The Effects of Temperature and Oxidation on D Retention in Solid and Liquid Li Films on Molybdenum Plasma-Facing Components

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56th Annual Meeting of the APS Division of Plasma Physics
New Orleans, LA

October 31, 2014

Acknowledgements

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- Bob Kaita, PPPL
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Funding:

- **DOE** (FES), PPPL LDRD, *Fundamental Studies of Deuterium Retention in Solid and Liquid Metals*

Outline

I. Motivation:

II. Our Approach:

- Using surface science test stands to understand PFCs in tokamak environments

III. D Retention in Li Films on TZM

- What is the role of:
  - Temperature?
  - Oxidation?

IV. Conclusions:

- Two regimes:

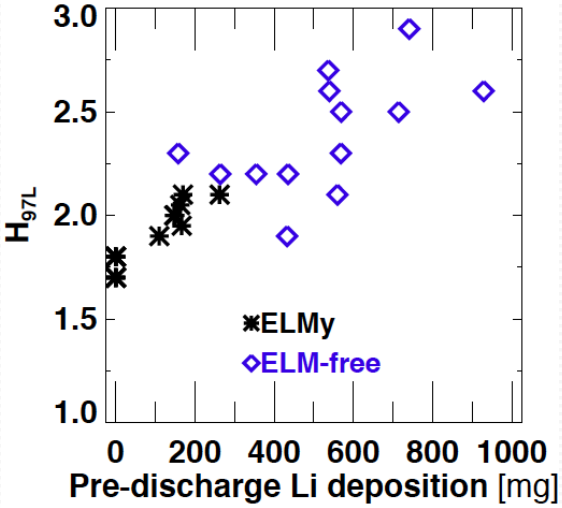
  (1) At low temperature, D retention is highest in Li_2O films,

  (2) At high temperature, D retention is highest in metallic Li films

Li films improve plasma performance and confinement time in LTX and NSTX

NSTX

R. Maingi et al., PRL 107, 145004, 2011.



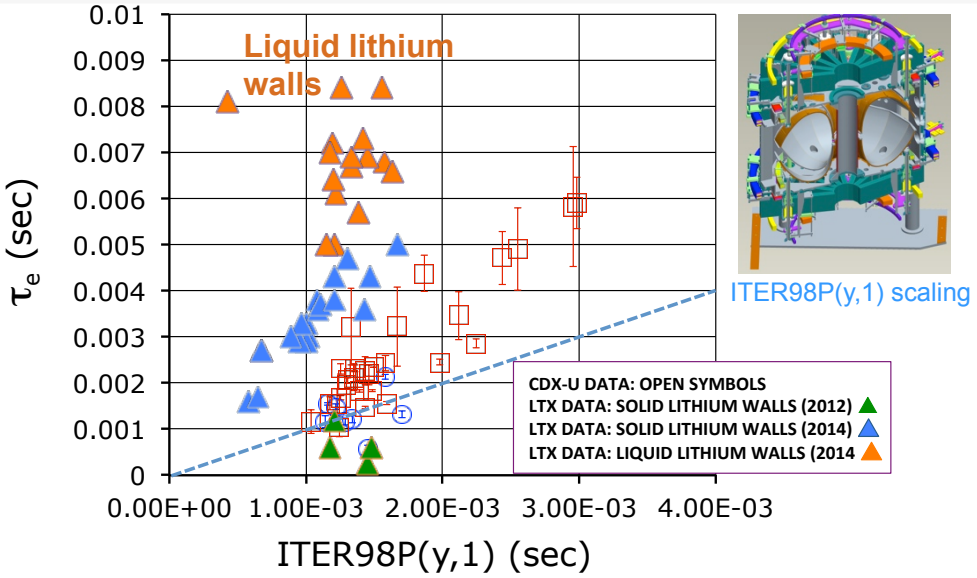
H factor increases with Li dose

Li causes reduction in:

- Divertor recycling
- Edge neutral density
- Electron transport

Lithium Tokamak Experiment

J. Schmitt, Invited talk Y12.3



Confinement time increases 10x with liquid Li

Low recycling with large-area Li walls

We don’t understand what happens at the surface

- Why does Li improve plasma performance?

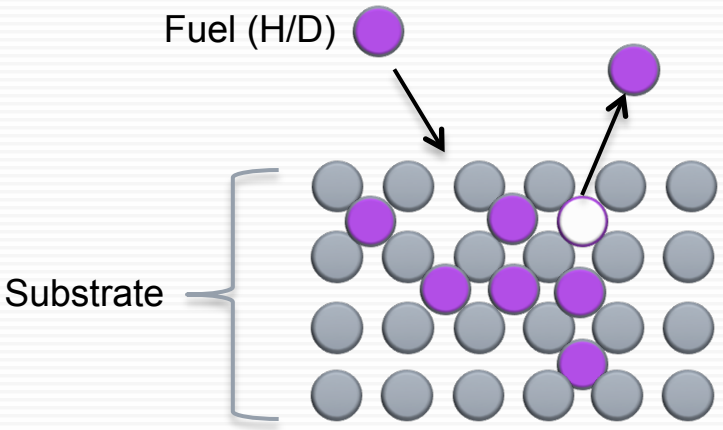
We don't understand what happens at the surface

- Why does Li improve plasma performance?

Working hypothesis: Deuterium retention

High D retention → Low D recycling → High edge temperature → Reduced temperature gradients

- Recycling Process:



We don't understand what happens at the surface

- Why does Li improve plasma performance?

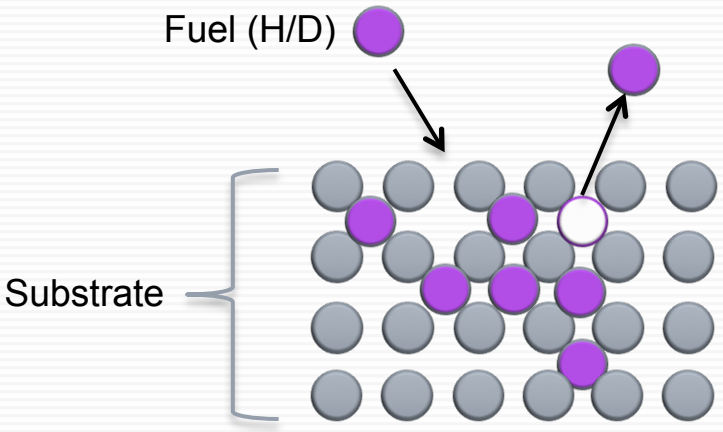
Working hypothesis: Deuterium retention

How is D retained in Li?

High D retention → Low recycling → High edge temperature → Reduced temperature gradients

1. Through volumetric conversion of Li to LiD *(Baldwin & Doerner)*

- Recycling Process:



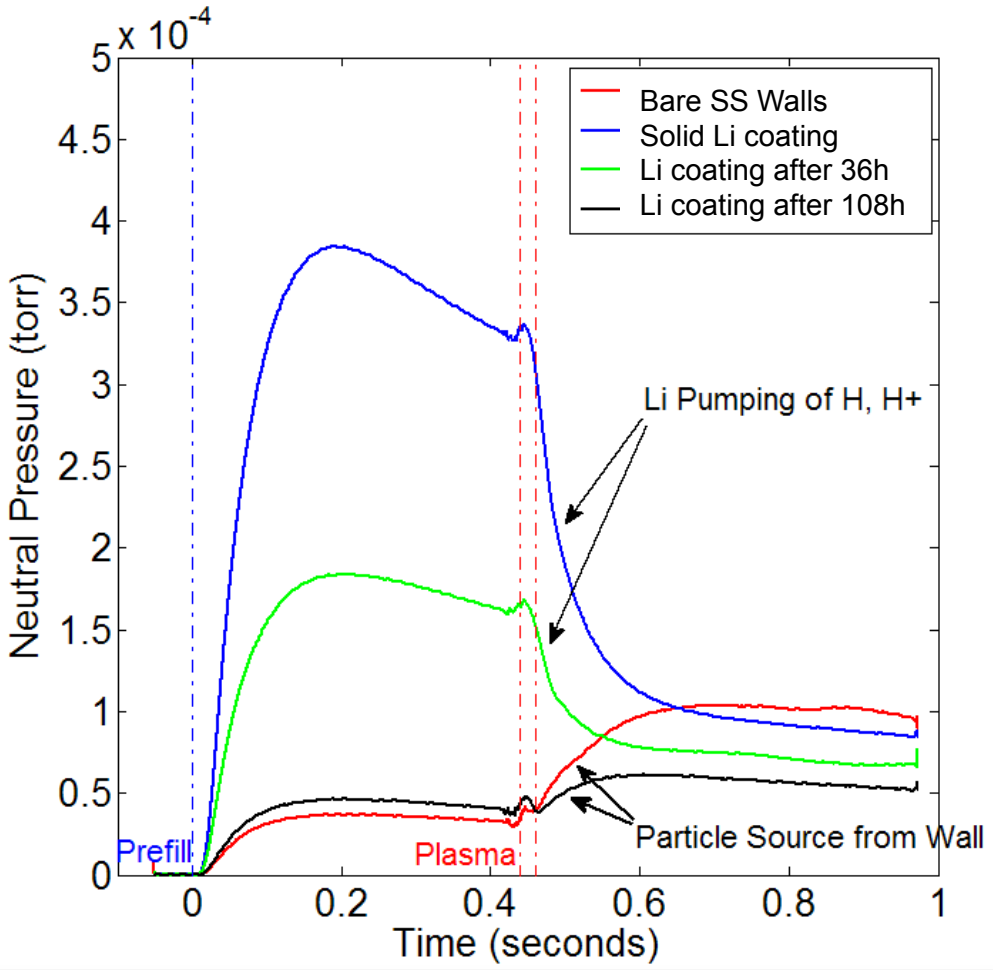
2. Through complexes that involve oxygen *(Krstic, Allain, Taylor)*

H pumping fraction is correlated with wall temperature and composition on LTX

- Hot, oxidized Li: lower H pumping
- Cold, oxidized Li: better H pumping

- With e-beam system:

  When Li is metallic, hot shells give improved plasma performance



J.C. Schmitt et al., JNM 438, S1096 (2013)

