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COOLING AND TRAPPING OF LASER INDUCED MULTIPLY CHARGED IONS OF MOLYBDENUM

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Abstract

Low-energy multiply charged ions of molybdenum have been produced and stored using a novel technique which combines laser ablation and ion storage. The charge states range from $q=+1$ to $q=+6$. The energy of these ions is estimated to be less than $5 \times 10^{-3} \text{ eV/amu}$ with the storage time of one second. The number of stored ions is about 10^5 . These findings suggest that we can now study the slow processes of low energy multiply charged ions of most elements.

1. Introduction

In the last decade, several techniques have been developed for the production [1,2] and storage [3,4] of near thermal energy highly charged ions. The limited choice of parent gases of the ions in these experiments, however, produces only a few types of singly and multiply charged ions. Thermal energy multiply charged ions from refractory elements such as molybdenum, important to our current fusion program [5], have not been produced and studied. We report in this study a novel yet simple approach that not only overcomes some of the limitations of earlier techniques but also can produce and store, for a substantial period, workable quantities of low energy multiply charged ions of almost any element.

2. Experimental Technique

Our approach combines ion production by laser ablation with storage of ions using the ion trap. Laser ablation has been used previously to produce both neutral atoms and ions from solid targets. Measures and Kwong [6] have reported on the production of neutral chromium atoms. Ehler [7] and Phanuef [8] reported the generation of multiply charged ions by laser ablation from a variety of target materials. The number of multiply charged ions produced typically ranges from 10^{15} to 10^{19} depending on the laser energy, the laser power density and the charge state of the ions produced. Nevertheless, to date only singly charged ions from laser ablation have been trapped. Johnson and Kwong [9] trapped Al^+ in cylindrical RF trap for the purpose of studying the lifetime of the metastable state. On the other hand, Knight [10] was able to trap Be^+ , C^+ , Al^+ , Fe^+ and Pb^+ in an electrostatic trap.

The absence of multiply charged ions in these experiments arose from the ions' relatively high kinetic energy compared with the trap's small potential well. This makes the trapping of these ions difficult if not impossible. To trap multiply charged ions from laser induced plasmas in a pseudo-potential well of a few eV, the kinetic energy of these ions must be reduced. We achieve this by cooling a small fraction of the ions inside the trap through momentum transfer by crossed beams of ions produced by ablation of solid targets with a high power Q-switched laser. A simple classical

analogy of this cooling effect is the elastic collision between two billiard balls of identical mass m and speed v_1 and v_2 which approach one another at zero impact parameter along exactly orthogonal trajectories, say from $-\infty$ along x and y -axes. Using conservation of energy and momentum, it is trivial to show that after a perfectly elastic collision, one ball remains at the origin with zero velocity and the other moves away on the xy plane with speed $\sqrt{v_1^2 + v_2^2}$. In the case of collisions between multiply charged ions in the trap, ions losing all or a large fraction of their energies and momentum during collision will be captured in the trap while those that gain additional energies and momenta will move out of the trap. However, only a small fraction of the number of collisions will result in ions which remain in the trap. Since there are 10^{15} or more ions in each ablation pulse, a small number is still a large number. The maximum number of ions stored in the trap will ultimately be limited by the space charge and is about 10^6 .

The schematic of the facility is shown in figure 1. Two pulsed beams of ions are created by the ablation of 99.9% pure molybdenum target using the focused light from a frequency doubled Nd:YAG laser. The ablation ion beams intersect each other at right angles at the center of the radio-frequency

