using titanium ions as a coolant are presented.

INTRODUCTION

A titanium injector has been built to provide evaporative cooling of highly-charged gold ions in the Electron Beam Ion Trap (EBIT) [1-5] at the Lawrence Livermore National Laboratory. The preliminary experiments reported here demonstrate the success of evaporative cooling in increasing both the total number and trapping lifetime of gold ions in EBIT. We report x-ray intensities as a function of various trap parameters. Experimentally, we define two limits. At low levels of cooling, the number of trapped gold ions in the electron beam increases linearly with the coolant (neutral titanium) density, and the calculated ion space-charge is small. In contrast to this, at higher levels of cooling the number of trapped gold ions in the beam is a weaker function of coolant density and the variation of x-ray intensity with the trap parameters is very different.

We discuss first the nature of the EBIT trap to justify our representation of the cooling process as a one-dimensional problem. Then we present the experimental results, and indicate some preliminary agreement with theory. Finally, we mention some practical considerations of evaporative cooling.

NATURE OF THE EBIT TRAP

EBIT[1-5] consists of a very intense electron beam which passes through and is accelerated by three drift tubes as it follows the field lines of a 3T superconducting magnet. The voltage applied to the drift tubes determines

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the electron beam energy. The two end drift tubes can be biased with respect to the central one to provide an axial trap. Slits in the central drift tube allow x-rays emitted perpendicular to the electron beam to be detected.

The ions are trapped in the radial direction by a combination of the space-charge of the electron beam and the magnetic field. Ions and secondary electrons modify the trapping potential. For a Gaussian radial distribution of electrons in the beam, the space-charge potential of the beam, V_b, at the radius of the beam which contains 80% of its charge ($r \sim 31\,\mu m$), is $0.55\ I/\sqrt{E}$ (Volts) where I is the electron current in mA and E is the electron energy in keV. For 100mA at 18keV, this is about 13V. At the drift tube wall, a radial distance of 0.5 cm from the center of EBIT, the potential is $9.4\ V_b$, or 122V. Thus while an ion of charge Q needs an energy of 122Q eV to 'escape'the trap radially, it needs only 13Q eV to leave the electron beam. For most experiments, an ion must be in the beam to be useful.

In addition, the magnetic field produces an effective potential[6] that further inhibits radial escape. The orbit of a charged particle in the trap, specified by its energy and generalized angular momentum (or, equivalently, its instantaneous position and momentum) is confined between minimum and maximum radii. In order to move from the electron beam to the drift tube wall an ion must diffuse both in energy and generalized angular momentum space, which is a slow process.

Axially, the trap is purely electrostatic. The 'bare' potential is the sum of the voltage (V_A) applied to the end drift tubes relative to the central one, plus the potential due to the narrowing of the end drift tubes ($2.1V_b$ or ~ 30V at I=100 mA, E=18keV). (The central drift tube is 1 cm in diameter and 2 cm long. The end drift tubes narrow from 0.5 cm to 0.15 cm in diameter 1.7 cm from the center of EBIT.) Finally, the space-charge of the ions contributes to the axial potential.

The minimum ion-ion collison time is expected to be on the order of a few hundred μs [7], but the ion velocities are roughly 10^4 cm/sec, so the ion mean-free path in the axial direction is longer than the 2cm long trap. An ion can escape axially as soon as it has enough axial energy. Because radial escape is much more difficult, the EBIT trap is here considered as a one-dimensional problem with V_{trap} equal to the axial potential.

EVAPORATIVE COOLING

The elastic collisions between the ions and the electron beam primarily increase the transverse momentum of the ions[2]. This kinetic energy is partitioned in all directions and among all the ions by ion-ion elastic collisions. The energy gain of the ions is large enough that

some ions will spend a significant amount of time outside the electron beam, and, as their energy grows, eventually escape the trap, often before they reach the maximium ionization state possible for the energy of the electron beam.