H pumping fraction is correlated with wall temperature and composition on LTX

- Hot, oxidized Li: lower H pumping
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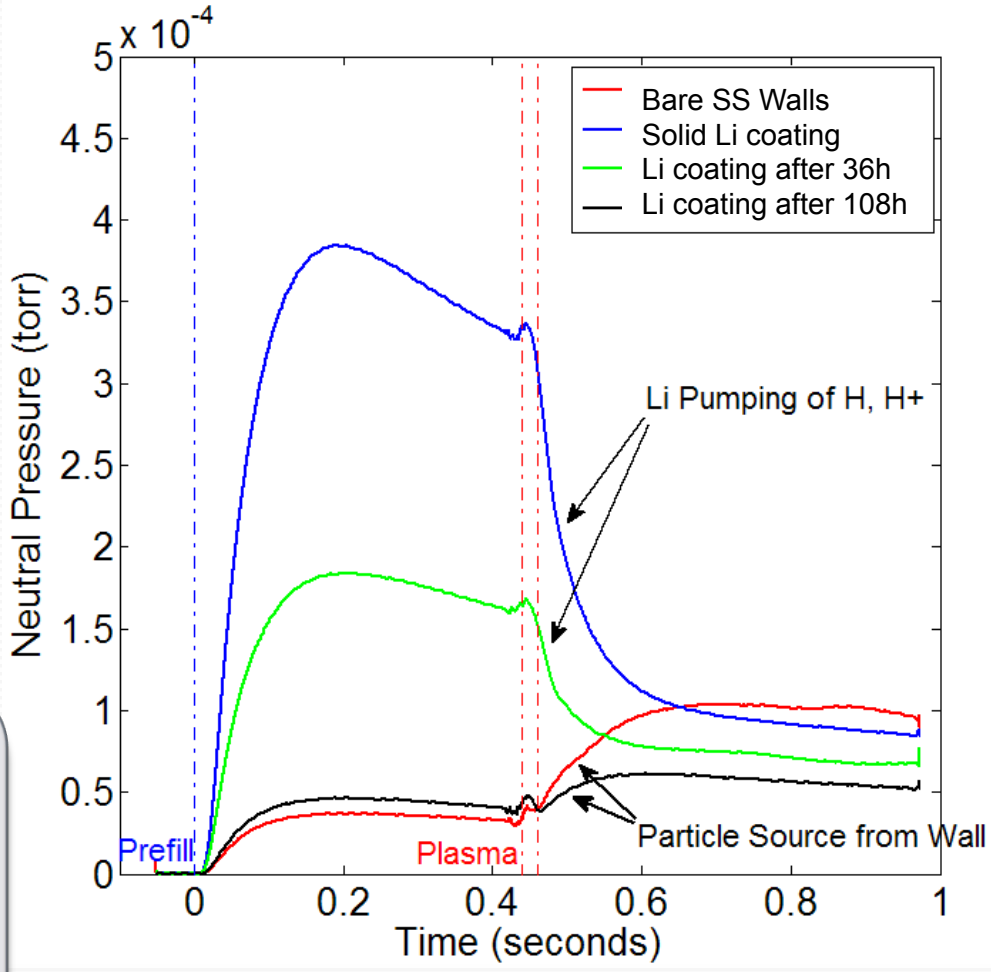
Key Question:

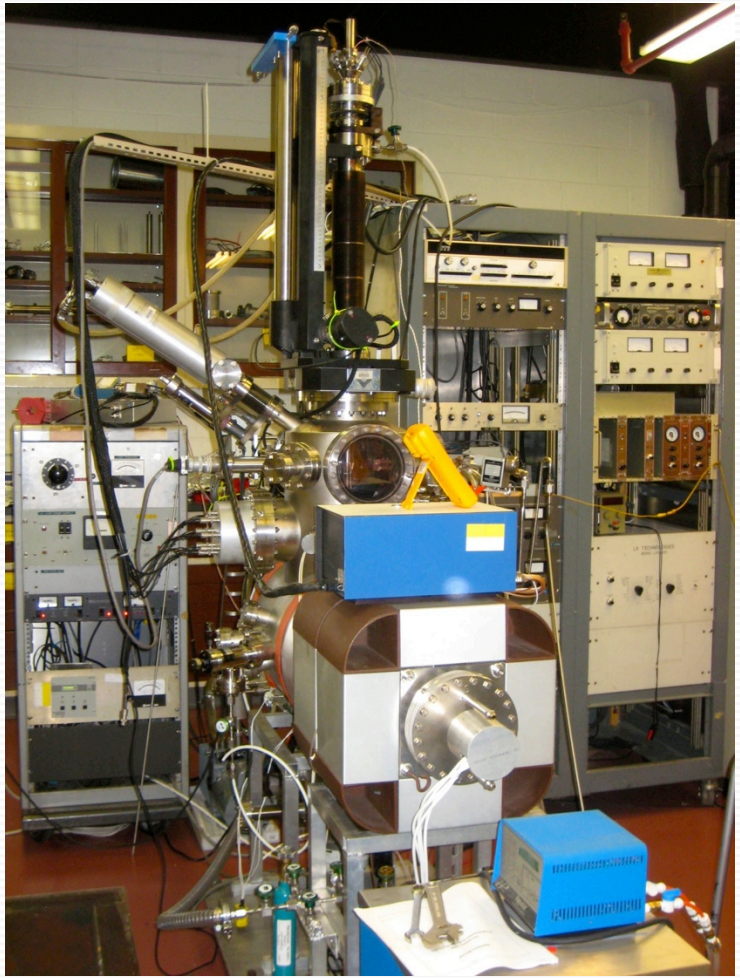
How is the pumping ability of Li affected by temperature & oxidation?

Our goal: To elucidate this data under carefully controlled conditions.



J.C. Schmitt et al., JNM 438, S1096 (2013)

Surface science provides fundamental information needed to understand plasma-wall interactions



Test stand instrumentation in the Surface Science & Technology Lab at PPPL

Key variables affecting chemistry at surface:

- Pressure (residual gases)
- Temperature (plasma heating)
- Composition (Mo, Li, D, etc.)

Lab-based surface science experiments enable independent control of all variables

…something we cannot achieve in a tokamak or linear plasma device!

Isolate effects of:

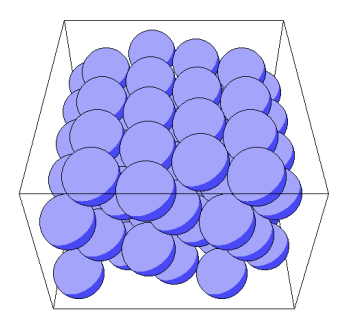
- Chemistry
- Incident particle fluxes and energies
- Substrate temperature
- Surface composition
- Morphology

Start simple, i.e. single effects, and add complexity to bridge gap between model systems and tokamak environment

Our capabilities span from the simple to the complex

Simple Model Experiments

More Complex Systems

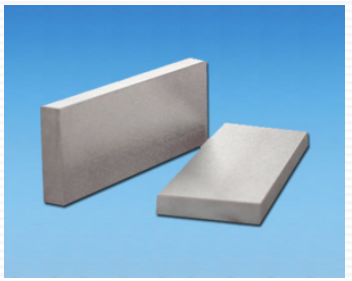


Mo(110) crystal

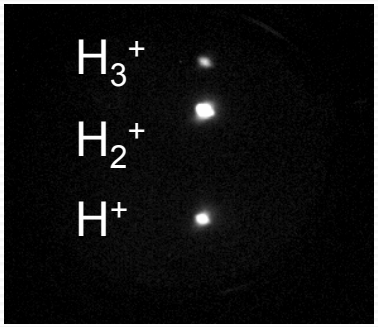
Grain boundaries

Alloying elements: Ti, Zr, C

Surface roughness



TZM Mo alloy



Monoenergetic ion beam

(Image of He ions on phosphor screen)

Multiple species: H^+, H_2^+, H_3^+

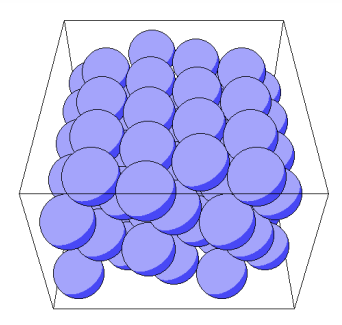
Increased flux: $10^{12} \rightarrow 10^{16}$ cm^{-2} s^{-1}

Atoms, ions, or atoms + ions

ECR plasma source

We will focus on more complexity in this talk

Simple Model Experiments



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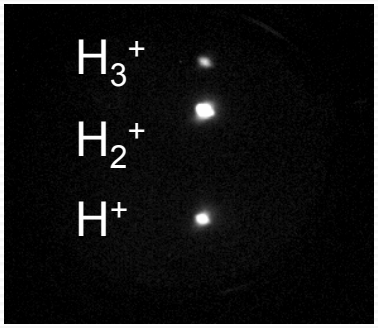

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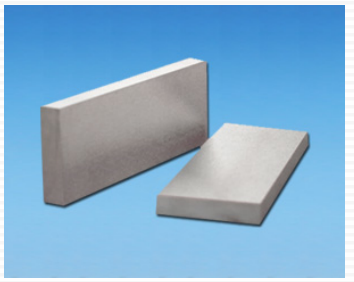
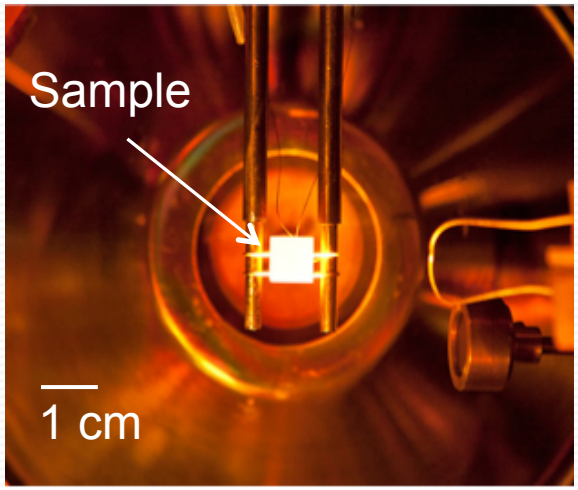
More Complex Systems

