X-ray absorption spectroscopy as a structural probe of dynamics in fuel cell and battery systems

Carlo Segre

Physics Department
&
Center for Synchrotron Radiation Research and Instrumentation
Illinois Institute of Technology

September 28, 2017

What's a physicist doing speaking at an analytical chemistry seminar?

Carlo Segre

Physics Department
&
Center for Synchrotron Radiation Research and Instrumentation
Illinois Institute of Technology

September 28, 2017

Outline

- Introduction to CSRRI & MRCAT
- X-ray absorption spectroscopy
- Operando synchrotron fuel cells
- Methanol oxidation on a PtRu catalyst
- Ru@Pt core-shell methanol catalysts
- Sn anodes for Li-ion batteries
- Accelerated capacity fading studies
- "Reversible" Sn_4P_3/graphite composite anode

CSRRI People

Tenure-Track Faculty

Carlo Segre	–	Physics
Grant Bunker	–	Physics
Jeff Terry	–	Physics
David Gidalevitz	–	Physics
Tom Irving	–	Biology
Andy Howard	–	Biology
Joseph Orgel	–	Biology
Adam Hock	–	Chemistry

Beamline Staff

John Katsoudas	–	MRCAT
Al Kwiatkowski	–	MRCAT
Bill Lavender	–	MRCAT
Weikang Ma	–	BioCAT
Carrie Clark	–	BioCAT
Rick Heurich	–	BioCAT
Mark Vukonich	–	BioCAT
Zou Finfrock	–	CLS@APS
Matt Ward	–	CLS@APS

Research Faculty

Jim Kaduk	–	Chemistry
Elena Timofeeva	–	Chemistry
Srinivas Chakravarthy	–	Biology
Elizabeth Friedman	–	CoS
Bhoopesh Mishra	–	Physics
Joshua Wright	–	Physics
Ali Khounsary	–	Physics
Derrick Mancini	–	Physics
Bernhard Adams	–	Physics

MRCAT - historical timeline

1993 – MRCAT started with materials physics focus
Notre Dame, Northwestern, Purdue, IIT, Amoco

1995 – Construction begins on Insertion Device line
Univ. of Florida, Argonne/CSE joins

1997 – First light on Insertion Device line

1998 – Argonne/ER joins

2002 – Honeywell, Sandia fund initial Bending Magnet line

2005 – EPA joins

2007 – UOP joins Bending Magnet line buildout begins

2009 – Bending Magnet line operational

MRCAT - present membership

Current active membership

- University of Notre Dame
- Illinois Institute of Technology
- Argonne Chemical Sci. & Eng.
- Argonne Biosciences
- Environmental Protection Agency
- UOP Honeywell
- BP p.l.c.

General users – catalysis

- UC Davis, Purdue, Penn State
- Illinois, Princeton, UCSB
- Rice, LSU, UC Berkeley, Michigan
- Wisconsin, Ohio State, MIT, ORNL
- NREL, WPAFB, Chicago,
- LANL, ...

ID Line

- XAFS (4 keV - 65 keV)
  - Continuous scan ($<$ 2 min)
  - Very dilute samples
- Microprobe
- Microdiffraction
- HAXPES

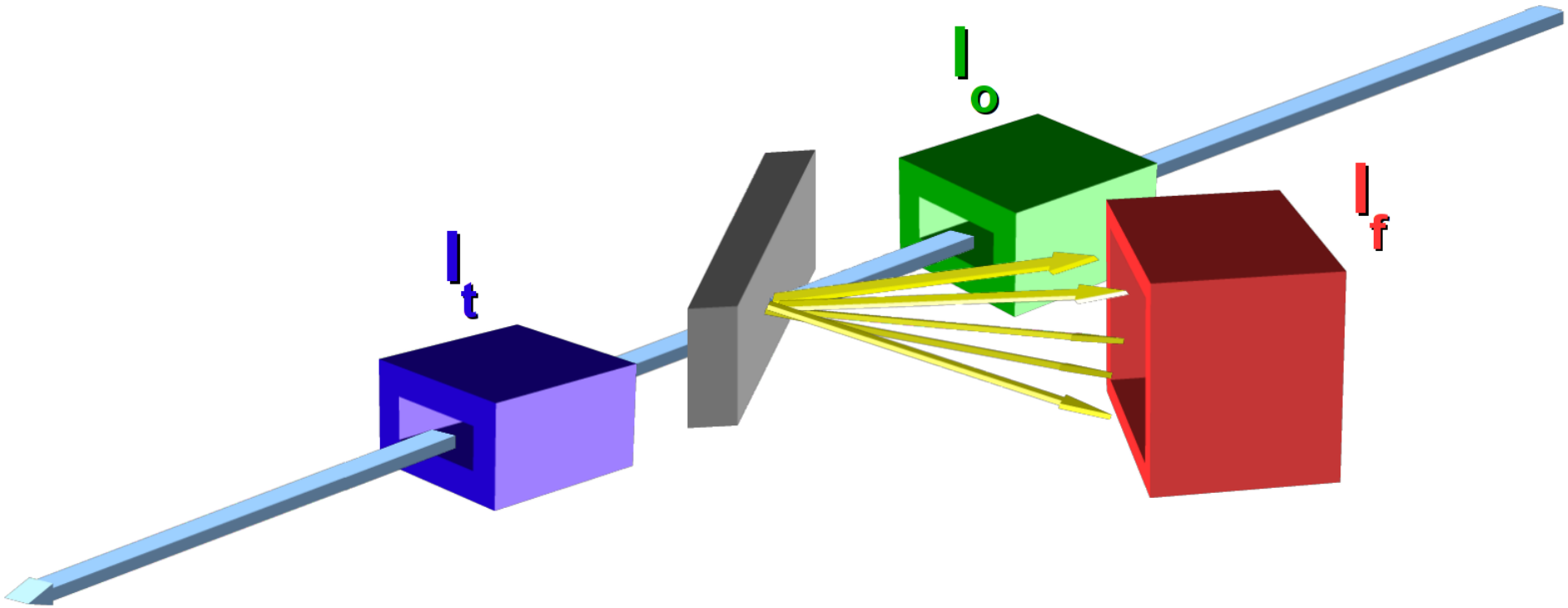
BM Line

- XAFS (4 keV - 32 keV)
  - Continuous scan ($\sim$ 4 min)
  - SDD for dilute samples
- Instrumentation

The EXAFS experiment

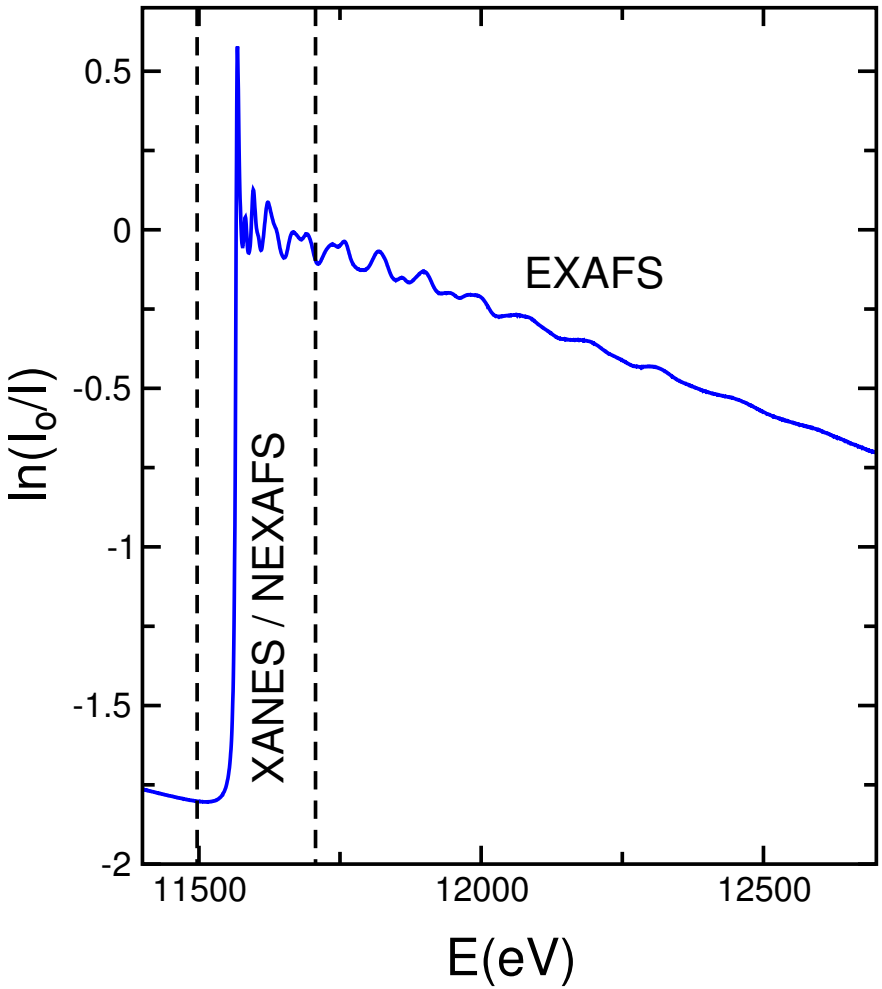
I_o = incident intensity
I_t = transmitted intensity
I_f = fluorescence intensity

x = sample thickness
$\mu(E)$ = absorption coefficient

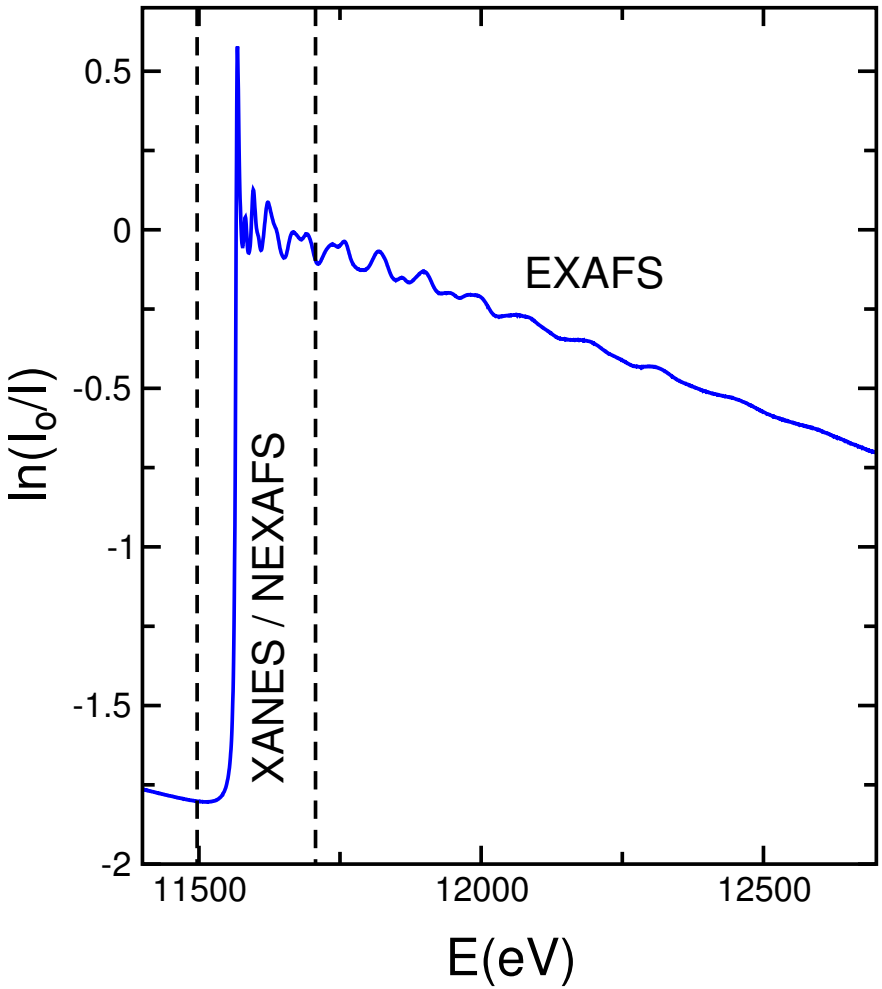


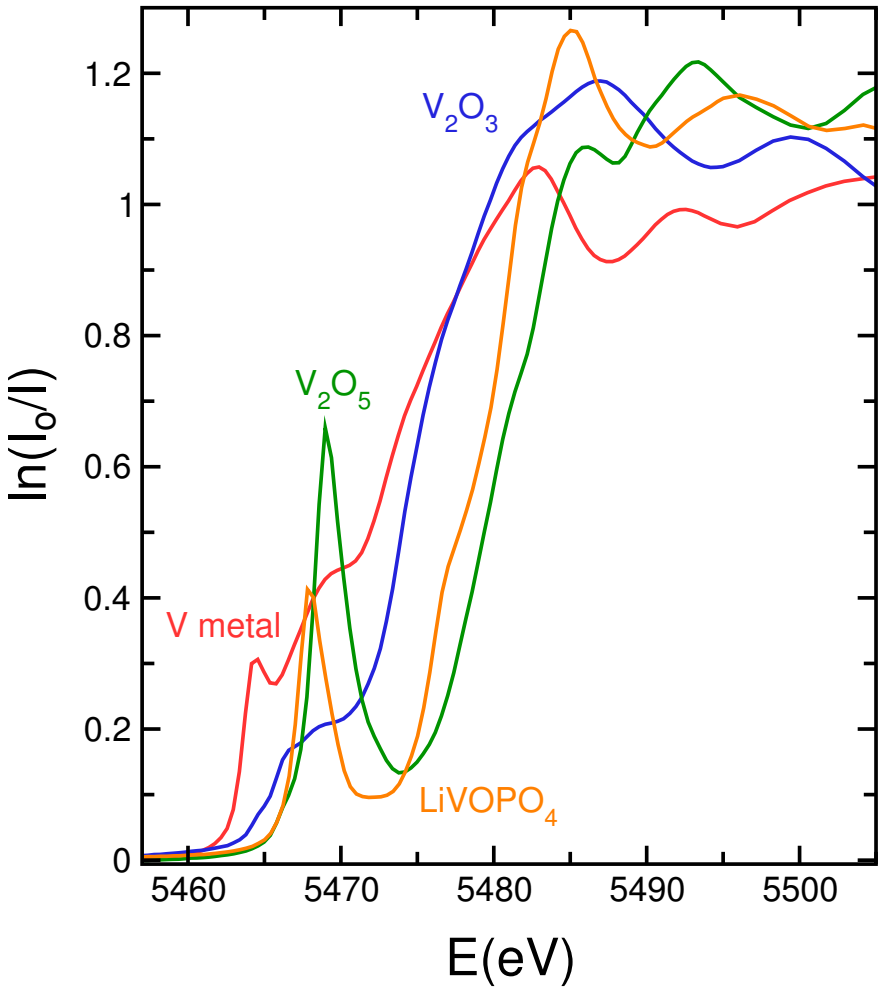
$$I_t = I_o e^{-\mu(E)x} \qquad \mu(E)x = \ln\left(\frac{I_o}{I_t}\right) \qquad \mu(E) \propto \frac{I_f}{I_o}$$

XAS data

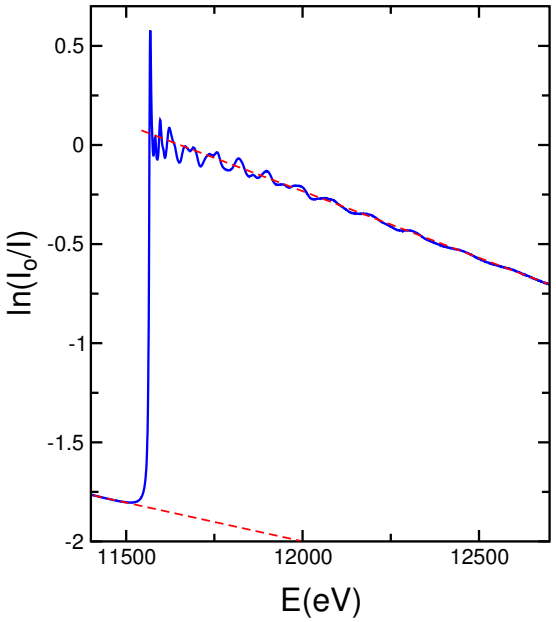


XAS data

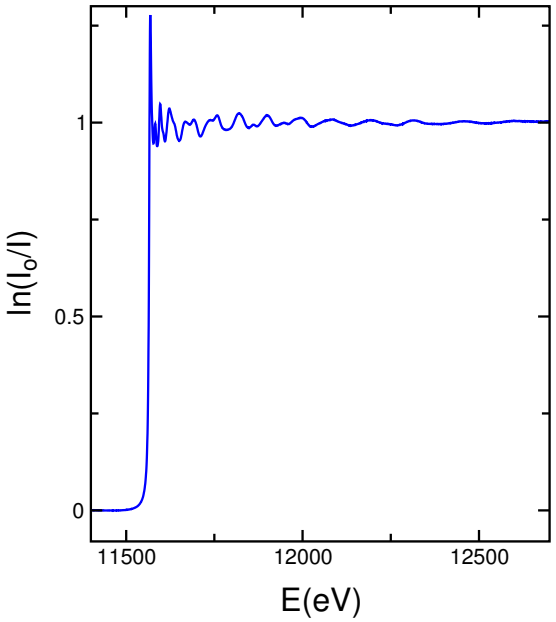

0.5
0
-0.5
-1
-1.5
-2
11500
12000
12500
E(eV)
ln(I0/I)
XANES / NEXAFS
EXAFS


1.2
1
0.8
0.6
0.4
0.2
0
5460
5470
5480
5490
5500
E(eV)
ln(I0/I)
V2O3
V2O5
V metal
LiVOPO4

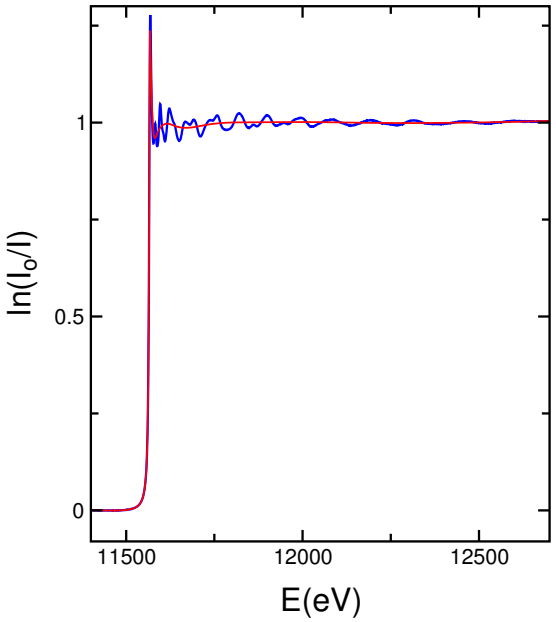
EXAFS analysis



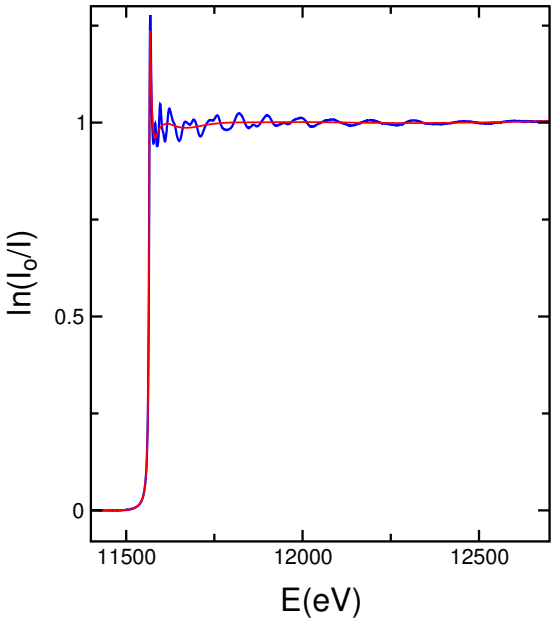
EXAFS analysis



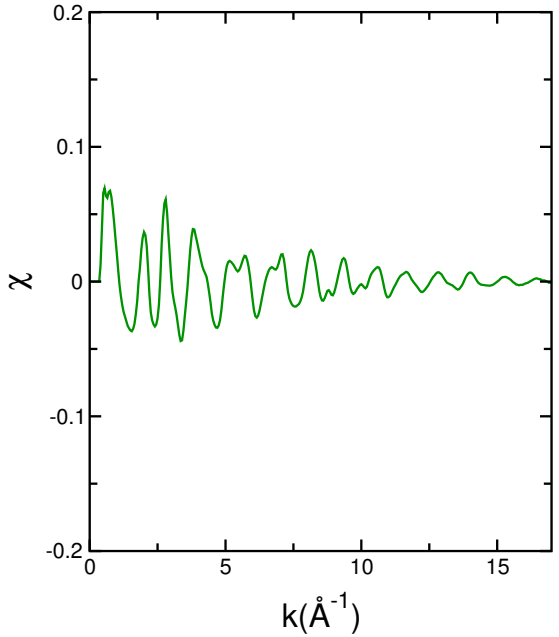
EXAFS analysis



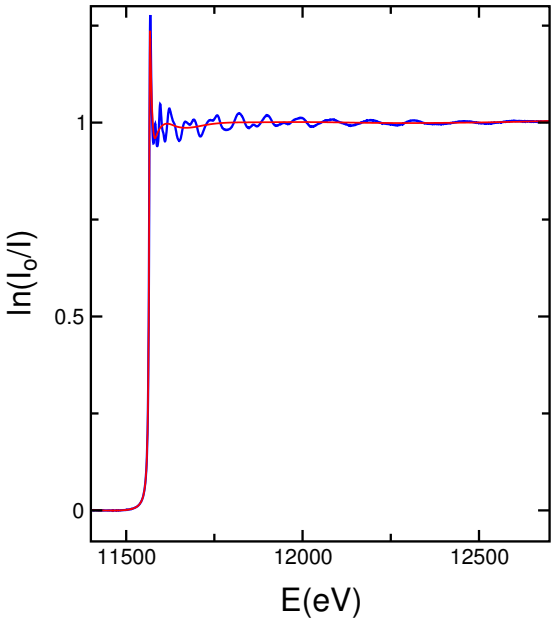
EXAFS analysis



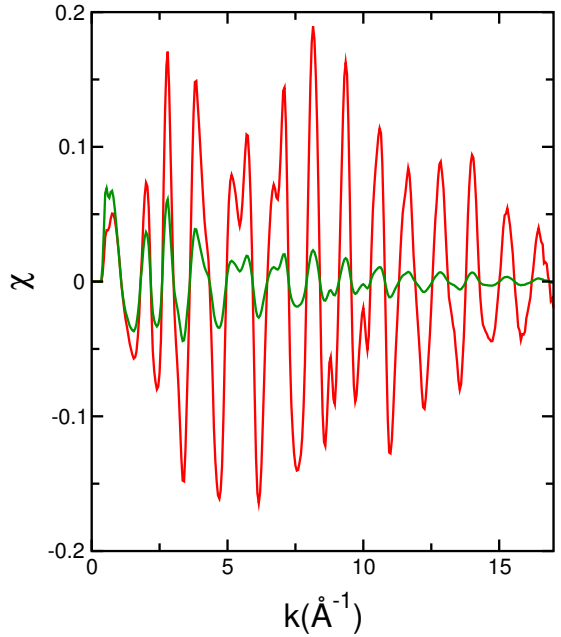
remove background



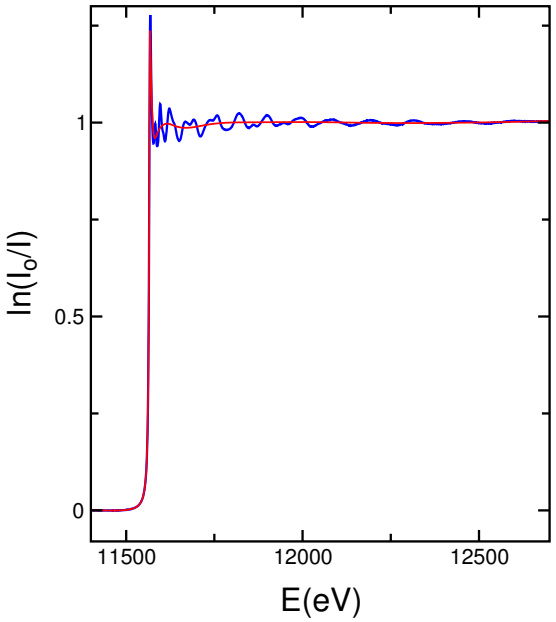
EXAFS analysis



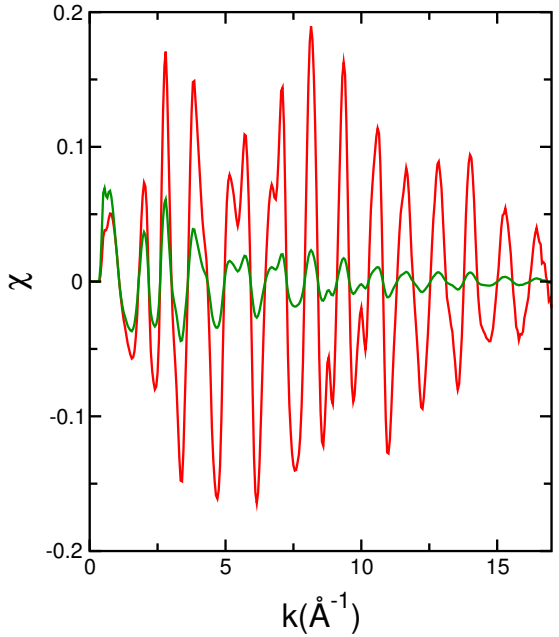
remove background and
apply k-weighting

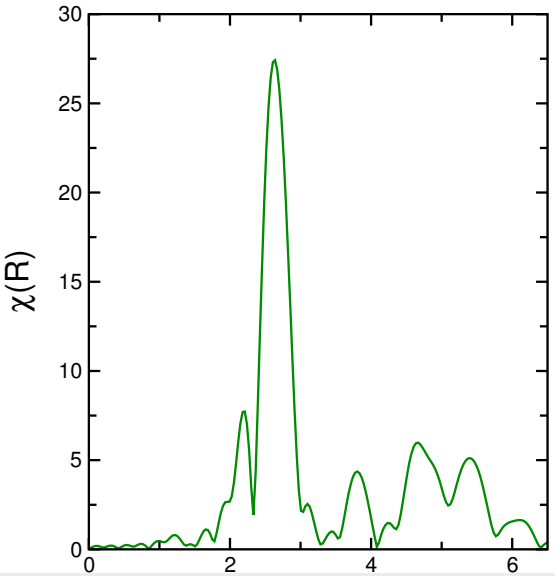


EXAFS analysis



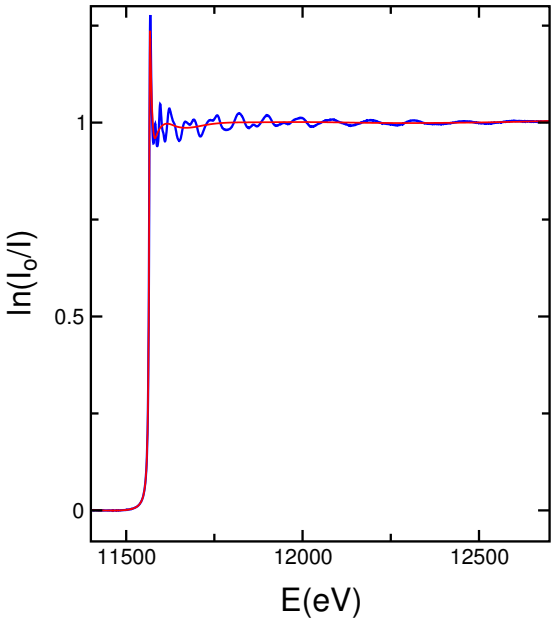
remove background and
apply k-weighting



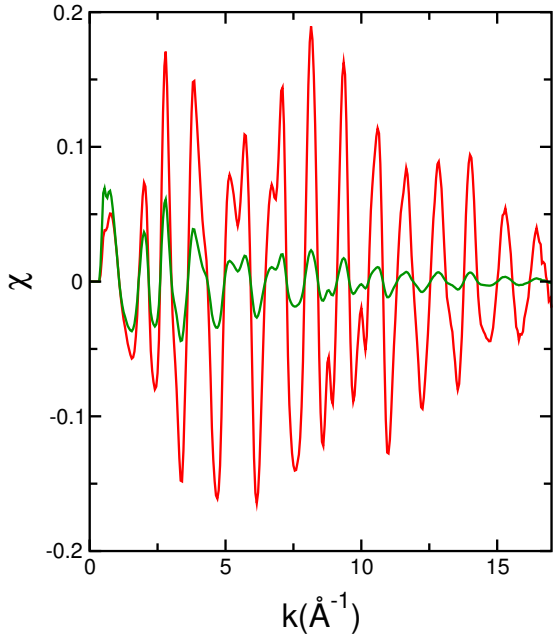


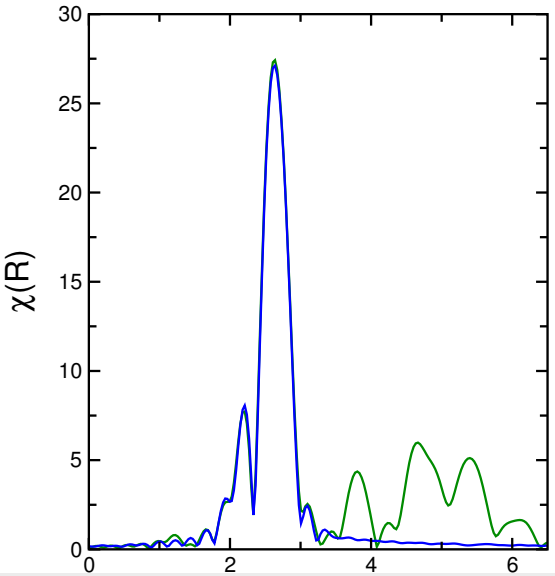
take Fourier Transform

EXAFS analysis



remove background and apply k-weighting

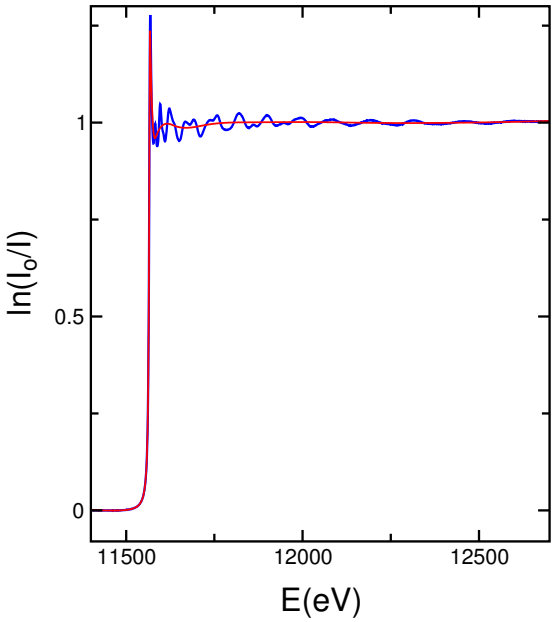




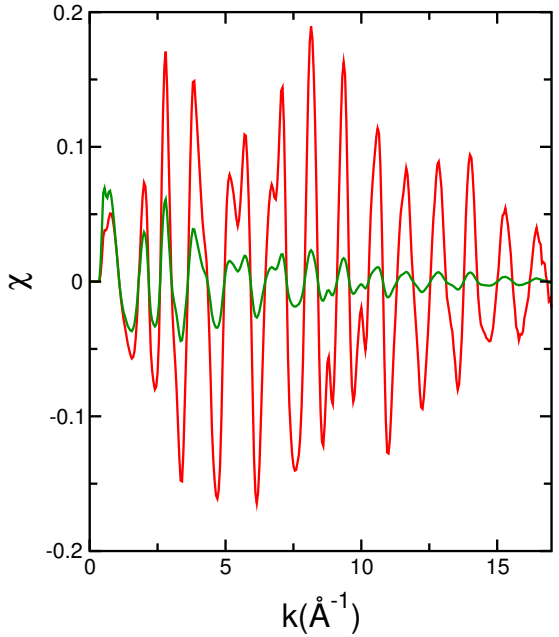
extract structural parameters for first shell

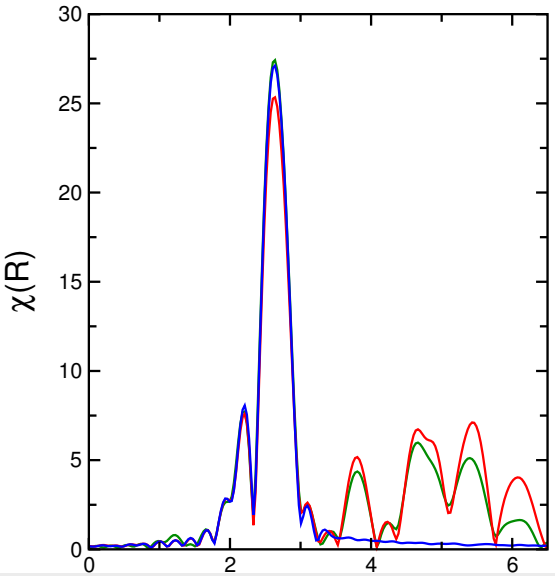
take Fourier Transform and fit with a structural model