In evaporative cooling, a second ionic species (LCIs) with a lower charge, q, is continuously added to the trap containing the desired highly-charged ions (HCIs). The LCIs are heated through ion-ion collisions with the HCIs until both species have approximately the same temperature. The LCIs, having a lower charge, need less energy per ion to escape the trap, so they 'evaporate', removing their kinetic energy from the trap. The continuous evaporation of the

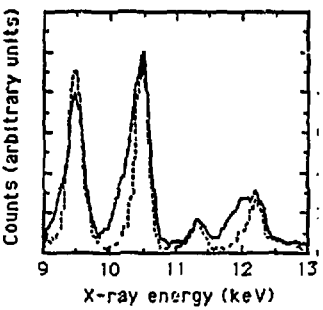

Fig.1. N=3->2 transition lines in near neon-like Au HCIs taken with a solid-state Ge detector. E=18keV, I=100mA. Solid: no evaporative cooling, V_{trap}=80V. Dash: evaporative cooling (Ti ions), V_{trap}=40V. The narrower lines with cooling indicate a narrower charge state distribution.

LCIs cools the HCIs. Fig.1 compares the n=3->2 transition lines of Au HCIs without evaporative cooling (solid) to those with evaporative cooling (dash). The electron beam energy was adjusted to maximize the formation of neon-like gold (Au^{69+}). The narrower lines in the second case indicate a more highly ionized charge state distribution. The 1/e lifetime of uncooled ions in the electron beam was measured to be 18s. The lifetime for the cooled HCIs was 210s, a factor of 10 larger despite a lower trapping potential (40V compared to 80V).

EVAPORATIVE COOLING EXPERIMENTS

To study evaporative cooling, we chose highly-charged (near-neon-like) gold (Au^{69+},Au^{68+},Au^{67+}. . .) for the HCIs and titanium ions (maximum charge = 22+) for the LCIs. Titanium atoms are evaporated from a calibrated Ti wire getter. The hot Ti atoms flow continuously into EBIT through one of the radial x-ray ports and are ionized by the electron beam. The 1/8" diameter Ti wire, 29cm from the center of EBIT, is imaged with a 0.25" hole in a metal mask onto a 1cm length of the electron beam. The mask is attached to a liquid nitrogen shield to minimize the background gas load

into EBIT. The Ti flow is monitored by measuring the temperature (~1500 C) of the wire with a pyrometer, and can be adjusted by changing the wire current. The density, n_o(Ti) of titanium atoms in the center of EBIT ranges from 10^5 to 10^7 cm^{-3}. The Ti wire deforms when it is hot and does not

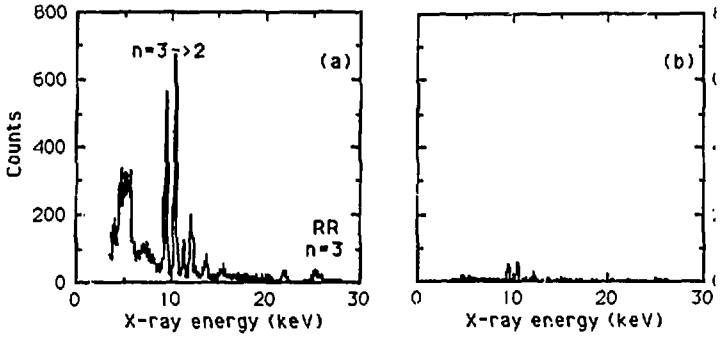

Fig.2. Time-routed Ge spectra of Au HCI (E=18keV, I=100mA, V_{trap}=130V). Ti shutter is kept open during (a) but kept closed during (b). The n=3->2 transition lines and the radiative recomination lines (RR) to n=3 are shown.

always fill the EBIT image, making the calibration of n_o(Ti) inaccurate by the unknown geometrical filling factor. A shutter in the Ti beam path can open or close in 25ms.

The dramatic success of evaporative cooling is shown in Fig.2. The first spectrum was taken for 60s, then the Ti shutter was closed and a second spectrum taken for 60s. (If the shutter is open, the ion lifetime in the electron beam is greater than 10 minutes, Fig.4,6).

Cooled Au HCIs can remain in the electron beam for hours. The longest 1/e trap lifetime observed was about 4 hours (Fig.3).

