Physica Scripta. T92, 208–210, 2001

Transport of Hollow Atoms Through Thin Dielectric Films

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Received August 2, 2000; accepted October 10, 2000

PACS Ref: 34.50.Dy, 34.80.Lx, 78.90.+t

Abstract

We have determined exit charge states and energy losses of slow, highly charged gold ions after transmission of thin (7 ± 3 nm) diamond like carbon foils. Average charge states of up to 37+ were observed for Th^{80+} at 8.2 keV/u (0.57 v_{Bohr}). The final charge state is populated through re-arrangement processes after the projectile has left the foil. High final charge states indicate that none of the M-shell vacancies in Th^{80+} could be filled inside the foil. The increase of the average exit charge state as a function of M-shell vacancies is a sign of strongly enhanced X-ray fluorescent yields for hollow atom decay in vacuum.

1. Introduction

The relaxation of slow ($v < v_{Bohr}$), highly charged ions (SHCI) into charge state equilibrium proceeds through the formation and decay of hollow atoms [1–3]. The first generation of hollow atoms forms when SHCI reach a critical distance above a target surface where resonant electron transfer into Rydberg states becomes classically allowed. Principal quantum numbers, n, for Th^{80+} approaching a gold target can be estimated from the classical over the barrier model to be as high as 60. Once the projectile reaches the target surface, electrons are peeled-off and a more compact screening cloud with $n \approx 8$–10 forms a second generation of hollow atoms, now inside the solid target. SHCI such as Th^{75+} and Au^{68+} have been found to reach charge state equilibrium in thin foils of amorphous carbon within a relaxation time of only 5 to 10 fs [4,5]. Using specular reflection inside a micro capillary target, Ninomiya *et al.* [6] demonstrated extraction of first generation hollow atoms into vacuum.

In the present article we substituted the semi-metallic amorphous carbon foils with diamond like carbon foils (DLC) [7]. We find that Th^{80+} can not reach charge state equilibrium inside the dielectric foil and a hollow atom is transported through the foil target into vacuum. Post-foil re-arrangement processes populate mean charge states up to 37+.

2. Experimental setup

A schematic of the experimental setup is shown in Fig. 1. A similar setup has been described in detail in Ref. [1]. Briefly, SHCI were extracted from the Electron Beam Ion Trap at Lawrence Livermore National Laboratory and impinged on thin DLC foils after momentum analysis in a 90° bending magnet. The target thickness was determined from proton energy loss measurements using the analyzing magnet as a spectrometer and comparison with literature data [8]. The foil density was 2.0 ± 0.4 g/cm^3 and the foil thickness was 7 ± 3 nm. A channeltron was placed close to the foils for detection of secondary electron pulses from the impact of individual SHCI. These pulses were used as start signals for determination of the energy loss in the foils through measurements of projectile flight times. Results of energy loss measurements will be discussed in more detail in a forthcoming publication. Projectiles transmit the foils and, after a flight time of about 500 ns, they reach a second target, which consisted of a gold crystal. The gold target was biased to -1 kV. Projectiles impinge on the gold target and emit secondary electrons. Secondary electron pulses were detected with an annular micro-channelplate detector [9]. Pulse height analysis showed a nearly linear increase of secondary electron emission with projectile charge [3,9] (Fig. 2). Projectiles populate a distribution of charge states after leaving the foil target and before impinging on the gold target. The average of this distribution can be calibrated by comparing pulse height distributions from projectiles that interacted with the foil and SHCI from the direct beam of selected charge states and at the corresponding velocities. The advantage of this technique is that it allows a rather fast evaluation of average charge states. Using a position sensitive detector is a direct way to achieve this, but the

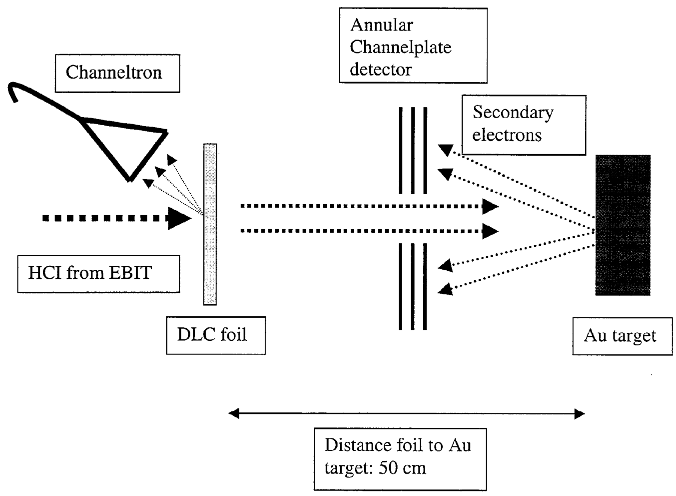

Fig. 1. Schematic of the experimental setup.