EXAFS analysis



remove background and apply k-weighting

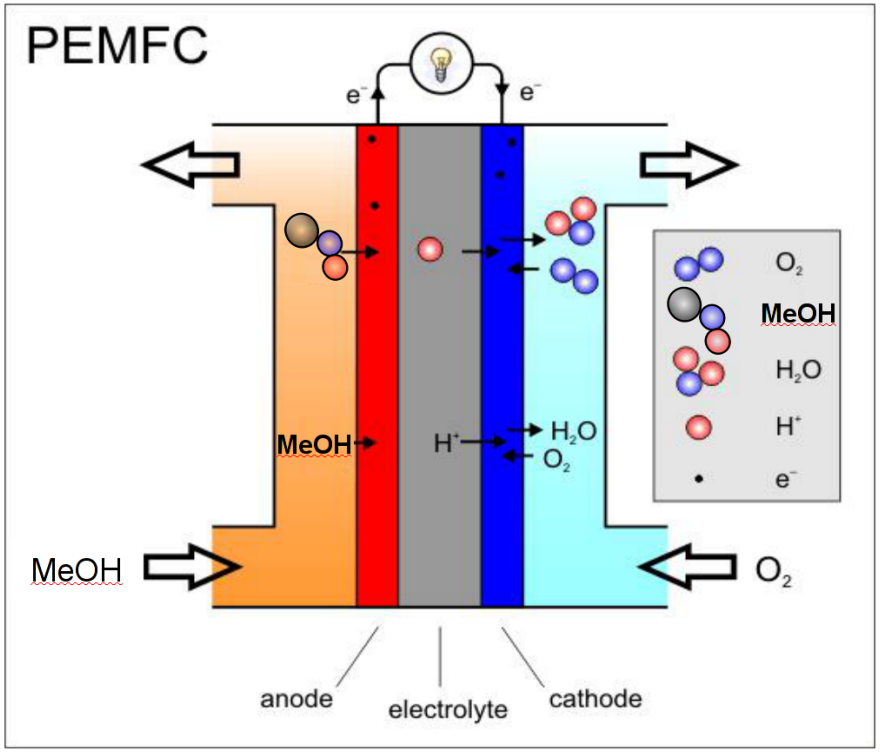




extract structural parameters for first shell or more distant atoms as appropriate

take Fourier Transform and fit with a structural model

Methanol oxidation by a PtRu anode



U.S. Department of Defense (DoD) Fuel Cell Test and Evaluation Center (FCTec)

Anode: 0.02 V vs. SHE

$$CH_3OH + H_2O \longrightarrow 6\,H + CO_2 + 6\,e^-$$

Cathode: 1.23 V s. SHE

$$\frac{3}{2}\,O_2 + 6\,H^+ + 6\,e^- \longrightarrow 3\,H_2O$$

Pt surface poisoned by CO

The presence of Ru promotes CO oxidation through a "bi-functional mechanism"

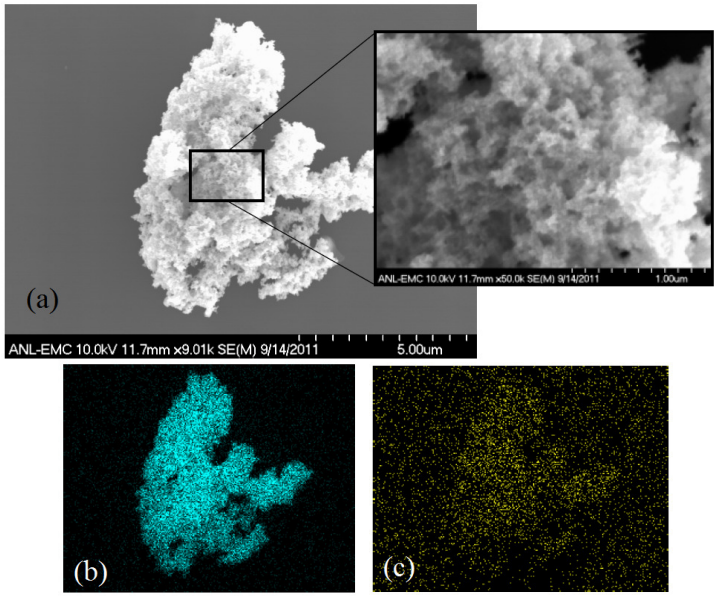
$$Pt{-}(CO)_{ads} + Ru{-}OH \longrightarrow Pt + RuCO_2 + H^+ + 2\,e^-$$

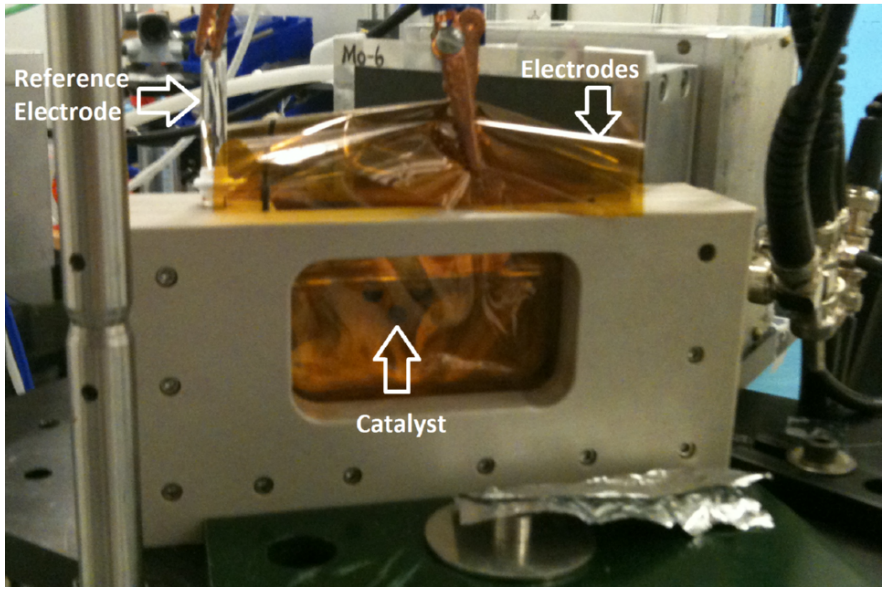
Role of Ru in CO oxidation?

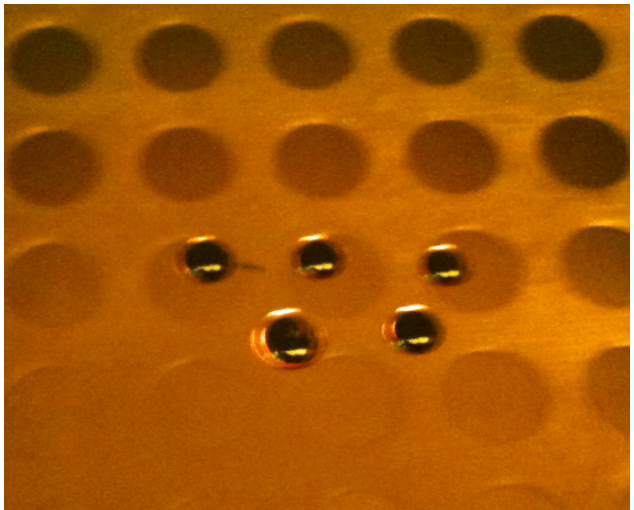
- PtRu bifunctional catalyst improves performance
- In commercial PtRu catalysts there is always a lot of inactive Ru-oxide (?)
- Ru signal dominated by metallic Ru environment
- How does Ru behave in the presence of reactants adsorbed on platinum surface?

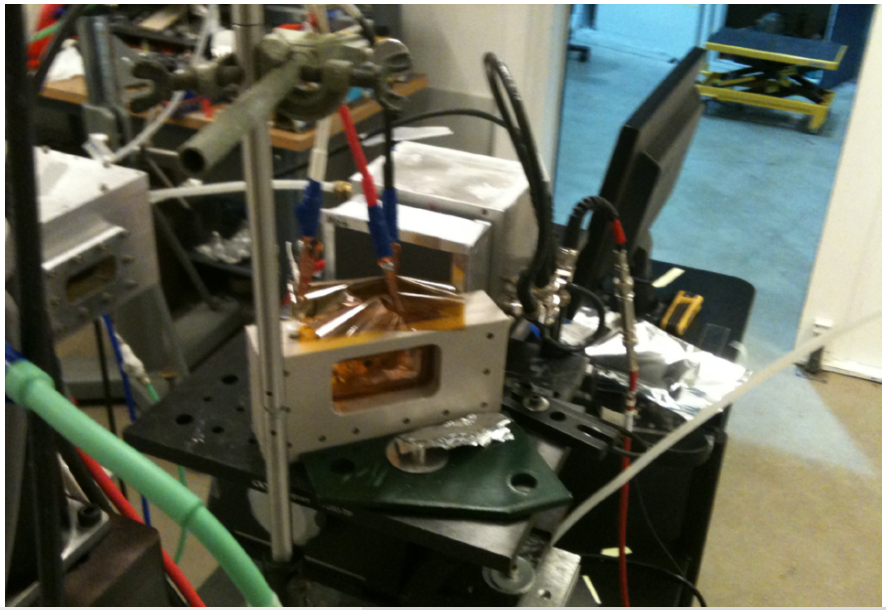
Core-shell nanoparticles can resolve these questions

Ru-decorated Pt nanoparticles

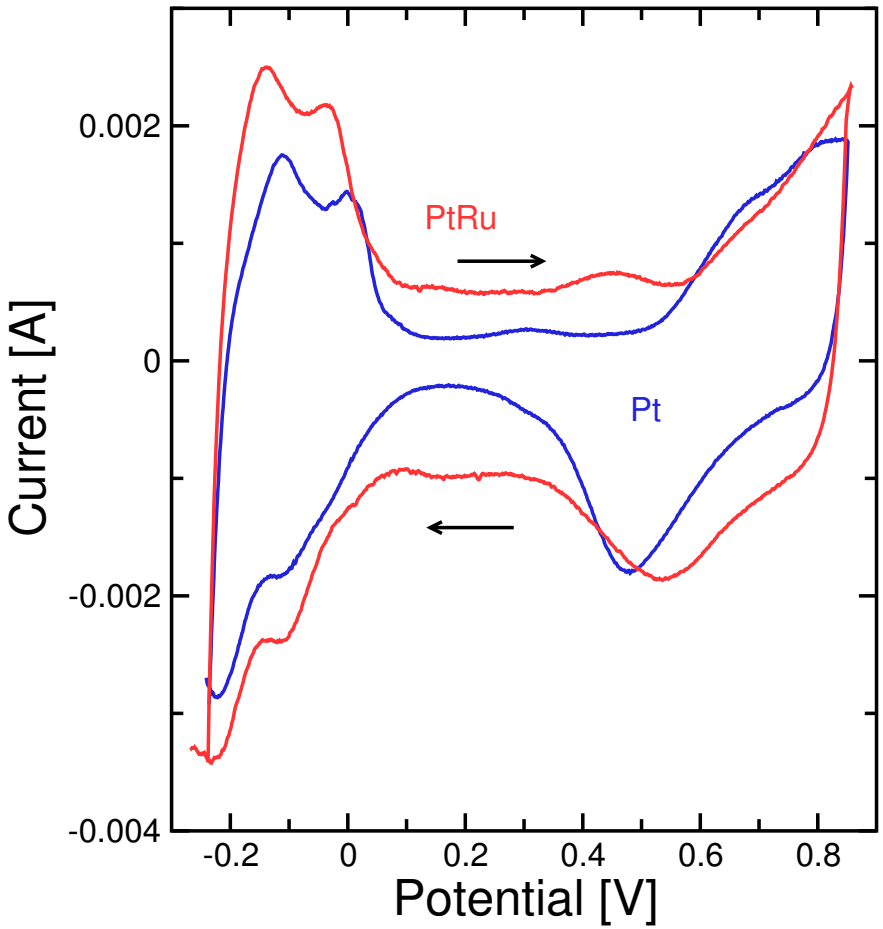








Electrochemical performance



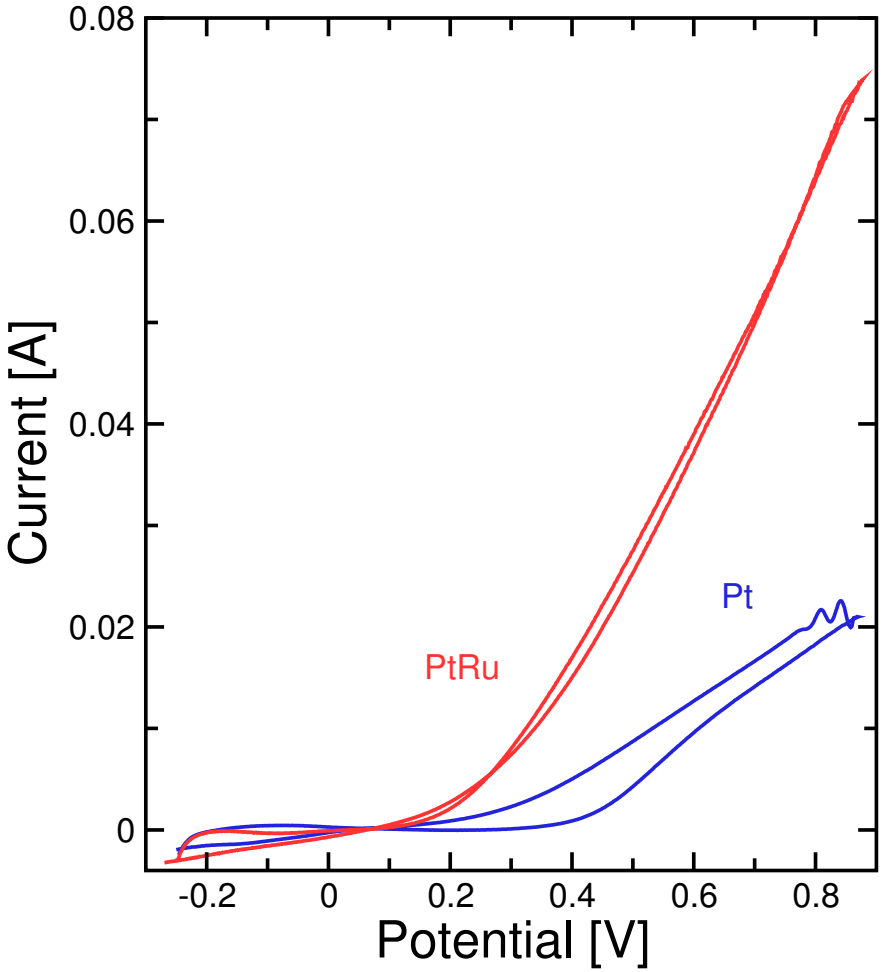
Without Methanol

Low V peaks are H^+ stripping

Dip at $\sim$0.5 V is oxygen stripping

Ru shifts potential on all peaks

Electrochemical performance



Without Methanol

Low V peaks are H^+ stripping

Dip at $\sim$0.5 V is oxygen stripping

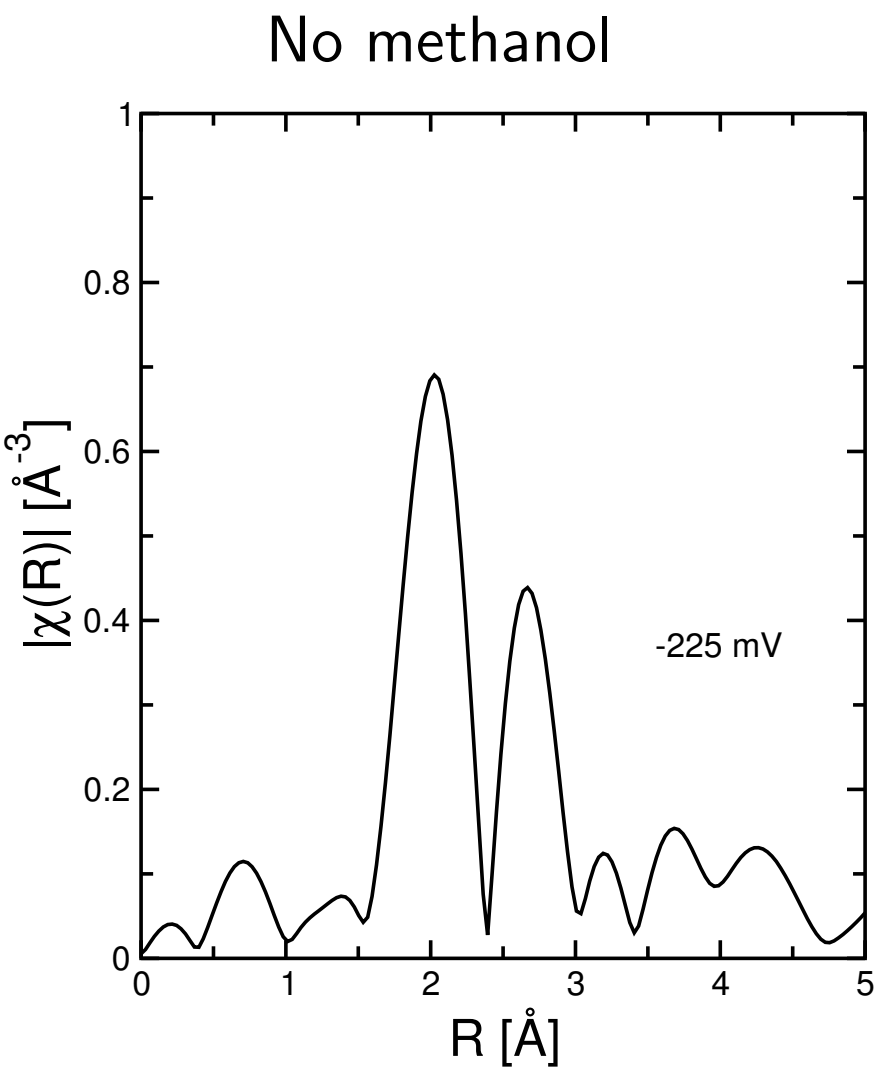
Ru shifts potential on all peaks

With Methanol

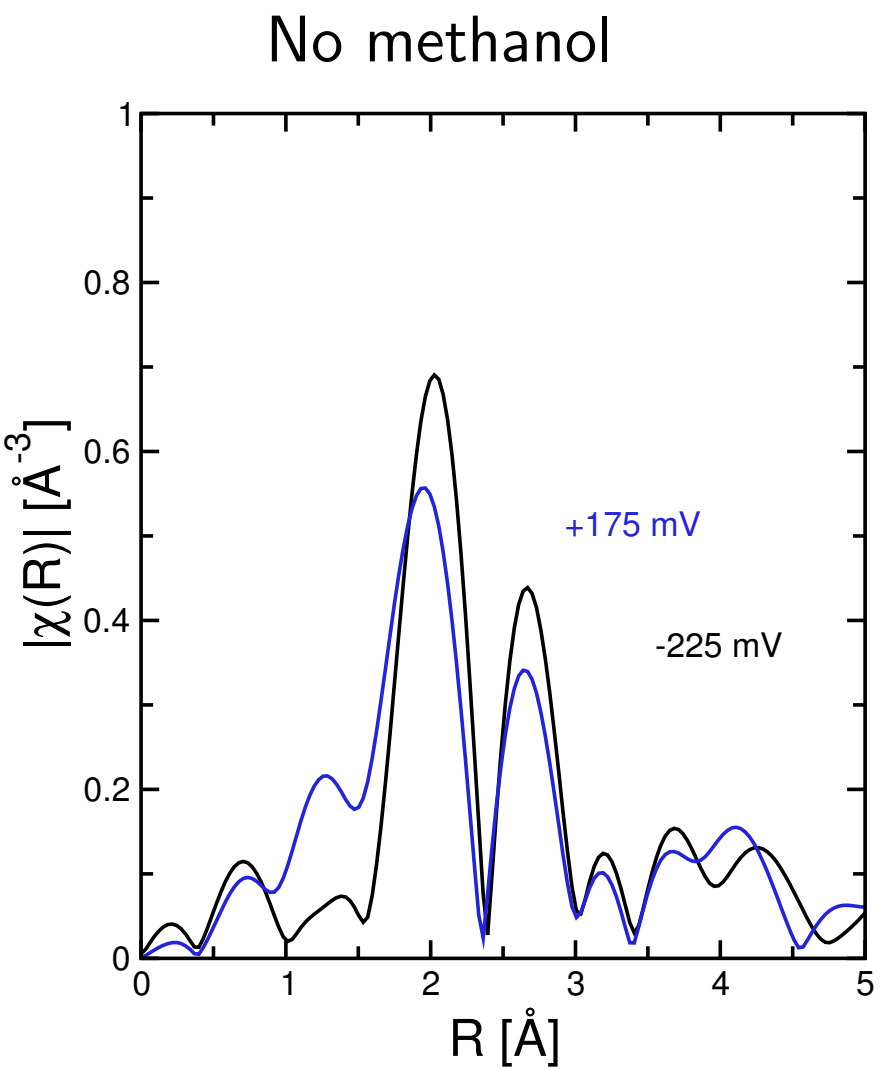
Continual current growth is due to methanol oxidation

Ru improves current by removing the CO which blocks active sites

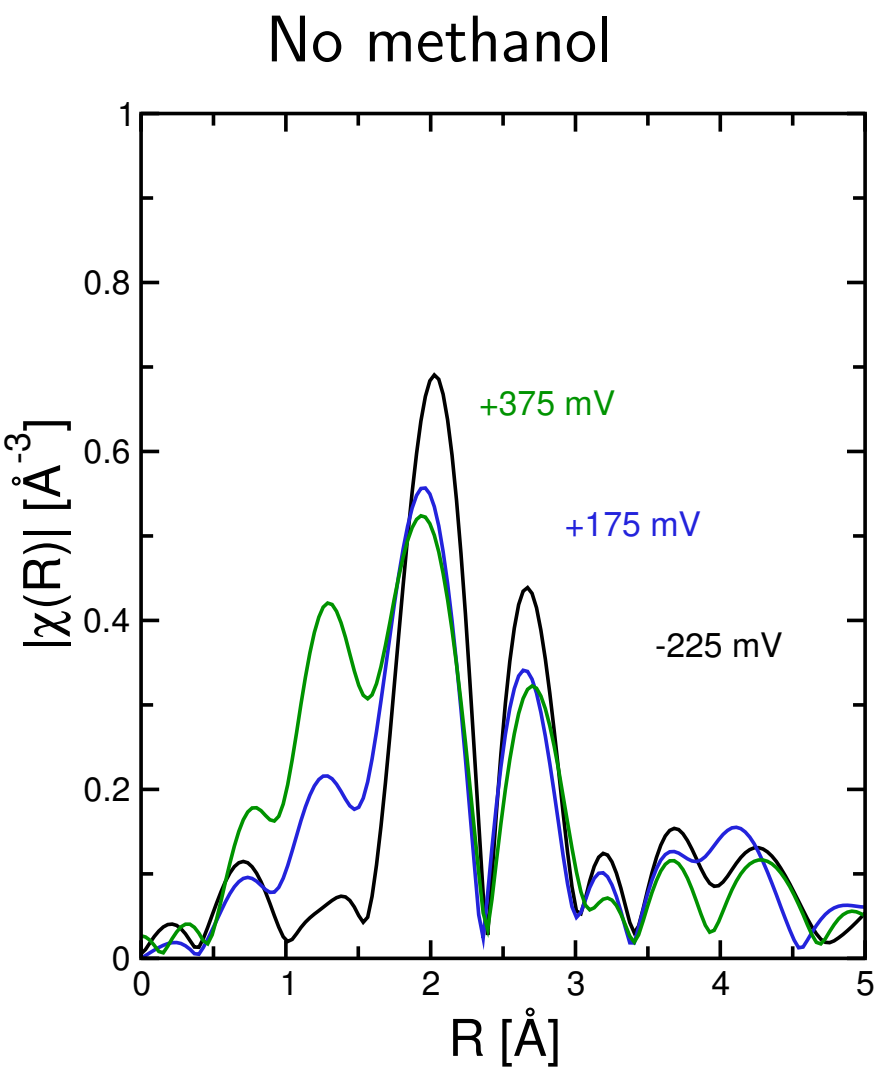
Ru EXAFS



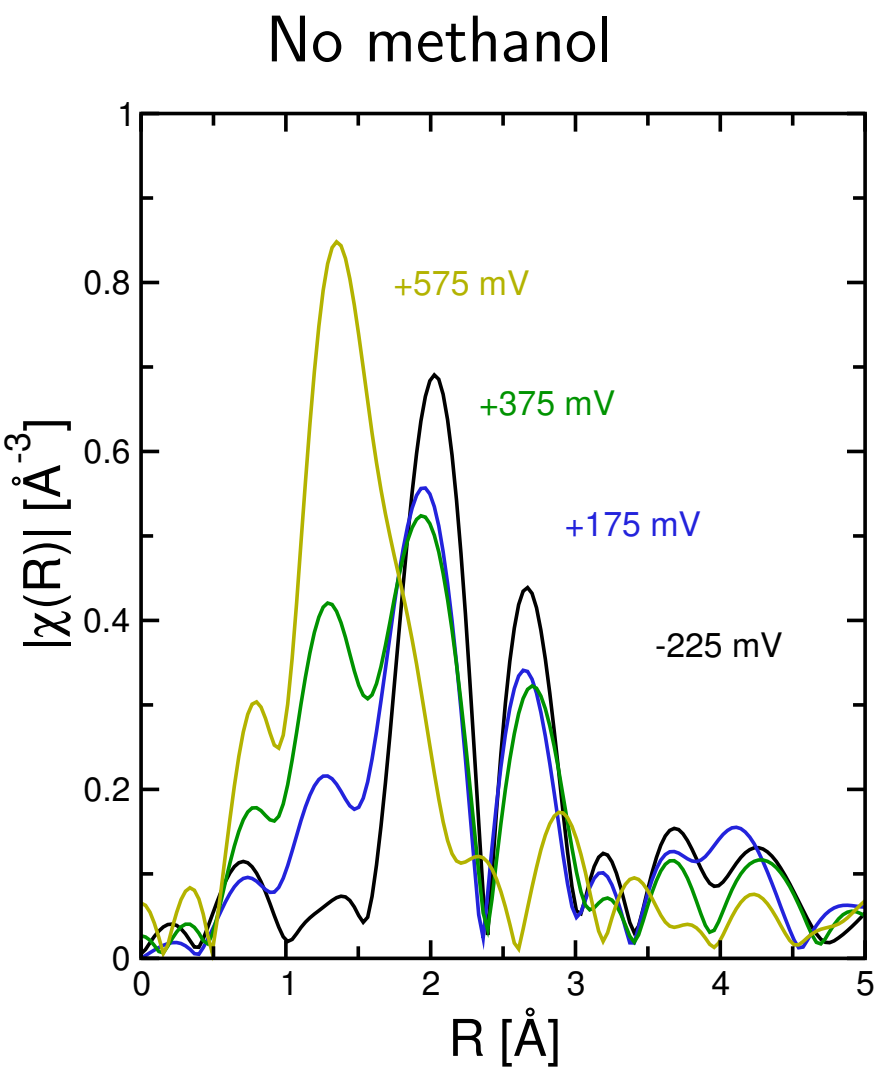
Ru EXAFS



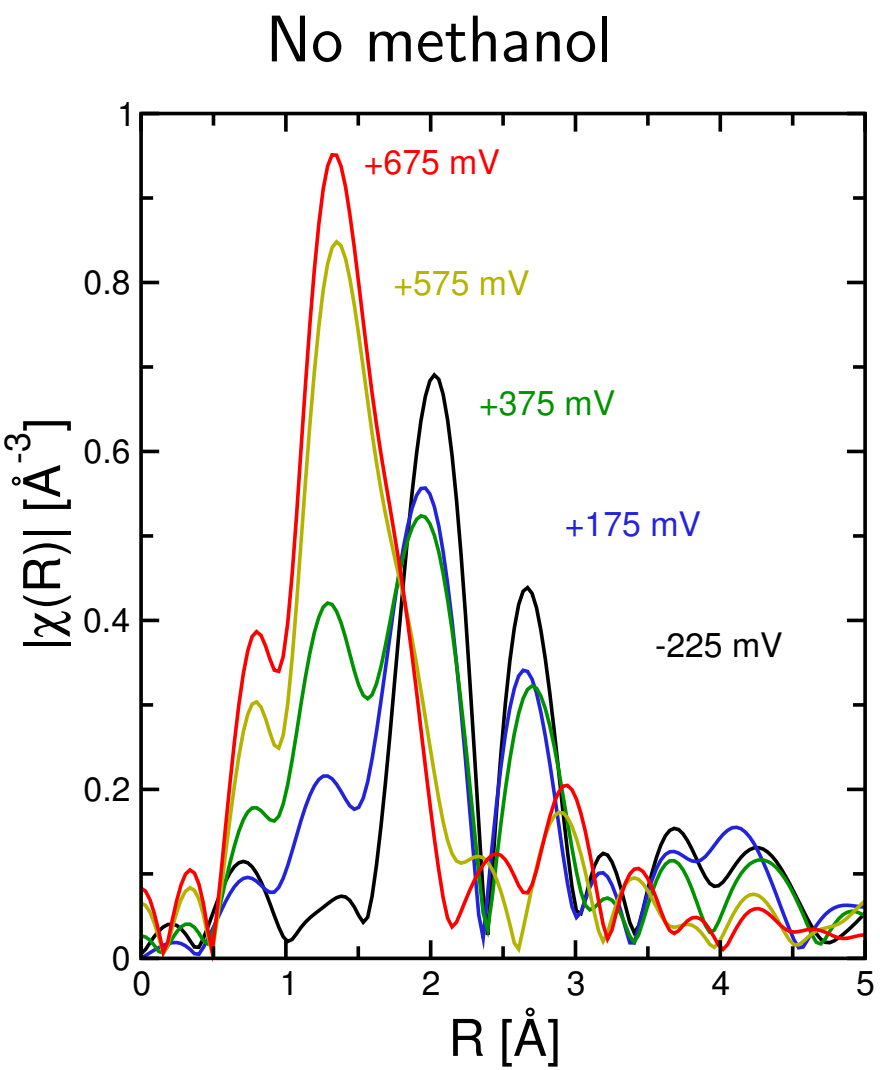
Ru EXAFS



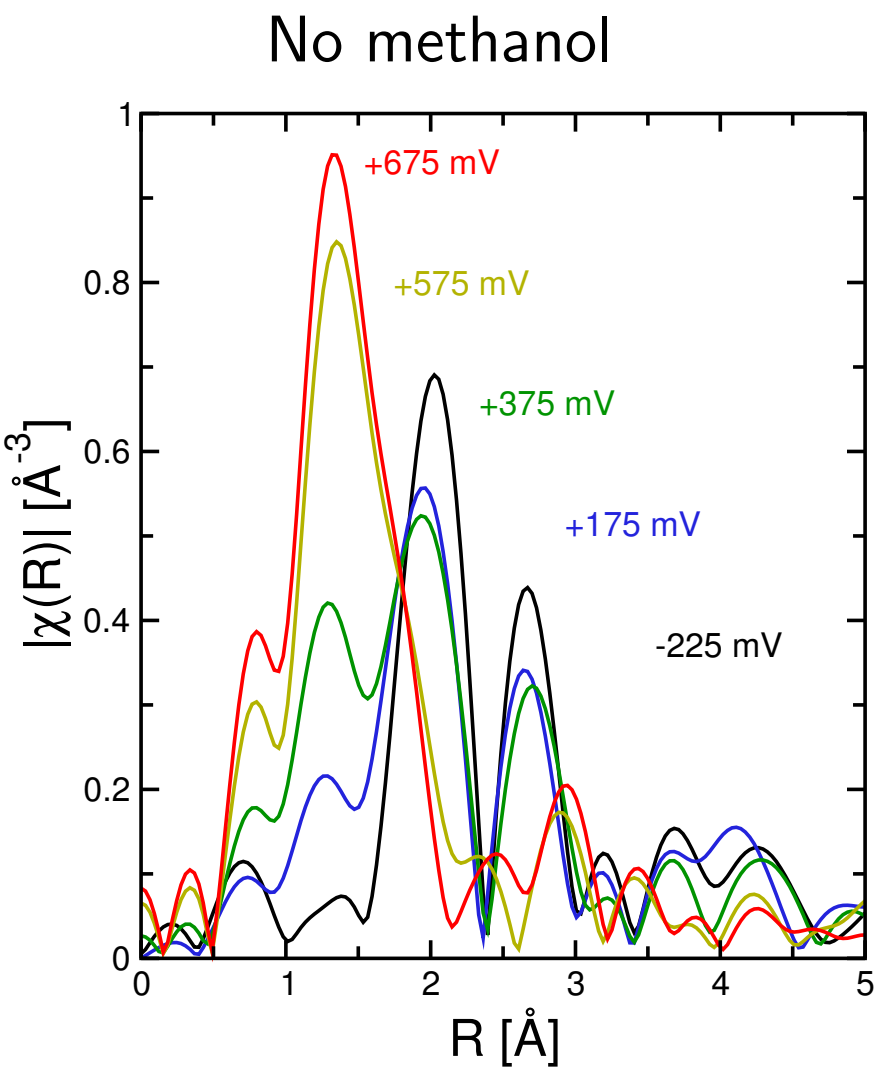
Ru EXAFS

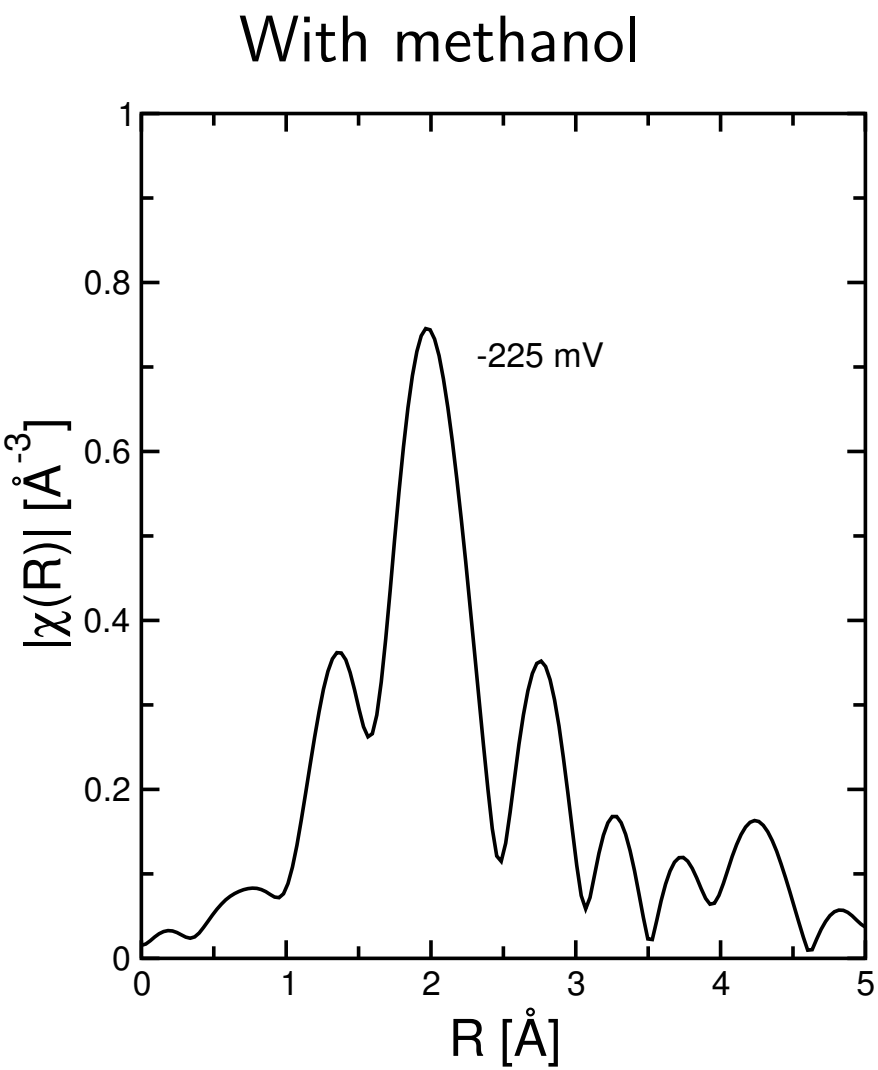

No methanol
+575 mV
+375 mV
+175 mV
-225 mV
|χ(R)| [Å^-3]
R [Å]
0
0.2
0.4
0.6
0.8
1
0
1
2
3
4
5

