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Sliding friction of neon monolayers on metallic surfaces

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Nanofriction of monolayers of simple gases on metals

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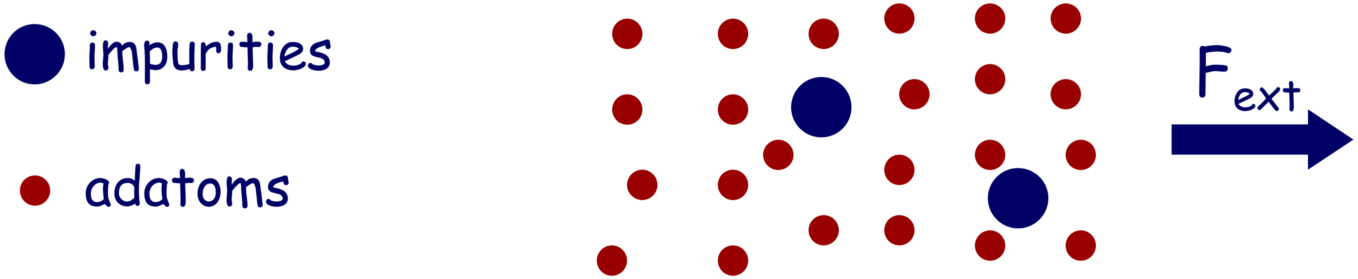
Outline

- Introduction
- QCM technique
- Kr on gold (e.g. dynamical depinning)
- Ne on lead (e.g. structural depinning)
- Ne on metals plated with rare gases multilayers (e.g. control of friction)

•Introduction

Tribology playground



Deposit atoms on a flat surface
Apply the same external lateral force on each atom
Study dependence of atomic friction on the various system parameters

Keep it simple!

Deposit gases (e.g. rare gases) characterized by simple physical interactions between them and with the surface

Use uniform crystalline surfaces without chemical impurities

Study dependence of atomic friction on
temperature,
External force strength,
film coverage (e.g. 2D phase of adsorbate),
chemical nature of substrate (e.g. vertical interactions),
physical nature of substrate (e.g. metal or insulator, lattice parameters),
...

and their interplay with impurities (chemical or structural)

Sliding of adsorbed monolayers

Model system for extensive theoretical studies

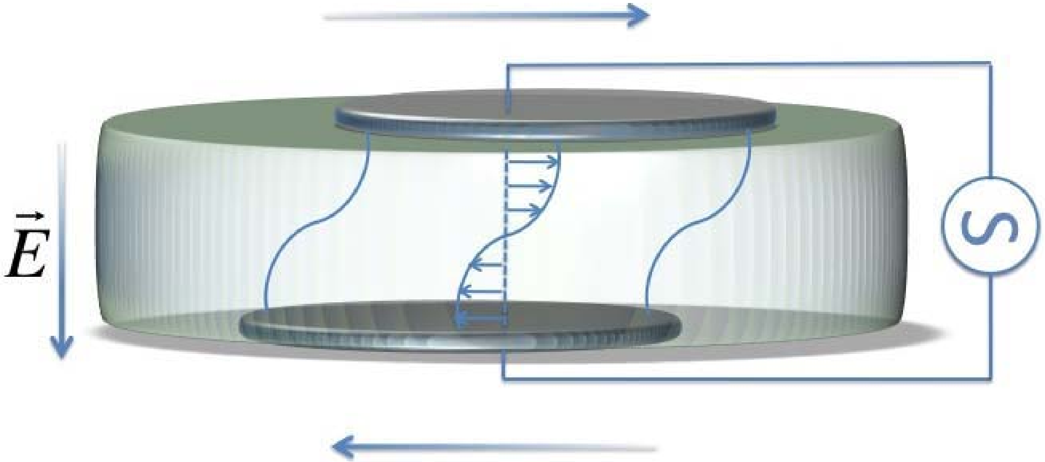
Experimentally, the most suitable probe to study these systems is the quartz crystal microbalance

•Quartz Crystal Microbalance

Quartz Crystal Microbalance (QCM)

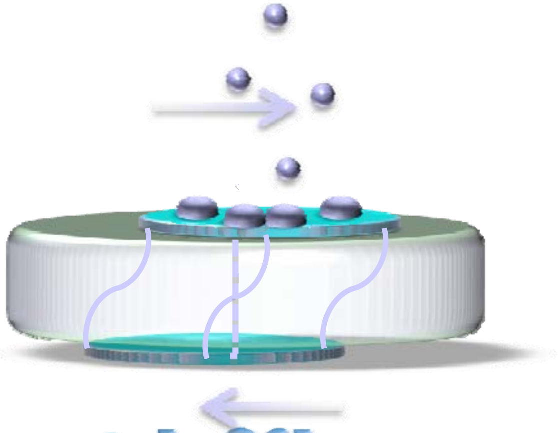
Standard technique to measure mass (e.g. thickness) in evaporators

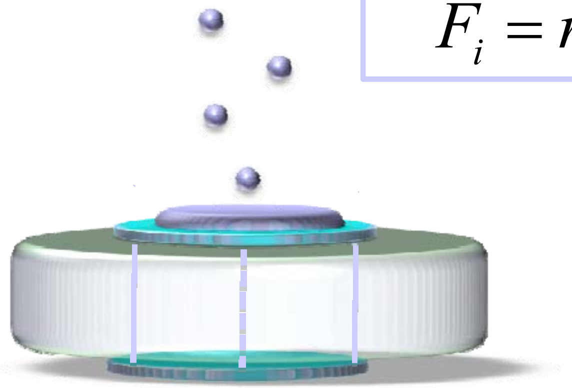
- quartz disk (D≈10 mm, t≈0.3mm) with two metal electrodes
- parallel faces undergo a shear motion by the application of a variable voltage
- automatic track of mechanical resonance (I harmonic 5MHz), instantaneous measurements of frequency and amplitude
- high quality factor Q≈10^5 ⇒ High sensitivity