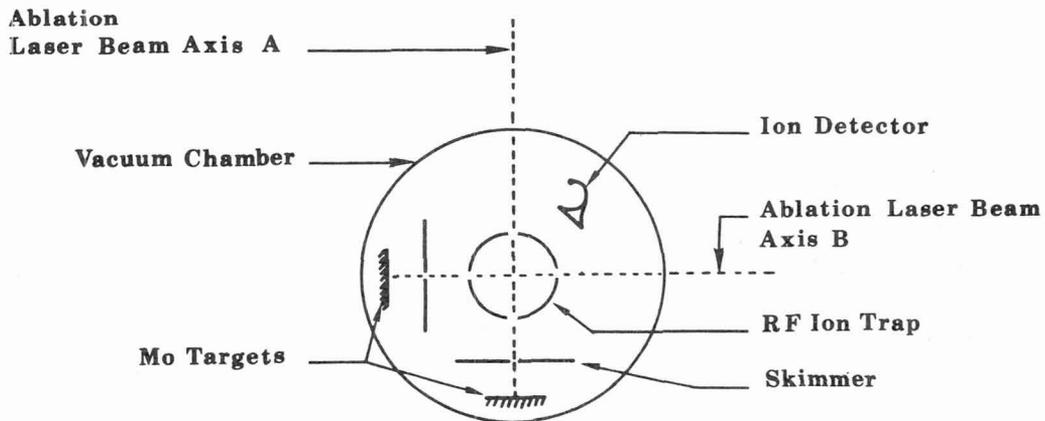


Figure 1. Schematic of the Facility

ion trap. Ions enter the trap through holes cut in the trap's ring electrode. The ablation beams are collimated by carefully positioned, grounded skimmers which minimize back-scattering of ions from the expanding cloud by preventing them from striking the ring electrode or its mounting structure. The contents of the trap are sampled at different times after the ablation event by applying a negative bias voltage to one of the trap's end caps. Ions extracted from the trap by the combination of the RF voltage and end cap bias voltage are detected by a channel electron multiplier (CEM) which is gated on after the ablation event. Gating of the CEM is necessary to avoid damage to detector caused by the large quantities of ions produced during laser ablation. As shown in figure 2, a large signal, with excellent signal-to-noise, is observed after both ablation beams are allowed to intersect. If either or both of the ablation producing laser beams is blocked, no signal is observed. Measurements using the Langmuir probe indicate that the ions in each beam have a mean energy of 250eV, a value much greater than the trapping potentials (1.1eV – 42eV) used in the current experiment. Collisions which lower the energy of a small fraction of the ions are clearly taking place.

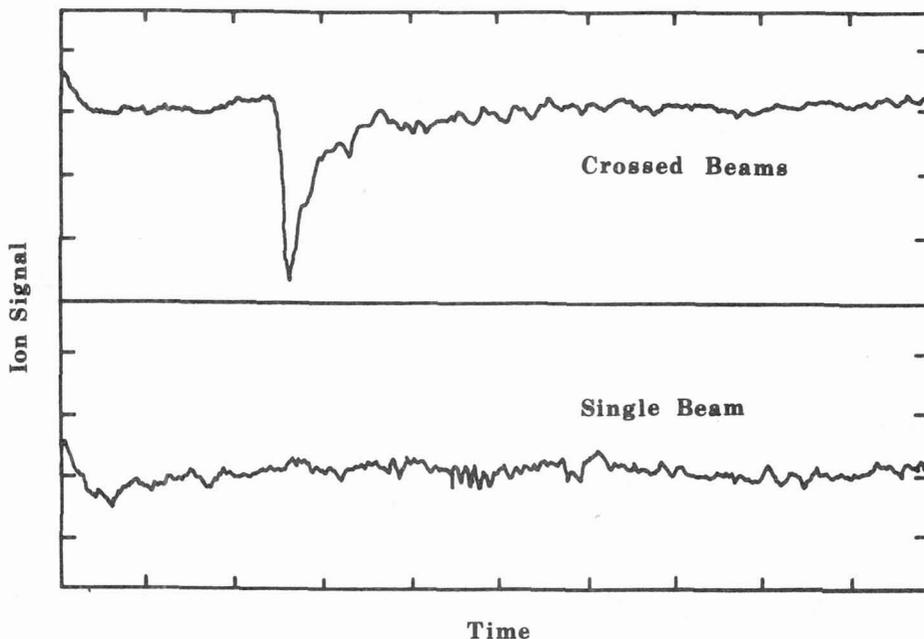


Figure 2 Typical Ion Signal

3. Results

3.1 Ion Identification

The highest charge state of the ions captured is identified by operating the trap near the edge of the unstable region for a specific ion. Figure 3 shows the theoretical stability diagram for molybdenum ions obtained from the solution of the Mathieu equation on the trajectories of ion in a periodic hyperbolic potential well [11]. Since the potential surfaces near the center of a cylindrical electrode approximate that of a hyperbolic electrode, and no ions are observed when the operating point of the