Ru EXAFS

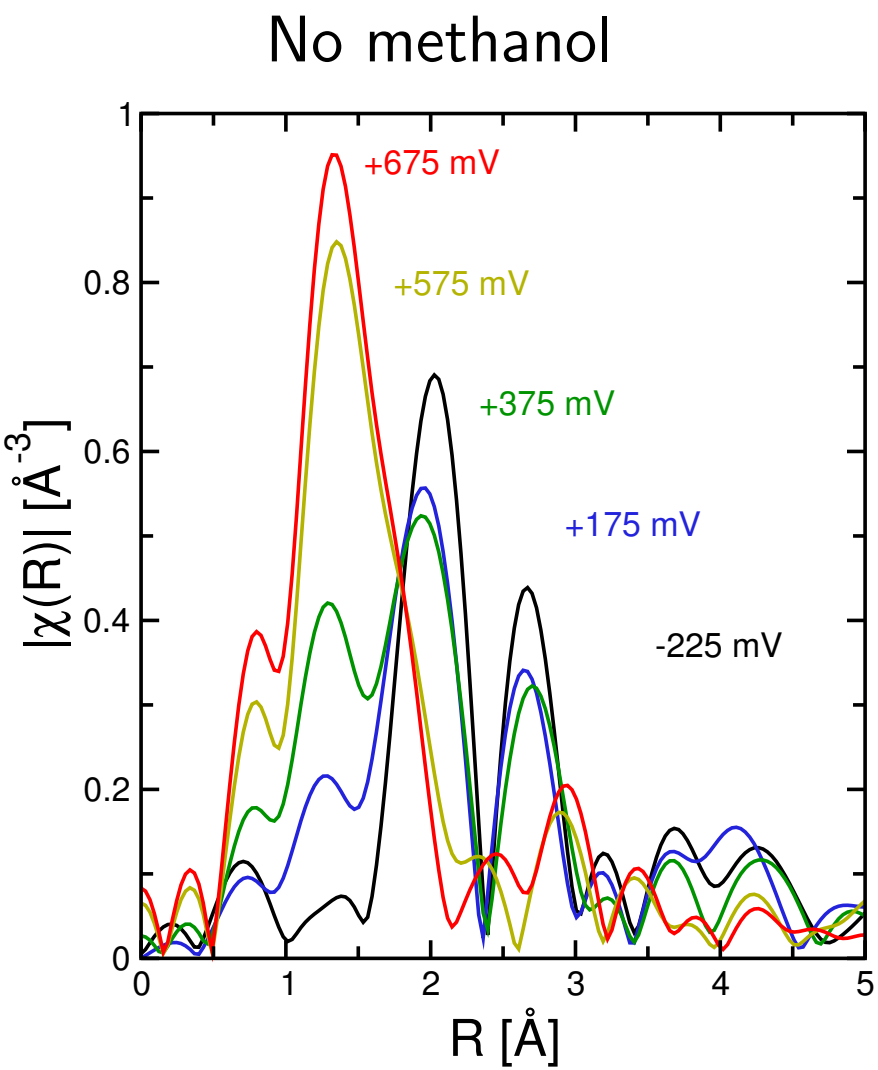

No methanol
+675 mV
+575 mV
+375 mV
+175 mV
-225 mV
|χ(R)| [Å-3]
R [Å]
0
0.2
0.4
0.6
0.8
1
0
1
2
3
4
5

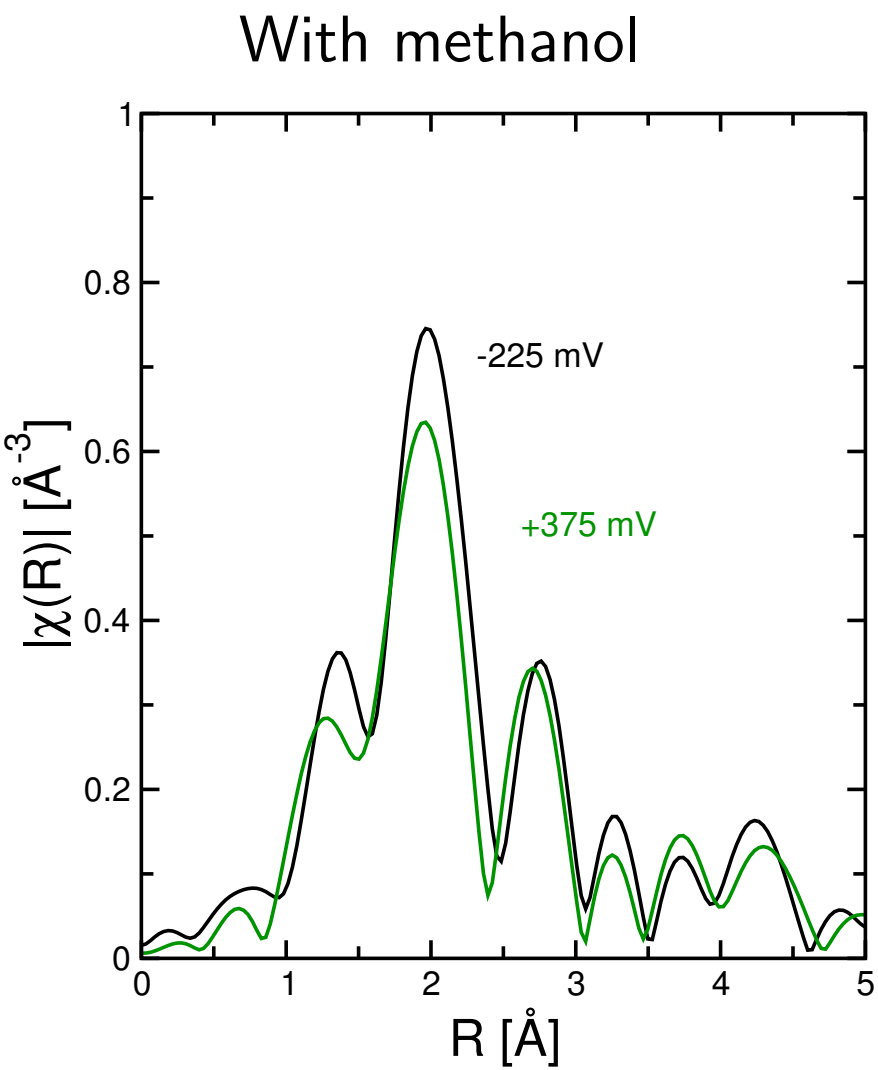
Ru EXAFS


No methanol
+675 mV
+575 mV
+375 mV
+175 mV
-225 mV
|χ(R)| [Å^-3]
R [Å]
0
0.2
0.4
0.6
0.8
1
0
1
2
3
4
5

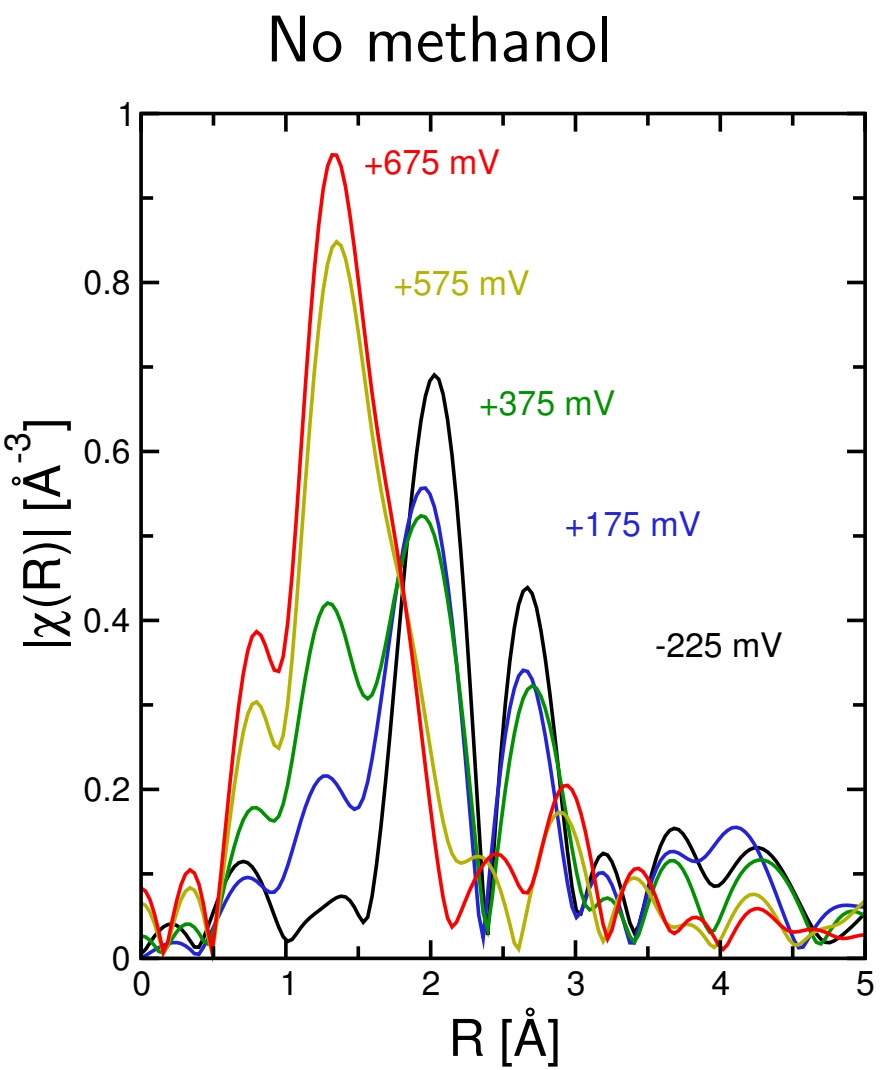

With methanol
-225 mV
|χ(R)| [Å^-3]
R [Å]
0
0.2
0.4
0.6
0.8
1
0
1
2
3
4
5

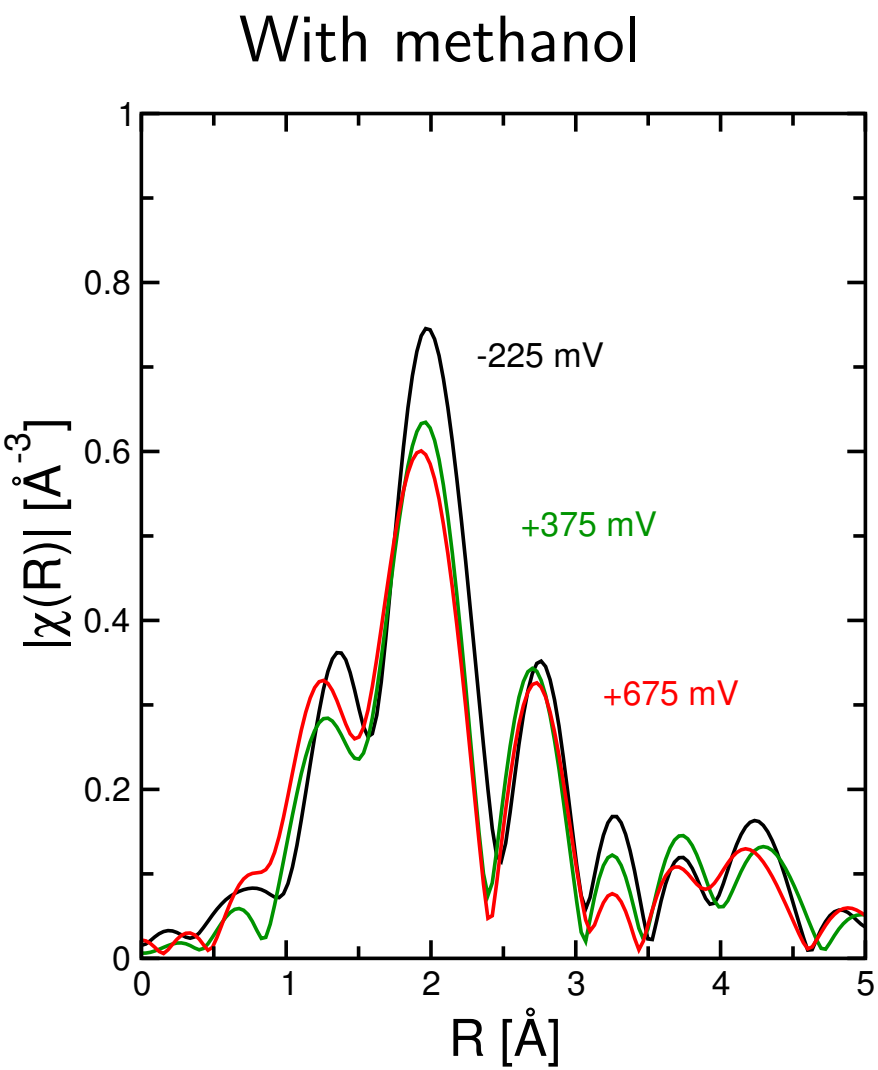
Ru EXAFS


No methanol
+675 mV
+575 mV
+375 mV
+175 mV
-225 mV
|χ(R)| [Å^-3]
R [Å]
0
0.2
0.4
0.6
0.8
1
0
1
2
3
4
5

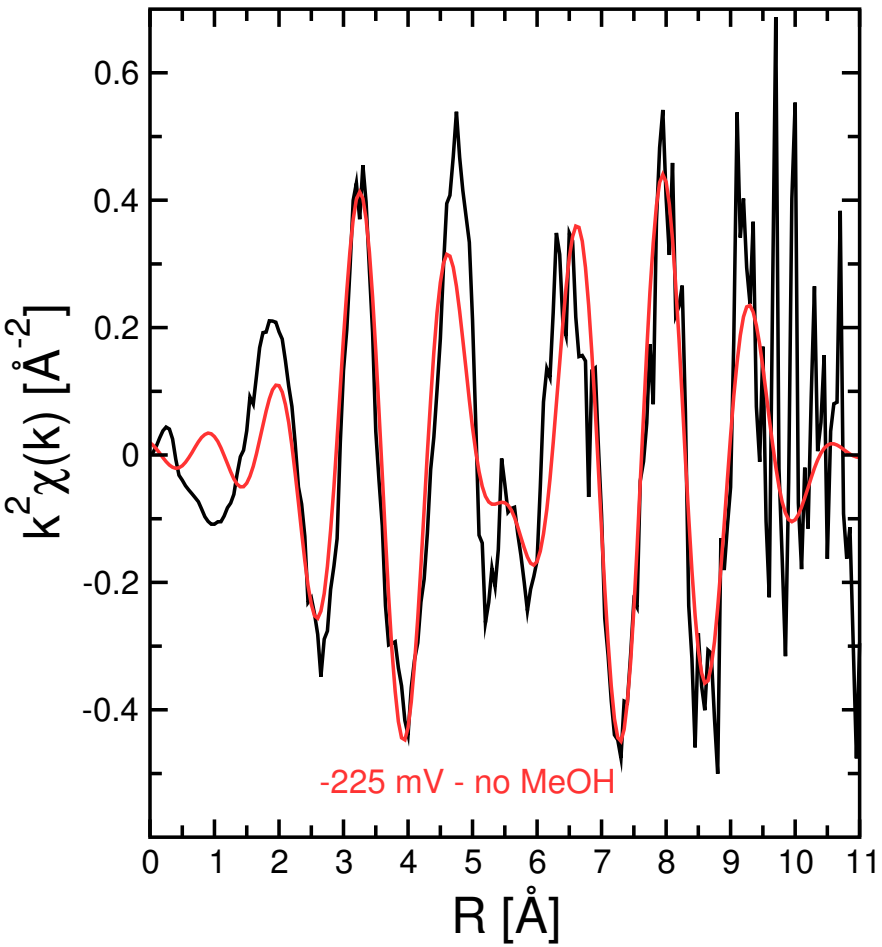

With methanol
-225 mV
+375 mV
|χ(R)| [Å^-3]
R [Å]
0
0.2
0.4
0.6
0.8
1
0
1
2
3
4
5

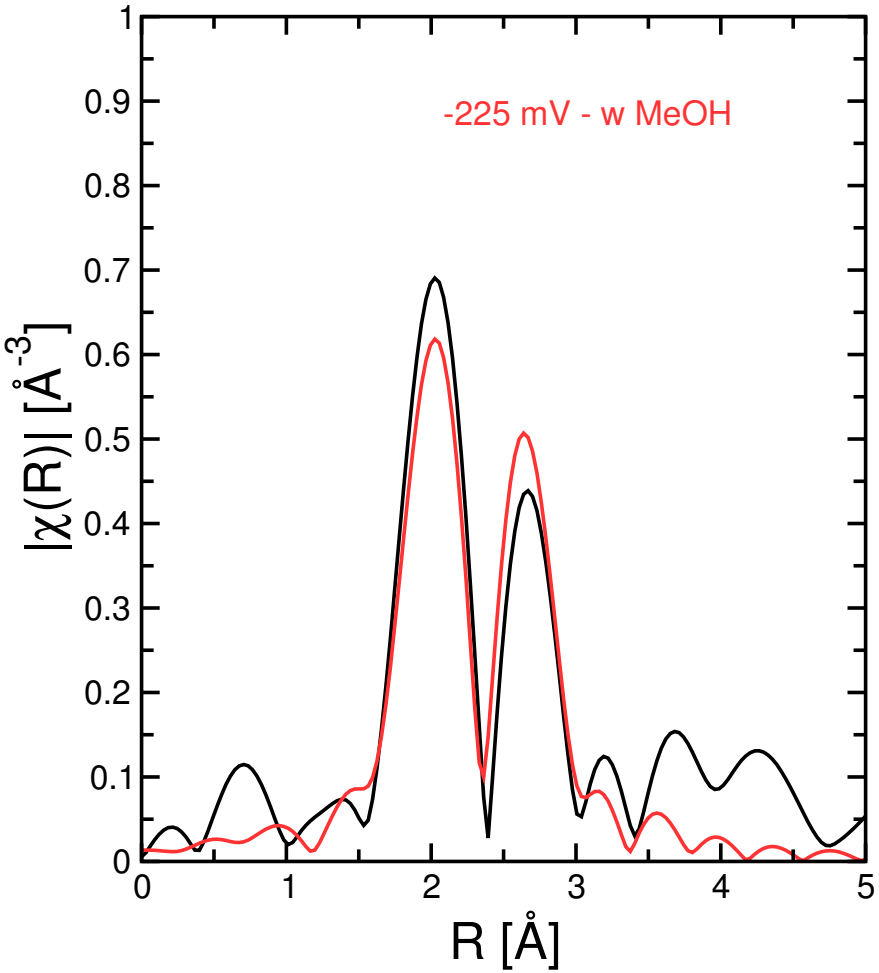
Ru EXAFS


No methanol
+675 mV
+575 mV
+375 mV
+175 mV
-225 mV
|χ(R)| [Å^-3]
R [Å]
0
0.2
0.4
0.6
0.8
1
0
1
2
3
4
5

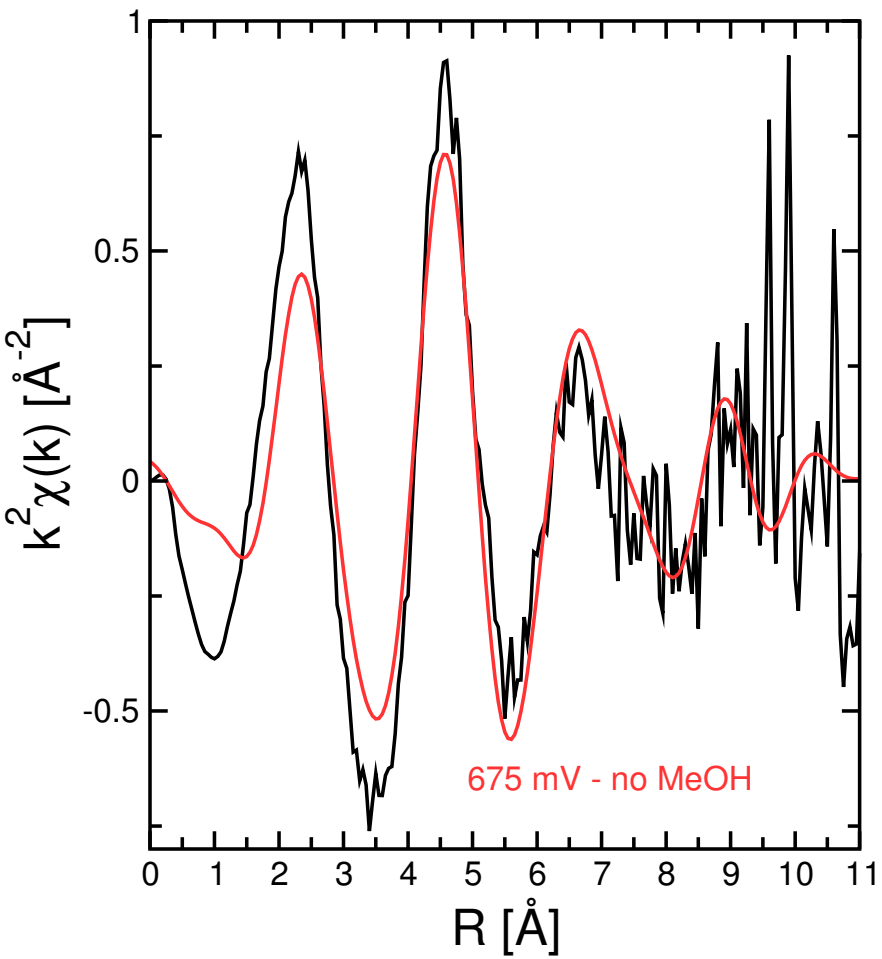

With methanol
-225 mV
+375 mV
+675 mV
|χ(R)| [Å^-3]
R [Å]
0
0.2
0.4
0.6
0.8
1
0
1
2
3
4
5