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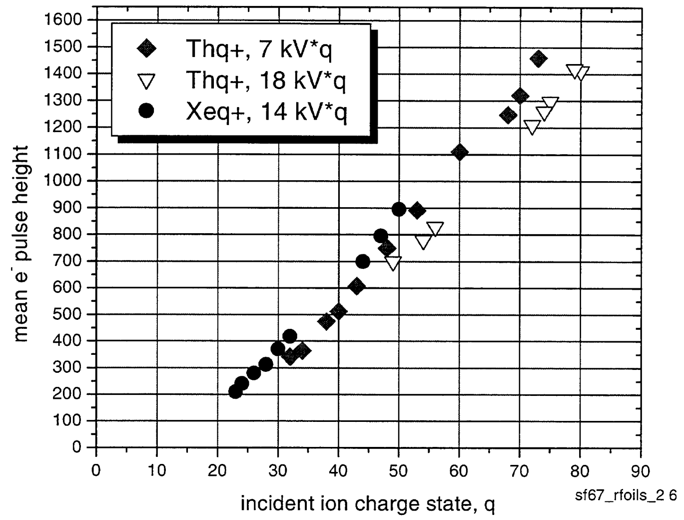

Fig. 2. Mean secondary electron emission pulse height as a function of projectile charge state for Xe^{q+} and Th^{q+} ions impinging on a gold target at three extraction energies.

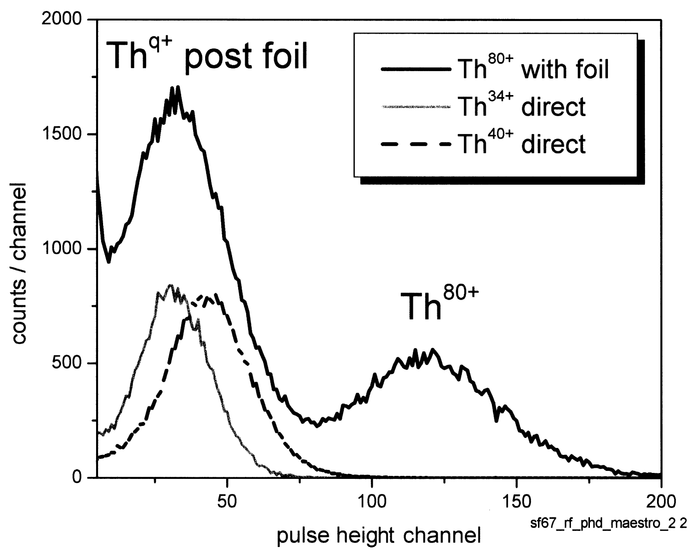

Fig. 3. Secondary electron pulse height distributions from the gold target following the impact of thorium ions. Th^{80+} ions transmitted the foil target through pinholes, the foil was removed for Th^{34+} and Th^{40+} ions. The Th^{q+} post foil peak stems from Th^{80+} ions that interacted with the foil and populated a charge state distribution in vacuum.

presence of charge states over 30+ brought the bending capabilities of our earlier setup to a limit [1]. Also, at a given detector diameter, the mapping of the full charge state distribution brings the required ion dose close to the dose limit on foil lifetime. Measurements of foil lifetimes for SHCI bombardment are in progress.

3. Results and discussion

In Fig. 3., we show pulse height distributions from secondary electrons emitted by Th^{80+} ions that passed through the foil, the direct beam of Th^{80+} from transmission through pinholes in the foil and distributions from the direct beam of Th^{34+} and Th^{40+}. The average charge state, q_{pf}, of Th^{80+} after interaction with the foil and post-foil relaxation is 37+. This very high value for q_{pf} indicates that the M-shell vacancies in the neon like Th-ion could not be filled inside the dielectric foil where the availability of electrons for fast feeding of a large ($> q$) number of Auger transitions is restricted.

Figure 4(a) shows the increase of the average post foil charge state of thorium ions as a function of charge state at a constant velocity of 1.26×10^6 m/s. The q_{pf} for Th^{75+} is 34+, while the value for an amorphous carbon foil at a similar ion velocity is only 8.2+ [4]. This result demonstrates the influence of the electronic properties of solids on the relaxation dynamics of SHCI [10]. Use of different phases of materials with (nearly) the same elemental compositions avoids convelution of effects of electronic properties with the influence of varying atomic mass numbers. Amorphous carbon is a semimetal with a specific resistivity at room temperature, ρ, of less than 0.01 Ωcm. In comparison, DLC foils with sp^3 contents of ~30% show values for ρ that are typically larger than 10^3 Ωcm [7]. Auger transitions are the dominant relaxation channel of SHCI