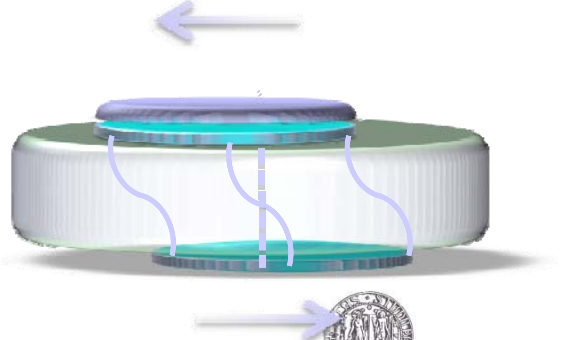


N$_2$ molecule

$$F_i = mA_0 f_0^{\,2} \approx 0.002\ fN$$

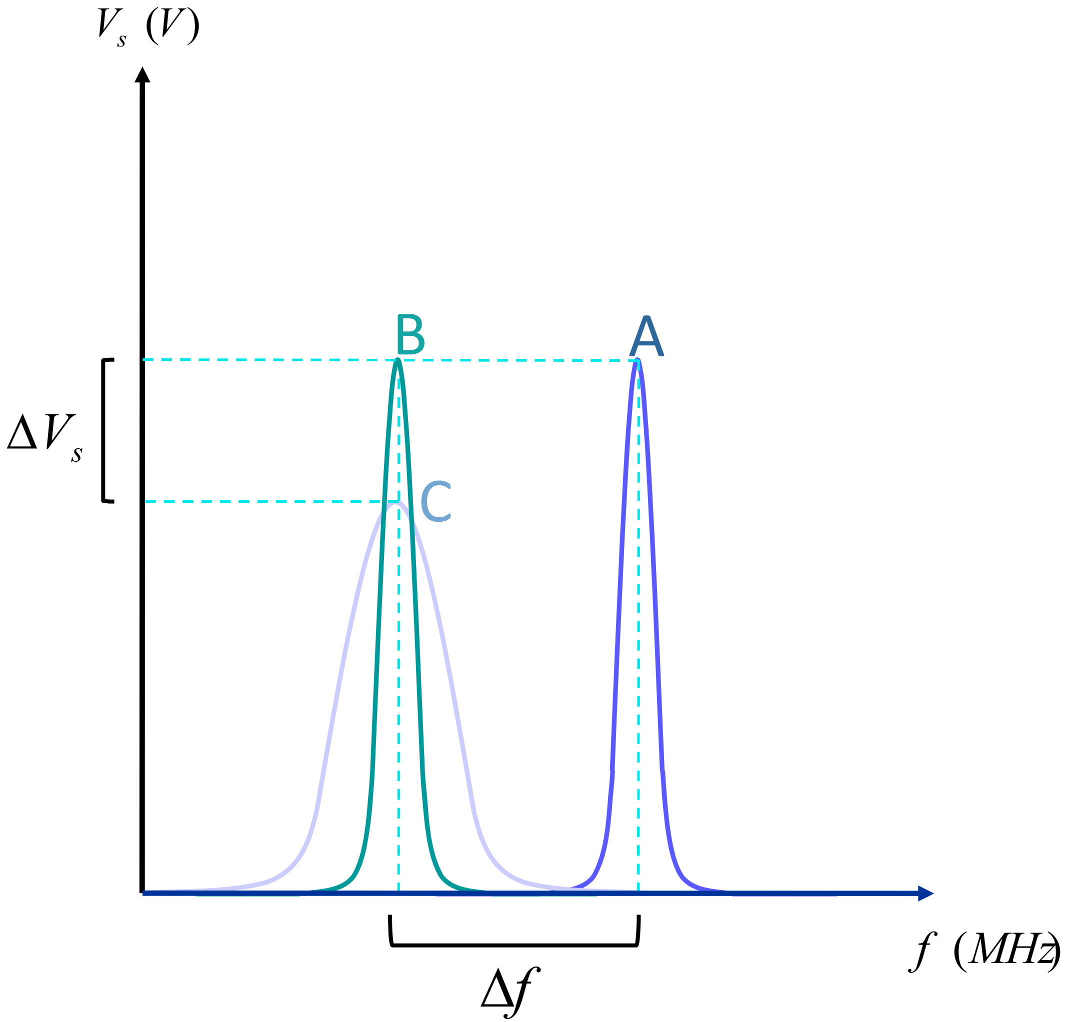


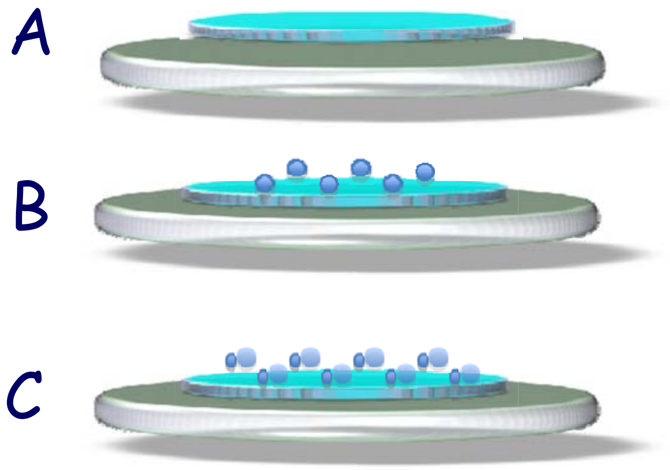




QCM as a nanofriction probe

In 1988 J. Krim suggested to use QCM to study sliding of adsorbed film



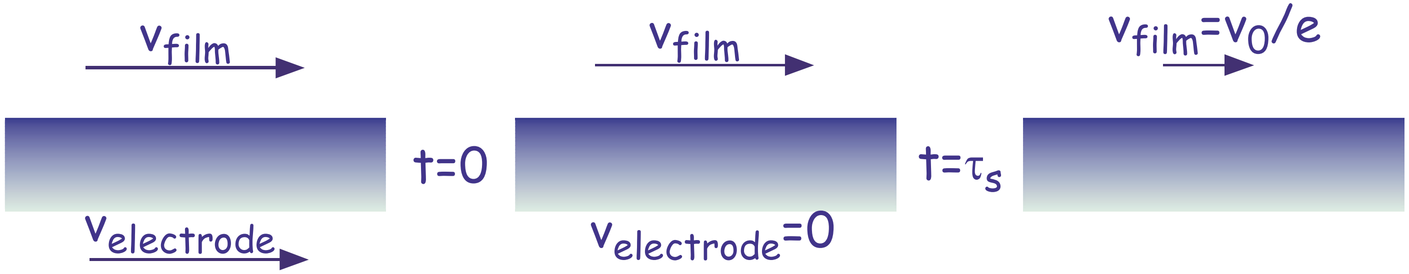


Δf→adsorbed mass
(2.3 Hz/5MHz for
Ne monolayer)
ΔV_S→dissipation

QCM as a nanofriction probe

From ΔV and Δf it is possible to determine slip time τ_s

Slip time is the time it takes the film to follow the electrode



v_{film} $v_{electrode}$

$t=0$

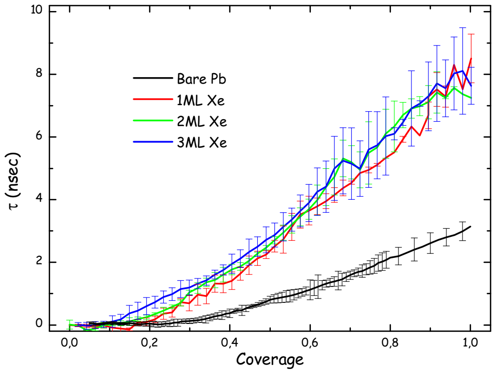
v_{film} $v_{electrode}=0$

$t=\tau_s$

$v_{film}=v_0/e$

$\tau_s = 0$	film locked to the surface
$\tau_s = \infty$	superfluid film
$\tau_s \approx 1 \div 10$ nsec	sliding Kr monolayer