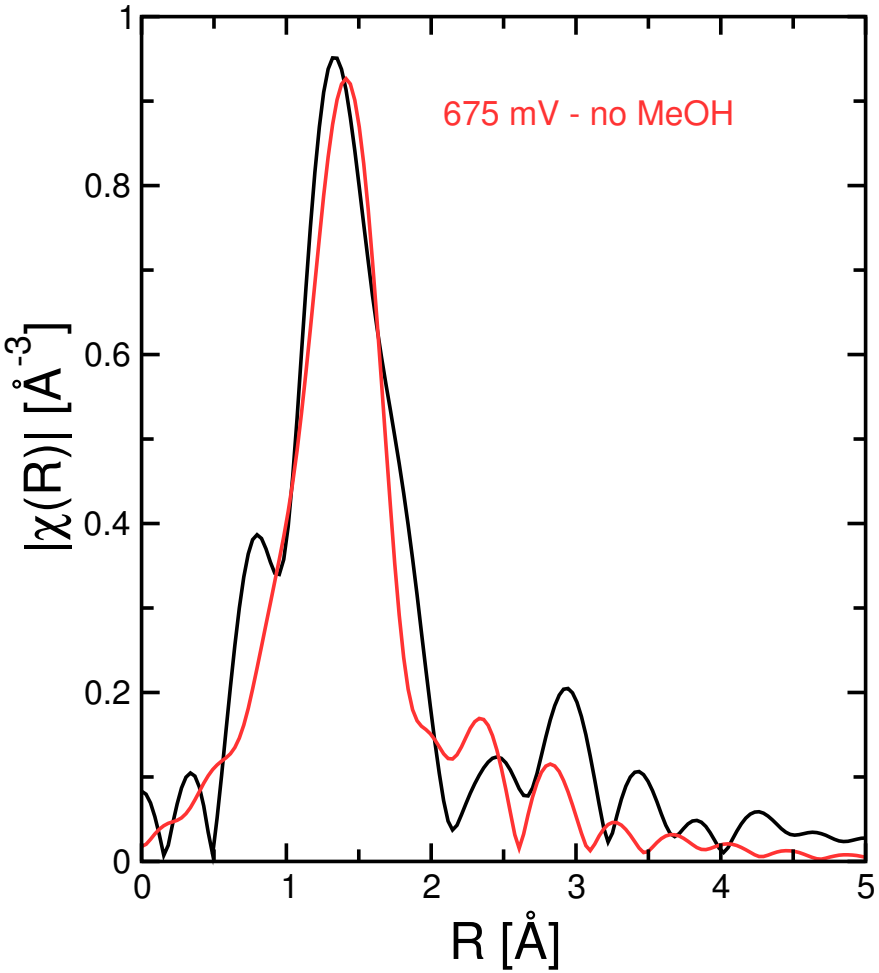
Fit example: -225 mV without methanol



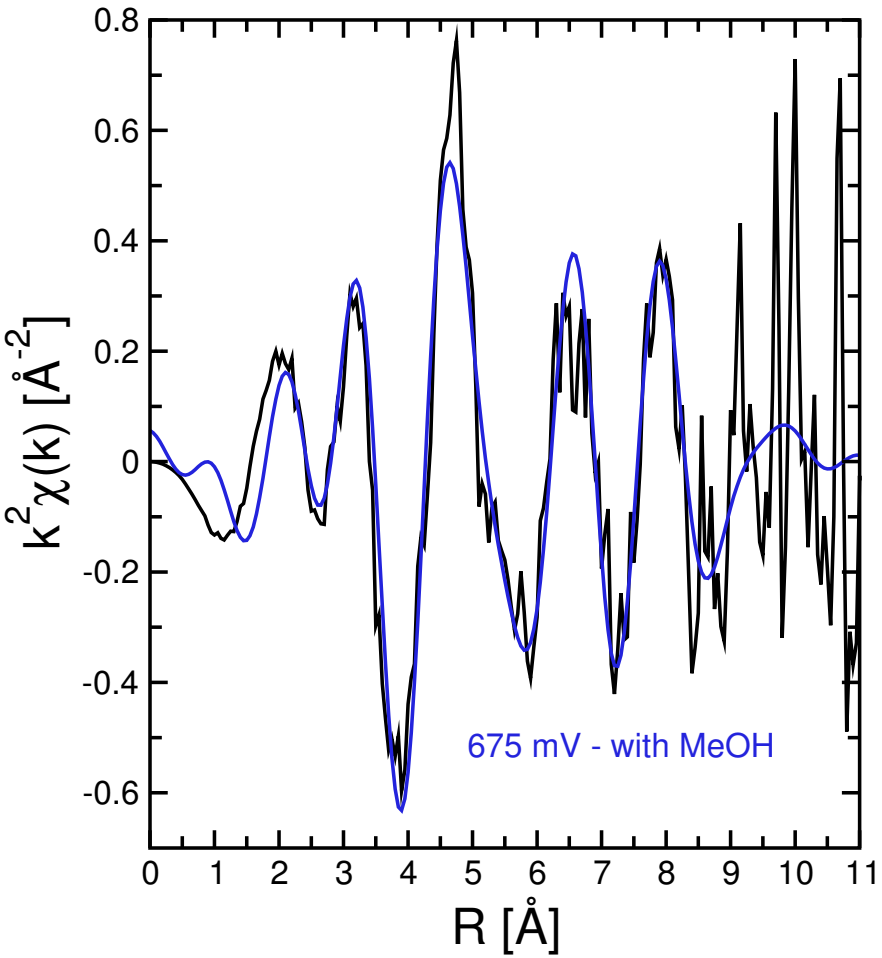


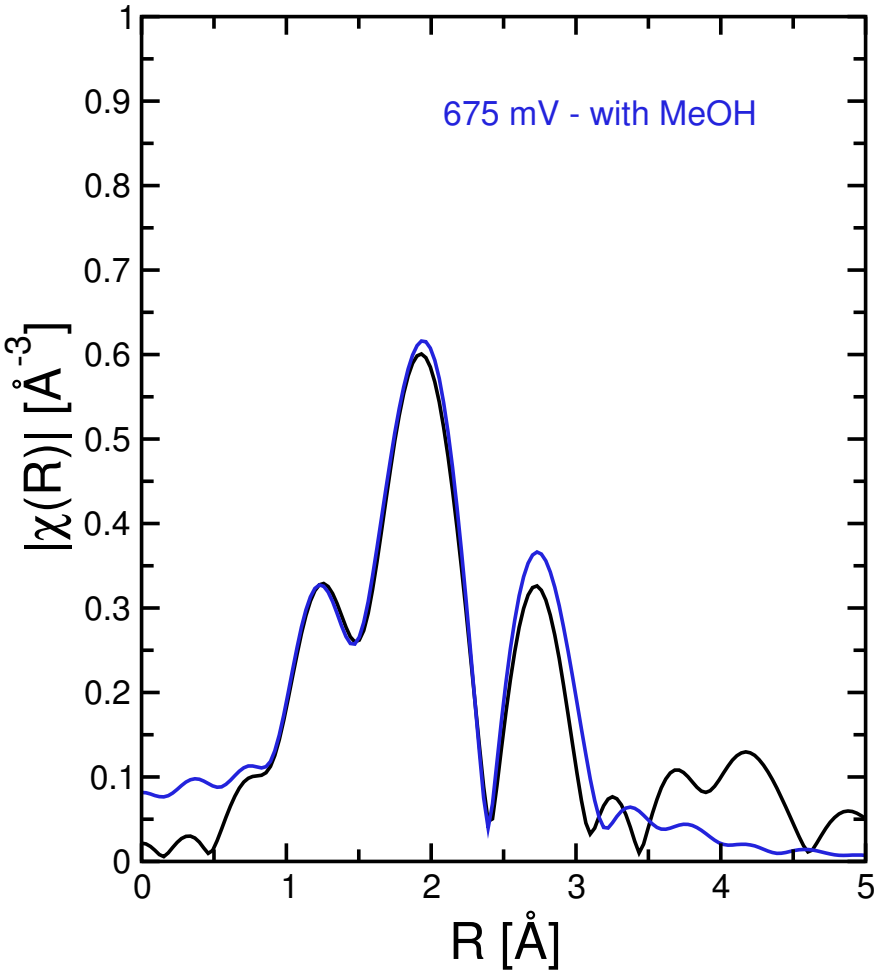
Fit example: 675 mV without methanol



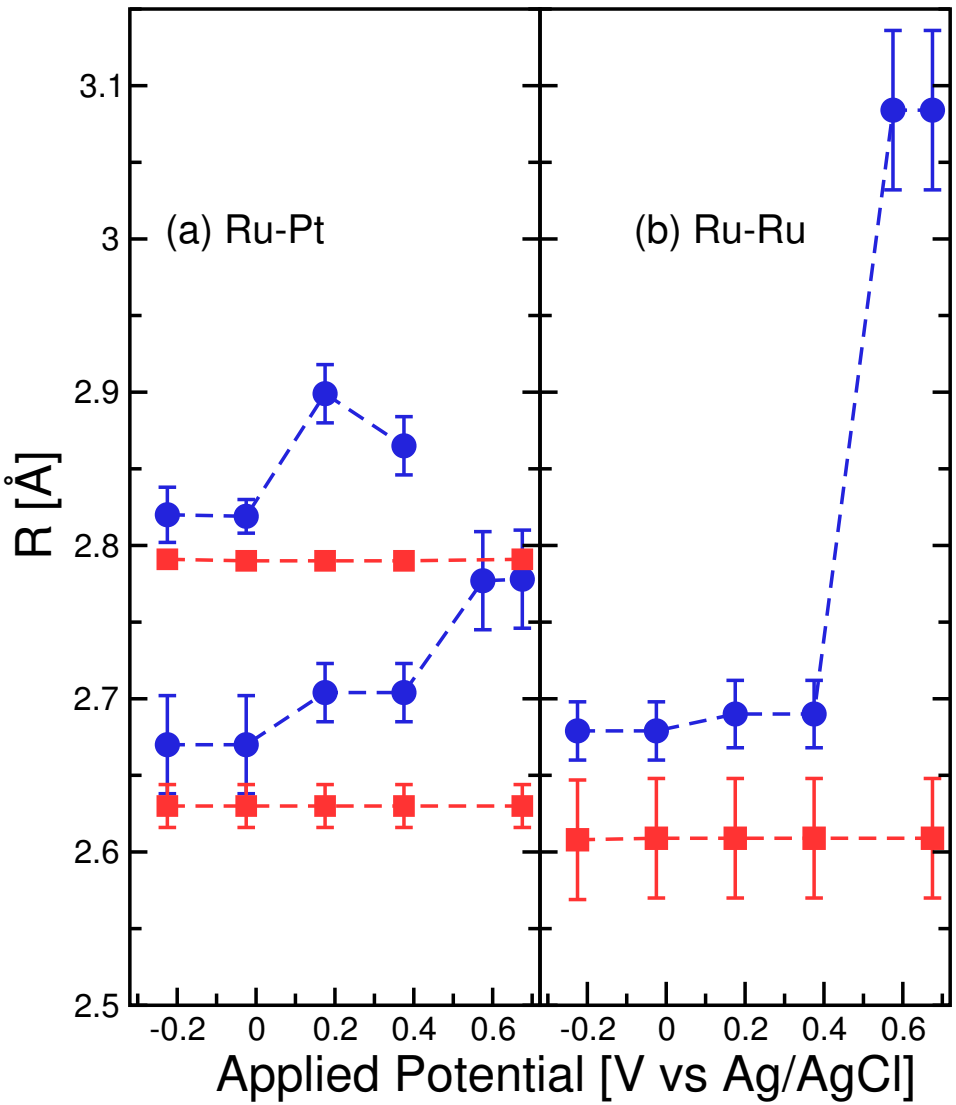


Fit example: 675 mV with methanol





Ru-M paths



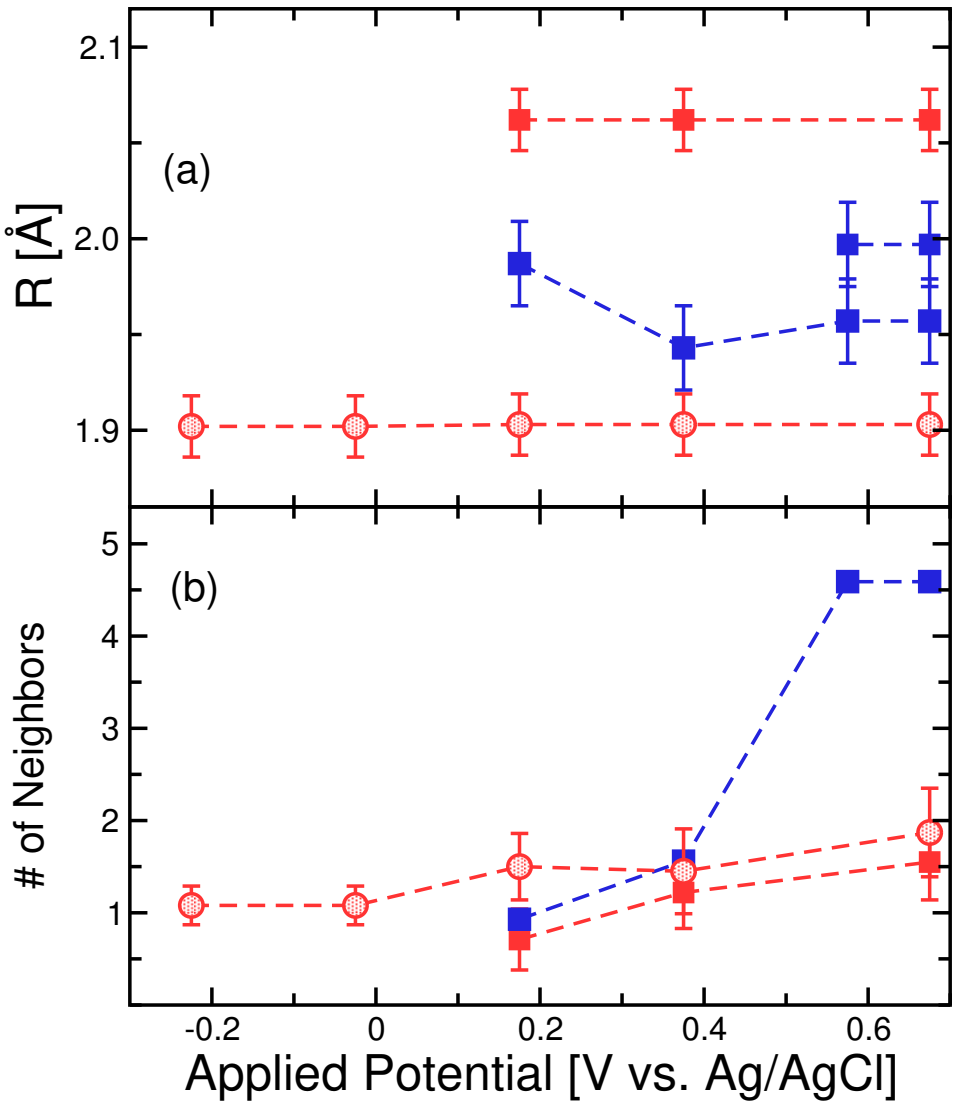
Without methanol

Ru-M distances are longer and RuO_2 is formed at high potentials

With methanol

Ru-M distances are shorter and remain the same at all potentials

Ru-O/C paths



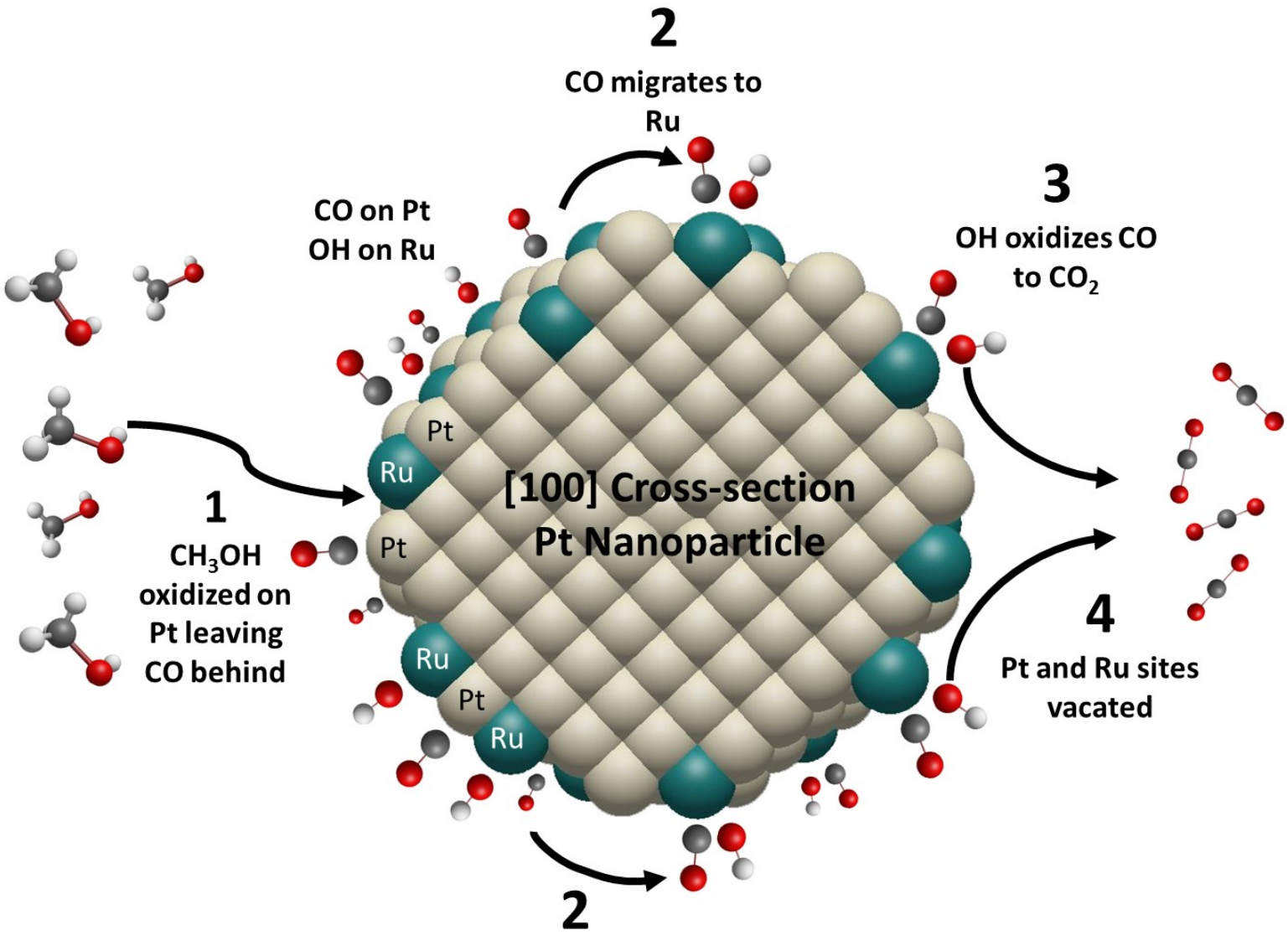
Without methanol

Above 375 mV Ru-O paths appear and total number of Ru-O neighbors increases to that of RuO_2

With methanol

Ru has one low Z neighbor at all potentials (carbon); a second above 175 mV (oxygen) with constant bond lengths and slightly increasing numbers

Bi-functional mechanism



C. Pelliccione et al., "In situ Ru K-Edge x-ray absorption spectroscopy study of methanol oxidation mechanisms on model submonolayer Ru on Pt nanoparticle electrocatalyst" *J. Phys. Chem.* **C 117**, 18904 (2013).

Battery chemistries accessible to XAFS

Cathode materials:

- $Ni(OH)_2@Co(OH)_2$
- MnO_2
- $LiCoO_2$
- $Li_{1.2}(NiMnCo)_{0.8}O_2$
- $Li_{1.2}(MnNiFe)_{0.8}O_2$
- $Li_3V_2(PO_4)_3$
- $LiFePO_4$

Edge	Energy
Li	0.055 keV
V	5.465 keV
Mn	6.539 keV
Fe	7.112 keV
Co	7.709 keV
Ni	8.333 keV

Li edge not directly accessible and 3d element energies challenging for *in situ* experiments.

Anode materials:

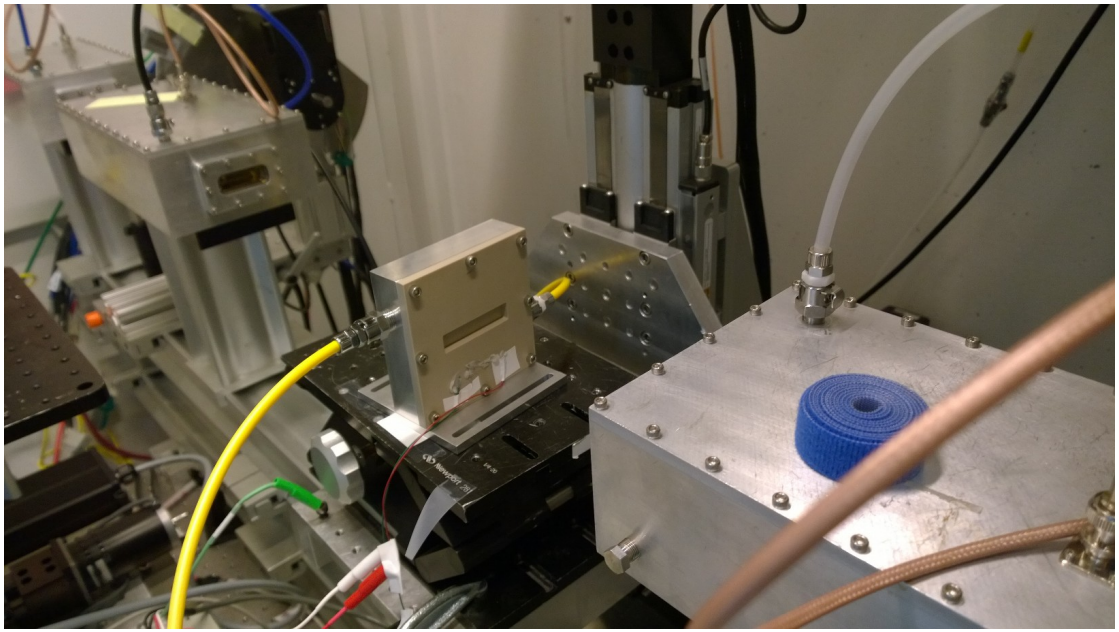
- Fe_2O_3
- ZnO
- MoS_2
- Sn
- SnO_2
- $Sn_3O_2(OH)_2$
- Sn_4P_3

Edge	Energy
P	2.145 keV
S	2.472 keV
Fe	7.112 keV
Zn	9.659 keV
Mo	20.00 keV
Sn	29.20 keV

P and S edges too low for non-vacuum experiments, Zn good in fluorescence, Mo and Sn ideal for *in situ* experiments.

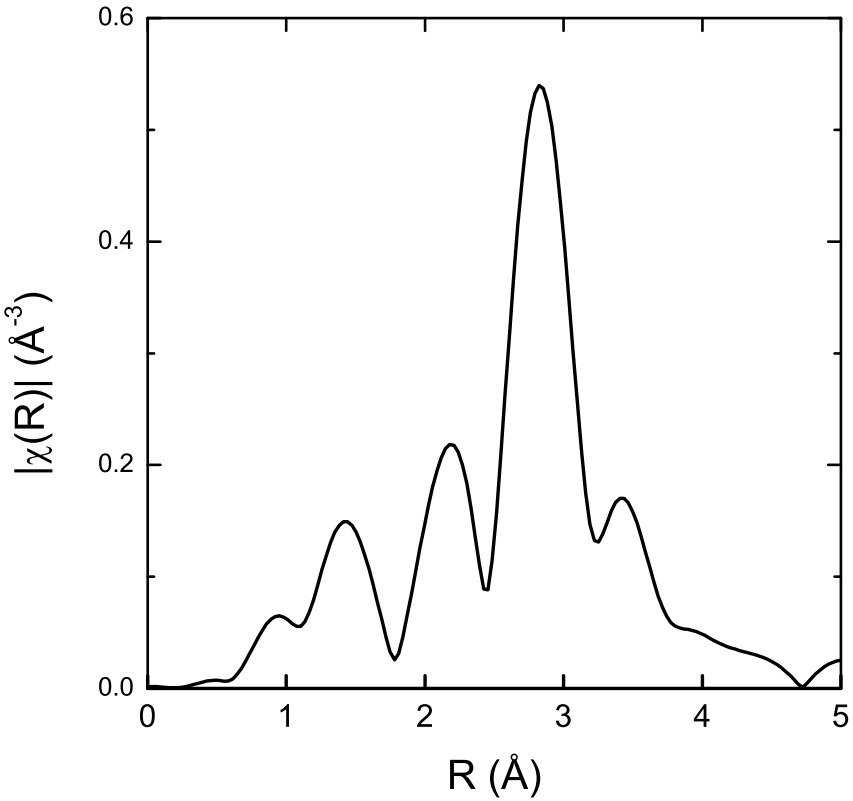
In situ lithiation of Sn

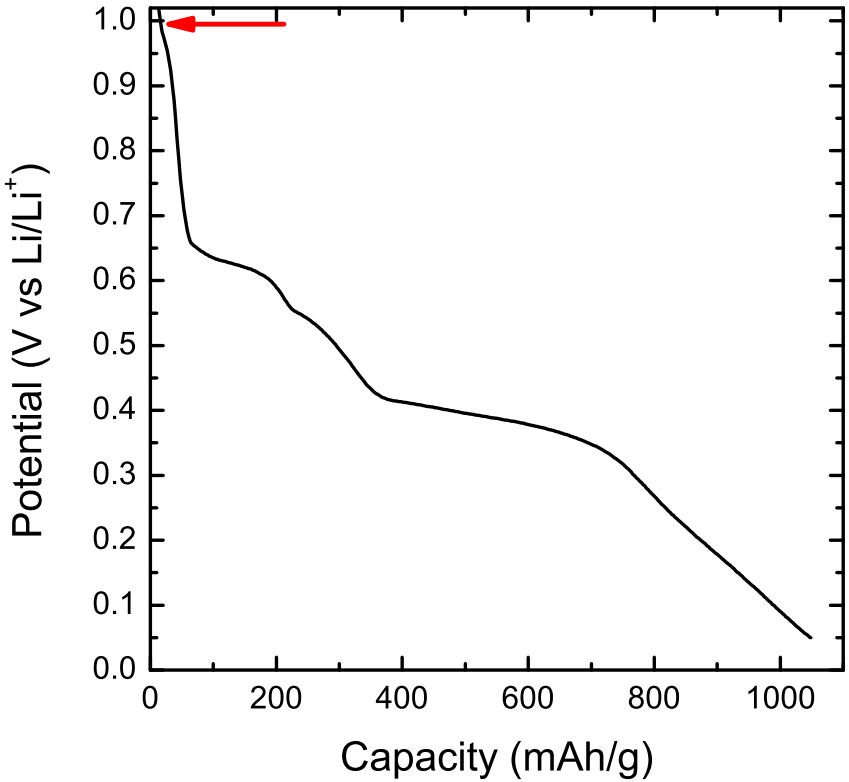
- In situ box for non-aqueous experiments
- Have measured $Sn_3O_2(OH)_2$, SnO_2, Sn, ZnO, MoO_2 ...
- Pouch cell simplifies experiment



- MRCAT 10-ID beam line scans EXAFS spectrum in 2 minutes
- Focus on Sn nanoparticles which have rapid failure rate
- Successfully modeled Sn-Li paths in $Sn_3O_2(OH)_2$ using 3 composite paths