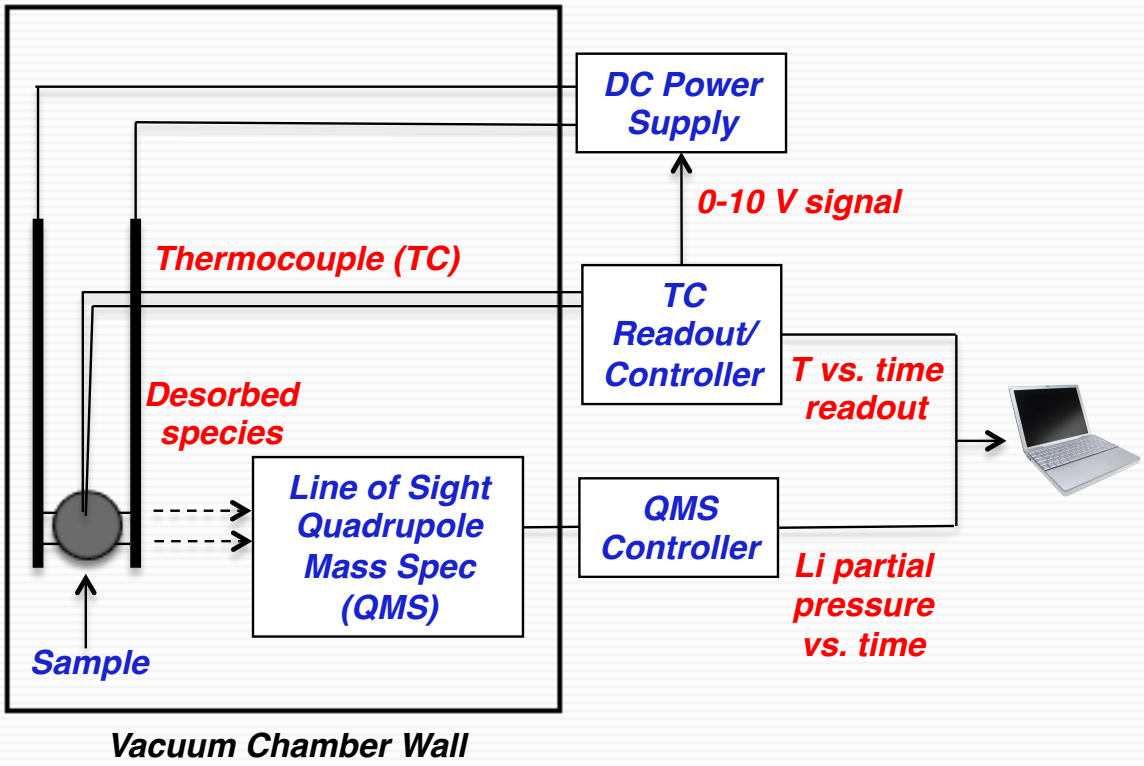


TZM Mo alloy

ECR plasma source

Temperature programmed desorption gives desorption energy, rate constants, & quantity desorbed

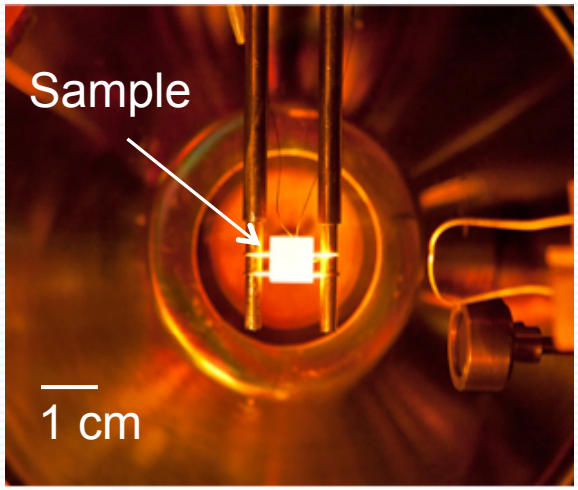


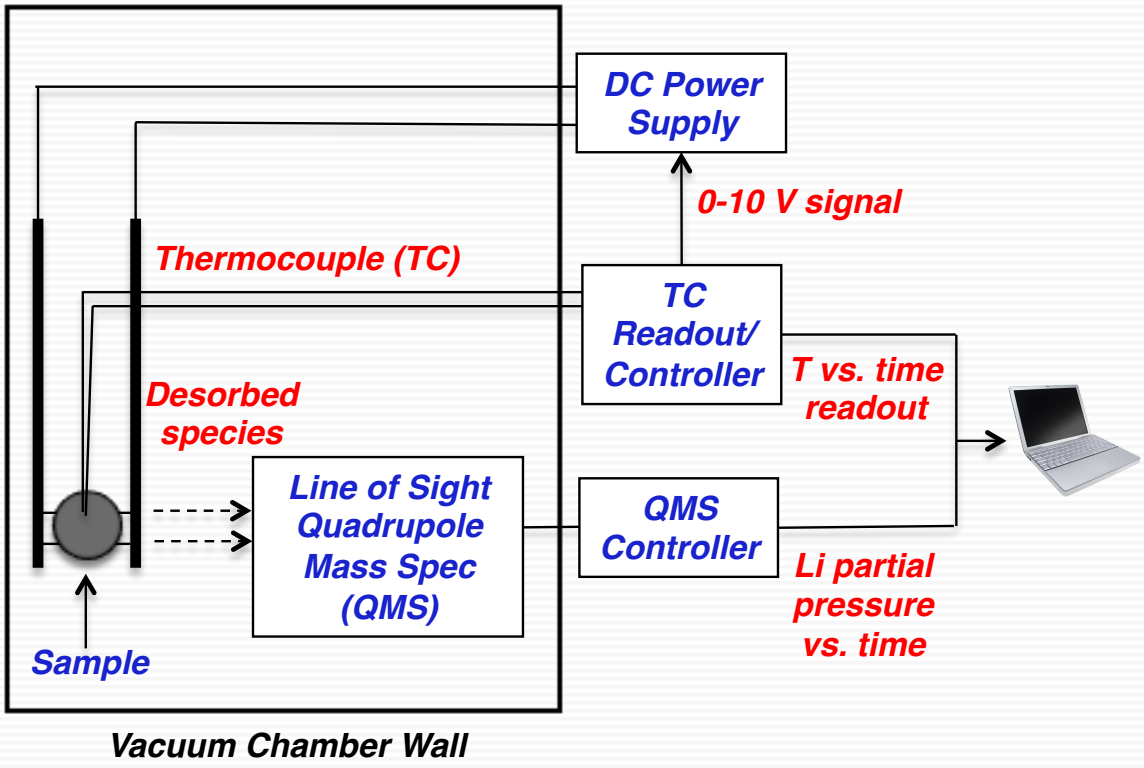


Temperature Programmed Desorption (TPD) Technique:

- Linear temperature ramp applied to sample
- Partial pressure of desorbing species measured
- Temperature of desorption peak relates to binding energy
- Area under pressure vs. time curve proportional to number of atoms desorbed

Temperature programmed desorption gives desorption energy, rate constants, & quantity desorbed

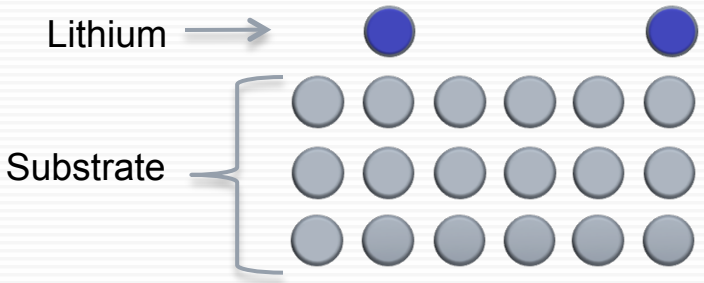




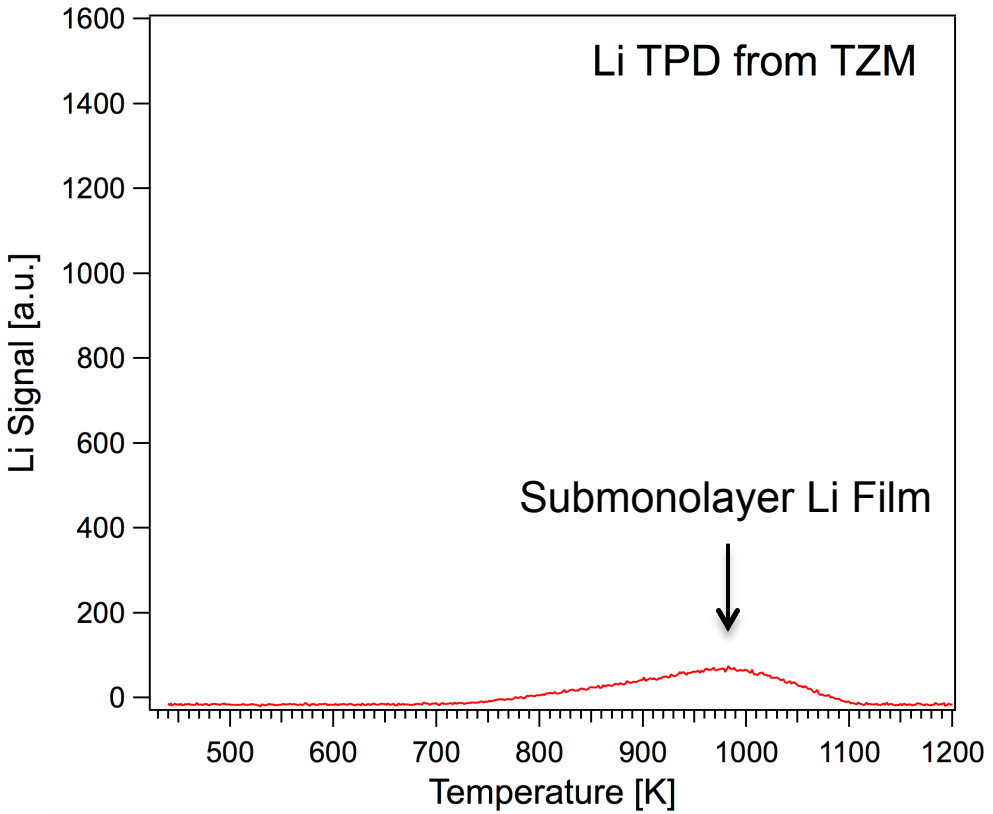
Area under pressure vs. time curve → # of atoms desorbed

TPD can be used to measure D retention!

TPD shows that Li is stable on TZM up to 1000 K



- Submonolayer Li film on TZM stable up to 1000 K
- Represents Li-Mo bonding
- Desorption energy ~2.7 eV

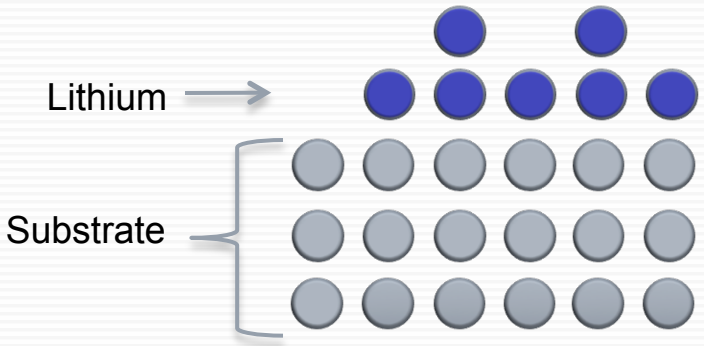


$$\frac{E^*}{RT} = \frac{1}{2} + Y - lnY + \frac{lnY}{Y} - \frac{lnY}{2Y^2}(2 - lnY)$$