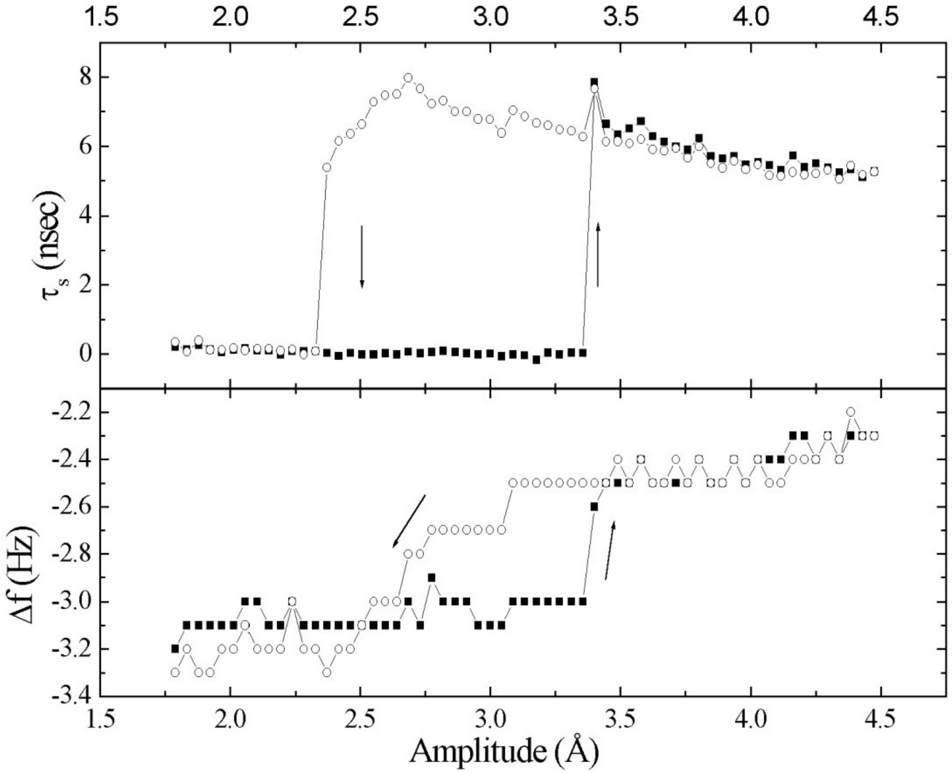
•Results



τ (nsec)
10
8
6
4
2
0
0,0
0,2
0,4
0,6
0,8
1,0
Coverage
Bare Pb
1ML Xe
2ML Xe
3ML Xe

Dynamical depinning

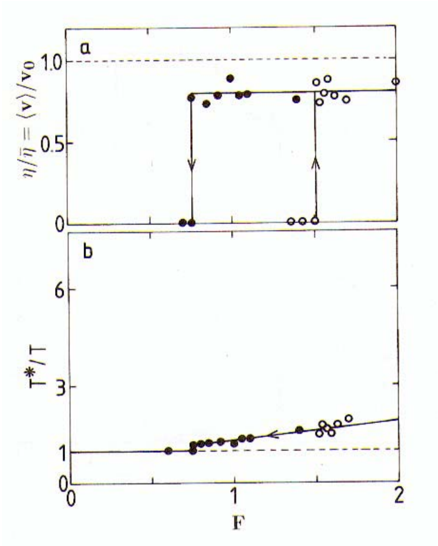
Kr film adsorbed on gold at T = 85K.   Coverage = 0.2 layers



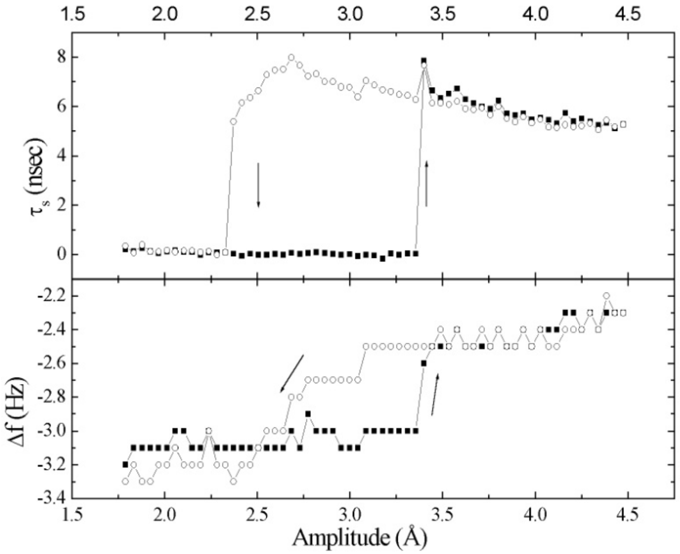
PRL 02

Data indicate dynamical depinning of Kr film
(e.g. static to dynamic friction)

Why is there hysteresis?



Persson '95



PRL '02

Molecular Dynamics simulations of model system Xe/Ag(100)
indicate that hysteresis is due to melting
of the solid adsorbate caused by frictional heating

Structural depinning

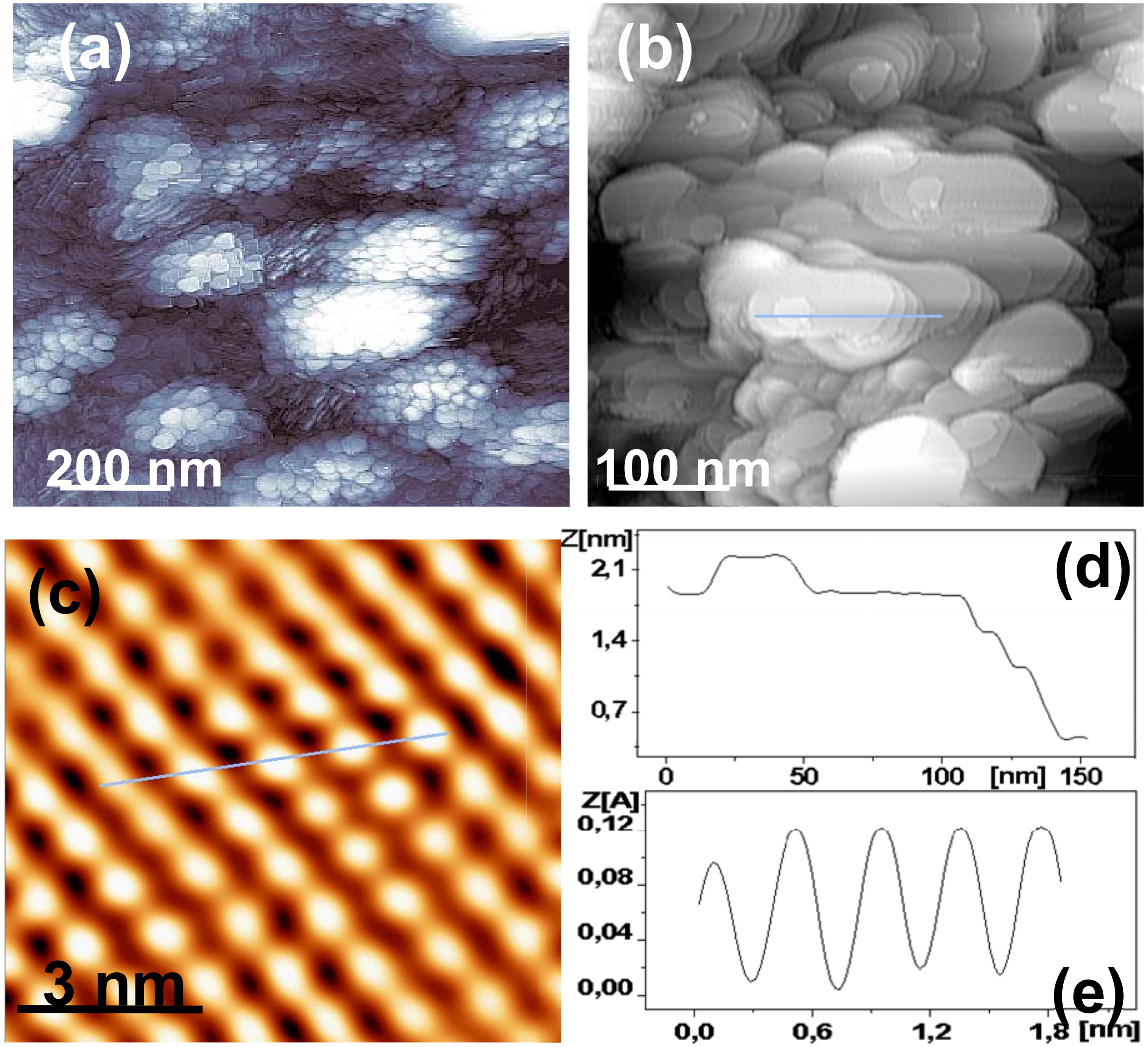
- Substrate: Lead
(“easy” to prepare good quality films even at room temperature / becomes superconducting at 7 K)