Sn EXAFS versus potential

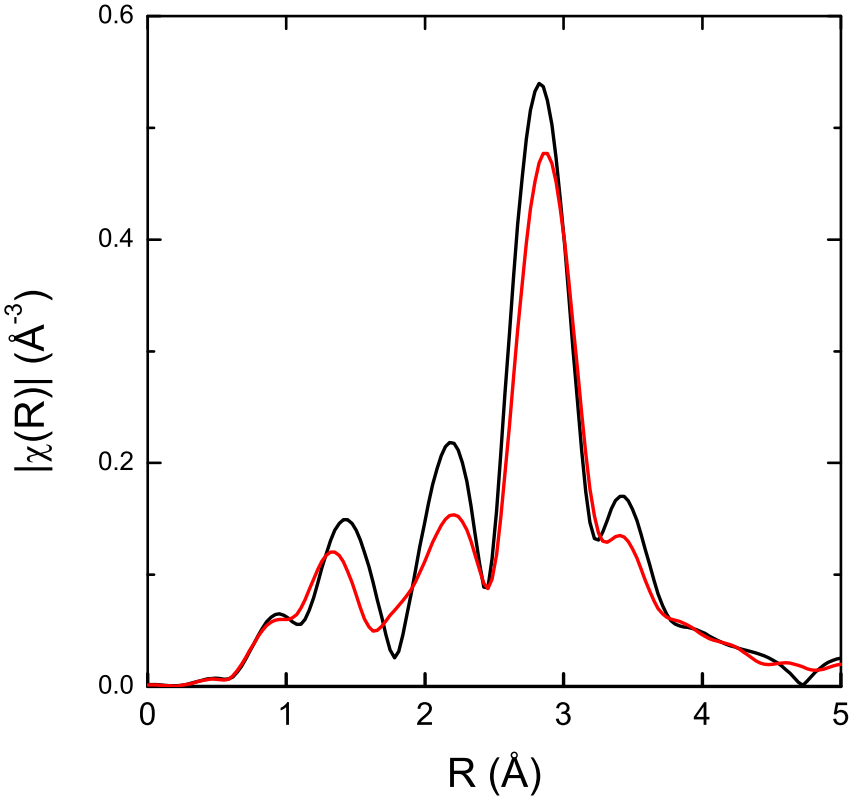


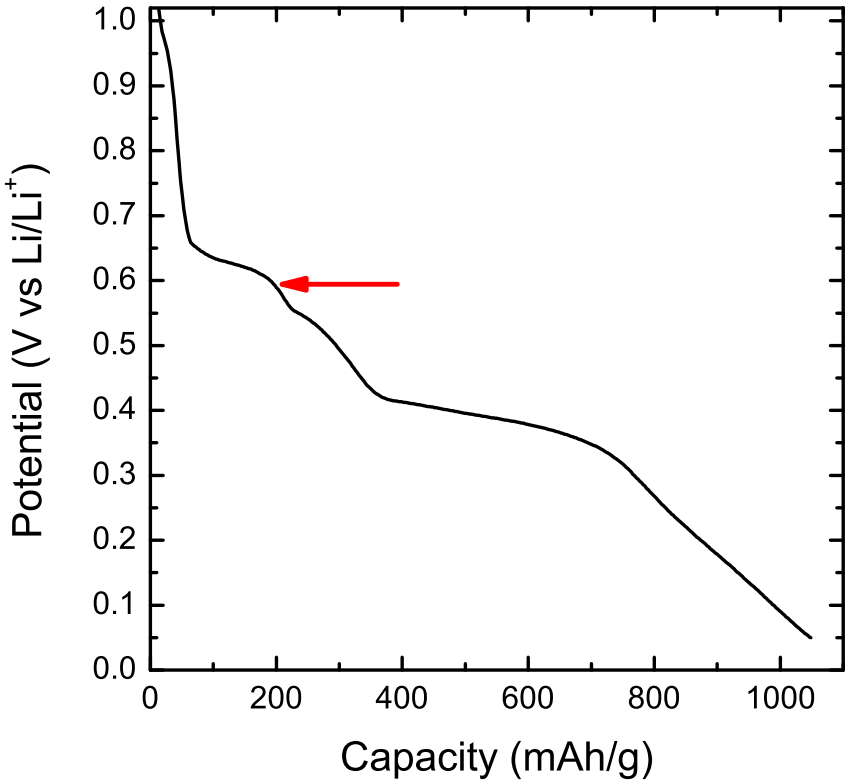


$Li_{22}Sn_5$ has 14 Sn-Li paths with distance 3.4Å or less

Thes are modeled using three Sn-Li paths at "center of mass" location

Sn EXAFS versus potential

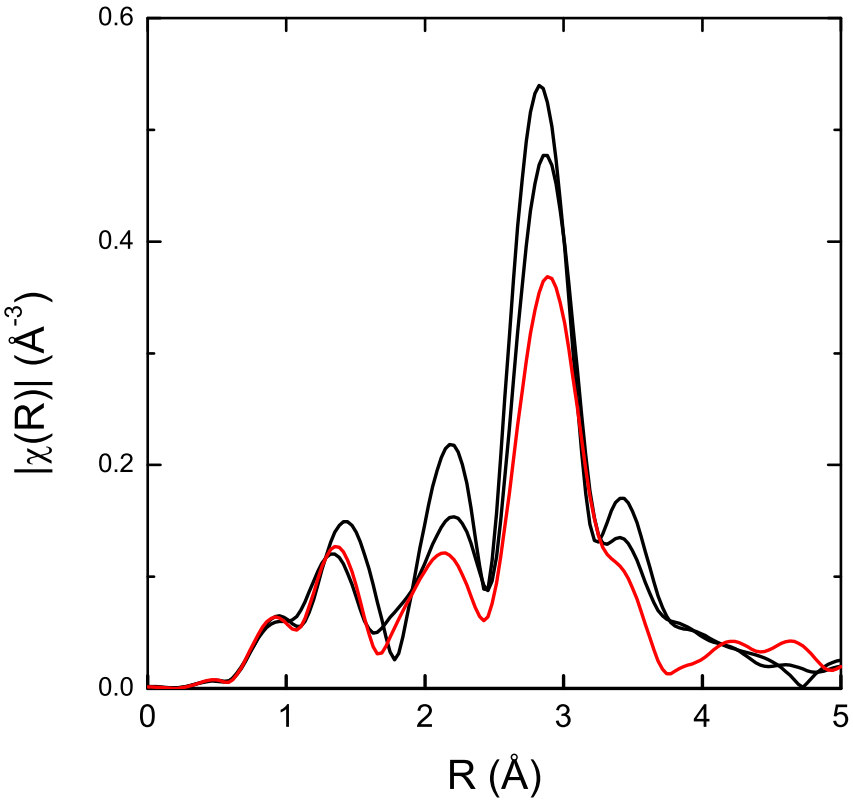


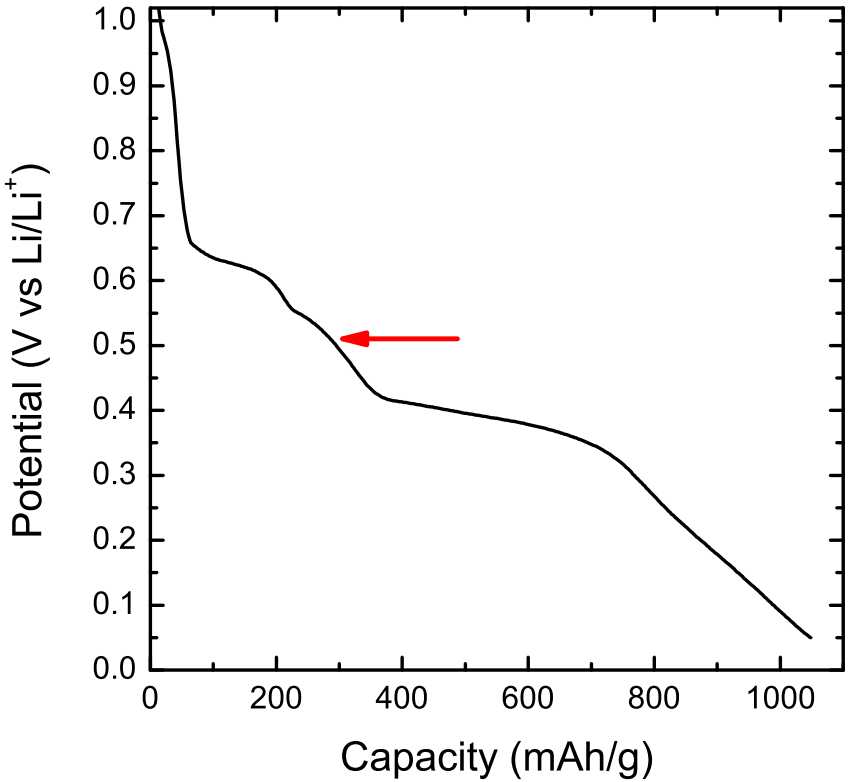


$Li_{22}Sn_5$ has 14 Sn-Li paths with distance 3.4Å or less

Thes are modeled using three Sn-Li paths at "center of mass" location

Sn EXAFS versus potential

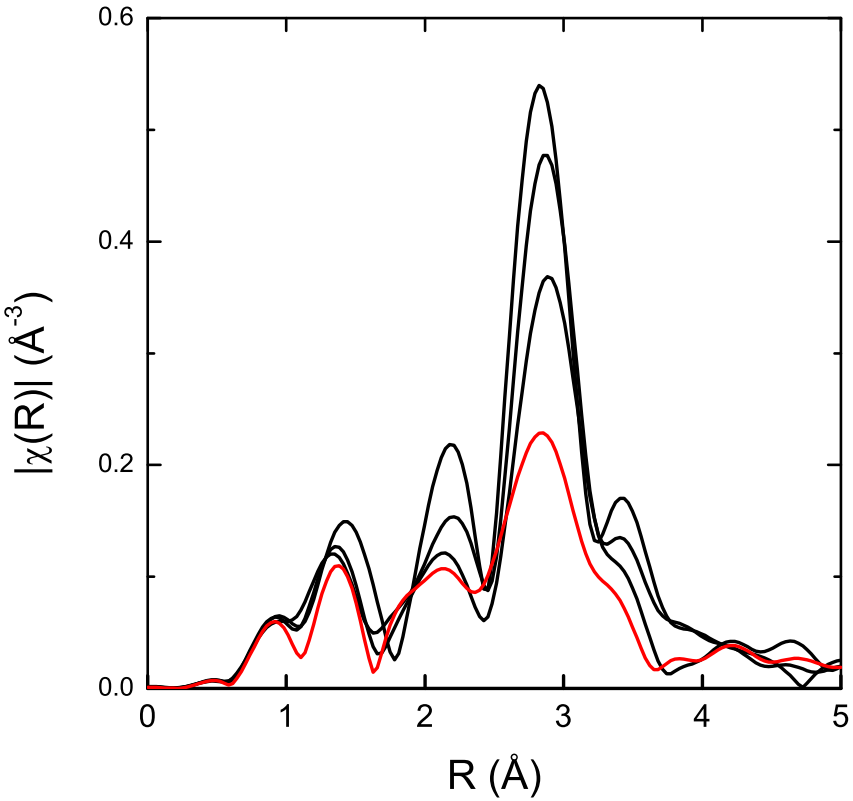


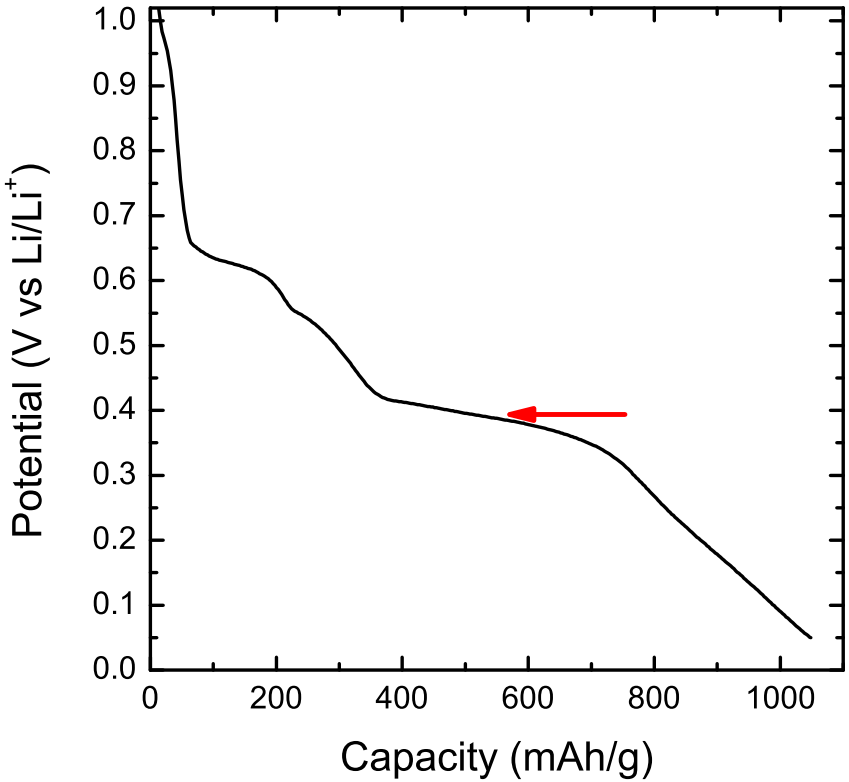


$Li_{22}Sn_5$ has 14 Sn-Li paths with distance 3.4Å or less

Thes are modeled using three Sn-Li paths at "center of mass" location

Sn EXAFS versus potential

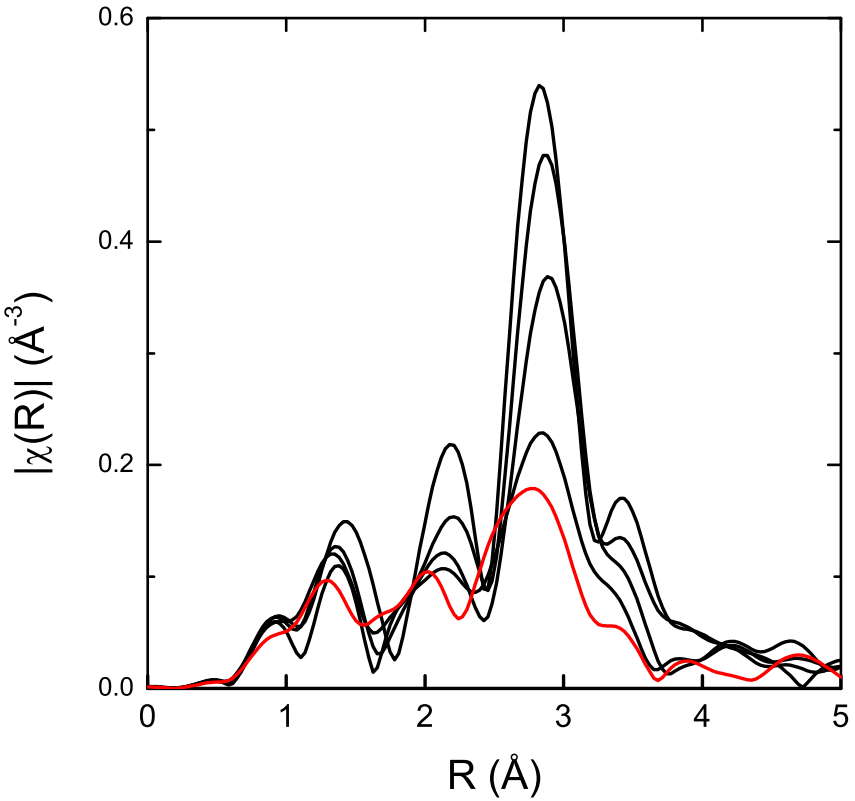


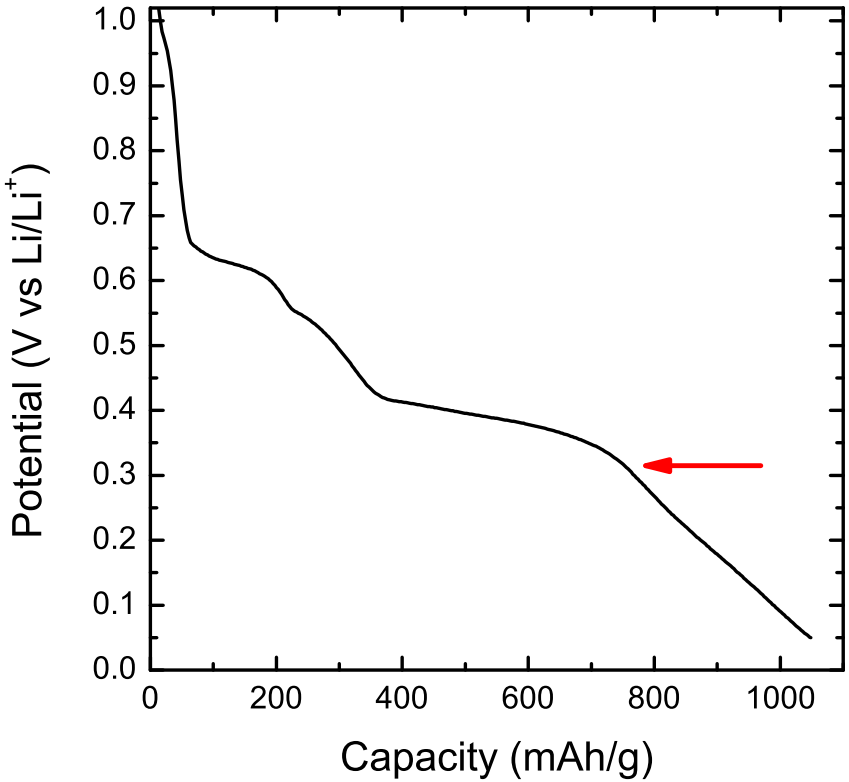


$Li_{22}Sn_5$ has 14 Sn-Li paths with distance 3.4Å or less

Thes are modeled using three Sn-Li paths at "center of mass" location

Sn EXAFS versus potential

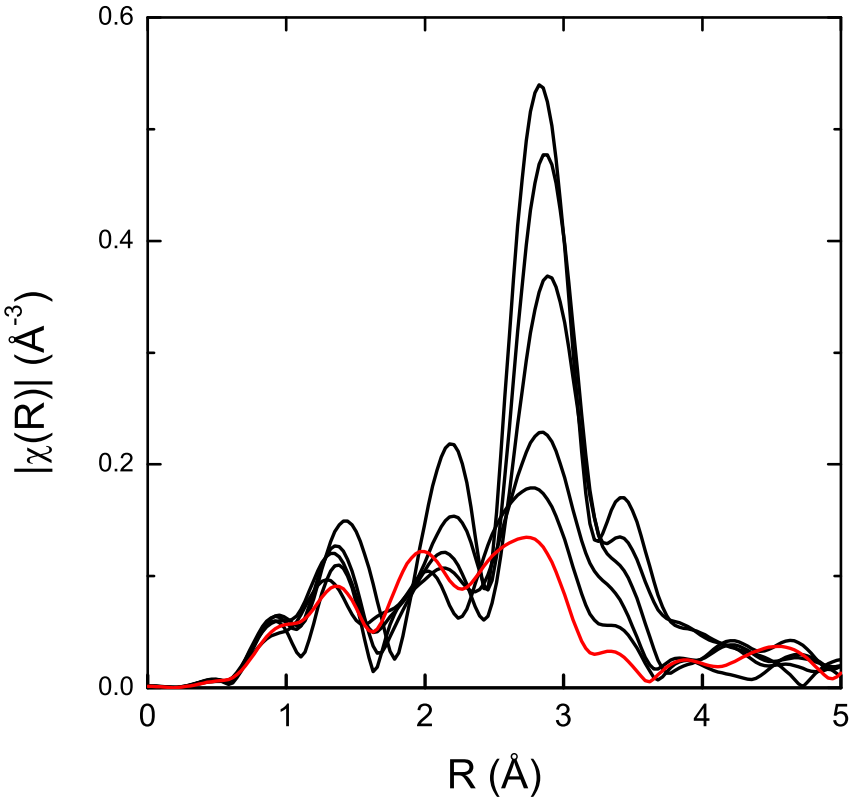


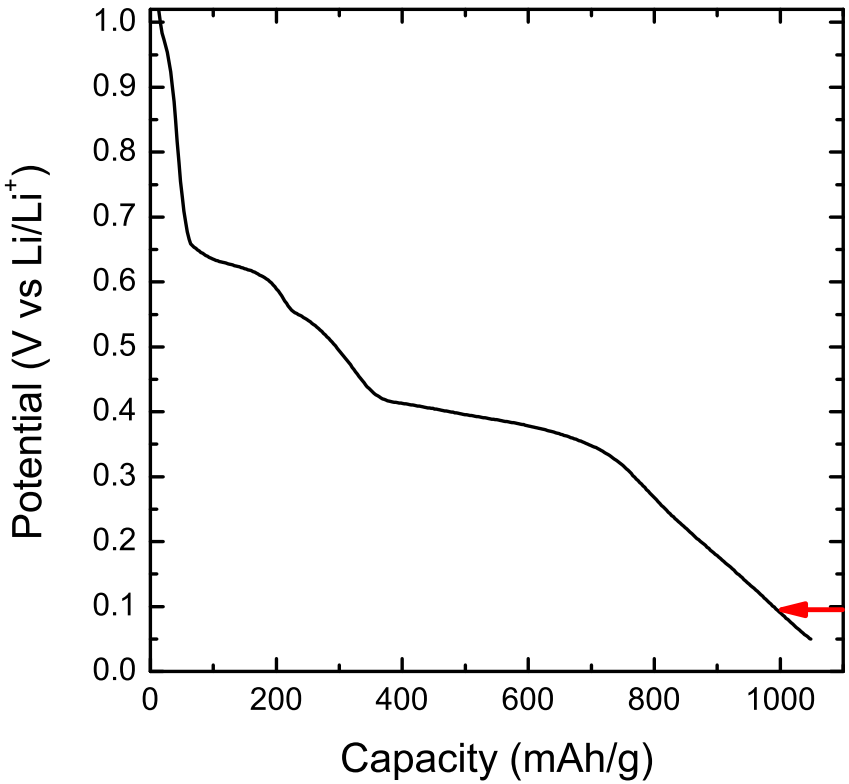


$Li_{22}Sn_5$ has 14 Sn-Li paths with distance 3.4Å or less

Thes are modeled using three Sn-Li paths at "center of mass" location

Sn EXAFS versus potential

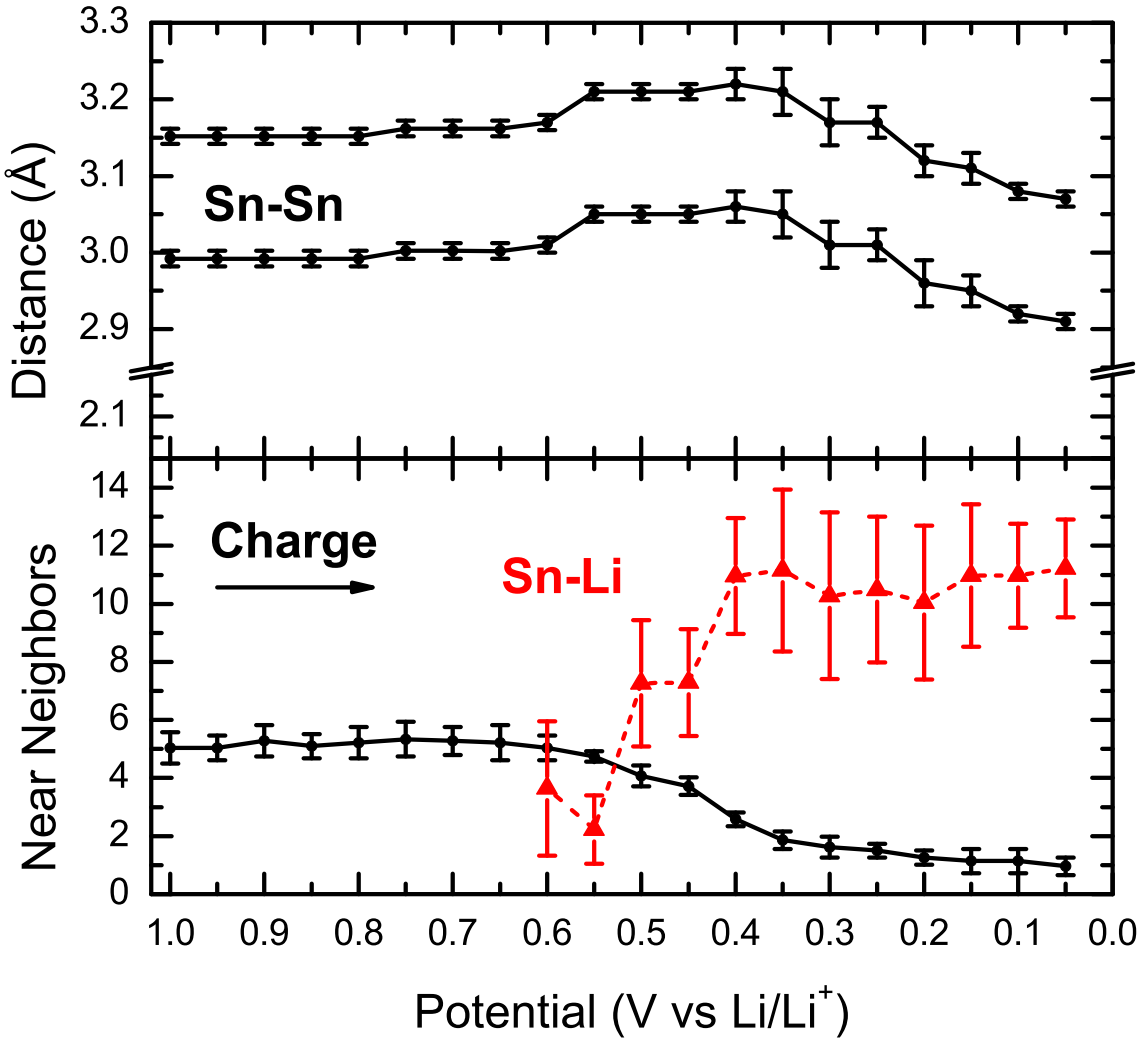




$Li_{22}Sn_5$ has 14 Sn-Li paths with distance 3.4Å or less

Thes are modeled using three Sn-Li paths at "center of mass" location

The Sn lithiation process

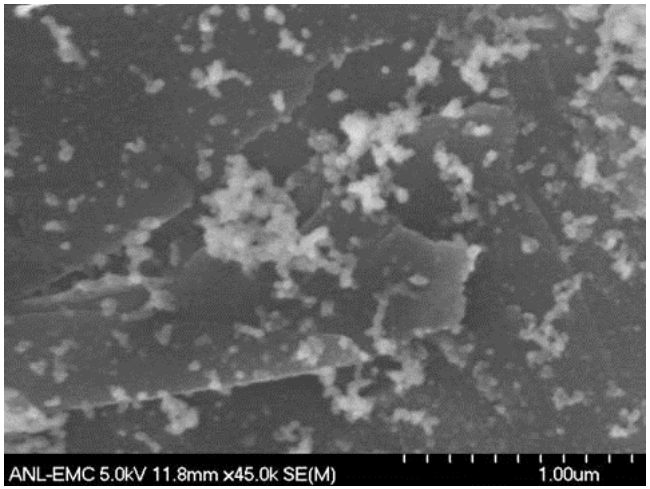


0.60V – Sn metal begins to break down and Li appears

0.45V – number of Li reaches 11 and stabilizes at near full $Li_{22}Sn_5$

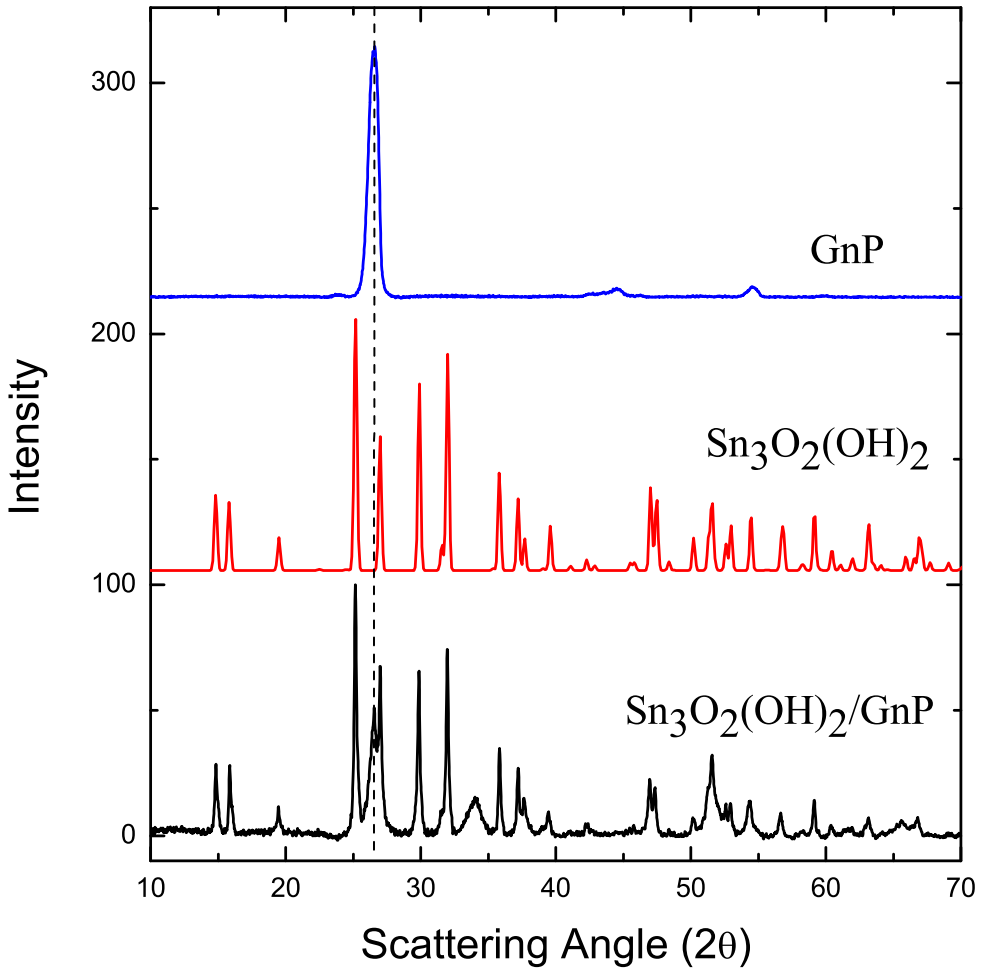
However, Sn fades rapidly due to electric conductivity loss. What can be improved?

Synthesis of Sn-graphite nanocomposites

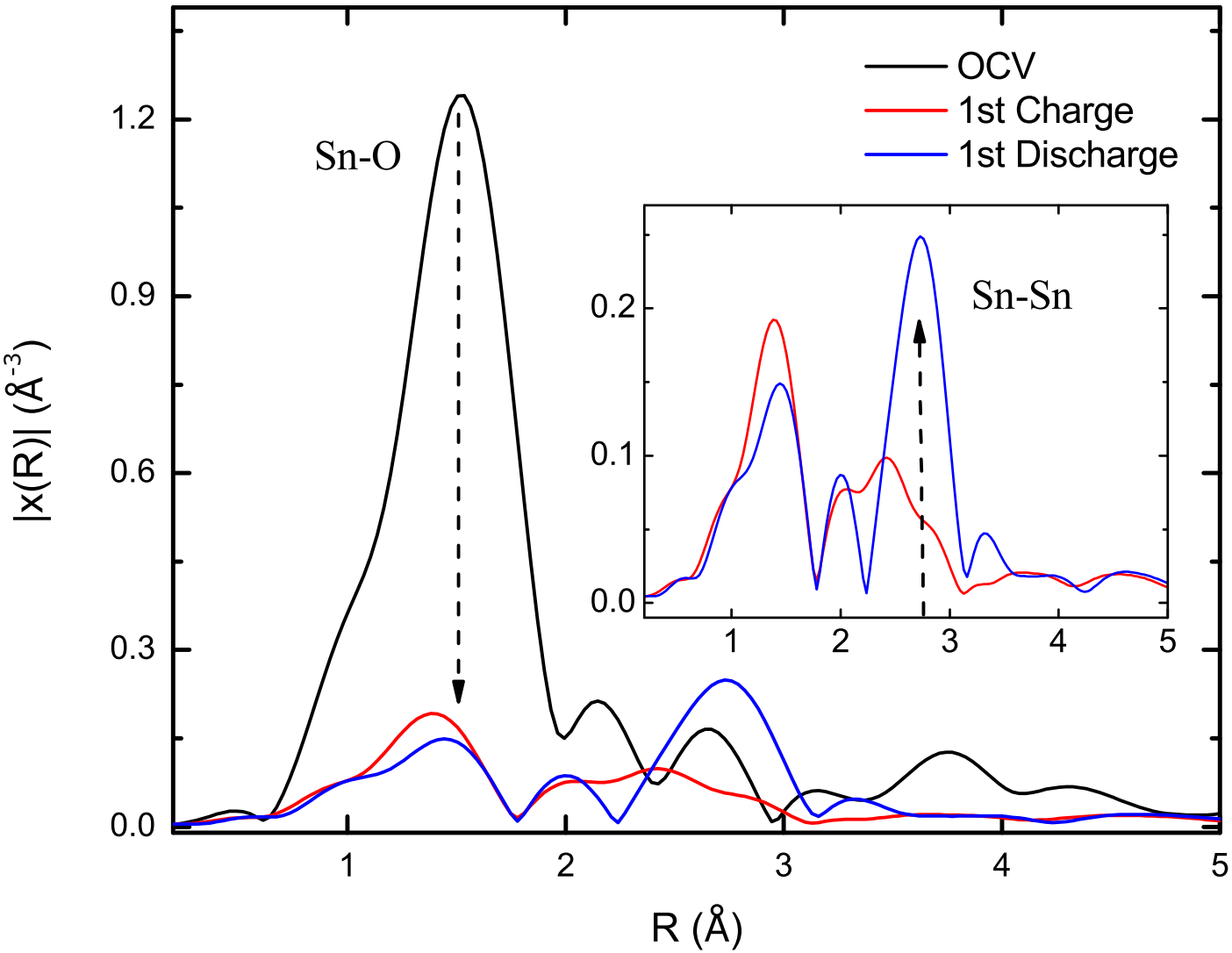


One-pot synthesis produces evenly distributed $Sn_3O_2(OH)_2$ nanoparticles on graphite nanoplatelets

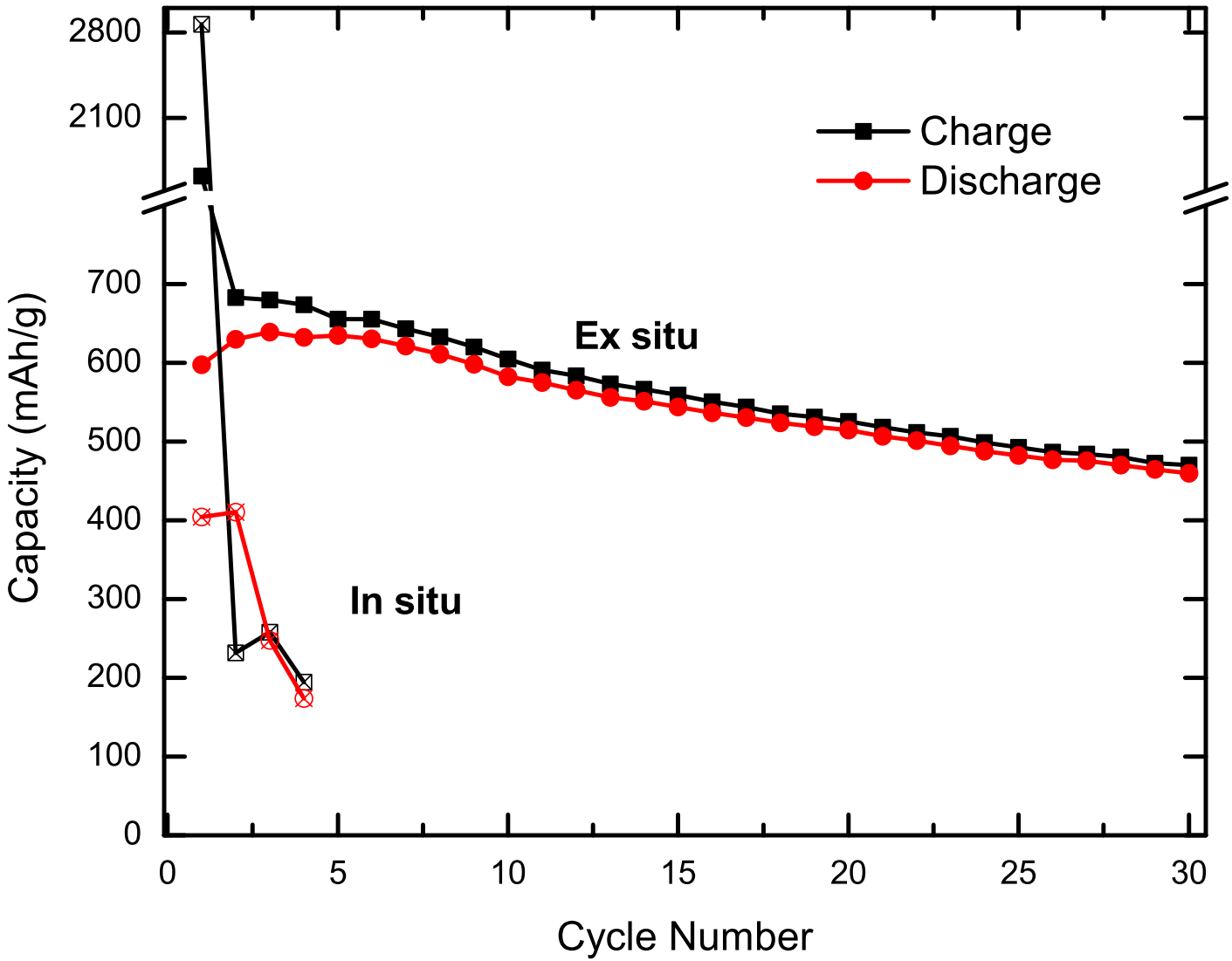
XRD shows a small amount of Sn metal in addition to $Sn_3O_2(OH)_2$



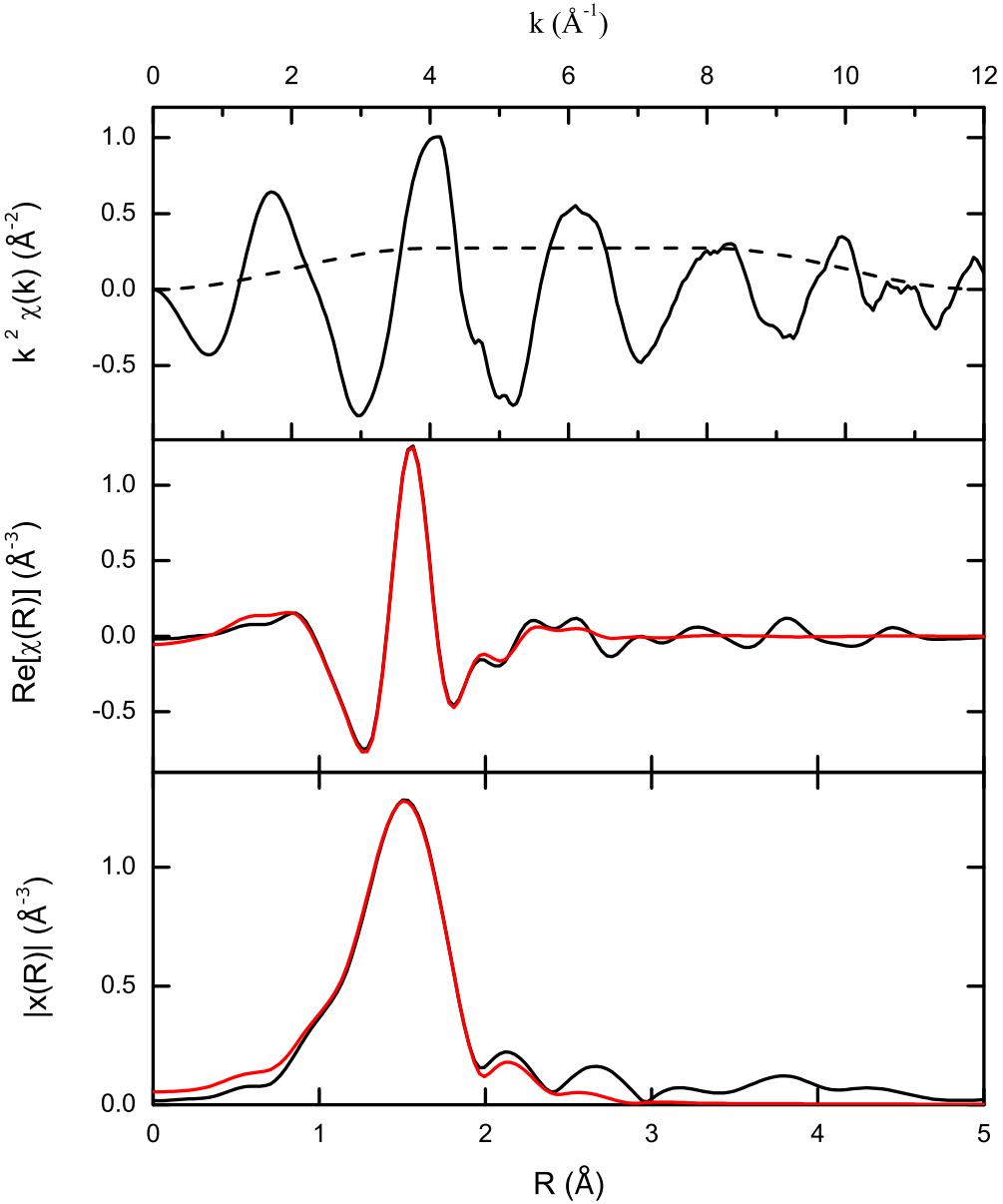
In situ XAS studies of lithiation



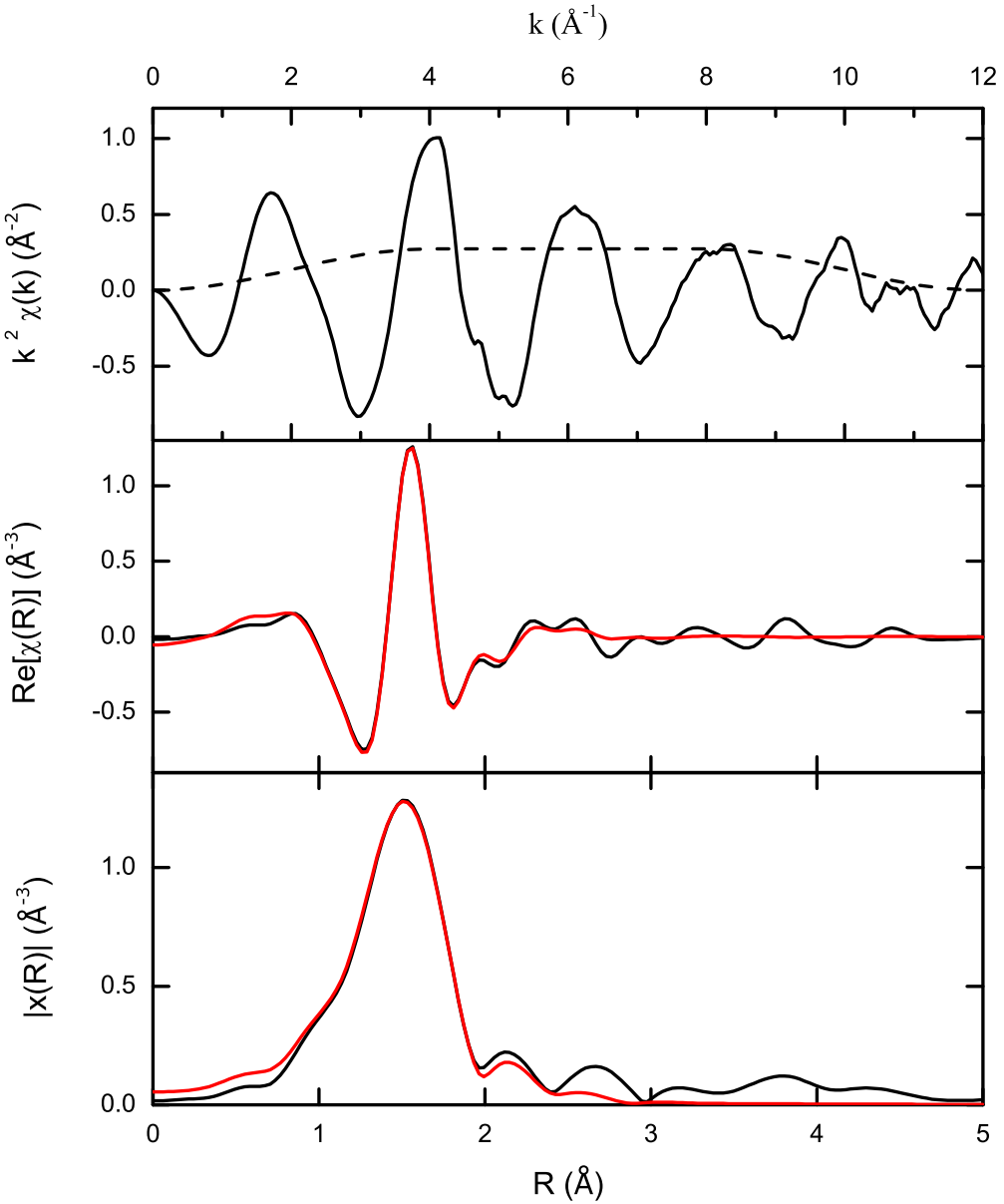
In situ XAS studies of lithiation



In situ XAS studies of lithiation

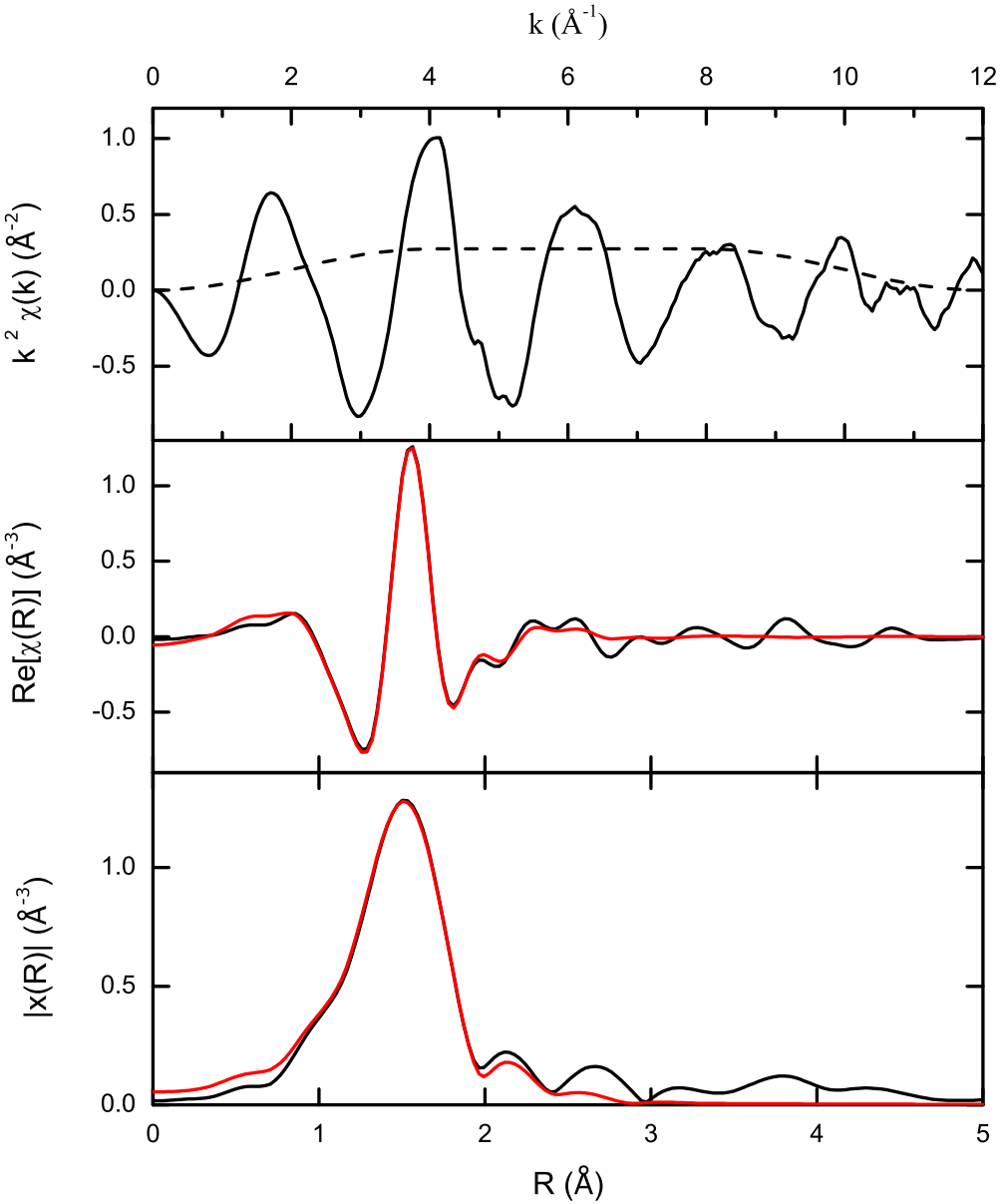


In situ XAS studies of lithiation



Fresh electrode can be fit with $Sn_3O_2(OH)_2$ structure which is dominated by the near neighbor Sn-O distances

