National Synchrotron Light Source II

X-ray Photoelectron Spectroscopy (XPS)

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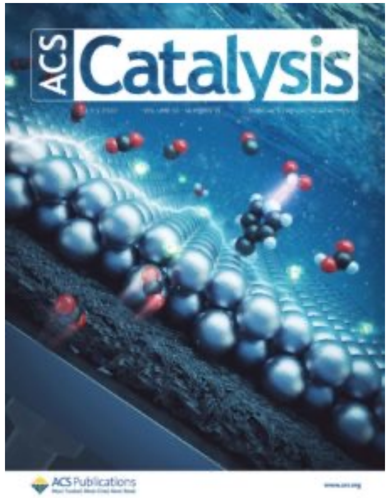
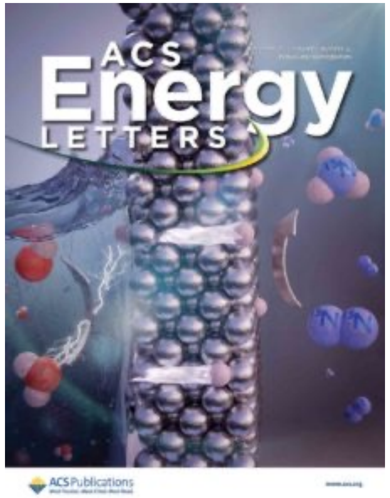
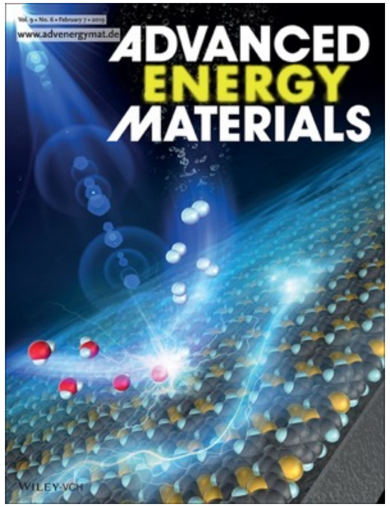
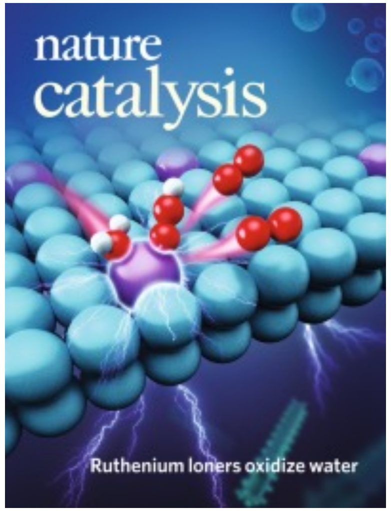
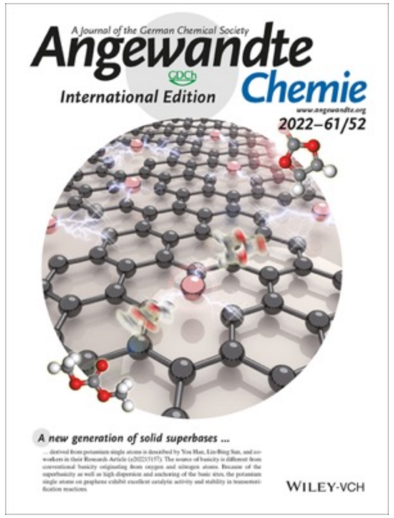


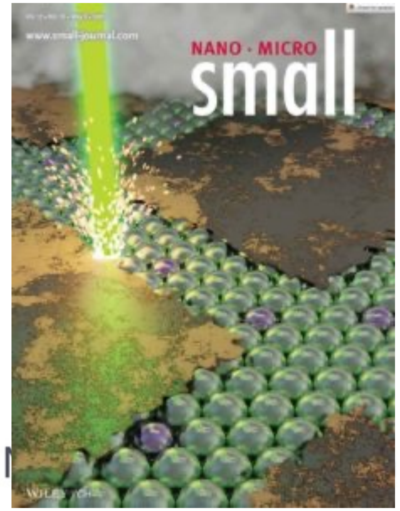








X-ray photoelectron spectroscopy (XPS) was featured in all of these research



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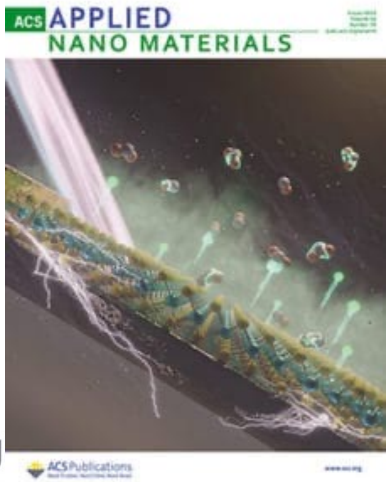
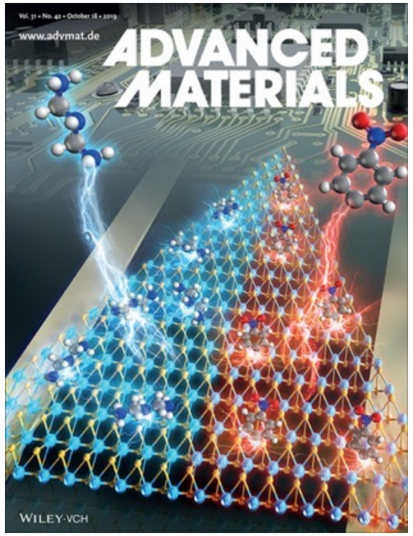
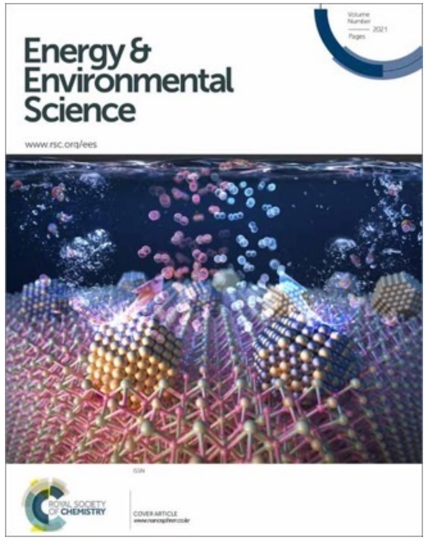
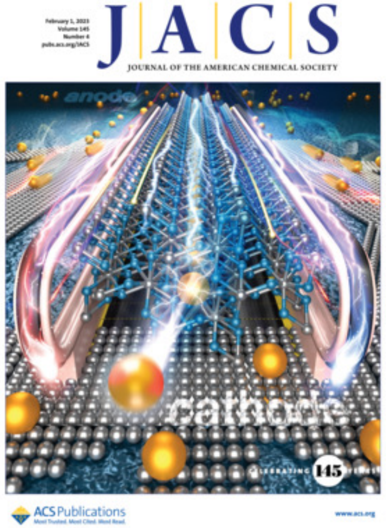
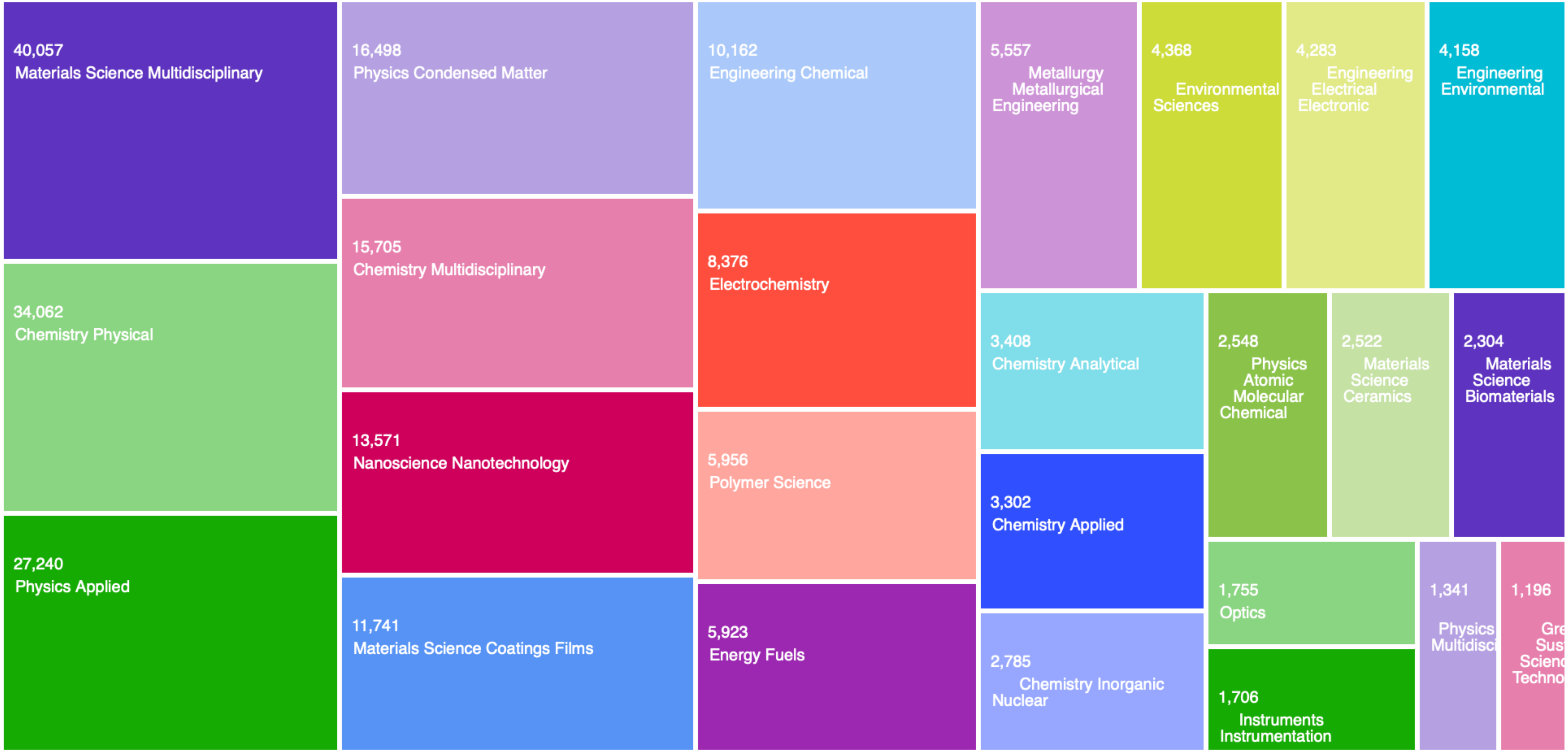






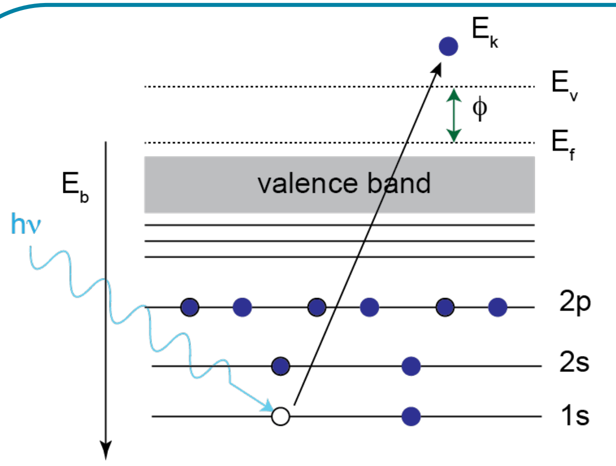


XPS is a powerful and versatile technique for studying the chemical and electronic state of surfaces as well as understanding phenomena and processes occurring on surfaces



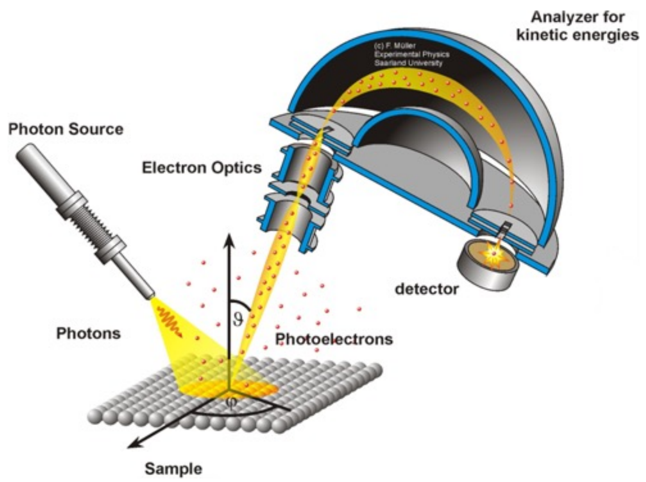
Webofscience.com search result from 2003-2023

What will you learn today?

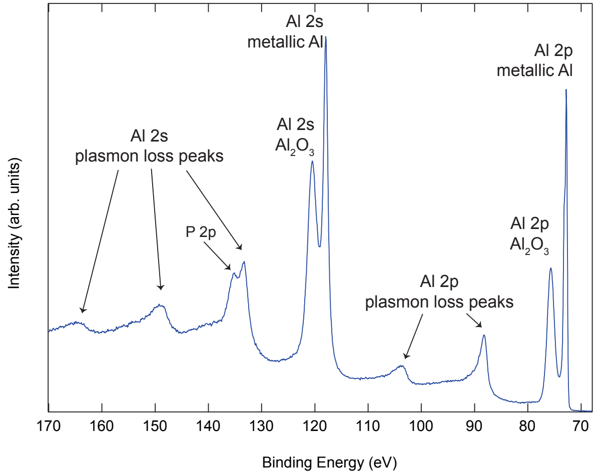


$$E_k = h\nu - E_b - \phi$$

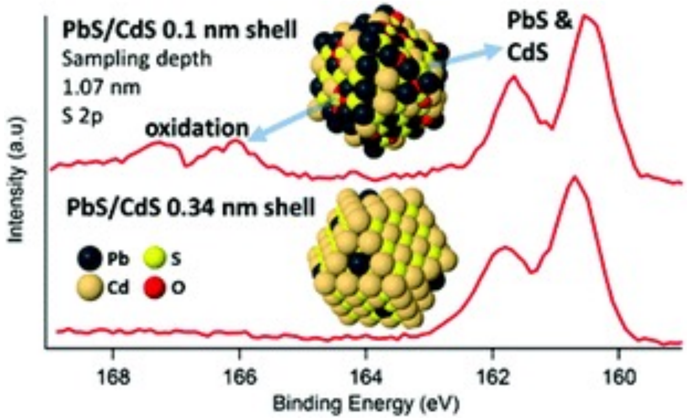
Fundamental principles of XPS



Basic instrumentation and experimental planning



How to interpret XPS data



Recent research examples

Part 1

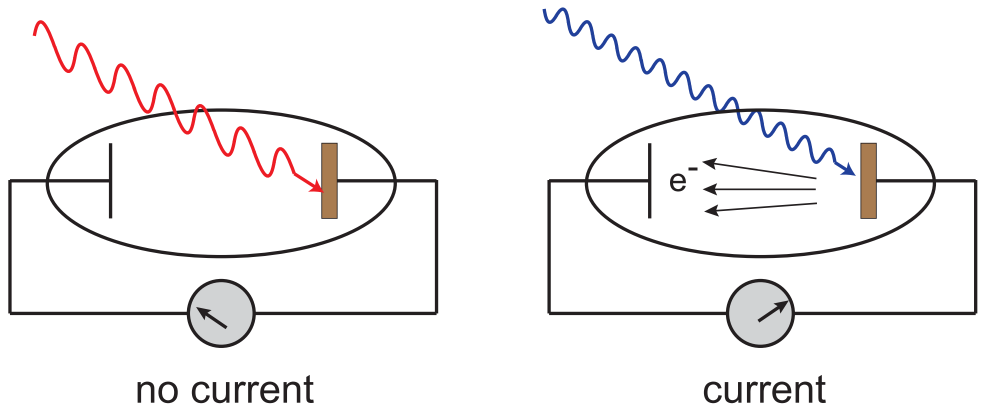
Basic Principles of XPS and Instrumentation

A little history: From the photoelectric effect…

1887 – Heinrich Hertz observed sparks when UV light hits metal electrodes.

1899 – J. J. Thomson discovered that UV light causes particles to be emitted. The particles were the same as the ones found in cathode rays (i.e. electrons).

1902 – Philipp Lenard found that the energy of the emitted electrons depend on the color (i.e. frequency) of the light, not intensity.



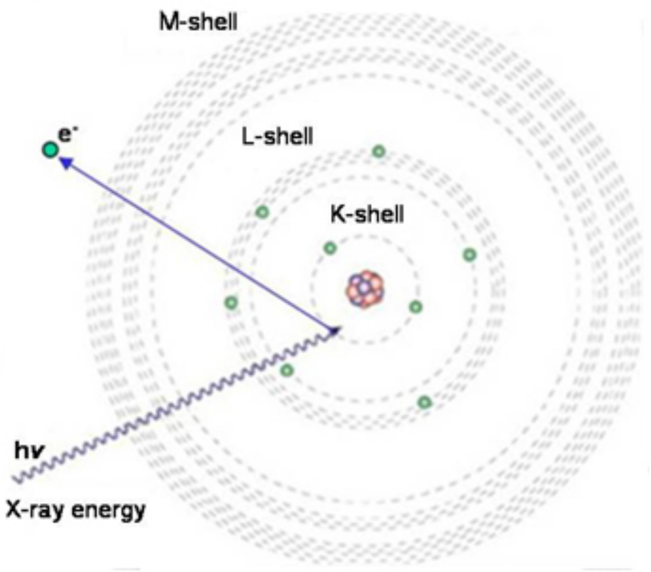
1905 – Albert Einstein explained this phenomenon. Light is composed of discrete packets of energy called “quanta” (later ”photons”) – Nobel Prize in Physics (1921).

…to Modern XPS

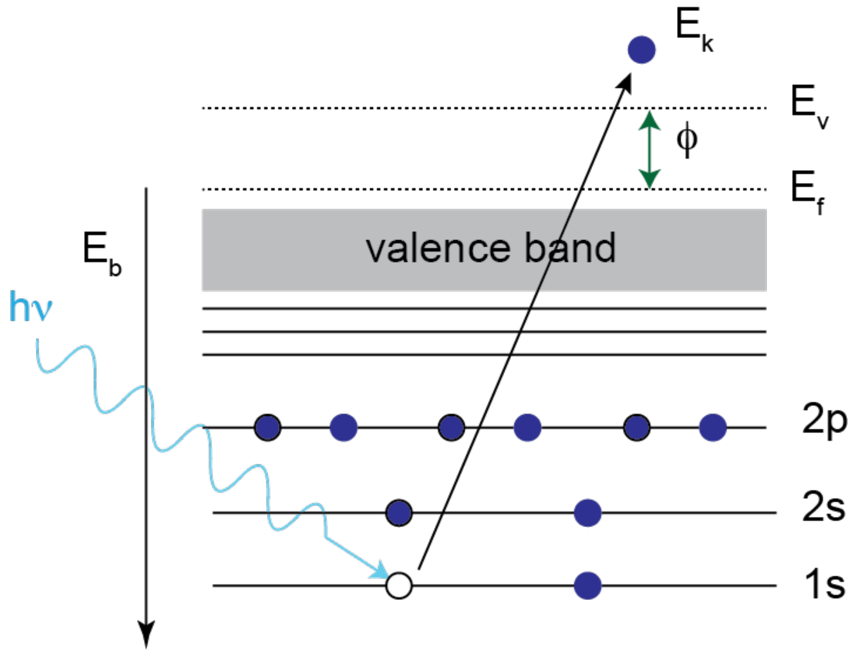
- Kai Siegbahn developed an instrument for analyzing emitted photoelectrons and used it for chemical analysis
- The technique was called Electron Spectroscopy for Chemical Analysis (ESCA)
- Awarded Nobel Prize in Physics in 1981

https://www.nobelprize.org/prizes/physics/1981/siegbahn/facts/
http://dx.doi.org/10.1016/j.nima.2018.03.018

Basic Principle of XPS



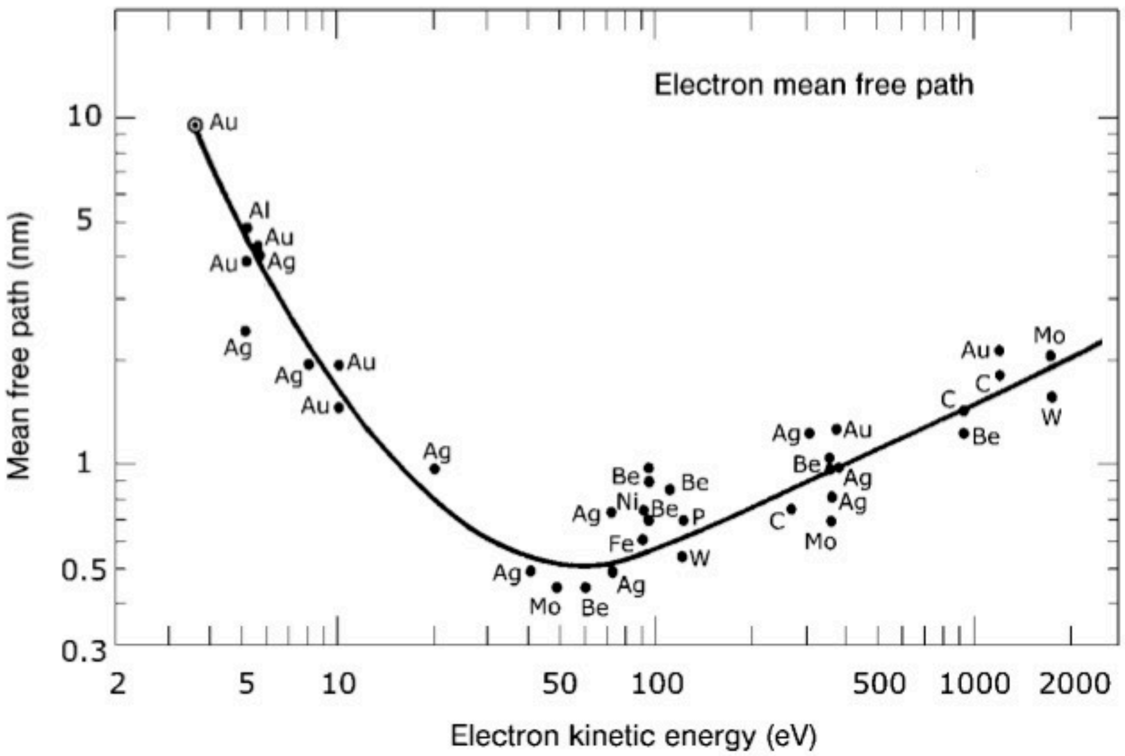
https://www-ssrl.slac.stanford.edu/nilssongroup/corelevel.html



$$E_k = h\nu - E_b - \phi$$

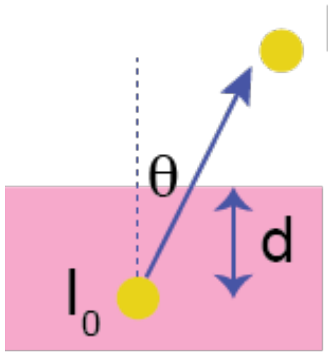
- X-ray photon ionizes an atom and causes the emission of a photoelectron.
- Kinetic energy of the photoelectrons depends on:
  - ➢ Energy of the incident X-ray photons
  - ➢ Binding energy of the electron
  - ➢ Work function of the sample (in practice we use the work function of the spectrometer)

Why is XPS Surface Sensitive?



- Inelastic mean free path (IMFP): how far can an electron travel before losing energy
- IMFP depends on electron energy and density of the material
- The “Universal Curve” shows the typical IMFP for electrons in a solid
- Typical IMFP (λ) is 5-20 Å for soft X-ray excitation

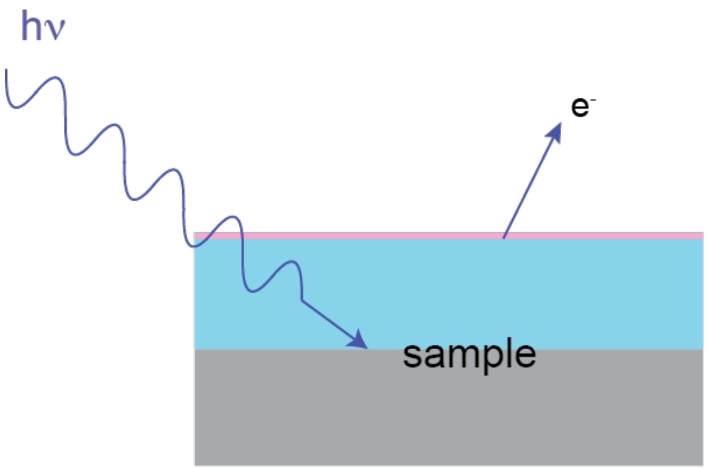
Sampling Depth



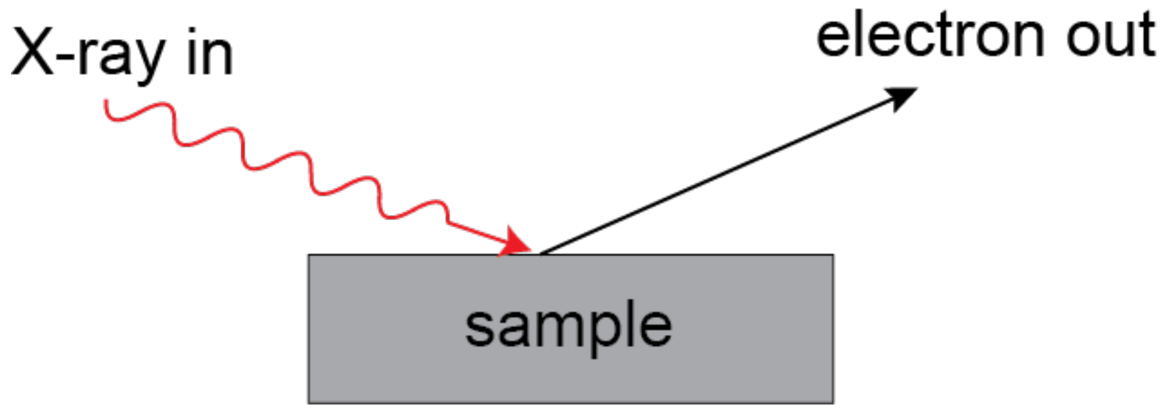
$$I = I_0 e^{-d/\lambda \cos\theta}$$

- Assuming normal takeoff angle ($\theta = 0$, cos θ = 1)
- For $d = 3\lambda$, $I = \sim 0.05\ I_0$
- This means 95% of electrons come from depth of 3λ
- Typical sampling depth = 1-5 nm

- Photons have greater penetration depth than electrons
- Photons: 100's nm for soft X-ray (<2000 eV)
- But you can only get electrons from the first top 1-5 nm
- This makes XPS highly surface sensitive



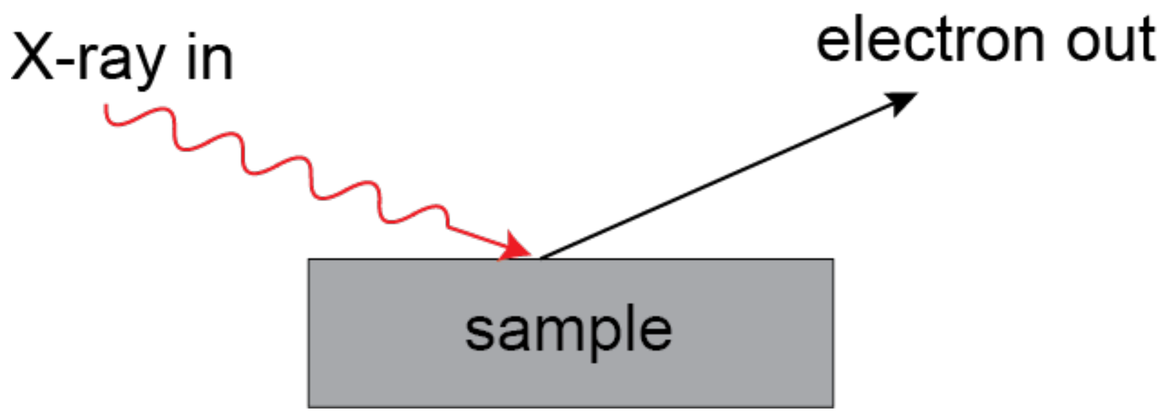
Basic Instrumentation



Three basic requirements:

1. We need an X-ray source
2. We need to be able to detect the electrons
3. We need the appropriate experimental environment

Basic Instrumentation



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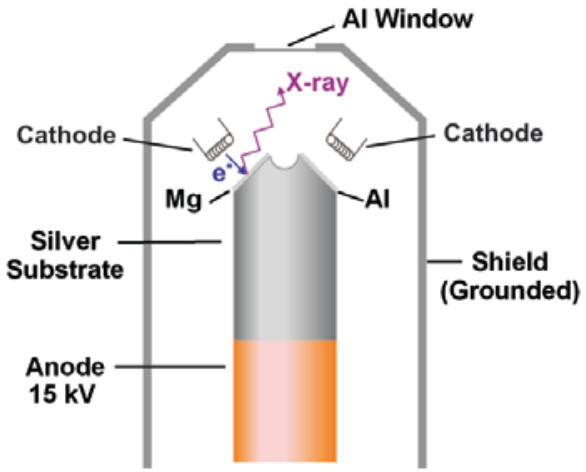
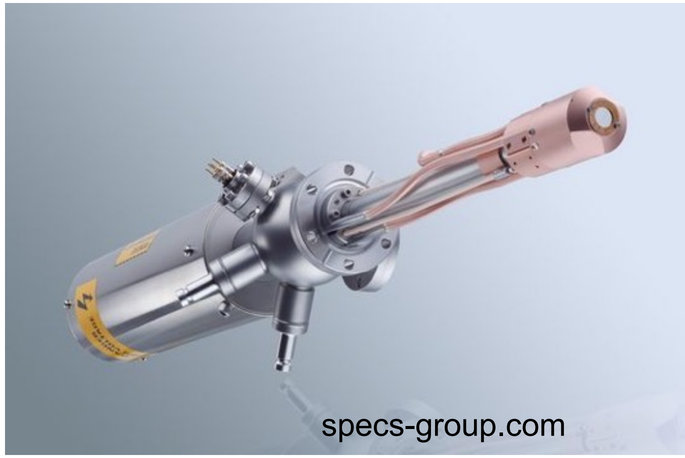
X-ray Source – X-ray anode (“lab source”)



thermofisher.com



ANODE	RADIATION	ENERGY (EV)	LINE WIDTH (EV)
Mg	Kα	1253.6	0.7
Al	Kα	1486.8	0.85
Zr	Lα	2042.4	1.6
Ag	Lα	2984.3	2.6

thermofisher.com

Pros:

- Cheaper than building a synchrotron
- Commonly available in research labs and shared university facilities

Cons:

- Fixed energy - various consequences
- Lower flux
- Poorer resolution

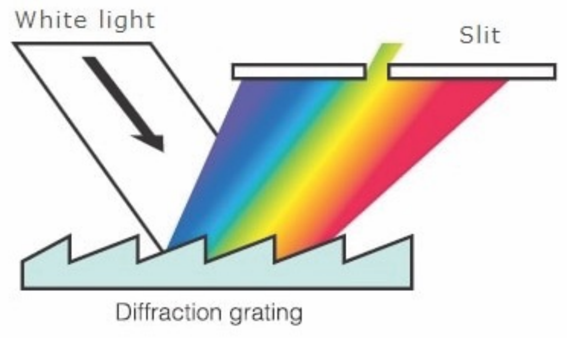
X-ray Source - Synchrotron

Pros:

- Tunable energy, usually 100-2000 eV for soft XPS, 2000-6000 eV for HAXPES
- Higher flux
- Higher resolution
- Beamtime is free

Cons:

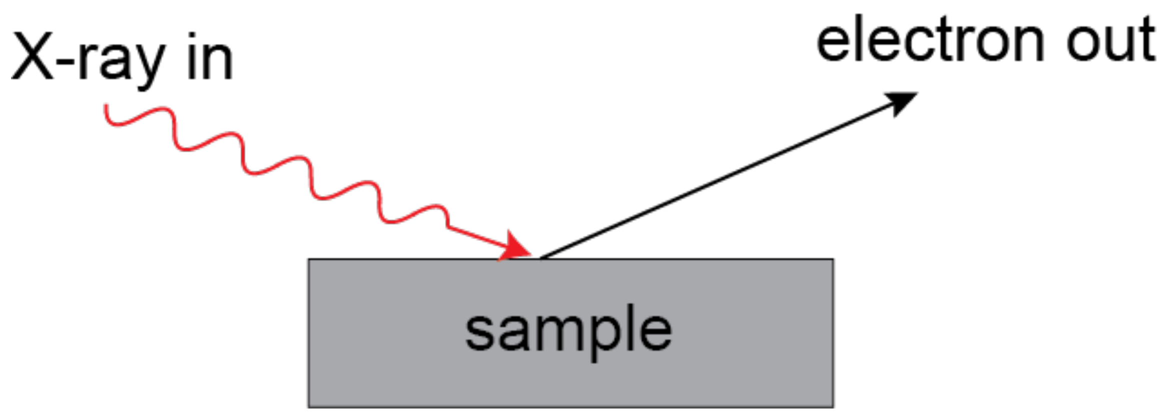
- Not too many facilities available
- Beamtime can be competitive (you need to do good science!)