- Adsorbate: Rare gases
(very simple interactions /
Ne still “active” at very low temperatures, e.g. <10K)

- measurements done in a UHV chamber and at low T
(reduce surface contamination)

RSI ‘05

Pb deposited on a bare QCM at room T and in UHV

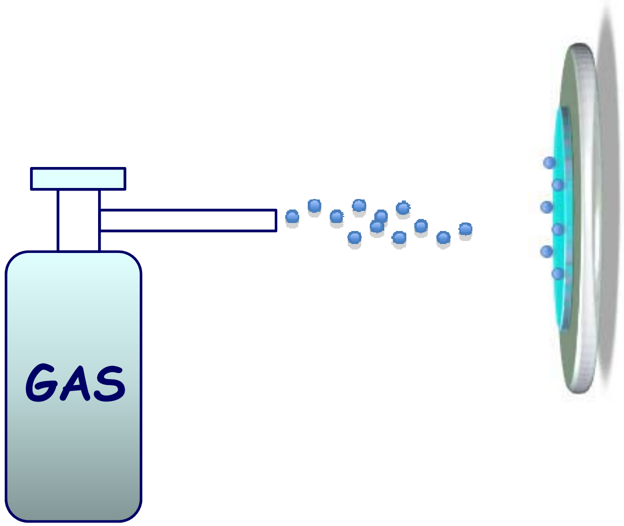


PRL '06

Experimental details

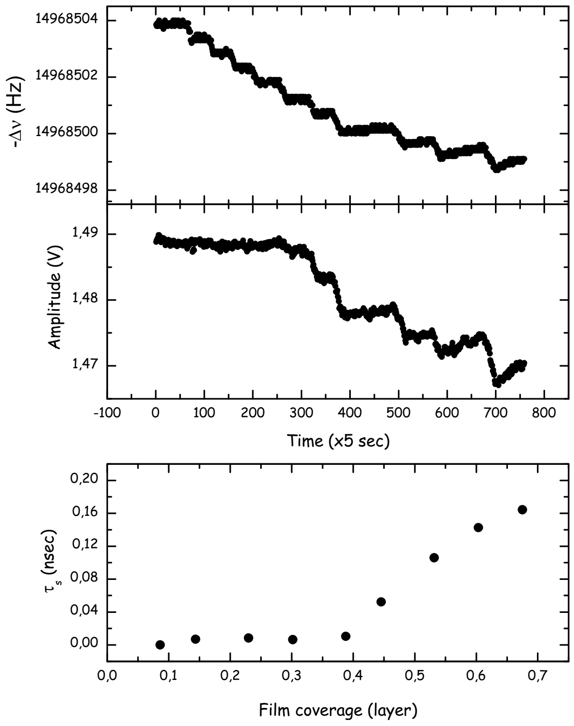
- QCM driven with FM technique
  Frequency stability ±0.1Hz overnight
  Amplitude stability ±0.05%
  Power dissipation < 1 μW

- In-situ deposition of the film at low T
  Deposition time comprised between 15 min and 90 min
  For heavy adsorbates (e.g. Kr, Xe, N_2 deposition followed by post-annealing



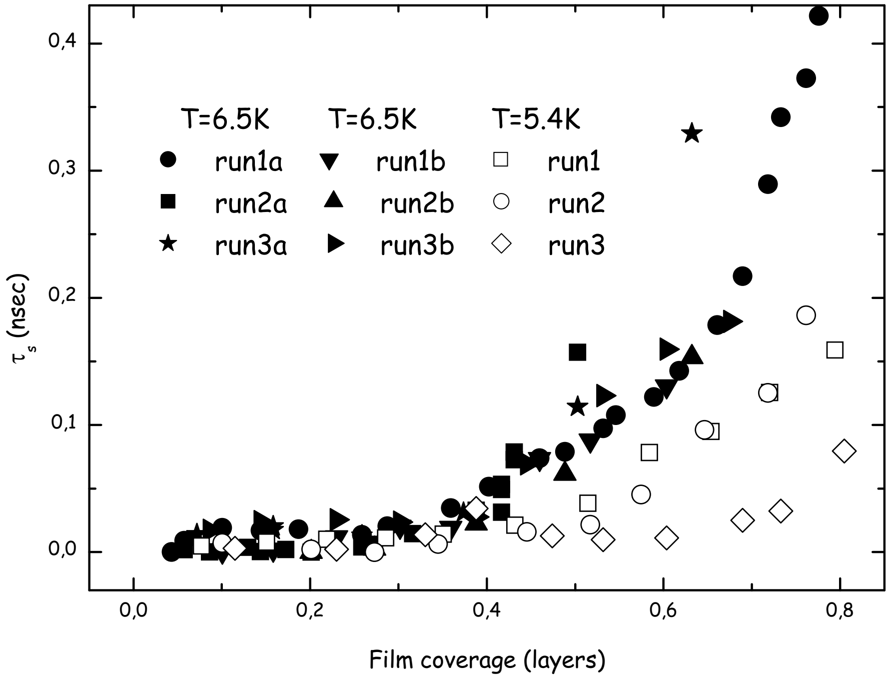
Structural depinning

Coverage scan of Ne on Pb(111) @ 6.5K



PRL '06

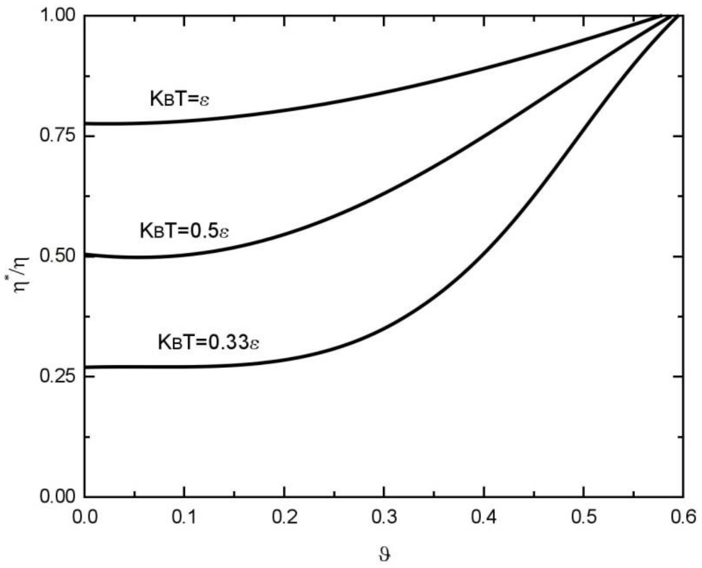
Coverage scans of Ne on Pb(111)