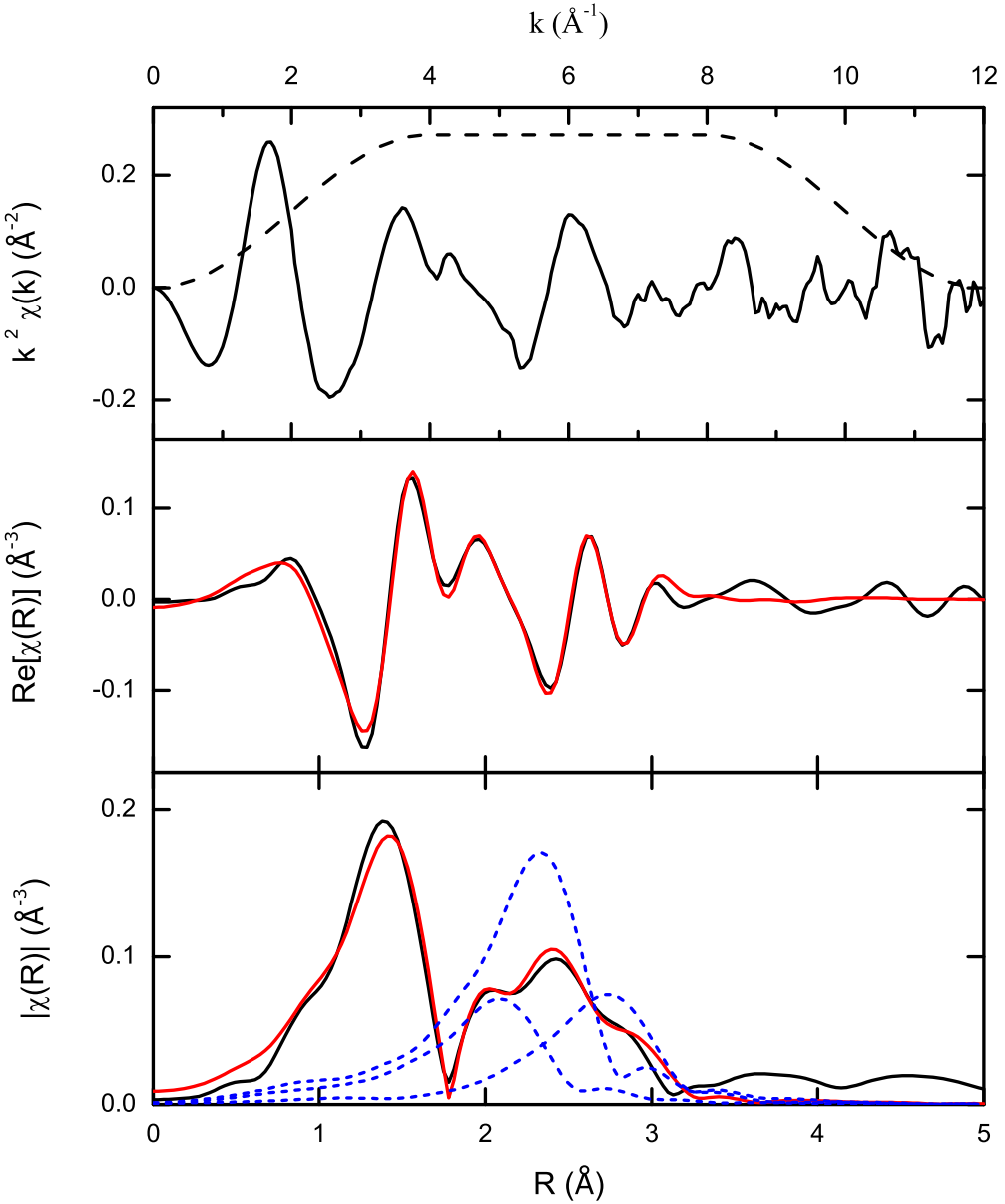
In situ XAS studies of lithiation



Fresh electrode can be fit with $Sn_3O_2(OH)_2$ structure which is dominated by the near neighbor Sn-O distances

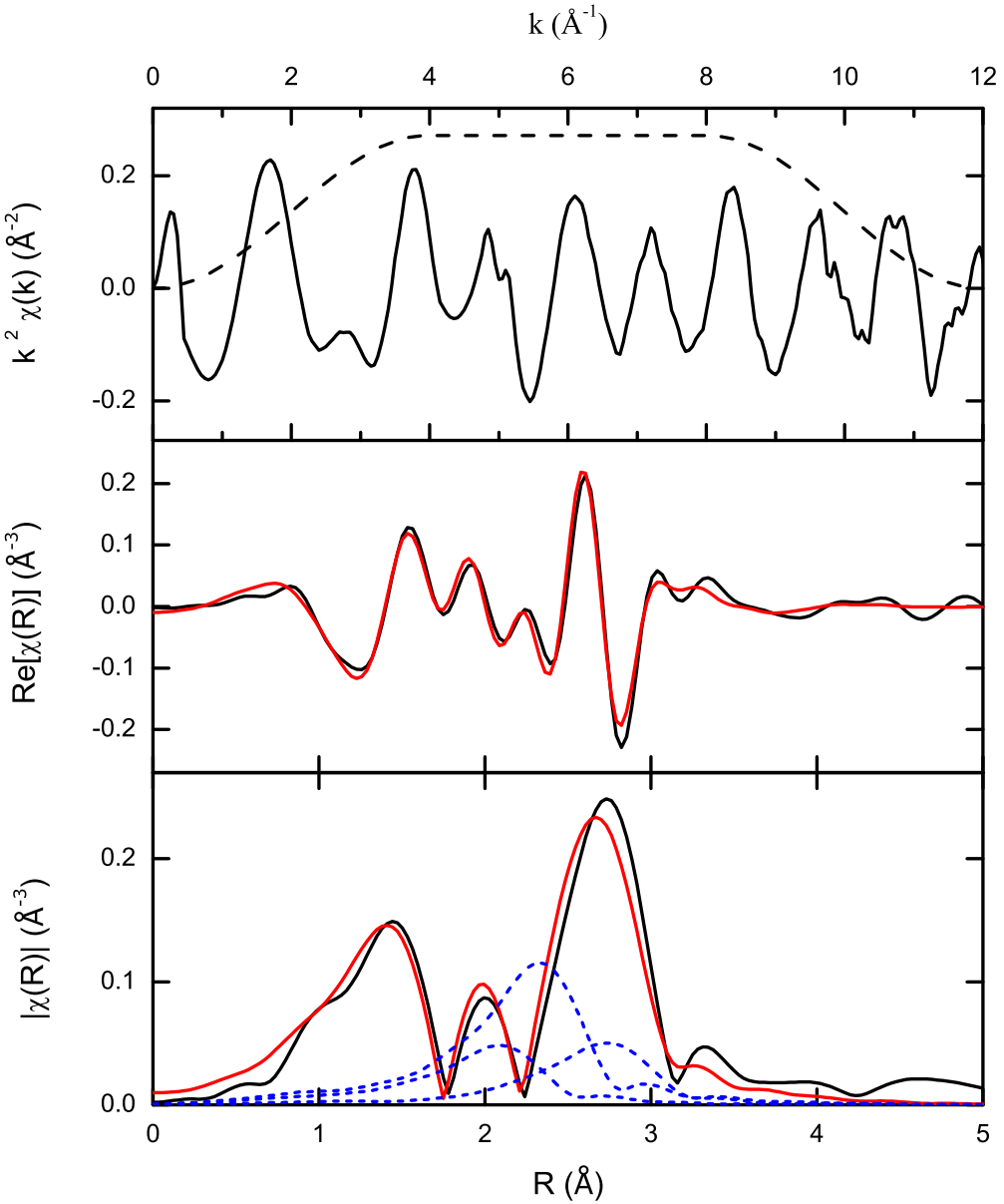
Only a small amount of metallic Sn-Sn distances can be seen

In situ XAS studies of lithiation



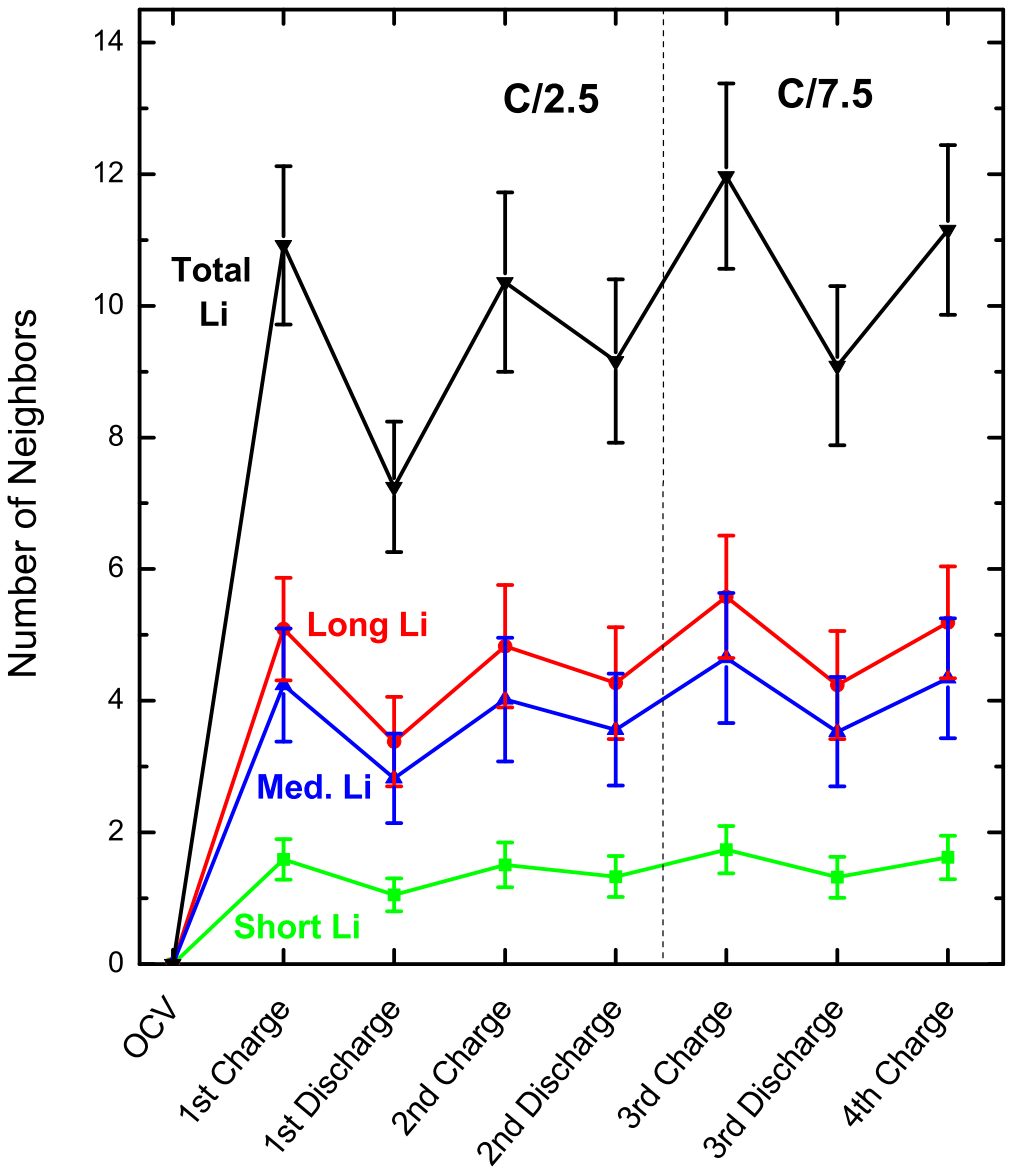
Reduction of number of Sn-O near neighbors and 3 Sn-Li paths characteristic of the $Li_{22}Sn_5$ structure

In situ XAS studies of lithiation

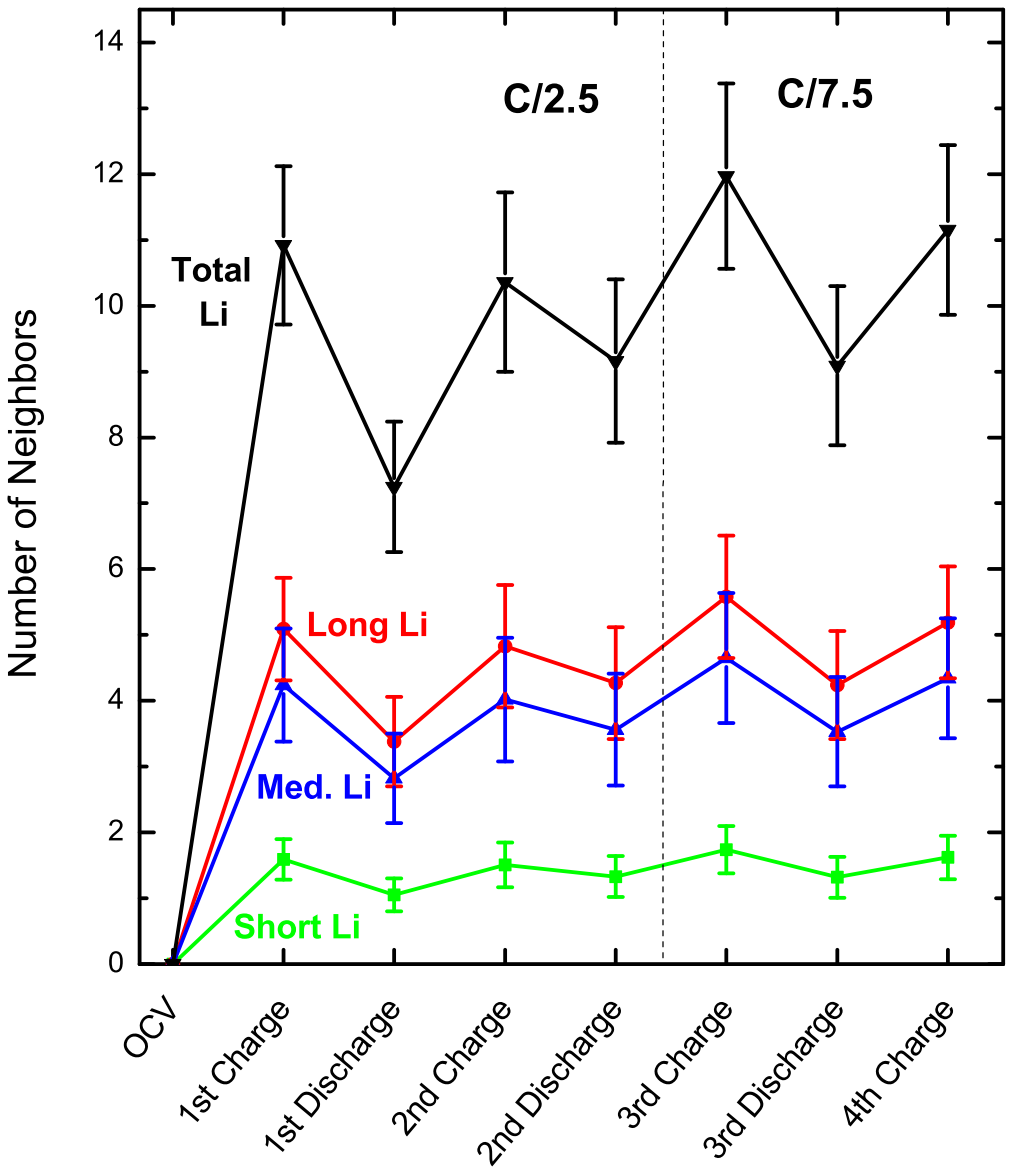


Metallic Sn-Sn distances appear but Sn-Li paths are still present, further reduction in Sn-O near neighbors.

In situ XAS studies of lithiation

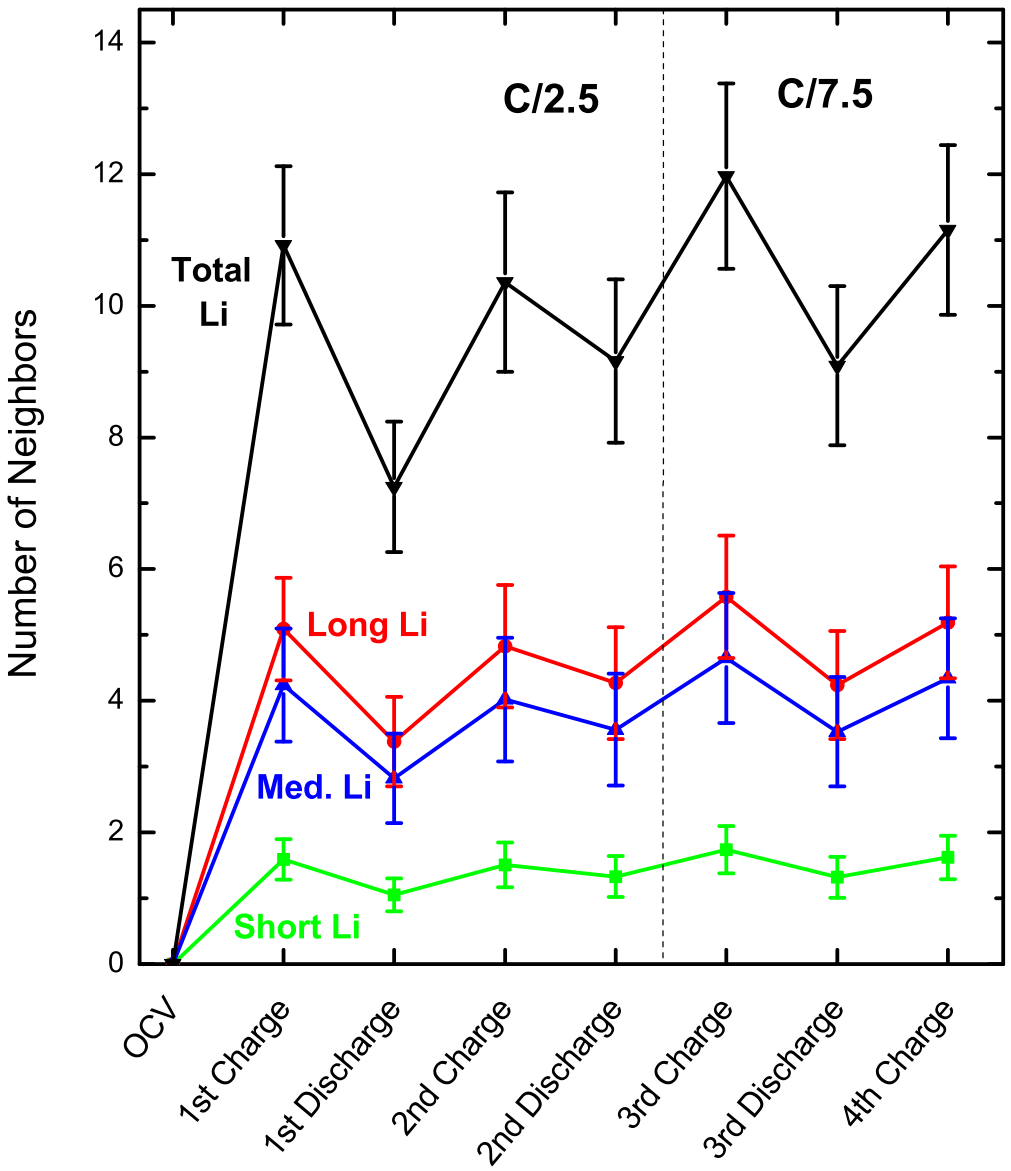


In situ XAS studies of lithiation



Number of Li near neighbors oscillates with the charge/discharge cycles but never returns to zero

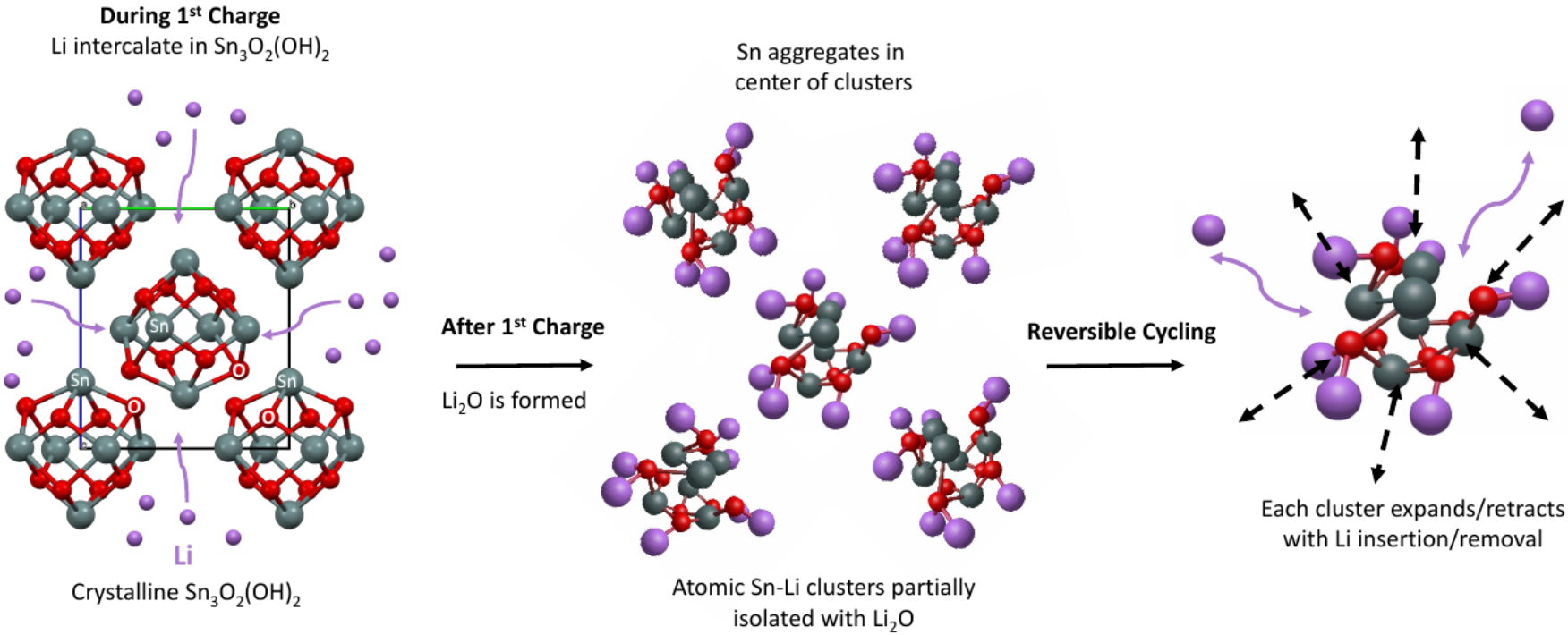
In situ XAS studies of lithiation



Number of Li near neighbors oscillates with the charge/discharge cycles but never returns to zero

In situ cell promotes accelerated aging because of Sn swelling and the reduced pressure of the thin PEEK pouch cell assembly

In situ XAS studies of lithiation

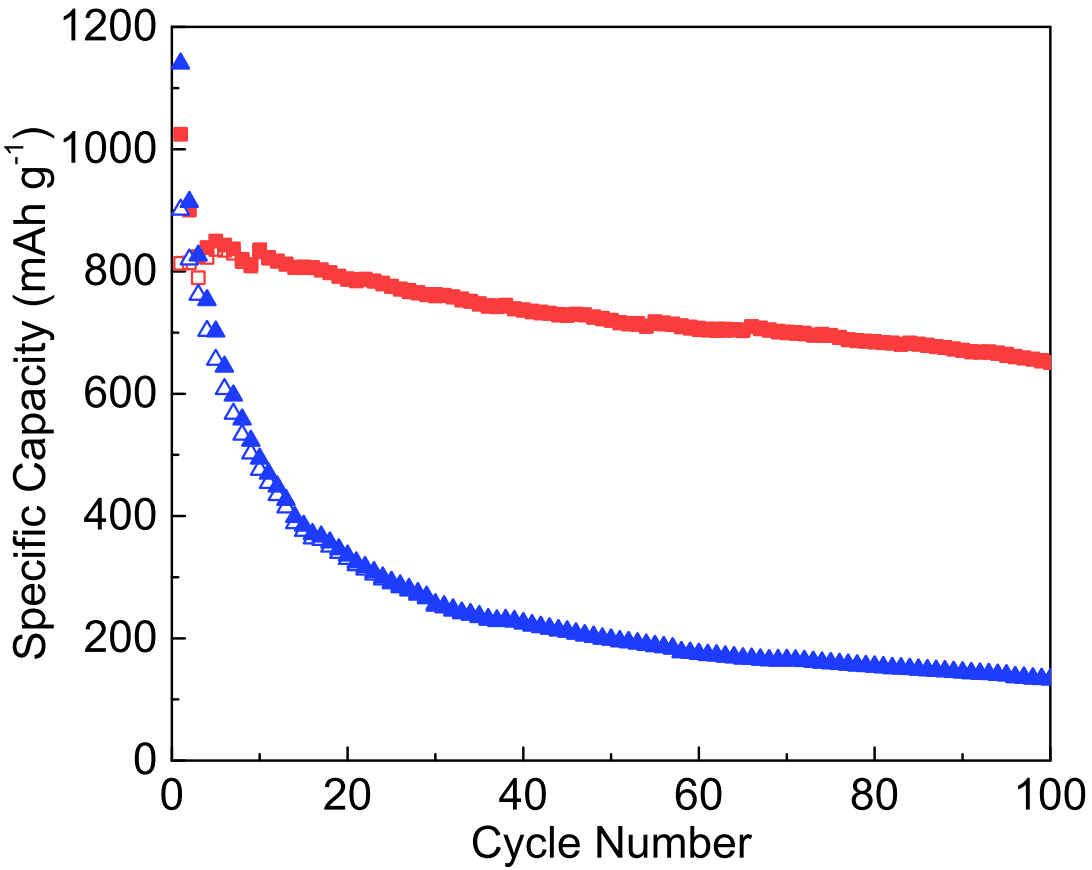


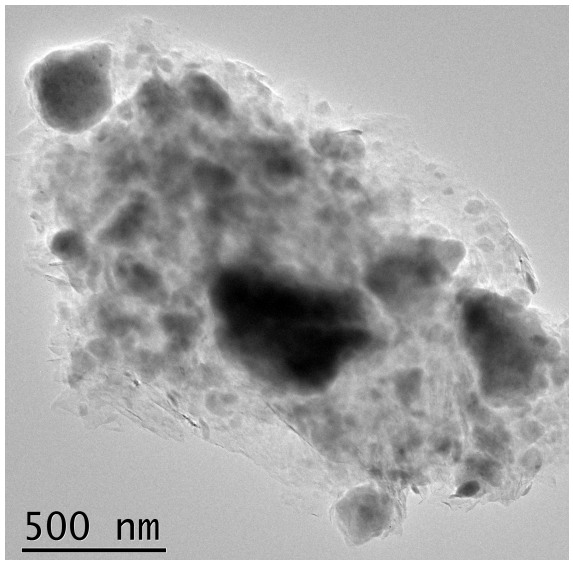
C. Pelliccione et al., "In situ XAS study of the capacity fading mechanism in hybrid $Sn_3O_2(OH)_2$/graphite battery anode nanomaterials", *Chem. Mater.* 27, 574-580 (2015).

Sn_4P_3/graphite composite anode

Sn_4P_3 synthesized by high energy ball milling, then ball milled again with graphite to obtain composite

Theoretically could transfer 9 or more electrons upon lithiation

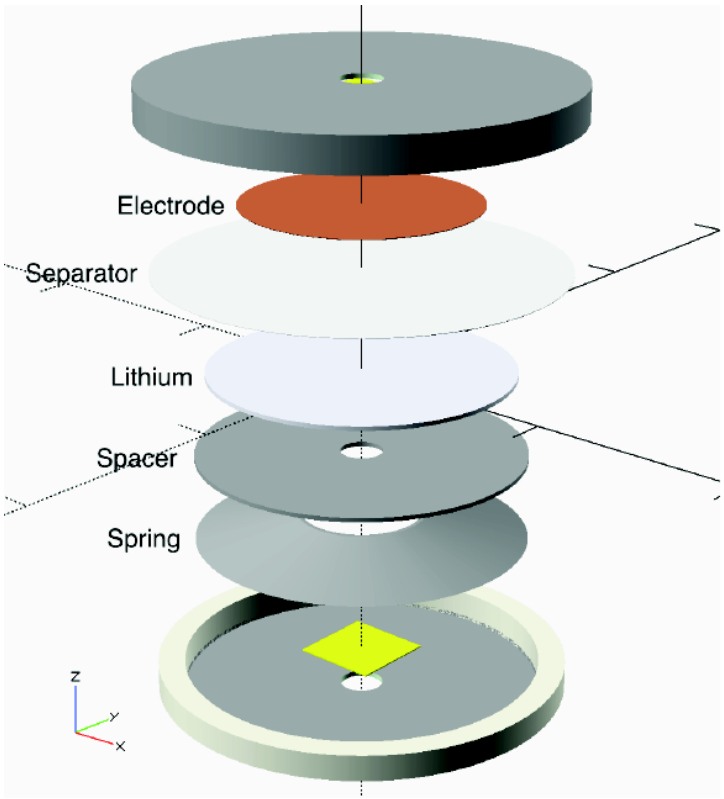


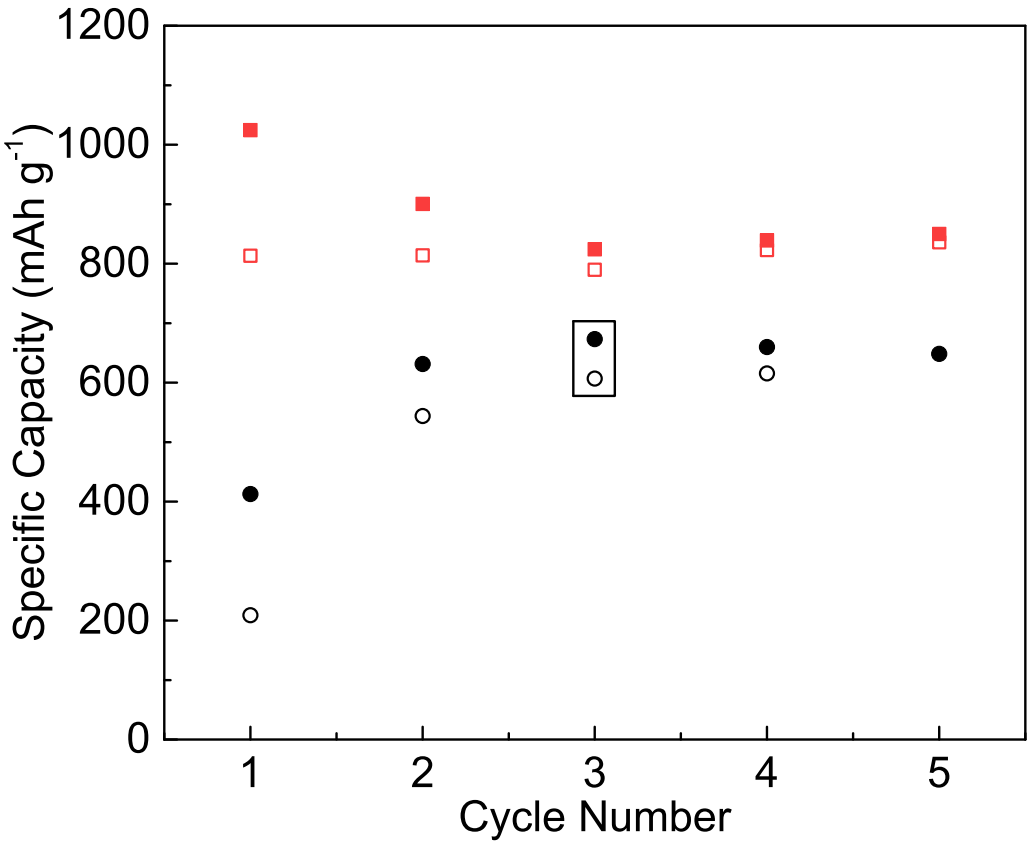


Sn_4P_3/graphite composite shows stable, reversible capacity of 610 mAh/g for 100 cycles at C/2 compared to rapidly fading pure Sn_4P_3 material.

How does the lithiation process differ from that of Sn metal?