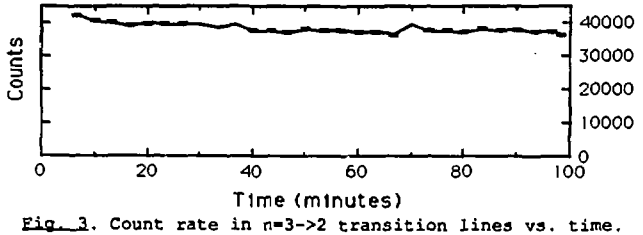

Fig. 3. Count rate in n=3->2 transition lines vs. time. Gold is injected into the trap at 0 minutes. The estimated 1/e trap lifetime is about 4 hrs. Ti shutter is always open.

TRAP LIFETIMES AND ION DENSITIES

Fig.4a shows the count rate in the n=3->2 lines in Au HCIs as a function of time for different value of n_o(Ti). The long lifetime in the case of n_o(Ti)=0 results from the

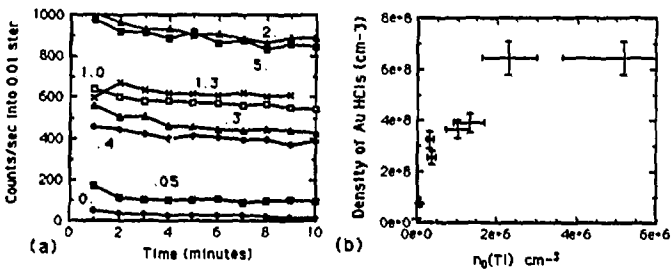

Fig.4. (a) Count rate vs time. The numbers give n_o(Ti) in units of 10^6 cm^{-3}. (b) Calculated density of Au HCIs vs estimated n_o(Ti). Data taken at E=18keV, I=75mA, V_{trap}=320V.

cooling from increased background gases in EBIT compared to the conditions of Fig.1, when there were no open apertures in the liquid nitrogen and helium shields[1-4].)

The density of highly charged Au ions in EBIT is estimated from the intensity of the radiative recombination lines using calculated cross sections[8], and is plotted versus n_o(Ti) in Fig.4b. The charge density of Au HCIs neutralizes 2% of the electron beam at the highest densities shown. There is no direct measurement of the LCIs' (Ti ion) density in the trap, but it is expected[1] to be several times the HCIs' density.

The MEVVA injects many more ions than can be trapped, so the equilibrium HCIs' density is determined by the amount of cooling available. The low level limit of cooling is defined to be the region where the HCIs' density in the electron beam varies linearly with n_o(Ti). From Fig.4b, the low level cooling limit is approximately n_o(Ti) < 10^6 cm^{-3}.

LOW LEVELS OF COOLING

In this limit, the HCIs' charge density in the electron beam is less than 1% of the electron charge density and ion screening effects are ignored.

The count rate in the 3->2 lines is proportional to the square of the electron beam current (Table I). This is true for two different values of the axial potential. Note that for a given current, the count rate is higher for the higher axial potential.

Table I Count Rate vs. Current for Different V_A

Data taken at E = 18keV, $n_o(Ti)=7\ 10^9\ cm^{-3}$

I (mA)	I^2 (mA^2)	V_A = 100V counts/sec	V_A = 300V counts/sec
74	5476	210	350
100	10000	420	600
Ratio:	0.55	0.5	0.6

Table II Ion Temperature vs. V_{trap} for Different I

Data taken at E = 18keV, $n_o(Ti) = 7\ 10^9\ cm^{-3}$.

I = 74 mA			I = 100 mA		
V_{trap}	Z_{RMS}	T/QV_{trap}	V_{trap}	Z_{RMS}	T/QV_{trap}
120 V	22.9	0.04	130 V	24.9	0.5
220 V	21.8	0.03			
320 V	21.3	0.03	330 V	22.2	0.4

As V_{trap} is increased, the x-ray intensity increases, and then levels off. This observation confirms the one-dimensional trapping model: beyond a certain value of V_{trap}, radial escape occurs more often than axial escape.