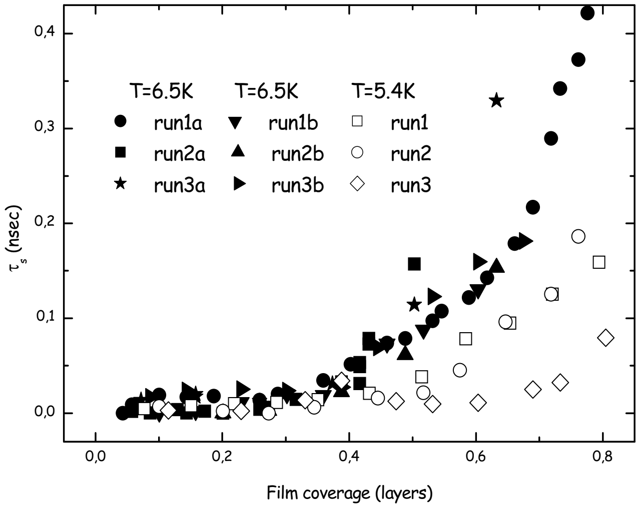


PRL '06

Pinning of the film at low coverages
Depinning onset depens on temperature

Why is there depenning?





Persson's calculations of the slippage of a simple adsorbate on a low-corrugated model surface.
ε is the adatom-adatom well depth
PRB '93, JCP '95

Ne on Pb(111)
Ne-Ne well potential ε=42K
⇒$K_B T=1/7\ \varepsilon$

⇒ Structural depinning of the adsorbed film

Superlubricity

Dry friction assumes very small values when the two crystalline surfaces are incommensurate:
The force coming from the mismatched atoms in the contact area point in all directions and sum up to zero.

Hirano and K. Shinjo, PRB 90

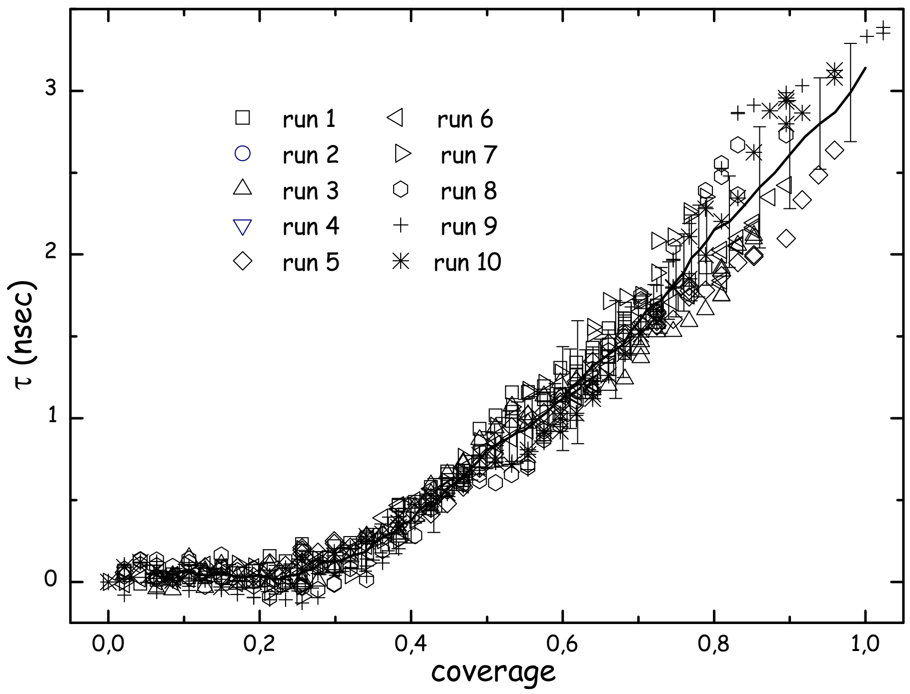
Vanishing friction on a silicon surface was observed with ultra-high vacuum (UHV) scanning tunneling microscopy

Hirano et al., PRL 97

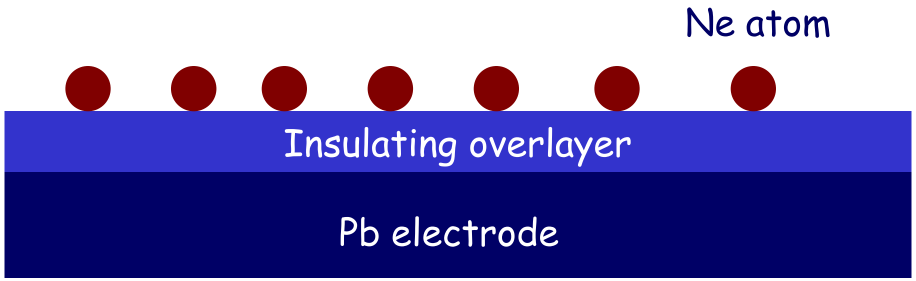
With a very sensitive frictional force microscope it was found that friction between a graphite flake sliding over a HOPG graphite was significantly reduced when the two graphite surfaces are rotated out of the commensurate locking angle.

Dienwiebel et al., PRL 04

Coverage scans Ne on Pb(111) @ 6.5K



Results on plated Pb



In-situ deposition of Kr, Xe overlayers of controlled nominal thickness (1 to 5 ML)

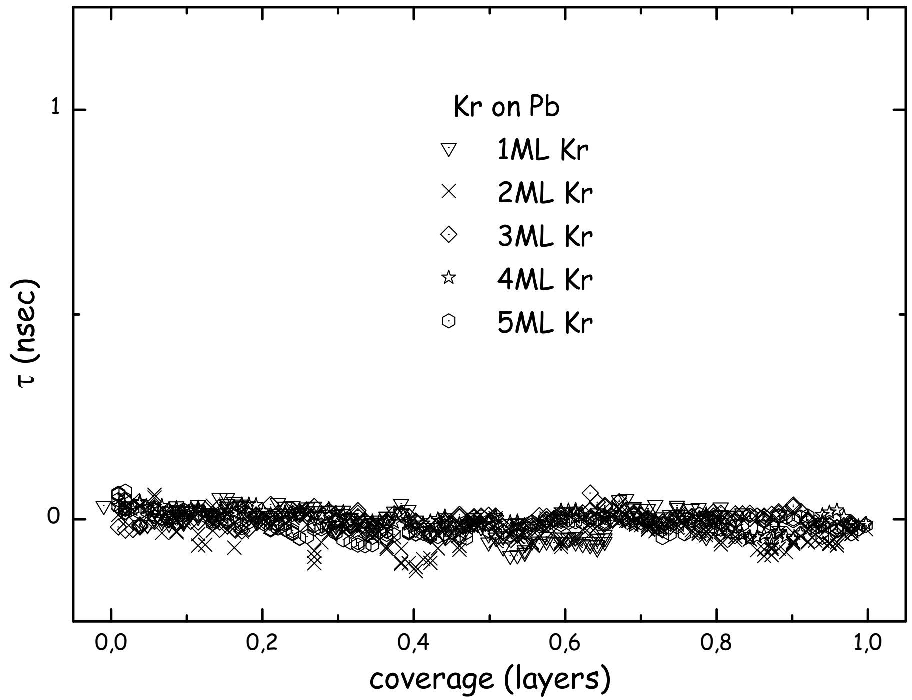
Rare gases can be very pure and are characterized by simple interactions