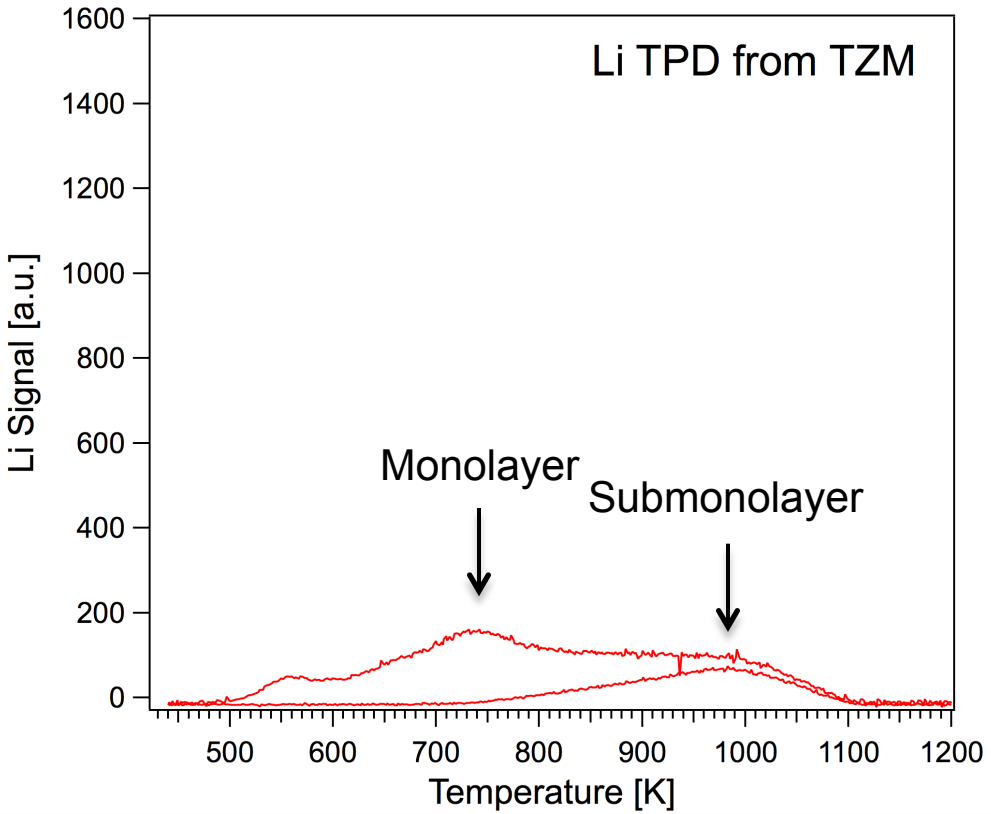
$$Y = ln\left(\frac{v_0 \cdot T}{\beta}\right)$$

C.H. Skinner et al., JNM 438, S647 (2013)

Area under Li TPD curve increases with Li dose



- Area under Li TPD curve increases with Li dose
- Dipole interactions lower the desorption energy
- Desorption energy of monolayer ~2 eV
- E_d is a function of coverage



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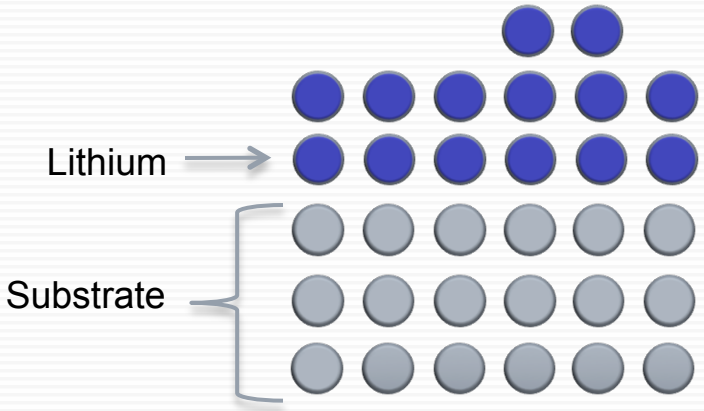
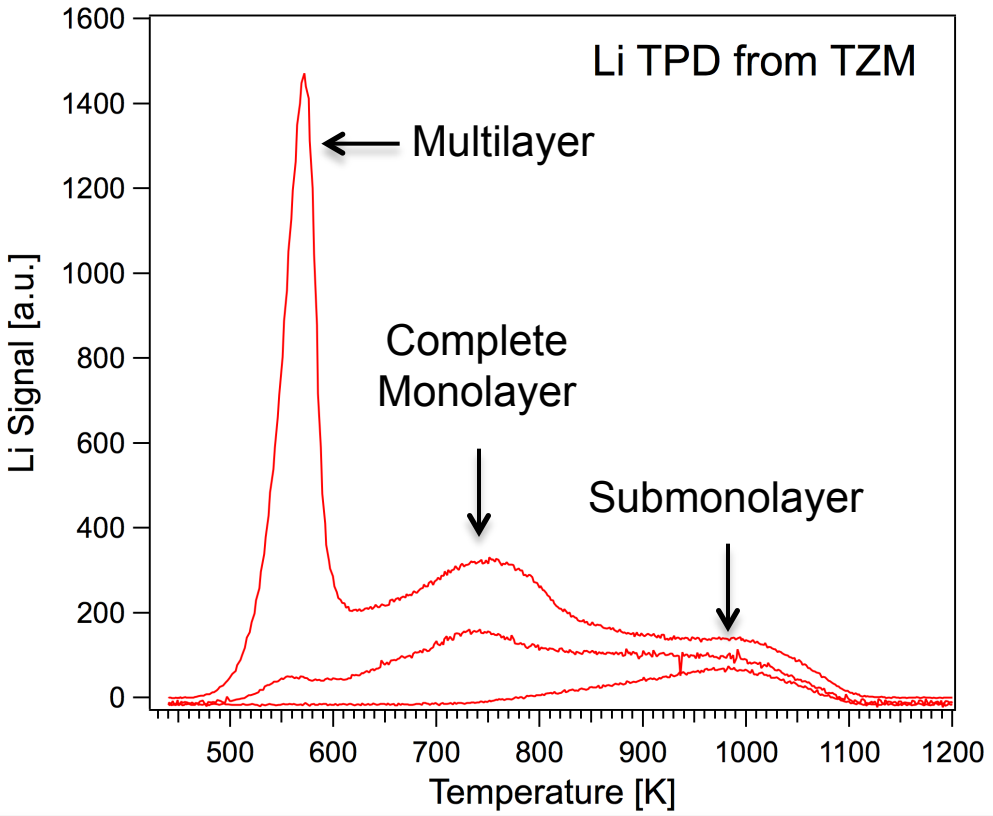
Thick Li layers evaporate at 500 K



- Thick Li films (multilayer) evaporate at 500 K
- Multilayer film represents Li-Li bonding
- Cohesive energy of metallic Li ~1.7 eV



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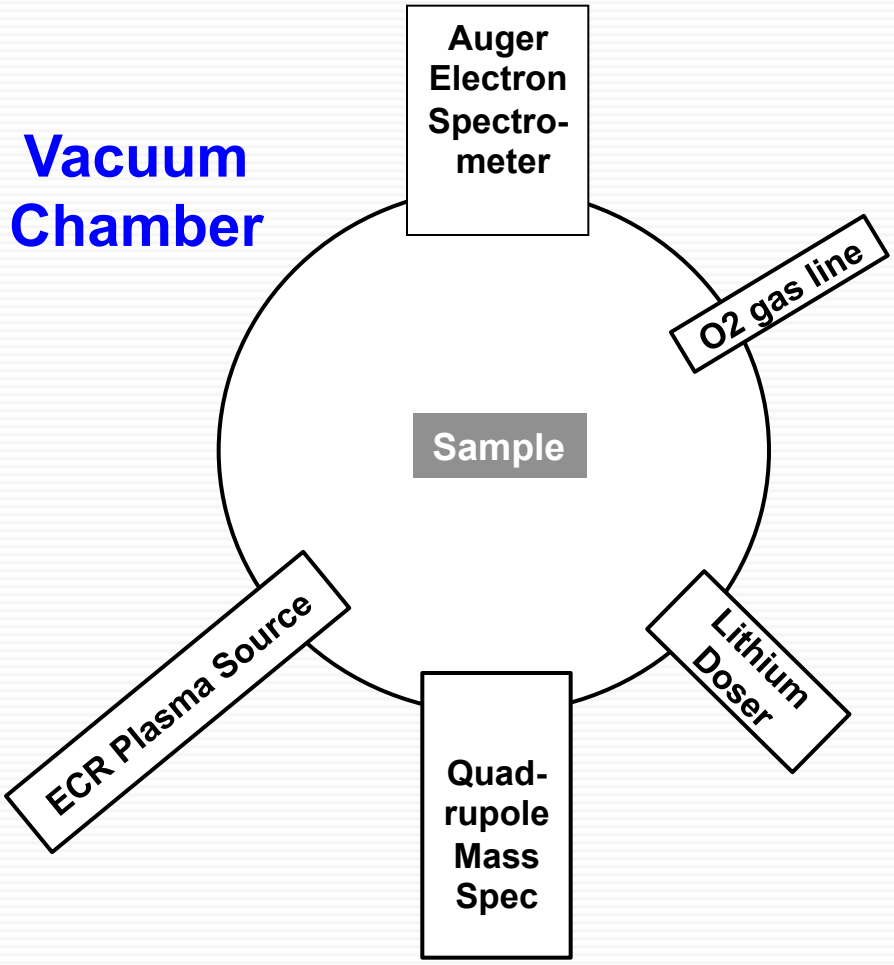
Li film on TZM is exposed to D plasma from ECR source



Experimental Parameters:

Sample:

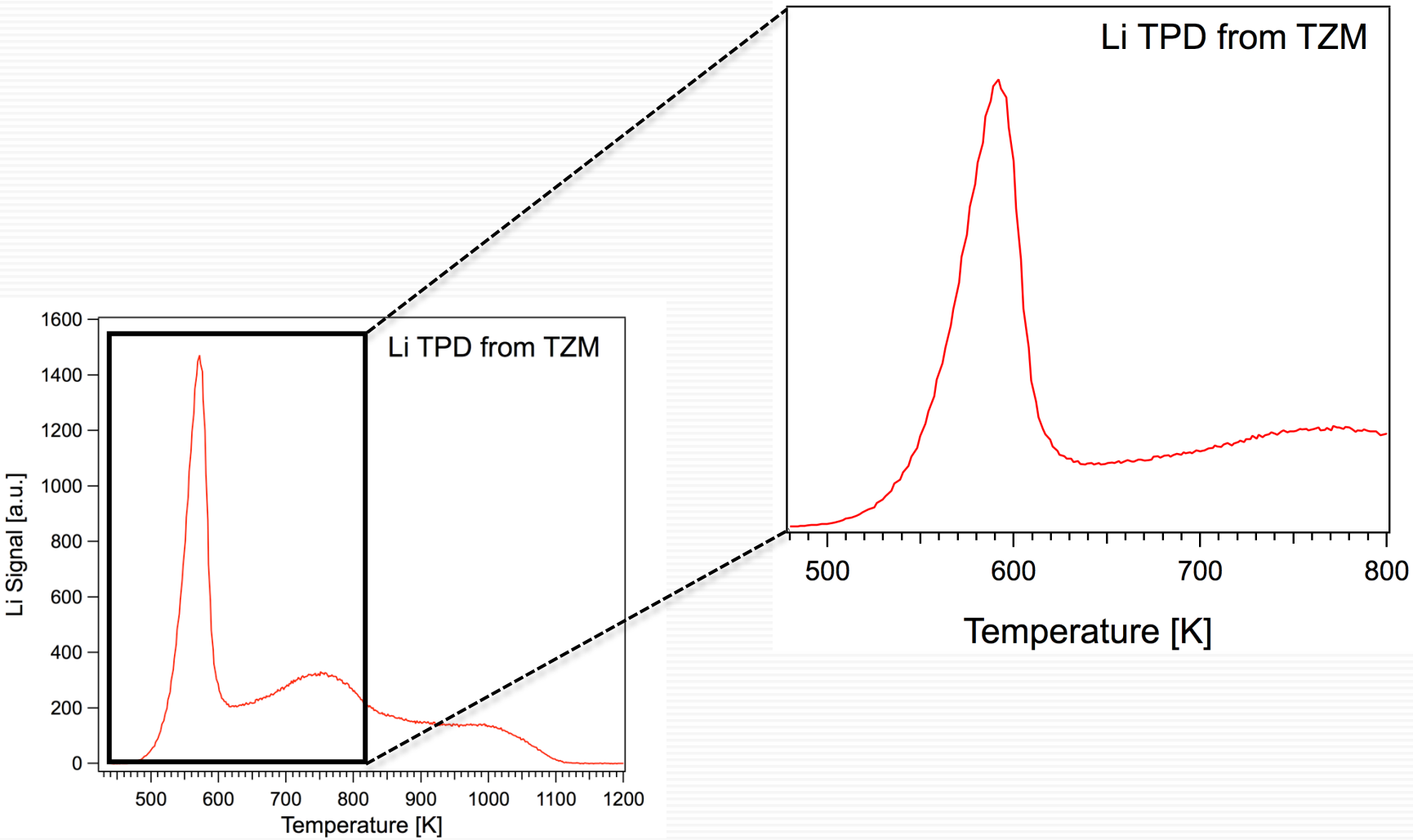
TZM Mo Alloy (99% Mo, 0.5% Ti, 0.08% Zr)
Li film thickness: 5 monolayers (ML)
Wall temperature: 315–460 K (42–187°C)

Chamber Pressure: 2 x 10^{-9} Torr

D_2^+ ion energy: 250 eV per D_2^+ ion
D_2^+ ion flux: of 1 x 10^{13} cm^{-2} s^{-1}
Exposure time: 100 s
Fluence: 2 x 10^{15} D cm^{-2}
D_2 exposure: 5 x 10^{-5} Torr for 100 s (5000 L)

ECR Plasma Source

D retained as LiD after exposure to D_2^+ from ECR plasma source



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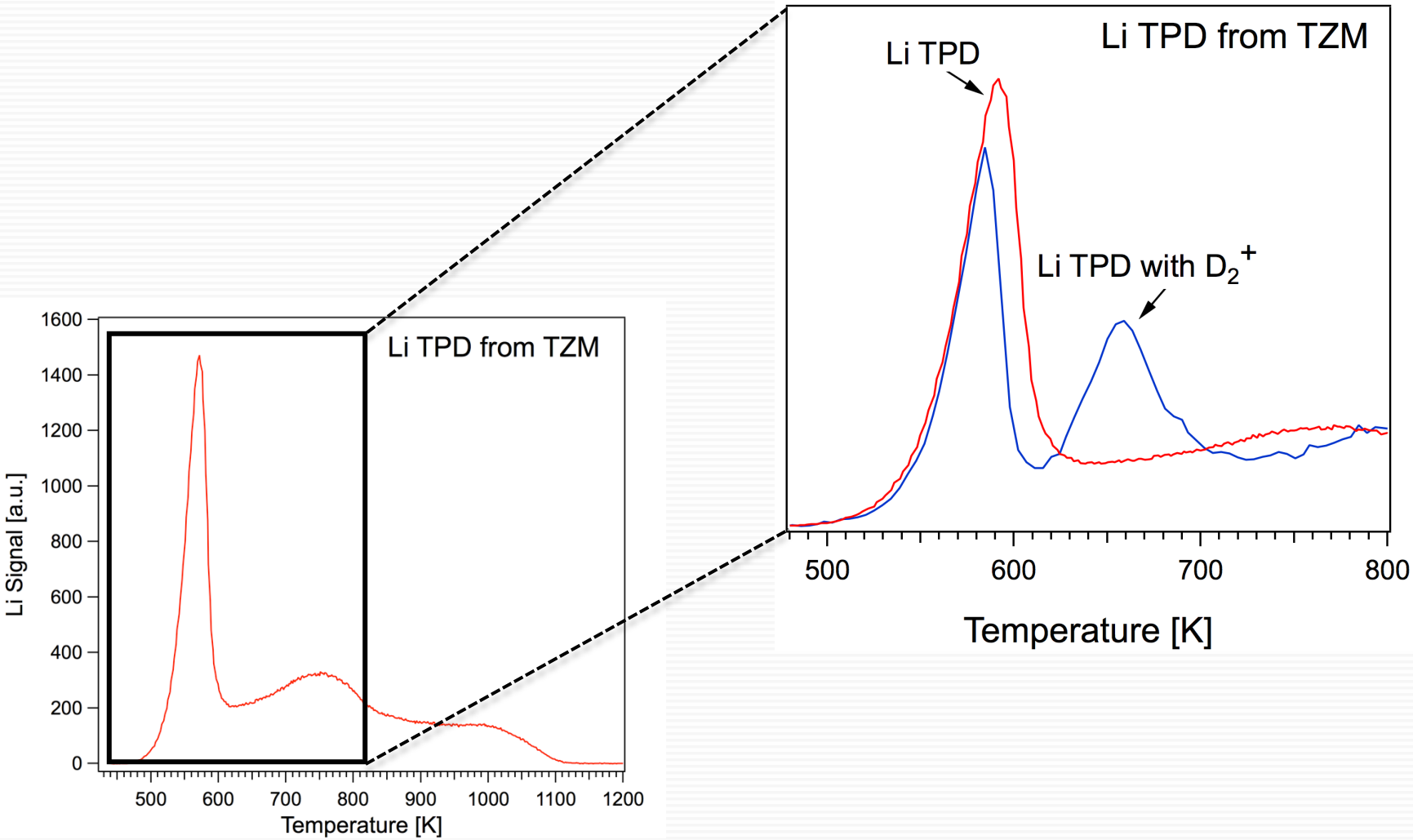