shimadzu.com

National Synchrotron Light Source II

Basic Instrumentation



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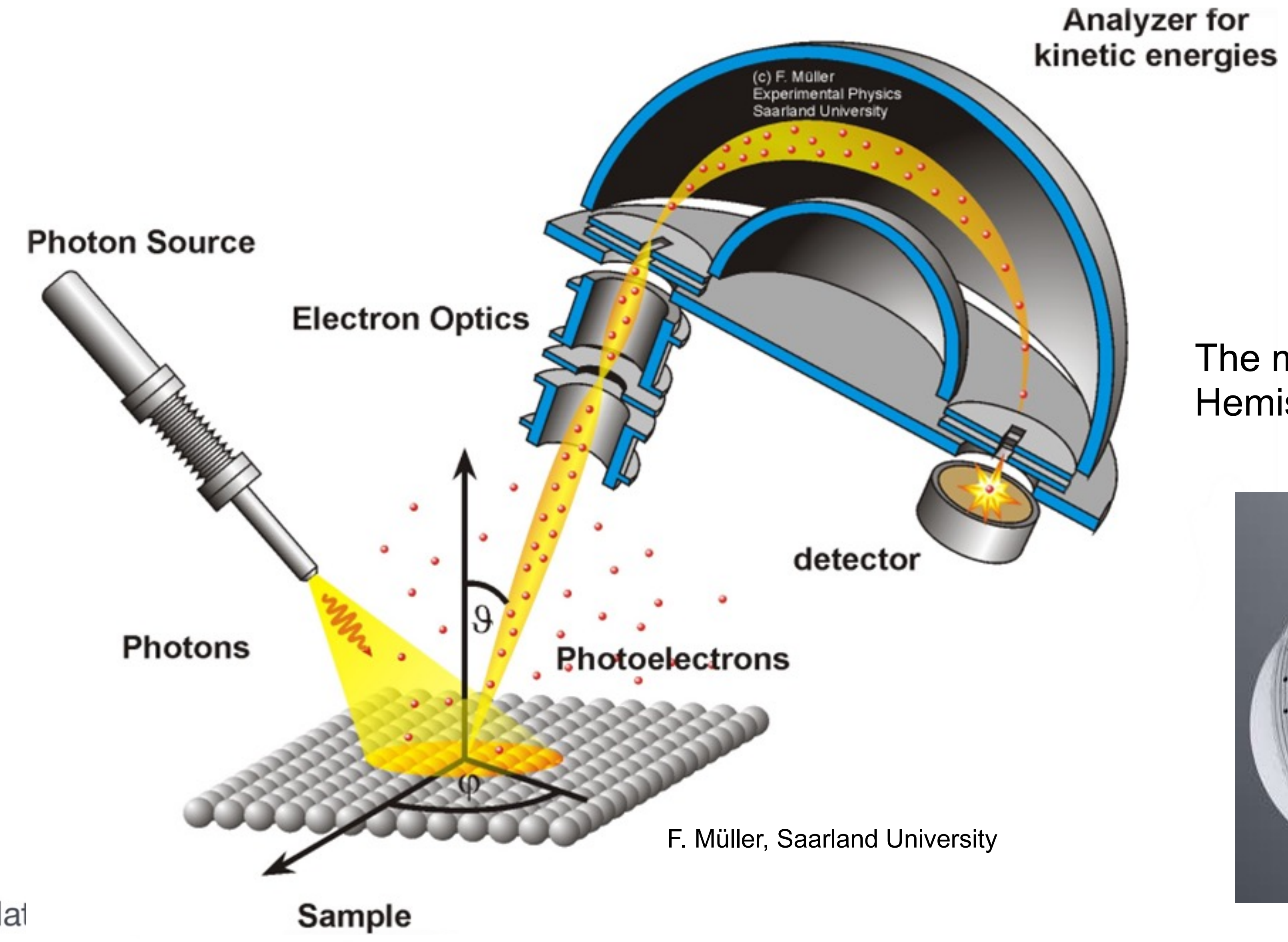
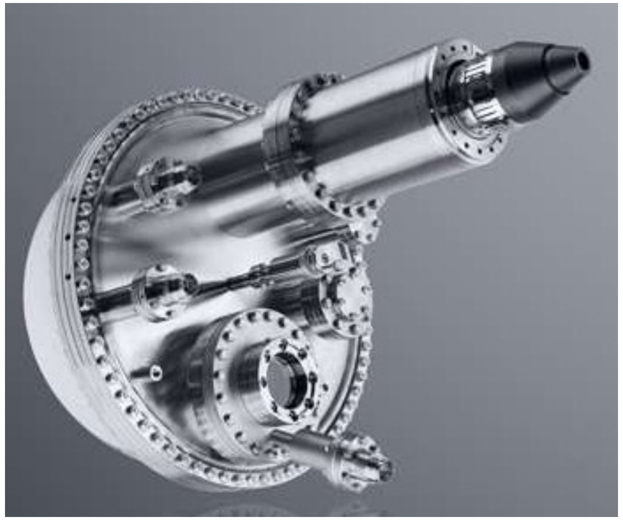
Detecting Electrons



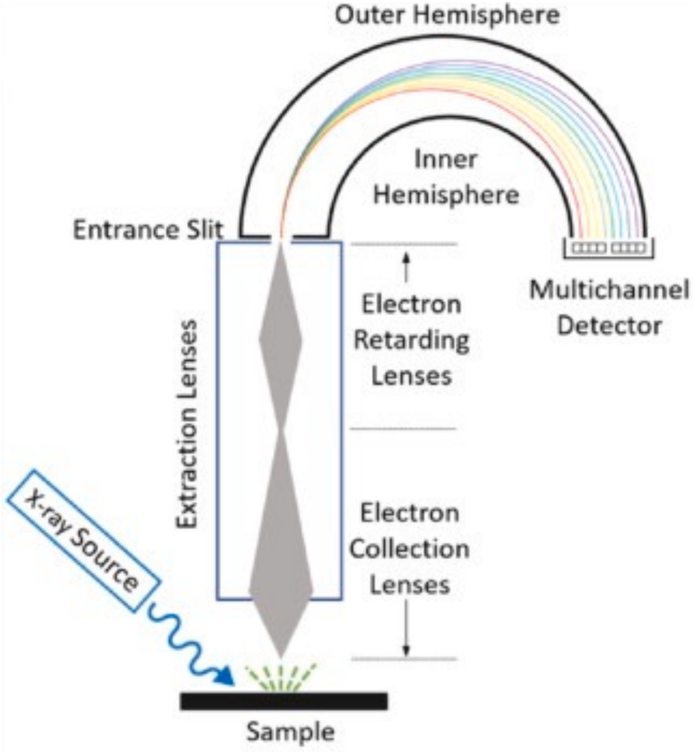
F. Müller, Saarland University

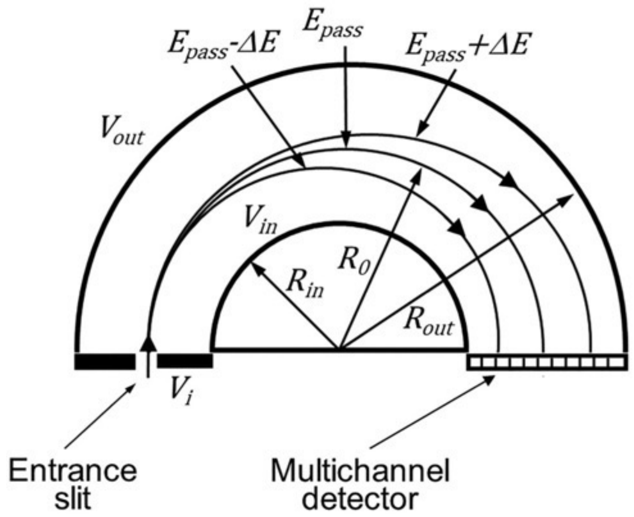
The most common electron spectrometer:
Hemispherical electron analyzer



www.specs-group.com

Hemispherical Electron Analyzer





$$\Delta E = E_0\left(\frac{W}{2R} + \frac{\alpha^2}{2}\right)$$

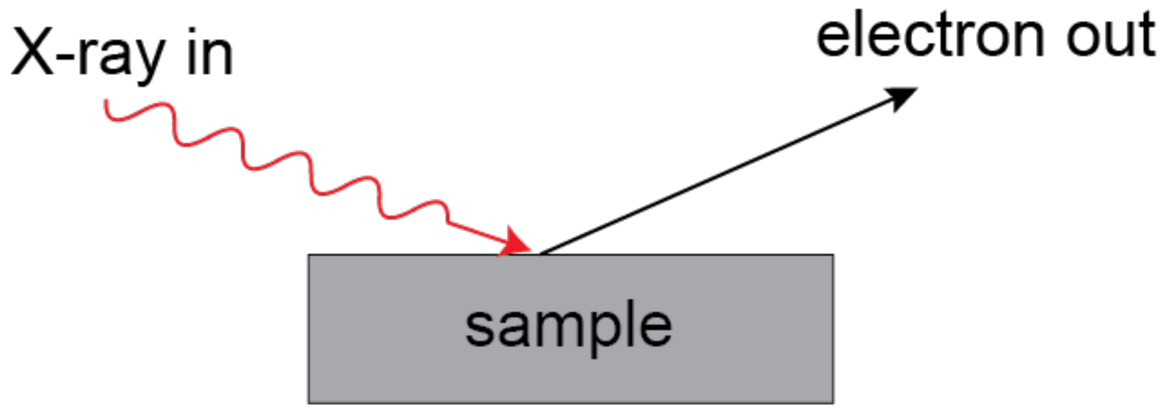
ΔE = energy resolution
E_0 = electron energy
W = slit width
R = mean radius
α = acceptance angle

- Electrostatic lenses focus electron to the detector
- Electron kinetic energy is adjusted to the same pass energy (E_p)
- To improve resolution, you need to:
  - Use lower pass energy
  - Decrease slit width

$$\Delta E = E_p\left(\frac{W}{2R} + \frac{\alpha^2}{2}\right)$$

Greczynski and Hultman, J. Appl. Phys. 132, 011101 (2022)
Stevie and Donley, J. Vac. Sci. Technol. A 38, 063204 (2020)

Basic Instrumentation



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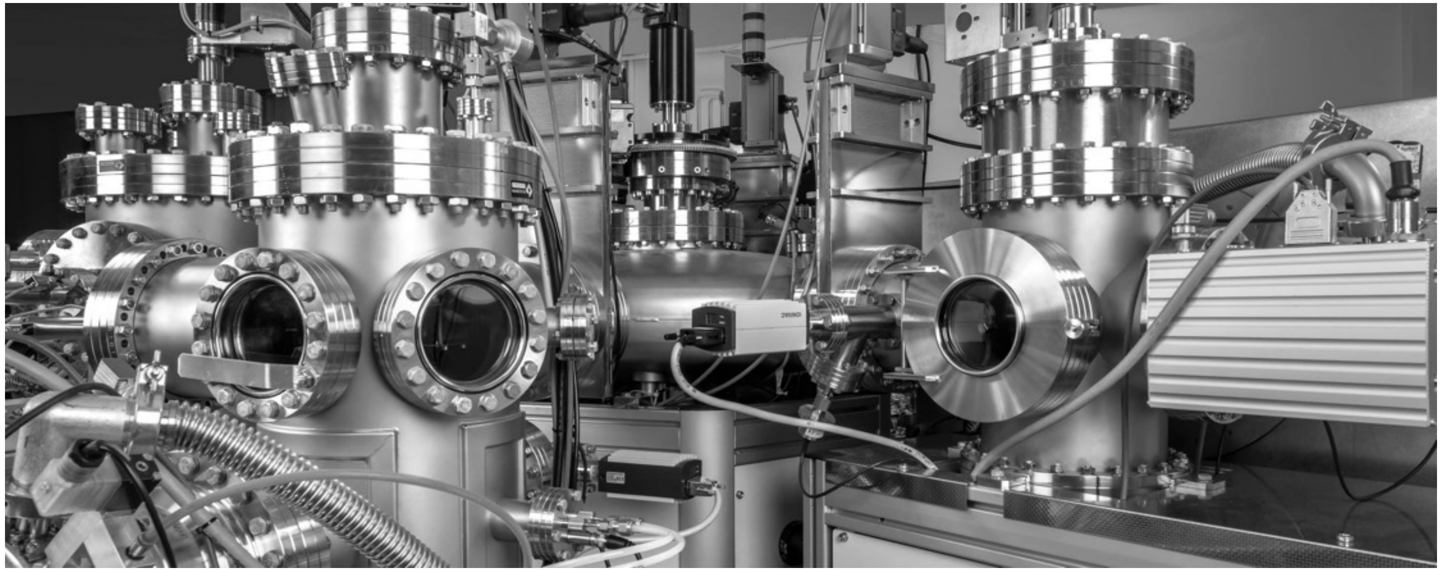
Sample Environment

- Electrons can't travel very far in a gas environment (short mean free path)
- A 200 eV electron can only travel 1 mm in 1 Torr gas (atmospheric pressure is 760 Torr)
- Need to minimize collision between electrons and gas molecules
- XPS needs ultra-high vacuum chamber (10^{-8}-10^{-10} Torr)
- Sample surface also needs to be kept clean from surface contamination

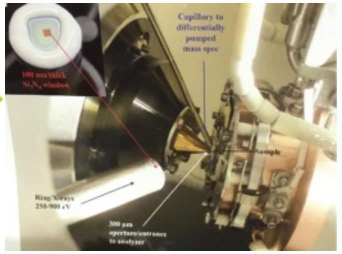


vacgen.com

Ambient Pressure XPS

XPS needs vacuum, but vacuum is not real life!

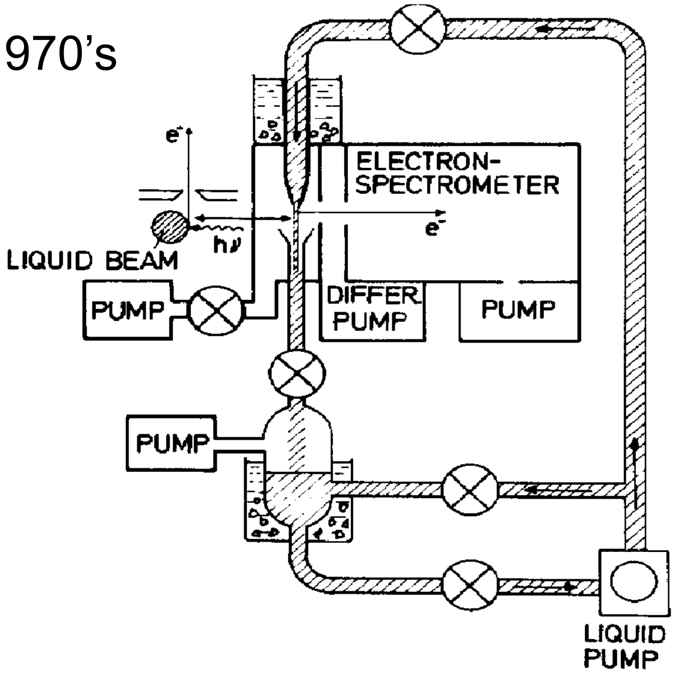
UHV surface science (<10^{-9} Torr)



Ambient pressure XPS

Industry (> 760 Torr)

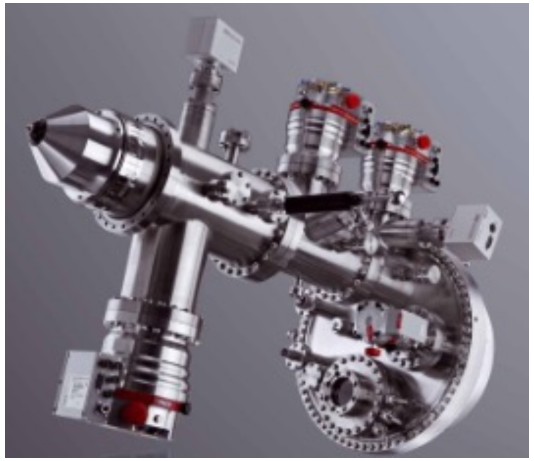
The first AP-XPS instrument was built by Kai Siegbahn's group in the 1970's
(H. Siegbahn and K. Siegbahn, J. Electron. Spectrosc. Relat. Phenom. 2, 319 (1973))



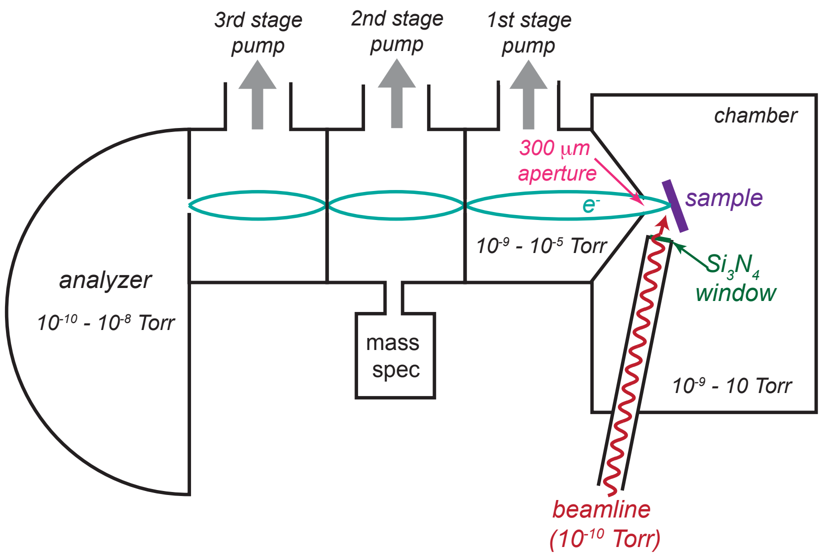
Applications in:

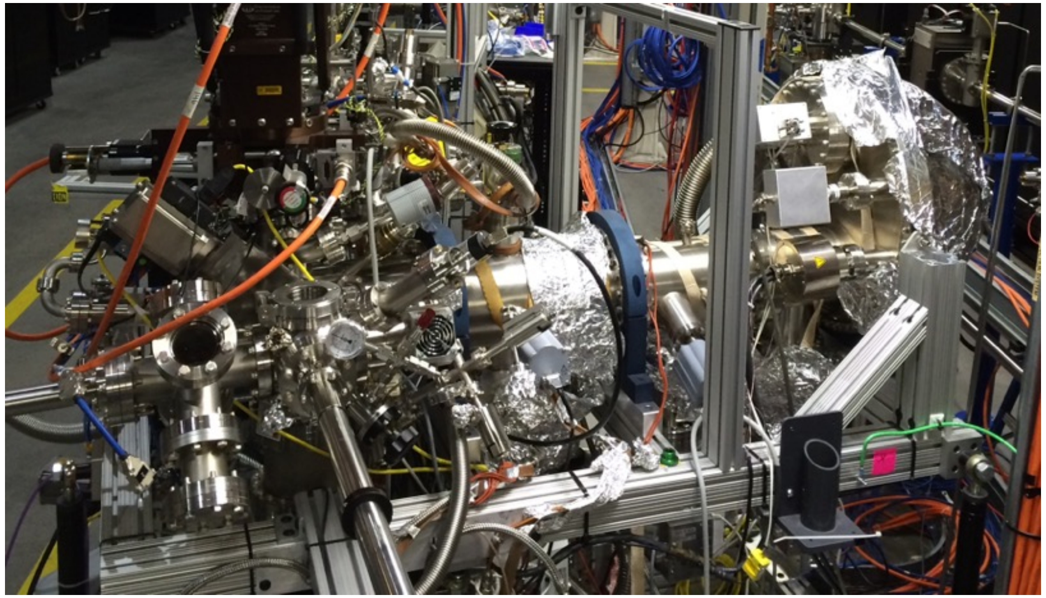
- Heterogeneous catalysis
- Electrochemistry
- Energy storage
- Corrosion science
- Quantum information science
- Environmental science
- Atmospheric chemistry
- and many more…

AP-XPS Instrumentation



SPECS Phoibos 150 NAP
specs-group.com

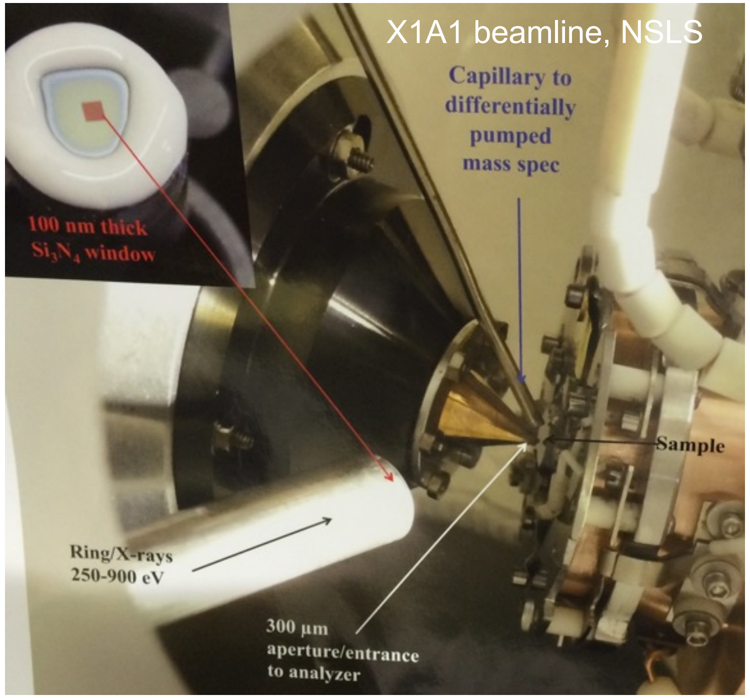


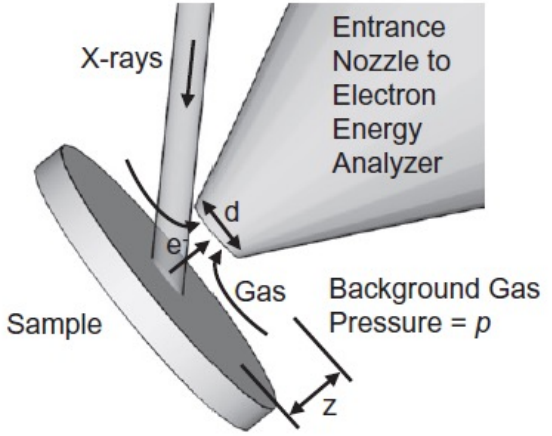


AP-XPS endstation at IOS beamline, NSLS-II

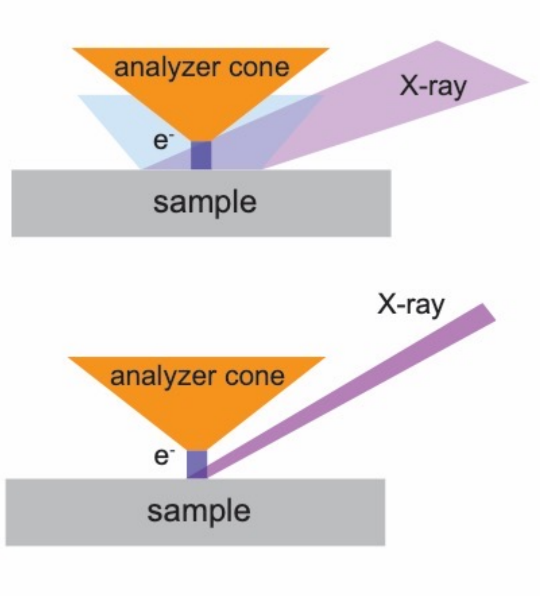
- By differentially pumping the electron analyzer, the pressure in the chamber can be raised while maintaining UHV in the analyzer
- Electrostatic focusing lenses needed to focus electrons to the analyzer

AP-XPS Experimental Setup





Starr et al. DOI:10.1002/9781118355923.ch12

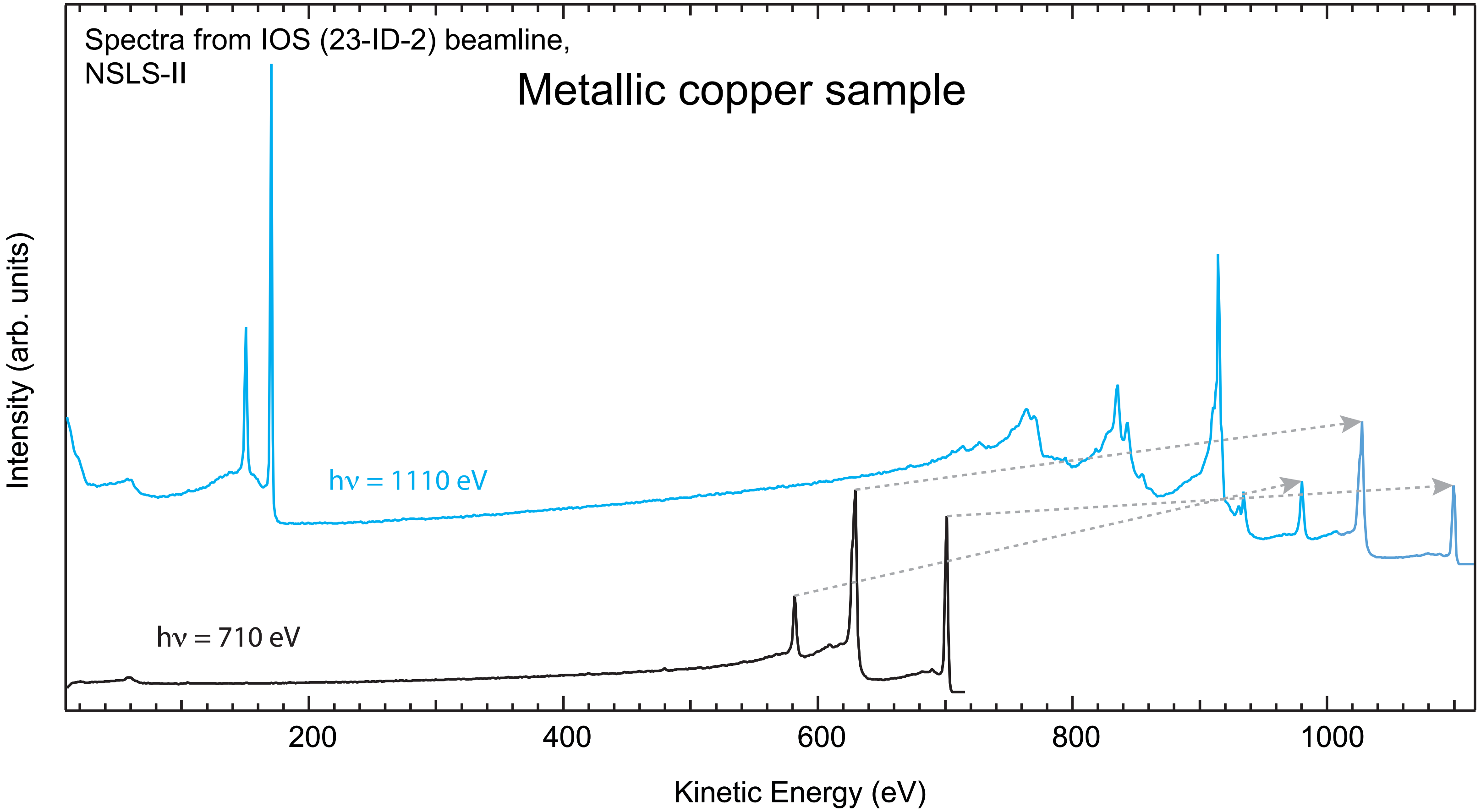


- A small aperture is needed to restrict the flow of gases into the analyzer
- Aperture diameter ~100 um to 500 um (smaller aperture → higher pressure)
- Sample needs to be close to aperture to minimize scattering by gases
- Small beam size is important!
- Chamber and beamline are separated by 100 nm thick Si_3N_4 window

Part 2

Understanding XPS Spectra

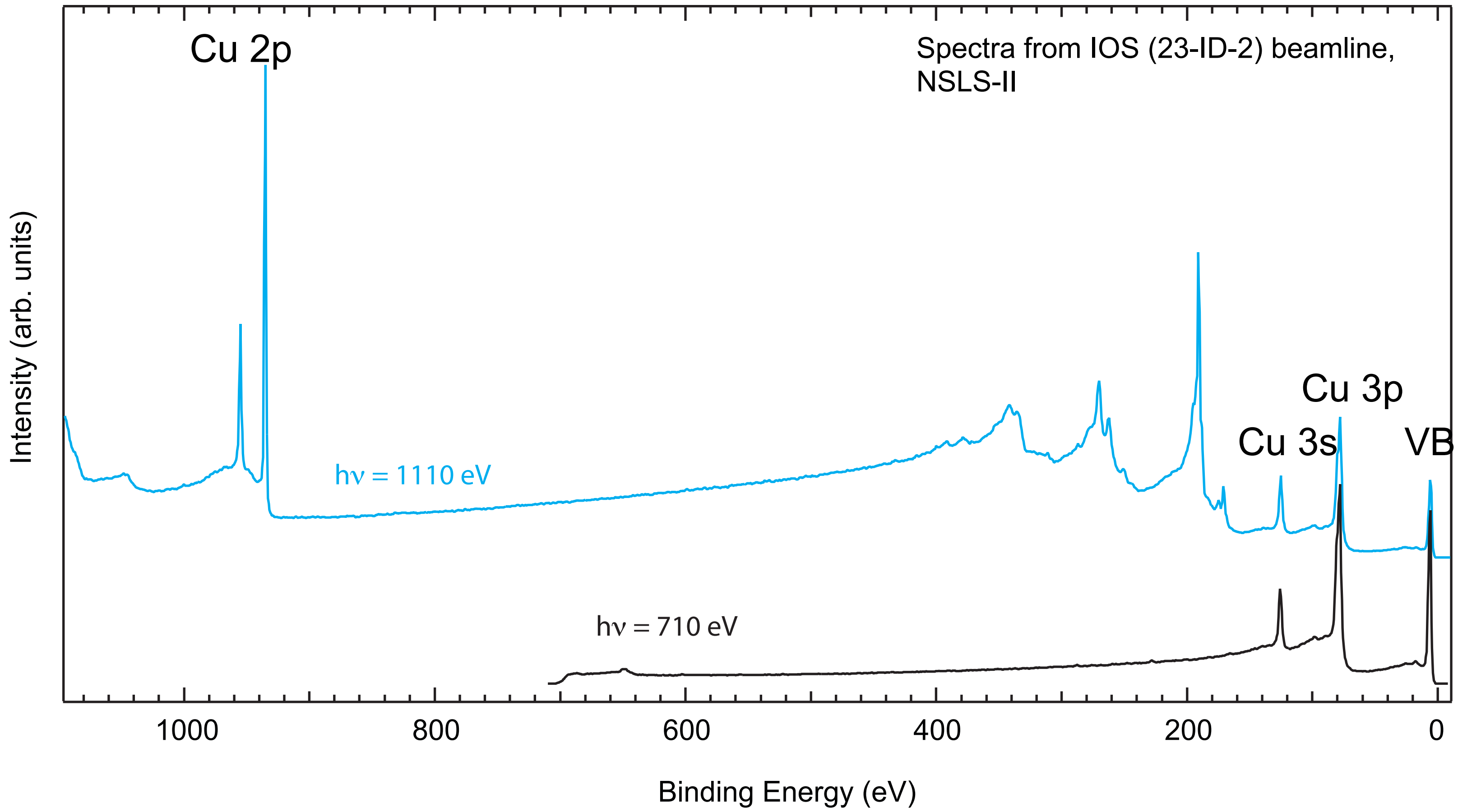
What do you get from the analyzer?