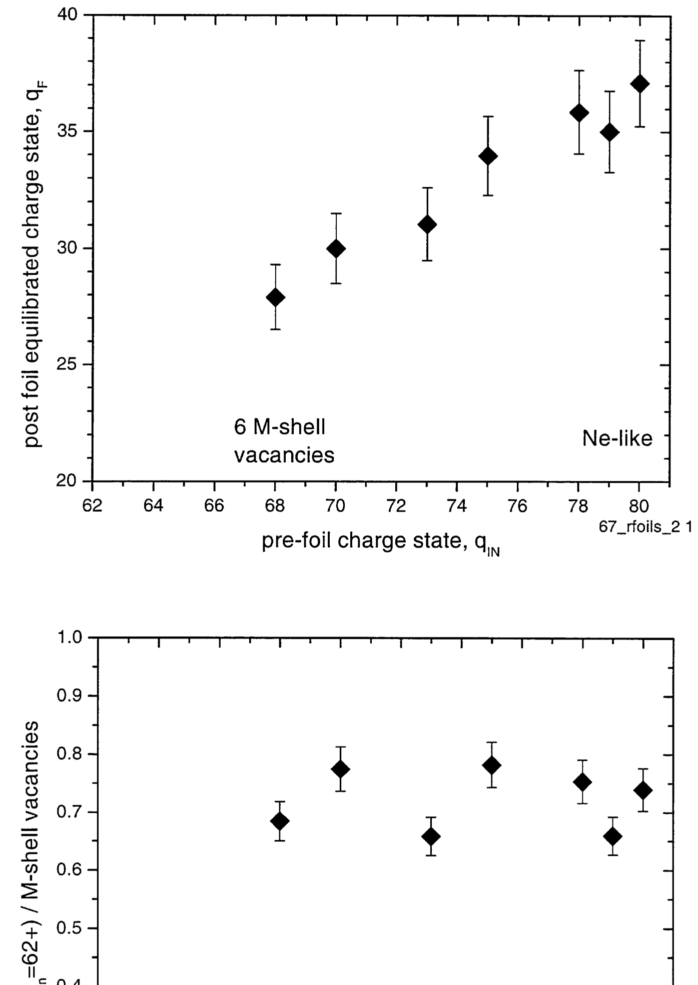

Fig. 4. (a) Post-foil equilibrated charge state as a function of incident charge state of Th^{q+} ions at a velocity of 1.26 10^6 m/s. (b) Normalized increase of the average post foil charge state distribution as a function of M-shell vacancies.

inside of solids. Our results indicate that the lack of quasi-free electrons in the dielectric foil limits the rate at which SHCI can dissipate potential energy and relax into charge state equilibrium through Auger-transitions. Preliminary evaluations of the energy loss data show a strong enhancement of the pre-equilibrium energy loss as compared to data from amorphous carbon foils. This enhancement is consistent with the observation of high exit charge states and also points to a drastic change in the structure of the screening cloud for SHCI interacting with semi-metallic vs. dielectric foils [10,11].

One key question in the relaxation of hollow atoms in vacuum is the balance of Auger decay vs. radiative transitions, i.e. the fluorescent yield. In order to pursue this question, we plot the increase of the mean post foil charge state as a function of M-shell vacancies in Th^{q+} ions (Fig. 4(b)). Here, we subtracted the value for the average post foil charge state for Th^{62+} (full M-shell) from the values for $q > 62+$ and divided by the number of M-shell vacancies. This normalization gives a measure on how much the average post foil charge state, q_{pf}, increases when the number of M-shell vacancies is increased. We find that q_{pf} increases by less than one charge state per M-shell vacancy. If the dominant mode of post-foil relaxation process was Auger transitions, then we would expect a cascade with several (two to three) Auger-transitions for the filling of every M-shell vacancy [4], so that the average charge state would be increased by this number of Auger transitions. The finding of a much weaker increase of q_{pf} with an increasing number of M-shell vacancies indicates that radiative transitions dominate the relaxation of heavy hollow atoms in vacuum. The direct determination of X-ray fluorescent yields is subject of ongoing experiments. The determination of conditions under which heavy hollow atoms can be extracted into vacuum opens the possibility to investigate their relaxation dynamics in greater detail.

4. Conclusion

Using dielectric diamond like carbon instead of semi-metallic amorphous carbon foils, we observed post-foil equilibrated mean charge states for Th^{80+} projectiles of up to 37+. The increase of the average post foil charge state with the number of M-shell vacancies indicates strongly enhanced fluorescent yields during hollow atom decay in vacuum.

Acknowledgements

This work was performed under the auspices of the U. S. Department of Energy by Lawrence Livermore National Laboratory under contract No. W-7405-ENG-48. We gratefully acknowledge the support from a NIST SBIR phase I grant (50-DKNB-9-90088). This work was also supported by the Director, Office of Basic Energy Sciences, of the U. S. Department of Energy under Contract No. DE-AC03-76SF00098.

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