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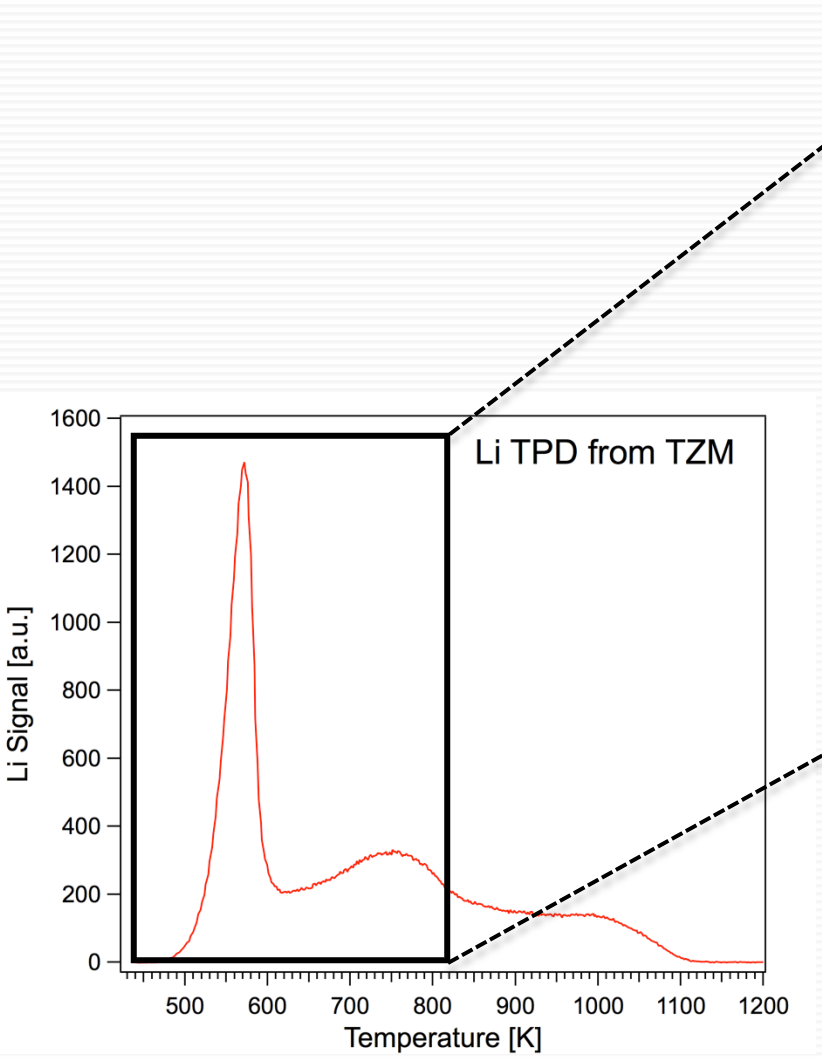
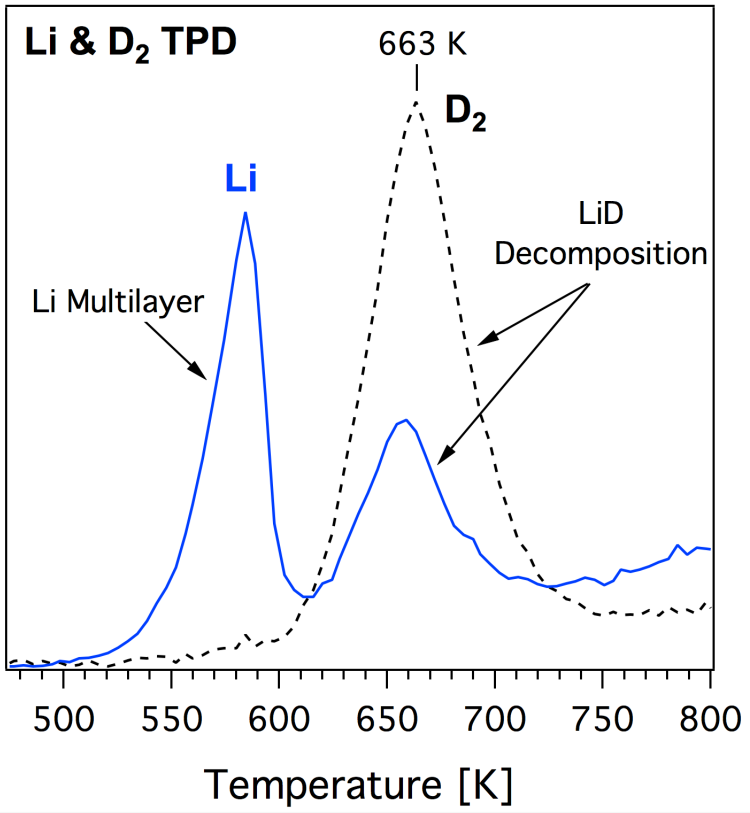
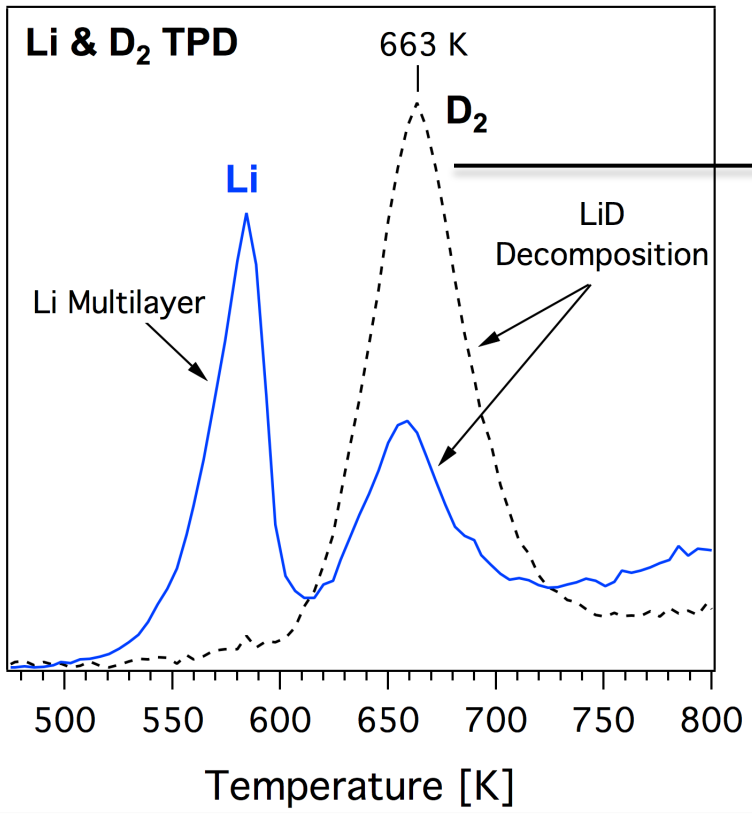
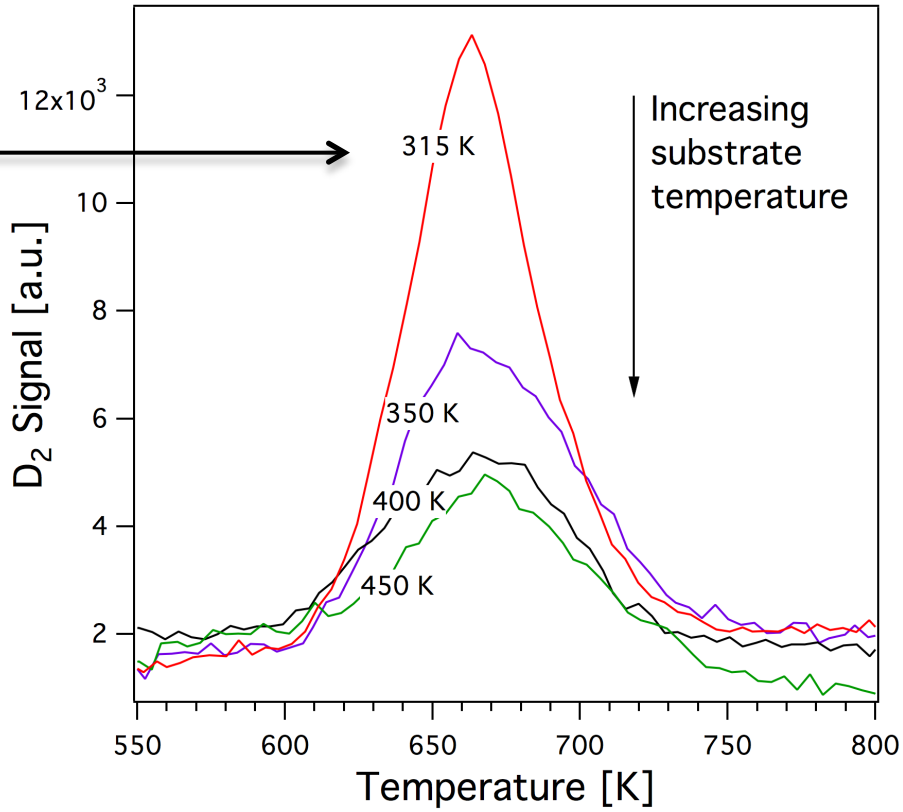




- New Li peak observed near 650 K
- Peak corresponds to LiD decomposition

D retention in ultrathin Li films decreases with substrate temperature from 315-460 K





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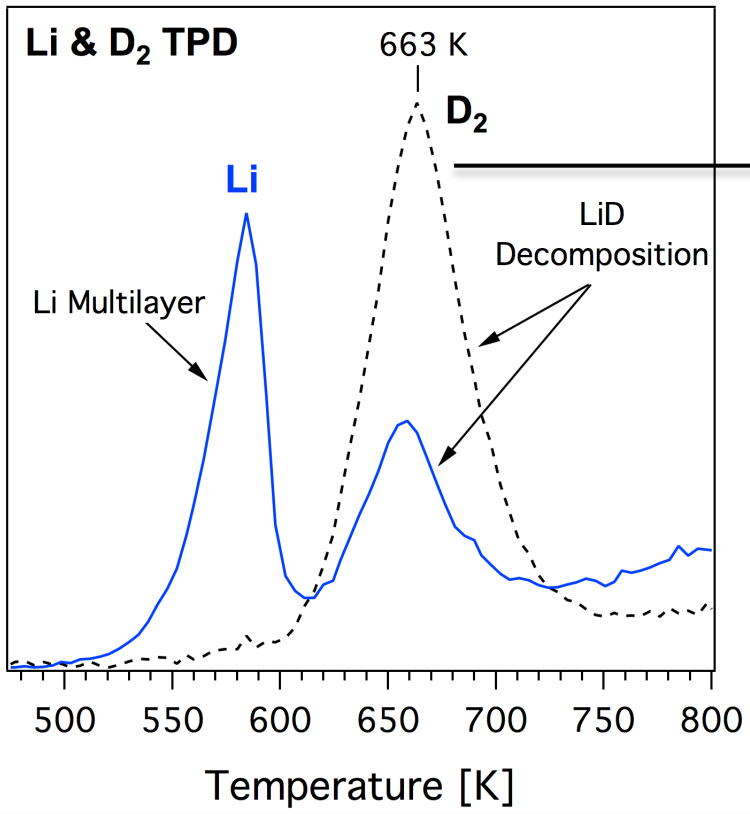