If you change the energy of the X-ray, the electron kinetic energy also changes

Convert to binding energy

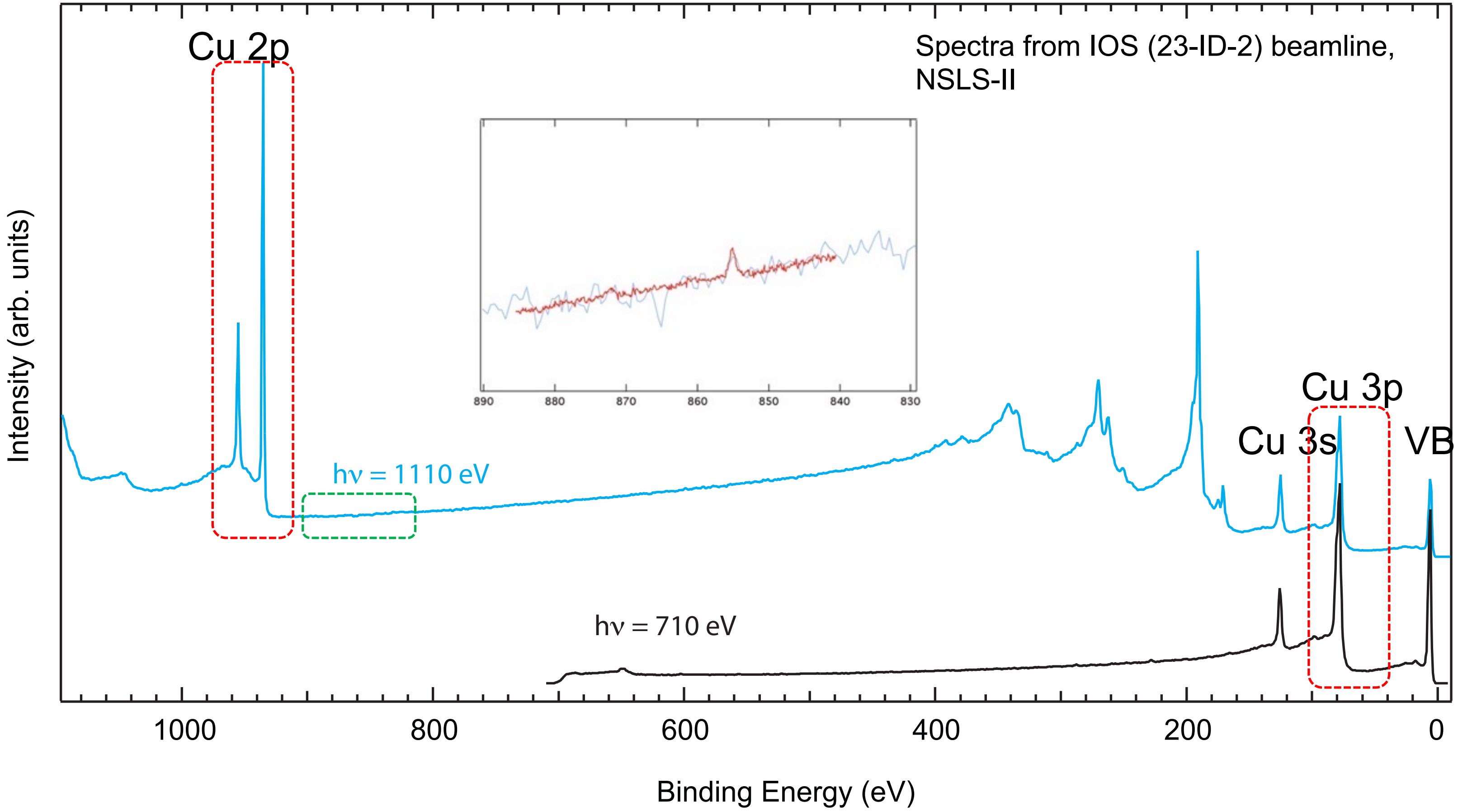
$$E_b = h\nu - E_k - \phi$$



Electron binding energy is fixed at any photon energy

Convert to binding energy

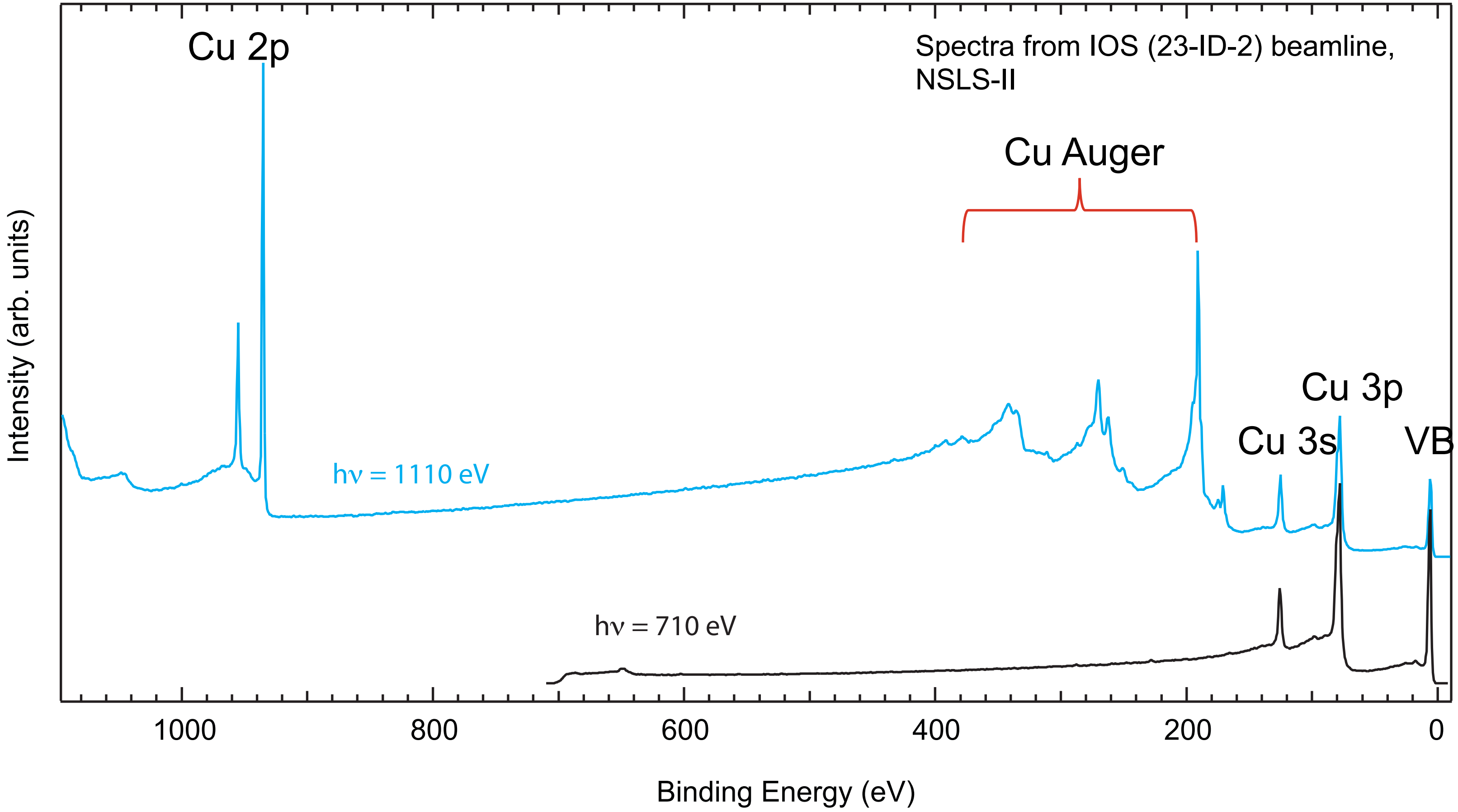
$$E_b = h\nu - E_k - \phi$$



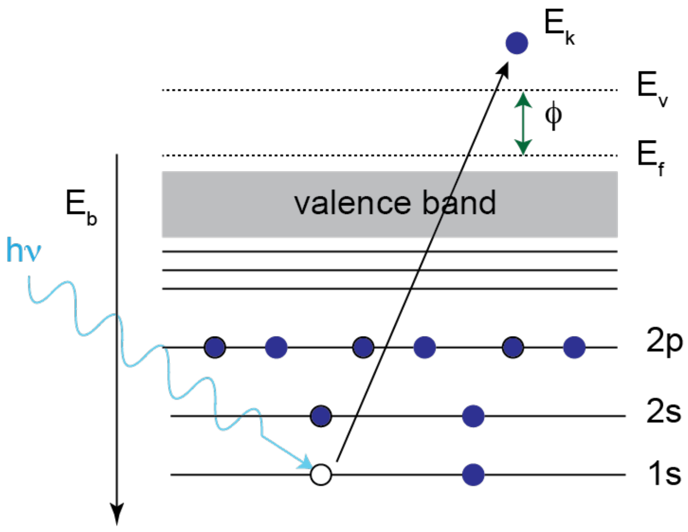
Select your scan regions, scan at smaller step size, and take multiple scans to improve signal-to-noise ratio

Auger Peaks

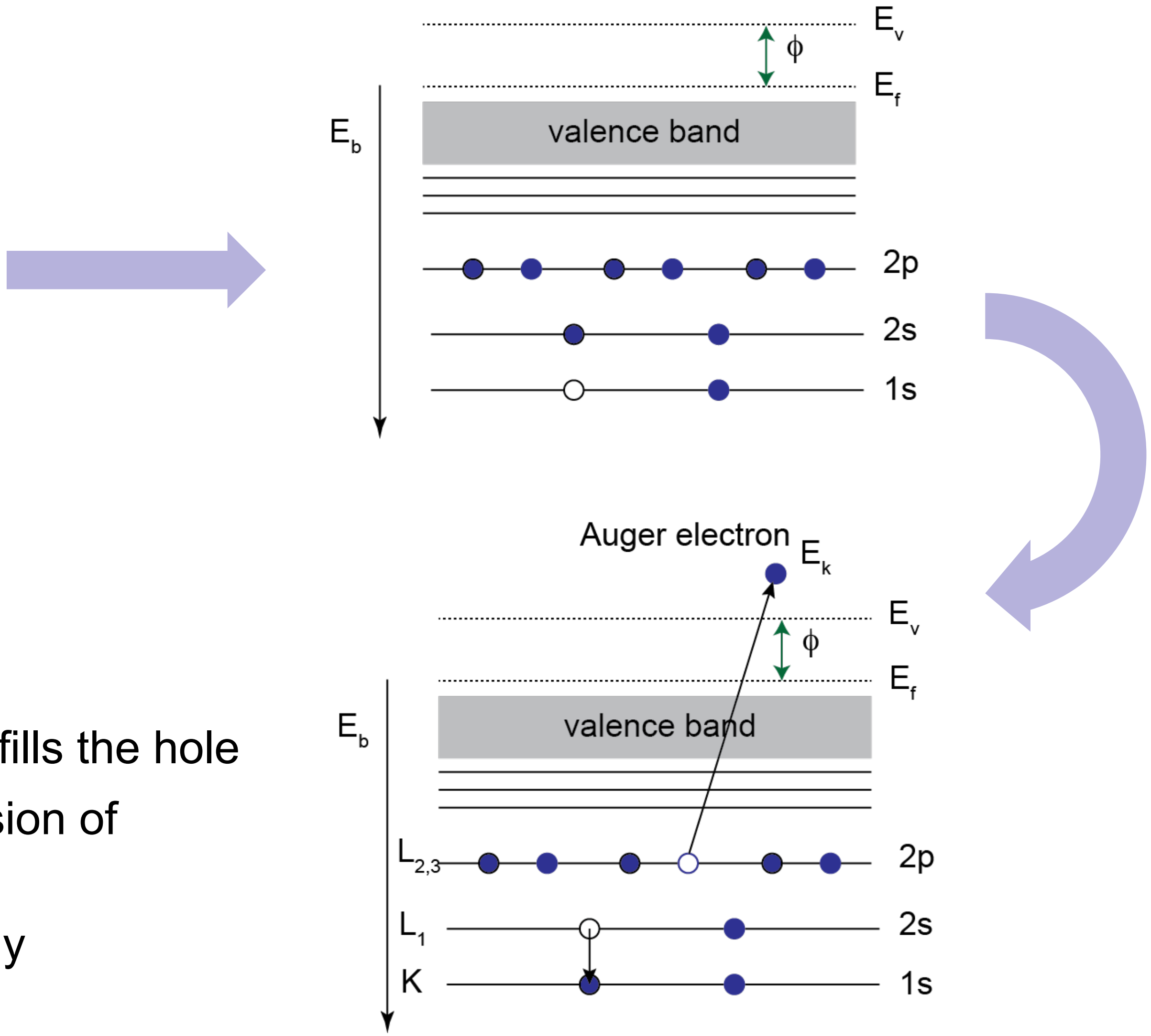
$$E_b = h\nu - E_k - \phi$$



Auger Electrons

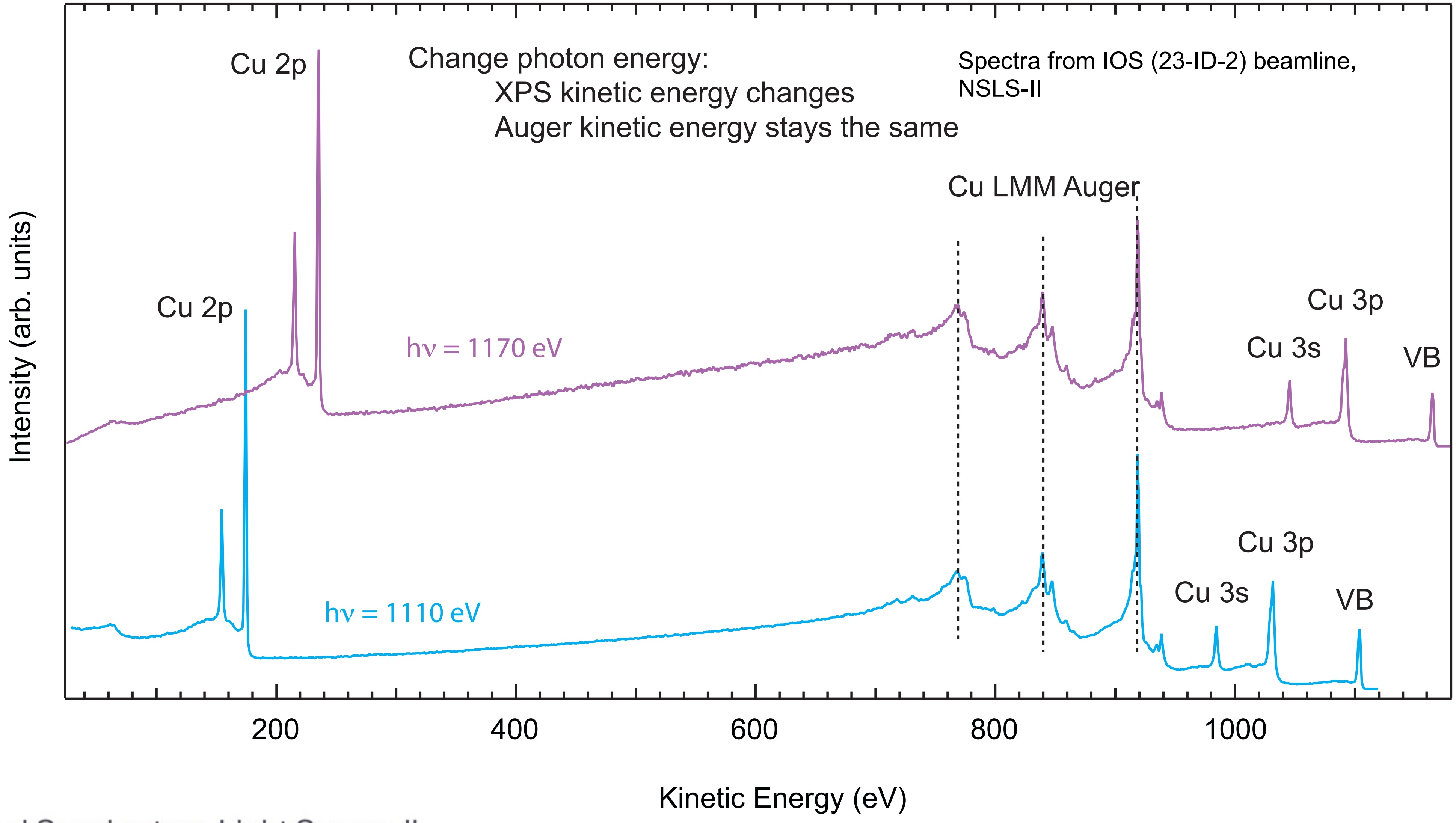


$E_k = h\nu - E_b - \phi$

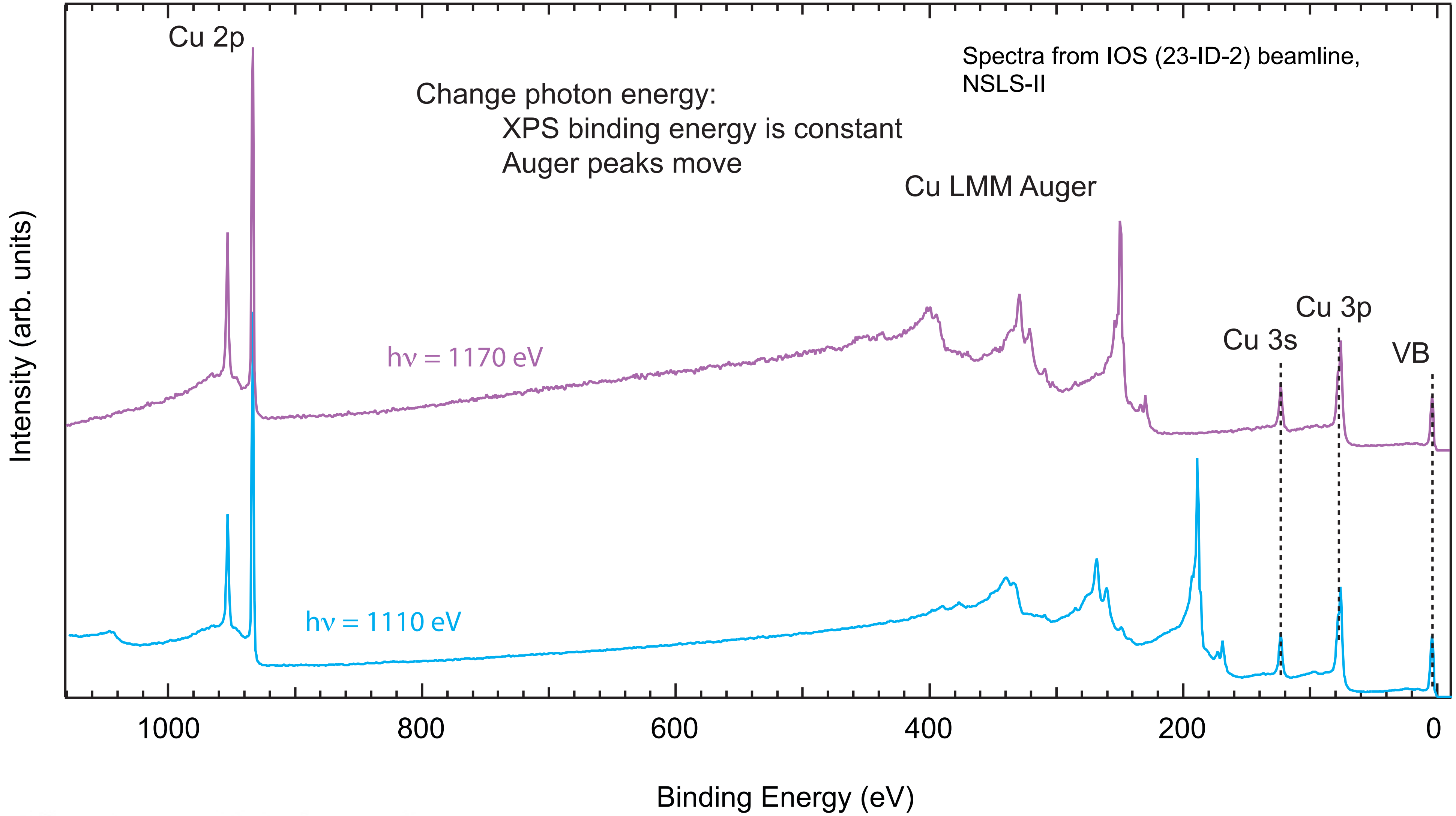


- XPS leaves a core hole
- An electron from a higher energy orbital fills the hole
- The released energy results in the emission of another electron
- Auger kinetic energy is not photon energy dependent

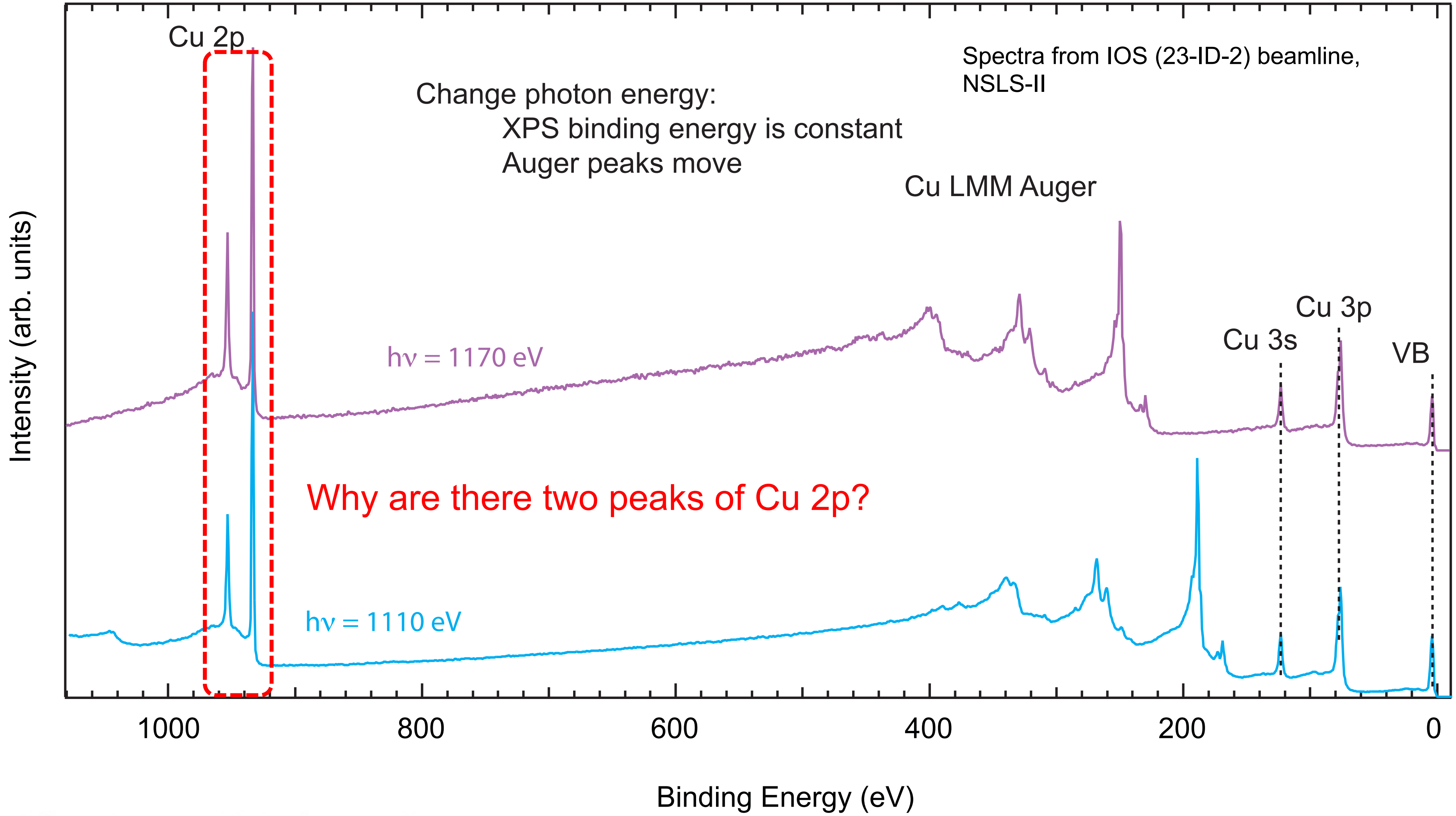
Identifying Auger Peaks



Identifying Auger Peaks

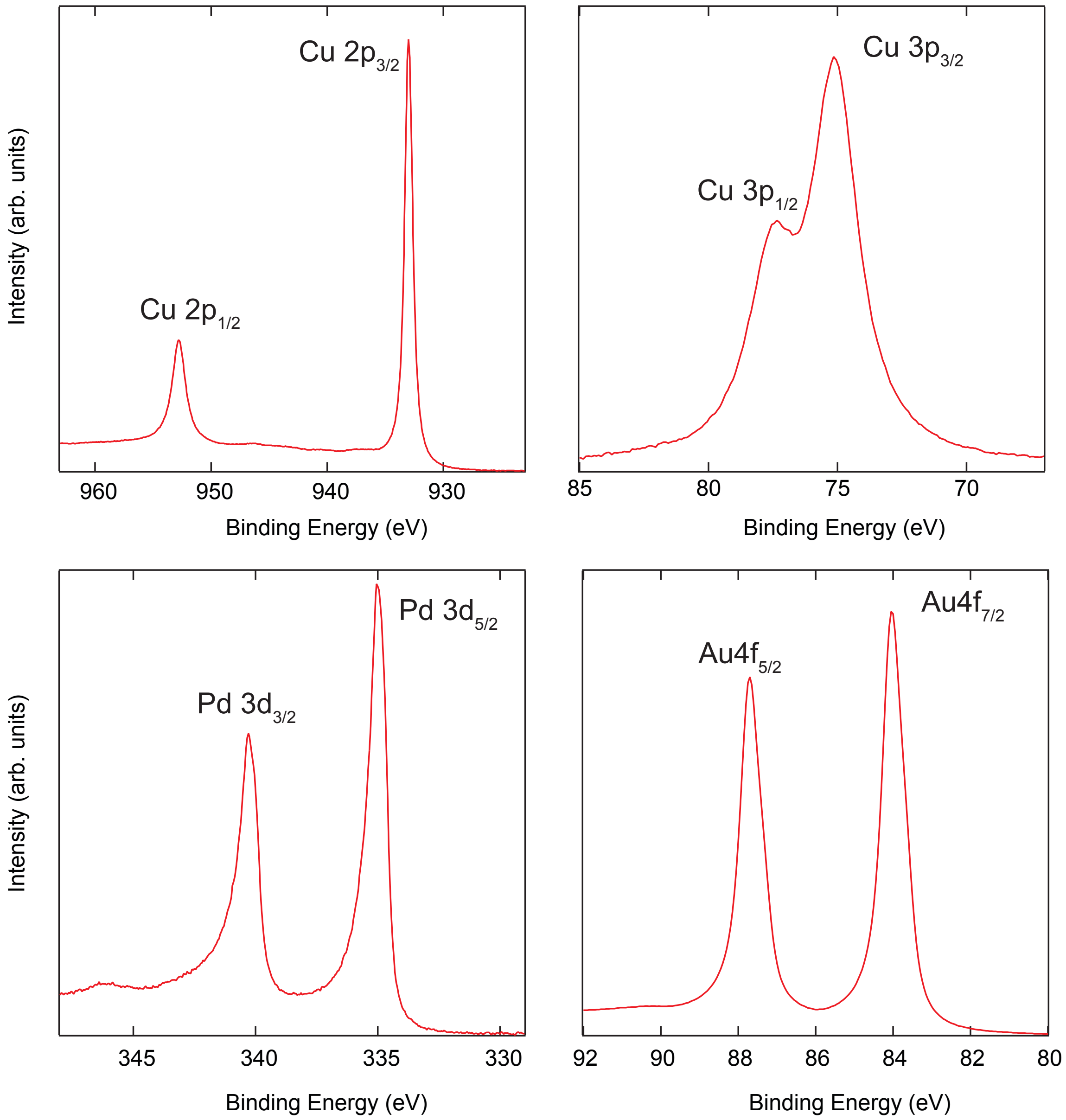


Spin-Orbit Splitting



Spin-Orbit Splitting

Doublets (two peaks) are always observed for p, d, f orbitals



Spectra from IOS (23-ID-2) beamline, NSLS-II

Spin-Orbit Splitting

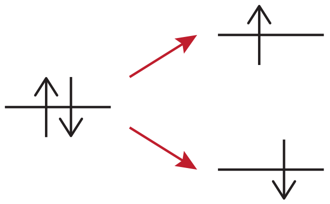
l = orbital angular momentum quantum number
(0 = s, 1 = p, 2 = d, 3 = f)

$2p_{1/2}$

j = total angular momentum quantum number
$j = |l + s|$

n = principal quantum number (1, 2, 3,...)

s = spin quantum number (-1/2 or +1/2)



s = +1/2

s = -1/2

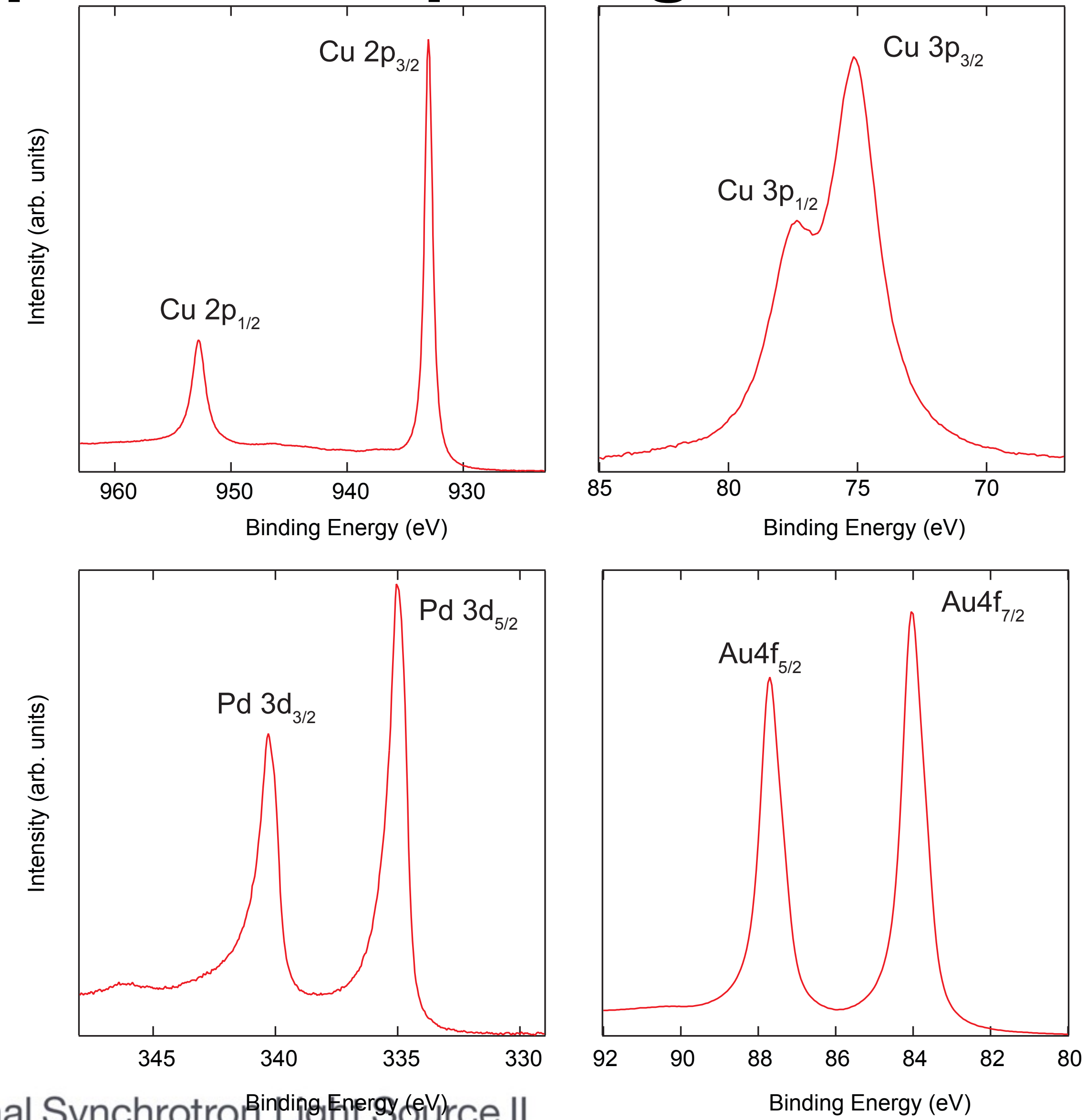
s: l = 0, no splitting

p: l = 1, j = 1/2, 3/2

d: l = 2, j = 3/2, 5/2

f: l = 3, j = 5/2, 7/2

Spin-Orbit Splitting

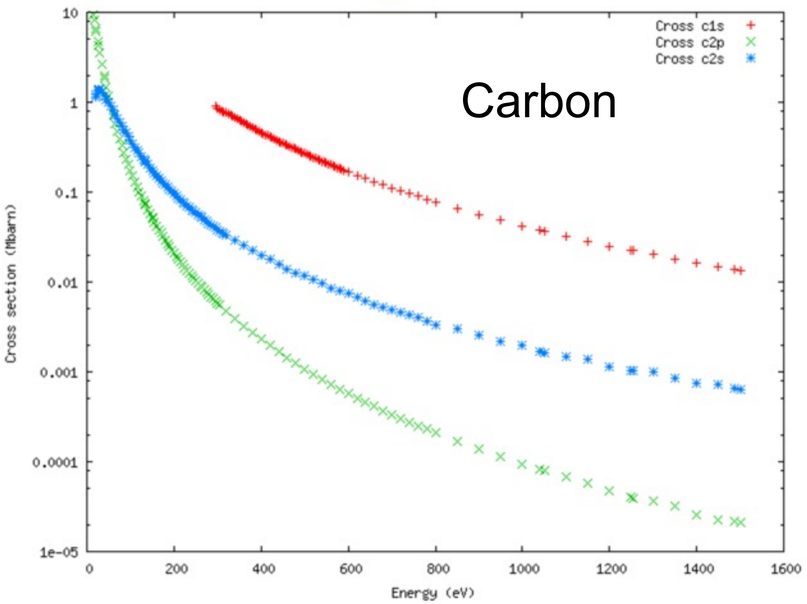


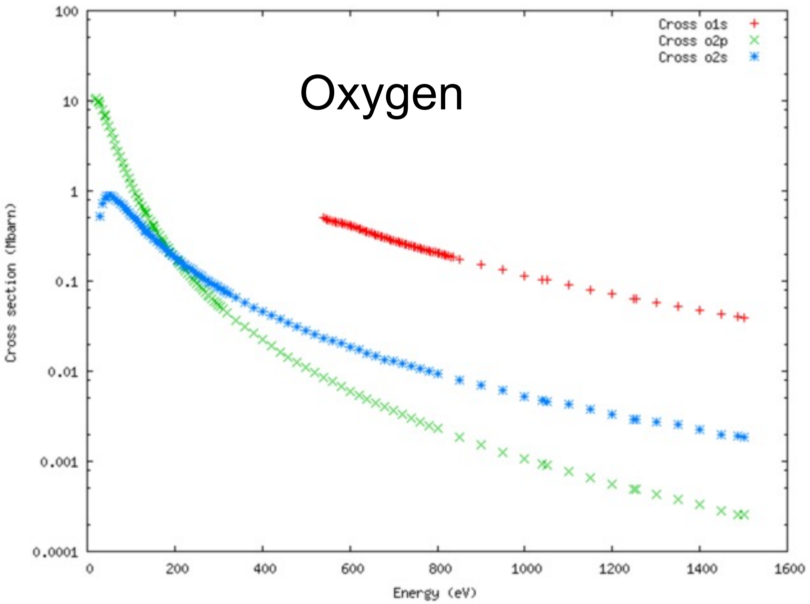
- Spin orbit splitting helps us identify peaks
- Energy splitting is always the same for the same core level of the same element
- Peak area ratio is determined by degeneracy $2j+1$
  - $p_{3/2}:p_{1/2}$ = 2:1
  - $d_{5/2}:d_{3/2}$ = 3:2
  - $f_{7/2}:f_{5/2}$ = 4:3