Heavy rare gases do not slide at low T

J. Phys.: Cond. Matt. '06

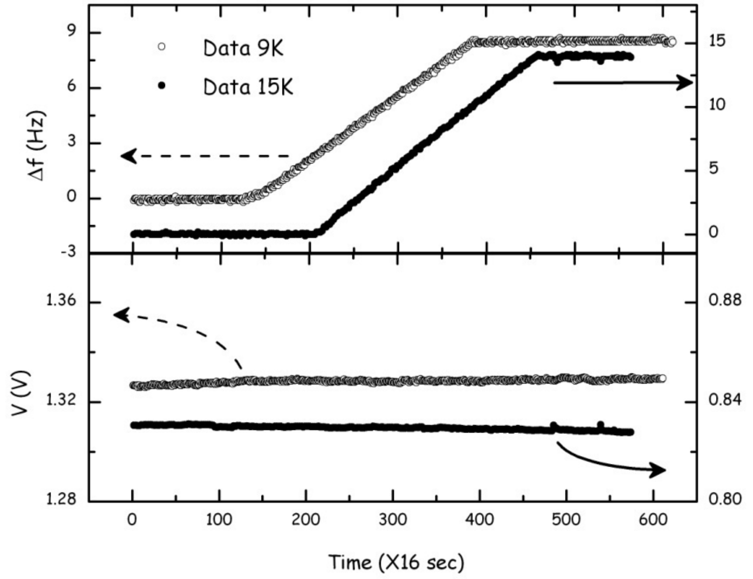
Heavy rare gases do not evaporate at T≤30 K

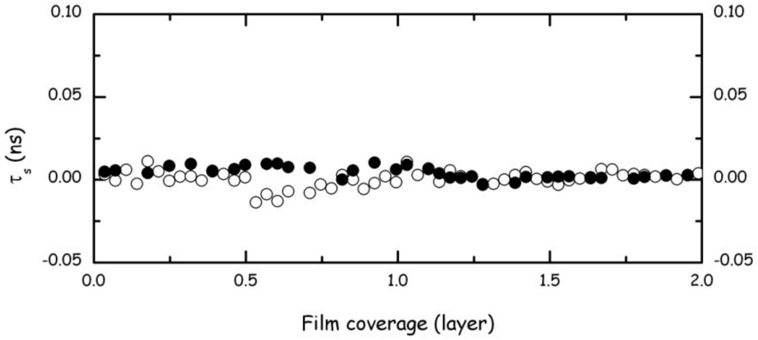
Deposition of Kr overlayers at 6.5 K



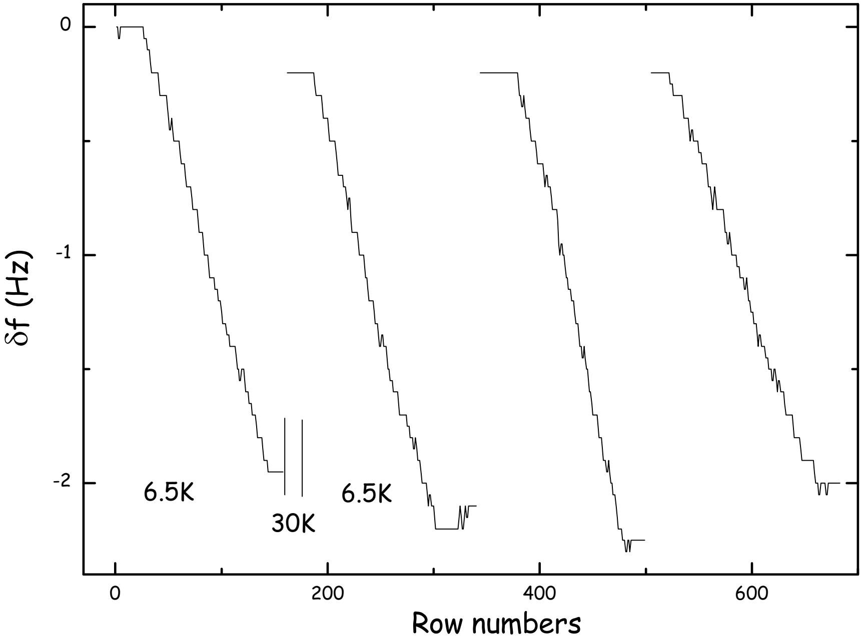
No sliding of Kr on bare Pb and on Kr plated Pb