In situ EXAFS of Sn_4P_3/graphite

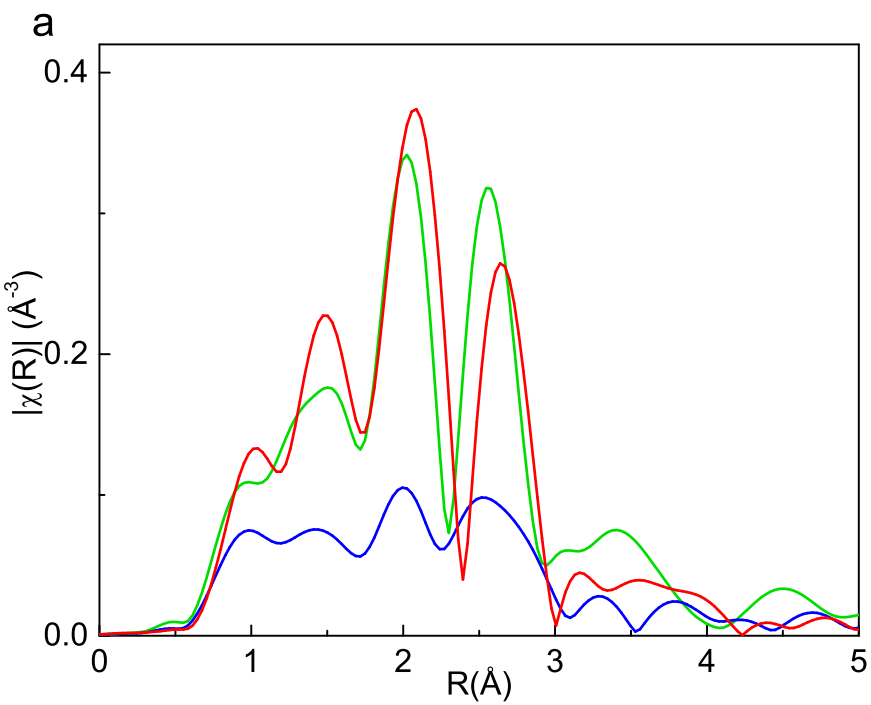




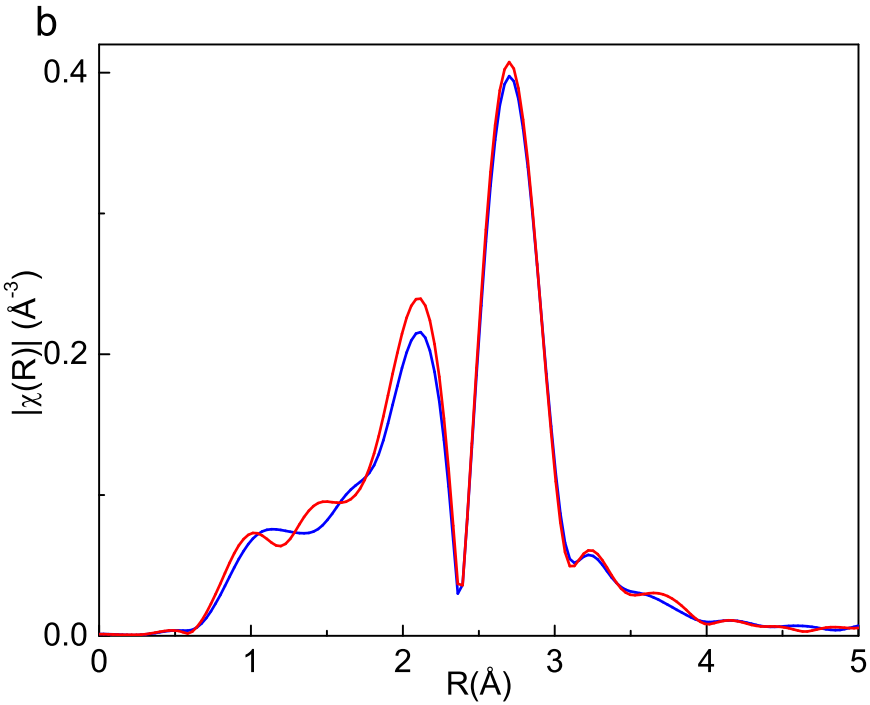
Results for *in situ* coin cell are close to the capacity of the unmodified cell at C/4, indicating good reversibility by the 3^{rd} cycle.

Third cycle comparison

By the third lithiation and third delithiation, the difference between pure Sn_4P_3 and the Sn_4P_3/graphite composite is clear.



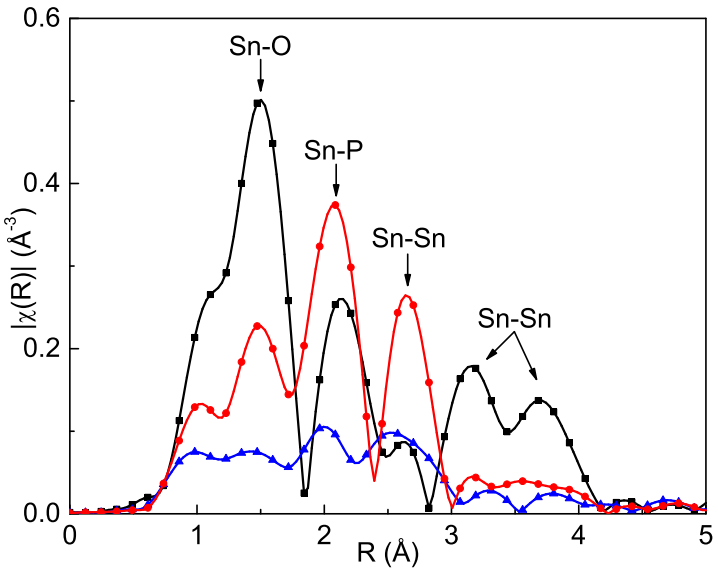
Sn_4P_3/graphite composite

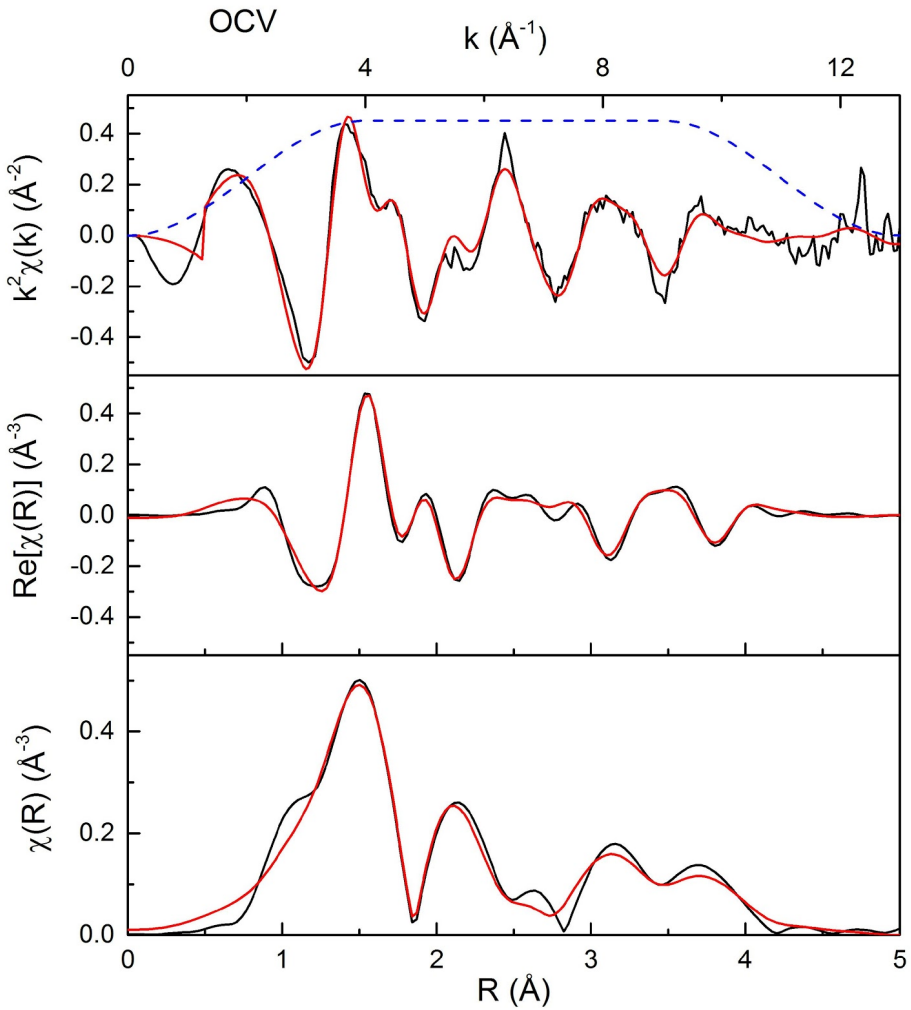


pure Sn_4P_3

Even at the 100^{th} delithiation, the Sn_4P_3/graphite composite measured *ex situ* is showing the same features as at the 3^{rd} cycle.

Example fits

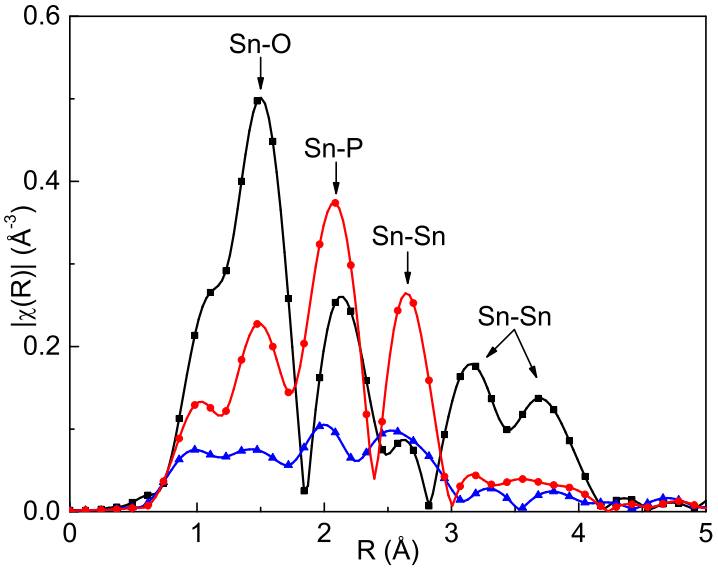


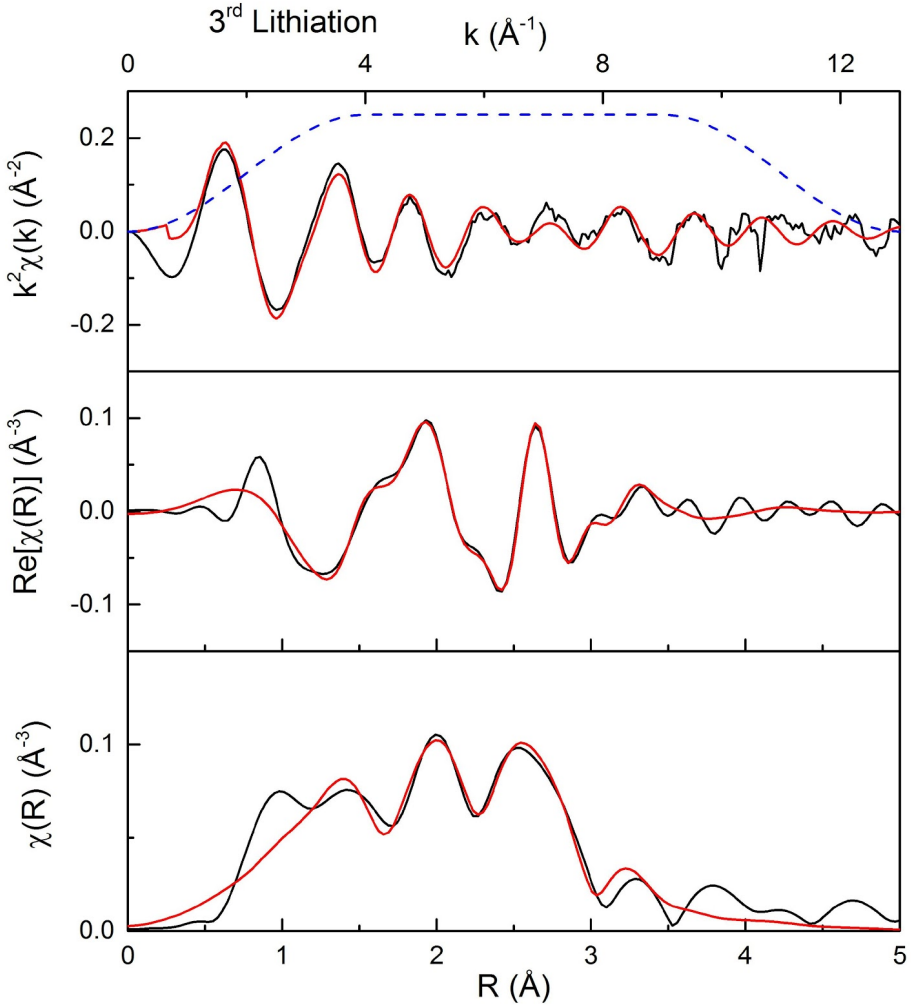


The EXAFS modeling of the Sn_4P_3/graphite electrode at OCV, 3^{rd} lithiation, and 3^{rd} delithiation, provides bond distances and coordination numbers

The Sn-O peak in the OCV spectrum is primarily due to the ball milling process which inevitably introduces some oxygen.

Example fits

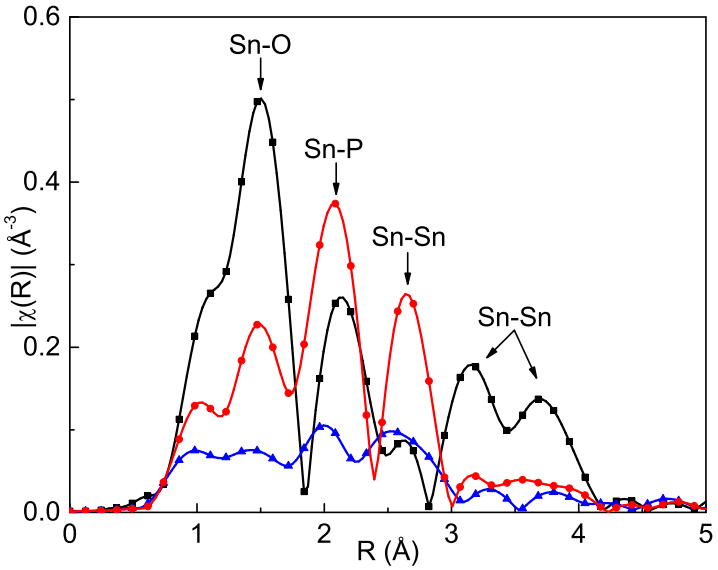


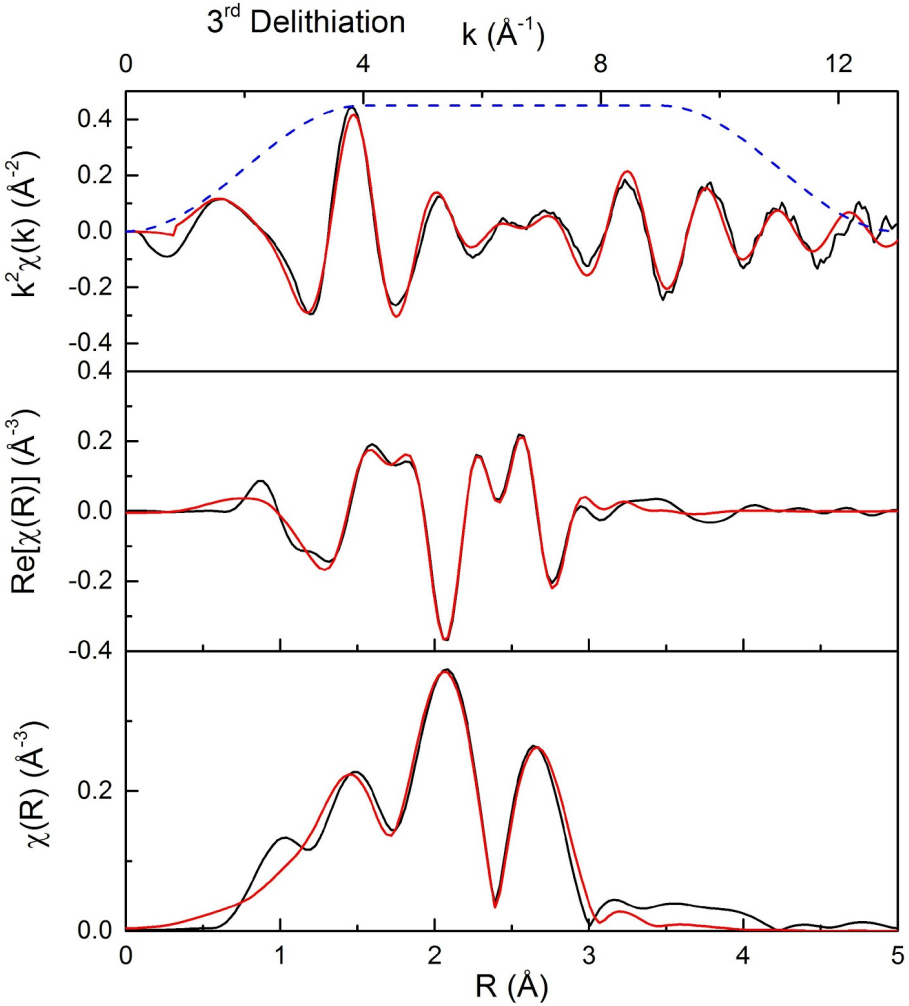


The EXAFS modeling of the Sn_4P_3/graphite electrode at OCV, 3^{rd} lithiation, and 3^{rd} delithiation, provides bond distances and coordination numbers

By the 3^{rd} fully lithiated state, the EXAFS is dominated by the Sn-Li paths at 2.7 Åand 3.0 Å.

Example fits

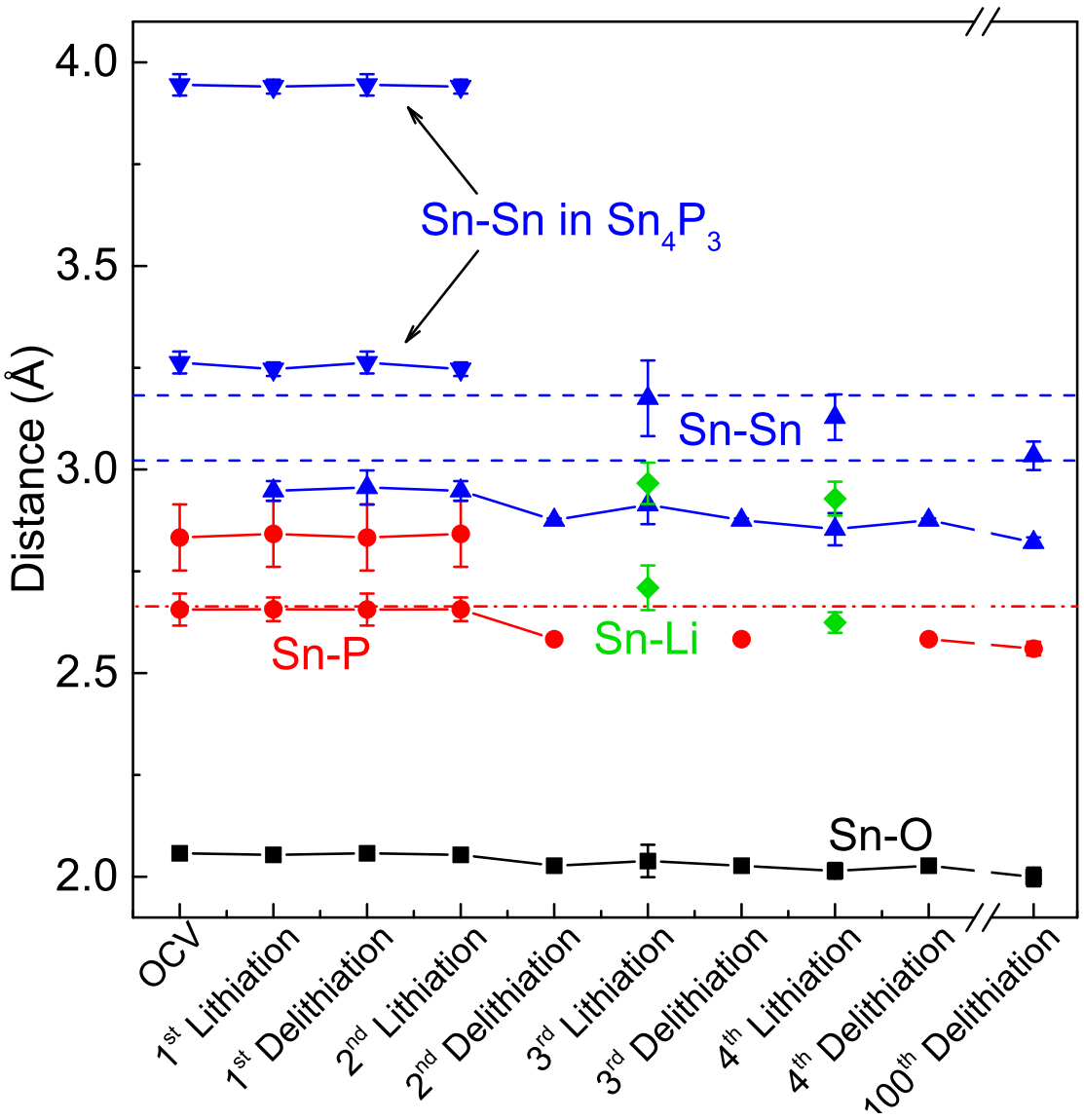




The EXAFS modeling of the Sn_4P_3/graphite electrode at OCV, 3^{rd} lithiation, and 3^{rd} delithiation, provides bond distances and coordination numbers

At the 3^{rd} delithiation, the Sn-P path reappears but at a shorter distance, in an amorphous SnP_x phase.

Sn_4P_3/graphite path lengths



Sn-Sn distance close to those of metallic Sn indicate the presence of smll Sn clusters which may never fully lithiate

Longer Sn-P distance characteristic of Sn_4P_3 is gone after initial conversion to the SnP_x amorphous phase is complete

Only 2 Sn-Li paths present in this material

Sn-O distances remain constant, likely indicative of surface contamination

Sn_4P_3/graphite coordination numbers

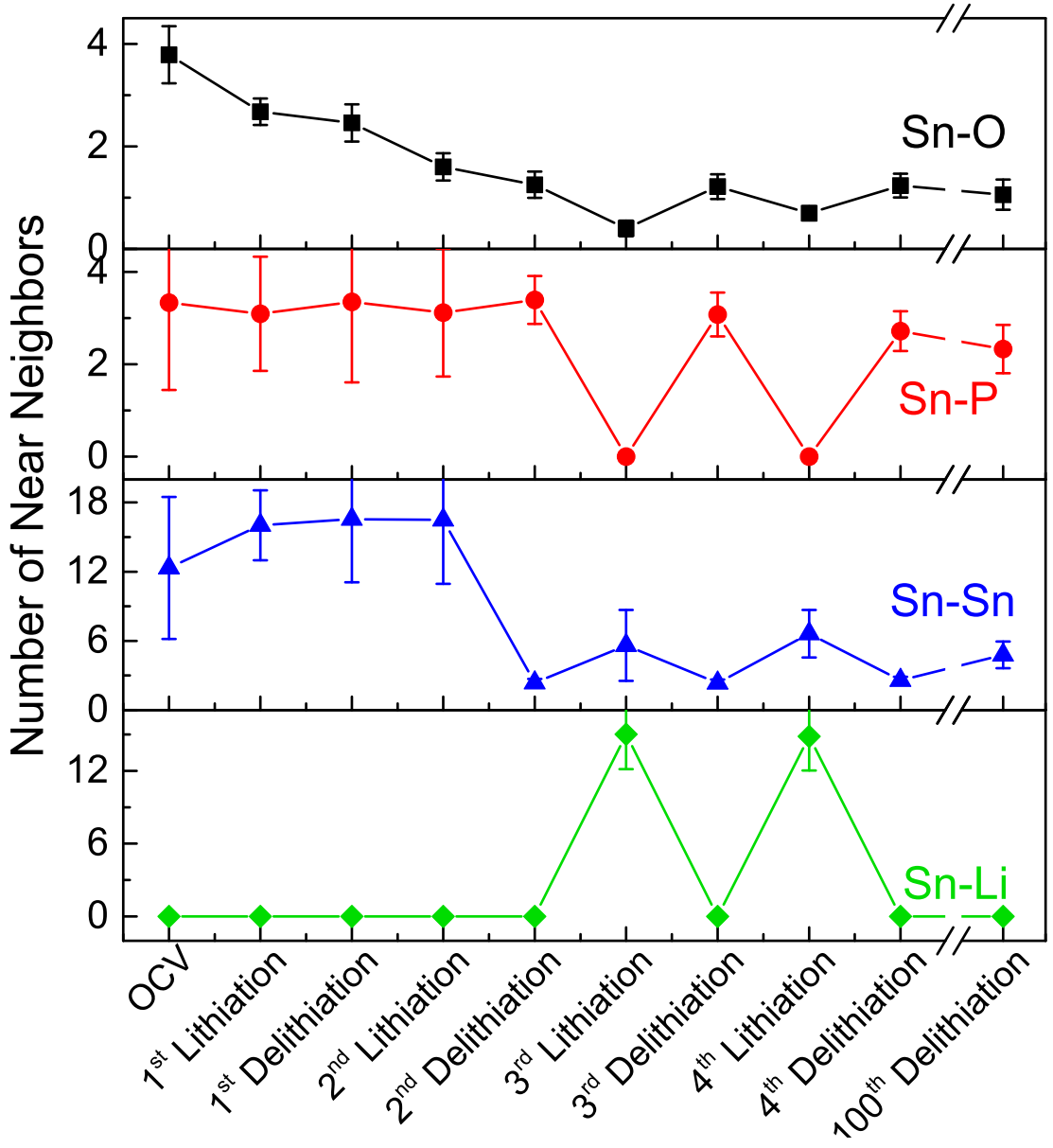
Sn-O neighbors decrease quickly, remaining small and partially reversible up to 100 cycles

Sn-P reversible after initial conversion with a slow decrease which correlates to capacity loss

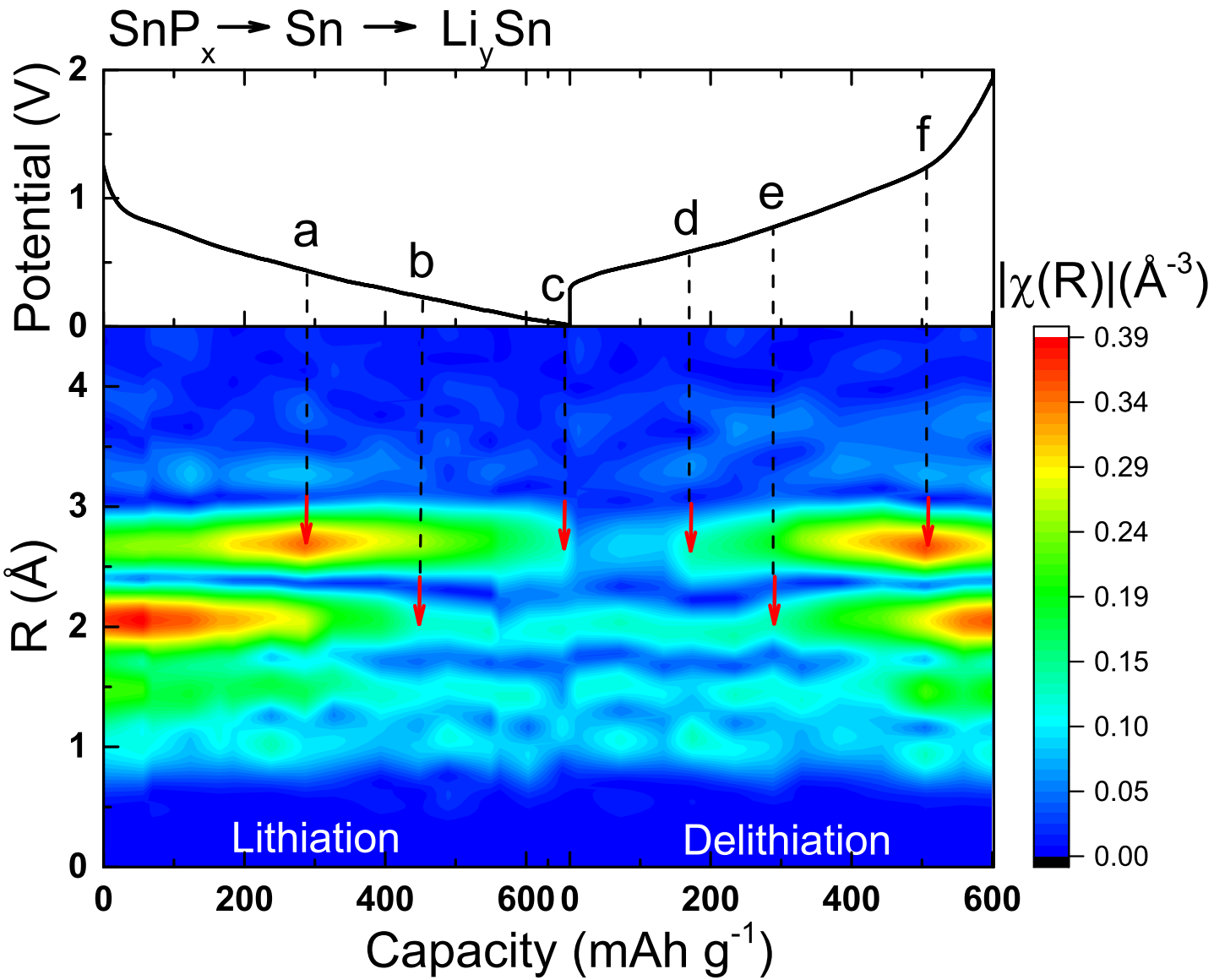
Very small Sn-Sn metallic clusters present throughout

The ~3.3 Sn-P neighbors in the delithiated state indicate a possibly tetrahedral Sn coordination in SnP_x

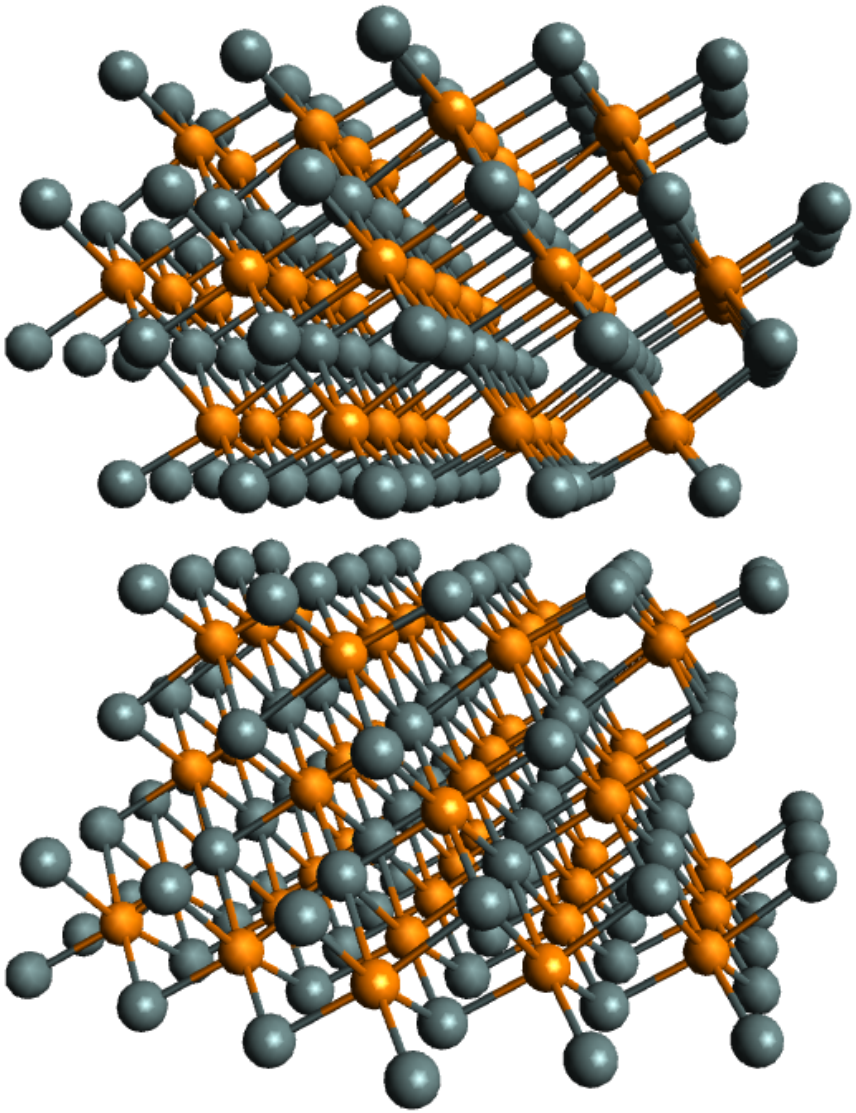
15 Sn-Li neighbors correspond to nearly full lithiation and fade with capacity.