Spectra from IOS (23-ID-2) beamline, NSLS-II

Photoionization Cross-section

- The probability of a photon ionizing the atom and causing the emission of an electron
- It varies for different elements
- It varies for different core levels of the same element
- It varies with photon energy for the same core level of the same element
- Need a synchrotron to tune energy to optimize cross-section

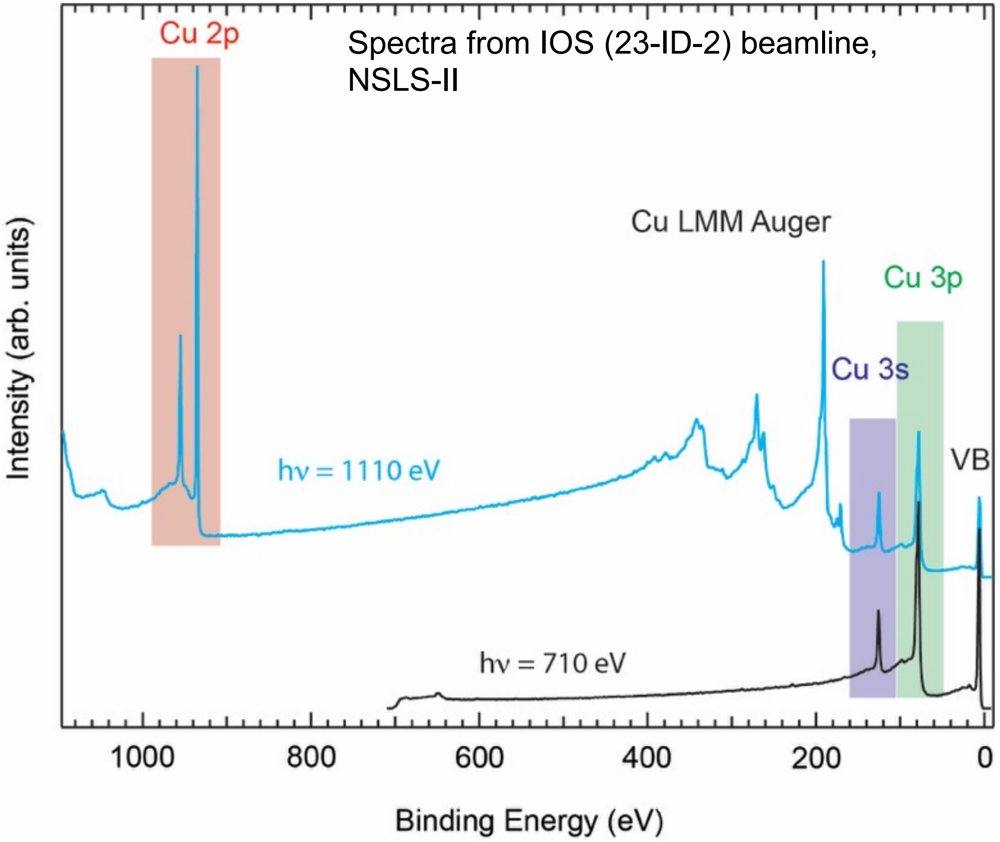




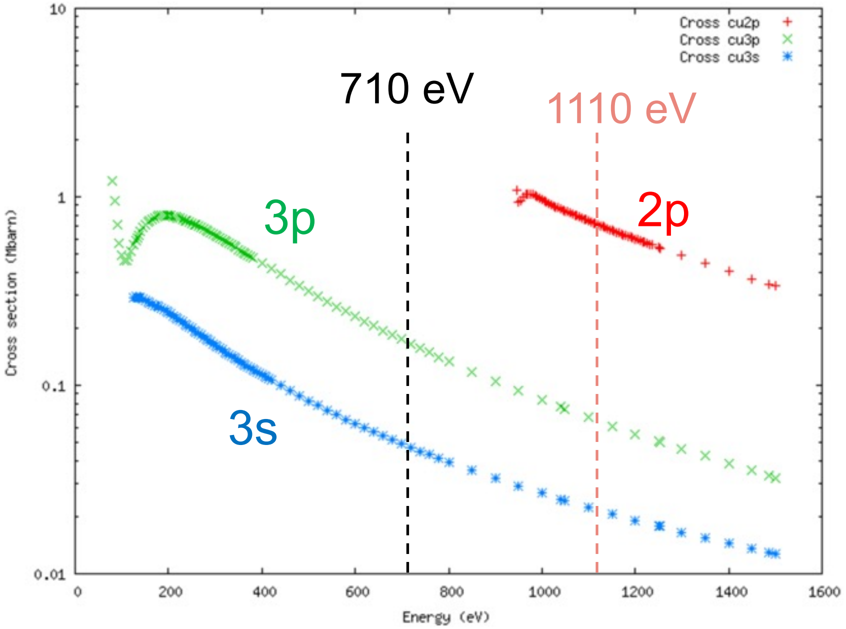
https://vuo.elettra.eu/services/elements/WebElements.html

Photoionization Cross-section

Copper survey XPS spectra



Photoionization Cross-section of copper



https://vuo.elettra.eu/services/elements/WebElements.html

What information can you get from XPS?

- **Elemental specificity**

  What elements do you have in the sample?

- **Chemical sensitivity**

  What is the chemical environment of each element in the sample?

- **Depth profiling**

  Where are the elements in the sample?

- **Quantitative analysis**

  How much is there of each element in the sample?

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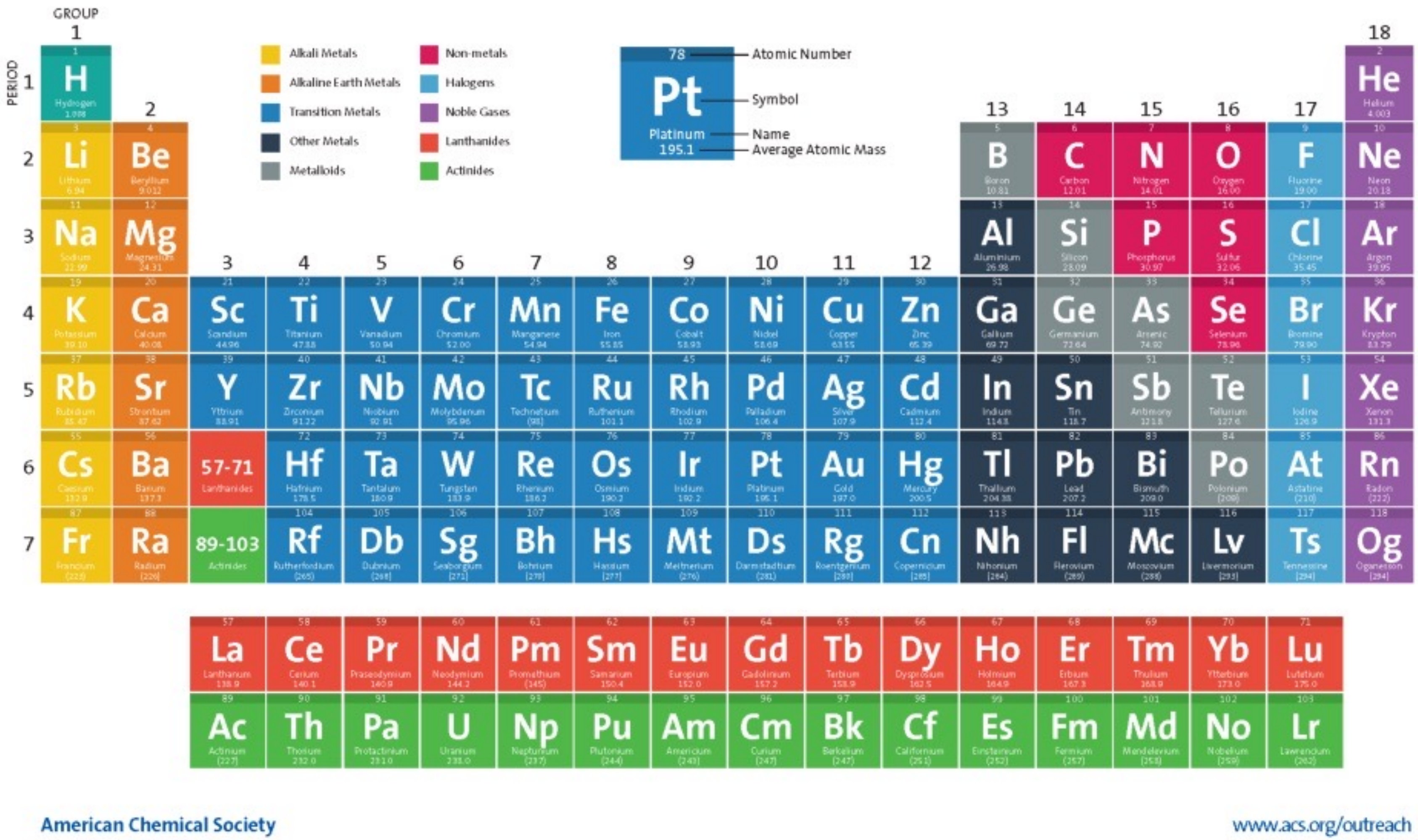
Elemental Specificity

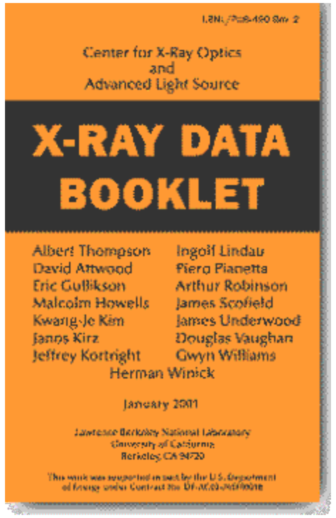


Each element has a unique set of electron binding energies

Electron Binding Energy Table

Table 1-1. Electron binding energies, in electron volts, for the elements in their natural forms.

Element	K 1s	L_1 2s	L_2 $2p_{1/2}$	L_3 $2p_{3/2}$	M_1 3s	M_2 $3p_{1/2}$	M_3 $3p_{3/2}$	M_4 $3d_{3/2}$	M_5 $3d_{5/2}$	N_1 4s	N_2 $4p_{1/2}$	N_3 $4p_{3/2}$
1 H	13.6											
2 He	24.6*											
3 Li	54.7*											
4 Be	111.5*											
5 B	188*											
6 C	284.2*											
7 N	409.9*	37.3*										
8 O	543.1*	41.6*										
9 F	696.7*											
10 Ne	870.2*	48.5*	21.7*	21.6*								
11 Na	1070.8†	63.5†	30.65	30.81								
12 Mg	1303.0†	88.7	49.78	49.50								
13 Al	1559.6	117.8	72.95	72.55								
14 Si	1839	149.7*b	99.82	99.42								
15 P	2145.5	189*	136*	135*								
16 S	2472	230.9	163.6*	162.5*								
17 Cl	2822.4	270*	202*	200*								
18 Ar	3205.9*	326.3*	250.6†	248.4*	29.3*	15.9*	15.7*					
19 K	3608.4*	378.6*	297.3*	294.6*	34.8*	18.3*	18.3*					
20 Ca	4038.5*	438.4†	349.7†	346.2†	44.3 †	25.4†	25.4†					
21 Sc	4492	498.0*	403.6*	398.7*	51.1*	28.3*	28.3*					
22 Ti	4966	560.9†	460.2†	453.8†	58.7†	32.6†	32.6†					



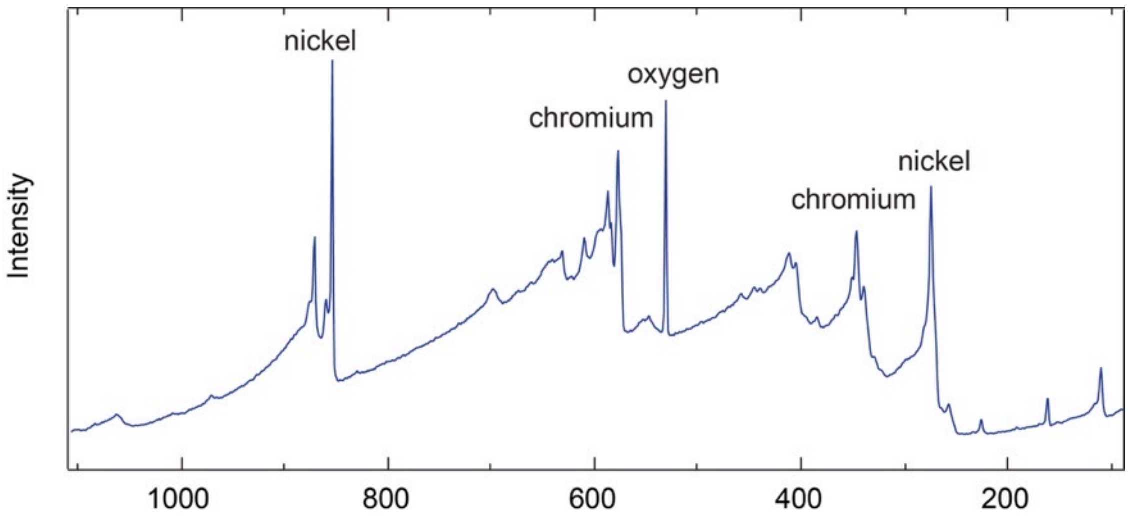
https://xdb.lbl.gov/Section1/Table_1-1.pdf

From X-ray Data Booklet: https://xdb.lbl.gov

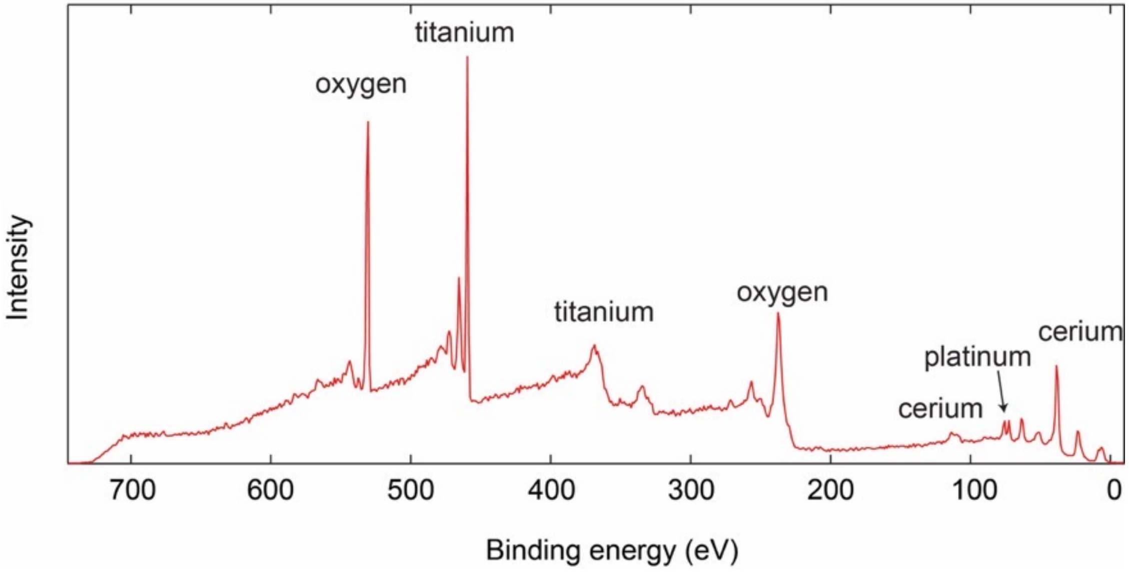
Elemental Specificity

Spectra from IOS (23-ID-2) beamline, NSLS-II

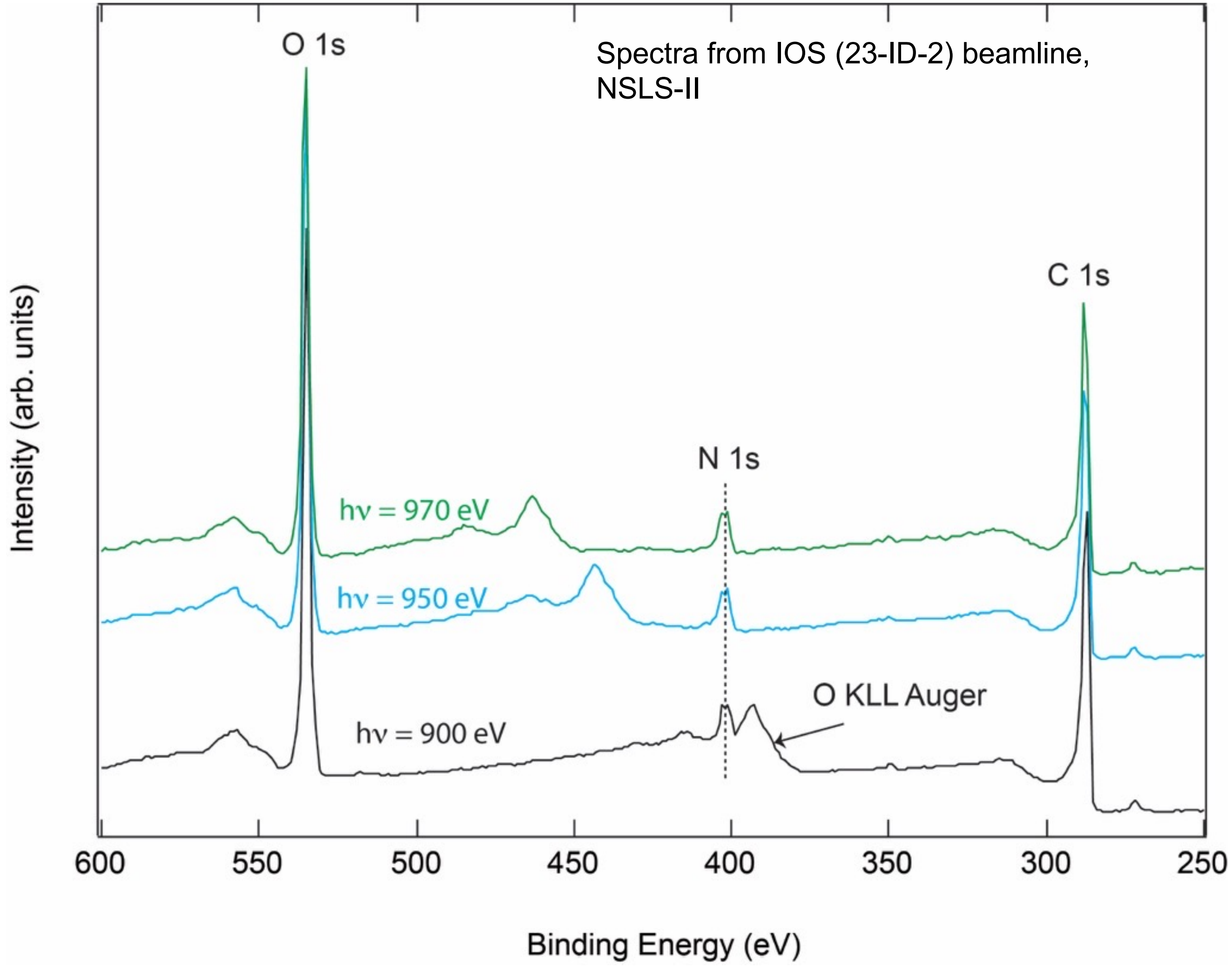
Nickel-Chromium alloy –
corrosion resistant material



$Pt/CeO_2/TiO_2$
catalyst for methanol production



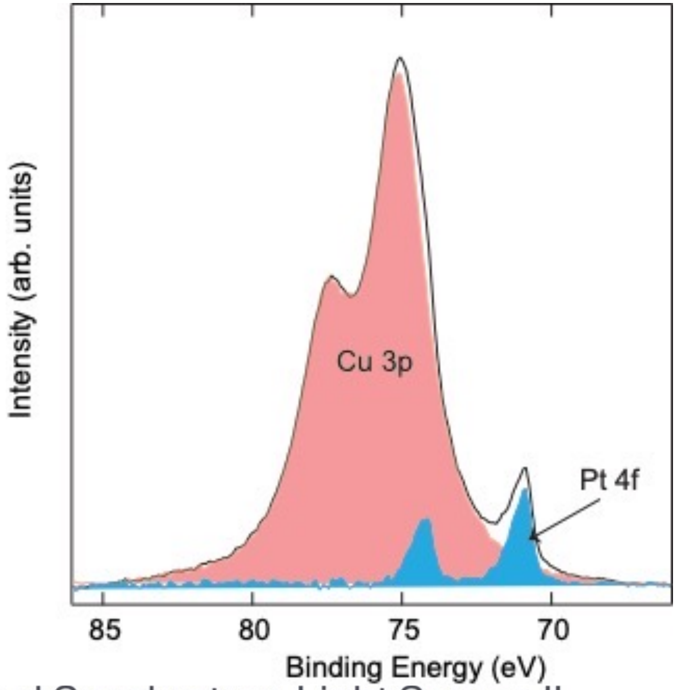
Overlaps with Auger Peaks

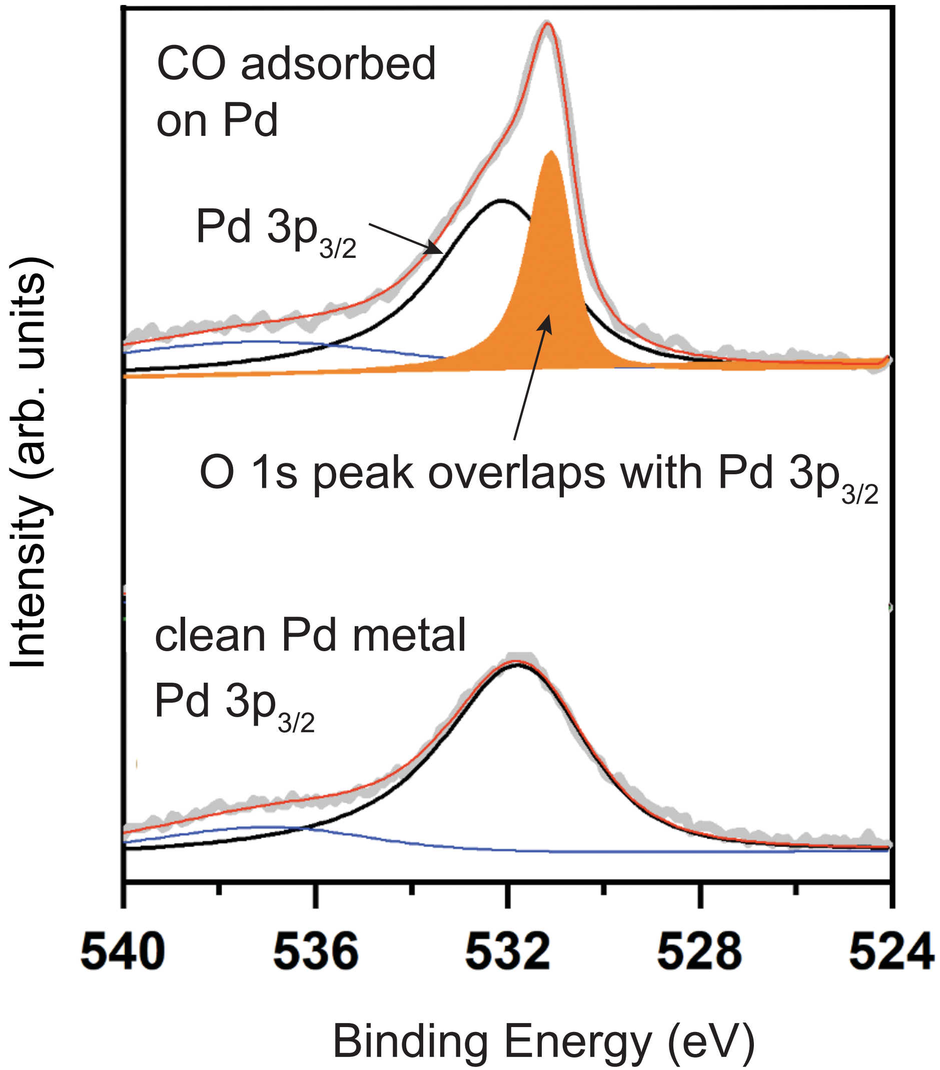


Overlapping Auger peaks can be shifted away by changing photon energy

Things are not always that simple…

- Some XPS peaks of different elements may still overlap partially or completely
- You need to look at other peaks to identify the element
- Peak fitting is important for separating peaks from different elements





Spectra from IOS (23-ID-2) beamline, NSLS-II

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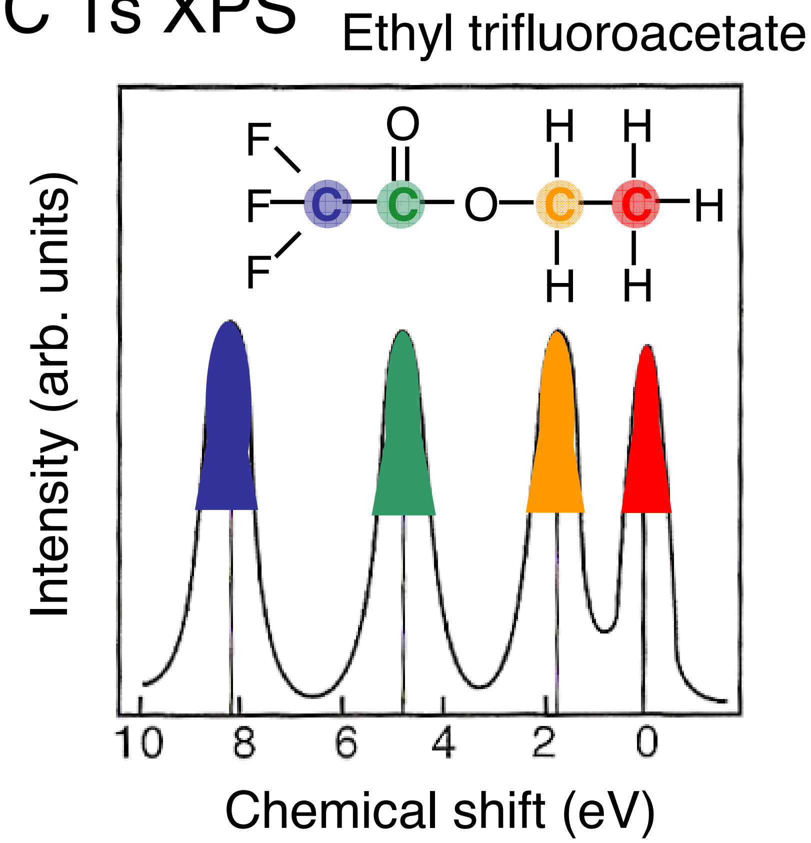
  How much is there of each element in the sample?

Sensitivity to Chemical Environment

C 1s XPS

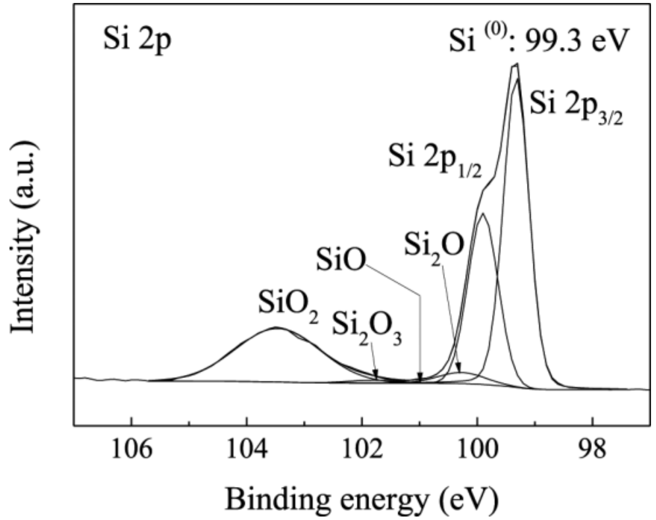


- Binding energy of an electron is affected by the chemical environment of the atom
- Energy shift can be up to 10 eV
- This makes XPS a powerful tool for chemical analysis
- You can tell the chemical bonding of the probed atom
- Bonding to a more electronegative atom → shift to higher binding energy

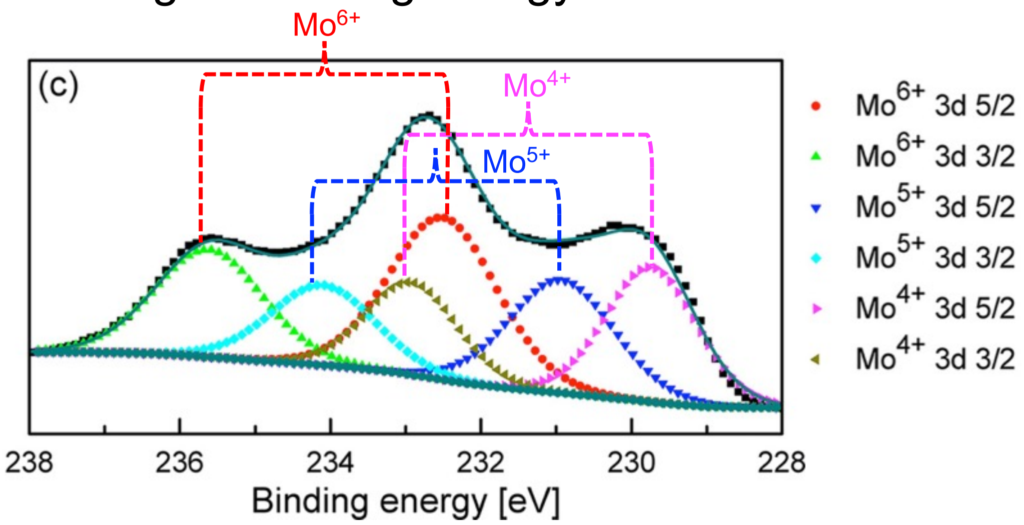
K. Siegbahn, J. Electr. Spectrosc. Relat. Phenom., 5, 3 (1974)

Core Level Shift due to Oxidation State

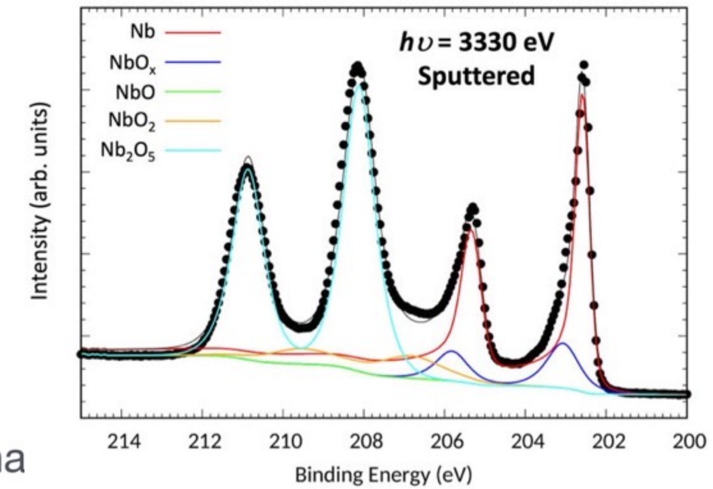
- In general, higher oxidation state causes a shift to higher binding energy



Zhang et al. IEEE Trans. Instrum. Meas., 66 1297 (2017)