Deposition of N2 at low T



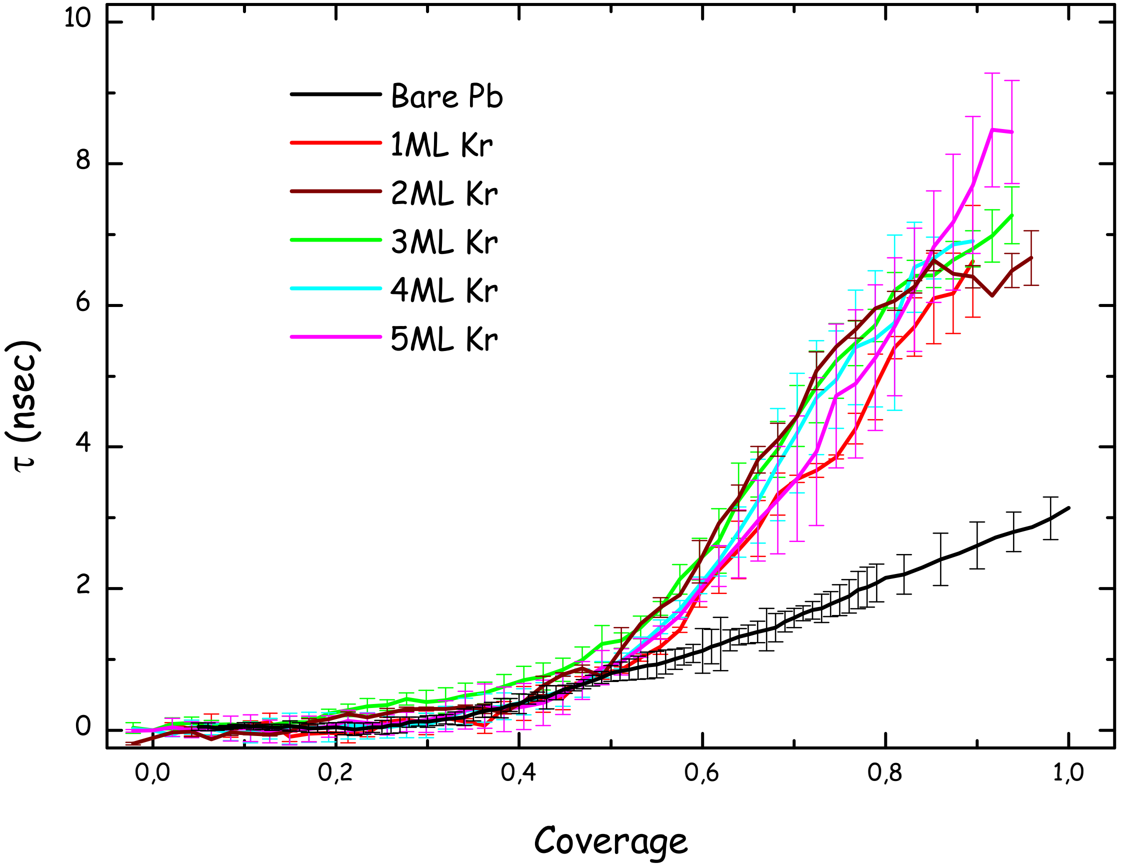


Ne deposition/evaporation cycles on overlayers

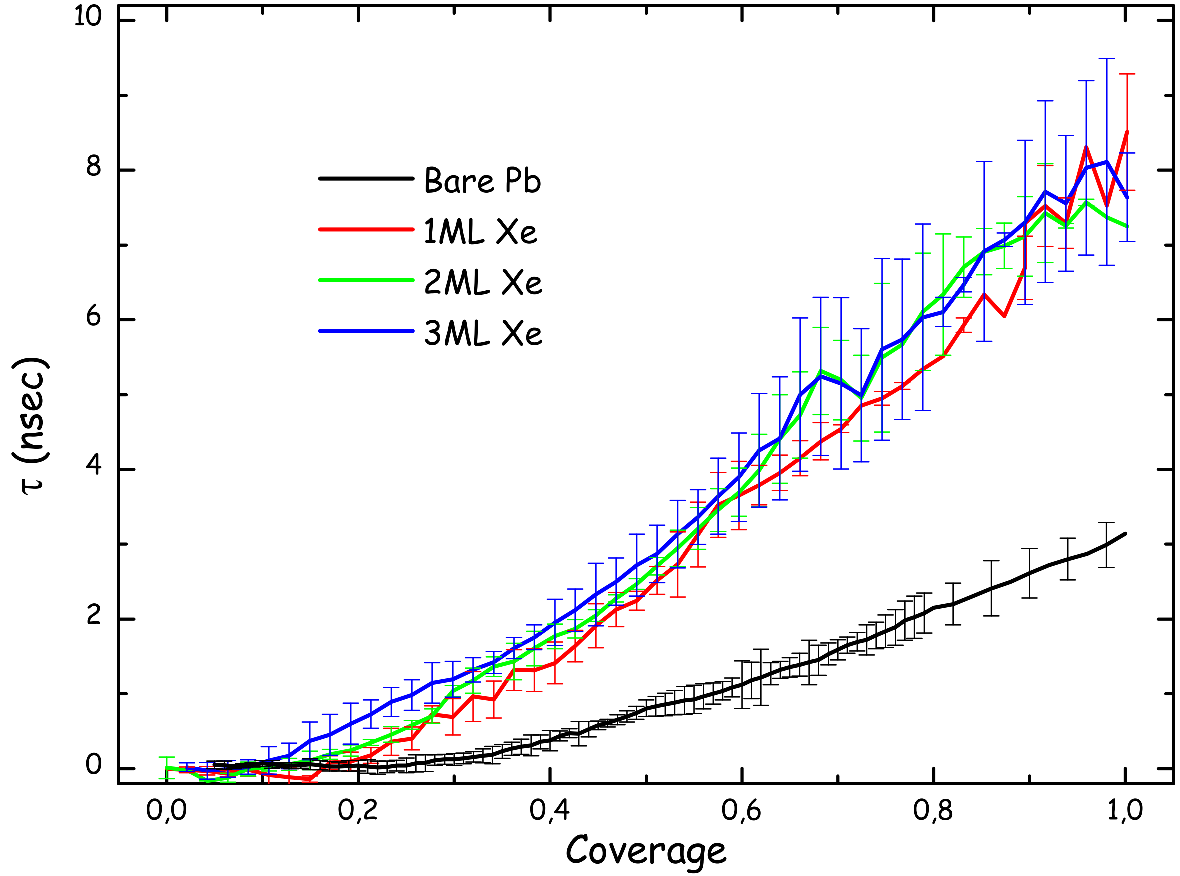


Heavy rare gases do not slide and they do not evaporate at low T
→ They are dynamically "inert"

Coverage scans Ne on Pb plated with Kr overlayers



Coverage scans Ne on Pb plated with Xe overlayers



Partial summary

- Plating Pb with a Kr or Xe overlayer increases slip time by a factor ~3

- This lubrication effect saturates after only 1 monolayer

- Depinning of Ne on Xe seems to occur at lower coverages than on Kr

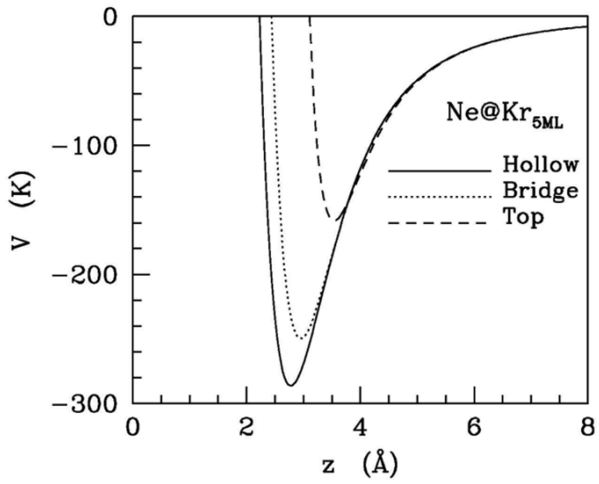
- NB. The heavy rare gas overlayer DOES NOT act as a conventional fluid lubricant:
  the overlayer is dynamically inert

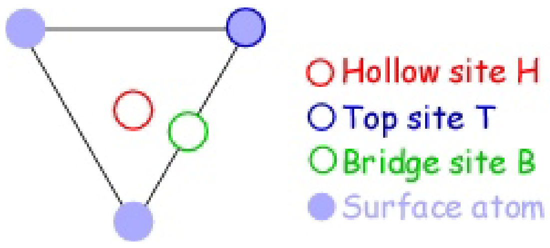
WHY NO DIFFERENCE BETWEEN Kr and Xe?

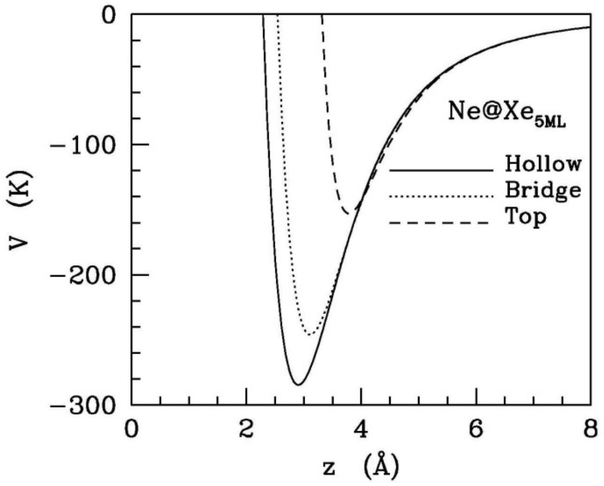
Calculations of Ne potential on Kr (Xe) overlayers of different thickness

$$V(R)=Ae^{-bR}-\sum_{n=3}^{M}\left[1-\sum_{k=0}^{2n}\frac{(bR)^{k}}{k!}exp(-bR)\right]\frac{C_{2n}}{R^{2n}}$$