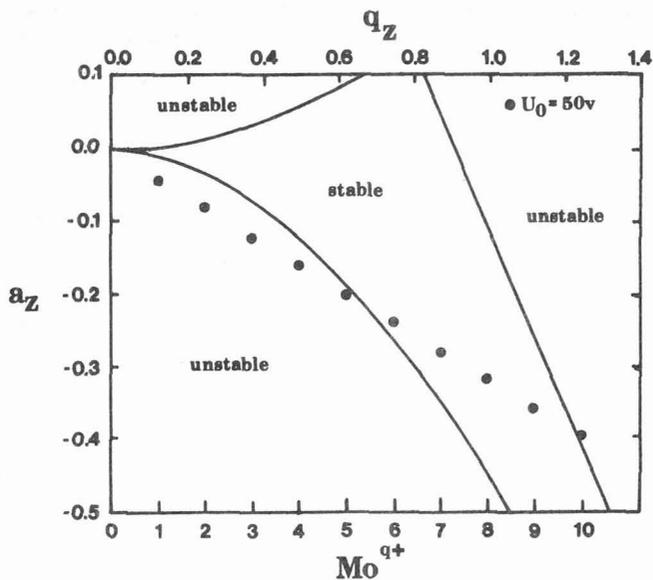


Figure 3. Ion Trap Stability Diagram. Ions in the region labeled "stable" can be stored in the trap. The D.C. voltage U_0 on the ring electrode selects which ions are stored [11].

trap is set at the edge and beyond the stable regions for test ions such as N^{2+} , N^+ , Ar^+ and Ar^{2+} , we conclude that the stability diagram can also be used to characterize the stable region for a RF trap with a cylindrical electrode with acceptable accuracy. To determine the highest charge state of molybdenum ions, the trap was biased so that only Mo^{q+} with $6 \leq q \leq 9$ are inside the stable region. A healthy ion signal is observed. However, no signal is observed when we biased the trap so that all Mo^{q+} with $1 \leq q \leq 6$ are outside the stable region. Since Mo^{6+} are the only ions that are shifted out of the stable region the highest charge state of molybdenum in the current experiment must be 6. This is further confirmed by pulsing the ion into a time-of-flight mass spectrometer. The highest charge state of the ions obtained in our current experiment is limited by the power density of our ablation laser which is about $2 \times 10^8 \text{ W/cm}^2$.

3.2 Ion Density Determination

Based on the gain of the channel electron multiplier, the magnitude of the ion signal and the geometry of the collection ion optics, we conclude that approximately 10^5 ions are stored..

3.3 Ion Storage Time

The storage time of the ions in the ion trap is determined by monitoring the decrease of the ion signals obtained by pulsing the stored ions out of the trap at a progressively longer delay time and detected by a gated channel electron multiplier. Based on the decay of the ion signal over delay time, the storage time is about one second.

3.4 Ion Energy Estimate

The lowest pseudo-potential well used in the experiment for trapping these multiply charged ions has been estimated to be 1.1eV. Therefore, the upper limits of the energy of the stored Mo^{q+} must be less than $5 \times 10^{-3} \text{ eV/amu}$.

4. Summary

Low energy multiply charged ions of molybdenum have been produced and trapped for a period of 1 second. The relatively long storage time and the substantial number density will enable the study of a various processes involving these slow ions. This technique has potential in the production and storage of low energy multiply charged ions of almost any element.

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