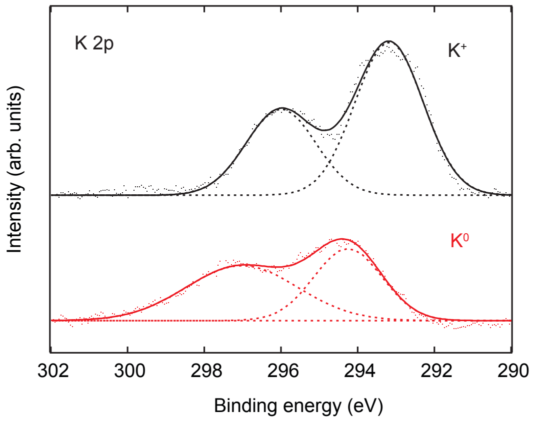


M. Ponce-Mosso et al. Catal. Today, 349, 150 (2020)



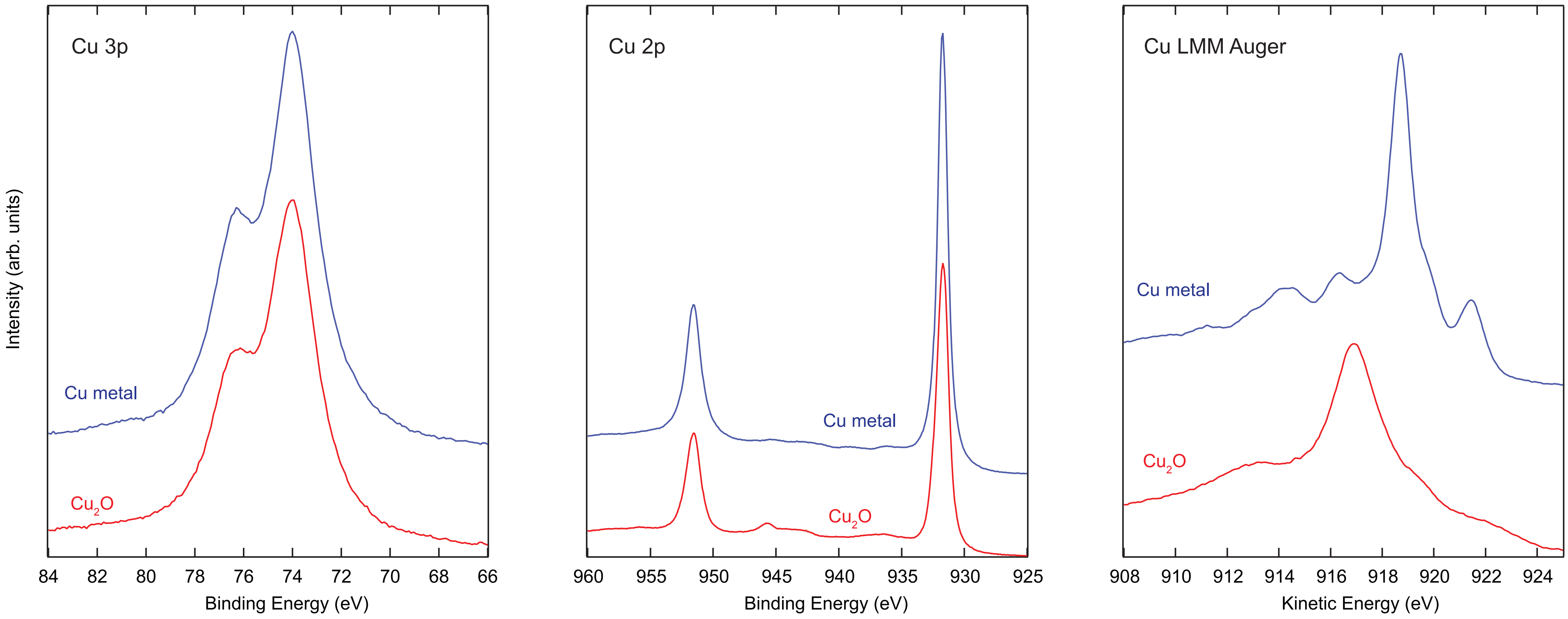
Premkumar et al. Comm. Mater., 2, 72 (2021)

But… alkali metals behave the opposite way



spectra from IOS beamline, NSLS-II

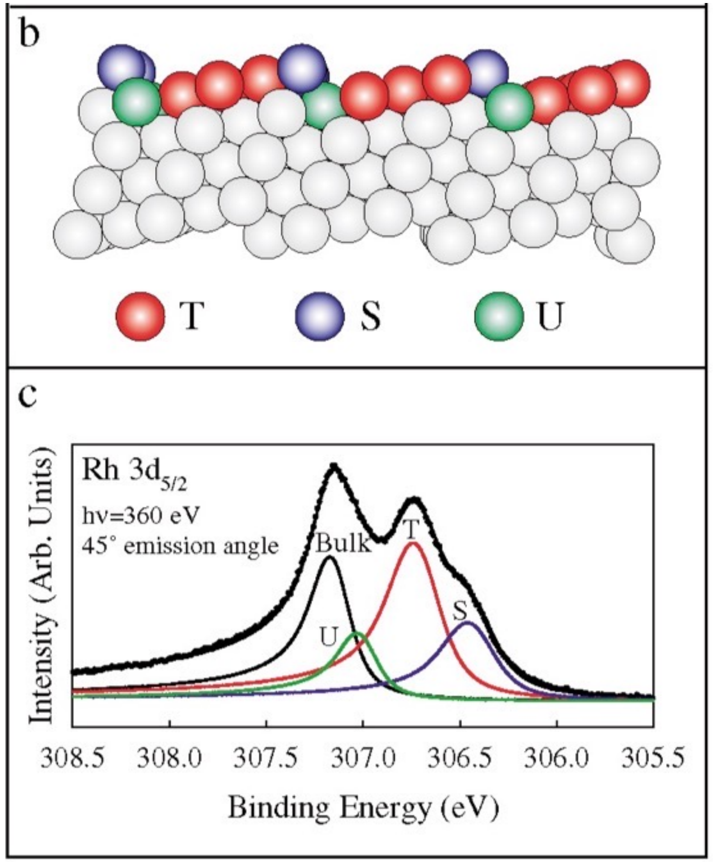
Sometimes it's not that clear…



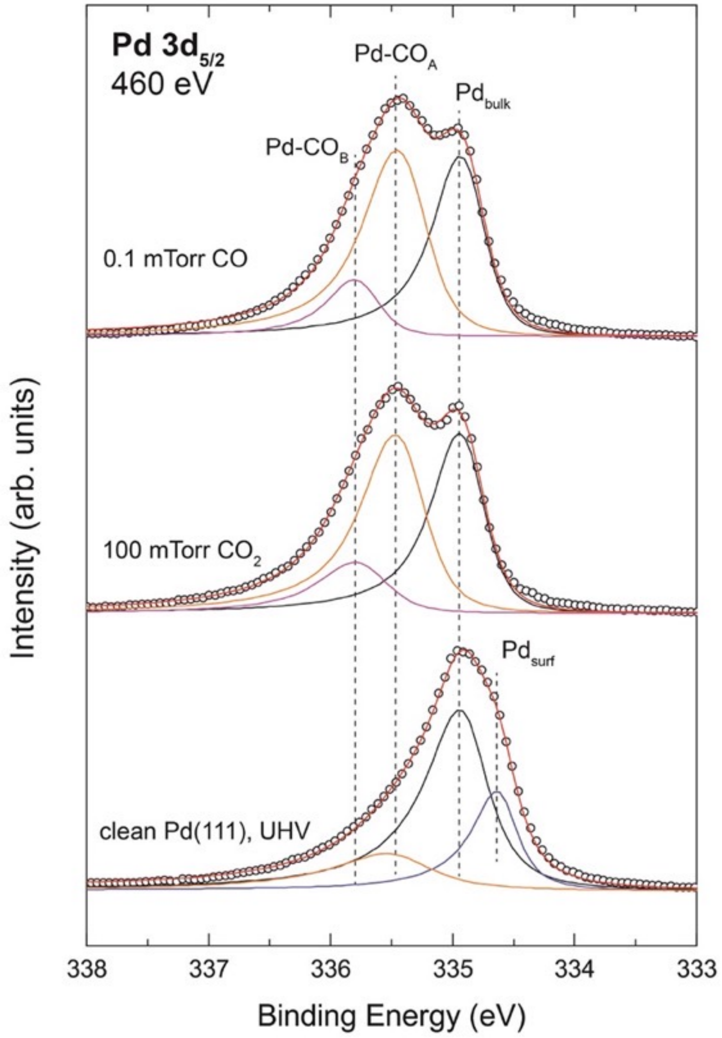
Spectra from IOS (23-ID-2) beamline, NSLS-II

Surface Core Level Shift

Surface atoms of a metal can have distinct binding energy from the bulk atoms

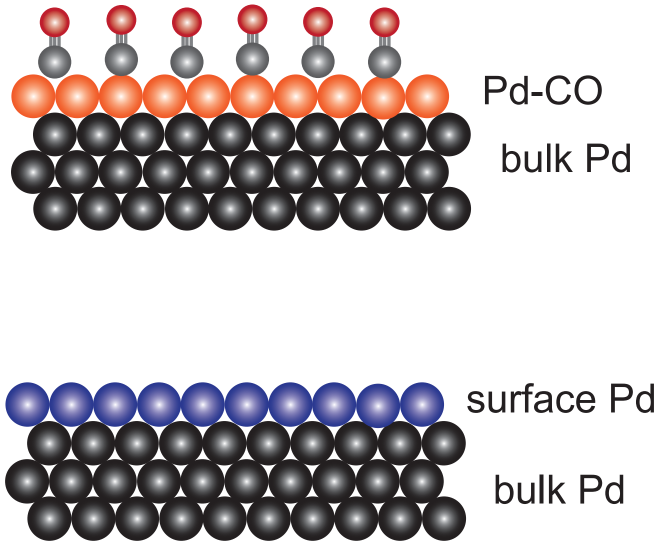


Gustafson et al. Phys. Rev. Let. 91, 056102 (2003)

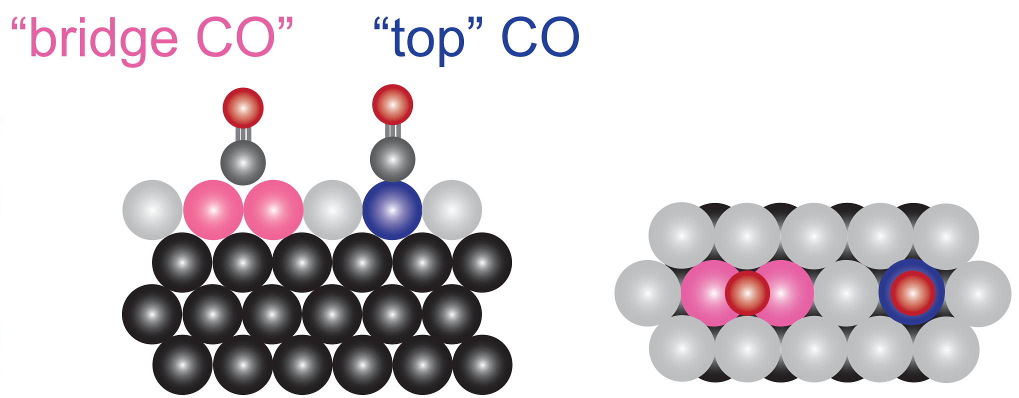


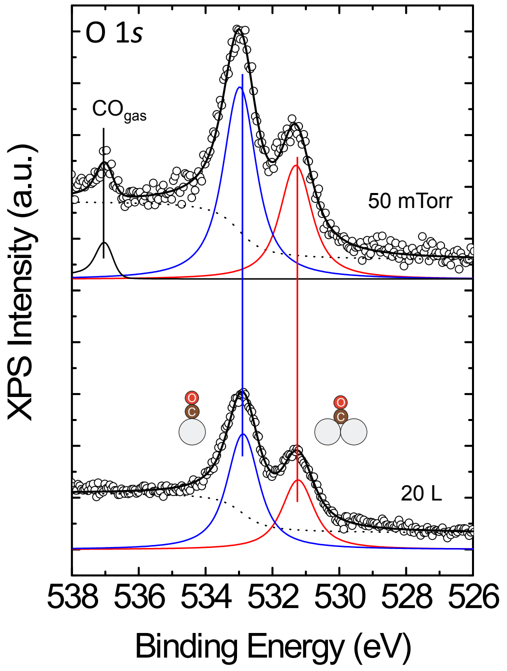
Simonovis et al. J. Phys. Chem. C 126, 7870 (2022)

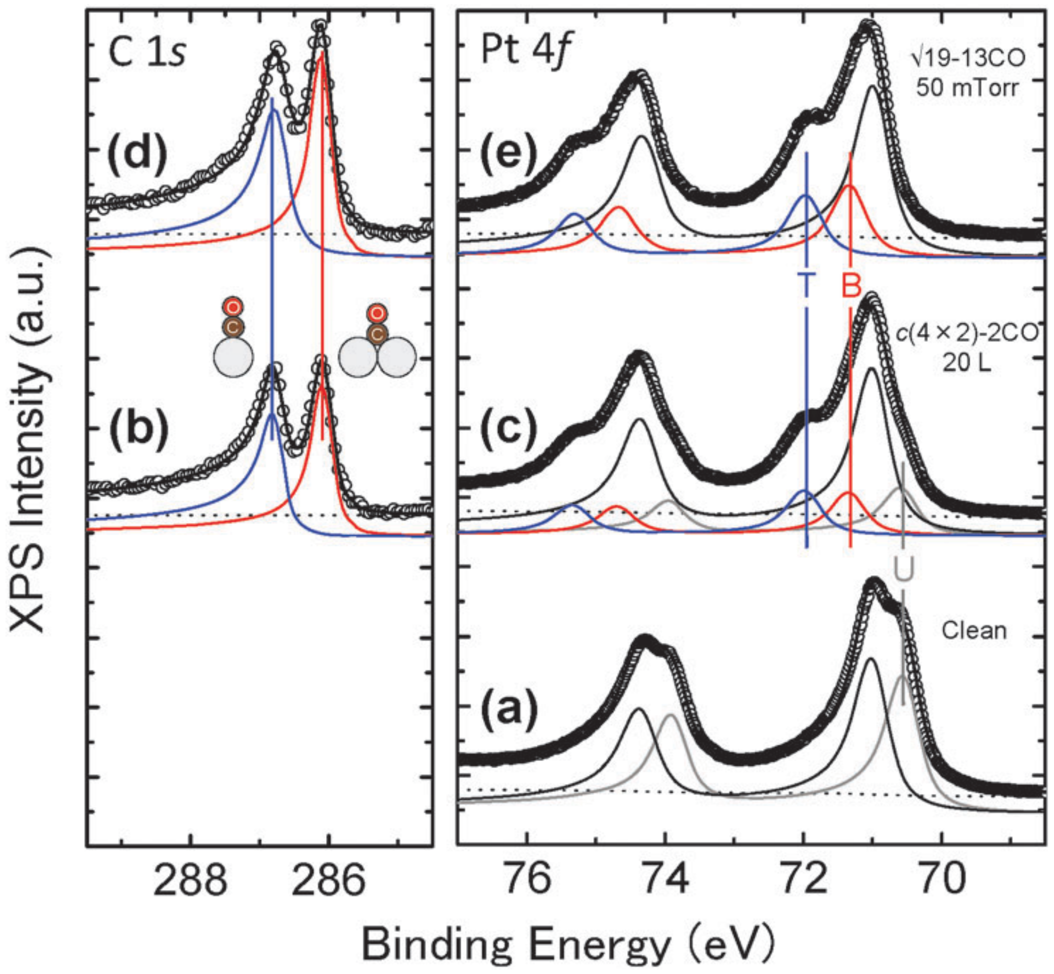
Surface peak is shifted by adsorbed molecules



Distinguishing Different Adsorption Sites







Toyoshima et al. Phys. Chem. Chem. Phys. 16, 23564 (2014)

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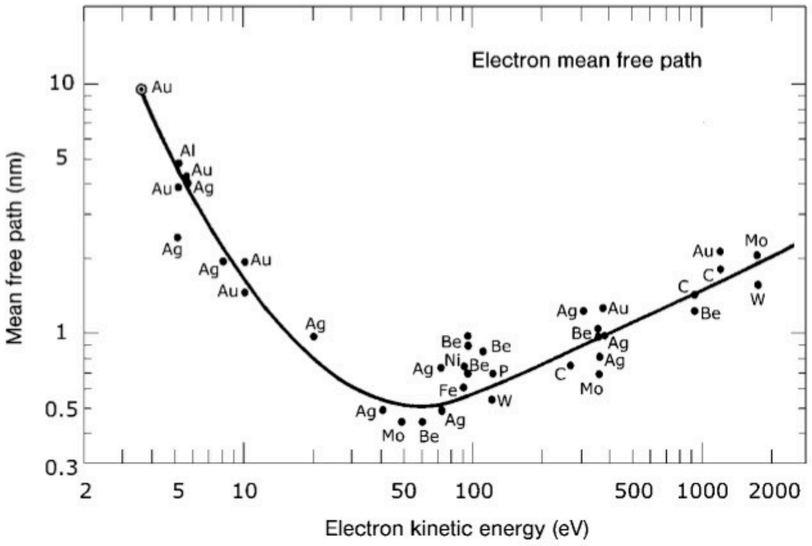
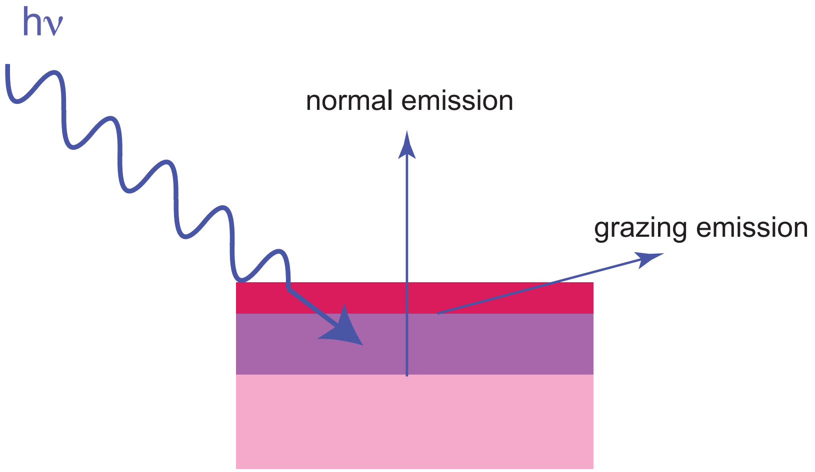
Depth Profiling

You can tune the sampling depth of XPS (non-destructively) in two ways:



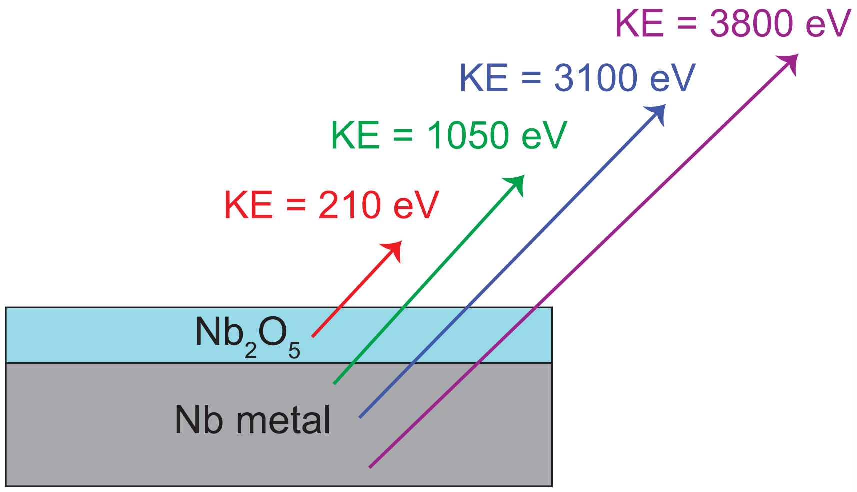


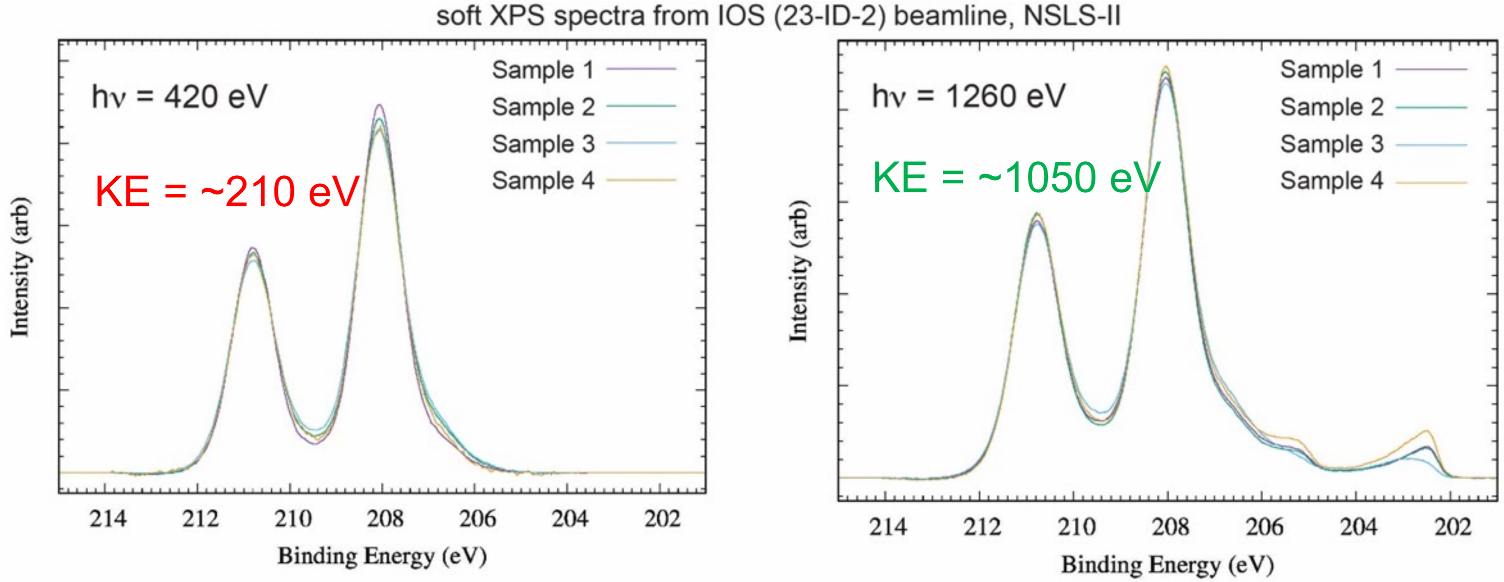
1. Change the photon energy → lower E_k means lower IMFP and more surface sensitive

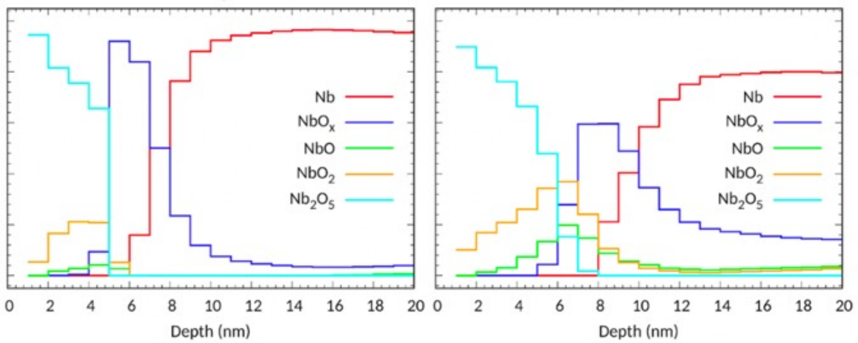
2. Change emission angle → more grazing emission is more surface sensitive

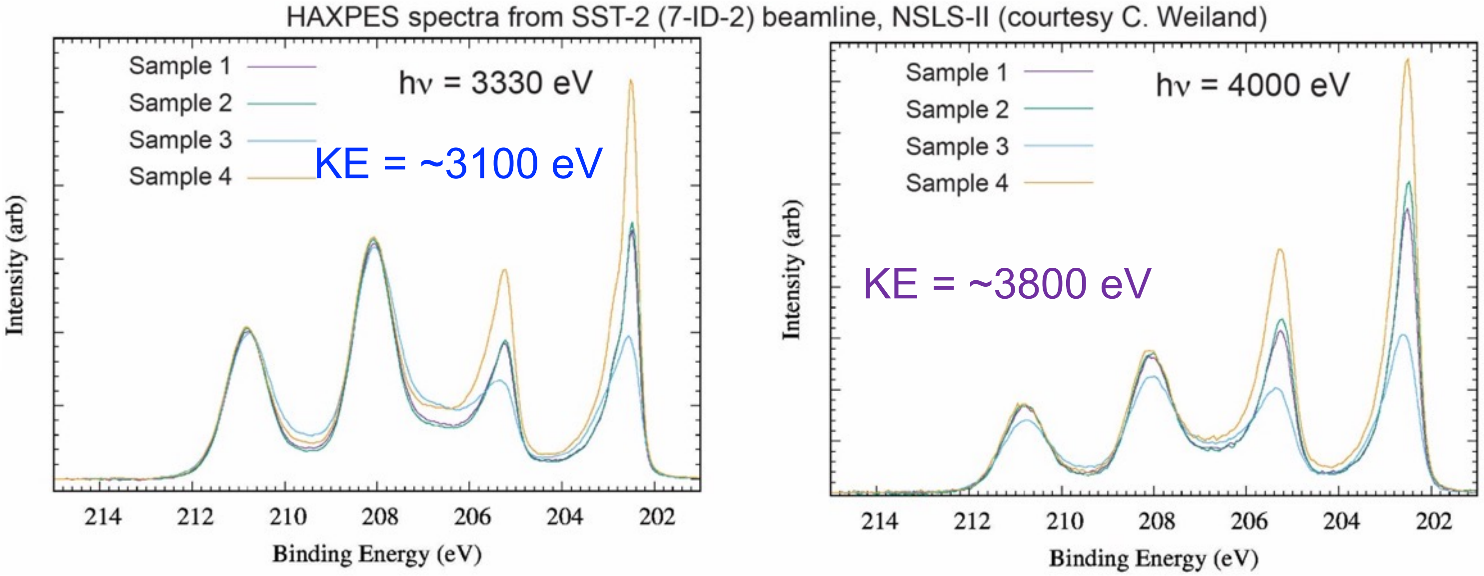
You can also depth-profile by sputtering (i.e. remove materials layer by layer) but that is destructive

Depth Profiling Example









Premkumar et al. Commun. Mater. 2, 72 (2021)

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Quantitative Analysis

$$I_x = J N_x \lambda \sigma K$$

I_x = peak intensity of element x

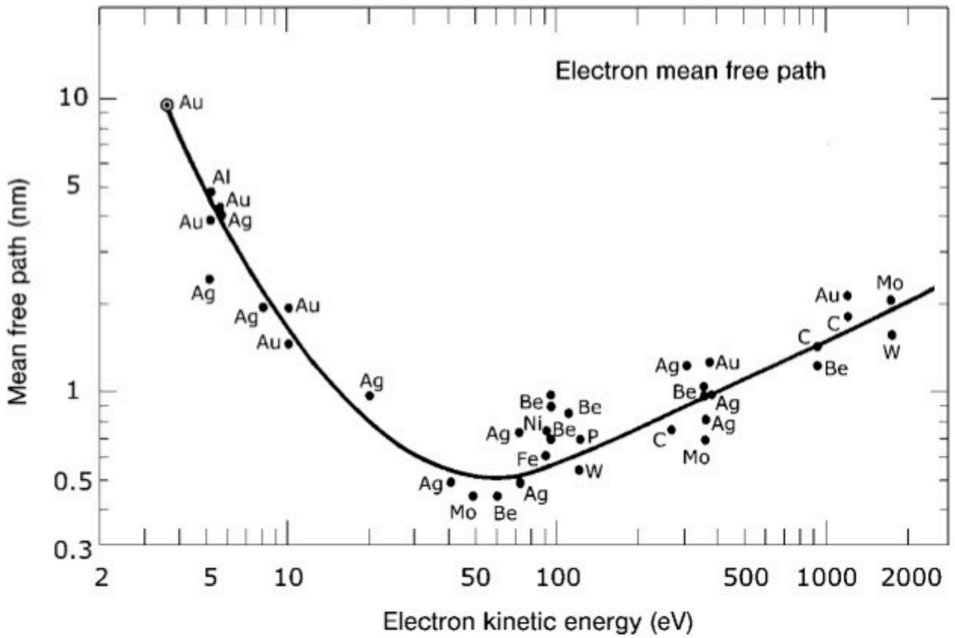
J = photon flux

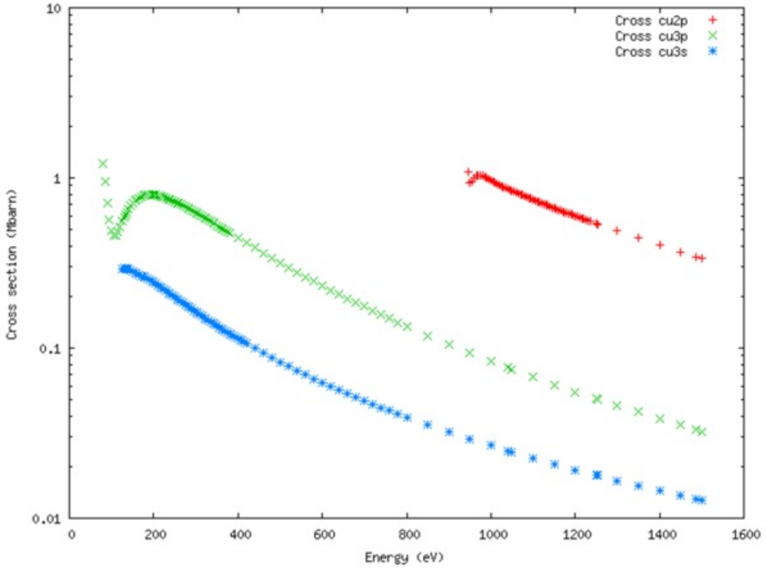
N_x = concentration of element x in the sample

λ = inelastic mean free path

σ = photoionization cross-section

K = instrumentation factors

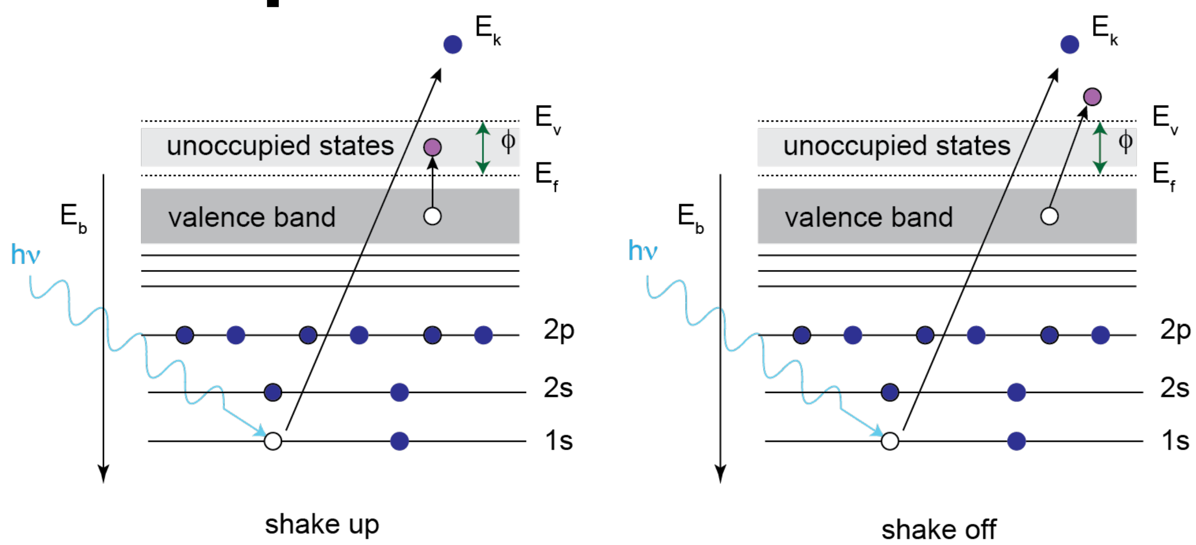




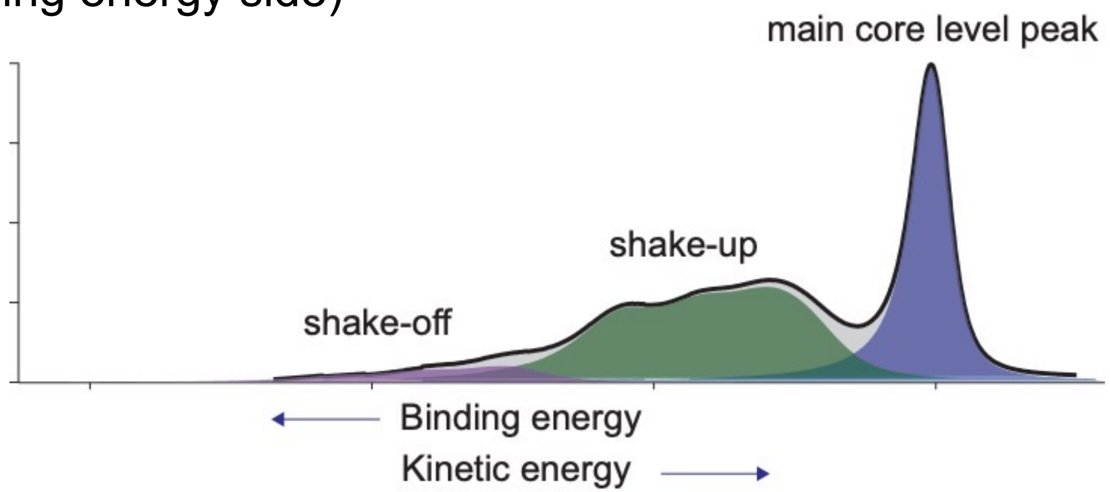
Other things to consider…

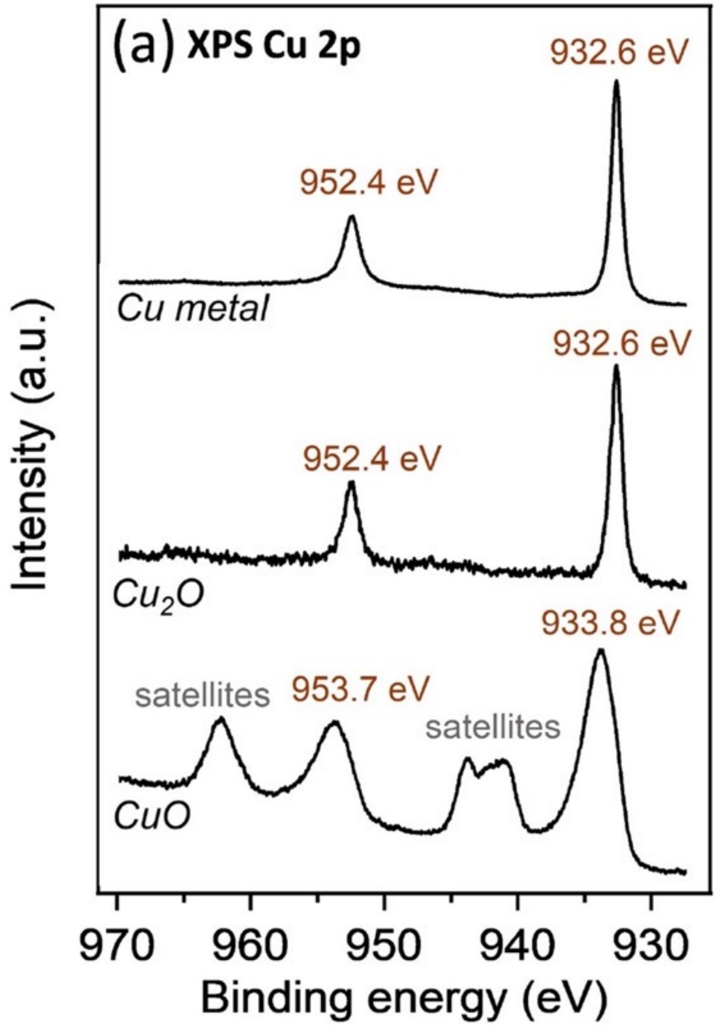
- Shake up/shake off
- Multiplet splitting
- Plasmon loss
- Charging