Tang and Tonnies, Z Phys D 86



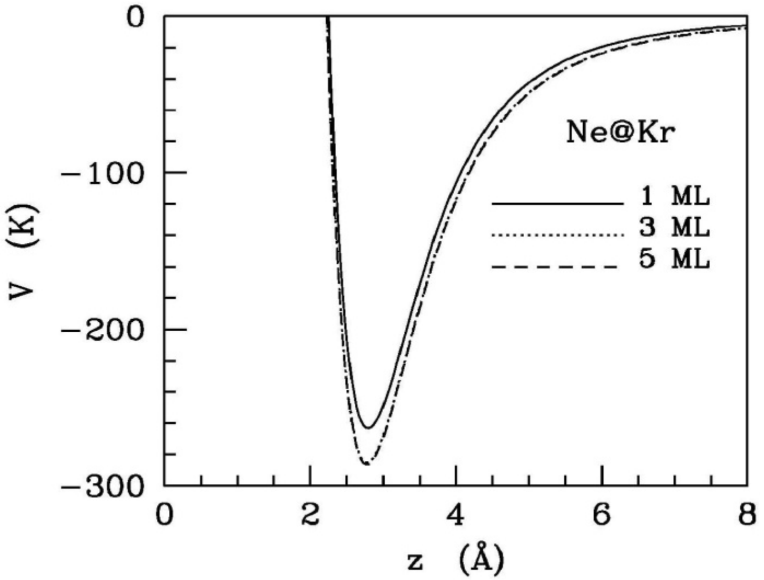




→No major difference between Ne-Kr and Ne-Xe adsorption potentials
OK with experimental data

WHY NO DIFFERENCE WITH Kr (Xe) THICKNESS?

Variation of calculated Ne-Kr potential with Kr overlayer thickness



→No big dependence of adsorption potential with Kr (Xe) thickness
OK with experimental data

WHY INCREASED SLIDING OF Ne ON Kr (Xe)?

- The Kr (Xe) multilayer may lower the surface corrugation potential experienced by the Ne atoms

- Differences in surface potential periodicity between Xe and Kr may be responsible for different depinning onset (?)

- The insulating overlayer may shield the electronic coupling between adsorbate-electrode reducing the electronic contribution (??)

Theoretical modelling and accurate surface potentials are essential for a reliable data interpretation !!!

WHY NO SLIDING OF Ar, Kr, Xe, N_2 FOR T<10K?

- Intrinsic pinning

Sliding of the adsorbate is an activated process.
Barrier energy ~ corrugation amplitude of surface potential.
Corrugation increases with adsorbate polarizability

	Corrugation	Well-depth
Ne/Kr	40K (H-B)	290K
Ne/Xe	40K (H-B)	290K
Ar/Cu(111)	45K (T-H) [1]	
Kr/Cu(111)	73K (T-H) [1]	
Xe/Cu(111)	98K (T-H) [1]	3000K [1]
Ne/Pd(111)	8K ([2]	220K [2]
Kr/Pd(111)	87K ([2]	2050K [2]
Xe/Pd(111)	116K [2]	3700K [3]

1. Righi and Ferraro, J Phys 07 2. DaSilva and Stampfl, PRB 08 3. Wandelt and Hulse, JCP 86

WHY NO SLIDING OF Ar, Kr, Xe, N_2 FOR T<10K?

- Extrinsic pinning

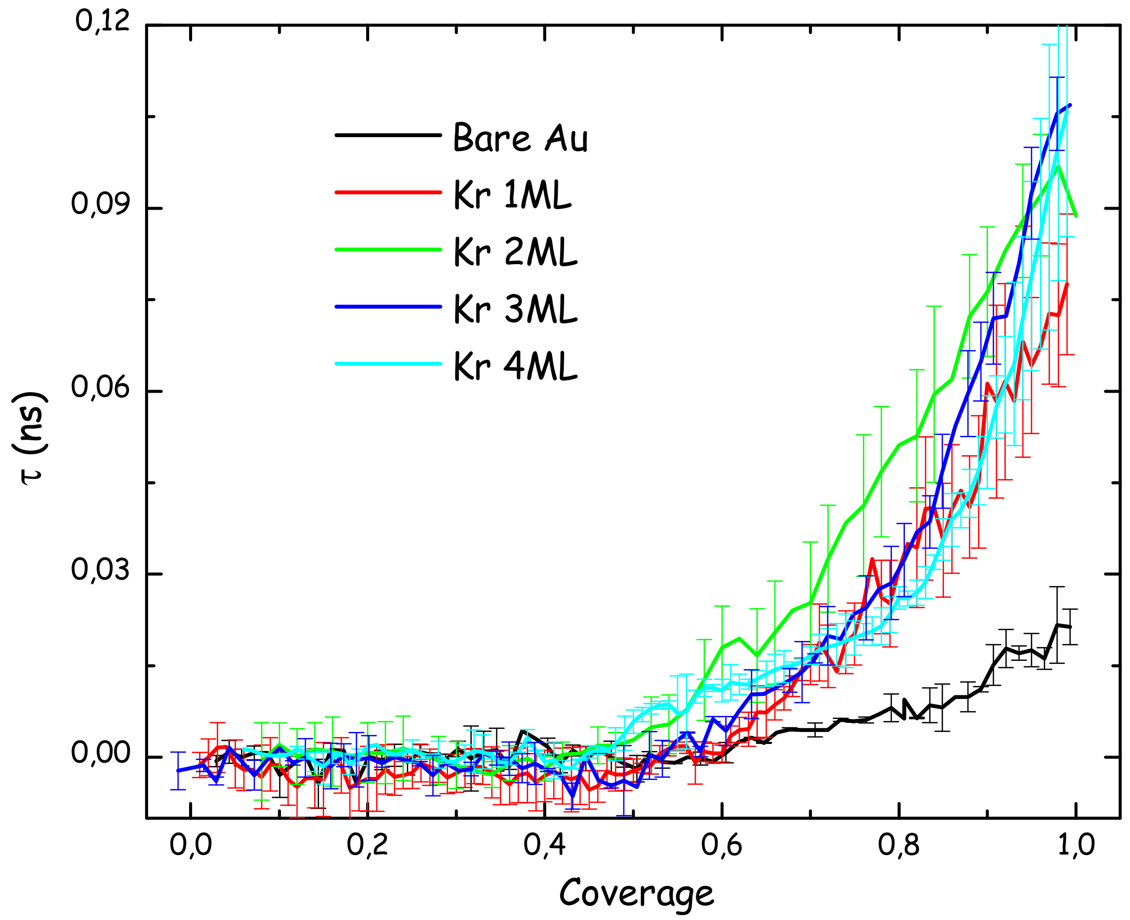
Electrode surface is defective (steps, missing atoms, chemical impurities…)
Low temperature will enhance binding of adsorbate at such defects

N_2 films deposited on Pb are highly susceptible to become pinned at low T
Highland and Krim, PRL 06

Static friction of N_2 films deposited on Pb for T<30K
Barigazzi et al., J. Phys. 07

Further studies are required to clarify the relative importance of intrinsic to extrinsic pinning of heavy adsorbates on metal surfaces at low T

Coverage scans Ne on Au(111) plated with Kr overlayers



CONCLUSIONS

- We have studied the sliding friction of Ne monolayers with a QCM technique

- Results are suggestive of a structural depinning of the Ne film

- Measurements on composite substrates indicate a significant increase of Ne slippage on metal films plated with ≥1 ML of Kr or Xe

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