Third cycle dynamic snapshot



Keys to Sn_4P_3/graphite reversibility



Graphite nanoparticle composite

- provides high electronic conductivity
- inhibits Sn nanoparticle aggregation
- promotes amorphous SnP_x formation

Reversibility of amorphous SnP_x phase and surrounding Li_3P

Structure of initial Sn_4P_3 material may be beneficial

Ball milled composites being tested for Sn, SnO_2, and SnS_2 nanoparticles

Further improvements to the in-situ cell needed to make better *in situ* studies possible

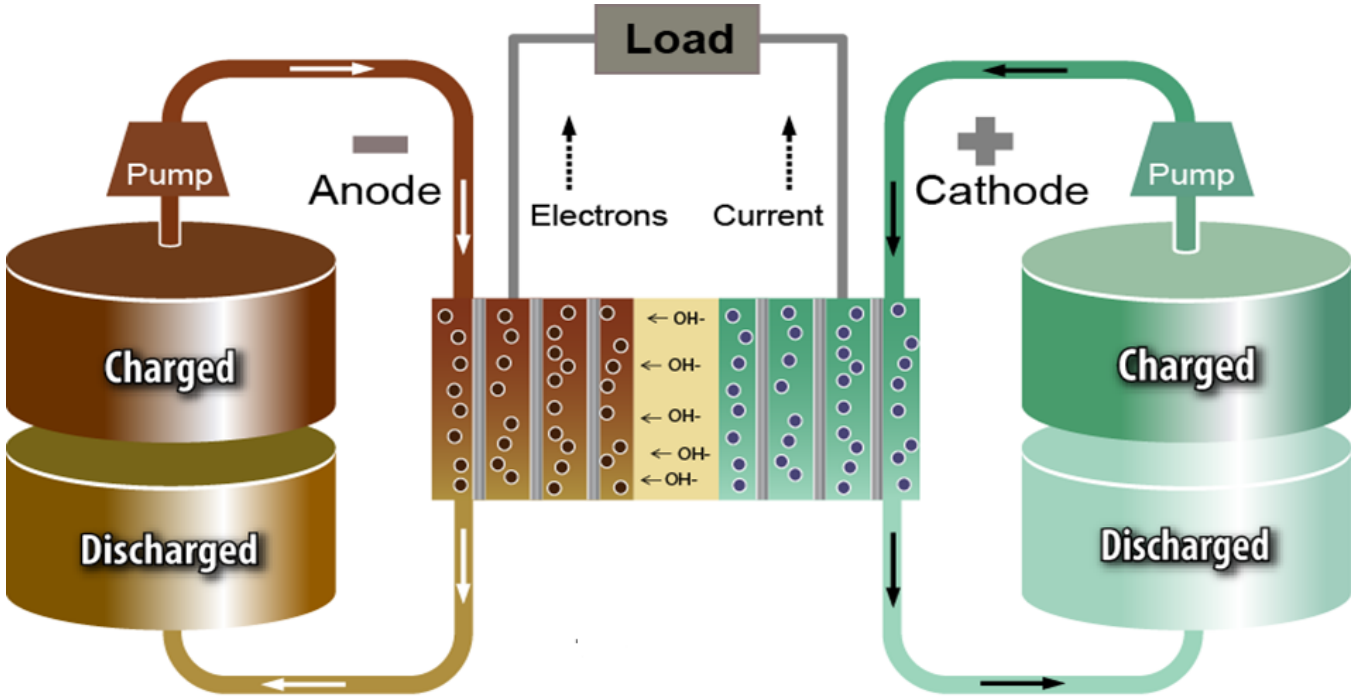
Principal collaborators - Thank you!

- Christopher Pelliccione – IIT Physics (Ph.D. student)
- Yujia Ding – IIT Physics (Ph.D. student)
- John Katsoudas – IIT (MRCAT staff)
- Elena Timofeeva – IIT Chemistry

Supported by

- Department of Energy ARPA-e Grant
- Department of Education GAANN Grant
- National Science Foundation MWN Grant
- Duchossois Leadership Program at Illinois Tech

Nanoelectrofuel flow battery



Suspended electroactive nanoparticles

Advantages of flow batteries

Energy density of solid state

Chemistry agnostic
aqueous or non-aqueous

Initial arpa·e funding

IIT/Argonne collaboration

Prototype: 1 kWh total energy stored
40 V, C/3 discharge rate

Develop commercialization plan

Advantages of nanoelectrofuel

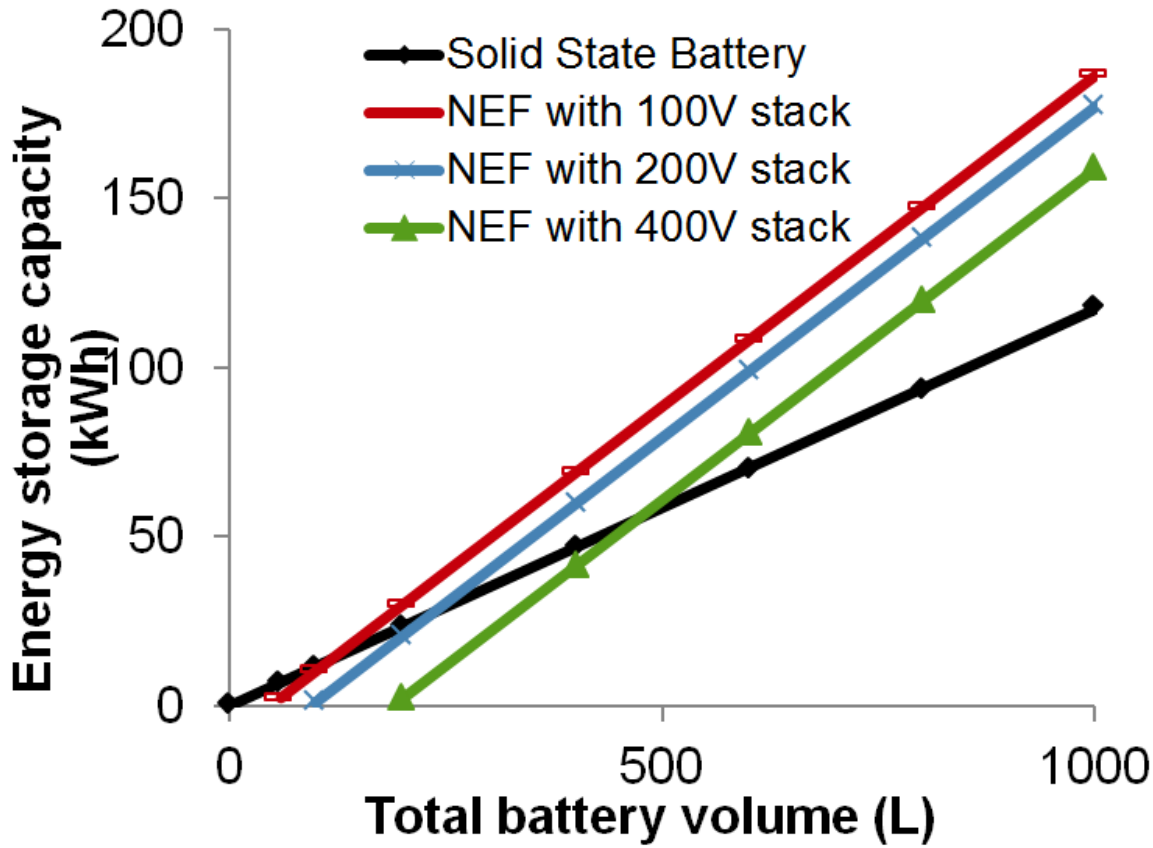
of active material in solid batteries

of active material in NEF flow batteries

initial overhead for power stack depends on desired voltage

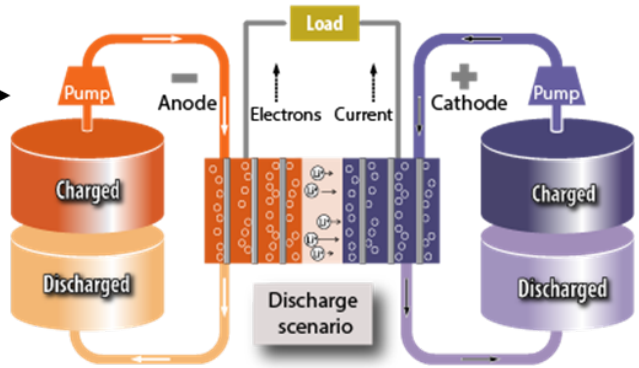
active material fraction depends on loading (50% shown)

beyond 50 kWh, NEF has higher volumetric capacity



Long term vision

Energy Generation Avenues



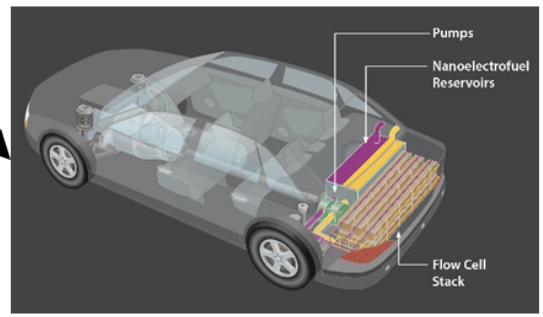
Nanoelectrofuels Charging

Enables Rate Shifting and Grid Leveling

Charged suspension to markets

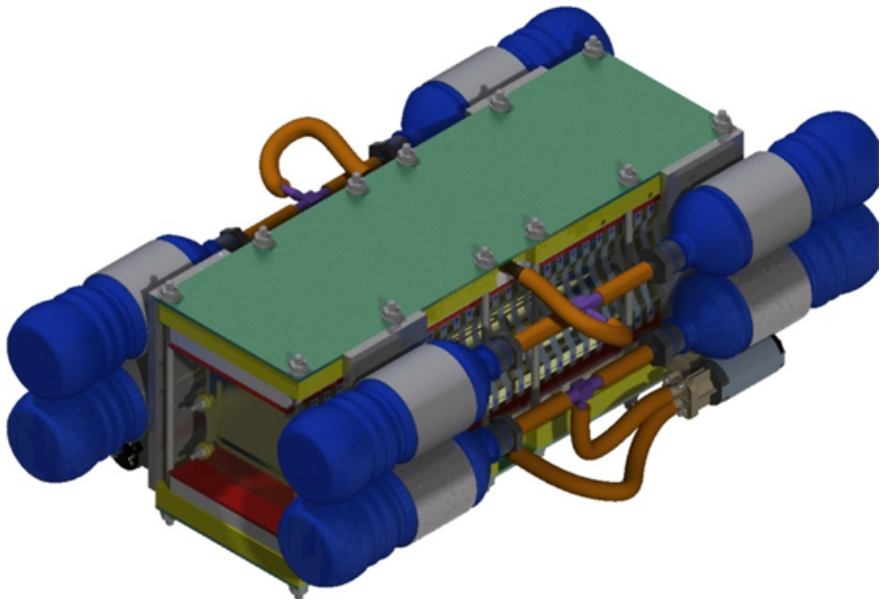
Enables V2H macro and micro grid applications

Rapid pump EV refueling



Nanoelectrofuel challenges

- What is the intrinsic performance of active materials in nanoparticle form?
- Can suspended nanoparticles be effectively charged and discharged during flow?
- How much loading can be stabilized in suspension?
- Will these nanoelectrofuels be pumpable and not destroy the enclosure materials?
- Can the technology be econmical enough to compete with more established technologies?



40 V aqueous chemistry stack

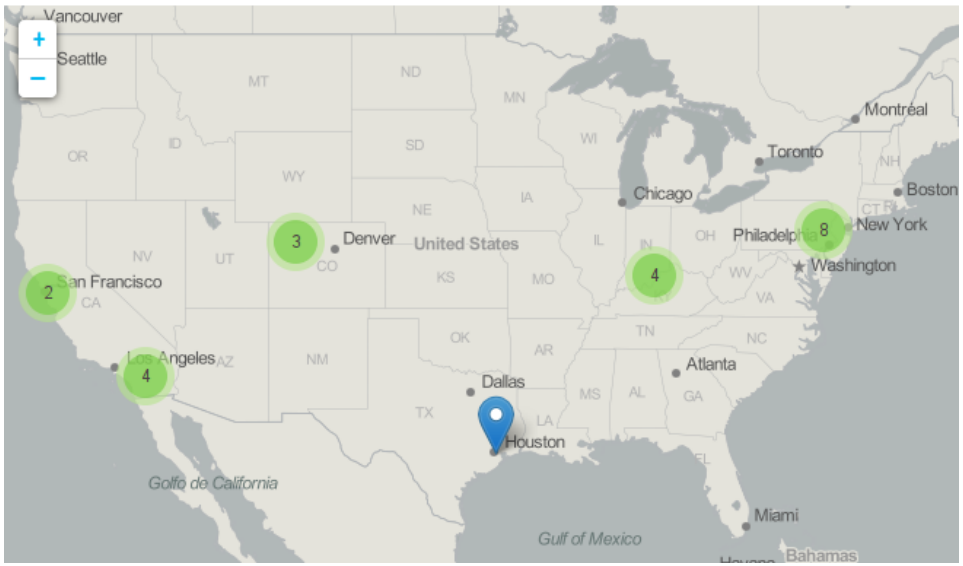
25 kWh using 4.5 L of nanoelectrofuel

26 kg stack, 10 kg 50% loaded fluid

70 Wh/kg (compare to 40 Wh/kg for Pb-acid)

Initial funding: the RANGE program (2014-2015)

Robust **A**ffordable **N**ext **G**eneration **E**nergy Storage Systems



Develop transformational electrochemical energy storage technologies for electric vehicles (EVs)

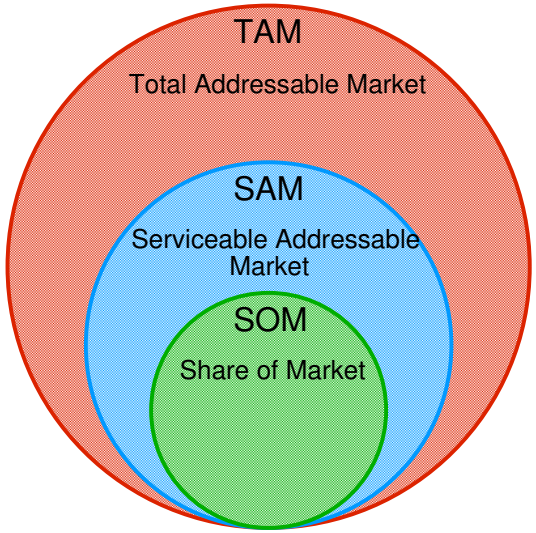
- provide greater EV driving range
- reduce overall weight of the vehicle
- maximize the overall energy stored in a vehicle
- enhance safety
- minimize manufacturing costs
- enable greater design flexibility for manufacturers

22 projects across the United States

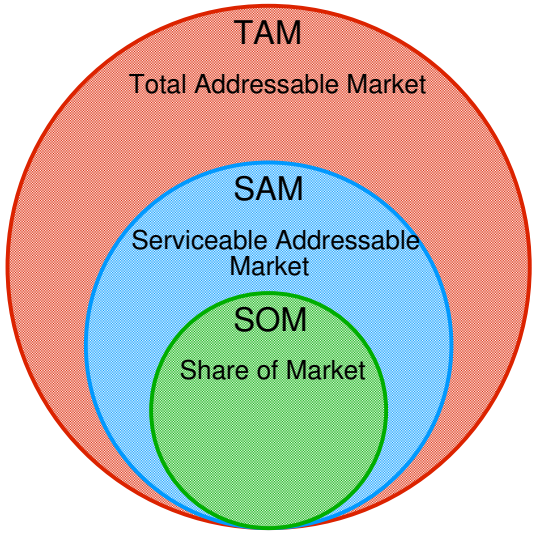
The I-Corps experience

The I-Corps experience

Participated in the I-Corps Energy & Transportation program sponsored by Next Energy in Detroit



The I-Corps experience



Participated in the I-Corps Energy & Transportation program sponsored by Next Energy in Detroit

- initial goal to grow the EV market by providing a better battery

Total Automotive Market

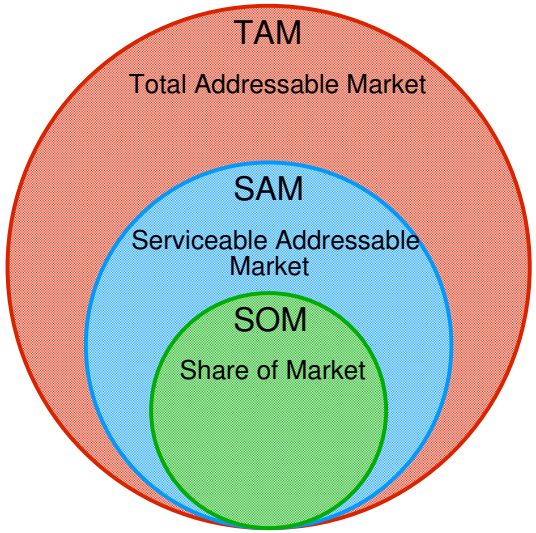
TAM – $40B

SAM – $10B

SOM – $ 2B

NEXTENERGY
ask us what's next

The I-Corps experience



Participated in the I-Corps Energy & Transportation program sponsored by Next Energy in Detroit

- initial goal to grow the EV market by providing a better battery
- conducted over 60 customer interviews in 1 month

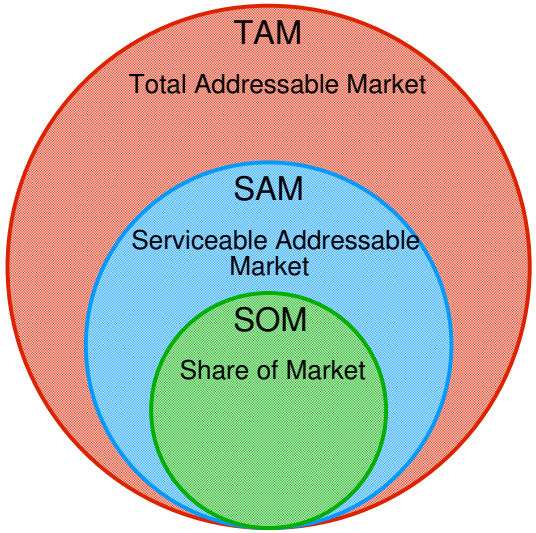
Total Automotive Market

TAM – $40B

SAM – $10B

SOM – $ 2B

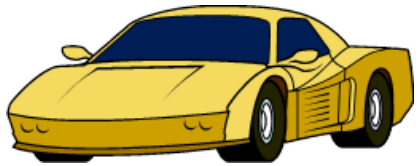
The I-Corps experience



Participated in the I-Corps Energy & Transportation program sponsored by Next Energy in Detroit

- initial goal to grow the EV market by providing a better battery
- conducted over 60 customer interviews in 1 month
- complex and interconnected value supply chain

Current EV Market



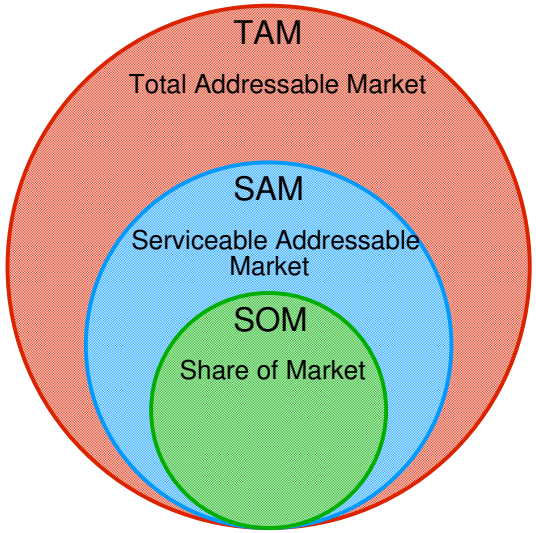
TAM – $720M

SAM – $140M

SOM – $ 7M

NEXTENERGY
ask us what's next

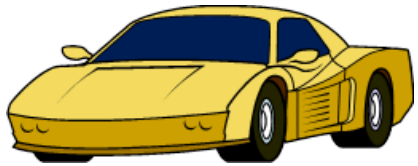
The I-Corps experience



Participated in the I-Corps Energy & Transportation program sponsored by Next Energy in Detroit

- initial goal to grow the EV market by providing a better battery
- conducted over 60 customer interviews in 1 month
- complex and interconnected value supply chain
- 10-20 years to break into the automotive supply chain!

Current EV Market



TAM – $720M

SAM – $140M

SOM – $ 7M

The I-Corps experience

Electric utility vehicles (EUVs) can bridge the "valley of death"

Participated in the I-Corps Energy & Transportation program sponsored by Next Energy in Detroit

- initial goal to grow the EV market by providing a better battery
- conducted over 60 customer interviews in 1 month
- complex and interconnected value supply chain
- 10-20 years to break into the automotive supply chain!

Current EUV Market

TAM – $600M

SAM – $300M

SOM – $ 75M

The I-Corps experience

Electric utility vehicles (EUVs) can bridge the "valley of death"

- EUV market 5× larger than EV

Participated in the I-Corps Energy & Transportation program sponsored by Next Energy in Detroit

- initial goal to grow the EV market by providing a better battery
- conducted over 60 customer interviews in 1 month
- complex and interconnected value supply chain
- 10-20 years to break into the automotive supply chain!

Current EUV Market

TAM – $600M

SAM – $300M

SOM – $ 75M

The I-Corps experience

I-CORPS NSF Innovation Corps

Participated in the I-Corps Energy & Transportation program sponsored by Next Energy in Detroit

- initial goal to grow the EV market by providing a better battery
- conducted over 60 customer interviews in 1 month
- complex and interconnected value supply chain
- 10-20 years to break into the automotive supply chain!

Electric utility vehicles (EUVs) can bridge the "valley of death"

- EUV market 5× larger than EV
- simpler vehicles with smaller value supply chain

Current EUV Market

TAM – $600M

SAM – $300M

SOM – $ 75M

NEXTENERGY ask us what's next

The I-Corps experience

Participated in the I-Corps Energy & Transportation program sponsored by Next Energy in Detroit

- initial goal to grow the EV market by providing a better battery
- conducted over 60 customer interviews in 1 month
- complex and interconnected value supply chain
- 10-20 years to break into the automotive supply chain!

Electric utility vehicles (EUVs) can bridge the "valley of death"

- EUV market 5× larger than EV
- simpler vehicles with smaller value supply chain
- lead-acid batteries must be replaced every year

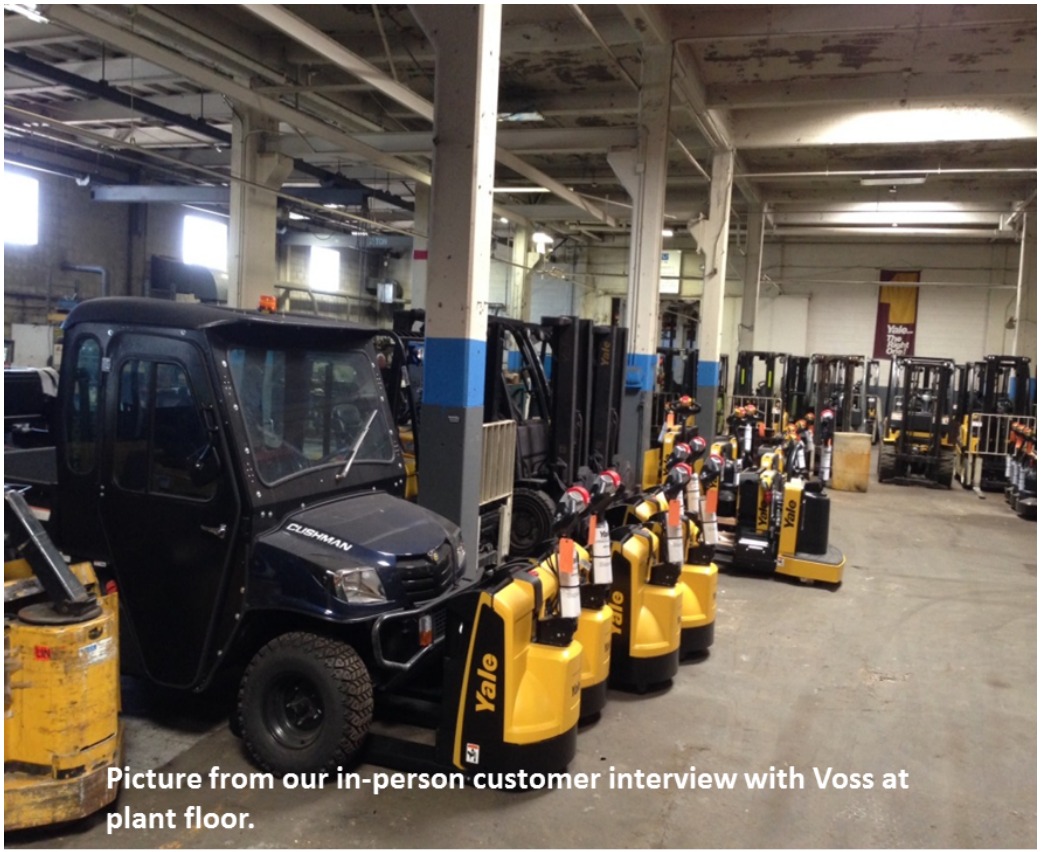
Current EUV Market

TAM – $600M

SAM – $300M

SOM – $ 75M

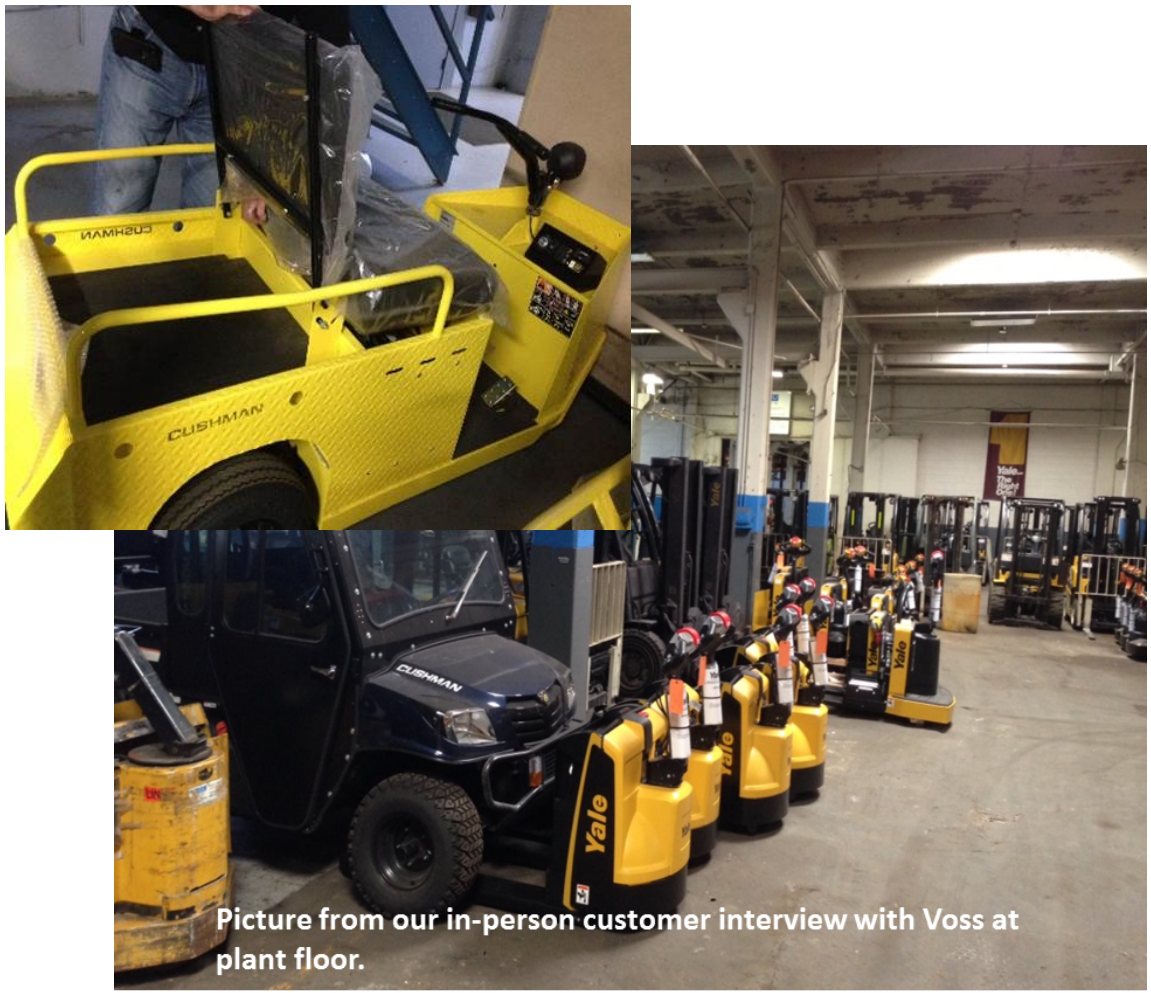
The first product



Picture from our in-person customer interview with Voss at plant floor.

EUVs and fork lifts are already predominantly electric

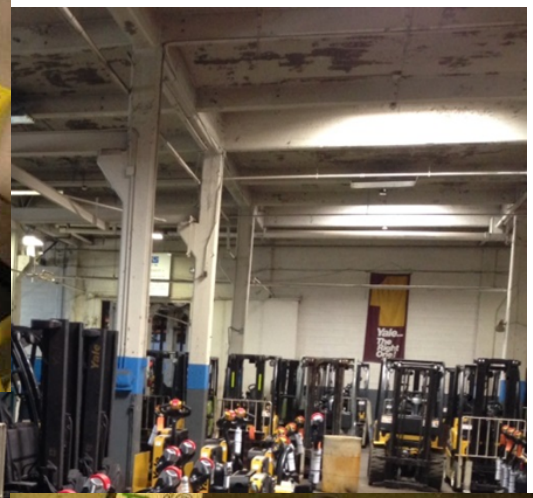
The first product

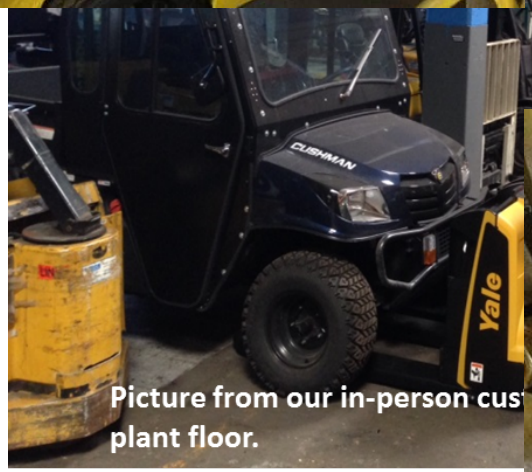


EUVs and fork lifts are already predominantly electric

batteries replaced at factory each year

The first product





EUVs and fork lifts are already predominantly electric

batteries replaced at factory each year

typical motor is 36-40V

The first product

EUVs and fork lifts are already predominantly electric

batteries replaced at factory each year

typical motor is 36-40V

4-pack of lead-acid batteries are most common

The first product

EUVs and fork lifts are already predominantly electric

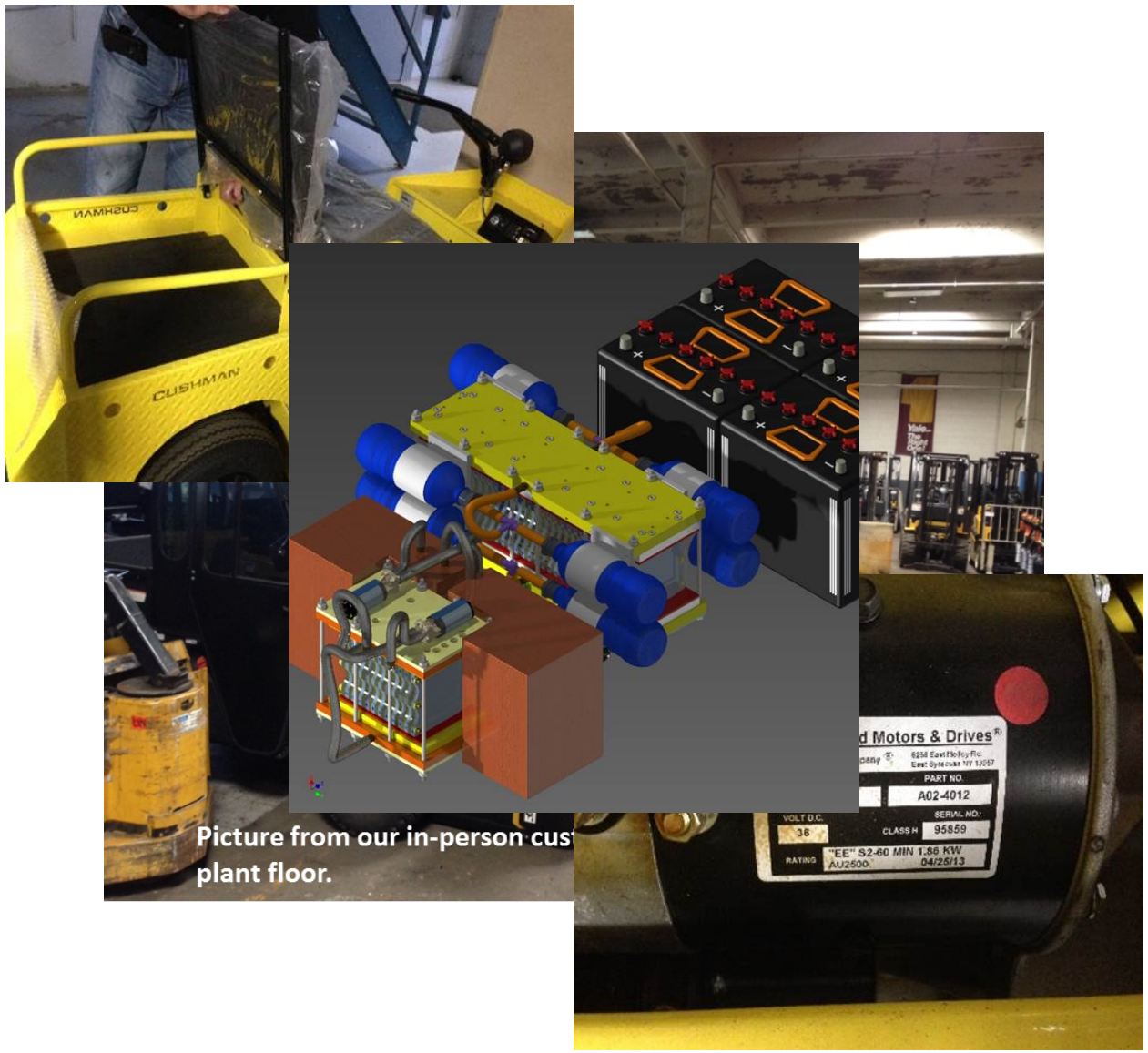
batteries replaced at factory each year

typical motor is 36-40V

4-pack of lead-acid batteries are most common

12-hour charge cycle required between uses

The first product



EUVs and fork lifts are already predominantly electric

batteries replaced at factory each year

typical motor is 36-40V

4-pack of lead-acid batteries are most common

12-hour charge cycle required between uses

a perfect match for our nanoelectrofuel prototype battery

Three years on... NSF Phase I SBIR