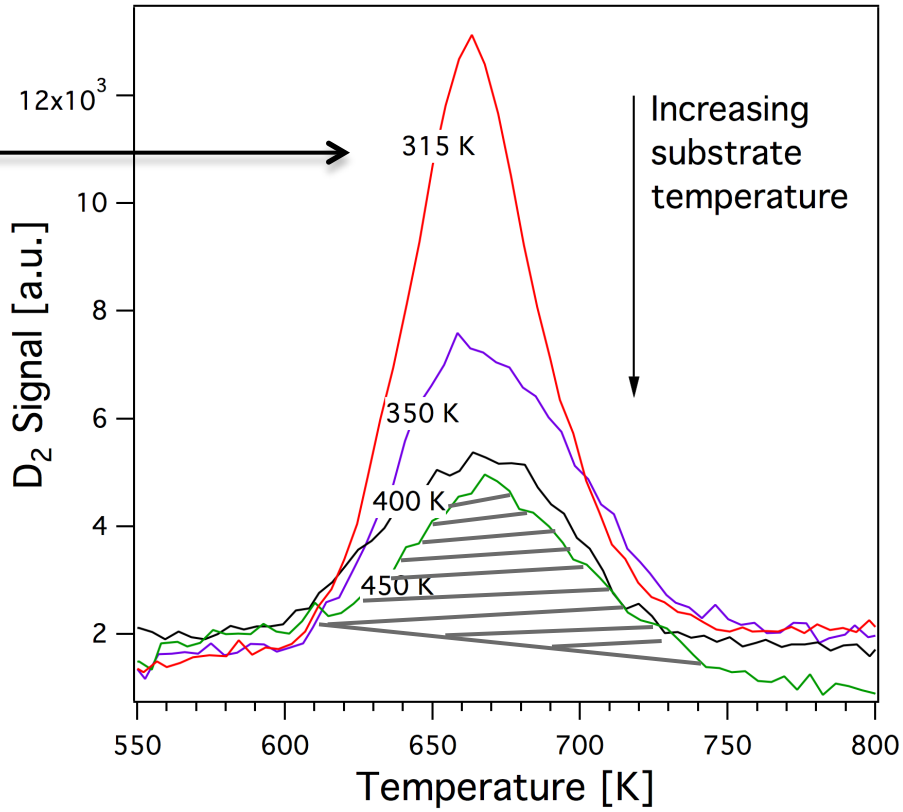

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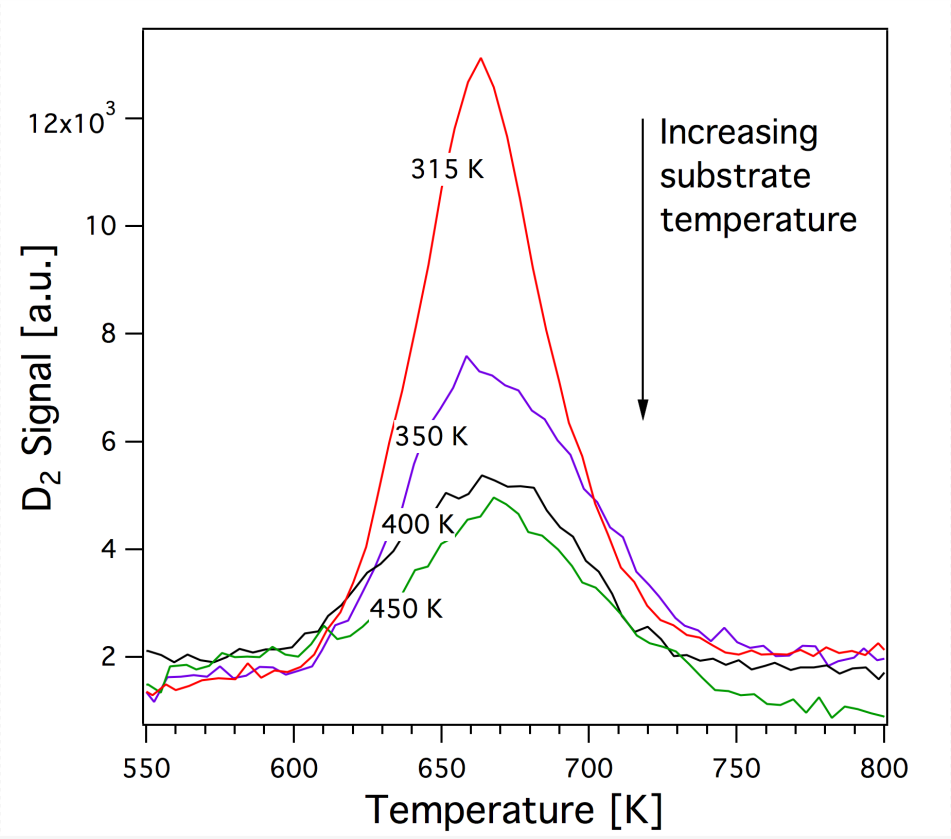
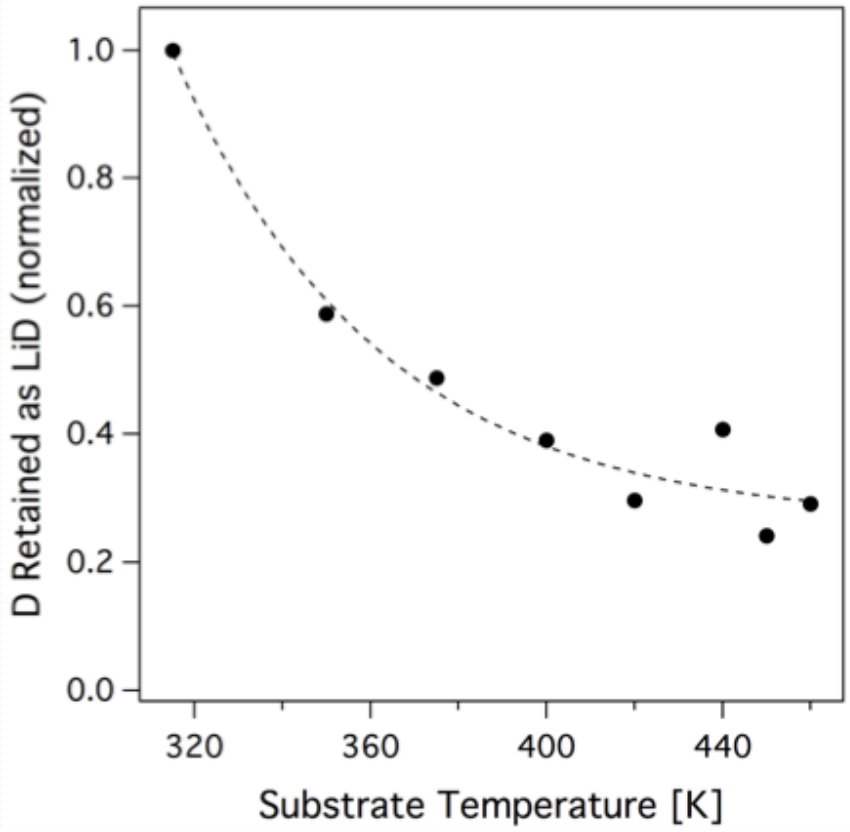




D retention in ultrathin metallic Li drops exponentially with temperature up to 460 K

D_2^+ is 10^4 times more effective than D_2 gas at forming LiD

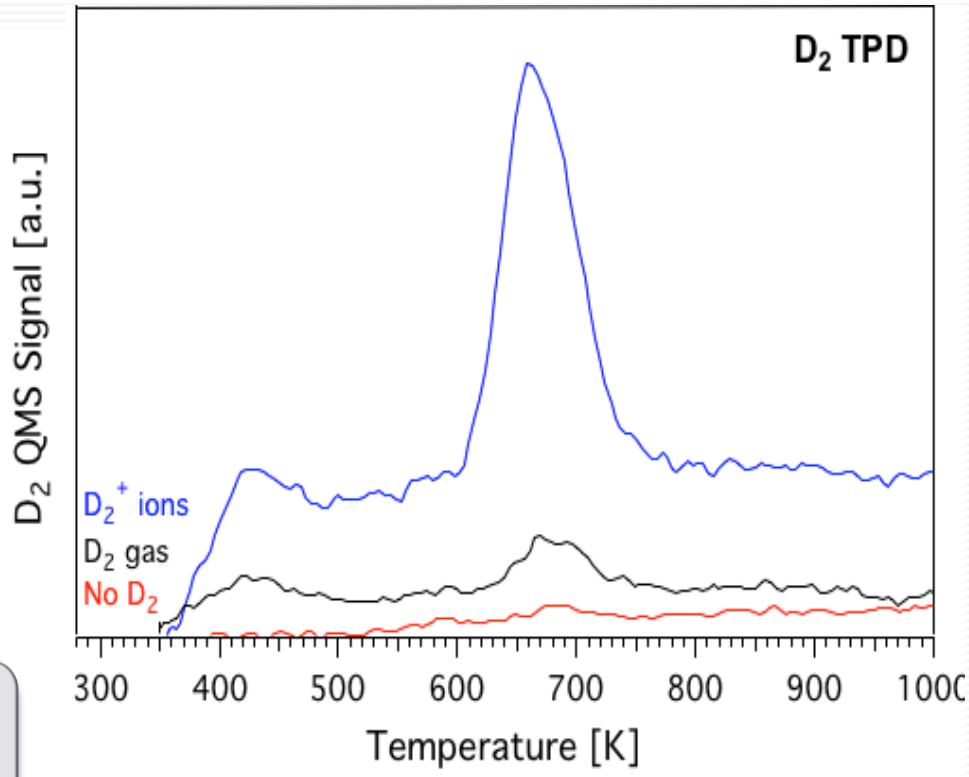
What is the effect of D_2 gas?

- Operate experiment without plasma

Ion fluence:
$2x10^{15}$ D^+ ions cm^{-2}
~ 2 monolayers

D_2 gas exposure
$5x10^3$ L (1 L = 10^{-6} Torr-s)
~ $5x10^3$ monolayers

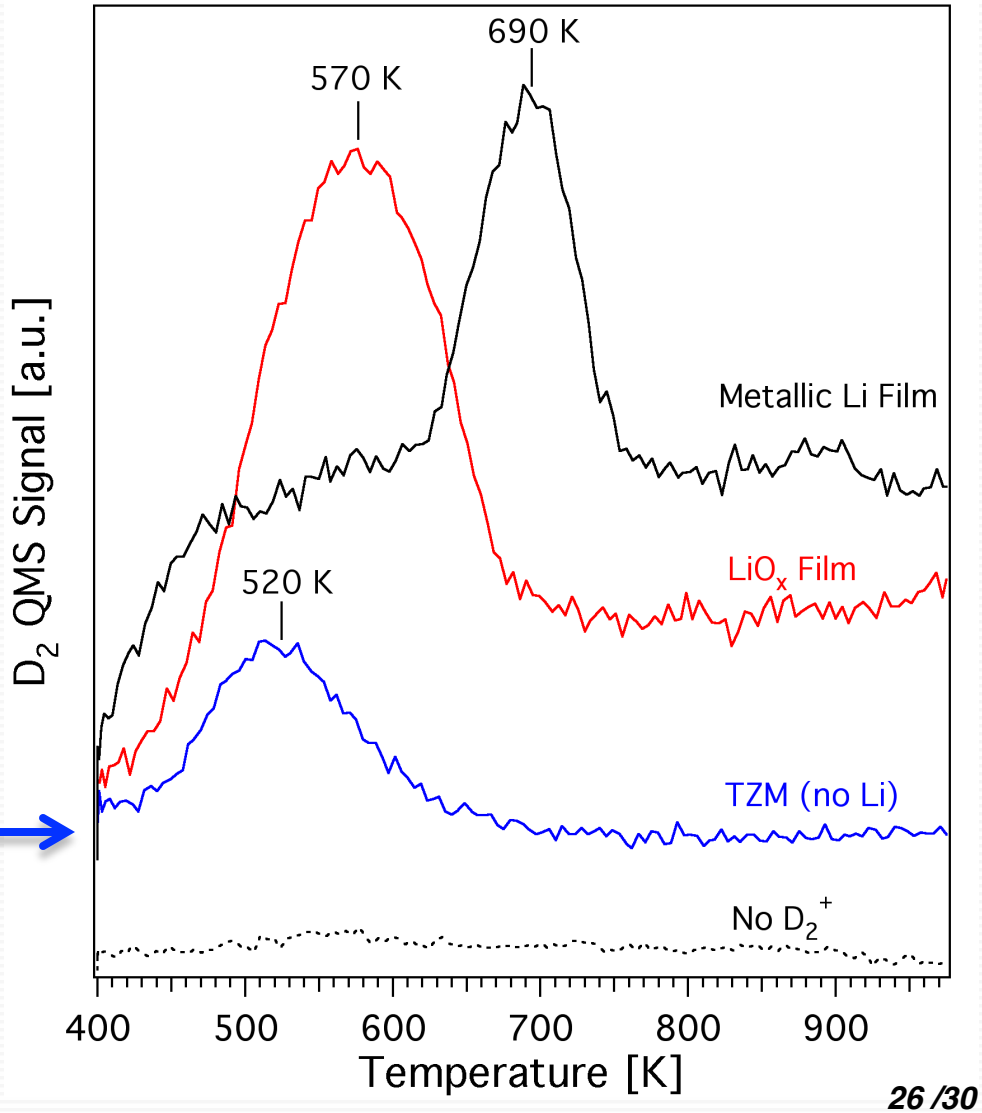
~2000x as much D_2 as D^+
But we make 10x less LiD



D_2^+ ions are 10^4 times more effective than D_2 gas at forming LiD!