In a one-dimensional model, the temperature, T should be proportional to QV_{trap} (the only characteristic energy in the problem). A measurement of how the ions fill the trap should determine the temperature. We have used a slit to axially image the ions in EBIT onto a position sensitive-detector gated to only count n=3->2 Au x-rays. The directly measured ion distribution can be characterized by its root-mean-square width Z_{RMS}, measured in channel numbers on the detector. To deduce a temperature we assume the HCIs' density in the electron beam is proportional to $\exp(-QV(z)/T)$ where V(z), the axial electrostatic potential at the height z neglects the space charge of the ions. Preliminary results, at two different electron beam currents, are that T/QV_{trap} is approximately constant (Table II). Using a similar technique to image the ions in the radial direction, we see a wider distribution for a higher V_{trap} (Fig. 5). This indicates that it is the axial potential that controls the ion temperature, and hence the ion spatial distribution.

HIGH LEVELS OF COOLING

More complicated effects occur at higher ion densities. Fig.6 shows that the x-ray intensity is now

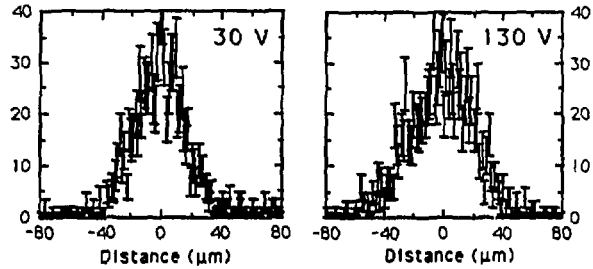

Fig.5 Radial image of ions (counts vs distance in EBIT). E=18keV, I=100mA, $n_e(Ti) = 10^6\ cm^{-3}$. (a) V_{trap}=30V (b) V_{trap}=130V.

linearly proportional to the current. A comparison of the count rate for the same current between V_A=100V and 300V in Fig.6 shows fewer ions in the beam for the higher trapping voltage, in contrast to what occurs at lower cooling levels (Table I). This is important because the simple theories

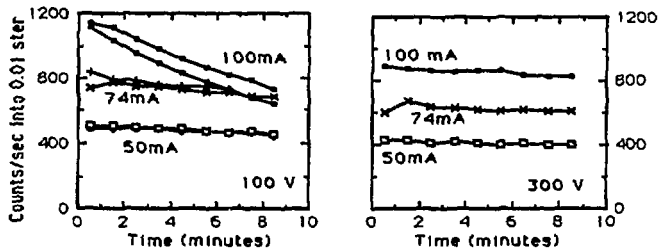

Fig. 6. Count rate vs time at high levels of cooling. Data taken at E=18keV, $n_e(Ti)=1.3\ 10^6\ cm^{-3}$ for V_A=100V , V_A=300V.

that ignore ion space charge cannot explain it. Also there is a noticeable decay (1/e lifetime = 18 min) at V_A=100V and I=100mA.

The best ratio of Au^{69+} to total Au ions we have obtained in EBIT is about 1:2. This corresponds to the theoretical limit given by the ratio of cross sections of electron impact ionization of Au^{68+} to radiative recombination onto Au^{69+}. This limit is not achieved at the higher levels of cooling. As the ion density increases, the space-charge of the ions begins to screen the electron beam, so the ions spend less time in the beam, and charge-exchange outside the beam destroys the charge state. In addition, charge-exchange is expected to become important even in the beam region at higher $n_e(Ti)$.

ADDITIONAL CONSIDERATIONS

Depending on conditions, Ti excitation and/or recombination lines may be a background to specific desired Au lines in a solid state detector. To overcome this, we have also used nitrogen gas as a coolant. Preliminary results indicate that nitrogen cools as well as titanium.

LCIs will cool anything that is more highly charged than itself, so impurites may become trapped. We have seen a slow buildup of barium and tungsten ions from the electron gun and lead from the titanium wire. The rate of buildup of barium and tungsten is higher with nitrogen cooling.

SUMMARY

Both the number and lifetime of Au HCIs have been increased with the use of Ti LCIs to evaporatively cool the gold ions. The cooling mechanism is consistent with the evaporation of hot ions from a one-dimensional potential well, which is the axial trap. In the limit of low-level cooling, the number of HCIs trapped in the electron beam is proportional to $n_e(Ti)$, and the contribution of the space-charge of the ions to the total potential is small. More complicated effects occur at higher levels of cooling, probably because ion space-charge effects become important and the ions spend much of their time outside the beam. Additional experimental and theoretical[1] work are planned to further our understanding of the cooling mechanism and its effects.

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