Shake up and Shake off



Extra “satellite” peaks appear on the lower kinetic energy (higher binding energy side)

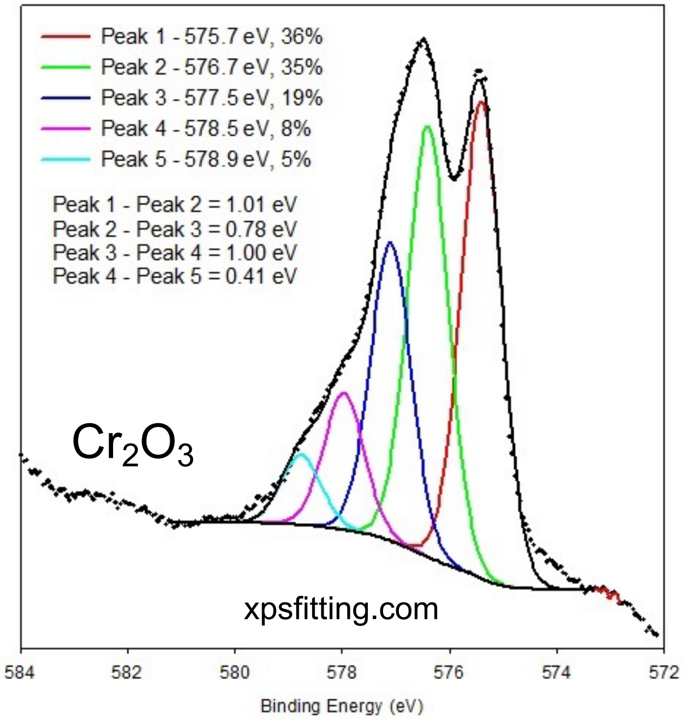


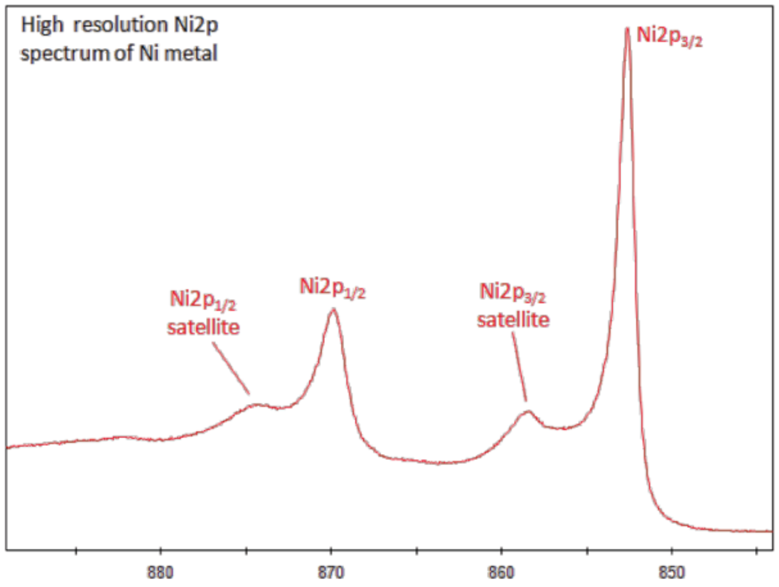


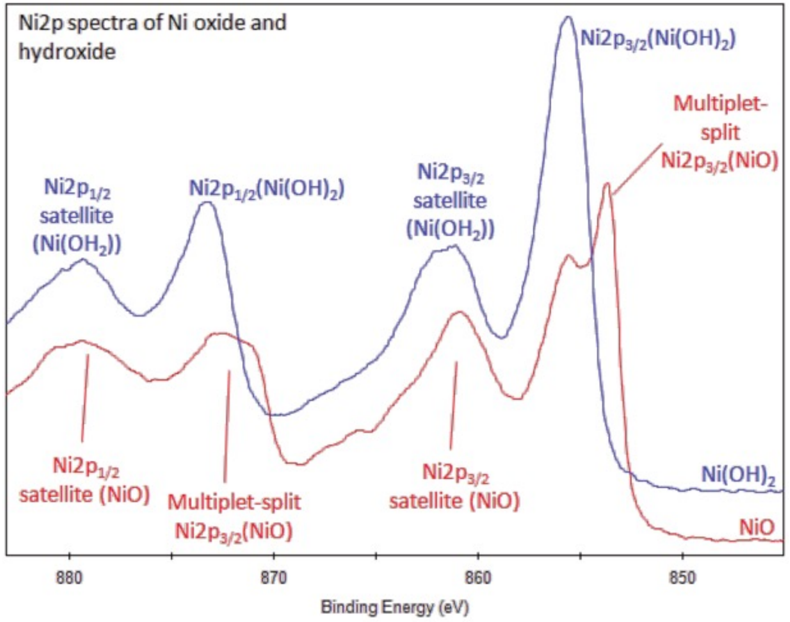
Khalakhan et al. J. Elect. Spectrosc. Relat. Phenom. 246, 147027 (2021)

Multiplet Splitting

- Observed for compounds that have unpaired electrons in the valence band
- Unpaired core electron interacts with unpaired valence electron, creating multiple possible final states



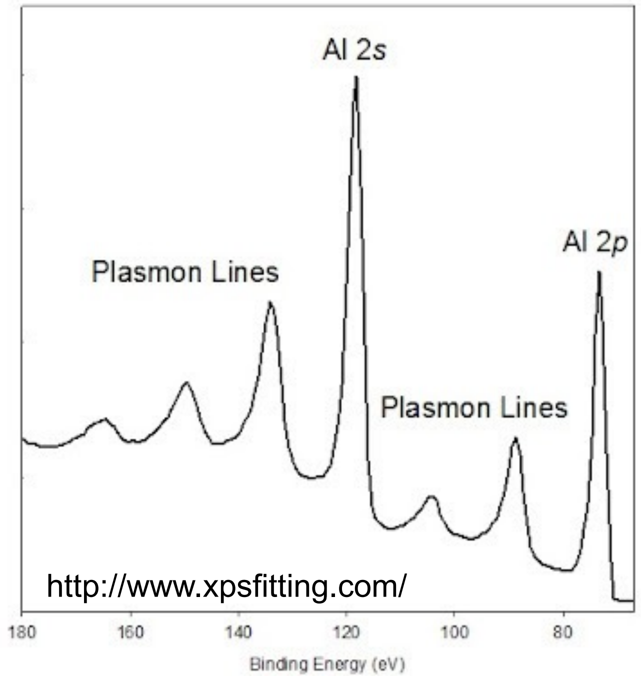


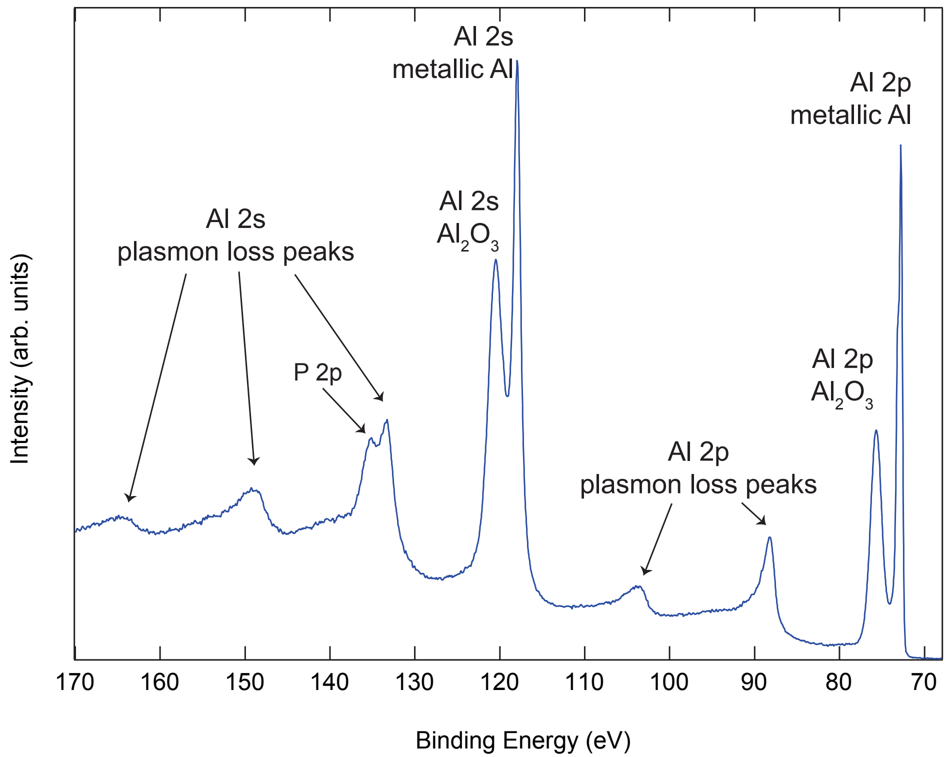


xpssimplified.com

Plasmon Loss

- Usually observed for metallic surfaces
- Outgoing photoelectron excites collective oscillations of electrons in the conduction band
- Photoelectron suffers energy loss and extra peaks appear at low KE/high BE at discrete energy values
- Can be strong for Al, which can interfere with other peaks in the region

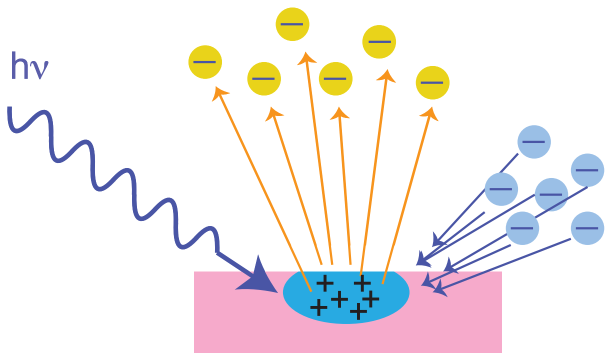


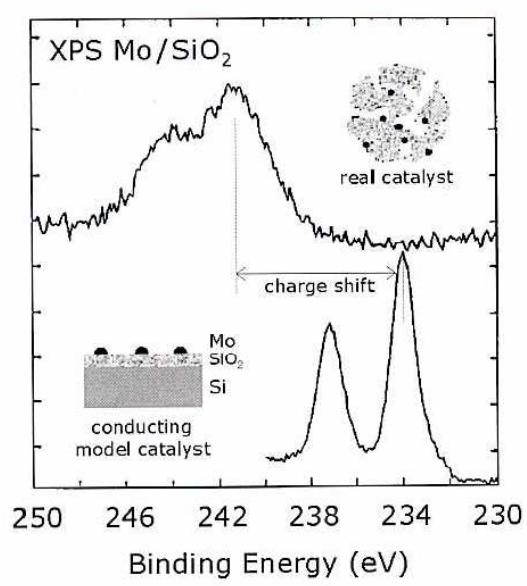


Spectra from IOS (23-ID-2) beamline, NSLS-II

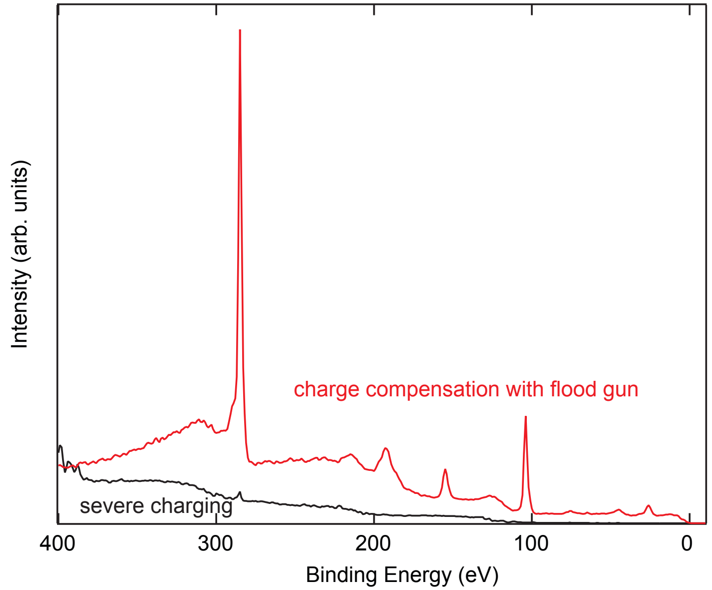
Charging and Charge Compensation

- Photoionization process causes positive charge on the surface
- For grounded electrically conductive samples, the charge is automatically neutralized
- For semi-conductive and insulating samples, the positive charge accumulates, photoelectron KE decreases
- Effect: shift to higher BE, peak broadening, double peaks, sometimes no peaks at all
- Charge compensation: add electrons back to the sample (use an electron flood gun, or with the presence of ambient gases)





J. W. Niemantsverdriet, Spectroscopy in Catalysis: An Introduction, 3rd. ed. Wiley (2007)



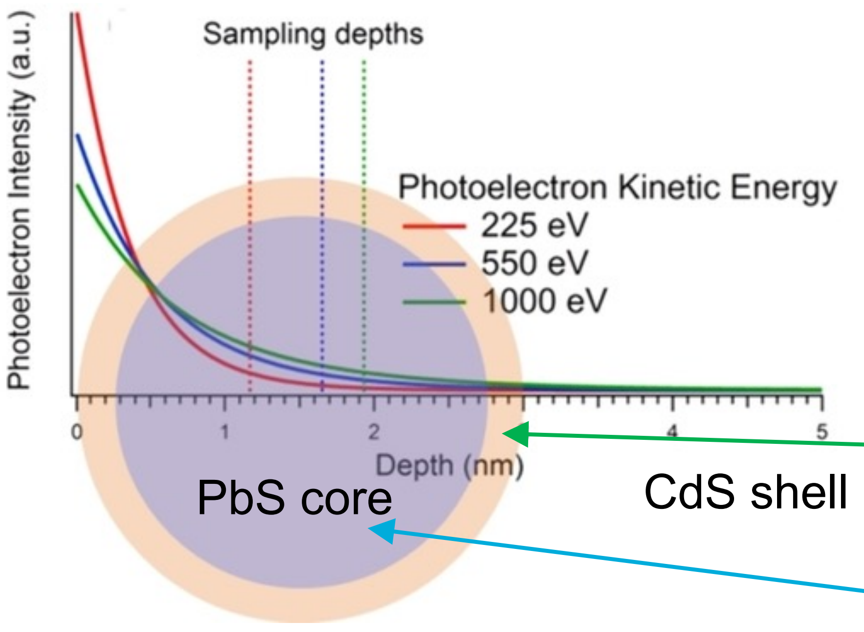
Spectra from IOS (23-ID-2) beamline, NSLS-II

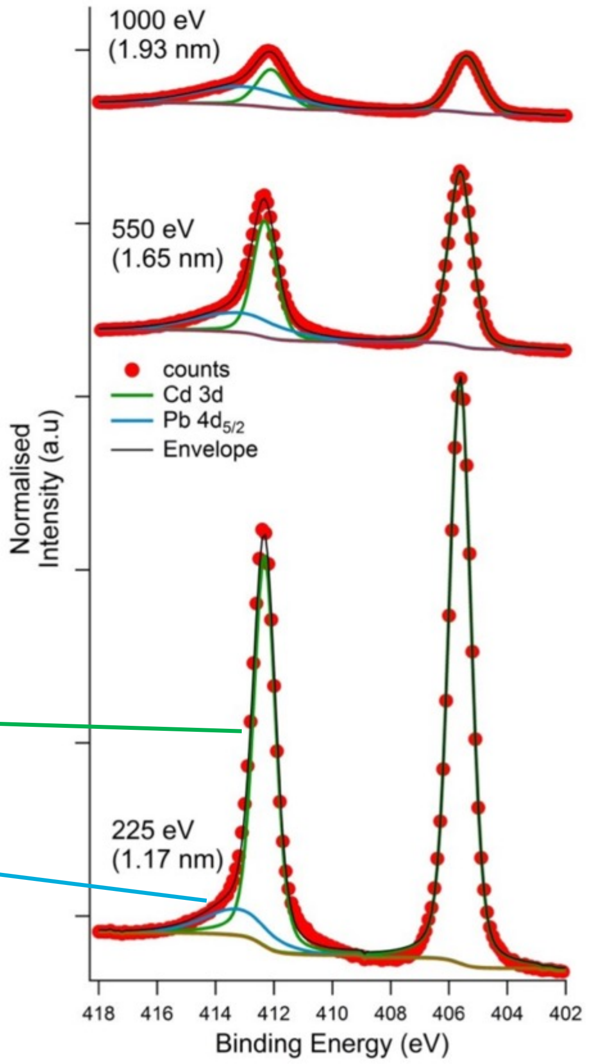
Part 3

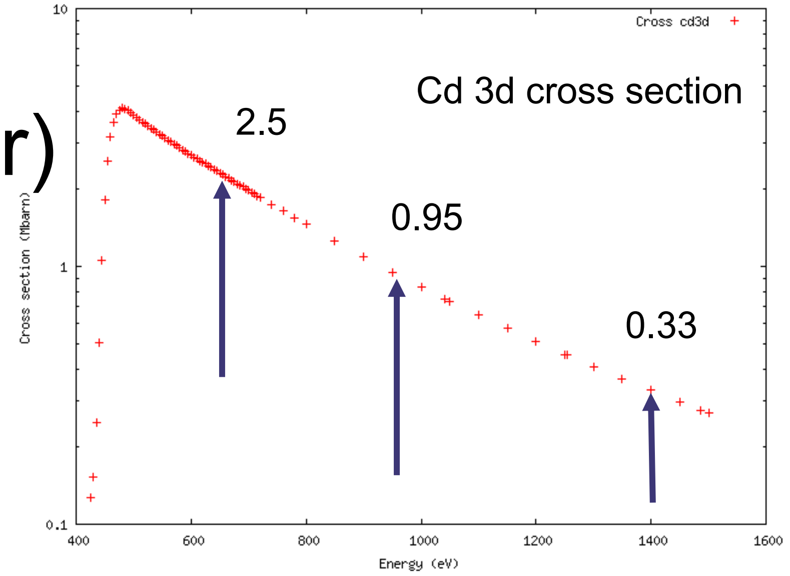
Recent Research Examples

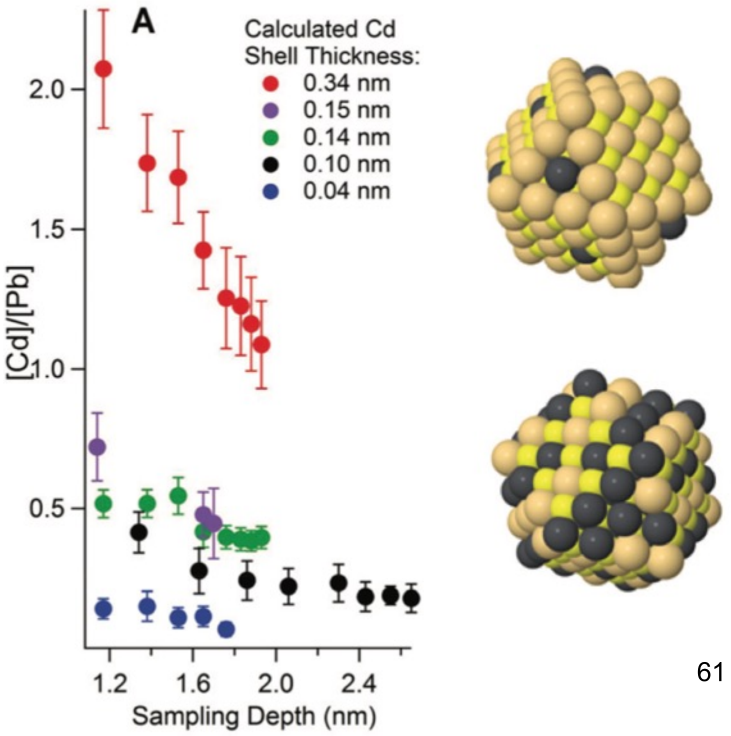
Studying Quantum Dots with XPS
(Wendy Flavell, University of Manchester)

XPS was used to study the passivating effect of Cd in PbS/CdS colloidal quantum dots



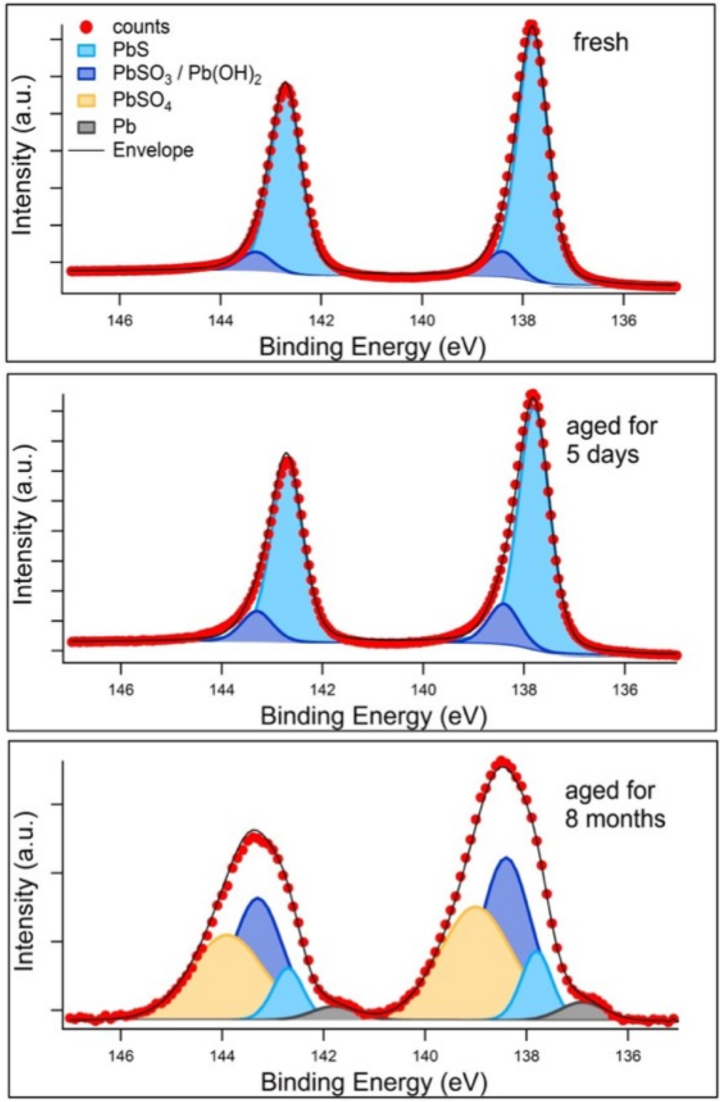


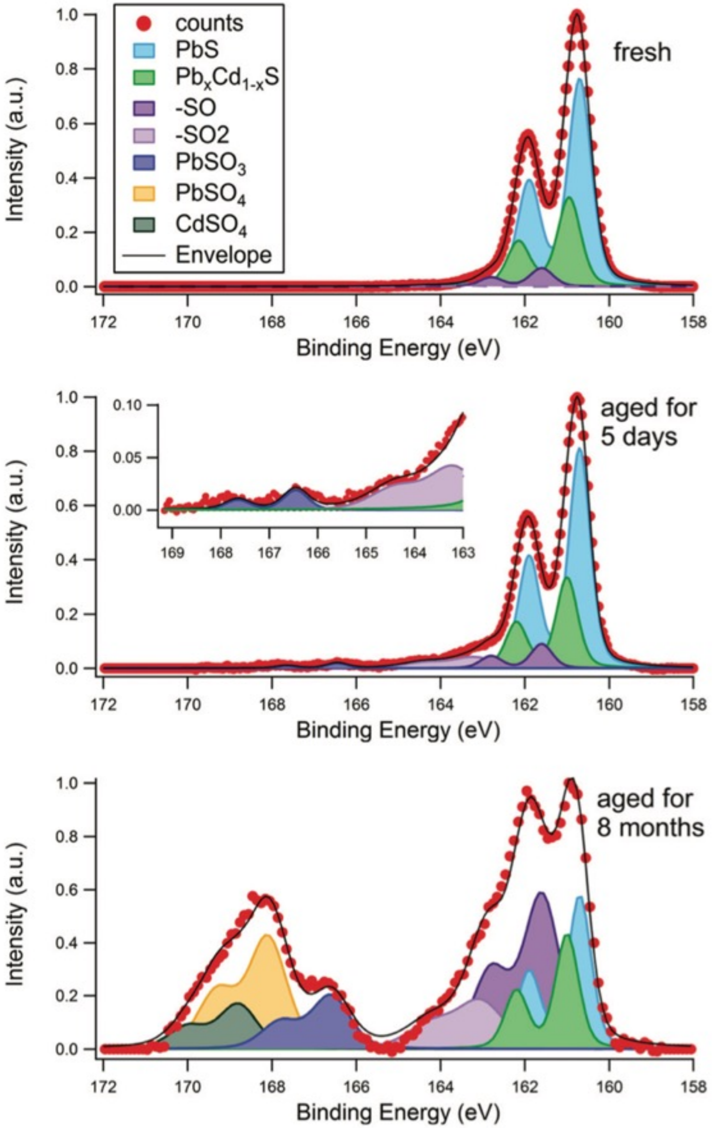


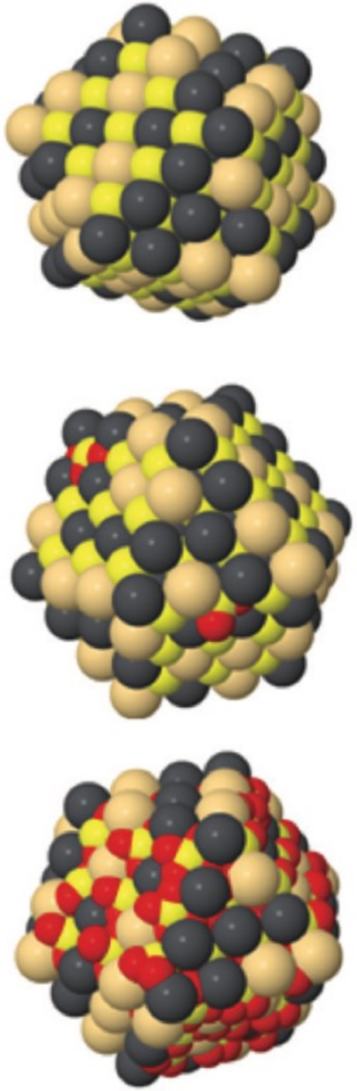


Clark et al. Nanoscale, 9, 6056–6067 (2017)

The Effect of Aging in Air

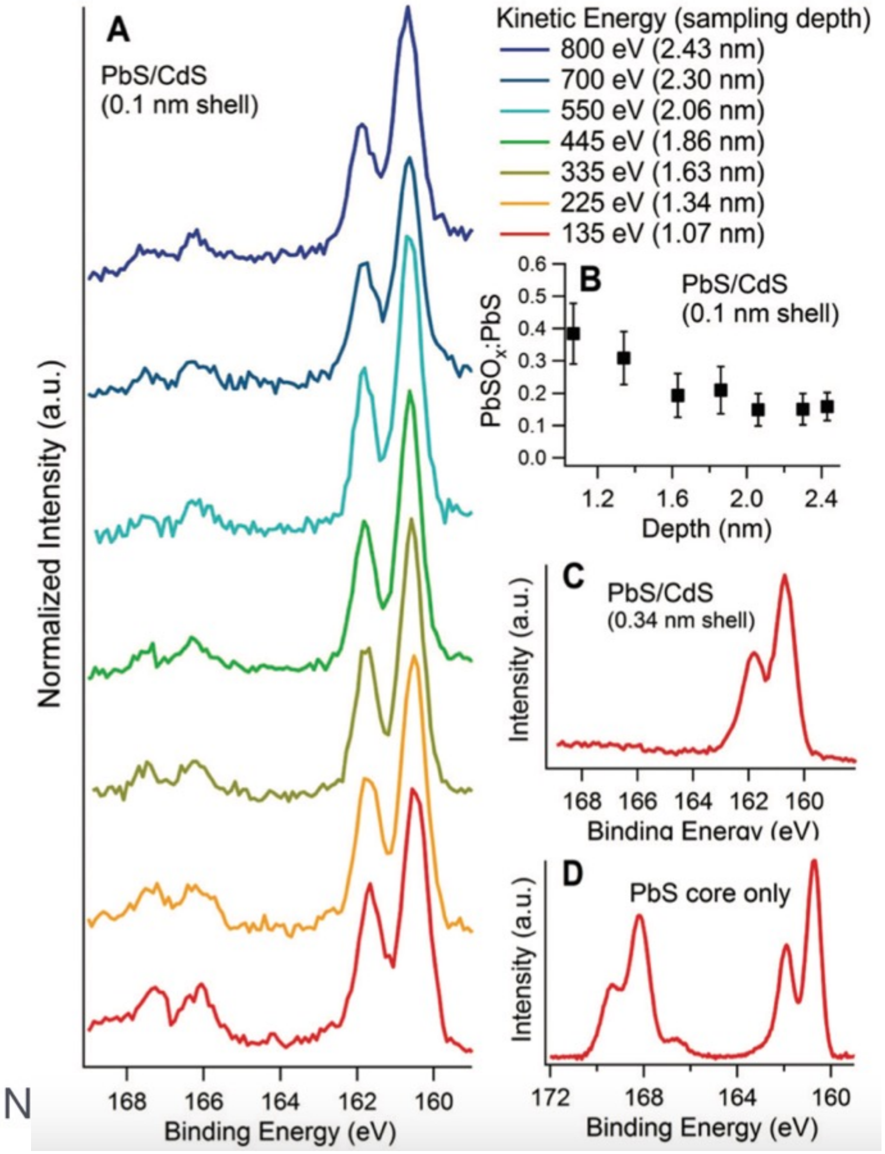


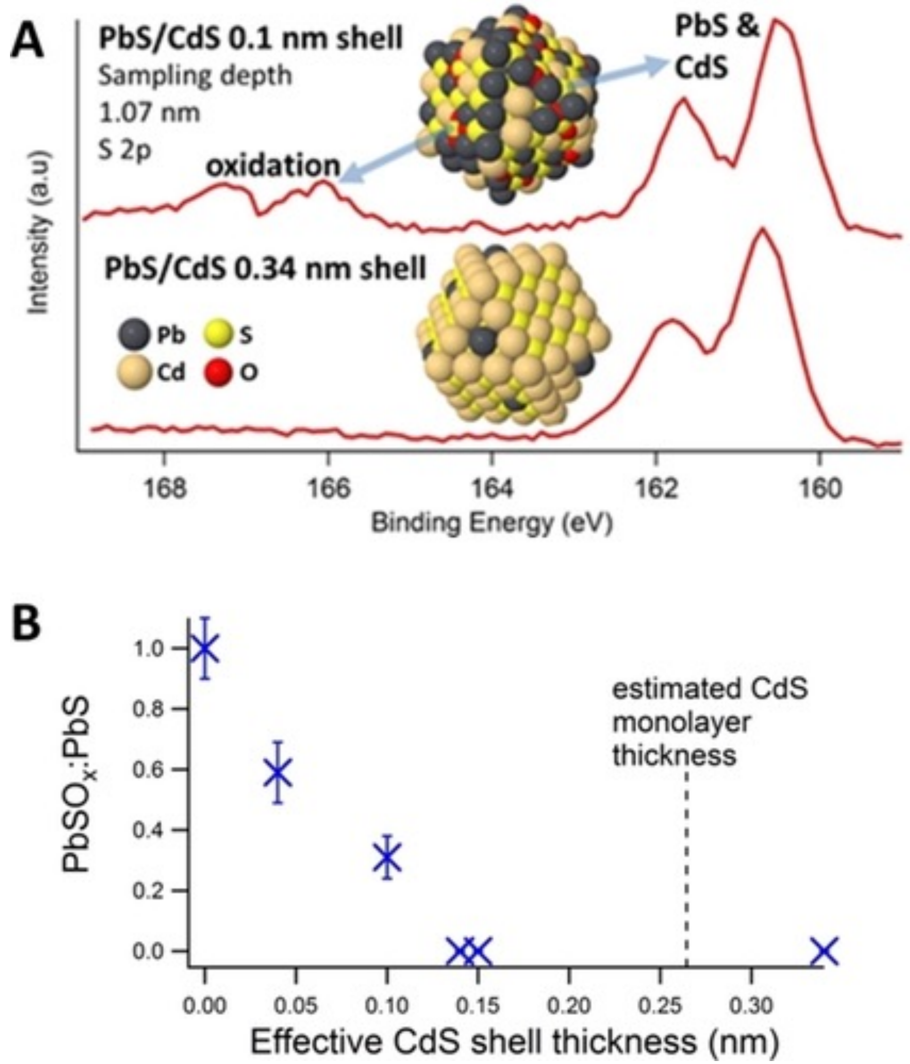




Clark et al. Nanoscale, 9, 6056–6067 (2017)