Li_2O retains more D, but film is less thermally stable than LiD

D is implanted in uncoated TZM



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4 to 5x more D_2 retained in Li_2O than TZM

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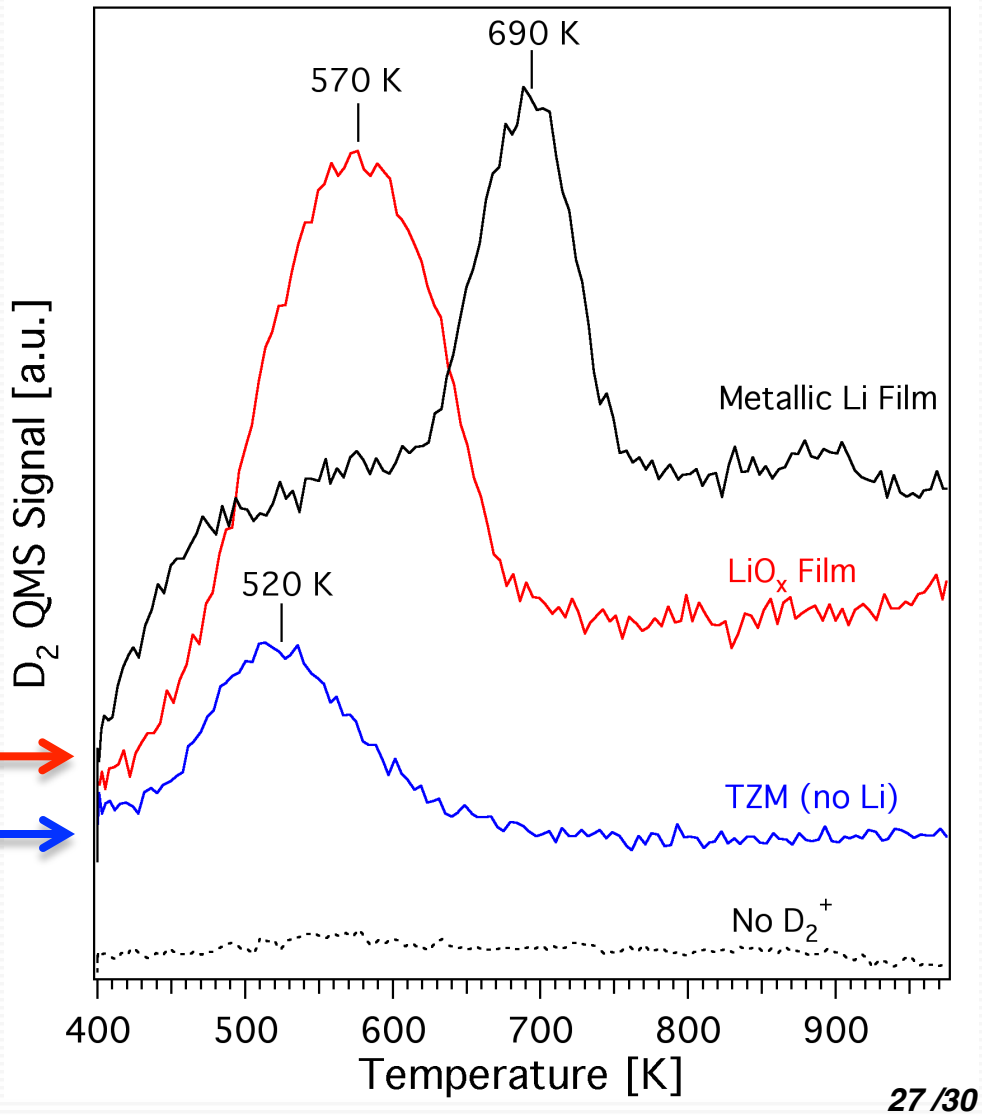

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2x less D_2 retained in metallic Li, but more thermally stable!

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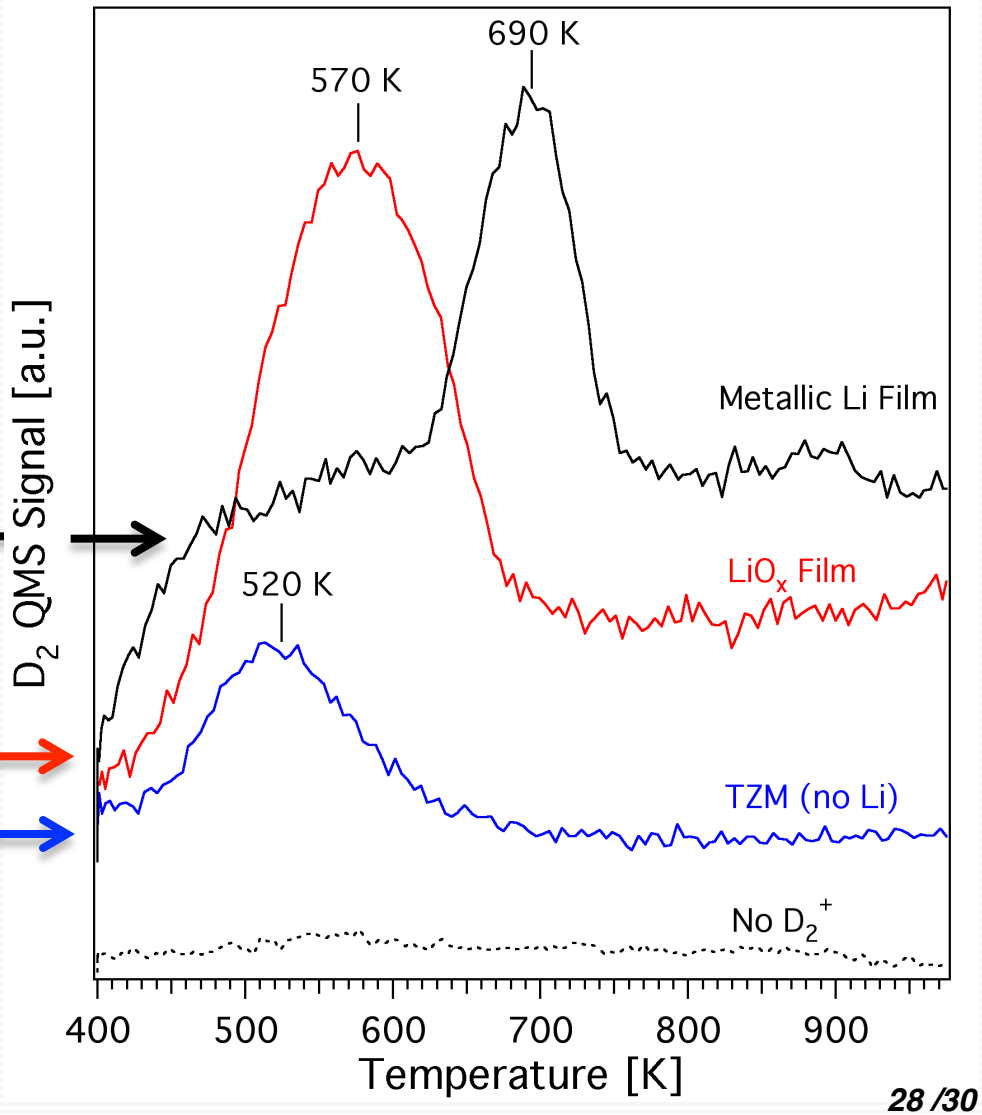


Li_2O retains more D, but film is less thermally stable than LiD

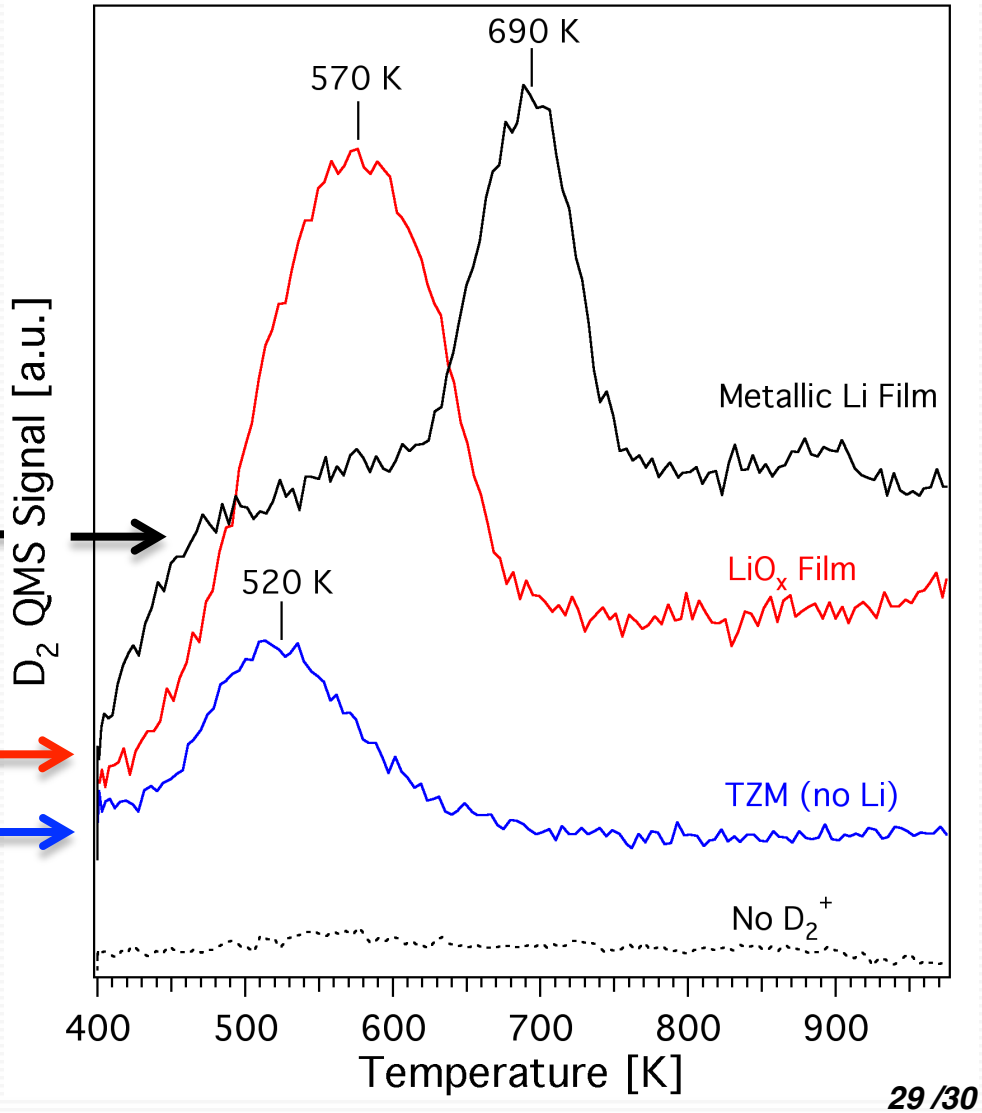
T < 130°C, Li_2O is best for D retention

T > 130°C, Metallic Li is needed for D retention

2x less D_2 retained in metallic Li, but more thermally stable!

4 to 5x more D_2 retained in Li_2O than TZM

D is implanted in uncoated TZM



Conclusions

T < 130°C, Li_2O is best for D retention

T > 130°C, Metallic Li is needed for D retention

D retention in metallic Li films drops exponentially up to 460 K

- D_2^+ are 10^5x more effective than D_2 gas at forming LiD
- Oxygen inhibits LiD formation at the surface

Oxidation improves D retention in Li films on TZM below 400 K

- D retention in Li_2O films is 2x higher than in metallic Li at 400 K
- D retained in Li_2O films is released at 400 K
- At elevated temperatures, metallic Li film is needed to retain D

Results are consistent with LTX

- Li does not pump D2 well
- Bare metal acts as particle source
- Cold Li_2O films will retain D