Passivating Effect of Cd

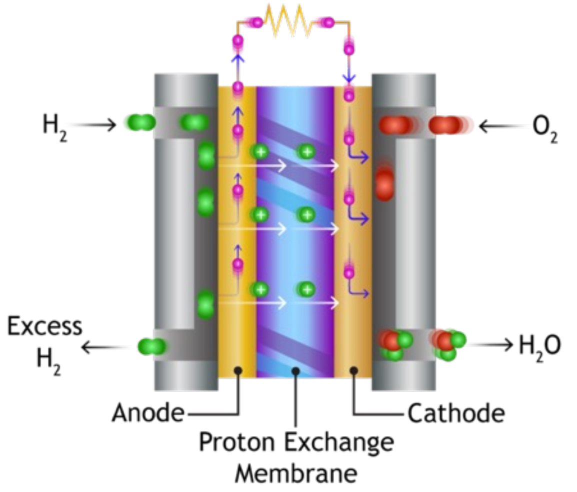




Clark et al. Nanoscale, 9, 6056–6067 (2017)

Single-Atom Catalysis

thermofisher.com

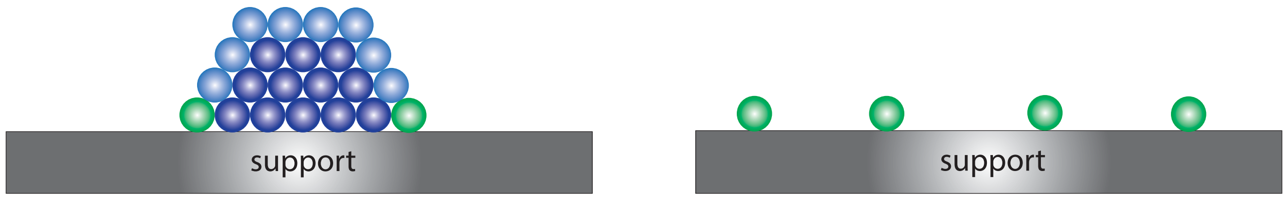


https://web.stanford.edu/group/frankgroup/

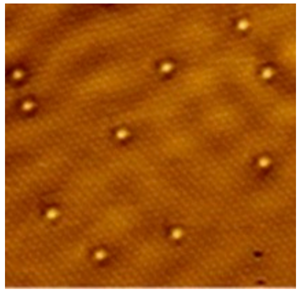
Metal	Price per oz
Pt	$978
Pd	$1,440
Rh	$10,100
Ni	$0.70
Cu	$0.28

www.dailymetalprice.com (updated March 2023)

- Precious metals (e.g. Pt, Pd, Rh) are highly active but expensive catalysts
- Single-atom catalyst approach: minimize the amount of active but expensive catalyst (e.g. Pt) by supporting it on a cheaper and more abundant material
- Reduces cost and optimize catalytic efficiency

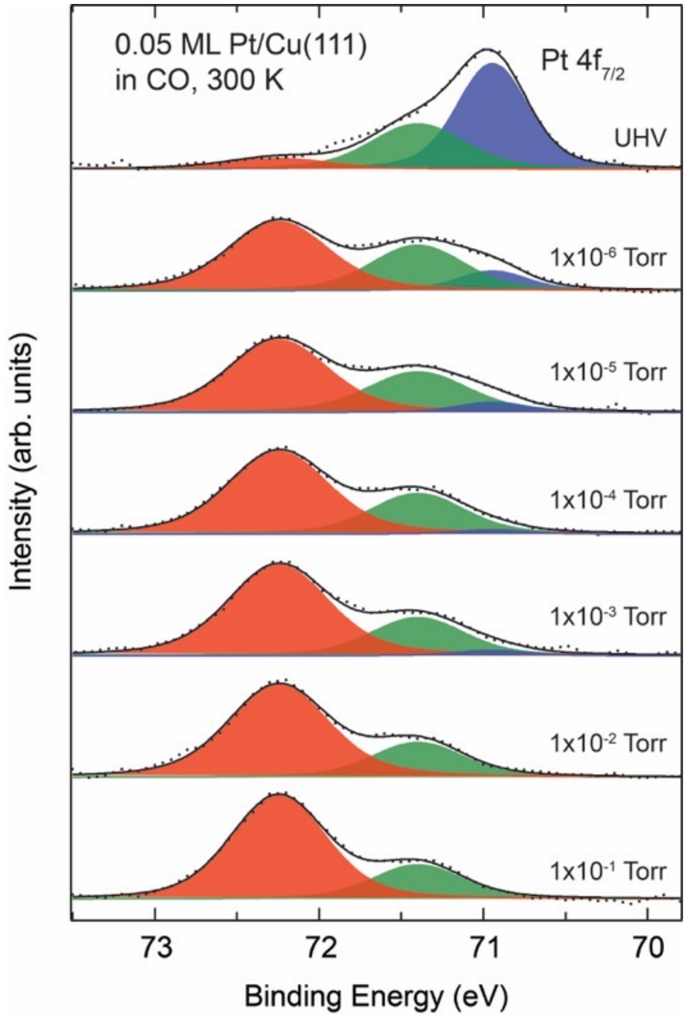


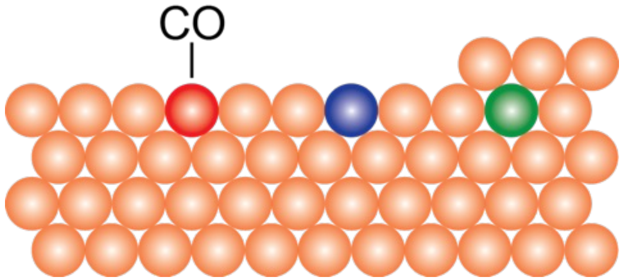
PtCu single atom alloy (SAA) → < 5% Pt forms isolated Pt atoms alloyed in the top layer of Cu metal



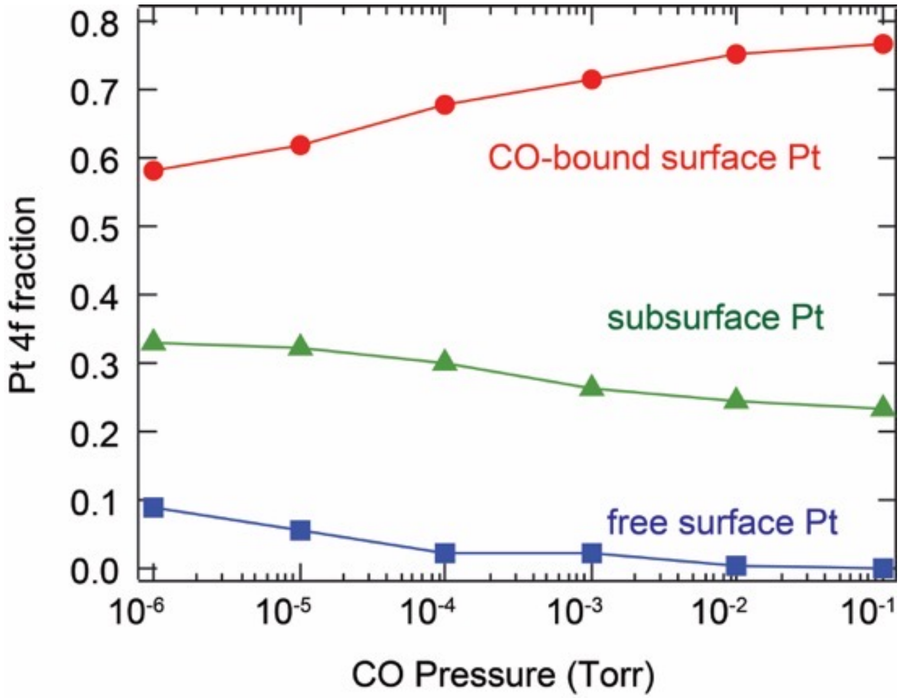
Hannagan et al. Chem. Rev. 120, 12044 (2020)

CO Adsorption on PtCu Single-Atom Alloy





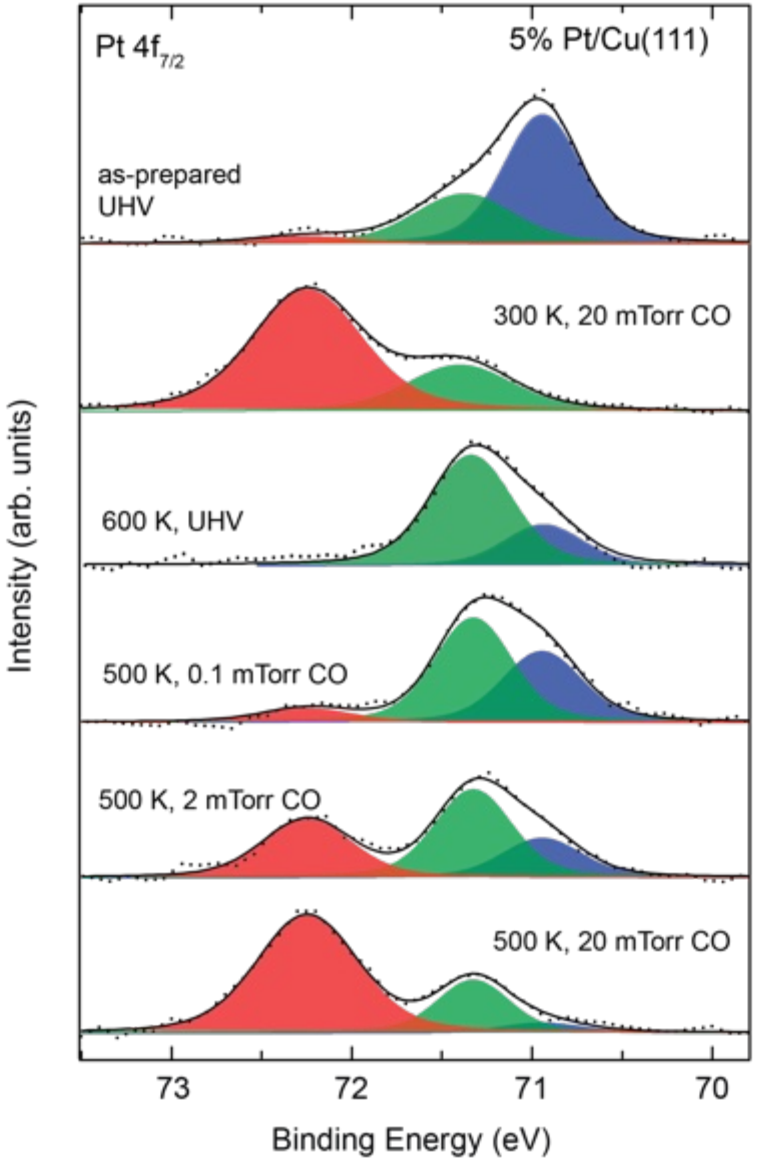
Three types of Pt atoms:
- Free surface Pt
- CO-bound surface Pt
- Subsurface Pt

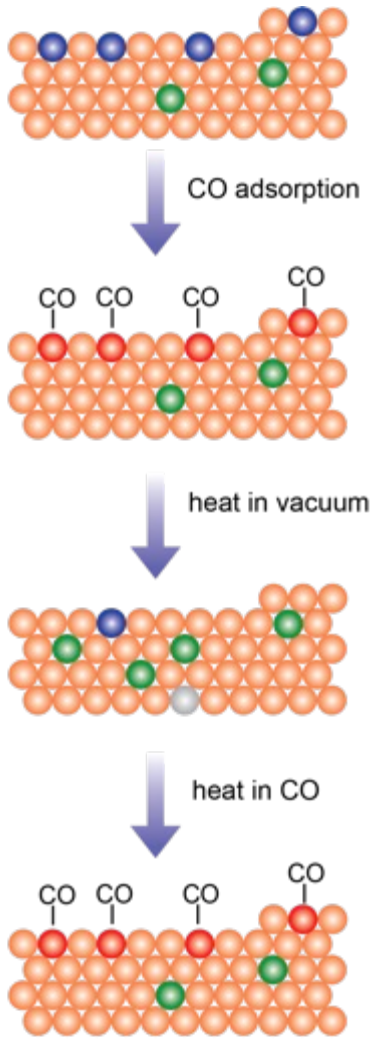


Simonovis et al. J. Phys. Chem. C 122, 4488 (2018)

Dynamic Surface State of PtCu SAA

- AP-XPS can track changes in the surface and near surface composition
- Heating in vacuum causes loss of active surface Pt
- Pt moves to subsurface and bulk of Cu
- Heating in CO causes surface segregation of Pt back up to the surface
- Initial surface composition is recovered



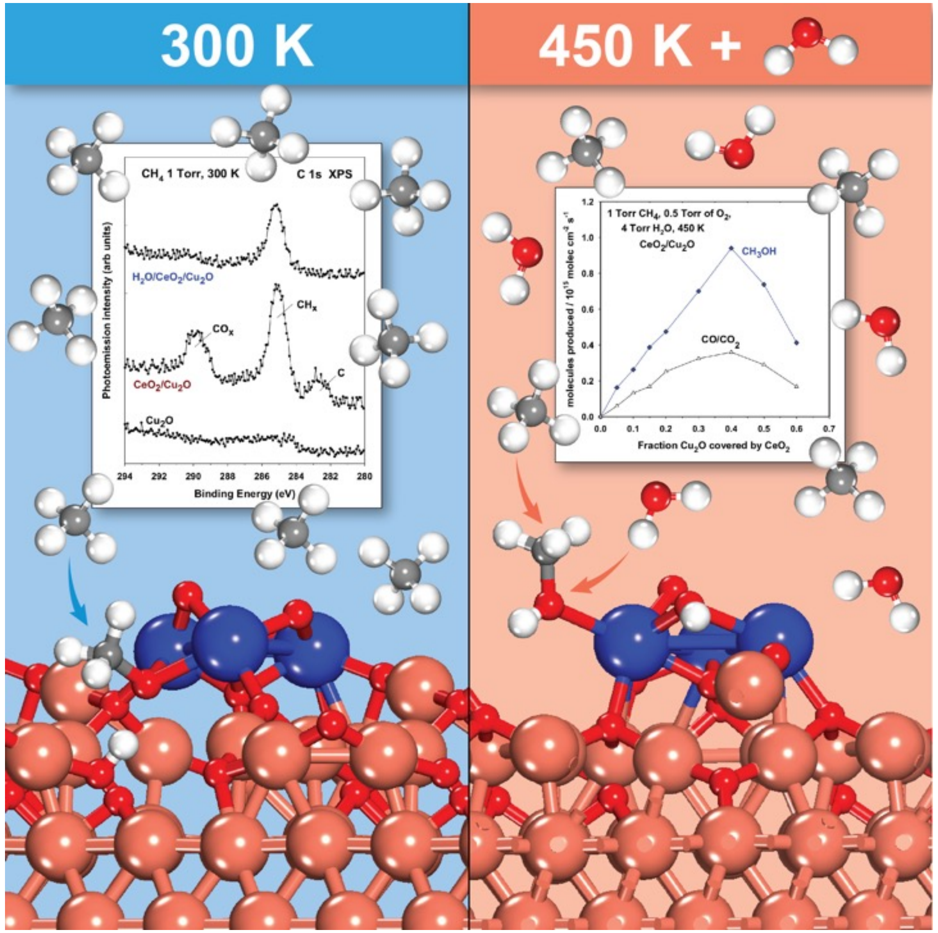


Simonovis et al. J. Phys. Chem. C 122, 4488 (2018)

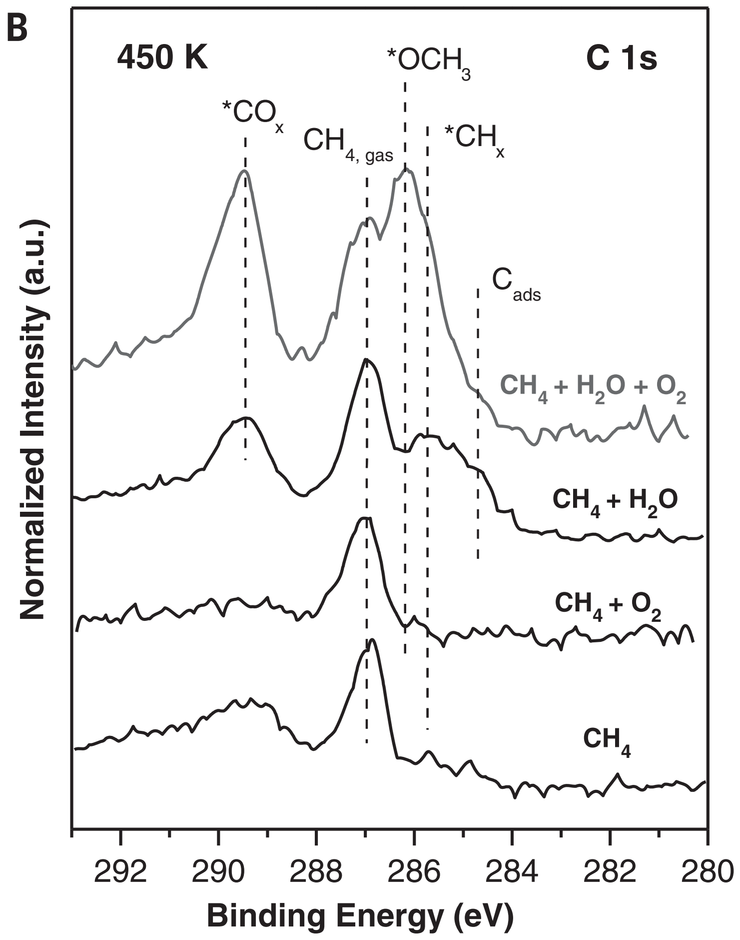
Watching Catalyst in Action (CRS Group, BNL Chemistry)

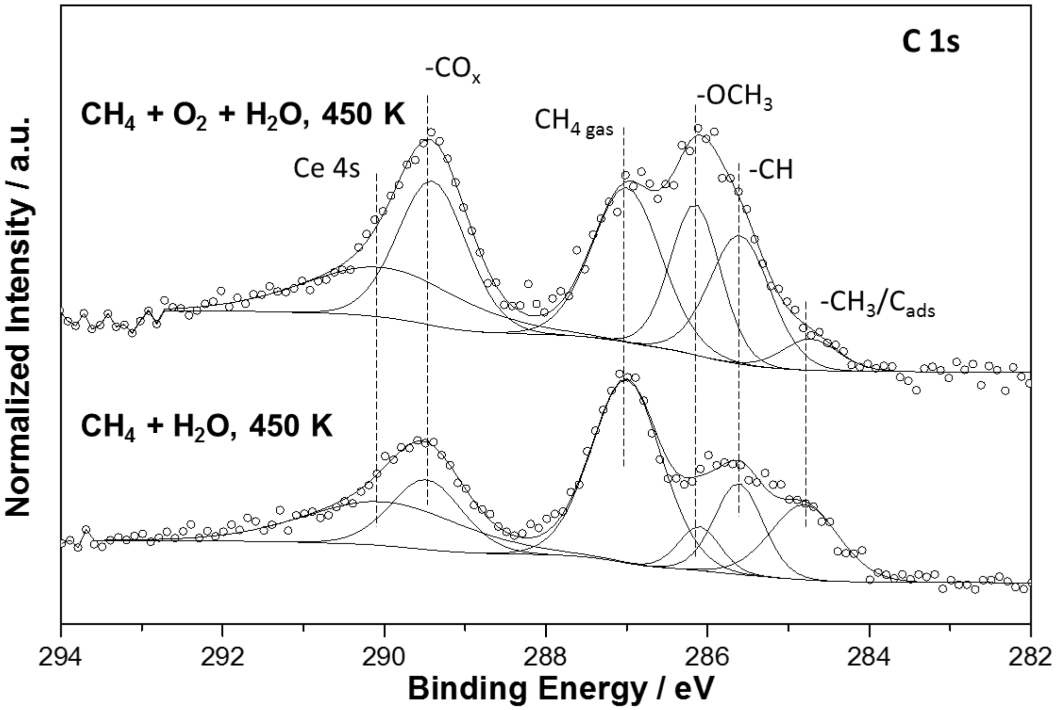
- Methane oxidation to methanol is a difficult process that requires high temperatures (600 K)
- A new catalyst was developed for low temperature methane oxidation promoted by water
- The catalyst: $CeO_2/Cu_2O/Cu(111)$
- The reactants: $CH_4 + O_2 + H_2O$
- How does this catalyst work?
- AP-XPS is a powerful tool for identifying reaction intermediates

Zuo et al. J. Am. Chem. Soc. 138, 13810 (2016)
https://www.bnl.gov/newsroom/news.php?a=26694



Converting Methane to Methanol

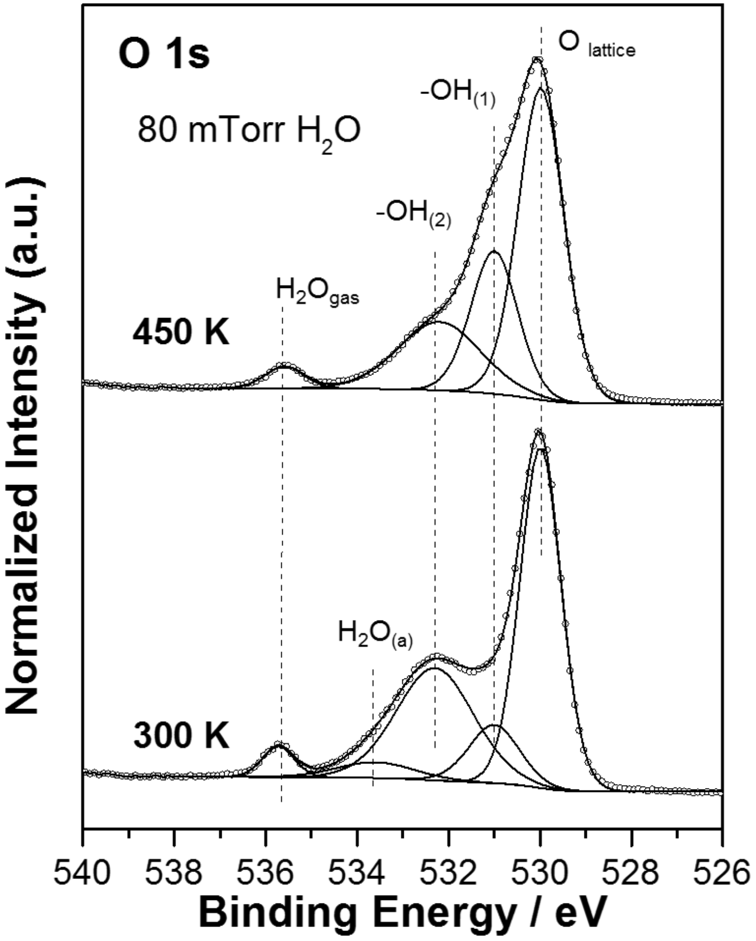


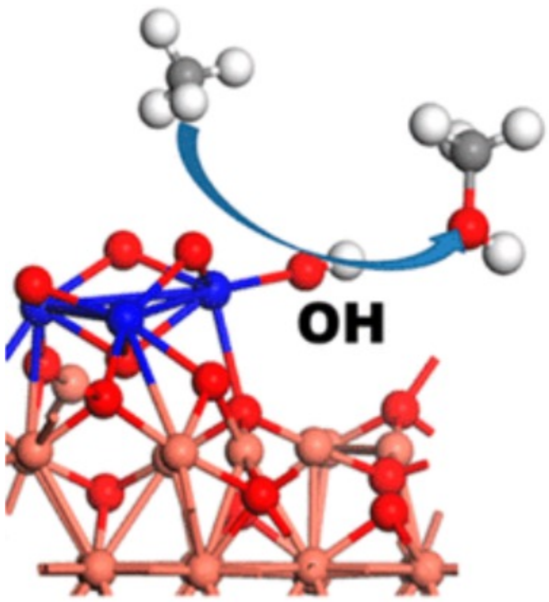


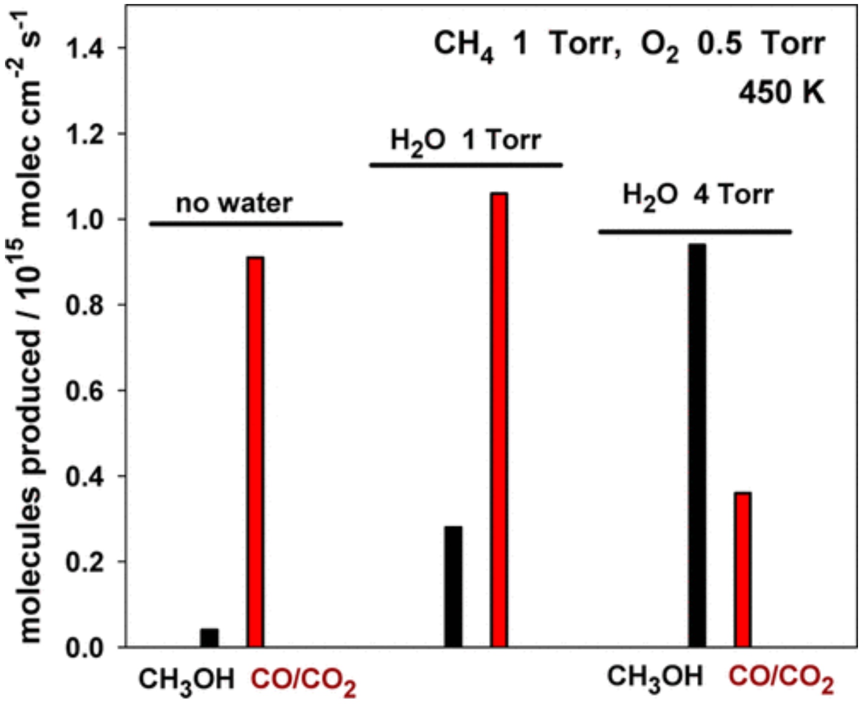
The formation of methoxy (precursor to methanol) is enhanced in the presence of water

Liu et al. Science, 368, 513 (2020)

Converting Methane to Methanol



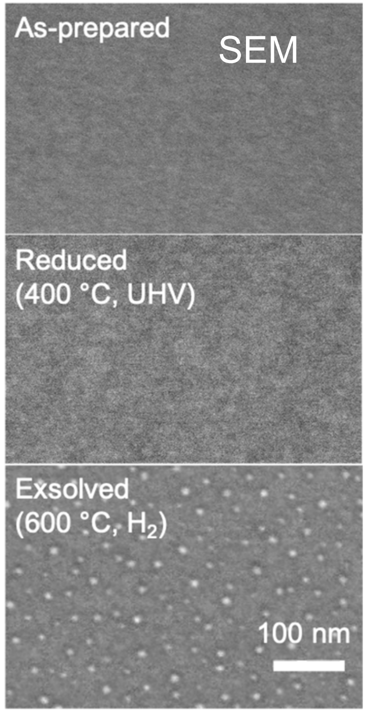


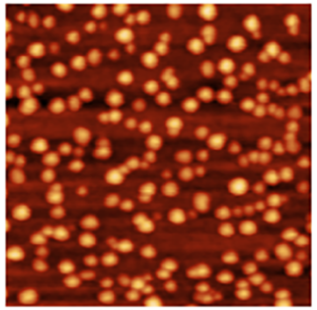


- Water is dissociated to hydroxide species on the surface

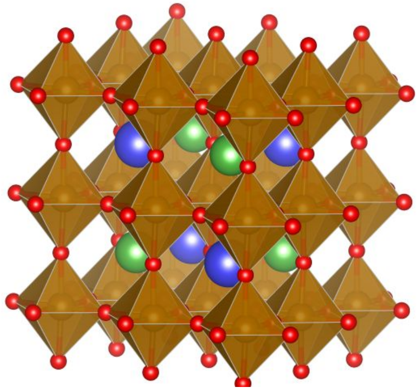
Zuo et al. J. Am. Chem. Soc. 138, 13810 (2016)
Liu et al. Science, 368, 513 (2020)

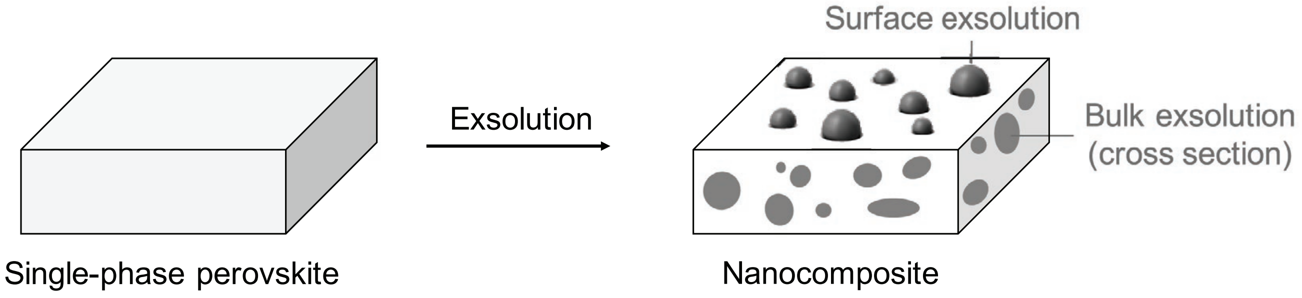
Metal exsolution from perovskites - Yildiz group (MIT)





AFM

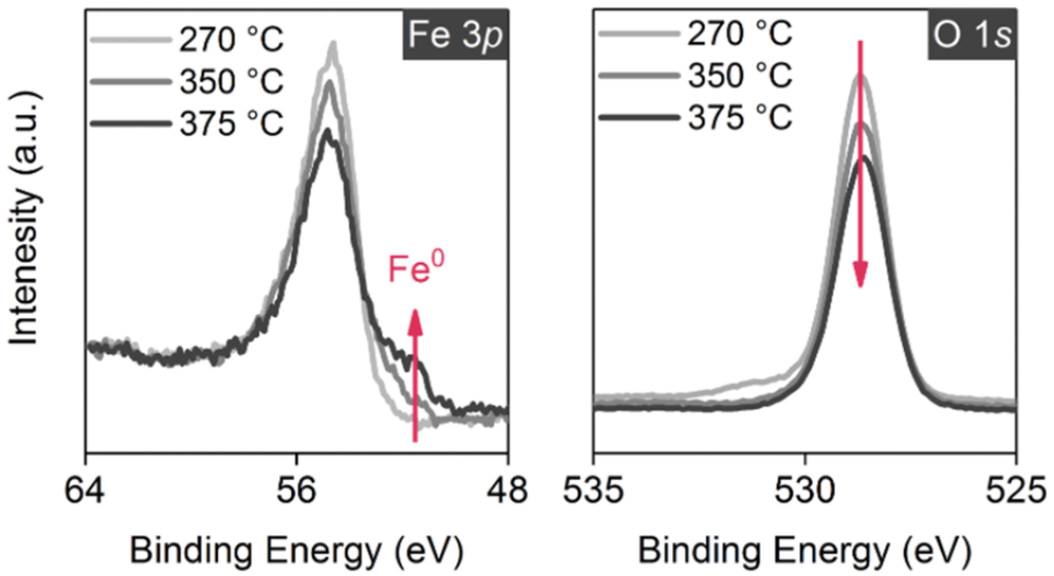


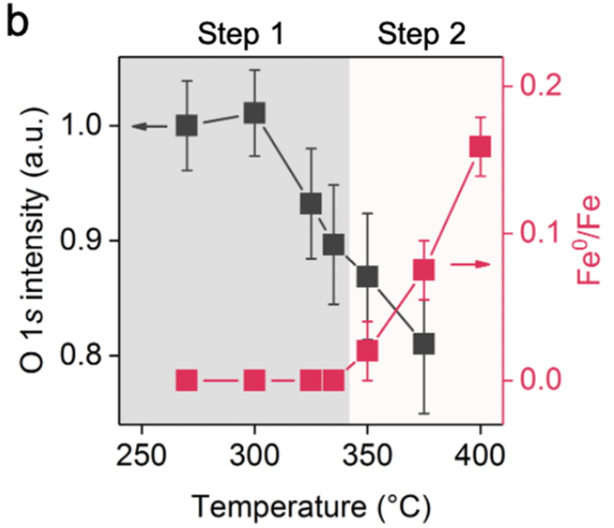


- Metals can exsolve from bulk perovskite under high temperature reduction condition, forming stable nanoparticles on the surface
- Synthesis method for highly stable, oxide-supported metal nanoparticles with applications in energy conversion and storage technologies
- Metal nanoparticles are uniformly distributed and resistant to agglomeration

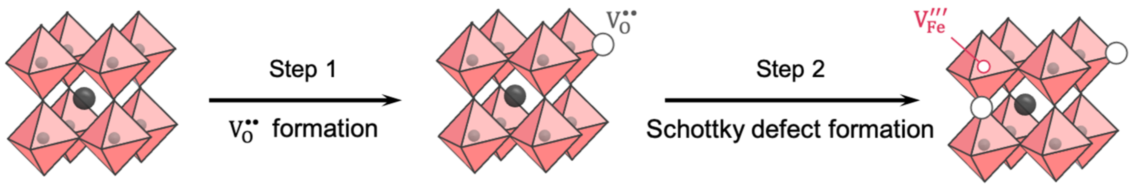
Wang et al. Chem. Mater. 33, 5021 (2021), Adv. Funct. Mater. 32, 2108005 (2022), Chem. Mater. 34, 5138 (2022)

Mechanism of Fe exsolution



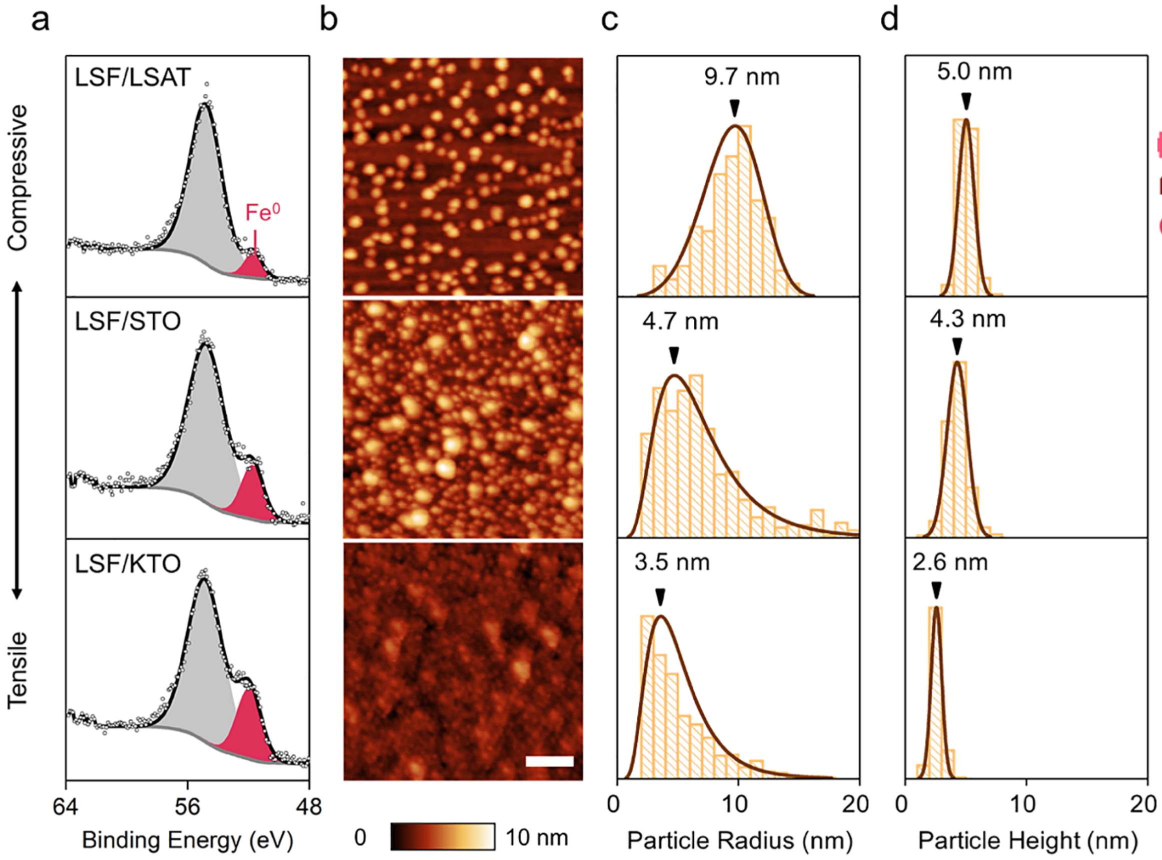


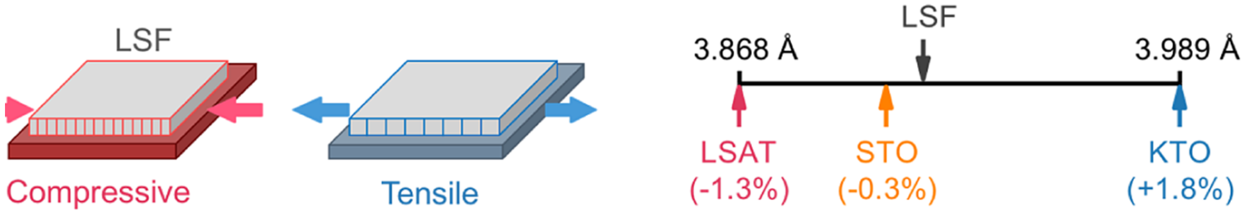
- Exsolution of Fe nanoparticles from $La_{0.6}Sr_{0.4}FeO_3$ (LSF) was studied in operando with combined AP-XPS and AP-XAS
- AP-XPS reveals a two step process for Fe exsolution: O vacancy formation, followed by metallic Fe precipitation

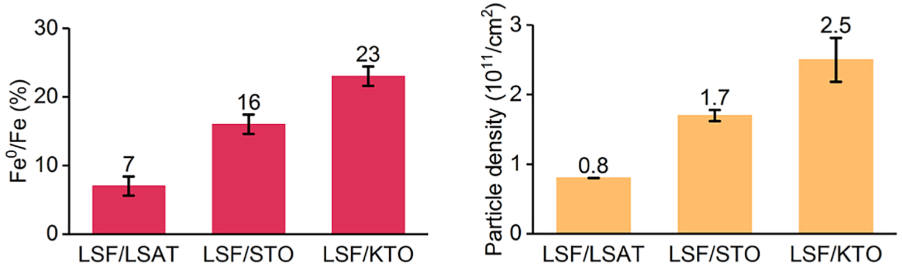


Wang et al. Chem. Mater. 33, 5021 (2021), Adv. Funct. Mater. 32, 2108005 (2022), Chem. Mater. 34, 5138 (2022)

Tuning Fe exsolution



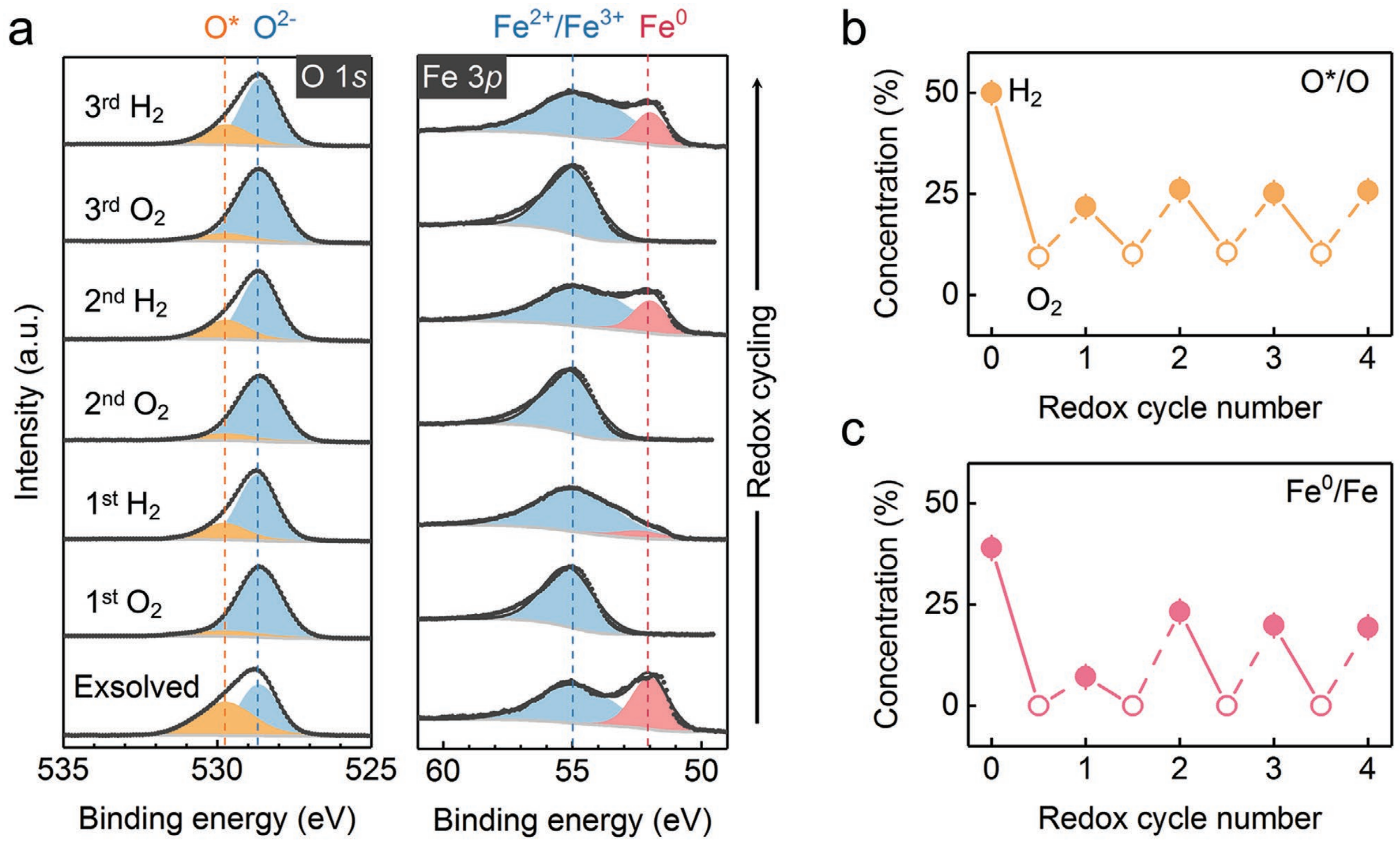




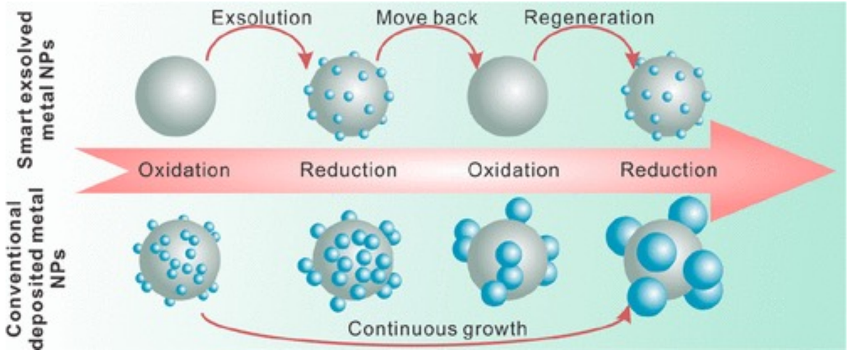
- Fe exsolution can be controlled by tuning lattice strain
- Different substrates with different strains result in different concentration, density, and size of exsolved Fe

Wang et al. Chem. Mater. 33, 5021 (2021), Adv. Funct. Mater. 32, 2108005 (2022), Chem. Mater. 34, 5138 (2022)

Redox Cycling of Exsolved LSF



- Exsolved Fe on LSF is stable under repeated oxidation and reduction cycles



Wang et al. Chem. Mater. 33, 5021 (2021), Adv. Funct. Mater. 32, 2108005 (2022), Chem. Mater. 34, 5138 (2022)

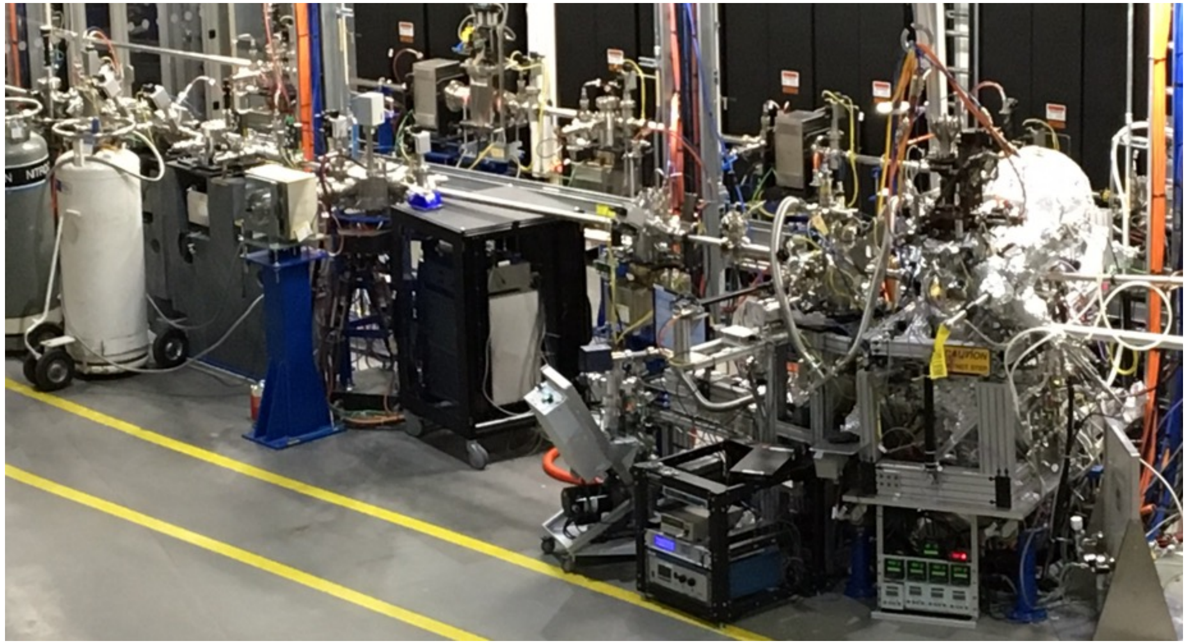
Summary

- XPS is a powerful technique for the surface characterization of materials
- It provides:
    - Elemental specificity
    - Chemical sensitivity
    - Depth profiling
    - Quantitative analysis
- Synchrotron-based XPS offers high flux, high resolution, and energy tunability
- Aspects that affect data interpretation: overlaps with Auger peaks, shake-up/off, multiplet splitting, plasmon peaks, charging
- XPS usually needs UHV conditions, but ambient pressure XPS can be performed for in situ/operando experiments

Useful Online Resources

- X-ray data booklet: https://xdb.lbl.gov
- Photoionization cross-section: https://vuo.elettra.eu/services/elements/WebElements.html
- NIST XPS Database: https://srdata.nist.gov/xps/main_search_menu.aspx
- http://www.xpsfitting.com
- https://xpssimplified.com/periodictable.php
- http://www.casaxps.com/ebooks/XPS%20AES%20Book%20new%20margins%20rev%201.2%20for%20web.pdf – CasaXPS is a popular XPS data analysis software. Their manual has a lot of useful basic information about XPS

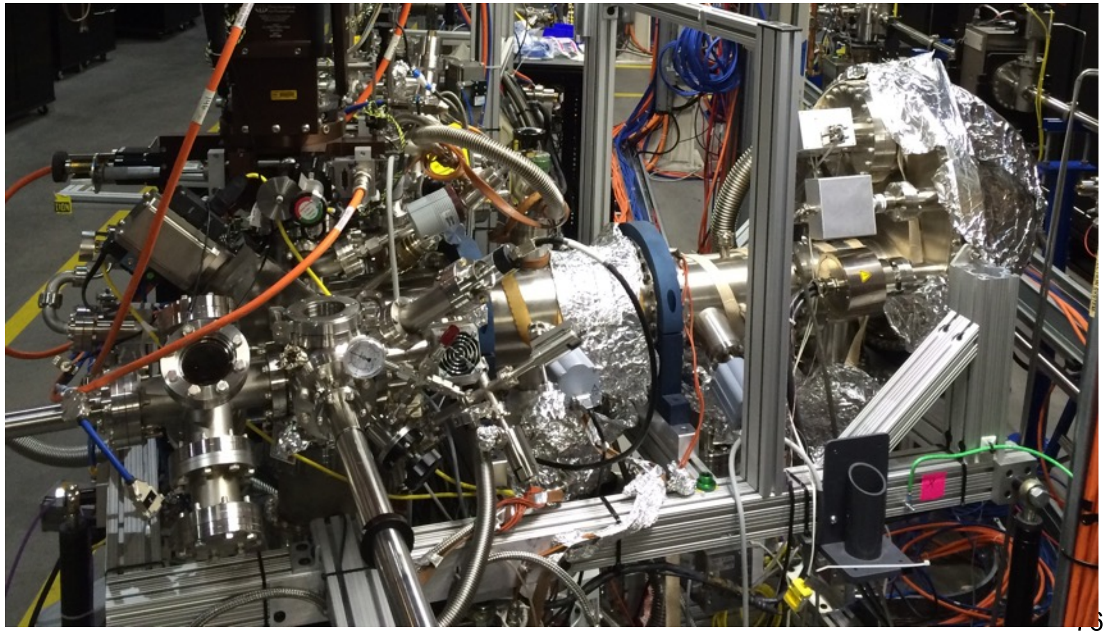
AP-XPS at IOS (23-ID-2) Beamline, NSLS-II



- Pressure = UHV to 10 Torr
- Sample temperature: RT to 900℃
- Sputter gun, flood gun, metal evaporator, RGA mass spec

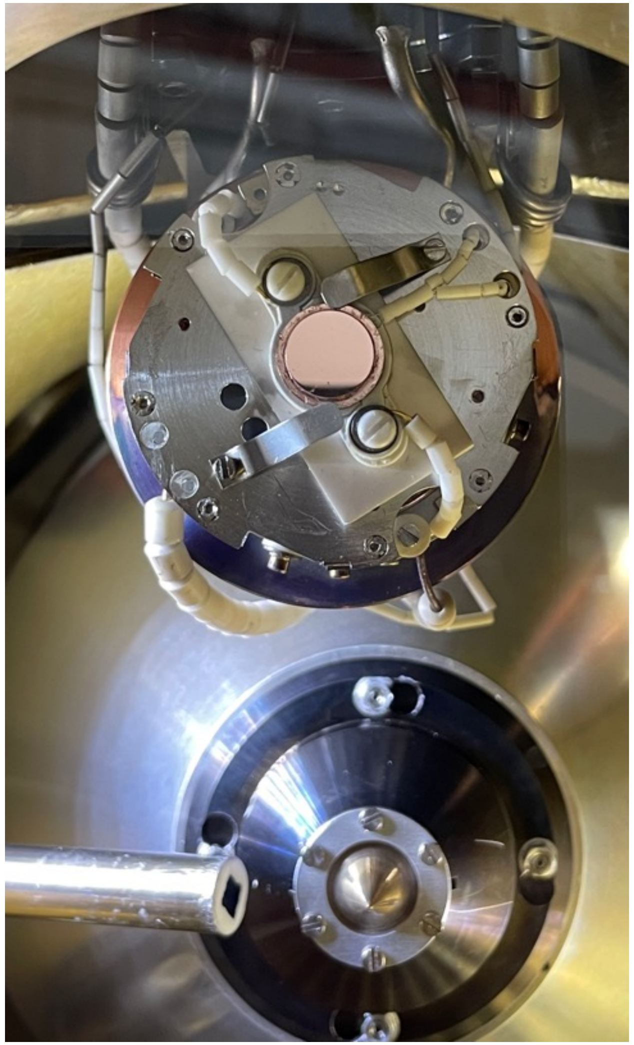
- Samples: single crystals, thin films, powders
- Gases: H_2, O_2, CO, CO_2, noble gases, C1-C4 hydrocarbons, water vapor, C1-C3 alcohol vapors

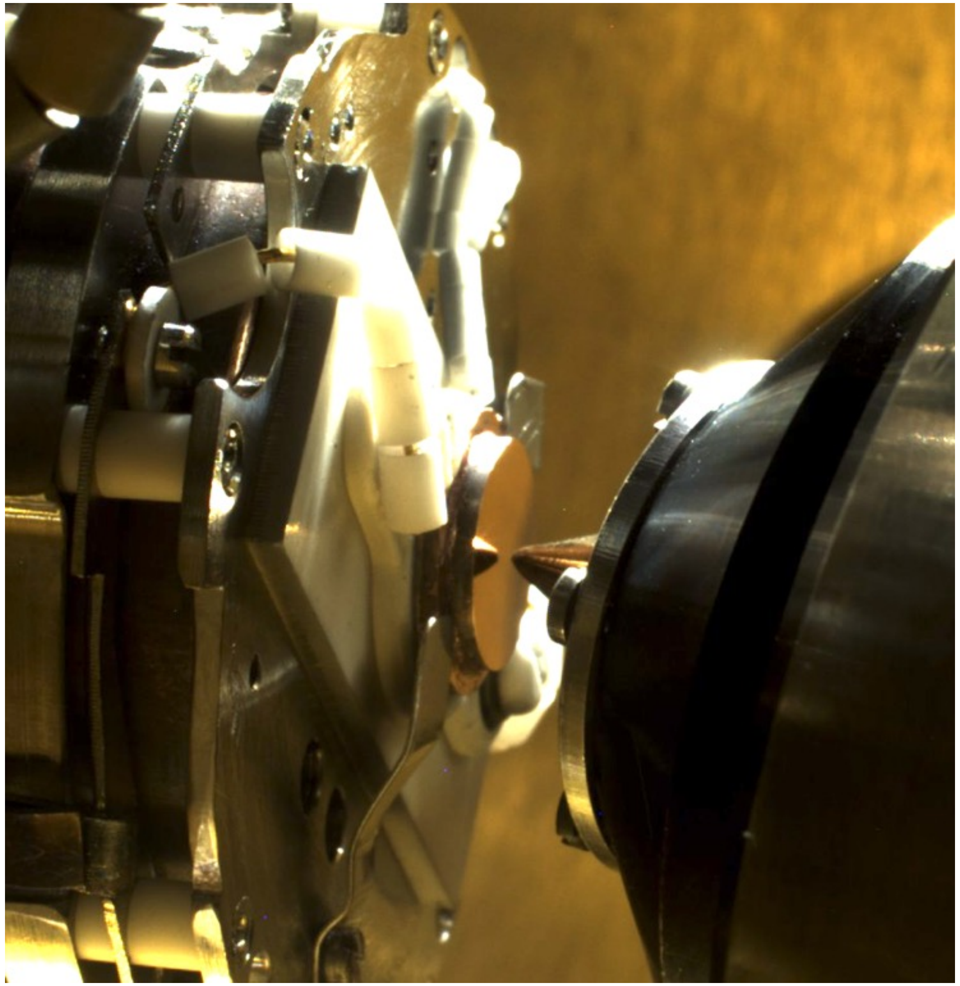
https://www.bnl.gov/nsls2/beamlines/beamline.php?r=23-ID-2



Photos from IOS (23-ID-2) beamline, NSLS-II

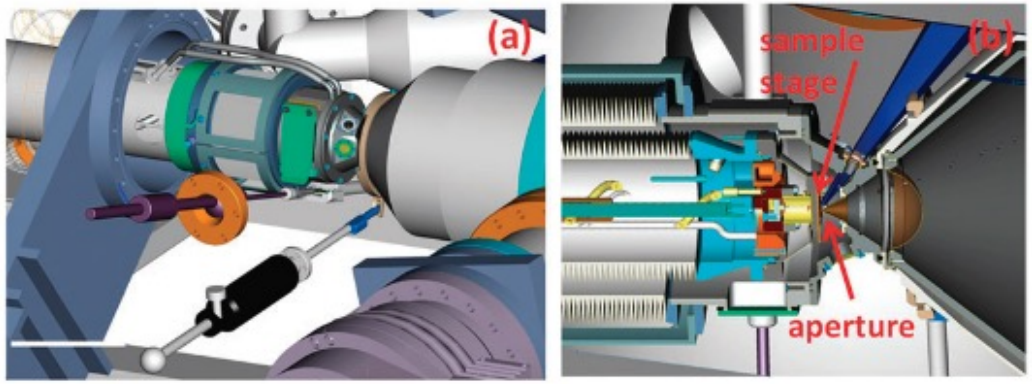
AP-XPS at IOS Beamline, NSLS-II



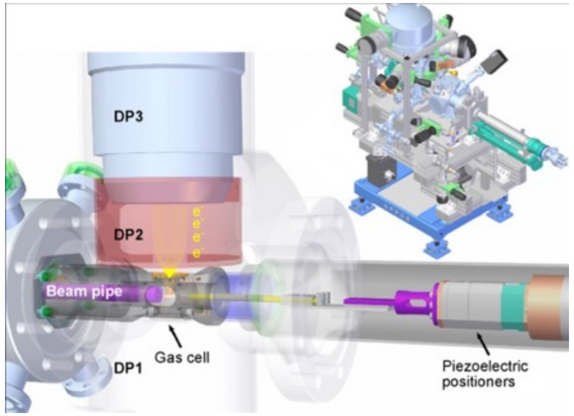


Photos from IOS (23-ID-2) beamline, NSLS-II

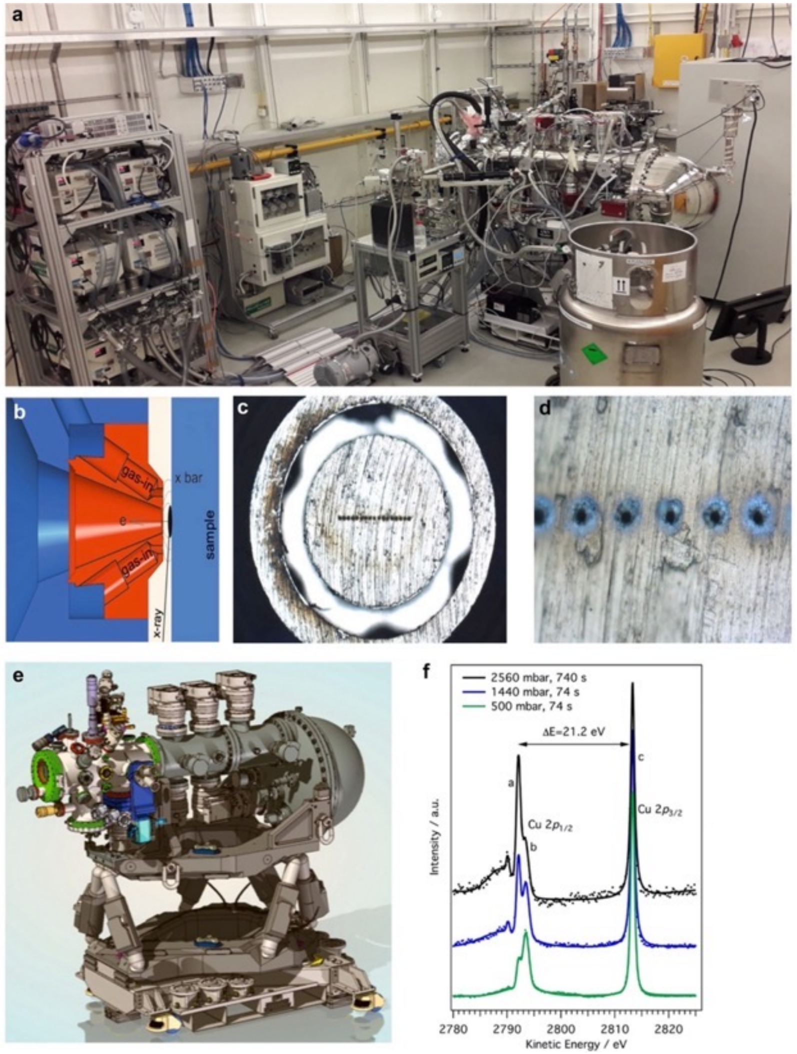
Other AP-XPS Setups



commercial high pressure cell from SPECS
specs-group.com



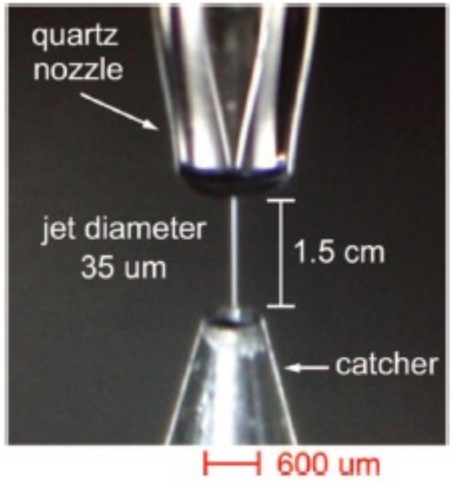
custom high pressure cell at SSRL
Kaya et al, Catal. Today 205, 101 (2013)

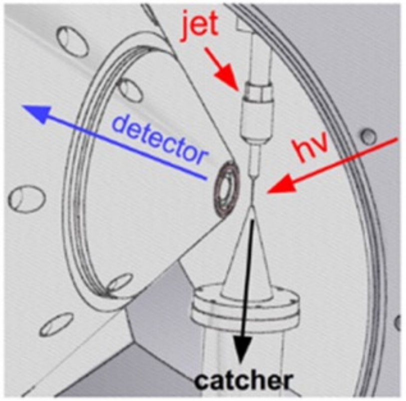


POLARIS AP-HAXPES at PETRA III, DESY
Degerman et al. Synchrotron Radiat. News, 35, 11-18 (2022)

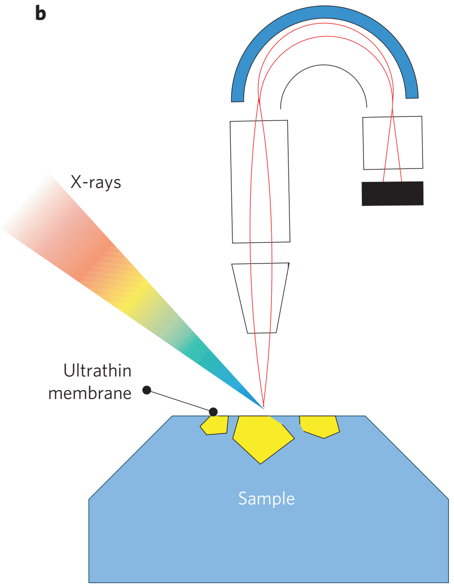
Liquid AP-XPS Setups

Liquid microjet

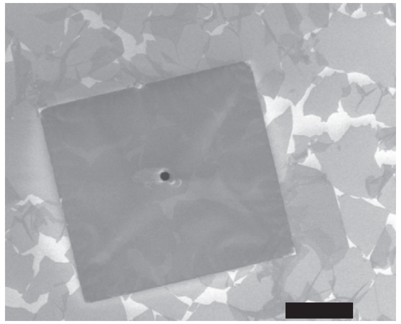




Brown et al., Nano Letters 13, 5403 (2013)

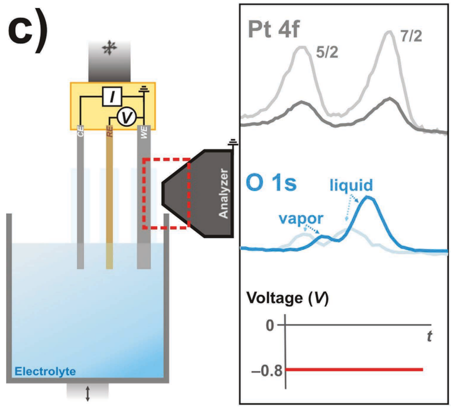


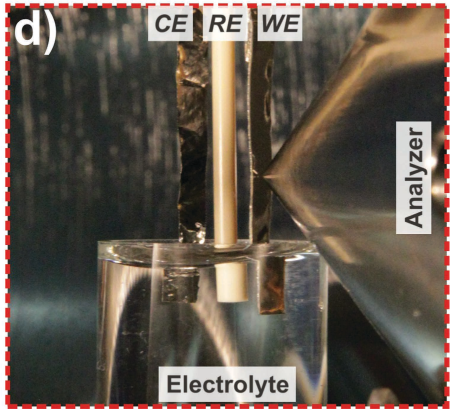
Graphene oxide window



Kolmakov et al. Nature Nanotech. 6, 651 (2011)

“Dip and pull” method





Axnanda et al. Scientific Reports 5, 09788 (2015)